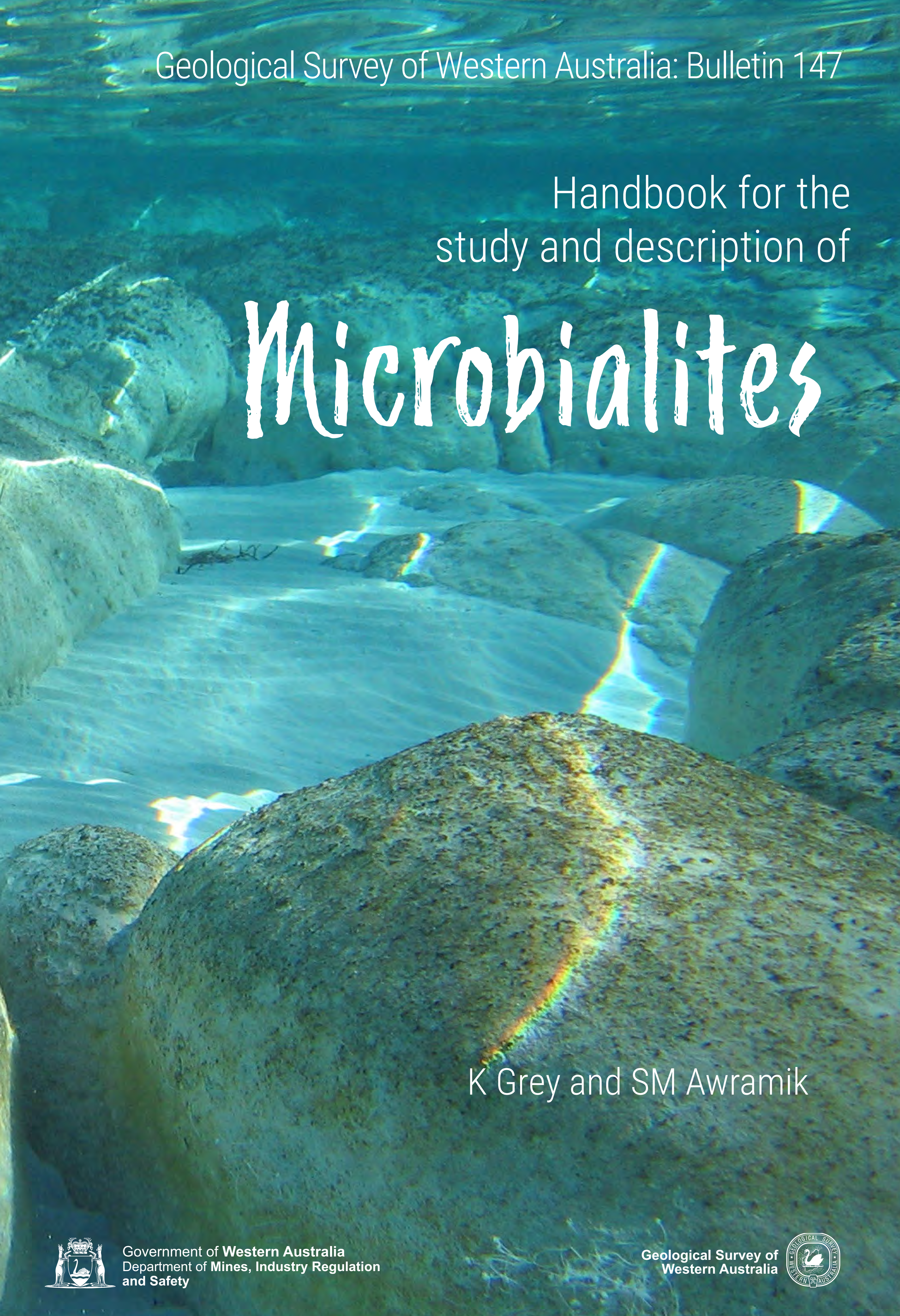

Geological Survey of Western Australia: Bulletin 147

Handbook for the study and description of Microbialites

K Grey and SM Awramik

Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

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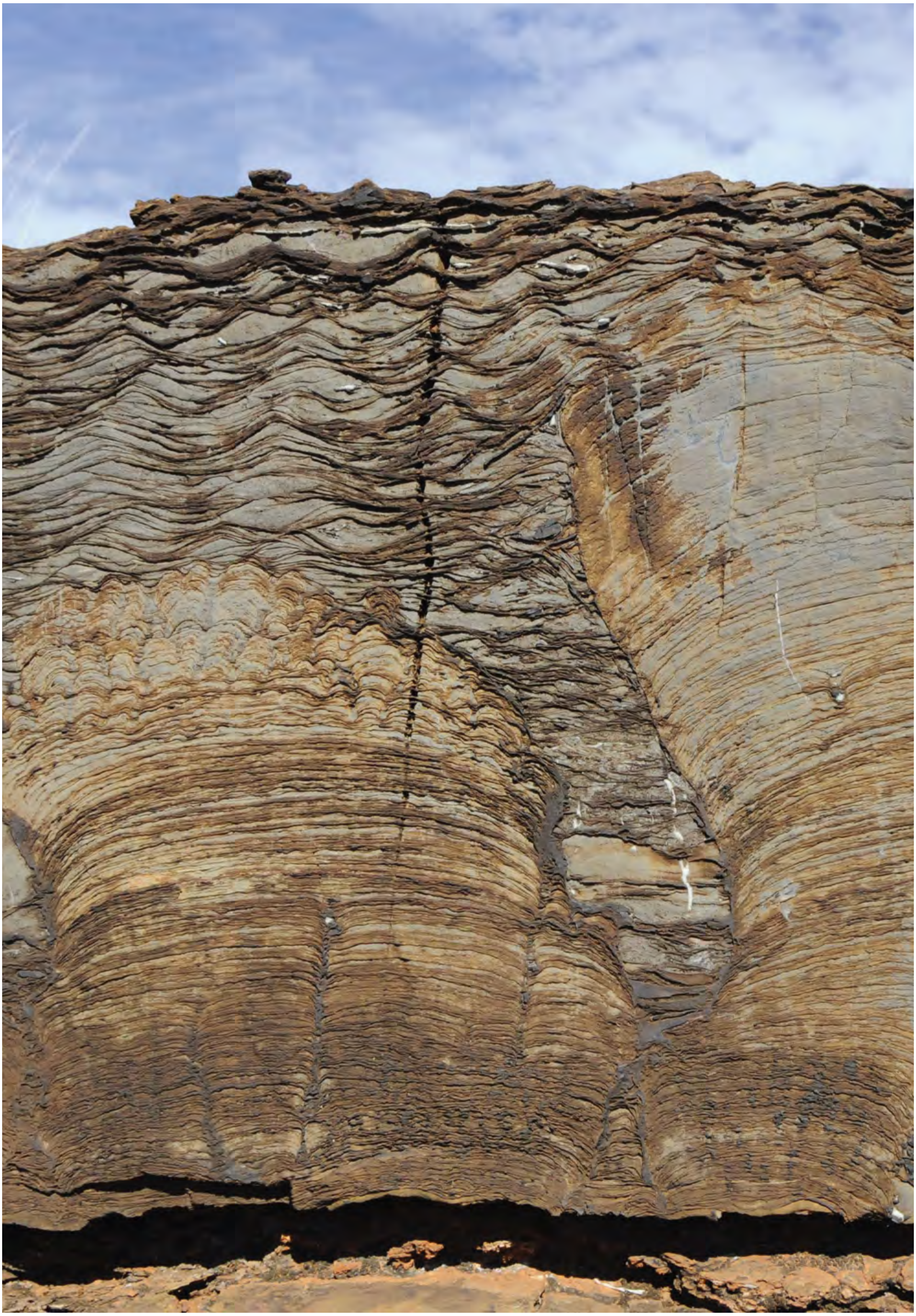

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BULLETIN 147

HANDBOOK FOR THE STUDY AND DESCRIPTION OF MICROBIALITES

by
K Grey and SM Awramik

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REFERENCE
The recommended reference for this publication is:
Grey, K and Awramik, SM 2020, Handbook for the study and description of microbialites: Geological Survey of Western Australia, Bulletin 147, 278p.

ISBN online 978-1-74168-861-0**; print** 978-1-74168-862-7
ISSN online 1834-2353**; print** 0508-4741

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 50. All locations are quoted to at least the nearest 100 m.

Copy editor: SR White
Cartography: M Prause
Desktop publishing: RL Hitchings
Printed by Daniels Printing Craftsmen

Published 2020 by the Geological Survey of Western Australia
This Report is published in digital format (PDF) and is available online at <www.dmirs.wa.gov.au/GSWApublications>.

Further details of geoscience publications are available from:
Information Centre
Department of Mines, Industry Regulation and Safety
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Front cover: Modern stromatolites at Hamlin Pool, Shark Bay, Western Australia. Photo by SM Awramik

Frontispiece: Columnar fossil stromatolites overlain by sediments with climbing ripples, Neoarchean Tumbiana Formation, Fortescue Basin, Western Australia. Photo by SM Awramik

Back cover montage: (clockwise from top left): 1) *Conophyton* new Form (Balfour type), Stag Arrow Formation, Mesoproterozoic, Western Australia; 2) *Baicalia safia*, Atar Formation, Mesoproterozoic, Mauritania; 3, centre) conical-columnar stromatolite, Tumbiana Formation, Neoarchean, Western Australia; 4) *Conophyton* new Form, Stag Arrow Formation, Mesoproterozoic, Western Australia; 5) minimicrobialites, Furnace Creek Formation, Pliocene, California; 6) thrombolites, Perth Basin, Holocene, Western Australia; 7) ridged stromatolite, Tumbiana Formation, Neoarchean, Western Australia; 8) thrombolite, Perth Basin, Holocene, Western Australia; 9) ?*Acaciella augusta*, Waltha Woora Formation, Neoproterozoic, Western Australia

Foreword

Geological Survey of Western Australia (GSWA) Bulletin 147 **Handbook for the study and description of microbialites** is a landmark publication in microbial paleontology. The authors have decades of experience in this field and this book should be used to guide all future studies. The handbook draws on examples from throughout the world but it is fitting that it is published in Western Australia where stromatolites have proven useful for interpreting the stratigraphy and sedimentology of successions as diverse in age as Archean and Devonian, and where the famous Shark Bay stromatolites and thrombolites form key modern analogues.

Studies of microbialites require there to be a consistent, detailed, agreed set of terms to describe these formations at all scales from the macroscopic in the field to the microscopic in the laboratory. Such an agreement does not yet exist, and to establish that is the primary purpose of this handbook.

Microbialites are morphologically, microstructurally and chemically diverse organosedimentary structures. They are known throughout the rock record back to 3.5 Ga, or controversially back to 3.7 Ga. They are found in deposits interpreted as marine and lacustrine, in former springs, and even as former crusts in deserts. They form the oldest known reefs. Studies in the former Soviet Union, starting in the 1930s, and later studies particularly in Mauritania, China, India and Australia, have identified temporal trends in microbialite morphology, the significance of which has been controversial. Opinions have polarised into two approaches: the morphological trends may represent a sampling of paleoenvironmental variation, or they record evolution of the constructing microbiotas. The truth probably lies in some combination of these two factors.

Whatever the preferred interpretation of the observed or proposed temporal trends, microbialites are a rich repository of information, both environmental and biological. That is especially true of examples from the Archean and Proterozoic when they were particularly abundant. Larger scale features such as the elongation of bioherms or the growth relief of columnar stromatolites have often been related to environmental parameters such as longshore currents and water depth, but less attention has been paid to features at the millimetric or centimetric scale.

In recent years, research on the microbiology of extant microbialites has provided deep insights into their ecology. Studies using microelectrodes have revealed chemical processes at the millimetre scale, and genomic studies have revealed the taxonomic and biochemical complexity of the microbial communities. Microbial mats might be architecturally dominated by cyanobacteria but they are diverse communities with intricate interactions between their component taxa. It follows from this that, as microbes evolved, microbialites will have changed. Cyanobacteria may have been the dominant microbes in microbialites from at least the late Archean, and at some time during the Proterozoic the various phyla of algae will have been added to the microbial communities. Similarly, the arrival of metazoa, presumably during the early Neoproterozoic, will have had substantial consequences.

It is postulated that if life ever existed on Mars, the evidence may be found in the form of microbialites, particularly those formed in thermal springs. At the other end of the spectrum, late Mesozoic lacustrine microbialites have recently captured the attention of the petroleum industry with discoveries of giant microbialite plays off the coasts of Brazil and Angola.

The morphological and microstructural diversity of microbialites is emphasized in this handbook. Decoding this diversity is a challenge; there is a wealth of information waiting to be interpreted. Experience shows that interdisciplinary studies combining microbiology and sedimentology can be fruitful. The approach to the study of microbialites set out here will be an excellent guide for future research.

Emeritus Professor Malcolm Walter AM FAA

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Handbook for the study and description of microbialites

by

K Grey and SM Awramik

Abstract

There has long been a need for a more rational and consistent approach to how stromatolites and other microbialites are described and recorded in the literature. Current practices often lack a methodical approach and discourage adequate description. This, in turn, hinders comparisons and prevents analysis. The abundant microbialites found throughout the rock record are undervalued, diminishing our capacity to interpret the valuable paleobiological, paleoenvironmental and biostratigraphic data contained within them. One of the main problems continues to be the lack of a stable and comprehensive descriptive terminology. The extensive international microbialite literature has been combed for definitions and useful terminology, and these have been consolidated into a rational and systematic manual that should address many of the existing problems that prevent effective comparative studies. The naming of microbialite structures has also been contentious. To overcome this problem and assist biostratigraphers, we are proposing an independent code of nomenclature that continues to recognize the thousands of already named taxa and allows for the description of new taxa. The main thrust of this handbook is to foster effective communication by presenting what should become internationally acceptable procedures and terminology for the study of microbialites.

KEYWORDS: dendrolites, handbook, International Code of Microbialite Nomenclature, leiolites, microbialites, stromatolites, terminology, thrombolites

Introduction

Consistency and clarity in communication are essential for progress in understanding microbialites. The application of standard descriptive methods using well-defined and generally accepted terms is crucial for comparative studies. This microbialite handbook assembles information on the methods of study, terminology, description and nomenclature of microbialites into a single volume, and makes recommendations for how to provide pertinent information to the scientific community.

This publication is the result of many years of research and practical experiences, and reflects our views based on extensive collaboration and consultation with other microbialite specialists. We have comprehensively illustrated the handbook with schematic diagrams and images of examples to assist in descriptions. We have also tried to provide as many pertinent references as possible. One of the problems of preparing a publication of this type is that opinions and practices inevitably vary. Colleagues have contributed in various ways, particularly in the early days of assembling information on microbialites, and are recognized in the acknowledgements.

The handbook is meant to be a guide, not a set of hard and fast rules. It endeavours to present state-of-the-art terminology and descriptive methodology for the study of microbialites.

Background

The handbook had its inception as a result of discussions held under the auspices of International Geological Correlation Program (IGCP) Project 261 'Stromatolites' 1987–91. Two aims of IGCP Project 261 were:

1) 'to clarify the basis of taxonomy by identifying the ground rules and rationalizing taxonomic description through the setting up of an international database on macrostructure and microstructure'

2) 'to facilitate the exchange of ideas and information between experienced and inexperienced stromatolite workers from various countries both in conferences and in the field to develop an international consensus on the techniques for the study and description of stromatolites'.

Work began on a handbook for the study and description of stromatolites in the late 1980s and a preliminary version (Grey, 1989, unpublished) was prepared for comment in the 'Stromatolite Newsletter'. This first draft was based on existing literature and was circulated to elicit comments from other researchers. It was not formally published, but is available online (https://d28rz98at9flks.cloudfront.net/72973/72973.pdf). It was considerably revised by K Grey and SM Awramik in 1990, and circulated to interested parties for comments and additions. About the same time, with regard to the first aim, a taxonomy subgroup of IGCP Project 261 met at the Western Australian Museum, Perth, Western Australia, on 12–16 November 1990, to examine the issue of systematic nomenclature and to evaluate the Code of International Botanical Nomenclature (ICBN) in relation to stromatolite taxonomy. A draft 'Code of Nomenclature for Stromatolites' was circulated for comment. A second draft of the handbook was presented at the International Symposium on Stromatolites and Plenary Meeting of IGCP 261 in Tianjin, People's Republic of China, on 15–17 October 1992 (Project 261 was on extended term). Copies were circulated for comments to interested parties in October–November 1993. Grey and Awramik, having written the text and code, asked others to supply dissenting opinions and alternative approaches where they disagreed with the views expressed. Only a limited number of dissenting views were offered and this was cause for encouragement. However, IGCP 261 officially concluded in 1992 and, without continuing international impetus, work on the handbook then lapsed.

An important focus of IGCP 261 was biostratigraphy. Research on microbialites has largely shifted away from biostratigraphy and has expanded to include the rapidly developing fields of astrobiology and geobiology. There are now more intense debates about determining the biogenicity of microbial-like structures, and verifying evidence of Earth's most ancient life. There is also widespread new research on present-day microbialites, lacustrine microbialites, and the role of microbialites as hydrocarbon reservoirs, the latter by the petroleum industry. This renewed and expanded research provided motivation for Grey and Awramik to revive the handbook. One of the aims was to provide illustrations of individual characteristics, both in theory (using diagrammatical representations) and with images of actual examples. Grey was able to draw on the extensive Geological Survey of Western Australia (GSWA) Paleontology Collection and associated GSWA field database, plus equivalent data from other Australian states, to collate information from more than 4500 records of mainly Precambrian fossils in Australia (dominated by stromatolites) for use as an empirical base for analysing stratigraphic distributions. Awramik was able to utilize his extensive collection of microbialites, which, in addition to Precambrian examples, contains numerous Phanerozoic examples with a large collection of lacustrine samples.

Aims and approach

Terms used in the microbialite literature have not always been rigorously defined or used in a consistent manner. In many cases, original sources of information were difficult to track down. Many terms were never defined or were used in successive publications without acknowledgment of the original paper and author. In some cases, meanings have drifted from the original application and multiple terms have been introduced for a single feature. Sometimes the same term has been used for different features. We provide a comprehensive glossary that tracks some of the history and attempts to eliminate ambiguities. We also provide page numbers for many citations so the reader can easily find where in the publication we obtained the information.

We acknowledge that not everyone will use terms as defined here, and that new terms will be introduced. Where incompatible views appear to be expressed in the literature, the most pragmatic approach is taken (although when appropriate, alternative views are presented). In some cases we have had to make an abitrary decision about which terminology to adopt. We have attempted to integrate the numerous terms employed in the literature into a usable system. In the interest of retaining stability of terminology, we recommend that authors who do not follow the terminology in this glossary explain how and why their usage differs, and that they formally define new or modified terms.

Despite the time it has taken to assemble this volume, we nonetheless regard it as a work in progress. Terminology is still evolving, new microbialites are being discovered, and those previously described in the literature are being reinterpreted. We fully expect future modifications as our understanding of microbialites progresses. This may be particularly true as:

- knowledge increases on microbially induced sedimentary structures (MISS)
- research on the role of microbes in tufa, sinter, travertine and other probable microbially produced structures becomes better known and then integrated with microbialites
- present-day products of microbial activity are better understood
- more examples of thrombolites, dendrolites and leiolites are described
- more comprehensive explanations of microbialite morphogenesis are developed.

Microbialites are significant components of the rock record. They are the most conspicuous evidence of life in the Archean (Lowe, 1980; Walter et al., 1980; Hofmann et al., 1999; Van Kranendonk et al., 2003; Allwood et al., 2007; Wacey, 2010, 2012; Hickman et al., 2011; Tice et al., 2011), with possible examples described from c. 3700 Ma rocks in Greenland (Nutman et al., 2016), although Allwood et al. (2018) questioned their biogenicity. They are a major feature of carbonate systems throughout much of the Proterozoic (Walter et al., 1992; Grotzinger and James, 2000; Semikhatov and Raaben, 2000), they occur in all systems of the Phanerozoic (Monty, 1977; Bertrand-Sarfati and Monty, 1994; Awramik, unpublished), they can be important indicators for paleoenvironmental interpretations (Serebryakov et al., 1972; Whalen et al., 2002; Allwood et al., 2006; Tomás et al., 2013), and can be sources of information on paleoclimates (Abell et al., 1982; Solari et al., 2010; Ghinassi et al., 2012; Petryshyn et al., 2015, 2016). There is good evidence that they can be used for biostratigraphy (Krylov, 1963; Raaben, 1969b; Walter, 1972, 1976a; Preiss, 1972, 1973a,b, 1974, 1976a,b, 1977, 1987; Dolnik and Vorontsova, 1974; Bertrand-Sarfati and Walter, 1981; Zhu, 1982; Golovenok, 1985; Valdiya, 1989; Dolnik, 2000; Hill et al., 2000; Semikhatov and Raaben, 2000; Raaben et al., 2001; Zaitseva et al., 2016), although such claims have been viewed with scepticism by a number of researchers, including Aitken (1967), Kah and Knoll (1996), Grotzinger and Knoll (1999), Turner et al. (2000), McLoughlin et al. (2008, 2013) and Bosak et al. (2013a).

Today, microbialites form in a wide variety of environments, most of them aqueous. The hypersaline marine microbialites from Hamelin Pool, Shark Bay, Western Australia are iconic (Logan, 1961; Logan et al., 1964; Jahnert and Collins, 2011, 2012; Playford et al., 2013; Suosaari et al., 2016). They provided the first widely used living analogue to interpret ancient microbialites (Kaufmann, 1964; Tuke et al., 1966; Aitken, 1967). Normal salinity marine examples are known from the Bahamas (Dill et al., 1986; Reid et al., 1995).

Microbialites are also forming in a wide variety of lacustrine environments including:

- freshwater, such as Pavilion Lake, Marble Canyon, British Columbia, Canada (Laval et al., 2000)
- hyposaline, such as Lake Clifton, Western Australia (Moore, 1987; Moore and Burne, 1994; Burne et al., 2014; Lluesma Parellada, 2015; Warden et al., 2016)
- soda, such as Lake Van, Turkey (Kempe et al., 1991) and Big Soda Lake, Nevada, US (Rosen et al., 2004)
- saline, such as Manito Lake, Saskatchewan, Canada (Last et al., 2012)
- hypersaline, such as Great Salt Lake, Utah, US (Newell et al., 2017) and Lake Thetis, Western Australia (Grey et al., 1990; Grey and Planavsky, 2009)
- on the bottom of permanently ice-covered lakes in Antarctica (Love et al., 1983, Anderson et al., 2011; Hawes et al., 2013; Mackey et al., 2015)
- in fluvial systems (Arenas and Jones, 2017)
- in active springs, both thermal (Walter et al., 1976) and cold (Takashima et al., 2011)
- in caves (Brunet and Revuelta, 2014)
- in calcretes or caliche, some of which involve microbial activity (Zhou and Chafetz, 2009)
- possibly in some soils (microbial earths; Retallack, 2012).

These living examples provide powerful tools to interpret morphologic analogues from the fossil record. The living microbialite can be viewed as a product that resulted from the interaction of microbes with its surrounding environment. The fossil record provides the product from which the processes must be interpreted. Understanding the chemical, physical and biological processes involved in living microbialite formation is critical for the interpretation of ancient microbialites. These processes manifest themselves at different structural levels including the overall shape or the macrostructure, the mesostructural components (lamination, mesoclots, shrubs, structureless), and the microstructure (texture, including fabric). One clear result of studies on living microbialites is that cyanobacteria often dominate the structure and are usually the most common microbes at the sediment–water interface. Thus, they are probably responsible for most macrostructure and mesostructure features. Microbiological studies on living microbialites have mainly relied on microscopy to identify microbes (Winsborough et al., 1994; Reid et al., 1995). Metagenomic analyses and other molecular biology techniques on living microbialites have come up with striking results. The outer, living portion of microbialites has an incredible diversity of microbes belonging to all three domains of life (Burns et al., 2004; Mobberley et al., 2015).

The most successful application of using a living analogue to interpret an ancient microbialite involves conical microbialites. Conical stromatolites are common in the Proterozoic and morphological analogues have been found in permanently ice-covered lakes (Love et al., 1983; Anderson et al., 2011; Hawes et al., 2013; Mackey et al., 2015) and thermal springs (Walter et al., 1976; Jones et al., 1998). They have been grown experimentally (Walter et al., 1976; Bosak et al., 2009). In examples observed in the field (Yellowstone National Park, Wyoming, US) and in laboratory cultures, motile filamentous cyanobacteria produced the cones by tangling together to form knots, which the filaments then used to create a tuft at the apex of the cone (Walter et al., 1976). Oxygen (O_2) released by photosynthesis may also be involved in producing the axial zone (Bosak et al., 2013a) and other possibilities, such as diffusion gradients, have been proposed (Petroff et al., 2010, 2013). However, living microbialites have yet to provide models for many significant features of ancient microbialites, primarily at the macrostructural and mesostructural scale. Surface conditions on the Earth have changed over time. Hoffman (1973, p. 188) stated that the recent 'is not an exact replica of the past' and continued '[t]he interpretation of ancient stromatolites will continue to depend on discoveries of Recent analogs.'

Despite reference to structures that would now be called microbialites in the literature almost 500 years ago by Paracelsus (Krumbein et al., 2003), and thousands of published papers mentioning, illustrating, describing, or discussing microbialites, many problems still exist in their study. This stems in part from both the structural and generative complexity of these biosedimentary constructions, and also because many descriptions of microbialites, both fossil and recent, lack rigorous morphological treatment. Some descriptions are woefully inadequate and illustrations are not included, or when included, are lacking in sufficient number and detail to allow the structures to be properly compared and interpreted. These complexities and our continuing ignorance of the degree to which many biological, physical, chemical, environmental and other factors operate in their generation, make the task much more difficult. Consequently, the abundant microbialites in the rock record and forming today are underrated and the vital (paleo)biological, (paleo)environmental and biostratigraphic data encoded in them are rarely fully utilized.

Analysis has been further hampered by the large number of variable characteristics in microbialites. Individual features are repeated many times throughout the geological record; for example, conical stromatolites with an axial zone have a near continuous record from the 3426–3350 Ma Strelley Pool Formation, eastern Pilbara, Western Australia, to the recent (Hickman et al., 2011). What does seem to be temporally significant is the combination of features. However, in order to demonstrate that a particular permutation of characters is chronologically restricted, it is necessary to record all the attributes and their range of variation. This is also important from a paleoenvironmental perspective: a particular combination of characters might reflect a certain environment. Such comparisons remain difficult without a common terminology.

We have been guided by the principle that a structure needs to be described adequately before it can be interpreted. Description and interpretation are separate activities. It is mainly by comparing and contrasting a feature of unknown origin with one of known origin that its genesis can be determined or more confidently interpreted. Such an exercise depends on a precise, unambiguous terminology that permits subtle differences to be distinguished.

Terms relating to the genesis of the structures are avoided in this handbook as much as possible, although an underlying principle is that microbialites are structures of biogenic or presumed biogenic origin (Awramik and Grey, 2005). We are well aware of the opinions and debate that exist in relation to the descriptive and genetic aspects of words like stromatolite and microbialite (Semikhatov et al., 1979; McLoughlin, 2011, p. 1604–1605). We have not taken lightly our decision to follow the so-called genetic definitions of microbialite as:

> …organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation. (Burne and Moore, 1987, p. 241–242)

The corresponding definition of a stromatolite as a laminated microbialite and adopted here is modified from Awramik and Margulis (1974, p. 5), Awramik and Margulis (cited in Walter, 1976, p. 1), and Burne and Moore (1987):

> …a laminated organosedimentary structure produced by sediment trapping, binding and/or precipitation as a result of the growth, behaviour, and metabolic activity of micro-organisms, principally cyanobacteria.

An alternative abiogenic definition of stromatolite was given by Semikhatov et al. (1979, p. 993) as:

> …an attached, laminated, lithified sedimentary growth structure, accretionary away from a point or limited surface of initiation.

However, many researchers have found this to be too broad, allowing practically any laminated structure to be regarded as a stromatolite (Walter, 1976b). The definition of a stromatolite should exclude 'similar laminated sediments and rocks that result from rhythmic deposition in the absence of microorganisms as organizing elements', as well as 'similar formations recognizable as skeletons of particular encrusting metaphytes and metazoans, such as laminated calcareous rhodophytes (e.g. rhodolites), bryozoans, worms, corals and others' (Lee et al., 2000, p. 16). However, we fully recognize that separating biogenic from abiogenic structures is not straightforward, which makes the biogenic definition problematic to some researchers.

Accepting a microbial influence on the construction of stromatolites positions them as a subset of microbialite, along with thrombolites, dendrolites, leiolites and MISS (Fig. 1) (see 'Microbialites and their constituents'). A hierarchical approach is used to arrange morphological characteristics, ranging from large scale (megastructure), through smaller scale (macrostructure and mesostructure) to microscopic (microstructure) structures (for definitions see 'Size classification and organization of microbialites' and Figs 2–4).

There have been several definitions of thrombolite. Aitken (1967, p. 1164) originally proposed the term thrombolite (from the Greek *thrombos,* bloodclot) for cryptalgal structures that are:

> ….related to stromatolites, but lacking lamination and characterized by a macroscopic clotted fabric. A thrombolitic limestone or dolomite is a rock largely composed of thrombolites, or one possessing a macroscopic clotted fabric of crystalgal [sic] origin.

Some years later, Pratt and James (1982; p. 545) revised the definition to:

> …[a] cryptalgal structure of variable shape, from prostrate to columnar, that may branch and anastomose, that lacks a distinctly laminated fabric, and that usually occurs in groups, imparting a macroscopically clotted appearance to the rock.

Shortly after, Kennard and James (1986, p. 500) stated that a thrombolite is characterized by:

> …a clotted mesoscopic fabric constructed by the penecontemporaneous growth and calcification of discrete colonies or growth forms of coccoid-dominated, internally poorly differentiated, microbial communities.

Kennard and James (1986) also recommended abandoning the definition given by Pratt and James (1982) and returning to that of Aitken (1967). More recently, Shapiro (2000, p. 169) defined a thrombolite as '...a microbialite composed of a clotted mesostructure (mesoclots).' For the purposes of this handbook, the preferred definition for a thrombolite is that of Shapiro (2000).

Riding (1988, p. 5; 1989, p. 11) introduced the term dendrolite for '…biomineralized microbial deposits with a dominant dendritic macrofabric.' Later, Riding (1991, p. 34) added that they were unlaminated. Calcimicrobes have been implicated in their formation (Riding, 1991, p. 34–35; Riding, 2000, p. 194–195), and Shapiro and Rigby (2004, p. 645) defined dendrolite as '…a centimetre-scale fabric dominated by vertically erect or radially oriented branching clusters of calcimicrobes.'

Dendrolite refers to the structure containing shrub-like microbialites, termed shrubs. Here we define dendrolite as:

> …a non-laminated, non-mesoclot-bearing microbialite composed of smaller, non-laminated dendritic microbialites, termed shrubs.

A leiolite was defined as 'a relatively structureless, aphanitic, macrofabric lacking clear lamination, clots or dendritic fabrics' (Riding, 2000, p. 195). (In the terminology of this handbook, macrofabric used by Riding equates to mesostructure.)

Microbially induced sedimentary structures (MISS) were defined as 'structures and textures in siliciclastic sediments [that] can be related to microbial activity' (Noffke et al., 1996, p. 315).

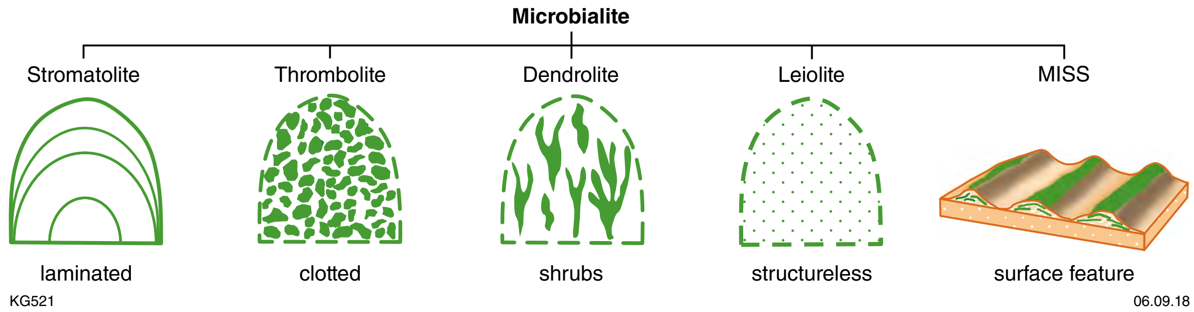

Figure 1. **Subsets of microbialite (after Grey and Planavsky, 2009, fig. 13). Abbreviation: MISS, microbially induced sedimentary structures**

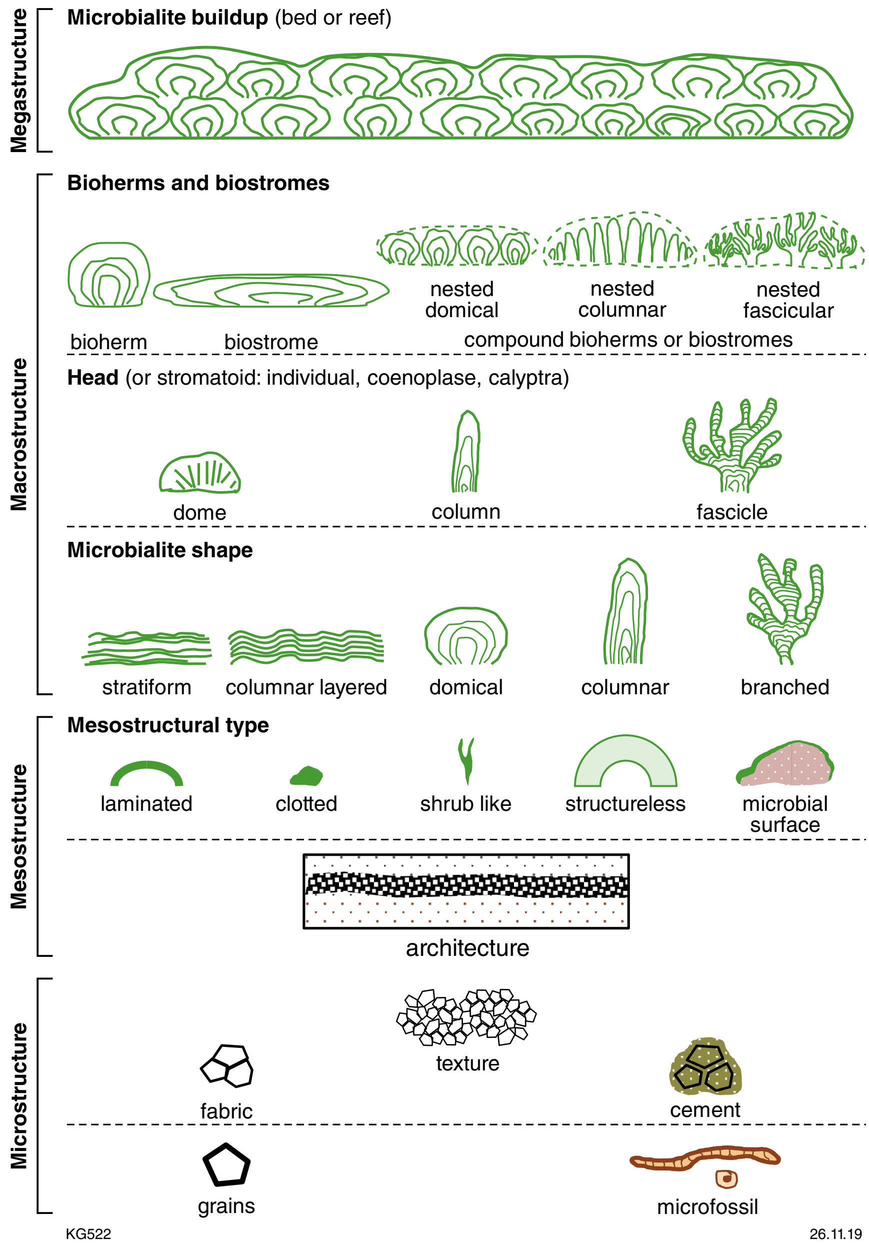

Figure 2. **Components of microbialite-bearing beds**

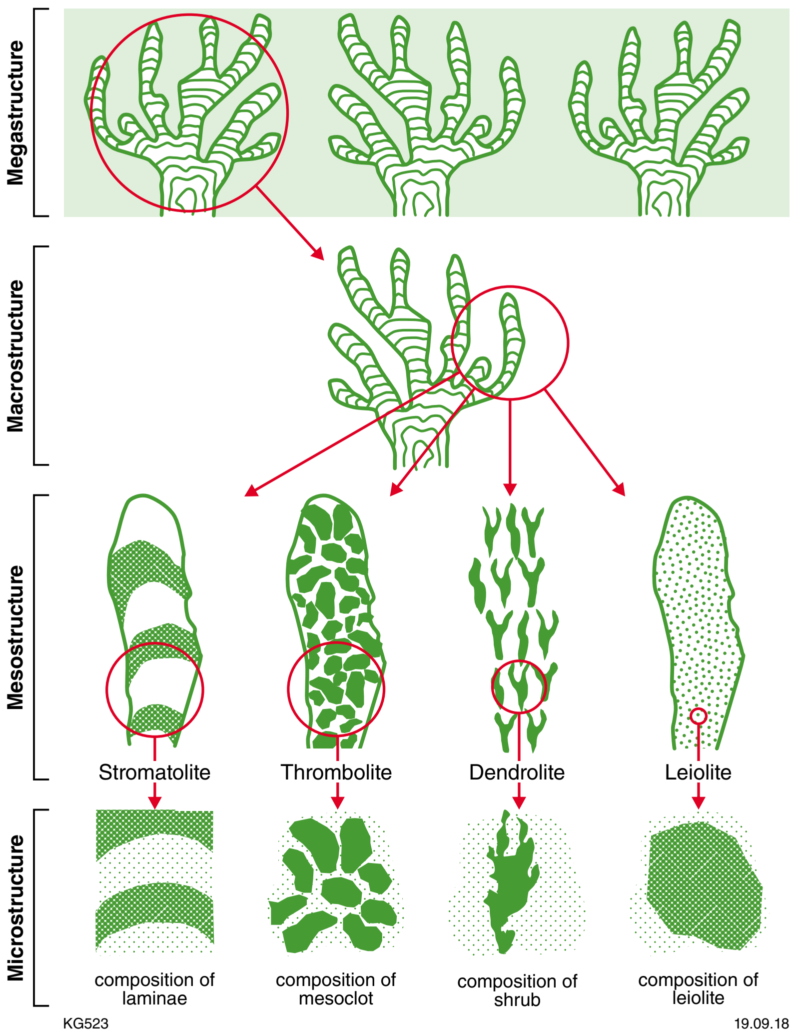

Figure 3. Hierarchy of observational levels for microbialites

Width (m)	Scale	Classification
	kilometric	gigamicrobialites (>100 m)
10^3	hectometric	
	decametric	megamicrobialites (1–100 m)
	metric	
10^0	decimetric	macromicrobialites (10–100 cm)
	centimetric	mesomicrobialites (1–10 cm)
	millimetric	minimicrobialites (1–10 mm)
10^{-3}	submillimetric	micromicrobialites (<1 mm)
10^{-6}		

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Figure 4. Size classification of microbialites (adapted from Hofmann, 2000, fig. 4)

We also recognize that there are other types of microbialites in addition to the five major catagories mentioned above. Among the other types in which microbial activity has been implicated wholly or in part are travertines (Chafetz and Folk, 1984; Pentecost, 2005), sinter (Konhauser et al., 2001), tufa (Gradzinski, 2010; Pope and Grotzinger, 2000), calcretes (terrestrial stromatolites; Wright, 1989), biocrusts (Belnap, 2013), hydrothermal vents (Emerson and Moyer, 2002), and speleothems (Boston et al., 2001).

The approach and terms presented in the handbook were developed mainly for fossil microbialites, especially Proterozoic stromatolites because they are the most studied. Many of the terms can be readily applied to Holocene, Phanerozoic and Archean microbialites, and many abiogenic structures that resemble microbialites (here referred to as dubiomicrobialites and pseudomicrobialites).

History, description, nomenclature and taxonomy

The history of microbialite studies has been widely discussed. Some of the most pertinent reviews are given in Cloud (1942), Maslov (1960), Vologdin (1962), Krylov (1963), Hofmann (1969a, 1973, 1981, 2000), Aitken (1967), Walter (1972, 1976a), Semikhatov (1976), Flügel (1977), Monty (1977), Bertrand-Sarfati and Walter (1981), Krumbein (1983), Schopf (1983a), Awramik (1984, 1992a), Cohen et al. (1984), Riding (1991, 1999, 2000), Schopf and Klein (1992), Bertrand-Sarfati and Monty (1994), Grotzinger and James (2000), Grotzinger and Knoll (1999), Riding and Awramik (2000), Semikhatov and Raaben (2000), Cao (2003), Krumbein et al. (2003), Awramik and Grey (2005), Reitner et al. (2011), Riding (2011a,b), Seckbach and Oren (2010), Tewari and Seckbach (2011), Bosak et al. (2013a), McLoughlin et al. (2013), Chen and Lee (2014), Lee (2015), Leis and Stinchcomb (2015), and Yamamoto and Isozaki (2015). Readers are referred to these publications for summaries.

Despite the extensive literature, many questions remain unanswered, including (but not limited to):

- the degree to which biotic processes influence microbialite formation, shape and specific characteristics, such as microstructure
- the interaction between environmental factors and biotic factors in microbialite construction
- establishing criteria to differentiate microbialites from abiogenic structures.

Where it can be demonstrated that microorganisms did not contribute to formation of the structure, avoid calling the structures microbialites or stromatolites; instead, it is better to follow Hofmann's (1972) introduction of the concept of dubiofossil, and use the terms *dubiomicrobialites* (*dubiostromatolites*) or *pseudomicrobialites* (*pseudostromatolites*) (Awramik and Grey, 2005). The term stromatoloid, introduced by Oehler (1972) for structures of uncertain origin that resemble stromatolites, is similar to dubiostromatolite. Stromatoloid has been used by several authors, including Buick et al. (1981), Dahanayake et al. (1985) and Wacey et al. (2009). The term abiogenic stromatolite is an oxymoron by definition (herein).

Three very different premises, first put forward by Krylov (1976), on the relationships among microbialites, the constructing microbiota, and the structure that results, have emerged from microbialite studies:

- neither the microbiota nor the environment alone plays a role in determining microbialite morphology
- the microbiota plays a role in constructing microbialites, but has no role in determining their shape (meso- and macrostructure), which is usually determined by chemical and physical environmental factors. The shape of the microbialite varies with environmental conditions (i.e. different microbial mats will produce similar morphologies under comparable environmental conditions, and similar microbial mats will form different morphologies under different environmental conditions)
- the biological makeup of the constructing microorganisms is a major factor in determining microbialite morphology (which varies consistently within definable limits), but there may be limited modifications by environmental conditions. It must be remembered that environmental factors influence the microbes that live in the environment and environmental factors have changed with time.

These views are not new and are still hotly debated. Cloud (1942, p. 374) elegantly stated: 'It is perhaps well to remind the reader that many objects resembling stromatolites may be inorganic in origin. On the other hand, some structureless masses of limestone or dolomite may be the result of algal precipitation of carbonates.'

The second of the above premises has been used to question or express reservations concerning the validity of microbialite biostratigraphy because of the influence of environment or because mesostructural and macrostructural control by the microorganisms that built them cannot be demonstrated in almost all cases (Cloud, 1942; Golovenok, 1985; Grotzinger, 1989; Grotzinger and Kasting, 1993; Grotzinger and Rothman, 1996; Kah and Knoll, 1996; Knoll, 1996, 2000; Knoll et al., 1989; Grotzinger and Knoll, 1999; Turner et al., 2000; McLoughlin et al., 2013; Bosak et al., 2013a).

By contrast, biostratigraphers find that stromatolites are useful for basinwide chronostratigraphic correlation (Allen et al., 2016) and, therefore, tend to accept the third premise and use this as the basis of their justification for erecting microbialite biostratigraphic schemes. The debate is not pursued here because the aim of the handbook is to provide an objective means of describing microbialites and related structures, and thus provide rigorous descriptions that will allow the differing opinions to be tested.

Before satisfactory testing of these three approaches can be carried out, it is essential that the evidence put forward for the various arguments be presented or understood in a comparable and compatible descriptive style. Accurate and rigorous description and the correct use of a standard terminology should enable any researcher to recognize the salient features of a microbialite described by another researcher, regardless of whether the description was originally for microbiological, paleobiological, sedimentological, biostratigraphic, paleoenvironmental or other purposes. Our approach has been to synthesize information that will aid in the collection, study, and description of microbialites. Much of this information is already published, but is scattered throughout the literature and written in many languages.

The naming of individual microbialite structures has been, and remains, controversial, and opinions have often been diametrically opposed — for example, compare Rezak (1957) with Semikhatov and Raaben (2000), and see below under 'Historical perspective on naming microbialites'. Disagreements abound. Nomenclature is most commonly applied to stromatolites for biostratigraphic purposes and stromatolite taxonomists justify the use of Linnean nomenclature on practical grounds (Cloud and Semikhatov, 1969; Semikhatov and Raaben, 2000; Shapiro, 2007). As Shapiro (2007, p. 388) pointed out in his analogy with trace fossils:

> It is not necessary to know the taxonomic affinity of the trace maker, nor does the trace itself need to evolve in a Darwinian fashion. The only requirement for utility is that the trace is unique, recognizable, and temporally constrained.

These criteria are satisfied by many Proterozoic stromatolites that have been named. The successful employment of stromatolite biostratigraphy in such places as Russia, India, China and Australia justifies its use on pragmatic grounds (Walter, 1972; Preiss, 1972, 1973a,b, 1974, 1976a,b, 1977, 1987; Semikhatov, 1974, 1976, 1991; Bertrand-Sarfati and Walter, 1981; Zhu, 1982; Grey, 1984, 1986a,b, 1994a,b, 1995, 2008; Grey and Thorne, 1985; Valdiya, 1989; Grey and Corkeron, 1998, Grey and Blake, 1999; Dolnik, 2000; Hill et al., 2000; Semikhatov and Raaben, 2000; Raaben et al., 2001; Cao, 2003; Medvedev et al., 2005; Filhol and Fairchild, 2011; Allen et al., 2012, 2016; McLoughlin et al., 2013, p. 1311; Sharma and Pandey, 2012; Zaitseva et al., 2016). We realize that most researchers working on microbialites will not name them. Nevertheless, biostratigraphic taxonomists tend to develop the most rigorous approaches to descriptive terminology and we have relied heavily on their research, as well as our own, in putting together this handbook.

Non-binomial (non-biological) methods of classifying and naming stromatolites (microbialites) have been proposed. Several approaches have been put forward, although none has been widely accepted. They include:

- polynomial systems proposed by Maslov (1953, 1960) and discussed by Hofmann (1969a) and Walter (1972)
- descriptive formulae of Logan et al. (1964)
- descriptive adjectives of Donaldson (1963, p. 7) and recommended by Aitken (1967, p. 1166)
- shape and lateral extension of laminae (Szulczewski, 1968).

See 'Recommendations for microbialite nomenclature'.

In addition, some other approaches have been proposed — the numerical approach of Cao and Bian (1985) and the microstructure approach of Komar (1989).

Usually those who advocate using non-binomial approaches have used them to classify only a small number of specimens. Few have attempted to categorize, compare and correlate microbialites at a basinwide or even intrabasinal level. These alternative approaches have not been widely adopted, and binomial nomenclature and taxonomy remain the most widely used and effective approach (Semikhatov and Raaben, 2000). The problems of finding an acceptable means of classifying and naming microbialites are discussed in more detail under 'Recommendations for microbialite nomenclature'. We propose an independent Code of Microbialite Nomenclature as a means of conserving existing names and naming practices because names erected over more than a century of descriptive work are no longer acceptable under the umbrella of the International Code of Nomenclature for algae, fungi and plants (ICNafp), the Melbourne Code (McNeill et al., 2012) and Shenzhen Code (Turland et al., 2018), here referred to as ICN.

Like many authors, we are uncomfortable with applying the terms genus and species to structures that are sediment–microbial ecosystem constructs rather than individual organisms. Maslov (1953) used the Russian terms 'gruppa' (plural 'gruppy') and 'forma' (plural formae) instead of genus and species, and this was followed by Korolyuk (1960a,b), Krylov (1963) and others in recognition that the taxonomy is an artificial one. Gruppa and forma have been customarily translated into the English 'group' and 'form' but in English usage group and form are common, everyday words that can create endless problems in writing microbialite descriptions when used in a specific sense as substitutes for genus and species. They can create havoc with carefully laid out text, increasing the authors' workload. Group can refer to a broad association of forms in a non-specific sense, to say nothing of the use of 'group' in the stratigraphic sense. Form can be used to refer to morphology. To overcome such problems, the idea of capitalizing the terms to indicate their use in the systematic sense was introduced, but this too causes problems with editors and in word processing. Some authors have used morphogenus and morphospecies (Wilson and Blake, 2011) or morphotype (Freytet et al., 1999; Freytet, 2000; Allwood et al., 2006, 2007, 2009; McLoughlin et al., 2013); however, these terms are not appropriate in the microbialite context because elsewhere in biology these words are used to imply a morphological variant of a particular genus or species. The terms 'form-genera' and 'form-species' have also been used (Bertrand-Sarfati, 1972a,b; Raaben et al., 2001) but are similarly inappropriate.

For now, we temporarily recommend retaining Group and Form, although consideration should be given to developing more appropriate terminology based on exclusive idioms. For example, Group could be replaced by 'prosapia' (plural 'prosapiae', from the Latin, prosapia, prosapiae, 1st declension, feminine; meaning family, lineage, stock, race or ancestry) and Form by 'communitas' (plural 'communitates' from the Latin communitas, communitatis, 3rd declension, feminine; meaning community, kinship, fellowship, partnership). However, as discussed under 'Current status of microbialite names', the whole question of how to formally name microbialites requires revision, and replacement terms for Group and Form would be best considered as part of any proposed changes associated with the current naming system.

Microbialite classification and nomenclature have mainly been applied to Proterozoic examples, mostly to stromatolites, and few Phanerozoic microbialites have been named. This could be due in part to greater morphological conservatism in Phanerozoic microbialites, of which stratiform, domical, and simple columnar stromatolites are relatively common. Also, the Phanerozoic fossil record is dominated by animals, plants, and protists, many of which provide excellent biostratigraphic information, so there has been no reason to look to microbialites for biostratigraphy.

General principles for microbialite description

There is still much to learn about microbialite growth and development before it can be determined with any degree of confidence which features are influenced or controlled biologically or physically. This is of critical importance in order to determine the significance of morphological features as well as using shapes and sizes as potential paleoenvironmental indicators. The need for rigorous, universally comprehensible, and unambiguous descriptions would be facilitated if all observable features are described using a standard descriptive format. The aim of the terminology and guidelines presented in this handbook is to make the description of microbialites as complete as possible. It should be clearly stated if data are not available for certain features; for example, when a description is based on field studies and does not include microstructure.

The section 'Descriptive terms for microbialites' deals with terminology and defines appropriate terms for this purpose; these terms are also in the glossary. As a general principle, descriptions of features should include no interpretation.

At the very minimum, a description should include the type of microbialite (Fig. 1) and information about the basic features indicated in Figures 2–4, and Appendices 1 and 2; however, descriptions need to be comprehensive.

The organization of the section on descriptions corresponds to the way a researcher usually encounters microbialites, initially in the field, followed by laboratory analysis and microscopy. Thus, the descriptive categories are presented in order from the largest scale (megascopic), through the medium scale (meso- and macroscopic) to the smallest scale (microscopic) (Figs 2–4). This is opposite to the order in which the microbialite was produced — that is, microscopically to megascopically.

Miscellaneous

References

References relating to terminology that are cited in the text and glossary are either, as best we can tell: 1) the first mention of the term or phenomenon; 2) an excellent summary; or 3) provide useful information for a better understanding of the topic. Where appropriate, we provide page numbers so the user of this handbook can find the information quickly.

Figures and figure captions

Wherever possible, we have exemplified specific characteristics by schematic line drawings, complemented by images of examples from our extensive photographic collections or from images supplied by colleagues. Except where noted, stratigraphic up is towards the top of each image. The authors had considerable access to the GSWA Fossil Collection and collections in the Department of Earth Science, University of California, Santa Barbara, as well as assistance in examining collections from other institutions, including the Commonwealth Paleontological Collection (Canberra), the Western Australian Museum, University of Adelaide, and Peabody Museum of Natural History, Yale University, as well as collections belonging to private individuals. We thank those responsible for making specimens available and allowing us to photograph them. Specimens from the GSWA collection are prefixed by 'GSWA F'; University of Adelaide numbers are prefixed by 'S'; specimens from other collections are identified by the relevant institution and collection number where available. In the figure captions, Australian 1:250 000 map names are shown in small capitals, e.g. MADLEY.

Stratigraphic names

Stratigraphic names for Australian and United States units (spelling, hierarchies, and age) follow official databases. For Australia, the Australian Stratigraphic Units Database (Geoscience Australia and Australian Stratigraphy Commission, 2014, <www.ga.gov.au/data-pubs/data-standards/reference-databases/stratigraphic-units>) was consulted; for the United States, the National Geologic Map Database (USGS and American Association of State Geologists, 2019) <https://ngmdb.usgs.gov/Geolex/search>. For China, stratigraphic names and spellings were obtained from the Stratigraphic Lexicon of China – the Precambrian (Editorial Committee of Stratigraphical Lexicon of China, 2000). For all these and other countries not mentioned, current literature was consulted for the most up-to-date information on stratigraphic assignment, chronostratigraphy and spelling, although it is difficult to rule out inconsistencies in the spelling of some stratigraphic names. Further data on Western Australian stratigraphic units, including the most up-to-date information on their ages, can be obtained from the Department of Mines, Industry Regulation and Safety Explanatory Notes System (ENS) <www.dmirs.wa.gov.au/ens>.

Authors' names

This handbook attempts to be consistent in the spelling of authors' names. When an author's name is derived from non-Roman languages and has variations in spelling that depend on the transliteration system used, a single spelling is adopted throughout the main text of the handbook. Alternate spellings are given in the references. Chinese names are given in the Chinese order of family name followed, where appropriate and without a comma, by the given names, except where given name initials are used in a publication.

Binomial names

Binomials are cited as originally published, including the use of qualifiers such as '?', 'cf.', 'aff.', 'sp' or 'spp.', and the modifiers are not italicized unless the identification is being queried in the handbook. Placement of '?' in the binomial indicates the degree of precision in identifications and follows the convention of the National Museum of Natural History, Washington, DC (Kornicker, 1979). A question mark (?) preceding the binomial indicates that the entire identification is doubtful. A question mark following the Group name indicates that the Group assignment is doubtful but the Form is identifiable. A question mark following the Form name indicates that the Form identification is uncertain but the Group assignment is correct.

In attributing authorship of taxa, we follow the practice proposed by Jansonius and McGregor (1996). In the text and text figures, we have omitted the names of authors of scientific names (except where citation of the author forms an intrinsic part of the discussion). A list of full authorship attributions (taxon name, author, and year) used in the text is given in Appendix 3.

Methods for the study of microbialites

This section presents methods that can be readily applied by most researchers to the description of stromatolites and other microbialites. For simplicity, we use the term stromatolite frequently throughout this chapter; however, the methods and some of the terminology can be applied to other microbialites (thrombolites, dendrolites, leiolites and possibly MISS) as well as to some abiogenic or presumed abiogenic structures (e.g. dubiostromatolites, pseudostromatolites) that resemble stromatolites.

As many observations as possible should be undertaken, although not all the techniques presented here need be used. At this stage in microbialite studies, descriptions of basic features need to be as comprehensive as possible and thus require detailed, standardized observations.

Although most researchers now have access to computerized image analysis and could undertake stromatolite morphometrics (Hofmann, 1969b, 1973, 1974, 1976b; Zhang and Hofmann, 1982; Banerjee and Chopra, 1986; Zhang et al., 1993), this type of data analysis has rarely been employed. The use of computer techniques for tasks such as three-dimensional (3D) reconstruction is being explored (Stevens et al., 2011), but is not at a stage where it is a standard method. There is much scope for digital imaging and modelling along the lines of work carried out on other organisms, such as seaweeds, sponges and corals (Kaandorp and Kübler, 2001). Promising developments using imaging analysis software, such as ImageJ (which is free and can be downloaded at <http://rsb.info.nih.gov/ij/>), allow a digital approach to tedious morphometric analysis. 3D reconstruction using serial sections is available, but so far no specific application for microbialite reconstruction has been created. A concerted effort is required to develop specific applications to microbialite data analysis; for example, the use of computerized tomography (CT) scans (Storrie-Lombardi et al., 2008; Howell et al., 2011; Machado et al., 2015). Visual exploration facilities are being used to investigate stromatolites (Rivera and Sumner, 2014; MacKey et al., 2015). Other imaging techniques, such as 3D sidescan sonar, are being employed to map living microbial structures (Mullins and Bird, 2007; Stevens et al., 2011; Baskin, 2014), as is drone technology (Vanden Berg et al., 2015), although little has so far been published. Another technological tool likely to have application, especially for microbialite reconstruction, is 3D printing technology. A variety of advanced techniques are being applied to living and fossil microbialites, such as Raman spectroscopy (Lepot et al., 2008), confocal laser scanning microscopy (Gérard et al., 2013), micro X-ray fluorescence spectroscopy (Thompson et al., 2015) and clumped isotopes (Frantz et al., 2014). Morphological descriptions must still be based on a combination of field and laboratory observations, possibly supplemented by some of the emerging technology mentioned above.

Once the main features of a microbialite are adequately documented, it may be possible to identify it even from small samples, for example in drillcore. For drillcore, a mirror-image technique gives a better impression of column shape. Where possible, the core is split down the centre and the two halves photographed side by side to produce a 'false' image that replicates the microbialite shape (Fig. 5). Best results are obtained if the cut passes through the maximum height of the column, and the two core halves arranged so that the column appears to be a single column.

Preparation for fieldwork

In addition to standard geological preparation for fieldwork it may be necessary in some jurisdictions to check on land usage. If localities are not on public (government administered) lands, consult with land owners. Some government administered areas require permits for access, research and collecting (sampling), and these can take considerable time to obtain, especially if more than one authority has to be consulted. Protected sites may require extra time and effort to obtain a permit. Permit numbers and details of the issuing authority must be included in publication.

In the field

The variation and distribution of different megascopic and macroscopic morphologies are best studied in the field, so field observations need to be as complete as possible. As discussed under 'Size classification and organization of microbialites', it is important to take into account the great variation in dimensions shown by microbialites (Figs 6–9) and to bear in mind that more than one morphological variant, or subset, may be present at any locality. Record the dimensions of the different component, such as the width and height of bioherms, and of the columns and branches that construct them. Vertical faces may provide sufficient information for identification, especially for taxa with distinctive features, such as *Conophyton*. Hofmann (1977, p. 193) pointed out that exposures that display extensive vertical and plan views of stromatolites can serve the same function as serial slabbing (see below) and provide much of the necessary information for the description. It may be useful to provide at least one or two 3D reconstructions (see section on '3D graphical reconstruction'), particularly for new taxa, so this should be kept in mind when sampling.

Approach the study from a hierarchical perspective, from megastructure to mesostructure, possibly even microstructure (Fig. 3). Shapiro (2005) provided a useful guide on this approach. Follow the comprehensive terminology for describing various features given in 'Descriptive terms for microbialites' and the checklist of characters (Appendices 1, 2). Such an inventory provides a ready reference to the main features to be observed and provides a record of salient features for later stages of description. Detailed field and laboratory notes and photographs should supplement observations.

At the outcrop scale, microbialites may not be readily apparent. However, differential compaction of microbialites and interstitial material can produce irregular bedforms and indicate the presence of microbialites, as can the pinching and swelling of carbonate beds. Differential erosion of bioherms and their enclosing sediment can produce exhumed bioherms with only their tops showing and better exposed microbialites can only be located by an extensive exploration of the outcrop (Roehler, 1993, figs 78–80).

Characteristics such as bioherm or biostrome dimensions, shape, spacing, and their relationship to the surrounding sediment are important to note and measure (Figs 10–15). Note the kind of structure present: is it stratiform, domical, columnar or branched (Fig. 11)? Is the structure a bioherm (Figs 12, 13) and is it tabular (Fig. 12a), domical (Fig. 12b) or subspherical (Fig. 13a), and is there linkage (Fig. 13b)? Is it a biostrome (Figs 14, 15)? Determine if there is any consistent elongation (Figs 12a, 14a–b) or inclination of the microbialites. If present, record the relevant azimuth of the axes for as many structures as possible. This might be useful for paleocurrent interpretations (Hoffman, 1967, 1975; Truswell and Eriksson, 1975; Young and Long, 1976; Sprechmann et al., 2004). Is the structure complex? For example, is it a compound biostrome composed of bioherms (Fig. 15a) or of vertically stacked biostromes, each composed of numerous small columns (Fig. 15b)? Examine the relationships and variation (both laterally and vertically) among the various components. Note the style, frequency and divergence of branching if present, and the shape of the individual microbialite in plan view (transverse section) and vertical profile.

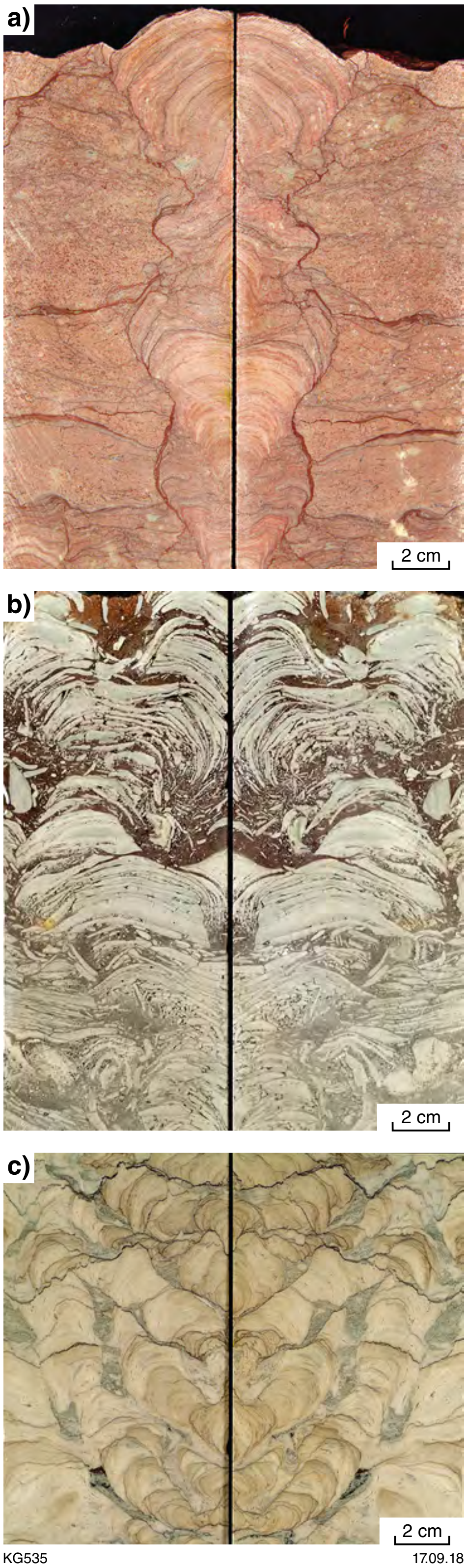

Figure 5. Examples of using core 'mirror images' to demonstrate morphology: a) *Basisphaera irregularis*; Woolnough Member, Browne Formation, lower Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Lancer 1, 1335.2 m, Gibson Desert, Herbert, Western Australia (photo by K Grey); b) *Baicalia burra*; eroded specimen in diamictite-filled cavity; Steptoe Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Empress 1A, 496.5 m, Gibson Desert, Westwood, Western Australia (photo by K Grey); c) *Tungussia wilkatanna*; Steptoe Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Empress 1A, 513.5 m, Gibson Desert, Westwood, Western Australia (photo by K Grey)

Figure 6. **Examples of size variation in microbialites – mega- and macromicrobialites: a) megamicrobialite; *Earaheedia kuleliensis*; Kulele Limestone, Miningarra Group; Earaheedy Basin; Orosirian to Statherian, Paleoproterozoic; Thurraguddy Bore, THROSSELL, Western Australia (photo by SM Awramik); b) mega- and macromicrobialites; stromatolites; Laney Member, Green River Formation; Sand Wash Basin; Eocene; near Vermillion Creek, Moffat County, Colorado, US (photo by HP Buchheim)**

Figure 7. Examples of size variation in microbialites – mesomicrobialites: a) *Acaciella australica*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Katapata Gap, HERMANNSBURG, Northern Territory, Australia; polished slab, GSWA F9976–46062, detail of columns (photo by HJ Allen); b) stromatolite; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Henry River, EDMUND, Western Australia (photo by DMcB Martin)

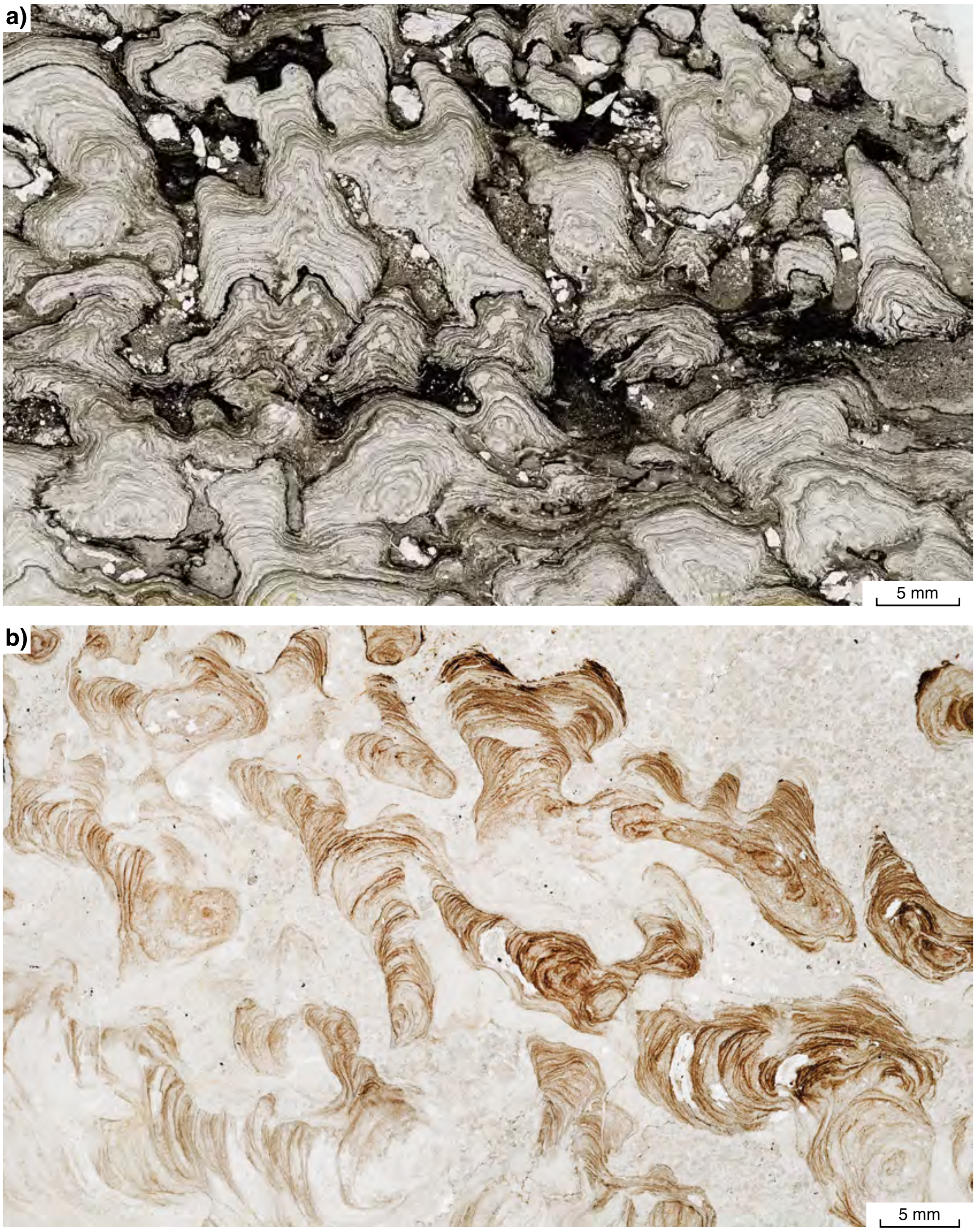

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Figure 8. Examples of size variation in microbialites – minimicrobialites: a) small, branched stromatolite; '*Gruneria biwabikia*', R2422 in Cloud and Semikhatov (1969); Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Cooletha Hill, Marble Bar, Western Australia; thick section, GSWA F52218–109292 (photo by SM Awramik and K Grey); b) *Murgurra nabberuensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, Nabberu, Western Australia; thick section GSWA F12365–46333 (photo by SM Awramik and K Grey)

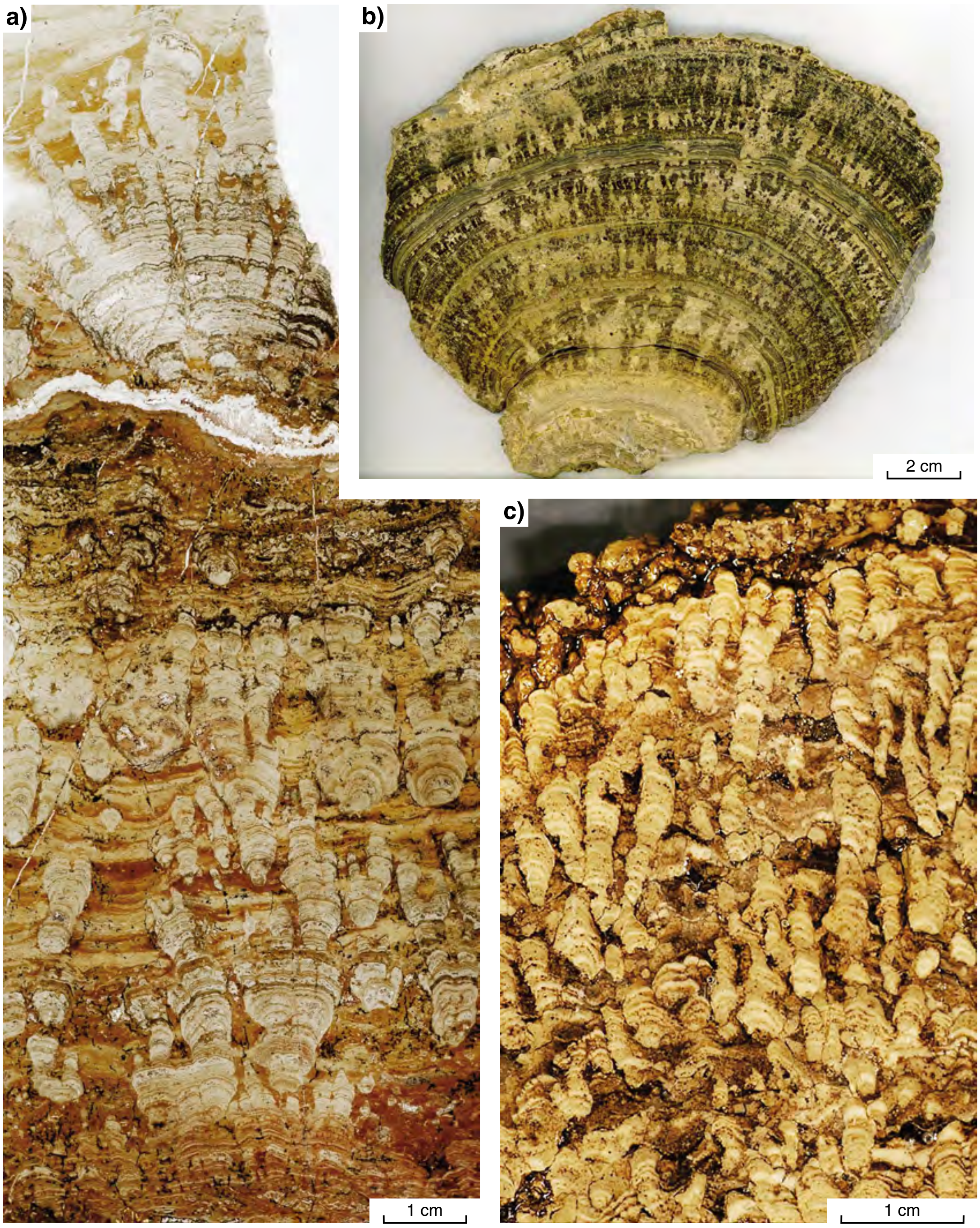

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Figure 9. **Examples of size variation in microbialites – minimicrobialites and microdigitate stromatolites: a) minimicrobialite and microdigitate; *Asperia digitata*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, Nabberu, Western Australia; thick section, GSWA F12390–46326 (photo by SM Awramik and K Grey). The mode of preservation in the upper third of this stromatolite is the type often referred to as microdigitate; however, the whole stromatolite is a minimicrobialite; b) minimicrobialite alternating with layered stromatolite (compound microbialite); Tipton Member, Green River Formation; Bridger Basin; Eocene; White Mountain, Sweetwater County, Wyoming, US; polished face, UCSB collection (photo by SM Awramik); c) minimicrobialites; stromatolite; Furnace Creek Formation; Pliocene; Black Mountains, Death Valley National Park, Inyo County, California, US; polished face, USCB collection (photo by SM Awramik)**

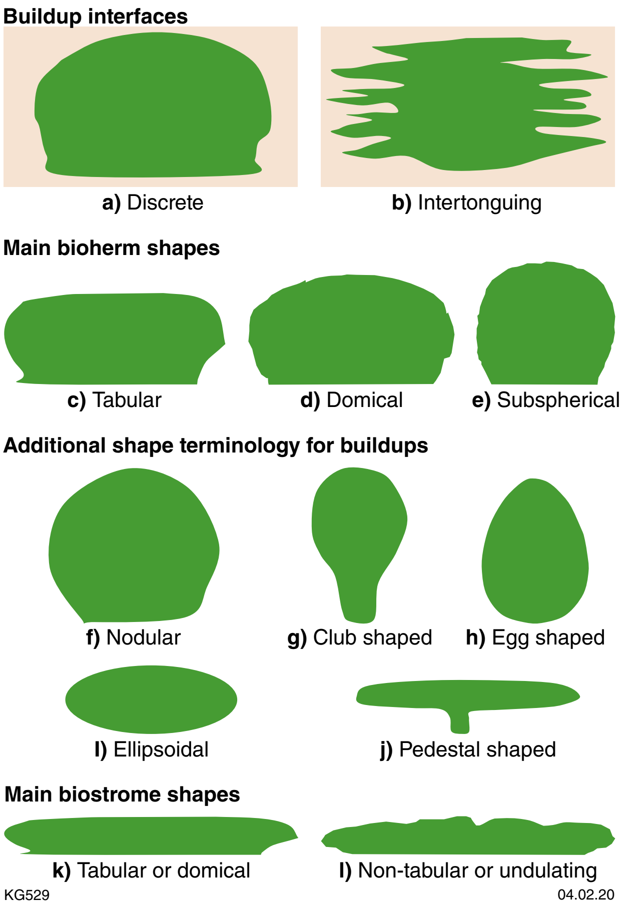

Figure 10. Microbialite buildups – interfaces, bioherm and head shapes, and biostrome shapes. a, b) Buildup interfaces: a) discrete, b) intertonguing. c–e) Main bioherm shapes: c) tabular, d) domical, e) subspherical. f–j) Additional shape terminology for buildups: f) nodular, g) club shaped, h) egg shaped, i) ellipsoidal, j) pedestal shaped, k, l) Main biostrome shapes: k) tabular or domical, l) non-tabular or undulating

Observe the mesostructure: does it have laminae (stromatolite), mesoclots (thrombolite) or shrubs (dendrolite), or is it structureless (leiolite)? Alternatively, is it suggestive of microbially influenced surface structure (MISS; Fig. 1 and under 'Microbialites and their constituents')?

Study the nature of the margins of the microbialite: are they smooth, bumpy, ragged, or with large overhangs, and is there a wall or patchy wall present? For stromatolites, note the laminar shape and arrangement. For thrombolites and dendrolites, record the shape and organization of the clots or shrubs respectively. In siliciclastic sediments, record the presence and types of MISS (Gerdes et al., 2000; Schieber et al., 2007a; Noffke 2010; Davies et al., 2016).

Small-scale features of stromatolites (laminar architecture and microstructure) and other microbialites are best studied using thick and thin sections or peels and can only be examined in detail after laboratory preparation. Nevertheless, some preliminary observations can be made in the field with a hand lens (loupe) and some microscopic features have a characteristic expression when viewed in the field — for example, laminae may display a distinctive wrinkling in the field, which on microscopic inspection, is caused by a specific type of microstructure. Recognition of the various types of architecture and microstructure provides the basis for the selection of samples suitable for laboratory preparation and more detailed study.

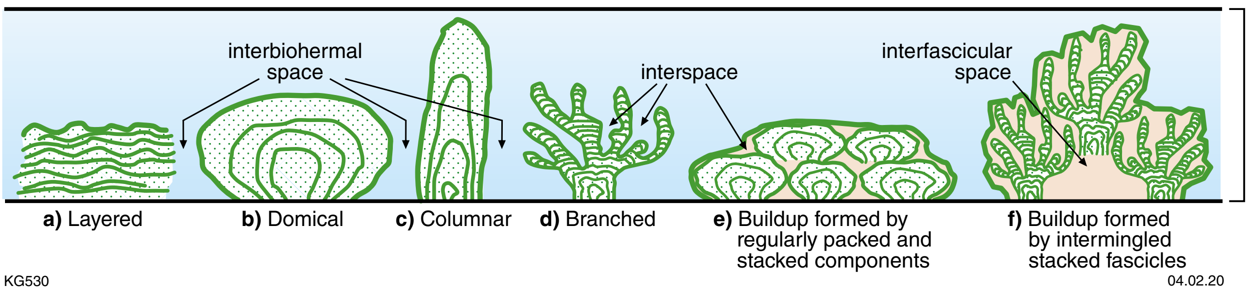

Figure 11. Main types of bioherm and biostrome components and their relationship to surrounding sediment or rock: a) layered; b) domical; c) columnar; d) branched; e) buildup formed by regularly packed and stacked components; f) buildup formed by intermingled stacked fascicles. Terminology for areas between buildups, bioherms and fascicles is also indicated

Figure 12. **Examples of microbialite buildups: a) tabular, slightly domical, elongated bioherm; *Jurusania derbalensis*; Oued Terrarit Formation (Unit I.8), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Aouinet ould bou Derbale, Mauritania; carbonate microbialite enclosed in siltstone (photo by SM Awramik); b) domical bioherm; *Tungussia* f. indet.; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; Muddauthera Creek, eastern Pilbara, NULLAGINE, Western Australia; carbonate microbialite enclosed in laminated mudstone (photo by K Grey)**

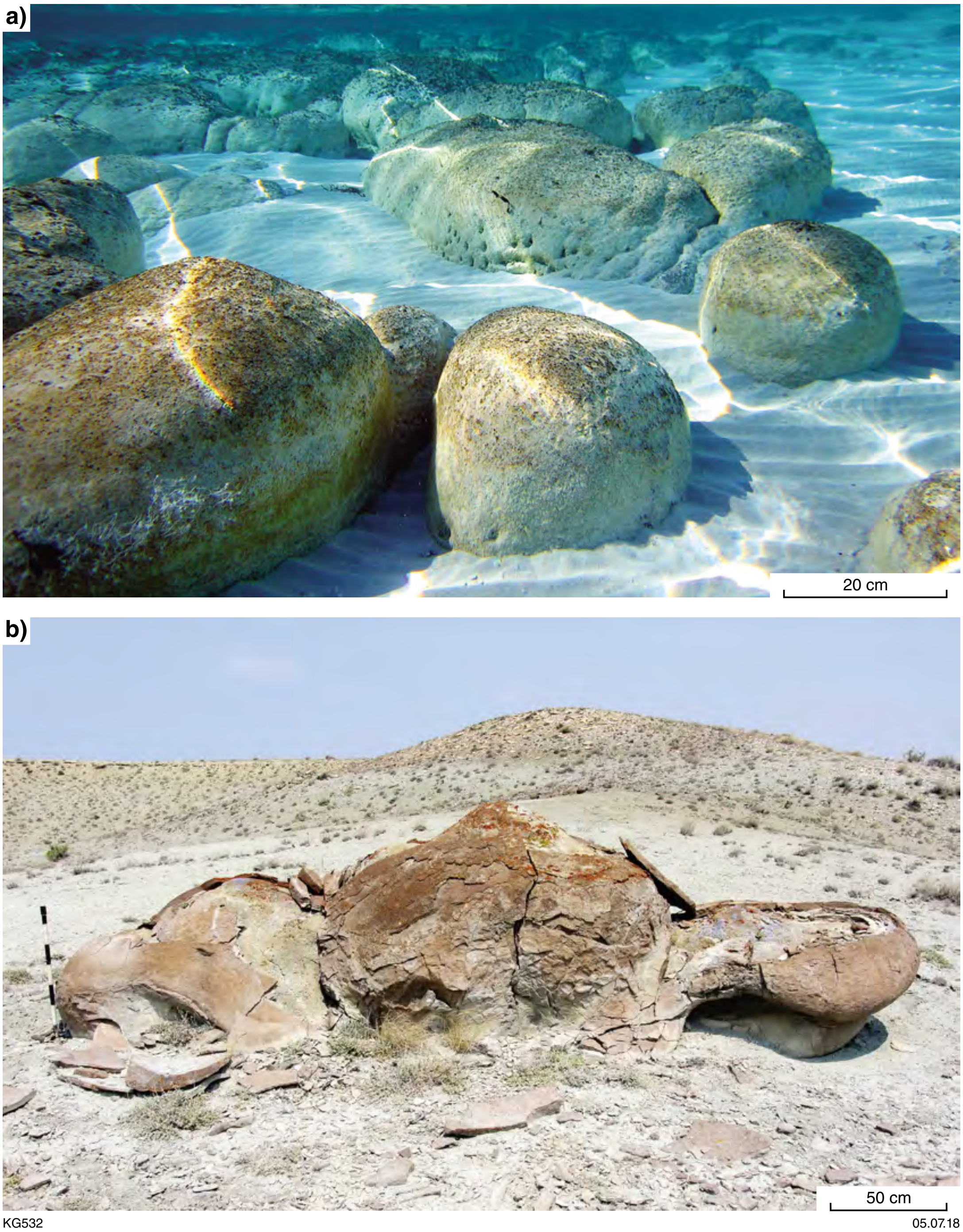

Figure 13. Examples of microbialite buildups: a) subspherical (hemispherical) buildup; Carnarvon Basin; Holocene; north of Carbla Point, Hamelin Pool, Shark Bay, Yaringa, Western Australia (photo by SM Awramik); b) linked, subspherical buildups; stromatolites; Bridger Formation; Bridger Basin; Eocene; Sweetwater County, Wyoming, US (photo by SM Awramik)

Figure 14. Examples of microbialite buildups – elongate: a) Carnarvon Basin; Holocene; south of Carbla Point, Hamelin Pool, Shark Bay, YARINGA, Western Australia (photo by SM Awramik); b) microbialites; Hellnmaria Member, Notch Peak Formation; upper Cambrian; House Range, Millard County, Utah, US (photo by K Coulson)

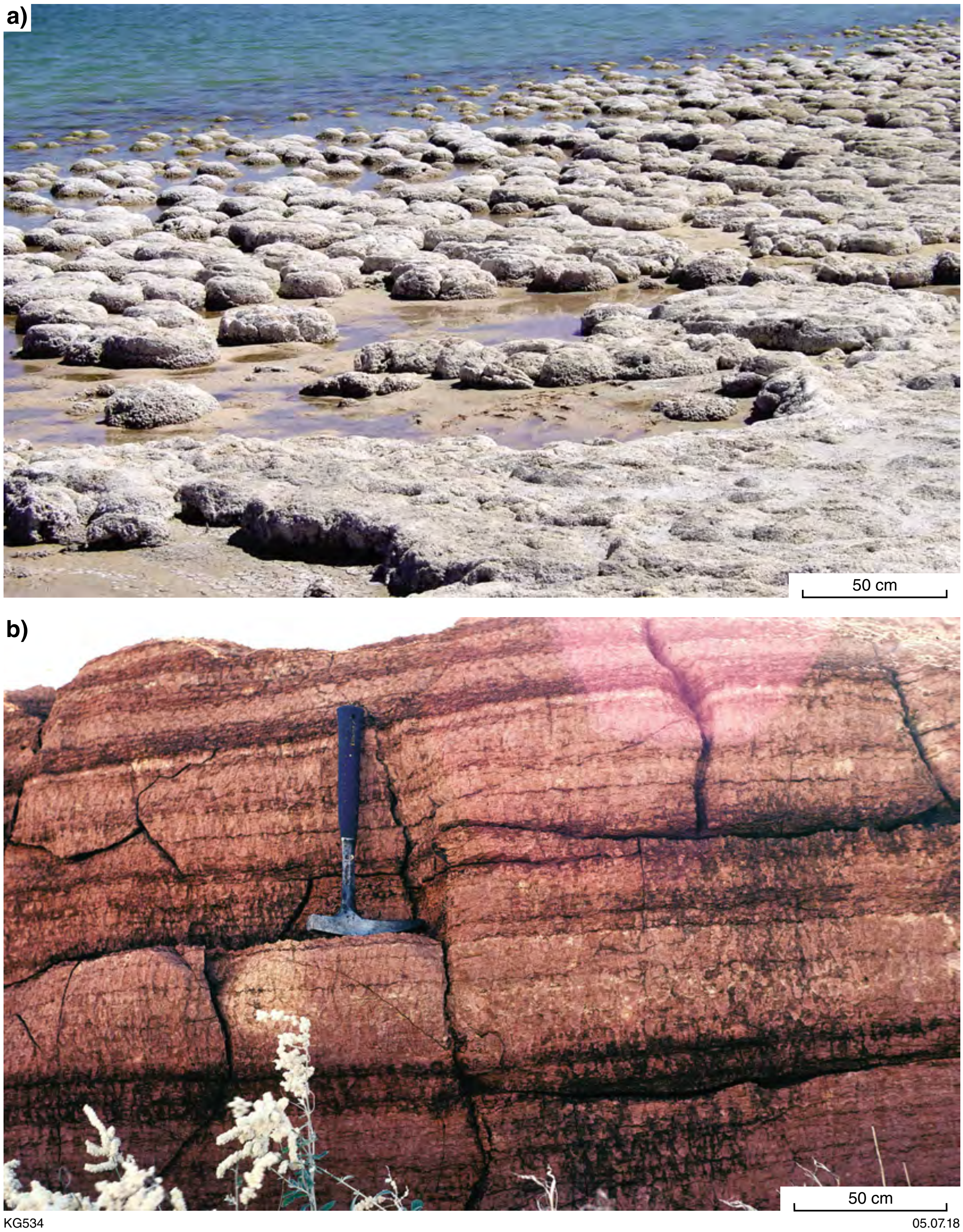

Figure 15. **Examples of microbialite buildups: a) large, elongate, tabular, compound biostrome composed of nested, individual, subspherical, thrombolitic bioherms; Perth Basin; Holocene; Mount John boardwalk, Lake Clifton, PINJARRA, Western Australia (photo by SM Awramik); b) successive tabular biostromes composed of small columns of ?*Acaciella augusta*; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; eastern Pilbara, NULLAGINE, Western Australia (photo by K Grey)**

Field photography

Images are particularly valuable for supplementing data where there are collecting problems because of large size, and where a great deal of variability occurs in outcrop (this is particularly true for lacustrine microbialites). Take photographs before sampling, and photograph specimens to be sampled in situ. With the advent of digital photography and the large number of images that can be saved, it is now possible to make comprehensive records of microbialite variation at different orientations in the field.

Microbialites in rock faces can be particularly difficult subjects and the following hints may improve the standard of photography.

Pay attention to the lighting. Shadows can be avoided by using uniform shading (try an umbrella), a flash, or by using a reflector screen or folding photographer's reflector). If time permits, try the lighting conditions at different times of day. Move any objects, such as loose rubble and vegetation (unless protected), that could confuse details.

Use a scale in photographs, preferably one marked in centimetres, although standard-sized objects such as lens caps and hammers can be substituted provided dimensions are noted in figure captions. The scale should be unobtrusive and placed close to the margin of the photograph with the long axis parallel to the frame of the image. In many cases it is best to substitute a drawn-on bar scale in the final print. A photomontage of juxtaposed (stitched) photographs can be used to improve focus (depth of field decreases under low lighting) or show elongated structures. Use field sketches, tracings and arrows to enhance particular features on images.

Some outcrops can be improved by the judicious use of a scrubbing brush, acetic or weak hydrochloric acid, or bleach (particularly effective in removing epilithic organisms). If the contrast is still insufficient for photography, it may be necessary to outline the columns with a water-soluble, felt-tipped marking pen (Walter, 1972, plate 21, fig. 3); preferably taking pre- and post-outlining images. Be thoughtful and comply with local conservation regulations when employing activities that could mar the outcrop (permanent pen) or affect biotas (bleach, acid, scrubbing).

Sampling

Sampling is one of the most important aspects of studying a microbialite. There is often variation across localities, between the centres and margins of buildups, within biostromes, and within individual microbialites. Record the site as accurately as possible, preferably using a dedicated global positioning system (GPS) device or camera with GPS. Photograph as many variables as possible and collect representative samples. Variation often occurs within a consistent range of parameters, so where possible, mid-range and end members should be sampled. Number samples carefully in the field, and note their orientation (mark stratigraphic up with an arrow) and relative positions. An ideal sample will include several columns or branches so that relationships and branching style can be examined later. Sufficient material for serial sectioning and thin section preparations should be collected.

It is not always possible to collect ideal specimens; constraints may arise from the nature of the outcrop, the large amount of material required, and restrictions on collecting. In such cases, choose samples that are as representative as possible. Where columns or domes are too large to be sampled in their entirety, collect smaller, oriented specimens from each structure. Field photography is critical to provide context for samples. Specimens from centres and margins can be used to determine the extent of variability. Sample the interspace as appropriate. Strategic sampling is often necessary for larger conical stromatolites, where it is important to collect representative portions of both the axial zone (if present) and outer margins in areas of best preservation.

Further sampling hints were suggested by Preiss (1976c, p. 9):

- samples should be selected so that they fit readily into the vice of a slabbing saw
- for columnar and branching microbialites, select samples to show several adjacent faces upon serial slabbing
- select single samples that exhibit transitions from one morphology to another (e.g. stratiform to columnar) or changes in style of branching.

Laboratory examination

Use the following laboratory techniques to supplement field studies.

Cleaning

Cleaning a specimen often reveals features previously obscured in the field. Remove particles of soil and encrusting organisms (e.g. lichen) by scrubbing with a nylon or wire brush, and use detergent or bleach, if necessary. Try cleaning particularly difficult surfaces with dilute hydrochloric acid. More thorough cleaning may be required for geochemical analysis. It may be worthwhile to photograph the clean surfaces.

Cutting on rock saw

Although some details can be determined from weathered surfaces, it is usually necessary to cut the sample to examine shape, spacing, branching and laminar details. Serial slabbing techniques and graphic reconstructions are particularly appropriate for determining 3D characteristics (see below). Hints on choosing and preparing samples were given by Hofmann (1976a, p. 16). He recommended that samples selected for cutting should show good cross-sections (i.e. vertical profiles), and preferably include at least two or three columns or branches.

A large-diameter, automatic-feed saw with diamond-tipped blade (at least 60 cm diameter) with an adjustable clamp or vice is commonly used. Rocks should be positioned in the vice in such a way that regularly spaced serial cuts can be made parallel to the columns. It may be necessary to reposition a large block several times during cutting. Casting in concrete, plaster, or epoxy first to create a flat base and sides (use a rectangular or square-sided vessel) results in easier slabbing.

For general study (for example, for simple columns and domes), a single vertical cut may suffice. The vertical cut should be normal to the bedding; avoid making tangential cuts if possible. Wedges of wood or polystyrene can be used to hold a sample with an irregular bottom or top surface in the correct orientation for sawing. It is advisable to check the first slab for preservation (quality control) and orientation. For irregular specimens, conserve as much of the specimen as possible. Set difficult samples in their correct orientation in a cardboard box filled with plaster of Paris, casting resin or concrete to provide a suitable planar surface. Saw cuts are made through the cardboard, plaster or resin and the specimen. This technique facilitates cutting, but remember the plaster will conceal features on weathered surfaces whereas resin does not. Impregnate specimens in danger of crumbling or cracking apart with epoxy or casting resin. Pay attention to numbering offcuts and serial slabs. Each cut sample should be labelled with the sample number and it is best to serially number each face in serial slabs.

Serial slabbing

Serial slabbing is a technique that allows understanding of 3D morphology and is essential for graphic reconstruction of complex microbialites. Krylov (1959, 1963) described the preparation of serial vertical sections in detail, and this method has been the most widely adopted, although Raaben (1969a) used horizontal cross-sections. This approach, with some modifications, was further described by Walter (1972, p. 6–8), Preiss (1976b, p. 9–11), and Hofmann (1976a, p. 16).

It is not always necessary to make two cuts at right angles to provide reference surfaces as recommended by Preiss (1976c). A reference line drawn normal to the growth axis can serve the same function, provided the position of the reference line is transferred onto the cut face so it can be used as the base line for reconstruction.

The number of slabs and their thickness are determined by the column diameters. Ideally each column should be present on four successive faces. Very thin slabs (less than 4–5 mm thick) can be cut from blocks without breaking if a piece of foam plastic or rubber is placed on the receptacle underneath the slices being sawn off and the slabs removed after each cut (Hofmann, 1976a).

The thickness of material lost in the saw cut should be estimated (usually about 2 mm; measure the thickness of the saw cut on a test piece). Hofmann (1976a) suggested that the finished thickness of the slices should be equal to, or multiples (2, 3 or 4) of the missing thicknesses. This is preferable because it makes graphical reconstruction easier, but is not essential. Provided the thickness of the saw cut is known, and as long as the thickness of the slab can be measured, acceptable reconstructions can be drawn. Each cut provides two faces, which are ground smooth (see below), and then traced on transparent overlays (such as drafting film) as described below, or which can be imaged and then outlined digitally. Vanyo and Awramik (1985, p. 133–138) presented an alternative to the sectioning methodology for analysis of stromatolites by using a precision grinding machine.

Polishing and alternatives

Numerous features, such as wall structure and the larger-scale details of microbialite mesostructures, are best observed on cut faces, but it is usually necessary to grind, polish or otherwise treat the surfaces to remove saw marks or enhance contrast. Many specimens are best studied by the use of large thick or thin sections, acetate peels, or thinly cut glass-mounted slabs. Polishing is time consuming, but usually produces the best results, especially for photography or display purposes. Select the best faces for polishing, and use a quicker technique for other faces (test the technique to be used on a non-critical face first).

Initial grinding is usually carried out on a vibrating lap or polishing lap using progressively finer grades of abrasive powder (generally carborundum from grade 180 up to about grade 600). The highest degree of polishing requires finer-grade powders (up to grade 1000), followed by a final polish using an oxide paste or similar compound on a vibrating lap or glass plate, or by applying paste to the slabbed surface with a soft cloth or piece of carpet. A carborundum disc on an orbital sander or a handheld concrete polishing tool can be used as an alternative to a polishing lap. The sample can be held in the hand and polished using a range of polishing pads.

Coating the surface is an alternative to high-gloss polishing. This can be with wax (Bouma, 1969, p. 133), or by brushing or spraying with a gloss-finish lacquer or polyurethane (use a fume hood). Results from this method are variable; lacquer and polyurethane may soak into porous samples, and sometimes it is difficult to obtain an even distribution. These substances are also difficult to remove, although acetone usually works.

A more practical approach is to grind the surface using (up to) grade 600 carborundum, and then make direct observations or images of the face using any of the following techniques:

- draw pencil lines directly on the face (sometimes this is necessary in order to clarify features but photograph or scan the surface before outlining features with pencil or other marking tool)
- wet the face and cover it with a transparent overlay and draw on that (see ‘Line drawings’)
- for photography, wet the surface with water, glycerine or oil (cooking oil is adequate)
- scan a wet face on a flat-bed scanner.

For carbonate rocks, textures can sometimes be enhanced by etching for 15 seconds in 10% HCl or another weak acid (HF etching can be used for chert samples under adequate safety conditions).

Thin and thick sections

Samples for thin or thick sectioning require careful selection to show representative portions of the microbialite and good preservation of microstructure. Orientation is important. Thick sections should be vertical to growth direction and crossing through the centre of the column or branch. Additional thick sections normal to growth direction can also provide useful information. Thick sections are usually larger and thicker than conventional petrological sections, but are prepared by the same techniques. The size of the section depends on the features to be examined, but thick sections, 105 × 65 mm, can often accommodate some of the more important features, such as mesoclots, column margins, laminar details, and interspace features. Normal petrological thin sections (commonly 30 µm thick) are usually too thin for adequate study of mesostructural and microstructural features; a thick section (thickness about 60 µm, but ranging between 40 and 120 µm depending on opacity) is better. Check frequently during grinding to ensure the specimen is thick enough to see the details of the lamination and other features. Thin sections may be necessary for petrography. Neither thin nor thick sections should have a coverslip, so that additional grinding can be undertaken if the section is too thick.

Examination of sections should be carried out at different magnifications (Preiss, 1976c) and include inspection for microfossils. Staining techniques can aid the petrological study of carbonate (Friedman, 1959; Warne, 1962; Bouma, 1969, p. 251). Use of a black, white or ground-glass backgrounds, or the white-card technique of Folk (1987), can improve observation of features. Other techniques, such as fluorescence microscopy (Dravis and Yurewicz, 1985) and cathodoluminescence (Bahniuk et al., 2015), have application for thin section observations.

Acetate and other peels

A variety of techniques for preparing peels has been described (Stewart and Taylor, 1965; Davies and Till, 1968; Bouma, 1969, p. 63; Price, 1975; Mandado and Tena, 1986; Miller in Tucker, 1988; Wilson and Palmer, 1989). The techniques applied are determined by factors such as lithology and preservation. Large-sized peels (Bouma, 1969, p. 2) can be prepared from weathered surfaces in the field using lacquer, polyester, epoxy or silicon. This method has rarely been attempted by microbialite researchers, but may be worth consideration.

The most common method of preparing peels of carbonates is the acetate sheet method (Bouma, 1969, p. 66; Preiss, 1976c). Acetate peels can be prepared rapidly and are particularly suitable for use with drillcore and cut faces of hand specimens. They can be used to cover large surfaces and are cheaper and easier to handle than thin sections, although it is becoming increasingly difficult to obtain acetate paper. The simplest method is as follows.

1. Grind smooth the cut face using grade 600 carborundum powder.
2. Lightly etch the prepared surface with 5–15% HCl. This usually takes between 10 and 30 seconds (longer for dolomite). Silicified specimens can be etched with hydrofluoric acid (Price, 1975), but extreme care is needed because HF is exceptionally dangerous (Muriale et al., 1996). Protective gear such as rubber gloves and a facemask are essential and work must be carried out in a fume cupboard (fume hood) with water readily available. It is also recommended to have calcium gluconate topical gel or some other form of HF antidote gel available.
3. Gently wash the surface with water and then dry. Air-drying is best but the process can be sped up by using a compressed-air jet, heat lamps, or acetone. Do not blot with rags or tissues because this will damage the etched surface.
4. Place the etched surface in a flat or gently inclined position (use a bed of sand or small beanbags if necessary) and then wet the surface with acetone. It is best to work with acetone under a fume cupboard. A preliminary wetting and drying with acetone will ensure that any traces of water are removed and will improve the quality of the final peel. Enough acetone should be used to form a thin film on the surface.
5. Lower an acetate sheet (preferably 0.076 mm thick, or 3 mil = 0.003 inches in imperial measurement) slowly on to the wet surface. Start at the lower edge and gently curve the sheet to make contact with the surface so that the slightly tilted slab traps the acetone by capillary action. Alternatively, using a flat-lying slab, gently bend the acetate sheet, and beginning in the middle, roll it out towards the edges or start on one side or corner and work towards the other. Any air bubbles should be pressed out, preferably using a roller because fingers can leave imprints.
6. Allow the peel to dry (about 10 to 30 minutes; if left too long, the peel may not be removable). Test that the peel is ready by lifting an edge. The peel should pull away freely taking with it an impression of the etched surface. The best results are obtained by pulling steadily at a 45° angle. Trim the dried peel and press flat under a weight to prevent curling.

Experiment with finer grinding powders, different thicknesses of acetate paper, and different concentrations of HCl to improve results. Two or three peels can be prepared before repolishing and re-etching the surface. Remove stuck peels with acetone (and sometimes a razor blade) and reprepare the damaged surface. Carbonate stains applied to the acetate peel, such as alizarin red, may enhance some features (Bouma, 1969, p. 251; Warme, 1962). Peels can be stored in plastic sheet protectors or between glass sheets, and scanned or photographed in the same way as thin sections.

A simple streak-print method (Morris and Ewers, 1978) can be used for making peels of siltstone or shale, which can be useful for studying MISS. This method uses transparent self-adhesive tape, which is pressed smoothly onto the rock surface, and then peeled off and mounted on a backing, usually of white paper (a darker sheet can show up light-coloured minerals). Alternatively, use a transparent plastic sheet as a base for mounting the strips of tape. For microbialite samples, cover the surface to be replicated with parallel strips of tape then remove and stick on the backing surface in the same relative positions. This method works with clayey or silty carbonate and some ironstone, but is only effective on surfaces that have not been highly polished. Stains can also be used with the streak-print technique (Morris and Ewers, 1978, p. 564).

Line drawings

Simple line drawings and tracings of microbialites from cut surfaces provide valuable information about column outlines, margin structures, and laminar profiles. These features can be traced directly from polished, lacquered and/or etched faces, although the simplest technique is to smooth-grind the cut face (using 600 grade carborundum powder), wet the cut surface to increase contrast, and position a sheet of transparent drafting film so that a thin film of water is trapped between the rock surface and drafting film. Details show up clearly through the film and can be traced directly using insoluble ink.

If features are indistinct, first pick out the relevant details by drawing pencil lines directly on the rock surface. Contrast can also be improved by etching or staining.

Line drawings can also be produced by tracing over digitized images that have been created either by direct scanning or photographically (e.g. Hickman et al., 2011, fig. 15b).

Three-dimensional (3D) graphical reconstruction

The procedure for 3D reconstruction from serial slabs was presented by Krylov (1959, 1963) and discussions of this method appear in Walter (1972), Preiss (1976c) and Hofmann (1976a). A more elaborate method was suggested by Horodyski (1976, fig. 3), who made 3D models from cardboard templates and modelling clay, but for most purposes 3D illustrations suffice.

3D reconstructions can be produced by computer graphics (Storrie-Lombardi et al., 2008). Digital reconstruction based on serial slabs has been applied to microbialites (Stevens et al., 2011; Rivera and Sumner, 2014) as well as calcified metazoans (Grotzinger et al., 2000; Watters and Grotzinger, 2001), and to seaweeds, sponges and corals (Kaandorp and Kübler, 2001). Unfortunately, these promising techniques have not yet been widely adopted for microbialite studies.

It is important to understand methods that were developed earlier in order to interpret literature containing pre-digital, interpretative 3D reconstructions based on serial slabbing. Much of the research on microbialite taxonomy was based on this. Preparation stages were illustrated by Walter (1972, fig. 2), Preiss (1976c, fig. 3) and Hofmann (1976a, fig. 1), and the method summarized below combines the methods described by these authors.

1. Wet a smoothly ground face, and cover with a sheet of transparent drafting film. Trace the outline of the microbialite on to the film to create Tracing 1, and then allow the film to dry. Do the same for successive cut face to create Tracing 2, Tracing 3, and so on.
2. Fasten a large sheet of graph paper with millimetre grid to the drafting surface to act as the control grid. Tape a large sheet of transparent drafting film on top of the graph paper to form the work sheet. Insert the original tracing between the work sheet and the control grid (graph paper). Reconstructions are made on block diagrams corrected for perspective by tracing outlines of columns from successive tracings usually offset at an angle of 45°. Work in pencil, so that only relevant lines are inked in on the final diagram.
3. Select a position for the point of origin for the block diagram. This coincides with the intersection of the base reference line (x axis) and the vertical reference line (y axis). This point can be on either the left or right side of the diagram as determined by the details on the tracings. Draw the x and y reference lines on the work sheet. (Number these x1 and y1 axis on the first sheet, and then sequentially thereafter).
4. Construct a line at a 45° angle from the point of origin. (This is usually drawn in the upper right quadrant to provide a dextral view, but sinistral views can also be constructed.) This is the lateral reference line (the z axis). The point of origin of successive tracings is located along this line.
5. Insert the first tracing (Tracing 1) between the control grid (graph paper) and the work sheet so that the x and y axes on both the tracing and work sheets coincide. Trace the outline of the columns onto the work sheet. For greater accuracy in column reconstruction follow the contour method devised by Hofmann (1976a). To do this, mark those points on the column margin that intersect grid lines. The spacing of the grid should be regular, but will need to be selected according to the size of the columns to be reconstructed. Remove Tracing 1.
6. Determine the actual thickness separating Tracing 1 from Tracing 2 and calculate the displacement distance corrected for perspective; i.e. the thickness multiplied by cosine 45° or thickness × 0.7. Mark the calculated value on the z axis. Construct reference lines x2 and y2 from this point. These are the new base lines for Tracing 2. Because the facing slabs present mirror images, every second tracing must be reversed for the reconstruction. Insert the reversed Tracing 2 so that the reference lines coincide with the x2 and y2 axes.
7. Imagine that the outline of Tracing 1 is opaque. Trace the 'visible' outline of columns from Tracing 2. Again mark all points where outlines intersect grid lines. Hofmann (1976a, p. 19) pointed out that:

   > [the] procedure is considerably simplified if the serial sections are cut and ground so as to be an even number of millimetres apart (4 mm, 6 mm, etc.): this is because the distance between successive horizontal reference lines in the projection chosen is equal to half the true distance as measured on the original sample $\cos^2(45°)$ allowing the horizontal reticule lines to be used directly as guides. Thus, if the sections are 4 mm apart in reality, the horizontal x-reference line of the second tracing lies along the grid lines 2 mm above the first, but shifted 45° to one side. This is equivalent to moving the reference points 4 × cos 45° = 2.8 mm along the projection's oblique y-coordinate.

   If Hofmann's suggestion of using even, regular spacing of faces has not been adopted, the contour intersection can still be marked by slipping a second sheet of graph paper, marked with x and y axes, under the work sheet. Position the sheet so that the axes coincide with x2 and y2, and use the same grid selected for Tracing 1 to mark off the intersections.

8. Repeat the operation for all the tracings, remembering to offset each by the appropriate distance, and to reverse every second tracing.
9. Join the points of equal elevation indicated by the column margin – grid intersections (if the reconstruction is a complex one, it may be simpler to join the points together after adding each outline).
10. Add any required intermediate profiles (Hofmann, 1976a, p. 19). The use of supplementary profiles should be recorded in the figure caption.
11. Reposition Tracing 1 and trace the outlines of the laminae on the cut face of the columns (this can be done earlier, but tends to clutter up the working diagram).
12. Make a clean copy of the drawing. The completed diagram can either retain hypsometric contours, or be stippled or shaded (Isham, 1965, p. 461), or consist of a combination of the two techniques. Stippling requires practice to produce the correct degree of shading, and is subject to the idiosyncrasies of individual authors. Nevertheless, well-executed stippled reconstructions sometimes provide the clearest image of the 3D properties of microbialite columns. Alternatively, the image can be scanned and air-brushed using computer software.

Depending on the state of preservation, ease of slabbing, and size of specimens (for example, very small columns are often difficult to depict accurately), it is not always possible to make accurate reconstructions. Walter (1972, p. 8) suggested the following reliability rating:

- R1: as accurate as the method allows with well preserved, distinct columns
- R2: column margins are slightly altered or indistinct; the gross shape is as accurate as for R1 but the margin structure is a little inaccurate
- R3: columns are very indistinct or altered; gross structures as reconstructed moderately inaccurate (e.g. may be more or less coalescing than shown, bridges may be missed or interspace laminae mistaken for bridges); reconstructions of the column-margin structure are very unreliable.

Sometimes an interpretative reconstruction, based partially on serial slabbing, but also on the observation of field relationships of the various components, can be used to illustrate 3D growth relationships. This is particularly useful with very large or very small specimens, but it is important that such diagrams are not mistaken for accurate reconstructions. They should be included in a separate category, here called R4:

- R4: interpretative; based on field observations of features, and using data from partial reconstructions.

Statistical parameters and morphometrics

Various statistical parameters have been used to characterize microbialite morphology (Komar et al., 1965a,b; Preiss 1972, 1973a,b, 1974, 1976c; Walter, 1972), and are especially applicable in the study of conical stromatolites. Most measured parameters can be plotted as histograms or frequency diagrams, and statistical methods can be used for more detailed bivariant or multivariant analyses.

Hofmann (1969a) described the geometric attributes of morphological features and then advocated a morphometric approach to stromatolite classification (Hofmann, 1969b, 1973, 1976a,b, 1977, 1978, 1994; Zhang and Hofmann, 1982). To date these methods have not been widely adopted, but as discussed above, this type of analysis should become more commonplace and is encouraged.

Parameters considered by various authors as suitable for statistical and morphometric analysis, and of possible significance for classification, are listed below:

- vertical profile (silhouette) (Hofmann, 1976b, 1977, 1978, 1994)
- plan view (cross-section) (Hofmann, 1976b, 1977, 1978, 1994)
- diameter variations of columns (Hofmann, 1976b)
- laminar profile (Hofmann, 1976b, 1977, 1978, 1994)
- degree of laminar convexity (Preiss, 1976c; Zhang and Hofmann, 1982)
- thicknesses of the laminae (Komar et al., 1965a,b; Preiss, 1976c; Suarez-Gonzalez et al., 2014)
- ratio of laminar thickness in conical or coniform stromatolites (Komar et al., 1965a; Preiss, 1972, 1976c; Walter, 1972), but see Hofmann (1978, p. 581) for a dissenting view
- coefficient of crestal zone thickening in conical or coniform stromatolites (Komar et al. 1965a,b; Preiss, 1972, 1976c; Walter, 1972), but see Hofmann (1978, p. 581) for a dissenting view
- microstructure (Hofmann, 1976b, 1977, 1978, 1994).

More sophisticated quantitative approaches and mathematical modelling have been applied to microbialites, in particular morphogenesis. Some explore differentiating biogenic from abiogenic microbialites (Grotzinger and Rothman, 1996; Corsetti and Storrie-Lombardi, 2003), while others examine the relationships of microbes, sediment, and the physical and chemical factors in the environment (Dupraz et al., 2006; Tice et al., 2011; Bosak et al., 2013a; Herminghaus et al., 2016).

Photography of prepared specimens

Images play a crucial role in disseminating information about microbialites and need to be of high quality. Microbialites can be difficult to photograph, so special care must be taken in the preparation of images for publication. Pay attention to correct orientation, low-angle incident lighting, elimination of reflection from polished surfaces, and obtaining maximum contrast. Photograph specimens against a suitable background. A sand tray, fabric or card can provide a neutral surface that reduces reflection and can be easily masked. A colour card placed alongside the specimen can be used to calibrate the colour balance. Specimens should be photographed for the optimum resolution of details, and to obtain this a fairly flexible approach is needed.

Some useful hints for photographing paleontological specimens in general were given by Douglass (1965) and Rasetti (1965) and are still relevant. Contrast is usually decreased with reflected light, and can be enhanced by techniques such as wetting the surface with water, glycerine, or cooking oil, or placing a plastic overlay sheet on a wet surface. Irregular surfaces when wetted can cause troublesome reflections. Bouma (1969, p. 75, 134) described various methods for the photography of peels, and for polished surfaces and thin or thick sections.

Computer-assisted drafting and photo editing software can be used to enhance the image of microbialites, but care must be taken not to alter the original image. Note in the caption any specialized enhancement of the figure and archive a version of the original image. Image stitching software can be used to assemble a mosaic from several images.

Because microbialites are a polymorphic group, the use of only one or two images is seldom adequate to give a representative view of the range of variation. However, because of space limitations imposed by many journals, it is often impossible to present an adequate set of images to illustrate the microbialites properly. In such cases, a composite plate (Hofmann, 1977, 1978) may satisfy journal requirements. As a minimum requirement, a photograph showing the microbialites in outcrop, in a slab (preferably demonstrating branching patterns if present), and illustrating microstructure, is recommended. If available, authors should take full advantage of the opportunity of publishing supplementary material. With regard to supplementary materials and websites, the archival nature of these venues is not certain, so critical illustrations of type material need to be included in the primary published paper.

The most useful and informative technique for microbialite illustration is to use a series of photographs of a specimen at successively larger scales, such as that adopted by Hofmann (1977, figs 11, 12; 1978) and followed by Grey (1984, 1994a,b). A rectangle is used to denote the area of enlargement and to build up a comprehensive picture of the components utilizing the concept of a nested hierarchy of observational levels (Hofmann, 1977, p. 177). The first image of the nested hierarchy should illustrate features observable in outcrop, such as the shape of the buildup, or the shape of a dome or fascicle (Grey, 1984, p. 4–5). For columnar microbialites this should show the spatial relationships of the columns and details of branching patterns in branched microbialites. More than one image for each observational level may be necessary. These are usually field photographs but can be augmented by images of polished slabs or large peels that provide general views of longitudinal sections, emphasizing features such as column shape, branching and laminar profiles. For columnar and branched microbialites, images of plan views are also important. Close ups of individual columns or branches show the laminae, margin structures, ornament and bridging. The next stage is to illustrate the finer details of laminar shapes and structure using low magnification microscope images, and then to photograph the microstructure at higher magnification.

Bar scales on the actual images are preferable to plate captions such as ‘magnification ×2’, because illustration size can be altered during publication or become meaningless when displayed onscreen. It is often simplest to place a scale adjacent to the specimen or to use a temporary scale during photography that can be cropped later and a drafted scale bar substituted in the final image. This avoids clutter and allows greater flexibility when enhancing contrast.

Preparing descriptions

Communication among researchers is enhanced by the use of standardized descriptive formats. Researchers are often confronted by descriptions in a foreign language. Deciphering the relevant parts becomes easier when the descriptive or systematic section conforms to a standard layout (Appendices 1 and 2). Microbialite descriptions play only a minor role in many papers, but the information presented may prove to be significant for another researcher interested in depositional environments, facies analyses, taxonomy, biostratigraphy, and patterns in the distribution of microbialites in time and space.

Translations of previous descriptions or diagnoses can be helpful, but to avoid confusion should be introduced by the words ‘from the original description/diagnosis of…’, be indicated by quotation marks, and end with ‘translated by [translator's name and date]’. Translations can be assisted by an online translator as well as dedicated translation programs. However, the vocabulary is often insufficient for technical words and therefore judgement needs to be exercised in improving the translation. If the description is not a direct translation of the original, perhaps because another author has given a more complete description, or it is an interpretation of an earlier description, this should be clearly indicated.

Guidelines given in Appendices 1 and 2 are designed to assist in preparing descriptions of both an informal and formal nature. Questions of nomenclature and classification are a matter for the interpretation of individual researchers.

Other study techniques

In recent years, a variety of other methods have been used for the study of microbialites. These include an array of geochemical techniques for ancient examples and variety of microscopic, biochemical, molecular techniques in living microbialites, but they are not focused on morphological terminology, so are not discussed further.

Descriptive terms for microbialites

The following discussion presents information and terminology that can be used for morphological descriptions. It is recommended that several main subheadings be used when describing microbialites, followed by paragraphs indicating the main features observed and their range of variation. Even for a researcher who intends to report on the presence of microbialites but not to study them in detail, this section may serve as a key to the essential features that will guide observations and allow the preparation of a concise and rigorous presentation. Some of the information listed below seems self-evident, but surprisingly, such key data have often been omitted, making later verification of results difficult.

Aspects that should be present in a description are defined and described in more detail below. Some descriptive terms have never been formally defined and it is difficult to trace their origin and the evolution of their usage. In practice some of the terms currently in use are synonymous, or may be ambiguous or misleading, and should be discarded. The glossary attempts to resolve some of these problems and indicate current usage.

Microbialites and their constituents

Microbialites consist of five main subsets (categories, types; Fig. 1): stromatolites, thrombolites (Figs 16–18), dendrolites (Fig. 19), leiolites (Fig. 20) and MISS (Figs 21, 22). In addition, there are other microbially induced sedimentary deposits, such as travertines (Chafetz and Guidry, 1999; Kleinteich et al., 2017), tufa (Pope and Grotzinger, 2000; Rogerson et al., 2010), speleothems (Thrailkill, 1976; Jones, 2010) and microbial crusts (Helm and Schülke, 2006). These deposits are not treated in detail in the handbook, primarily because morphological descriptions of them usually lack detail (unlike the first four of the five microbialite categories listed above) and it is just now becoming widely accepted that microbes can sometimes play a significant role in their construction, so travertine, tufa, speleothems, calcrete, geyserite and similar structures will probably be included in microbialites as research on them advances. As mentioned elsewhere, this handbook's method of study and terminology can also be applied to these structures.

Figure 16. Examples of thrombolites – living thrombolites: a) Perth Basin; Holocene; Lake Thetis, Cervantes, Hill River, Western Australia (photo by NJ Planavsky); b) Perth Basin; Holocene; Mount John boardwalk, Lake Clifton, Pinjarra, Western Australia (photo by SM Awramik)

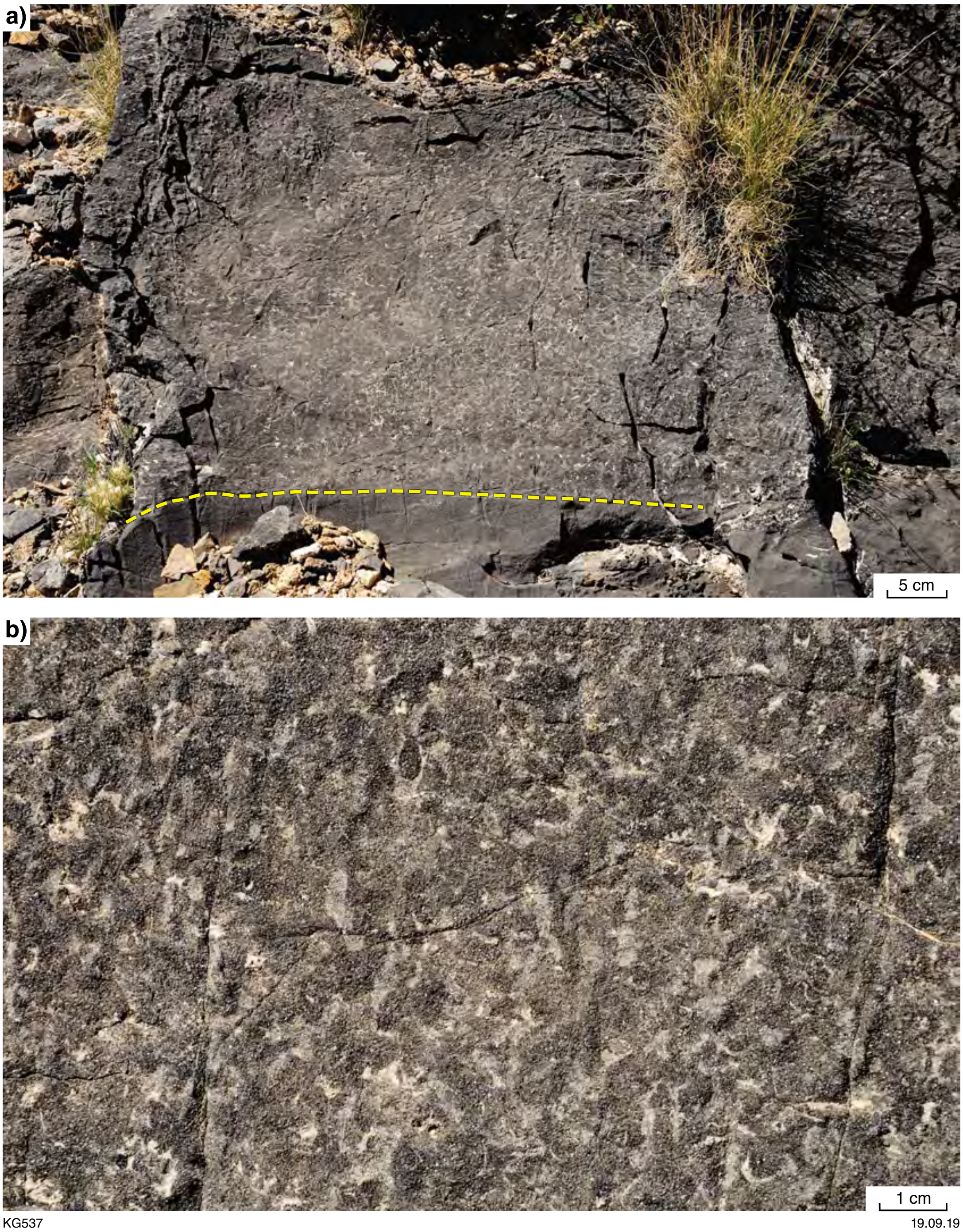

Figure 17. **Examples of thrombolites – domical thrombolite (above dashed line) overlying eroded, cross-bedded grainstone, with dark mesoclots surrounded by light cement; Desert Valley Formation (lower dark dolomite member); upper Cambrian; Delamar Mountains, Lincoln County, Nevada, US: a) thrombolite head; b) detail of mesoclots (photos by SM Awramik)**

Figure 18. Examples of thrombolites: a) Mulali Member, Skewthorpe Formation, Carlton Group; Southern Bonaparte Basin; middle Cambrian; East Onslow Hills, northeast Kimberley, CAMBRIDGE GULF, Western Australia (photo by AJ Mory); b) part of an extensive thrombolite biostrome; Holocene; Bridger Bay, Antelope Island, Great Salt Lake, Utah, US (photo by SM Awramik)

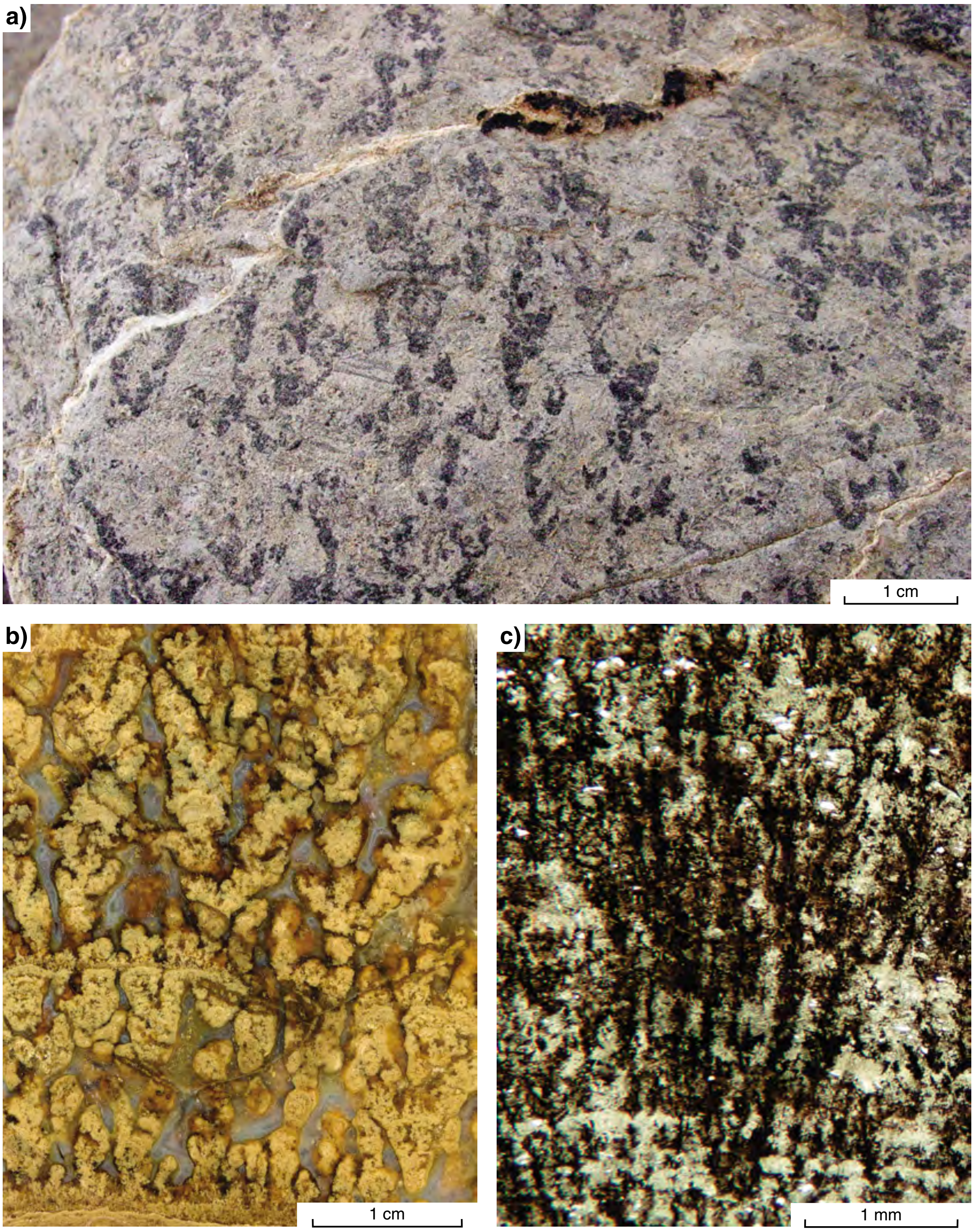

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Figure 19. Examples of dendrolites: a) dendrolite composed of shrubs; Bonanza King Formation; middle to upper Cambrian; locality uncertain, Nevada, US (photo by SM Awramik); b) dendrolite composed of shrubs; Laney Member, Green River Formation; Sand Wash Basin; Eocene; near Vermillion Creek, Moffat County, Colorado, US; polished slab, UCSB collection (photo by SM Awramik); c) dendrolite composed of *Frutexina rubia*; Bianca Member, Min'yar Formation, Karatau Group; Tonian, Neoproterozoic; Southern Urals, Russia; thick section donated by ME Raaben (part of GIN AN SSSR, sample 4580/210); UCSB collection (photo by SM Awramik)

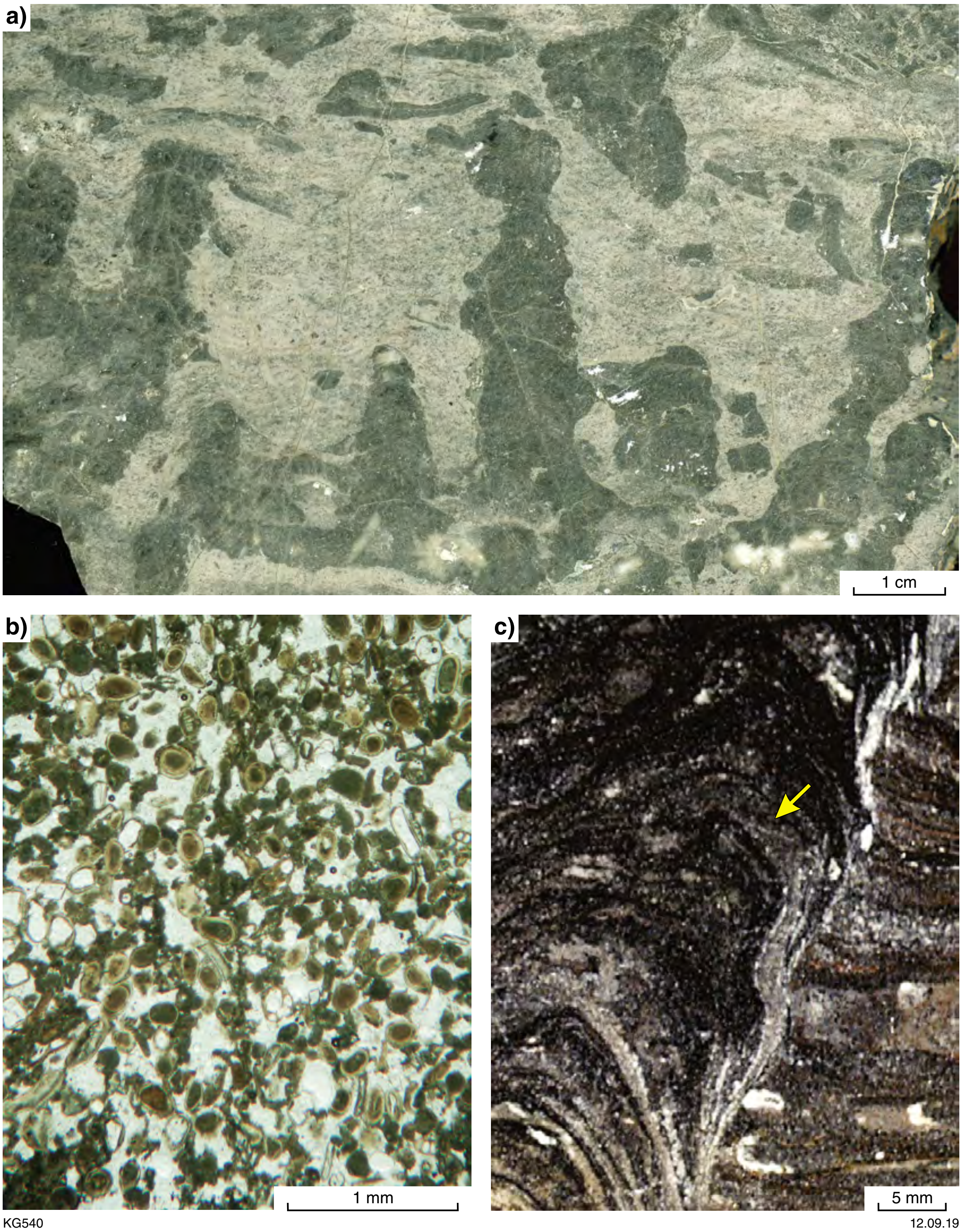

Figure 20. Examples of leiolites and microbial boundstones: a) leiolite; Bonanza King Formation; middle to upper Cambrian; Potosi Mountain area, Spring Mountains, Clark County, Nevada, US; UCSB collection. The microbialites are generally aphanitic but locally show lamination and mesoclots (photo by SM Awramik); b) boundstone from a living microbialite; Carnarvon Basin; Holocene; Carbla Point, Hamelin Pool, Shark Bay, Yaringa, Western Australia; UCSB collection (photo by SM Awramik); c) boundstone in fossil microbialite (arrow); *Cryptozoon proliferum*; Hoyt Limestone; upper Cambrian; near Lester Park, Saratoga County, New York, US; UCSB collection (photo by SM Awramik)

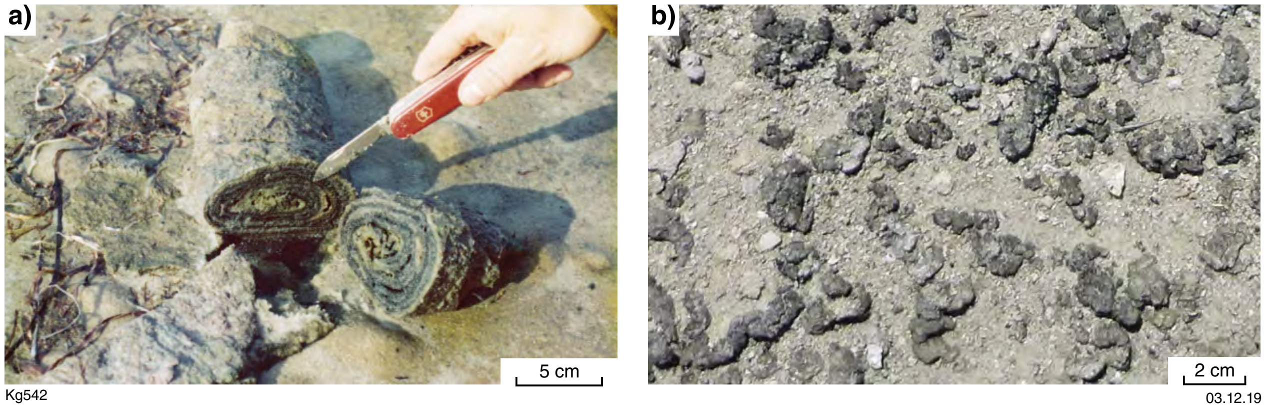

Figure 21. Examples of living microbially induced sedimentary structures (MISS): a) roll-up microbial mat; Holocene; Sippewissett Salt Marsh, Barnstable County, Massachusetts, US (photo by SM Awramik); b) blister mat; Perth Basin; Holocene; Lake Yalgorup, Yalgorup Lakes System, PINJARRA, Western Australia (photo by SM Awramik)

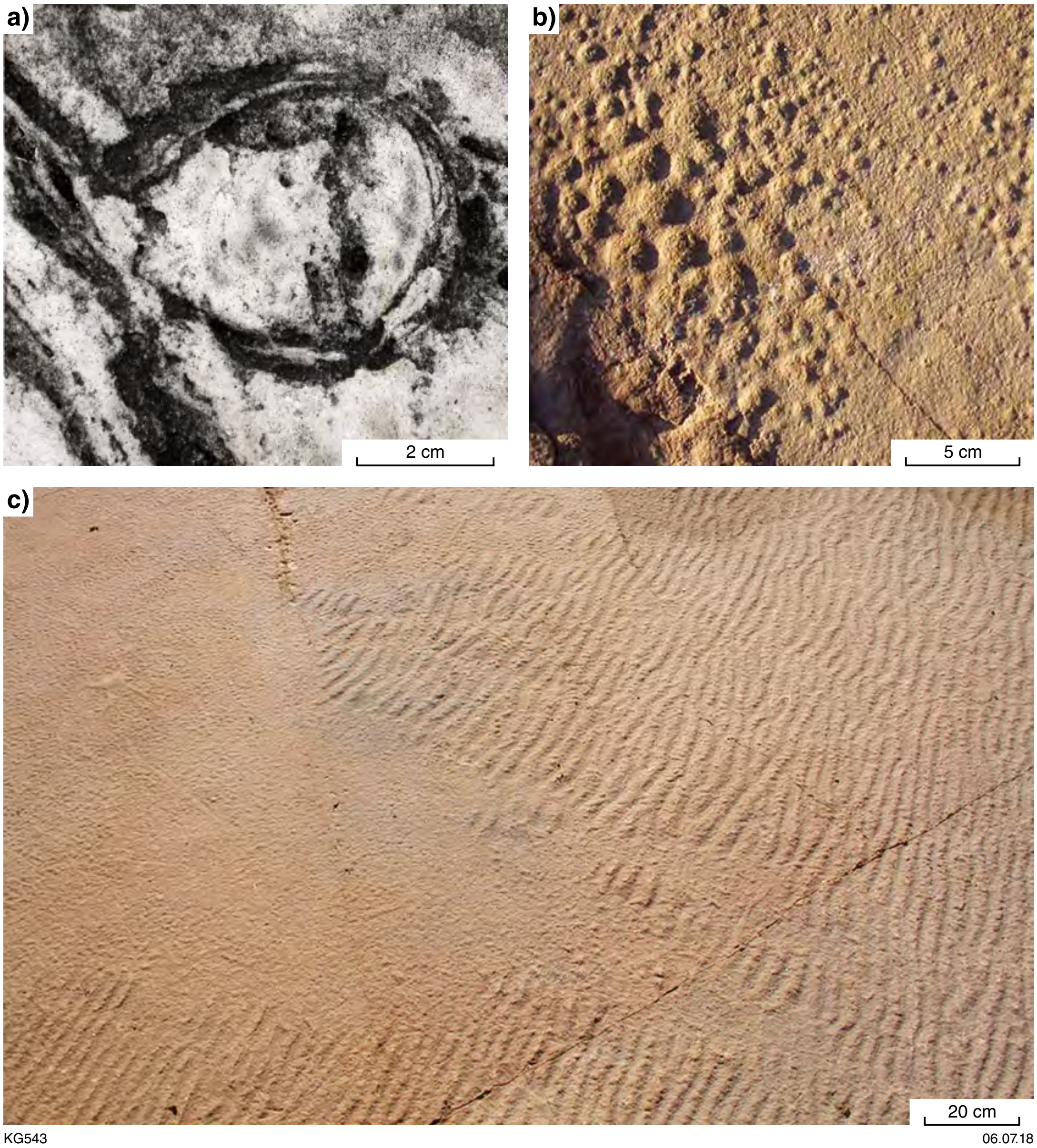

Figure 22. Examples of fossil microbially induced sedimentary structures (photos by JW Hagadorn). These have also been called sand stromatolites (Bottjer and Hagadorn, 2007): a) roll-up microbial mat; Nepean Formation; upper Cambrian; Ottawa, Ontario, Canada; b) blister mat; Elk Mound Group; upper Cambrian; Mosinee, Marathon County, Wisconsin, US; c) patchy, mat-preserved ripples and blister mat on sandstone; Elk Mound Group; upper Cambrian; Mosinee, Marathon County, Wisconsin, US

Many examples have been reported where the different subsets or categories of microbialites described above are closely associated with each other or even transition from one type to another (Fig. 23). There may be transition between stromatolites and thrombolites (Fig. 23a; Kennard et al., 1988), between all or any combinations of microbialite subsets, such as stromatolite, thrombolite and dendrolite (Fig. 23b–d), or between microbialites and other microbially influenced deposits; for example, between stromatolites and tufa (Shiraishi et al., 2010), sometimes called tufa stromatolites (Riding, 1991). We propose that such associations be referred to as composite microbialites (see later section). Several authors have attempted to show transitional relationships on triangular plots (Schmid, 1996; Leinfelder and Schmid, 2000; Riding, 2008, 2011a).

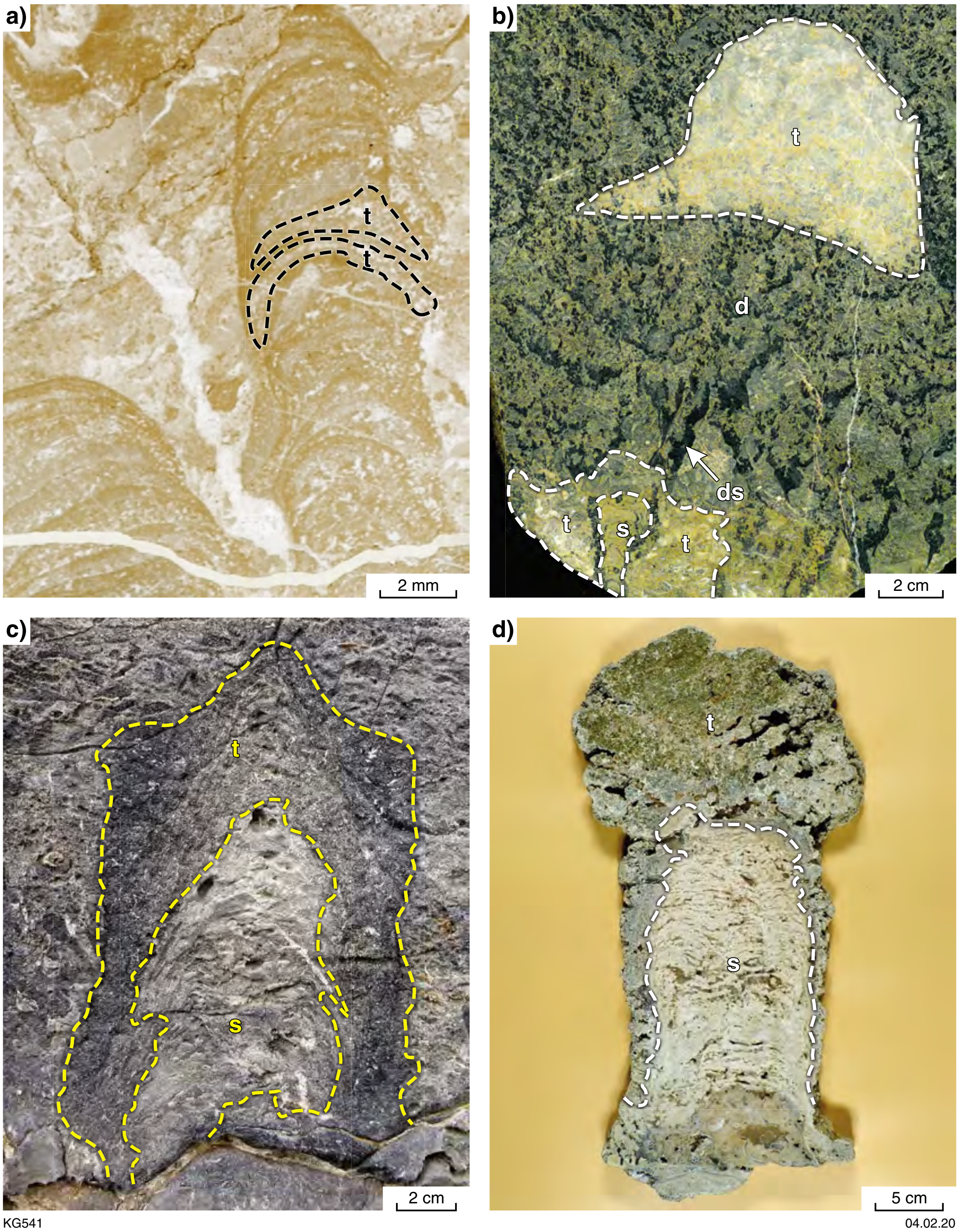

Figure 23. Examples of a composite microbialite – stromatolites alternating with thrombolites or dendrolites: a) thrombolite (t, outlined) alternating with stromatolite, *Madiganites mawsoni*; Shannon Formation, Pertaoorta Group, Amadeus Basin; Cambrian; Ooraminna Anticline, Alice Springs, Northern Territory, Australia; thick section, GSWA F52662–109256 (photo by SM Awramik and K Grey); b) small, columnar stromatolite (s, outlined), overlain by thrombolite (t, outlined), then dendrolite (d), and another thrombolite (t, outlined); individual shrubs are dark grey (ds); Highland Peak Formation; upper Cambrian; Delamar Mountains, Lincoln County, Nevada, US; polished surface, UCSB collection (photo by SM Awramik); c) stromatolite (s) rimmed by a thrombolite (t, outlined); Nopah Formation; upper Cambrian; Dry Mountain area, Death Valley National Park, Inyo County, California, US (photo by SM Awramik); d) thrombolite (t) capping a stromatolite (s); Carnarvon Basin; Holocene; Hamelin Pool, Shark Bay, Edel, Western Australia; F54145, cut section of sample collected by RP Reid and EP Suosaari (photo by SK Martin and K Grey)

The Phanerozoic has some additional complexities for microbialites. Both composite and compound (see section on 'Microbialite shape') microbialites appear to be more common in the Phanerozoic than in the Precambrian. However, features such as complex branching patterns are generally much more common in the Precambrian than in the Phanerozoic. Skeletal eukaryotes can be found in Phanerozoic microbialites and they may contribute to the buildup. Selected examples include calcareous algae (Chuvashov and Riding, 1984), sponges (Soja, 1994), archaeocyathan sponges (Kruse, 1991), corals and sponges (Leinfelder et al., 1993), corals and calcareous algae (Montaggioni and Camoin, 1993), and bryozoans (Füchtbauer, 1968). Where these can be recognized, it is important to mention and, if possible, identify them.

Stromatolites, thrombolites, dendrolites, and leiolites can be described under four main headings, in order of decreasing scale: megastructure, macrostructure, mesostructure, and microstructure (Figs 2, 3).

Terminology for these four scale categories is common for megastructure, macrostructure and, to a large extent, microstructure, but diverges at mesostructural level (Fig. 3). The corollary of acknowledging a commonality at these three levels of organization is that the fundamental distinguishing feature between types of microbialites (Figs 1, 3) is the mesostructure. This is a basic principle, because it not only simplifies terminology, but also has repercussions for the interpretation of microbialite formation through time. Thrombolites and dendrolites require separate terminology for some features.

Stromatolites

Stromatolites are by far the most abundant type of microbialite and the most readily recognized because of the presence of lamination (Figs 1–3). Some authors — for example, Playford (1990), Reid et al. (2003, p. 299), Playford et al. (2013, p. 176) and Suosaari et al. (2016) — used the term stromatolite for all microbialites. We prefer to follow prevailing usage of stromatolite as a subset of microbialite for structures that have lamination, as originally intended by Kalkowsky (1908) and expanded by Burne and Moore (1987), and as discussed above.

Thrombolites

The term thrombolite (Figs 1–3, 16–18) is used here as defined by Shapiro (2000, p. 169): 'microbialites composed of clotted mesostructure (mesoclots)' (Fig. 16a,b). This was based on the original definition of Aitken (1967, p. 1164): 'cryptalgal structures related to stromatolites but lacking lamination and characterized by a macroscopic clotted fabric'. Aitken's (1967) 'macroscopic clotted fabric' is synonymous with Shapiro's 'clotted mesostructure'.

Over the years, various interpretations of the term thrombolite have arisen (Pratt and James, 1982; Kennard, 1994; Kennard and James, 1986; Burne and Moore, 1987; Feldmann and McKenzie, 1998; Turner et al., 2000; Myshrall, 2010; Bernhard et al., 2013) but cannot readily be resolved (Harwood Theisen and Sumner, 2016). Shapiro (2000) analysed these differences and suggested that differing concepts may have developed because researchers studied different aspects of thrombolites and applied terms differently (Shapiro, 2000, fig 1, table 1), resulting in indiscriminate usage. He pointed out that, '[t]he lack of a consistent terminology is due to the perspective (= material repertoire) of the individual worker … I believe the problem lies in part on the lack of many authors to publish clear figures and plates' (Shapiro, 2000, p. 168). He added that, '…it is apparent that we need: (1) the most all-encompassing terminology; (2) to avoid a duplicate set of macrostructural terms; (3) to set as a systematic guide, terms that are the least cumbersome' (Shapiro, 2000, p. 169).

Myshrall (2010) pointed out that there is still no clear understanding of thrombolite form and function and that researchers 'need to take a step back and evaluate what we do know about thrombolites, what is still needed to be known to fill in the gaps of knowledge, and ask why we don't know more at this point.' Her conclusion that 'an extensive, collaborative effort on understanding a particular system' was needed, and that it would only be once a collective effort had been made 'to put the pieces together' that we would 'begin to gain a clearer understanding of how thrombolites are created and function', remains true and unrealized.

Disparities have also possibly resulted from:

- a heavy dependence on interpretations of genesis
- material being described from successions of differing ages
- the point of view of the individual researcher; Shapiro's (2000, p. 168) 'material repertoire'.

There may be morphological differences between thrombolites recorded from the Paleoproterozoic (Kah and Grotzinger, 1992; Kunzmann et al., 2014; Barlow et al., 2016), Mesoproterozoic (Tang et al., 2013), Neoproterozoic (Aitken and Narbonne, 1989; Grotzinger and James, 2000; Turner et al., 2000; Harwood and Sumner, 2011, 2012; Wood and Curtis, 2015); Cambrian (Shapiro and Awramik, 2000; Benssaou and Hamoumi, 2004; Lee et al., 2014; Harwood Theisen and Sumner, 2016), Ordovician (Pratt and James, 1982), later Paleozoic (Webb, 1987, 2005; Matysik et al., 2015), Mesozoic (Leinfelder et al., 1993; Martin et al., 1993; Mancini et al., 2004; Baud et al., 2007; Homann, 2010; Tomás et al., 2013), and Holocene (Moore, 1987; Burne and Moore, 1987; Moore and Burne, 1994; Reid et al., 1995, 2011; Laval et al., 2000; Planavsky and Ginsburg, 2009; Bernhard et al., 2013; Patterson, 2014; Lluesma Parellada, 2015). For example, Kah and Grotzinger (1992, p. 305) pointed out that Paleoproterozoic thrombolites from the Rocknest Formation, Canada, were 'significantly different from younger Proterozoic thrombolites and their Phanerozoic counterparts.' The recognition of some thrombolites may be doubtful if their interpretation is based solely on the presence of 'mesoclots' because some, like those from the Rocknest Formation, Wopmay Orogen, Northwest Territories, Canada, 'lack distinct mesoscale structures' (Harwood Theisen and Sumner, 2016, p. 2218). We need to know if mesoclots and clots in general vary through time.

In general, many papers on thrombolites are so inadequately illustrated that it is difficult to tell the nature of the mesostructure. Careful detailed descriptions and illustrations are needed at the mesostructural level as well as the microstructural level with special attention to diagenetic alteration. What is clear is that thrombolites are not laminated, do not contain shrubs, and do not have a structureless mesostructure (Figs 16, 17,18a). They are a work in progress.

Laminated and unlaminated subsets can be present in the same microbialite (Pratt and James, 1982; Kennard and James, 1986), particularly in Cambro-Ordovician microbialites (Kennard, 1994). Kennard and James (1986) proposed a quantitative classification scheme for microbial mounds that contain multiple components, but it has not been widely accepted. The interrelationships between subsets and their mesostructural components can be complex (Fig. 23b–d) and should be noted in detail. Stromatolite or thrombolite can be used in an adjectival form to describe mixed thrombolites or stromatolites (examples being stromatolitic thrombolite and thrombolitic stromatolite).

Laminae and mesoclots or a clotted appearance occupy parallel positions in the hierarchy of descriptive terminology (Fig. 3). Much of the terminology applied to laminated microbialites at the megastructural and microstructural levels can also be applied to thrombolites and dendrolites. It is only at the mesostructural level that there are fundamental differences and it is here that separate terminology is required.

Dendrolites

Dendrolites (Figs 1, 3, 19) have been recorded from several intervals in the geological record (Sheehan and Harris, 2004; Woo et al., 2008), but as yet they are not well understood and specific terminology has not been developed. The term dendrolite was introduced by Riding (1988, p. 5) and reprinted in Riding (1989, p. 11) for 'biomineralized microbial deposits with a dominant dendritic macrofabric.' Riding (1991, p. 34) later added that they were unlaminated. According to Riding (2000, p. 195) 'they are only known to form by microbial calcification, and not by agglutination of particles.' Non-calcimicrobe-bearing dendritic structures produced under the influence of microbial activity are known, although they are usually called shrubs (Fig. 19a,b; Chafetz and Folk, 1984; Guo and Riding, 1999). Most of these are travertines (Chafetz and Guidry, 1999; Gandin and Capezzuoli, 2014). Some spring mounds, such as at Pyramid Lake, Nevada, US, have a dendritic mesostructure and microstructure (Wright, 2011). There are also non-travertine types, such as in the Lower Cretaceous 'pre-salt' of offshore Brazil (Ceraldi and Green, 2017) and Angola (Saller et al., 2016), as well as the Eocene Green River Formation of Colorado, US (Awramik and Buchheim, 2015). Only a few living equivalents are known, such as those in Pavilion Lake, Marble Canyon, British Columbia, Canada (Laval et al., 2000; Omelon et al., 2013); an example from Hamelin Pool, Shark Bay, Western Australia (Suosaari et al., 2018) and a possible example from Little Hot Creek, Long Valley Caldera, California, USA (Bradley et al., 2017).

To date, there have been few records of dendrolite occurrences and descriptions have not been very rigorous. Consequently, our understanding of dendrolites is at an early stage and there are ambiguities even in the use of the term. The terms dendrolite and dendritic structure appear to have been used interchangeably. Some authors have used dendrolite to mean a macroscopic structure composed of a collection of small, shrub-like masses and this reflects the original definition (Riding, 1988, 1989, 2011a, p. 637, fig. 1; Howell et al., 2011). Other authors seem to imply that a single, small, shrub-like mass is the dendrolite (Ibarra et al., 2014). The shrub-like masses have also been called dendroids (Howell et al., 2011). Because of the confusion and contradictory nature of what could be viewed as yet another parallel set of terms — stromatoid (stromatolites) and thromboid (thrombolites) — dendroid should not be used. We recommend that dendrolite is used for the macroscopic structure and shrub is used for the mesostructural element within a dendrolite.

In addition, Kershaw et al. (2012, p. 28) pointed out 'there is overlap between thrombolites and dendrolites in some cases because of mixed components' in the case of branching thrombolites. Kershaw et al. (2012, p. 28) also reserved the term dendrolite for structures composed of branching calcimicrobes. Dendrolites should be used for microbialites that have a dendritic (shrub-like) mesostructure, whether or not they contain calcimicrobes.

Dendrolites can probably best be described using a combination of the terminology applied to stromatolites and thrombolites, or other descriptive terms. Whatever terminology is used should be accompanied by clear definitions and illustrations so that the terms can be understood and applied consistently in future studies.

Leiolites

Leiolite (Fig. 20) is another category of microbialite that is poorly understood. Some of the microbialite terminology, particularly with regard to megastructure, macrostructure, and microstructure can be applied. As originally defined in Braga et al. (1995, p. 352), leiolites are microbial deposits with structureless macrofabrics (treated as mesostructure in this handbook; Figs 1 and 20a). Later, Riding (2000, p. 195; 2011a, p. 637) used the term 'aphanitic' for the internal fabric as well as macrofabric (Riding, 2011b, p. 50) (see 'Describing leiolite mesostructure'). Since leiolites are structureless at the mesostructural scale, unless there is a suggestive macrostructure, such as domes (Braga et al., 1995) or accumulation on steep slopes (Kenter et al., 2005), recognition could be difficult (but see Mei, 2007a,b). Seemingly equivalent terms have been suggested in the past, including 'massive cryptalgal fabrics' (Monty, 1976, p. 235), 'undifferentiated microbial boundstone' (Kennard and James, 1986, p. 497), and 'structureless microbialites' (Siahi et al., 2016, p. 259). The handbook defines leiolite as a microbialite with a structureless mesostructure.

Dunham (1962) introduced the term 'boundstone' (Fig. 20b) for loose sediments that are bound during deposition. Of the three examples he discussed, he recognized stromatolites as boundstones because of 'lamination contrary to gravity' (Dunham, 1962, p. 117).

Embry and Klovan (1971) recognized that Dunham's boundstones lacked detail with regard to organisms responsible for binding. They stressed the role of skeletal metazoans as binding agents. The role of microbes as a binding agent was not fully appreciated. The term 'microbial boundstone' began to be used frequently in the late 1980s. Burne and Moore (1987, p. 242) used microbial boundstone for a rock that formed principally by microbial trapping and binding (Fig. 20b). Prior to that, such terms as 'algal boundstone' (Bertrand-Sarfati and Moussine-Pouchkine, 1983, p. 227) and 'cryptalgal boundstone' (Knight and James, 1987, p. 1930) were used.

Boundstones and microbial boundstones are important to the petroleum industry where cores contain detrital grains that indicate buildups or accumulations on slopes steeper than the angle of repose, and are interpreted as having a microbial origin (Keim and Schlager, 1999; Kenter et al., 2005). Therefore, a mesostructurally featureless microbial boundstone (Chen et al., 2002; Kenter et al., 2005) could be called a leiolite. Not all boundstones are leiolites; some boundstones are laminated (Fig. 20c) and are therefore referred to as a stromatolitic boundstone (Goldstein et al., 2013), while others are associated with mesoclots and called a thrombolitic boundstone (de Freitas, 1998; Mancini et al., 2013).

We recommend that leiolite be used for a microbialite with a structureless mesostructure regardless of grainsize.

Microbially induced sedimentary structures

Microbially induced sedimentary structures (MISS; Figs 21 and 22) were defined as 'sedimentary structures in siliciclastic sediments and rocks induced by microbial activity' (Noffke et al., 1996, p. 315). Besides MISS, other terms have been used for these sedimentary structures, among them: matgrounds (Seilacher and Pflüger, 1994; Pflüger, 1999), mat-induced sedimentary structures (Scheiber et al., 2007, p. 1), microbially bound sandy surfaces (Bottjer and Hagadorn, 2007, p. 53), and mat-related sedimentary structures (Seilacher, 1999, p. 86). Although most of the research on MISS has been carried out on siliciclastic sediments, MISS also occur with carbonate sediments (Bose and Chafetz, 2011).

Noffke (2010, p. 77–114) recognized and discussed five types or categories of MISS that are mainly process based and therefore not exclusively descriptive:

1. Structures arising from growth ('enrichment of biomass by cell replication', p. 77)
2. Structures arising from biostabilization ('the response by benthic microbiota to erosion', p. 77)
3. Structures arising from baffling and trapping ('baffling is the response by benthic microbiota to the deposition of sediment', p. 78 and 'trapping is the effect of sticky EPS on the surface of microbial mats', p. 79)
4. Structures arising from binding ('the formation of a mat fabric by active movement of cyanobacteria', p. 79)
5. Structures arising from the interference of all microbial activities interacting with physical sediment dynamics ('arise from interference of growth, baffling, trapping and binding, as well as biostablization', p. 114).

Schieber et al. (2007a) presented numerous illustrations to help identify the structures, but these descriptions are primarily process based as well.

Because MISS are mainly process based and the emphasis is on genesis, they are difficult to integrate into the descriptive approach based on morphological characteristics used in this handbook. MISS are primarily 2D, sediment-surface features (Figs 21, 22), whereas other microbialites are predominantly 3D (Noffke and Awramik, 2013). Although some microbialite terminology presented below may apply to MISS, for now it is probably best to refer to the publications cited above and any other recent publications when describing examples of MISS. Davies et al. (2016) provided a comprehensive review of MISS and because of difficulty establishing a biogenic origin for MISS, suggest that the term sedimentary surface textures be used instead. This is a non-genetic term that does not indicate biological involvement. They also presented a new classification scheme, which is also process based. Microbially induced sedimentary structures are an emerging field and some handbook terminology could be used to develop a descriptive approach.

Composite microbialites

Many examples have been reported where the different categories or subsets of microbialites described above are closely associated with each other or transition from one type to another (Fig. 23). We propose that such associations be referred to as a composite microbialite (new term). A composite microbialite is defined here as an association of different subsets of microbialite (stromatolite, thrombolite, dendrolite, leiolite, MISS) or an association between microbialites and other microbially influenced deposits, such as tufa. Subsets are distinguished from each other by differences, or a combination of differences, at macro-, meso- or microstructural levels. By contrast, a compound microbialite (new term) only combines different macrostructural shapes, such as layered and minicolumnar microbialites or a cone with a branched microbialite (see 'Microbialite shape' below).

Size classification and organization of microbialites

Microbialites can cover an area extending for hundreds of kilometres or be as small as a millimetre or less. This variation in size ranges over eight orders of magnitude. Hofmann (2000, p. 322, fig. 4) introduced a size classification (Figs 4, 6–9) to provide terminology for discussing variation in size.

Although these size terms and concepts are useful when dealing with absolute measurements, they are somewhat misleading because it is not enough to only consider stromatolite size; the hierarchical organization within a microbialite (see below) is often of greater significance.

Microbialite structures may cover an extensive area, but be made up of smaller scale components that are similar to the larger ones with regard to morphological characteristics such as bioherm shape, branching patterns, details of laminae and microstructure. These structures are in turn composed of smaller scale structures, resulting in a nested effect at several levels. In other words, they follow the matryoshka principle (or nested-doll principle) and many stromatolite attributes can be regarded as fractals (Hofmann, 1994, p. 708–709, fig. 5). Dupraz et al. (2006, p.195) pointed out that stromatolite morphospace could be modelled using a combination of Diffusion Limited Aggregation and cellular automata. The model 'can simulate morphologies at various scales (giving it a fractal property)' (Dupraz et al., 2006, p. 195) and, because it is based on self-similarity, it is not dependent on scale.

Microbialites are not unique in this. Australia's Great Barrier Reef shows the same type of organization, with the reef as a whole covering an area of 348 000 square kilometres. Within the Great Barrier Reef are some two and half thousand individual reefs, and most of these smaller reefs are made up of even smaller bioherms, with each bioherm consisting of numerous individual heads of coral.

There are many examples of Great Barrier Reef-like microbial buildups. For example, in Mauritania, massive Mesoproterozoic reefs of *Conophyton* and other stromatolites extend over a distance of up to 1000 km and consist of biostromes between 30 and 100 km long (Bertrand-Sarfati and Moussine-Pouchkine, 1988a, p. 257). In the Kilohigok Basin, Bathhurst Inlet, Canada, microbialite buildups in the platform facies of the Paleoproterozoic Western River Formation 'consist of vast, elongate, high-relief bioherms of branching columnar stromatolites' (Campbell and Cecile, 1981, p. 108). The bioherms are up to 100 m long and 2–20 m wide. These bioherms, in turn, comprise an association of domical, pseudocolumnar, columnar and branched individuals. Each of these entities has lower levels of organization that relate to the nature of the lamination and the microstructure.

In order to describe these hierarchical structures, we use the terms megastructure, macrostructure, mesostructure and microstructure (Fig. 2). These levels of organization are broad-scale groupings of observable characteristics. They are somewhat flexible and are not mutually exclusive.

Megastructure (Figs 2, 3, 6) (from *megas*, Greek = large, great) deals with the large-scale aspects of the microbialites and the beds in which they occur. Megastructure includes various levels of organization from the highest level, the bed or stratum, through large buildups, to the larger bioherms and biostromes.

Macrostructure (Figs 2, 3, 6b) (from *makro*, Greek = large) refers to aspects of the majority of bioherms and biostromes and includes features of the gross morphology of individual microbialites. It is intermediate between megastructure and mesostructure. Features to be described include the shape, such as stratiform, linked, domical, columnar, conical, coniform, branched, or oncoidal (see below for details).

Mesostructure (Figs 2, 3, 7–9) (from *mesos*, Greek = intermediate, middle) is used here for features intermediate between macrostructure and microstructure in individual microbialites and deals with the visible internal organization. It is one of the key characteristics for description, and it is at this level that thrombolites, dendrolites, and leiolites, show their distinction from stromatolites (Figs 1, 2).

Microstructure (Figs 2, 3) (from *mikros*, Greek = small) is here restricted to those features best studied under the microscope and includes texture, fabric, and microfossils and microorganisms if present. Originally, Preiss (1972, p. 93) defined microstructure as, 'the fine-scale structure of the stromatolite lamination, in particular the distinctness, continuity, thickness and composition of the laminae.' Many of these elements are here considered part of the architecture of the laminae and are included with mesostructure. Microstructure applies equally to stromatolites, thrombolites, dendrolites, leiolites, and MISS.

Describing microbialite megastructure

Megastructure (Figs 2–4, 6, 10a,b, 11–15) deals with the broader, highest-order, aspects of microbialites. It includes several levels ranging from the bed or stratum, through microbialite reefs and large buildups, to the larger bioherms and biostromes. Megastructure is mainly determined by examination of microbialites from satellite and landsat imaging, aerial photography, drone photography and observation at outcrops. Record key data about the outcrop, such as the bed thickness, extent and shape of microbialitic structures within the bed, and any cyclicity that may be seen. Make detailed observations on the nature of the bioherms and biostromes and on the individual structures within them (Figs 6–15).

Microbialites at outcrop level

A precise location and concise description of the outcrop are necessary for comparative purposes. Include information on the following features in descriptions of the outcrop.

Location

Microbialite localities are best given in UTM (note datum), although latitude and longitude, or a map grid reference, also allow for relocation. In the United States, the older literature used township and range. When reporting on these localities, include UTM (or latitude and longitude) along with the older location information. Include a map with general locations for the area under consideration with specific localities clearly marked in any publication. For localities that require conservation, consider publishing only generalized locality information and provide a repository with precise information, as in Awramik and Buchheim (2015). The repository could be the permitting agency, the institution where the specimens are deposited, or some other relevant institution (for example, a museum or geological survey). If several locations are being discussed, it may be simplest to give each locality a code number, mark it on the map, and then group all locality data in an appendix; for example, see

Grey (1984). For remote localities it could be helpful to include access information, such as ‘four-wheel drive’, ‘boat’, ‘helicopter’, ‘3 km strenuous hike from main road followed by 30 m easy climb’.

1. *Areal extent and nature of outcrop*: give a clear account of the lateral and vertical extent of the outcrop, and the extent and quality of the exposure. Information on preservation, lithology, weathering, and diagenetic and/or other secondary alteration (e.g. ‘30 m section in river bank’; ‘poorly exposed, deeply weathered bedding plane showing extensive recrystallization’; ‘rubbly outcrop on hillside scree slope’) should be included.
2. *Stratigraphic setting:* document the group, formation and/or member and provide pertinent information on the sequence or parasequences containing the microbialites. If the microbialites are present at more than one locality, include a discussion of any variation in morphology between localities. Document the overall stratigraphic succession of the outcrop, locality, and/or area where the microbialites occur.

Measured sections provide valuable stratigraphic information and context for microbialite-bearing beds. Provide precise latitude and longitude, UTM (note datum), or a map grid reference of any measured (logged) section(s).

For beds or complex successions containing diverse microbialites, the position of particular microbialite components should be noted in both the formal description and by means of a stratigraphic section or a drawing of the bed with the multiple components. The relationship of microbialites to surrounding strata should be described carefully (Figs 10a,b, 11). Microbialites may all be of a single type, or consist of several types in association; for example, components may consist of bioherms, biostromes, fascicles or various combinations of all three types. They may occur as a single unit or be arranged three dimensionally (Fig. 11e,f). Components in a single horizontal plane can be aligned (either two dimensionally or three dimensionally) into a lattice pattern (regular) or their arrangement can be random (irregular). Specific lattice patterns may be present; for example, they may show square or hexagonal packing. Components may also be vertically stacked. Stacking can be regular or irregular, or intermingled (i.e. the base of one component is offset relative to the base and top of another; Fig. 11e,f). Describe the relationship between microbial components, as well as between microbial components and enclosing sediment, paying particular attention to the features listed below, which are discussed in greater detail under ‘Describing microbialite mesostructure’.

1. *Microbialite context*: record the thickness and geometry of the bed or unit containing the microbialites. There may be variations in thickness. Note the lateral extent of the unit that contains microbialites. Describe the lithology of the enclosing strata; for example, a limestone bioherm may occur in a calcareous siltstone or shale. Describe the lithology of the microbialite itself using appropriate petrographic terminology. Describe the depositional setting of the microbialite; for example, lacustrine, hot spring, marine carbonate ramp, marine carbonate platform, cavity fill. Note the facies in which the microbialites occur.
2. *Microbialite substrate*: microbialites develop on different types of substrate (Figs 24–29). They can grow directly on the bedding surface, on soft sediment, firm ground or hard ground (Fig. 25a,b), on clasts sourced from a variety of origins (Figs 25c, 26), on other microbialites (Fig. 27), or on any other convenient surface (Fig. 28). They may initiate on areas of positive relief such as beach ridges, ripple crests, or clasts, and the initial shape of the microbialite may conform to the substrate profile, but once well established they generally revert to a preferred architecture that no longer reflects the substrate. They can also form as linings in cavities, cracks or solution pipes (Fig. 29).
3. *Microbialite initiation*: the initial phase of microbialite development is often an important diagnostic feature. Columns and branches may develop directly on the substrate, or from stratiform or domical laminae (Figs 30–32, 33a,b).
4. *Microbialite–sediment interface*: record the nature of the upper, lower and lateral boundaries among the microbialites and enclosing sediments (Fig. 10a,b). The relationships between the microbialite and the enclosing strata may be discrete (sharp; Fig. 10a), discontinuous or gradational into overlying and underlying sediments. The relationships can be intertonguing (Fig. 10b), onlapping, abutting, or draping, and the microbialite body may be tabular (Fig. 10k), undulating (Fig. 10l), or lensoid. There may be evidence of erosion or an unconformity. The base of the bed may coincide with the base of the microbialite, or the microbialites may be dispersed throughout the bed. The contact between the microbialite and the substrate may be transitional or sharp.
5. *Growth direction*: is an important attribute of microbialites. In most cases, growth direction is perpendicular to the plane of the substrate, for example see Serebryakov (1975, fig. 33) and Smith and Mason (1991), but can be downward, oblique, horizontal, or in several directions. Inclination (see below under ‘Attitude’) has been noted in a variety of microbialites; for example, see *Conophyton inclinatum* in Rezak (1957), and is often attributed to currents (Hofmann, 1967; Hoffman, 1974; Campbell and Cecile, 1981). Departures from vertical growth might also be induced by heliotropism (Bosak et al., 2009; Vanyo and Awramik, 1982, 1985).

Mode of occurrence

Mode of occurrence refers to the gross manifestation of a microbialite and its spatial relationships. Features such as reefs, mounds, buildups, bioherms, and biostromes are elements of mode of occurrence (Figs 2, 6, 10–15). Use of the term 'reef' should be restricted to those structures that have the distinctive features of reefs such as 'erect rigid, wave-resistant topographic structures' (Lowenstam, 1950, p. 433), and as discussed in Heckel (1974). The term 'buildup' (Heckel, 1974, p. 92) may be preferable, particularly where the structure is inadequately exposed and it may be difficult to determine its nature. The terms buildup, bioherm and biostrome can be further qualified by the use of descriptors such as 'microbialitic', 'stromatolitic', 'thrombolitic', 'dendrolitic', or 'leiolitic'.

A buildup can be a complex structure and it is often multifaceted (see below; Fig. 11e,f). It can comprise a single bioherm, or a biostrome constructed by laterally contiguous bioherms. The dimensions of bioherms and biostromes may vary from a few millimetres to many kilometres, in particular for biostromes. The terminology shown in Figures 2 and 4 should be used to indicate the scale of structure being described. Other factors to be considered as contributing to the mode of occurrence are the density, spacing of the elements, and any variation or gradation between the bioherms or biostromes.

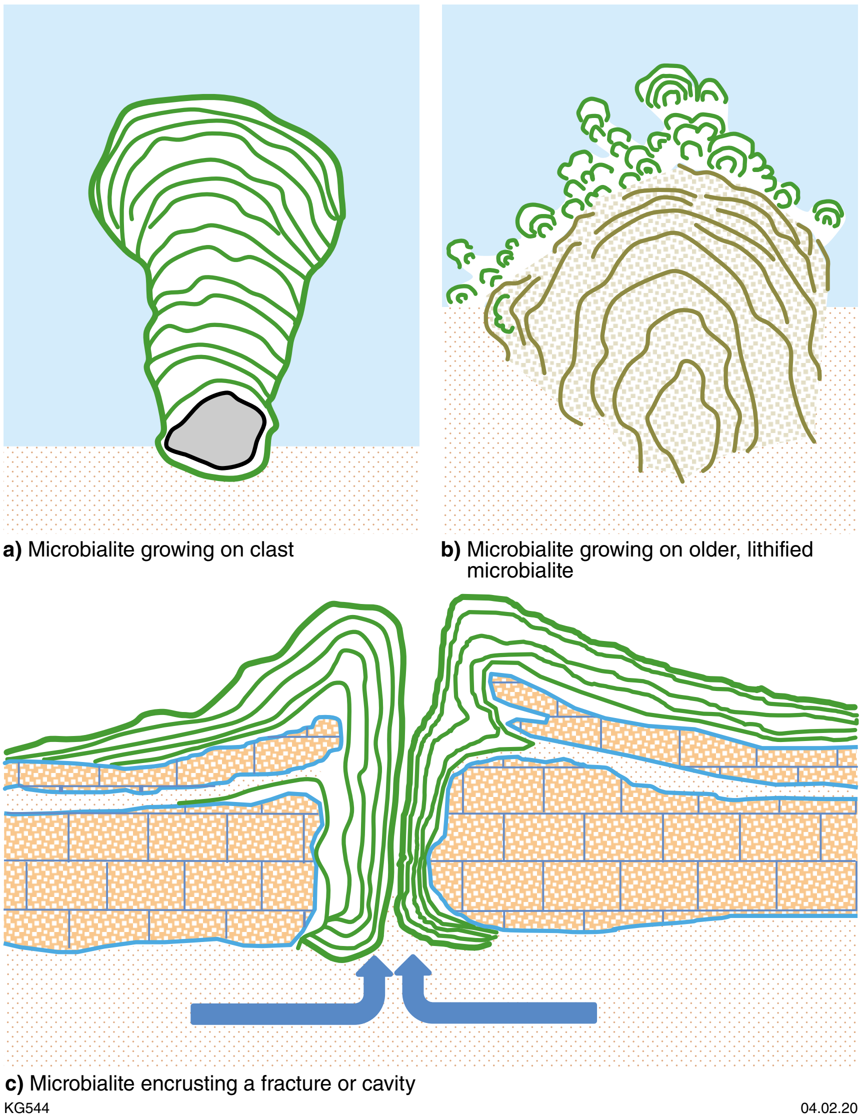

Figure 24. Relationship of microbialite to substrate: a) microbialite growing on clast; b) microbialite growing on older, lithified microbialite; c) microbialite encrusting a fracture or cavity, usually in response to water flow into the cavity

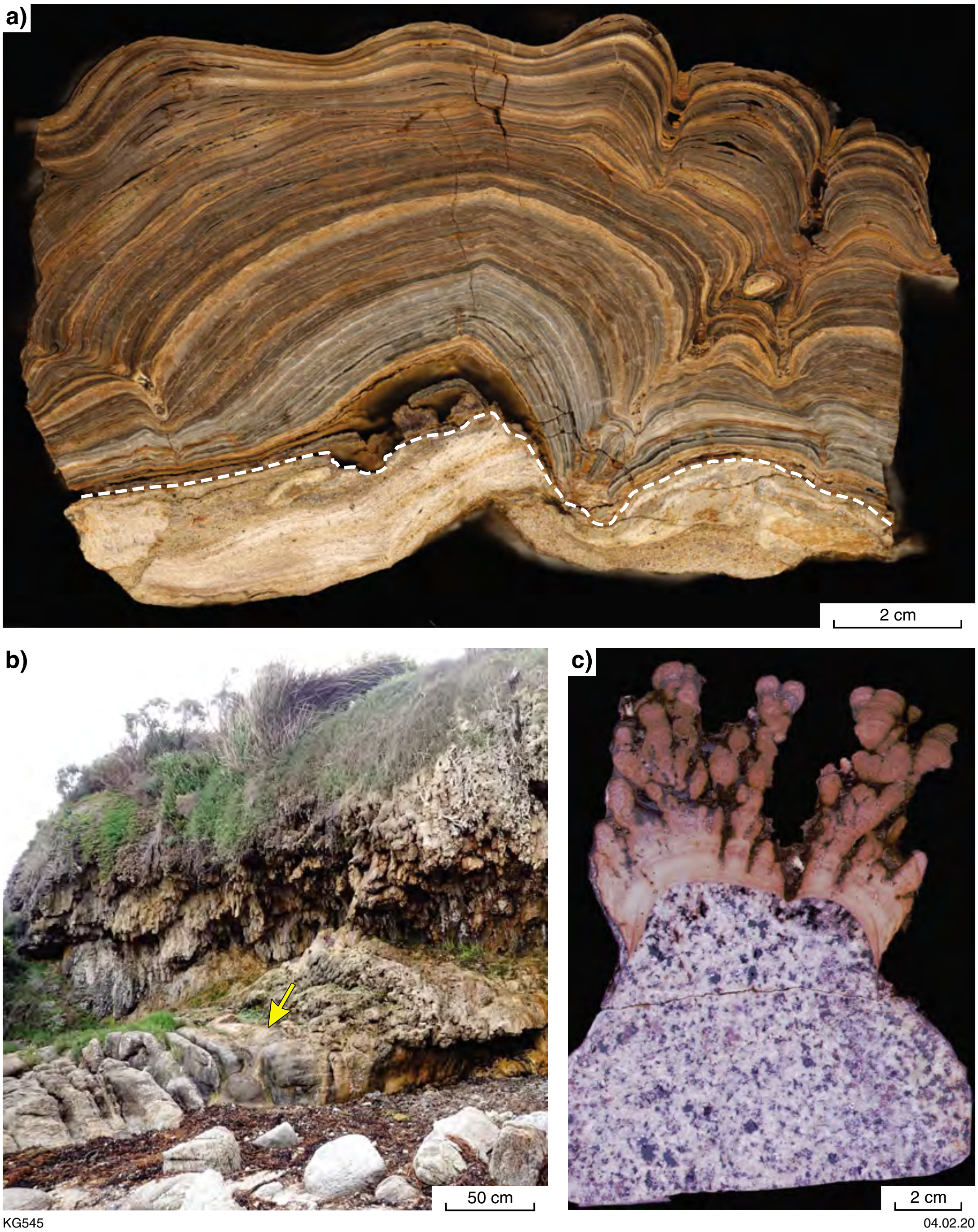

Figure 25. **Examples of relationship of microbialite to substrate: a) microbialite on a sedimentary substrate (soft or lithified; below dashed line); stromatolite; Laney Member, Green River Formation; Washakie Basin; Eocene; Kinney Rim, Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik); b) tufa (microbialite) on a granitic gneiss substrate; Leeuwin Inlier; Holocene; Quarry Bay, Augusta, AUGUSTA, Western Australia; microbialite contact with substrate is arrowed (photo by SM Awramik); c) stromatolite encrusting a granitic cobble; Holocene; west shore of Walker Lake, Mineral County, Nevada, US; polished slab, UCSB collection (photo by SM Awramik)**

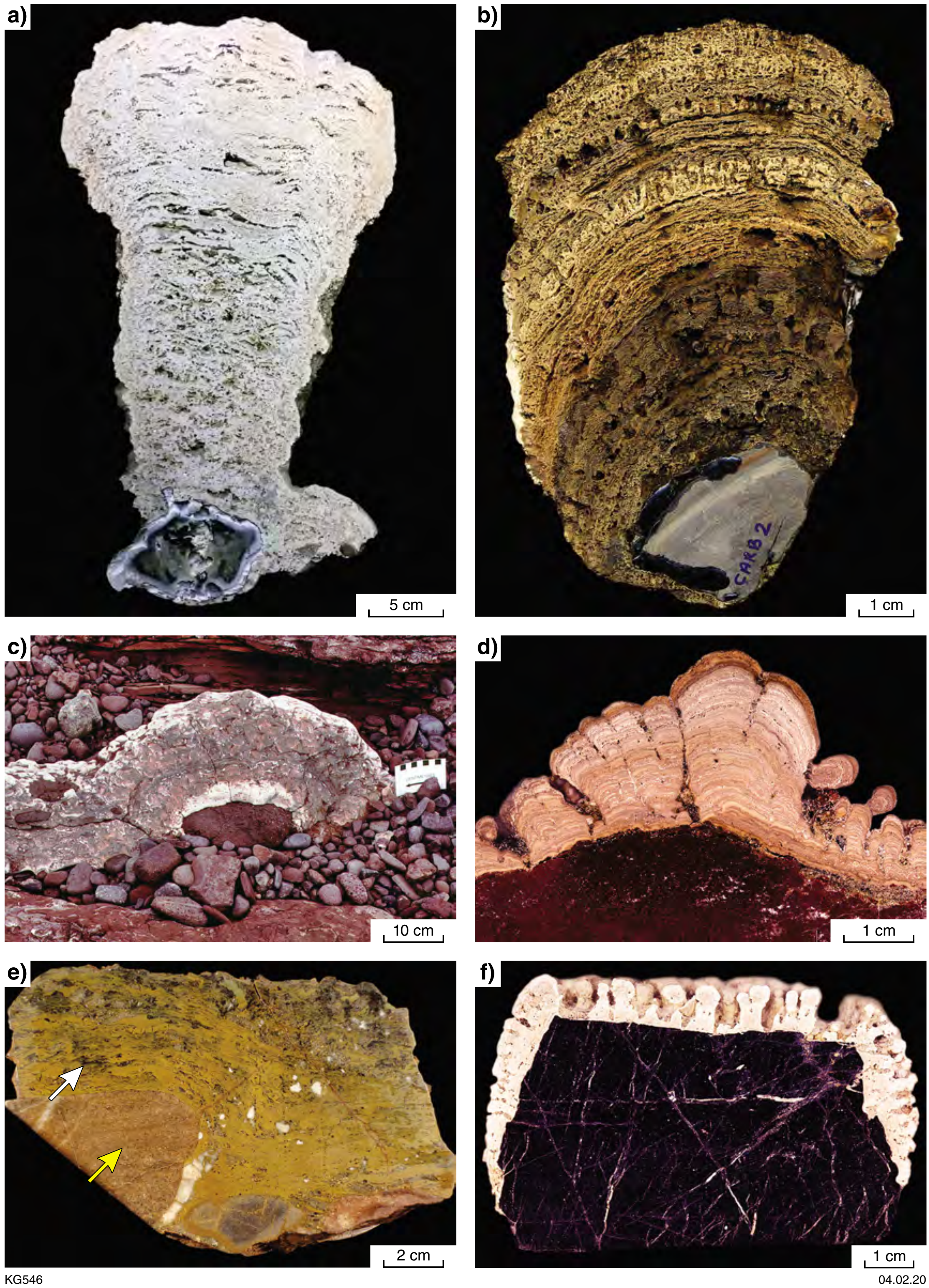

Figure 26. **Examples of substrates – clast substrates: a) stromatolite; Carnarvon Basin; Holocene; Hamelin Pool, Shark Bay, Yaringa, Western Australia; cut section of sample in University of New South Wales collection (photo by MR Walter); b) microbialite developed on clast of basalt, unnamed Holocene unit; Lake Hayk, Southern Wollo, Ethiopia; UCSB collection (photo by SM Awramik); c) stromatolite growing on basalt clast; Copper Harbor Conglomerate; Oronto Group, Keweenawan Trough; Mesoproterozoic; Keweenaw Peninsula, Upper Peninsula, Michigan, US (photo by SM Awramik); d) stromatolite growing on rhyolite substrate; Manix Formation; Manix Basin; Pleistocene; near Afton, San Bernardino County, California, US; UCSB collection (photo by SM Awramik); e) incipient columns of *Tungussia julia* (white arrow) growing on glacial erratic of Pentecost Sandstone (yellow arrow); Egan Formation, Louisa Downs Group; Ediacaran; near Mount Cummings, Kimberley, Mount Ramsay, Western Australia; polished slab, GSWA F49865–138927 (photo by K Grey); f) stromatolite growing on basalt substrate; Manix Formation; Manix Basin; Pleistocene; near Afton, San Bernardino County, California, US; UCSB collection (photo by SM Awramik)**

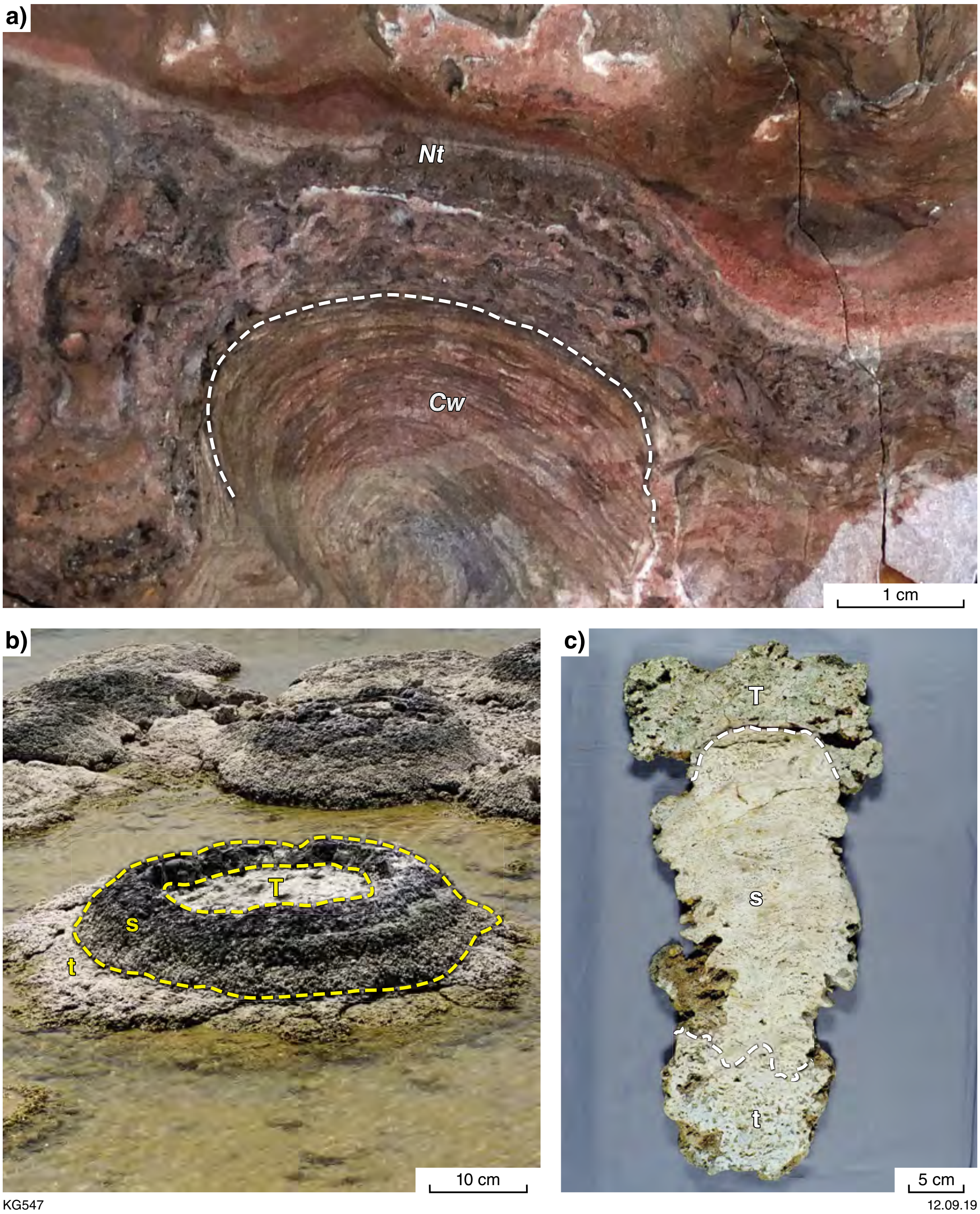

Figure 27. **Examples of substrates – encrusting: a) small columns with banded architecture; *Nabberubia toolooensis* (*Nt*), encrusting (dashed line) larger, pre-existing columns with filmy microstructure, *Carnegia wongawolensis* (*Cw*); Windidda Member, Frere Formation; Earaheedy Basin; Orosirian, Paleoproterozoic; Tooloo Bluff, Kingston, Western Australia; polished slab, GSWA F12366–46597. *N. toolooensis* encrusts several other taxa in the Windidda Member (Grey, 1984) (photo by K Grey); b) small stromatolitic columns (s, area outlined) encrusting a thrombolitic base (t) and core (T, outlined); Perth Basin; Holocene; Lake Thetis, Cervantes, Hill River, Western Australia (photo by K Grey); c) thrombolite (T, outlined) encrusting a stromatolite (s) with thrombolitic base (t); Holocene; Hamelin Pool, Shark Bay, Yaringa, Western Australia; F54107, cut section of sample collected by RP Reid and EP Suosaari (photo by SK Martin and K Grey)**

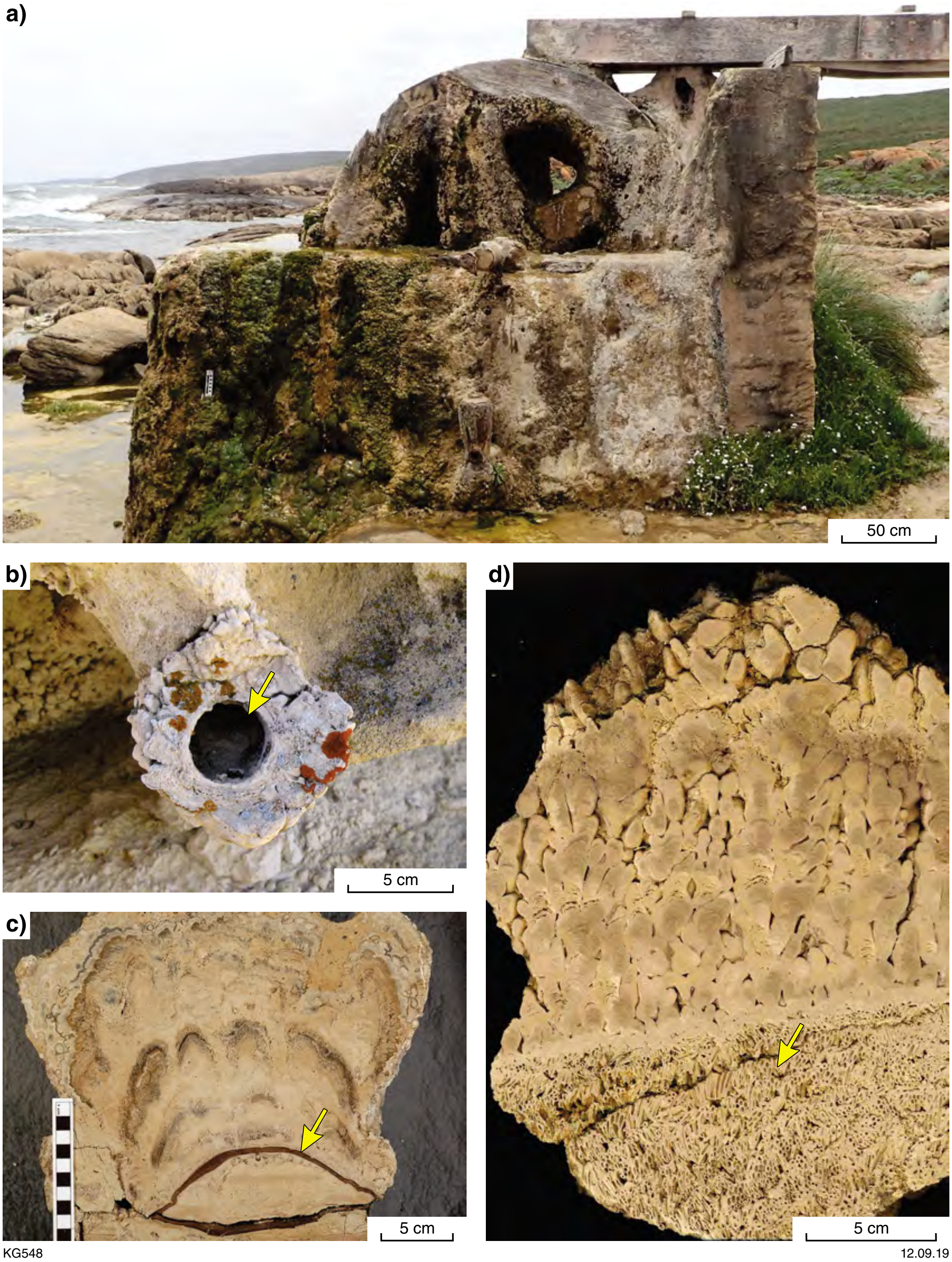

Figure 28. **Examples of unusual substrates: a) tufa microbialite encrusting an old water wheel; Leeuwin Inlier; Holocene; Cape Leeuwin, near Augusta, AUGUSTA, Western Australia (photo by SM Awramik); b) columnar stromatolite encrusting small (now decomposed) log (arrow), an example of an arboreal stromatolite; Wilkins Peak Member, Green River Formation; Bridger Basin; Eocene; Little Mesa near La Barge, Sublette County, Wyoming, US (photo by SM Awramik); c) vertical view of slab showing microbialite encrusting a turtle shell (arrow); Wilkins Peak Member, Green River Formation; Bridger Basin; Eocene; Chapel Canyon, Sublette County; Wyoming, US; polished slab, Loma Linda University collection (photo by SM Awramik); d) vertical view of slab showing stromatolite encrusting a hard substrate formed by caddisfly pupal cases (arrow); Wilkins Peak Member, Green River Formation; Bridger Basin; Eocene; Little Mesa near La Barge, Sublette County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik)**

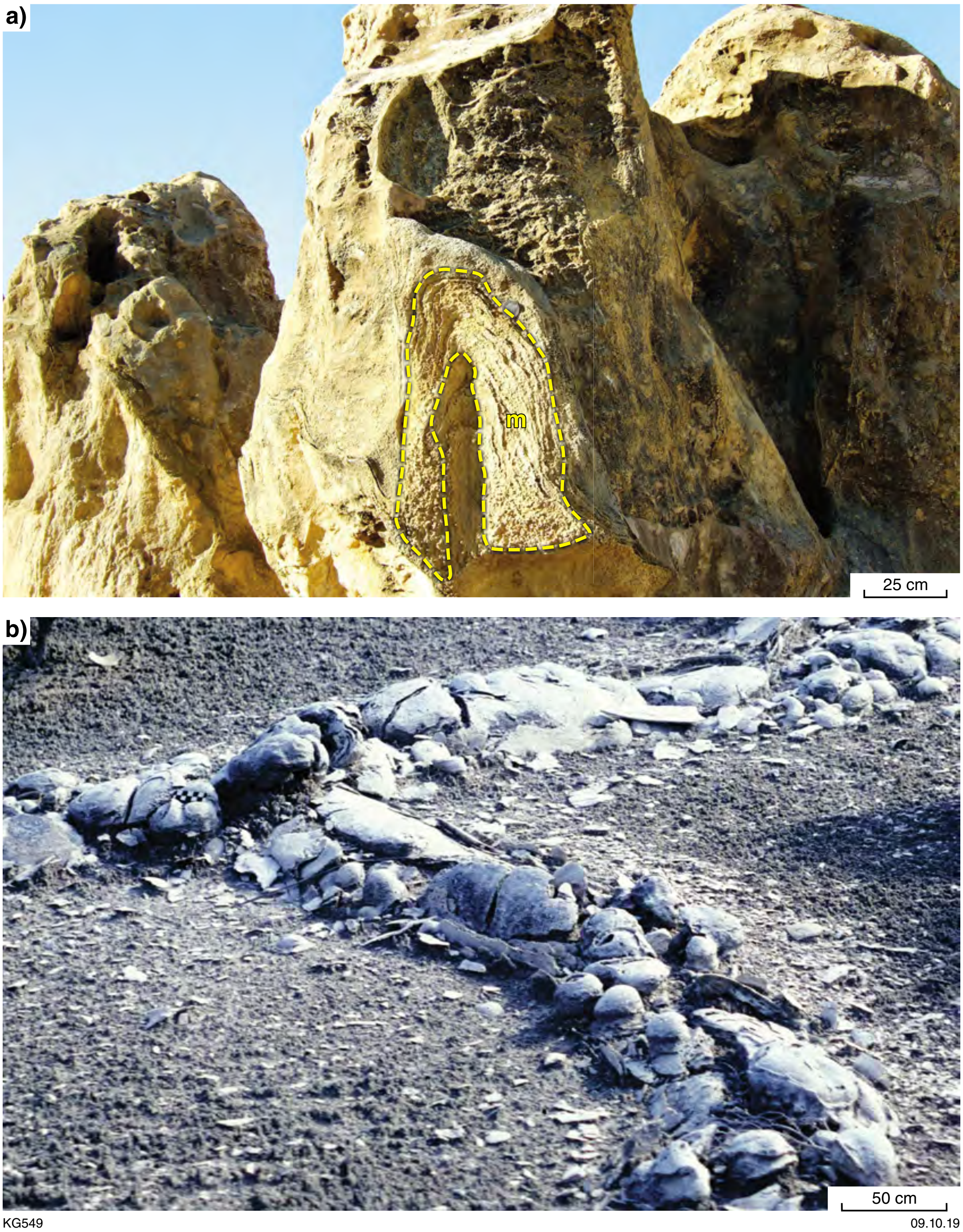

Figure 29. **Examples of cavity-encrusting microbialites: a) encrusting microbialite (m, outlined) developed in a solution pipe (Lipar and Webb, 2014); Pinnacles Desert Member, Tamala Limestone; Perth Basin; Pleistocene; Nambung National Park, Cervantes, Dongarra–Hill River, Western Australia (photo by NJ Planavsky); b) encrusting and hemispherical stromatolites forming on tepee structures marking sites of groundwater discharge along polygonal cracks in a former lake bed; sub-fossil to Holocene; Marion Lake, Yorke Peninsula, Maitland Special 1:250 000 sheet, South Australia (photo by K Grey)**

Buildups

There is some flexibility in how buildups, bioherms, biostromes and heads are described. Large, single structures should be described under megastructure. Smaller, individual buildups, which could be called a bioherm or head (Figs 33, 34), might be better described under macrostructure.

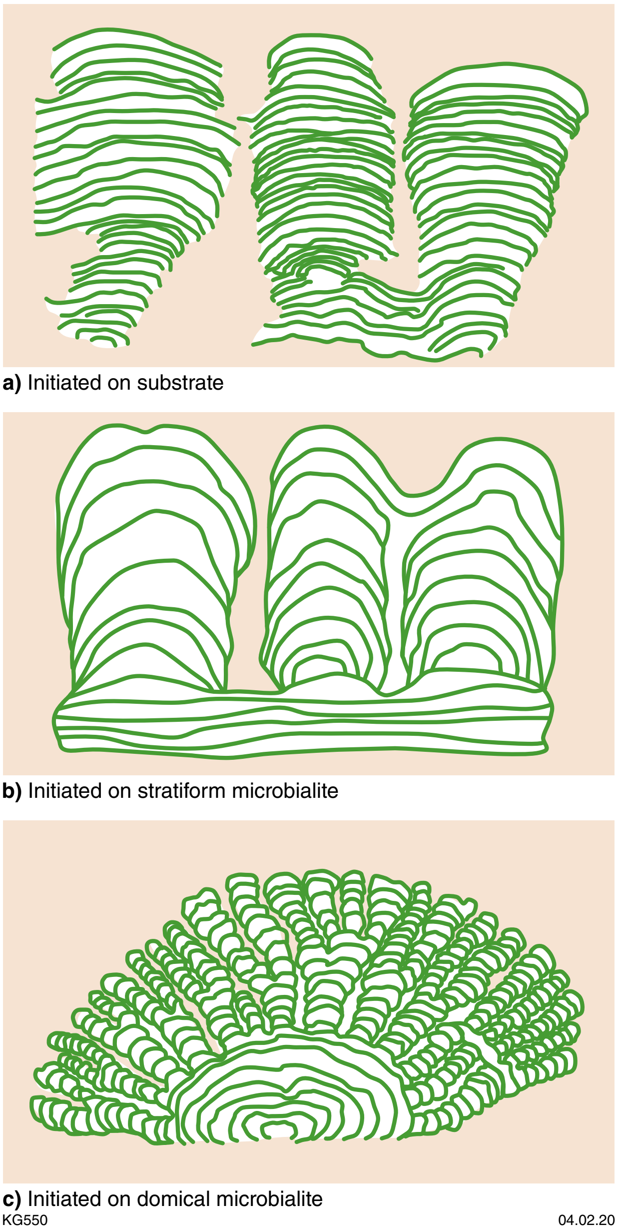

Figure 30. Microbialite initiation: a) directly on the substrate, b) from a layered or stratiform stromatolite or microbialite; c) from a domical stromatolite or microbialite

The terms reef, buildup, bioherm, and biostrome have been used in a variety of ways, and thus there is need to define how the terms are used in relation to microbialites. The term bioherm was used by Cumings and Shrock (1928, p. 599) and subsequently defined by Cumings (1930, p. 207) as 'any dome-like, mound-like, lense-like or otherwise circumscribed mass, built exclusively or mainly by sedentary organisms such as corals, stromatoporoids, algae, brachiopods, molluscs, crinoids, etc., and enclosed in normal rock of different lithologic character.'

Biostrome, proposed by Cumings (1932, p. 334), was defined as 'purely bedded structures, such as shell beds, crinoid beds, coral beds, etcetera, consisting of and built mainly by sedentary organisms, and not swelling into moundlike or lenslike forms.'

As applied to microbialites today, the basic difference between bioherms and biostromes is that a biostrome has a much greater lateral extent than height or thickness. For example, Preiss (1972, p. 92) and Walter (1972, p. 9) used an arbitrary boundary between the two so that, for a biostrome, 'the minimum width must be at least one hundred times the maximum thickness.' Reconstructions of typical biostromes were provided by Walter (1972, figs 21–24) and a biostrome can consist of bioherms (Walter, 1972, fig. 22).

A bioherm or biostrome commonly has its own complex structure. It can consist of a single microbialite, or of many closely spaced microbialites, perhaps extending for many kilometres. In turn, the individual entity may be a discrete layered microbialite, dome, column (a non-branching microbialite; Figs 2, 6, 10c–l, 11a–c, 12–14, 15a, 26a, 27b,c, 29, 33, 34) or a fascicle (a branching individual; Figs 2, 11d, 25c, 31a,b, 32b,c, 35). Multiple combinations can occur, so it is essential to describe clearly the relationships between the various components.

Some buildups show vertical and lateral variations in morphology (Figs 11e,f, 27, 32, 33, 36, 37). They must be documented from the base upwards and centre outwards, keeping in mind the way they are built. They may terminate abruptly in the lateral or vertical extent, or revert to continuously laminated structures that form a capping or wall (Bertrand-Sarfati and Moussine-Pouchkine, 1988b). There may be evidence of cyclic development (Fig. 37; Grey and Thorne, 1985; Southgate, 1989, 1991). It is necessary to describe and analyse any variation within a buildup because the mode of occurrence can be important for paleoenvironmental interpretations, and deciphering the relative roles of biological and environmental control on microbialite growth, as well as for taxonomic treatment.

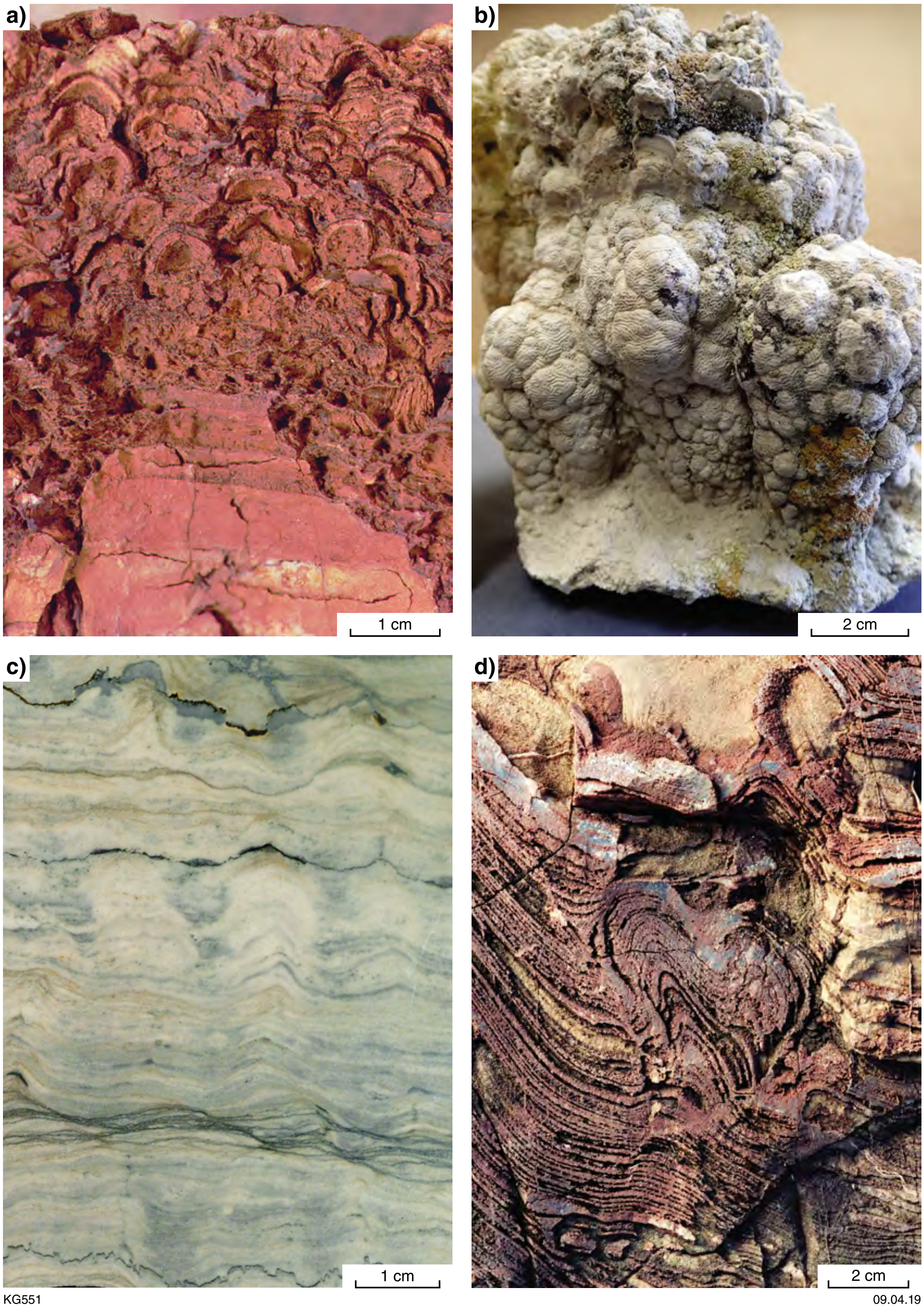

Figure 31. Examples of initiation – directly on substrate or from layered or stratiform microbialites (stromatolites): a) microbialite growing directly on substrate; *Alcheringa narrina* with columns growing directly on siltstone; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, Nullagine, Western Australia (photo by SM Awramik); b) composite microbialite growing directly on substrate; Laney Member, Green River Formation; Bridger Basin; Eocene; near Little Mesa near La Barge, Sublette County, Wyoming, US; UCSB collection. When slabbed, the core consists of linked to locally linked stromatolites with a tufa-like rind (photo by SM Awramik); c) small, columnar stromatolites growing on layered stromatolitic substrate; Steptoe Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Empress 1A, 520.7 m, Gibson Desert, Westwood, Western Australia; cut face of core (photo by K Grey); d) branching columnar stromatolite ('Mickey Mouse ears'), growing on flank of a large cone; Strelley Pool Formation, Pilbara Supergroup; East Pilbara Terrane; Paleoarchean; Hickman Geoheritage Reserve, east Pilbara, Marble Bar, Western Australia (after Hickman et al., 2011, fig. 18d) (photo by K Grey)

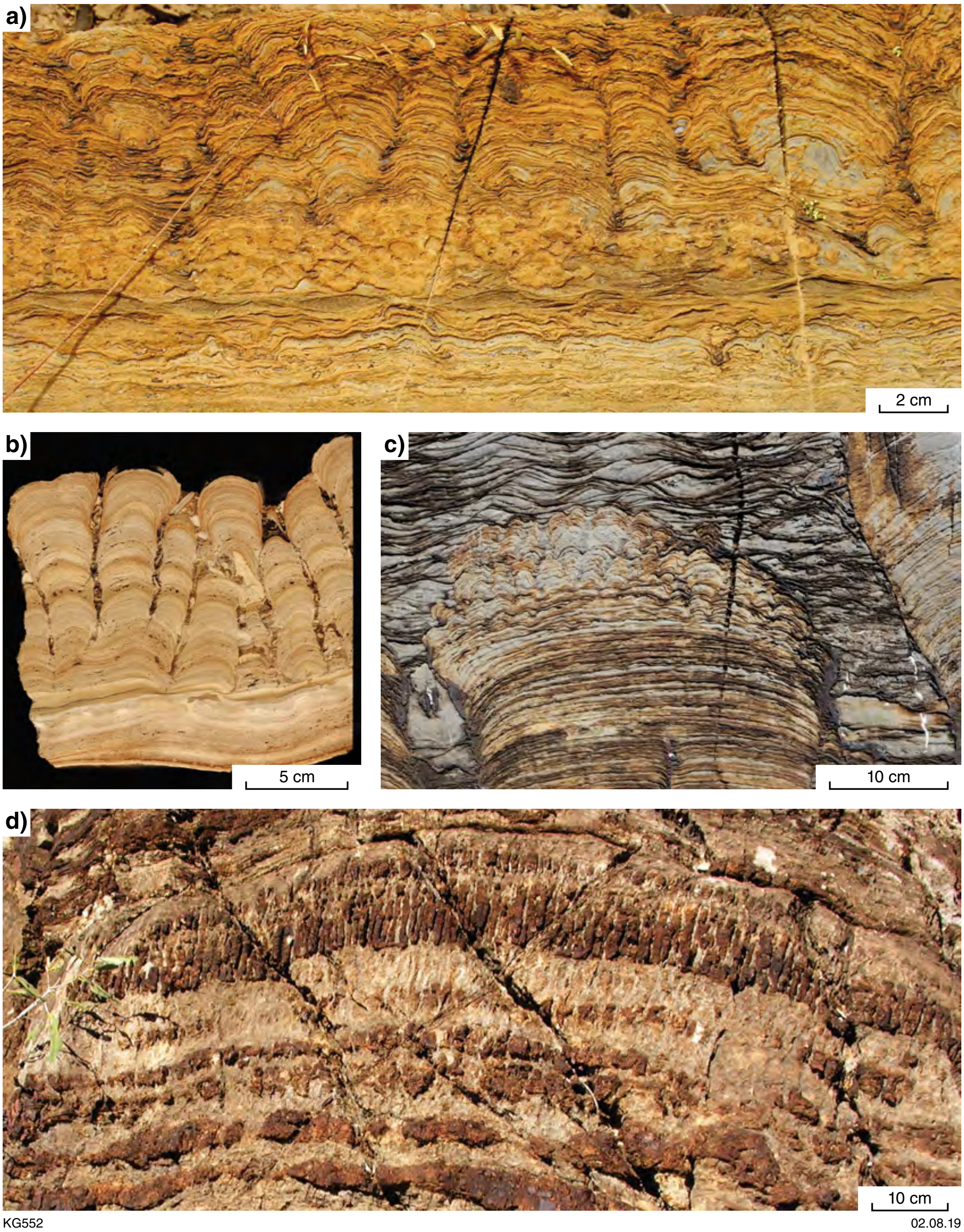

Figure 32. **Examples of initiation – directly on or from layered microbialites: a) stromatolite columns developing from a layered stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia (photo by SM Awramik); b) stromatolite columns developing from a layered stromatolite; Douglas Creek Member, Green River Formation; Piceance Creek Basin; Eocene; Douglas Pass, Colorado, US; UCSB collection (photo by SM Awramik); c) columns developing on a dome; small columns developed on broader columns overlain by climbing ripples; stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Ripon Hills Road, NULLAGINE, Western Australia (photo by SM Awramik); d) columns developing on a dome, *Acaciella australica*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Ross River, ALICE SPRINGS, Northern Territory, Australia (photo by RM Hocking)**

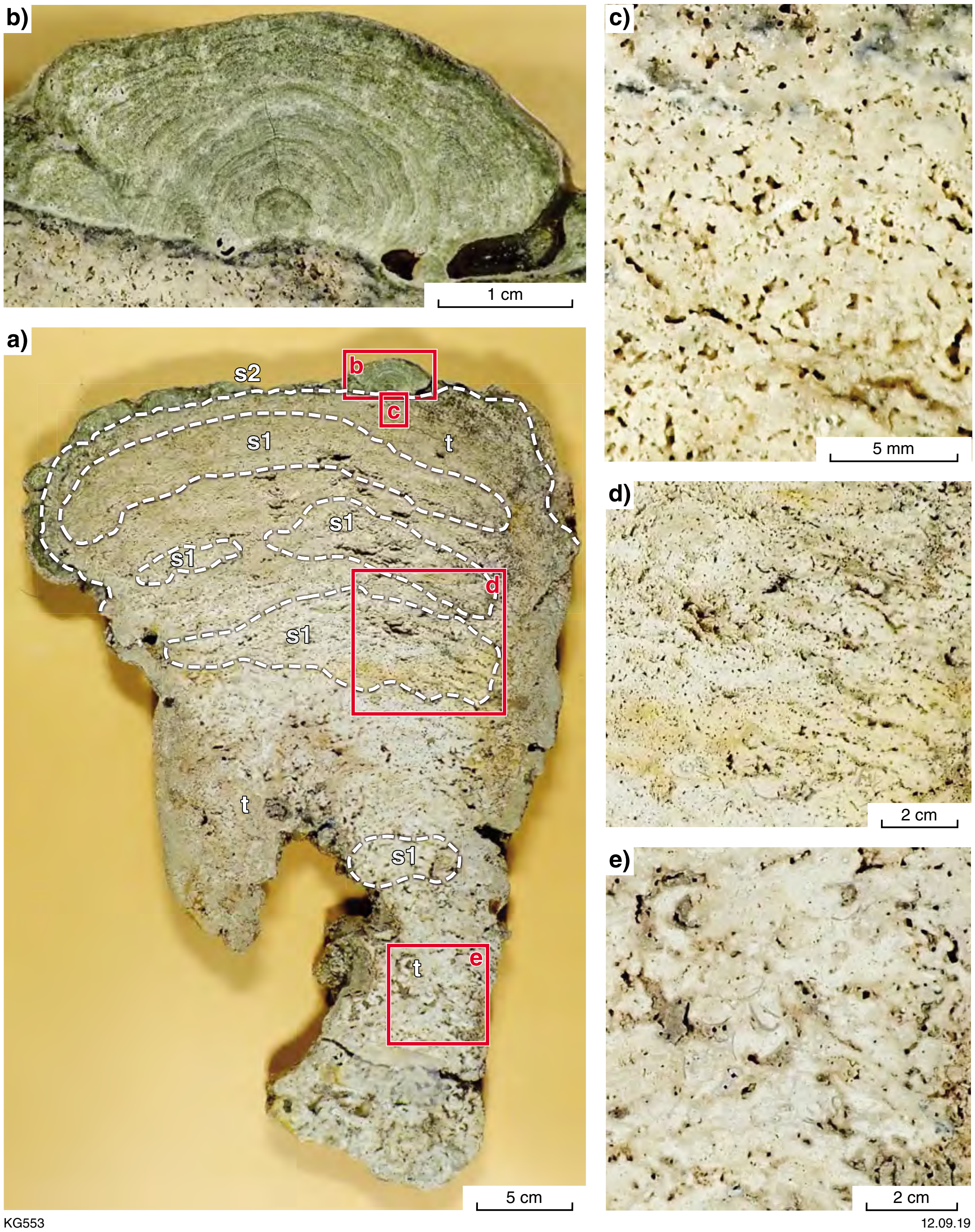

Figure 33. **Variability in a microbialite head – thrombolite (t) grading upwards, and interposed with, laminated stromatolites (s1) and capped by tussocky stromatolites (s2); Carnarvon Basin; Holocene; Hamelin Pool, Shark Bay, Yaringa, Western Australia; F54112, cut section of sample collected by RP Reid and EP Suosaari (photos by SK Martin and K Grey): a) whole specimen; b) details of tussocky stromatolite; c) thrombolite; d) stromatolite; e) lithified thrombolite**

Figure 34. Examples of microbialite heads – individual: a) thrombolite head; Perth Basin; Holocene; Mount John boardwalk, Lake Clifton, PINJARRA, Western Australia (photo by K Grey); b) microbialite head consisting of a thrombolite core with an outer stromatolitic rim (purple colour is from drifted sulphur bacteria originating on lake bottom); Perth Basin; Holocene; Lake Thetis, Cervantes, HILL RIVER, Western Australia (photo by K Grey); c) microbialite head; Carnarvon Basin; Holocene; Carbla Point, Hamelin Pool, Shark Bay, YARINGA, Western Australia (photo by SM Awramik); d) pedestal-shaped head of *Basisphaera irregularis*, whole specimen; Skates Hills Formation, Sunbeam Group; Officer Basin; Tonian, Neoproterozoic; Skates Hills, TRAINOR, Western Australia (photo by K Grey); e) bulbous stromatolite head; Holocene; Keene Wonder Springs, Death Valley National Park, Inyo County, US; thick section; UCSB collection (photo by SM Awramik)

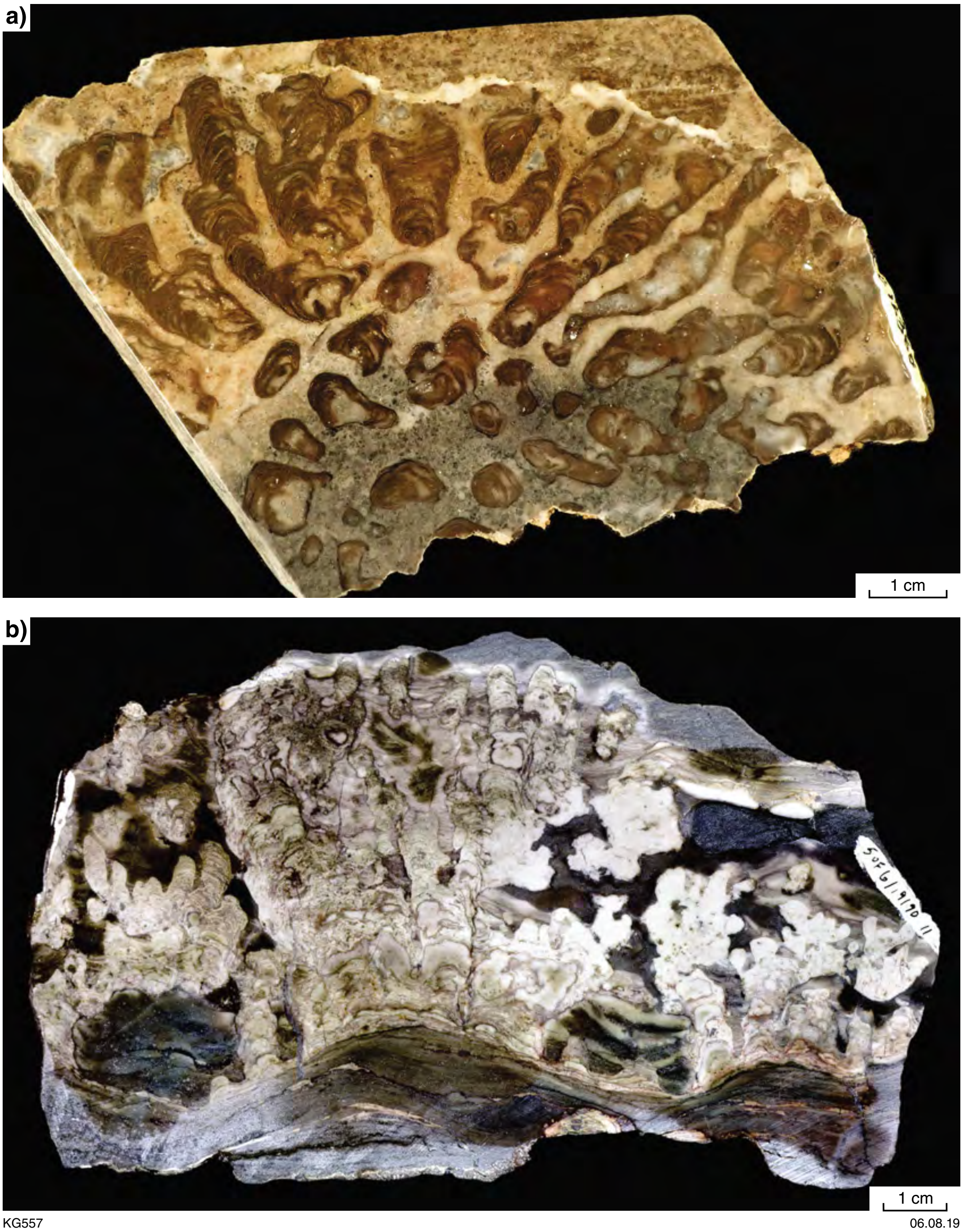

Figure 35. Examples of fascicles: a) fascicle of *Murgurra nabberuensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian to Statherian, Paleoproterozoic; near Sweetwaters Well, Nabberu, Western Australia; polished slab, GSWA F12365–46333 (photo by SK Martin); b) several stromatolite fascicles; Wollogorang Formation, Tawallah Group; McArthur Basin; Statherian, Paleoproterozoic; Seven Mile Creek, Calvert Hills, Northern Territory, Australia; polished slab, UCSB collection (photo by SM Awramik)

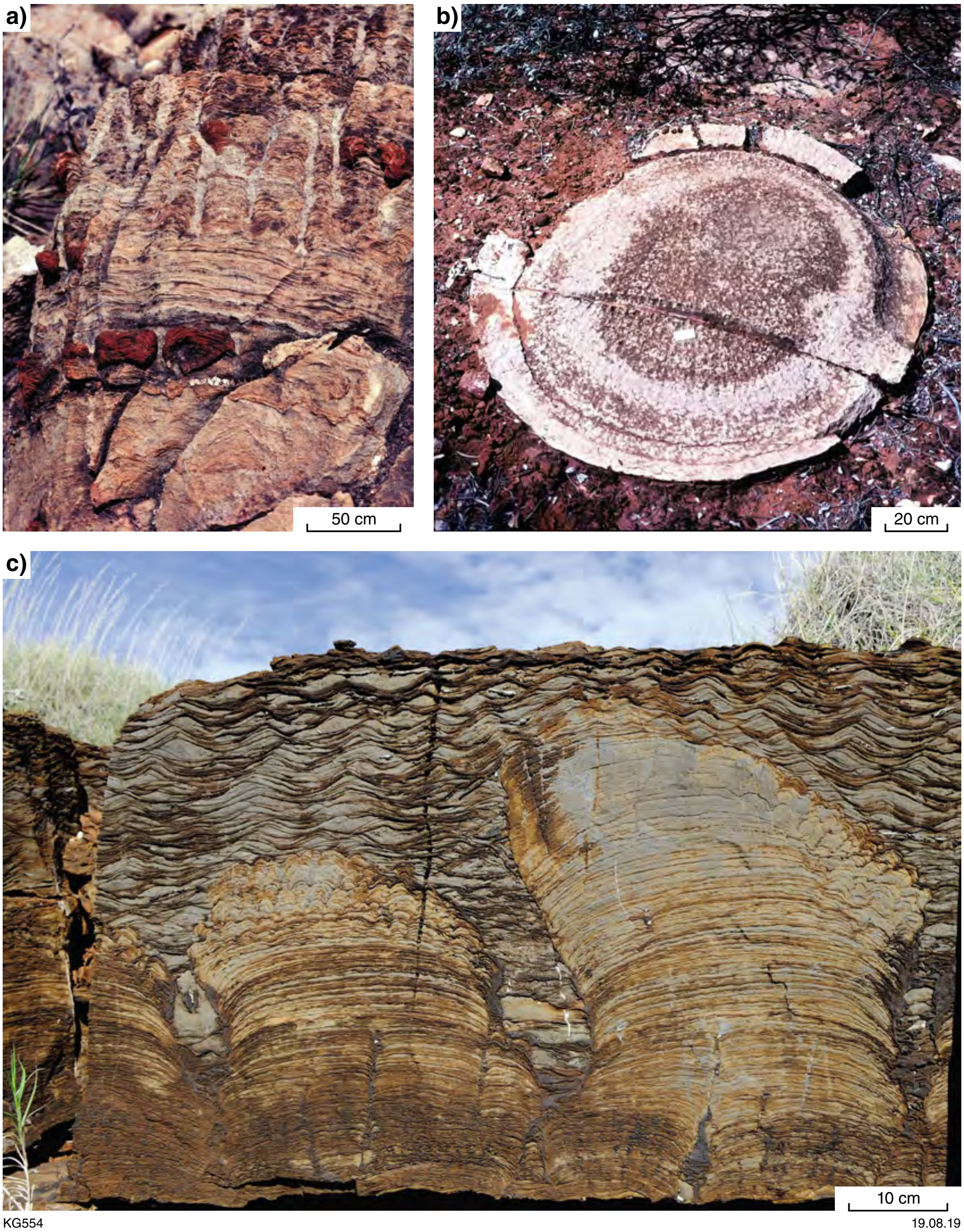

Figure 36. **Examples of variability within a bioherm or biostrome: a) vertical view of broad dome developing upwards into medium then small columns; *Acaciella australica*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Katapata Gap, HERMANNSBURG, Northern Territory, Australia (photo by K Grey); b) plan view of dome developing upwards and outwards into medium then small columns, and finally surrounded by a rim; *Acaciella australica*; Skates Hills Formation, Sunbeam Group; Officer Basin; Tonian, Neoproterozoic; Skates Hills, TRAINOR, Western Australia (photo by K Grey); c) broader columns on which small columns have developed, overlain by climbing ripples; stromatolite; Meentheena Member; Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Ripon Hills Road, NULLAGINE, Western Australia (photo by SM Awramik)**

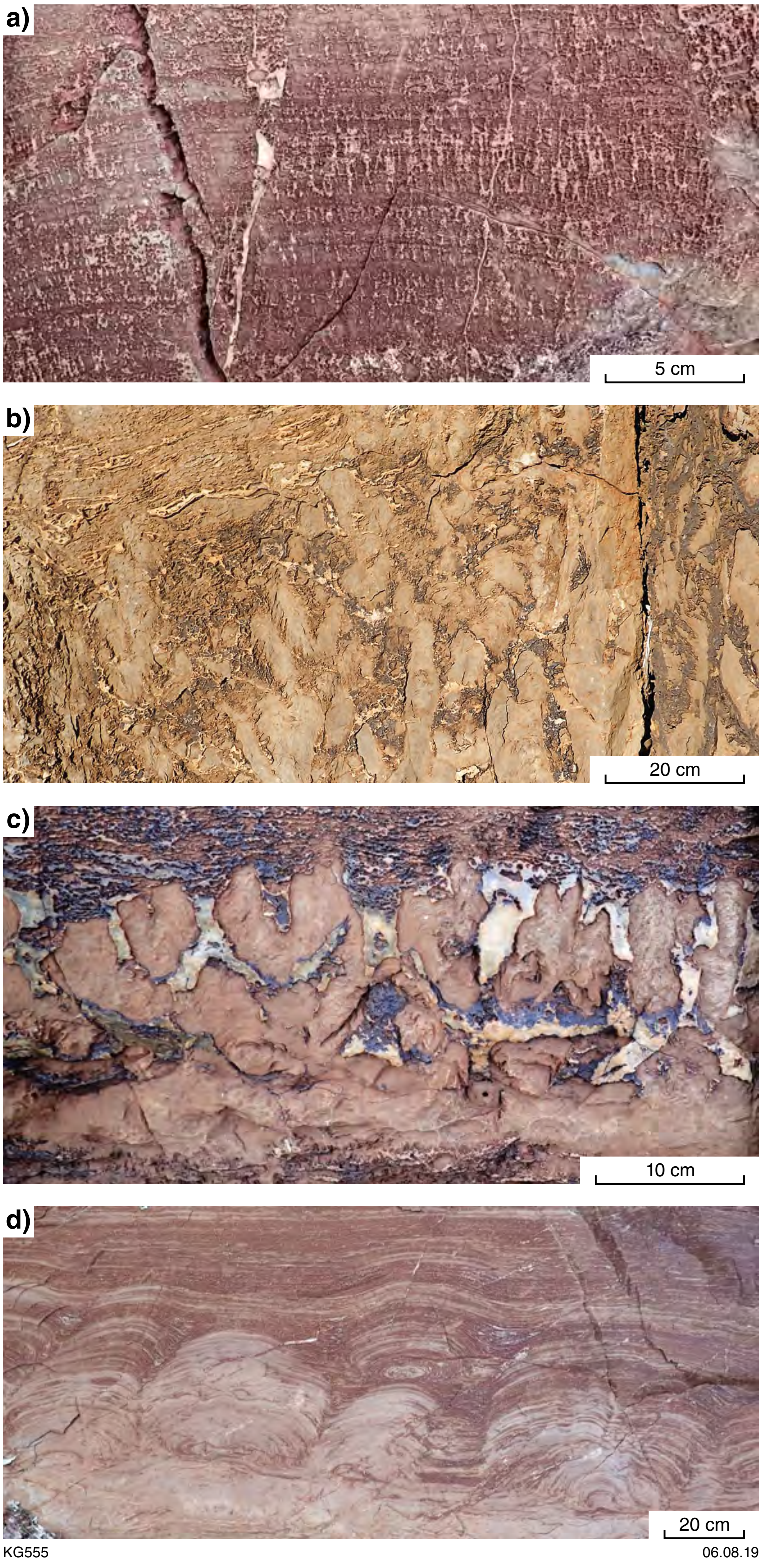

Figure 37. **Examples of variability within a sedimentary section; upward-shallowing cycles, Duck Creek Dolomite, Wyloo Group; Ashburton Basin; Orosirian, Paleoproterozoic; Duck Creek, Ashburton region, WYLOO, Western Australia (photos by HJ Allen): a) *Asperia ashburtonia*, small digitate columns forming large domes in supratidal facies (subaerial ponds); b) *Pilbaria* cf. *perplexa*, broader, more irregular columns in high-energy, wave-active, intertidal to subtidal facies; c) *Pilbaria perplexa*, smaller, more regular columns in low-energy, lagoonal to periodically intertidal facies; d) broad domes of unnamed stromatolites overlying oncoids in high-energy, transgressive facies**

Bioherm shape

Bioherms have distinctive shapes (Figs 10c–j, 12, 13, 34). These should be described, and dimensions and orientations given where possible. Bioherms vary considerably in size (Cecile and Campbell, 1978; Aitken, 1988; Raaben, 2006) and in describing them, relative proportions are more important than actual dimensions. In addition to the three main shapes, tabular, domical and subspherical, a variety of subsidary shapes can also be used to describe a bioherm or head:

1. *Tabular*: (Figs 10c, 12a) a bioherm with clearly defined margins, a tabular top that parallels the lower surface, and height-to-width ratios of between 1:5 and 1:10. The base is only a little narrower than the maximum diameter
2. *Domical*: (Figs 10d, 12b) a bioherm with clearly defined margins, a rounded top, and a height-to-width ratio about 1:3. The base is only a little narrower than the maximum diameter
3. *Subspherical*: (10e, 13a,b) a bioherm in which the width equals the height
4. *Nodular*: (Fig. 10f) a domical microbialite (bioherm) that is generally equal in height and width with the plane of maximum diameter generally at mid-height. The diameter of the base is much less than the maximum diameter and the structure may be almost, but not quite, detached from the substrate
5. *Club shaped*: (Figs 10g, 26a, 34c–e) the height-to-width ratio is about 3:2, the base is less than one third the maximum diameter and forms a stalk. Maximum diameter is more than two-thirds the height of the bioherm
6. *Egg shaped*: (Figs 6b, 10h) a buildup with a height-to-length ratio 3:2, the base is very narrow compared with maximum diameter. The maximum diameter is at about two-thirds the height of the bioherm
7. *Ellipsoidal*: (Fig. 10i) a buildup with a height-to-width ratio about 1:3, with a rounded top and bottom. Commonly the base is considerably narrower than the maximum diameter. The maximum diameter is at about half the height of the bioherm
8. *Pedestal*: (Fig. 10j) a bioherm with a tabular top, and a narrow, stalked base.

Biostrome shape

Biostromes, like bioherms, can show variation in shape (Figs 10k,l, 14, 15), usually in the nature of the upper boundary and there is some overlap in terminology. Sometimes a biostrome is formed by a series of discrete or laterally linked bioherms that have amalgamated into a single structure (Fig. 15a). Biostrome shape is simply described in one of two ways:

1. *Tabular*: (Figs 10k, 15a foreground, 15b) a biostrome with clearly defined margins, a tabular top that parallels the lower surface, and a flat or gently domed upper surface (Fig. 15a background)
2. *Non-tabular*: (Figs 10l, 14a) a biostrome with clearly defined margins, and an undulating or irregular upper surface.

It is also important to note the relationship of the biostrome to the adjacent sediments. As with a bioherm, it can be discrete, having a sharp contact and distinct margin (Fig. 10a), intertonguing (Fig. 10b), or have a poorly defined contact with margins that are difficult to define.

Heads (individual microbialites)

Bioherms and biostromes are complex structures that may be formed by a single microbialite (Figs 10c–l, 34), but which are more commonly formed by large numbers of individual microbialites (Figs 11e,f, 13–15, 18b). Terminology for individual microbialites has been a problem. Twenhofel (1919, p. 342), apparently unaware that Kalkowsky (1908) had introduced the term ‘stromatolite’, coined the term ‘coenoplase’ for distinct growth forms of what are now called microbialites. Hofmann (1969a, p. 5, 56) suggested that coenoplase be used for an individual structure. However, coenoplase has never been widely used. Luchinina (1973) and Zhuraleva and Miagkova (1977, p. 89) used ‘calyptra’ for small bioherms or individual microbialites, but again this term has never been widely adopted. Another term ‘stromatoid’, introduced by Kalkowsky (1908, p. 101), has been used in the sense of head or individual by Hoffman (1988), apparently following Hofmann’s (1969a, p. 5; 1973, p. 341; 1976) usage, and Shapiro and West (1999) also used it in the sense of head or individual. Confusion exists because others use stromatoid for the lamination in a stromatolite (Monty, 1977; Semikhatov et al., 1979; Paul et al., 2011). The terms ‘head’ (paralleling the concept of coral ‘head’) or ‘individual structure’ are employed in this handbook (Fig. 34).

A head usually has a uniformity of microstructure; it arises from a locus and generally has a well-defined boundary with surrounding sediment (Figs 10a, 11b–d, 12, 34, 36b,c). There may be some exceptions. For instance, a structure with a thrombolitic core and stromatolitic outer layer (or vice versa) could still be regarded as a head (Figs 23c,d, 27b,c, 33, 34b). ‘Individual’ should preferably only be used in its adjectival form (individual microbialite). When referring to the level of macrostructure in thrombolites, dendrolites, or leiolites, use head or individual structure. A microbialite that is multi-branching is referred to as a fascicle (Figs 10d, 31a,b, 35; Grey, 1984).

Bioherm series

The wide range of morphological variation observed in some buildups prompted Krylov (1975, p. 76) to propose a concept that he called the ‘bioherm series’. Krylov (1975, fig. 2) applied different taxonomic names to those parts of a single bioherm that showed different morphologies. Taxa from the same buildup were distinguished on the basis of variations in features such as column shape, branching pattern, and laminar profile. Krylov gave the following description, as translated in Bertrand-Sarfati and Walter (1981, p. 362), and claimed that a bioherm series has stratigraphic significance.

> For most bioherms it is possible to put all constructions from them into rather distinct series of variations. Such series (call them bioherm series) are all the main morphological variants from one bioherm, or uniform bioherms from one bed, with a uniform microstructure (or complex of microstructures). They are the totality of morphological modifications of one species or one regular association of algal species that built the microbialites. Under different conditions (sometimes the difference is only in position within the bioherm) the same alga [microbe] could build morphologically different constructions. And the totality of such modifications, instead of seeming limitless in diversity, is quite distinct and not very large.

An additional discussion of the bioherm series concept was given by Walter et al. (1988, p. 83–84). They proposed distinguishing the taxonomic name for a bioherm series by capitalizing the entire name — for example, BALBIRINA PRIMA — and that the description of the bioherm series should precede the descriptions of its component taxa.

The term and concept have not found favour. With regard to the description of macrostructure, the necessity to invoke the bioherm series concept depends to a large extent on one's philosophy in the naming of microbialites, and more particularly, in the way in which names are applied. Use of the bioherm series concept has important taxonomic ramifications and for the moment should be used with caution. If the bioherm series is going to be used in the sense of a taxonomic category above Group level, it is recommended that the bioherm series be named after a component present in the series, analogous to what is required by international codes. It is probably better to avoid using bioherm series and refer to assemblages of microbialites. For example, in the Duck Creek Dolomite, Ashburton Basin, Ashburton region, Western Australia, where there are consistent associations of different morphologies related to their position in sedimentary cycles and the whole assemblage is referred to as the *Asperia–Pilbaria* Assemblage after two main components (Fig. 37; Grey and Thorne, 1984), and the *Acaciella australica* and *Baicalia burra* Assemblages common in all Austalian Neoproterozoic basins (Hill et al., 2000).

A slightly different approach was taken by Walter (1972) and Grey (1984), who argued that most microbialite bioherms have microstructural uniformity and that microstructure is the feature most closely allied to the original benthic microbial community (BMC). Where a homogeneous microstructure is associated with specific macro- and mesostructural features in an individual structure (head or fascicle) or part of the buildup, then this individual forms an entity. Where taxonomy is applied, it is this entity that should be formally named using Linnean nomenclature. An individual buildup may contain several entities (or taxa), recognized by their individual microstructural uniformity. Recurring associations of particular microbialite entities (or taxa) are well documented in biostratigraphic literature (Hill et al., 2000, Grey et al., 2011, 2012). Grey in Hill et al. (2000) applied the term Assemblage to such associations (for instance, the *Acaciella australica* Stromatolite Assemblage).

Describing microbialite macrostructure

There is some overlap between features at the lower end of megastructure and the higher end of macrostructure, as well as between the lower end of macrostructure and the higher end of mesostructure. The terms bioherm and biostrome sometimes refer to smaller individual structures, which may be a component of a bioherm or biostrome, or may be independent structures. As discussed above, it is simplest to refer to such structures as a head. Terminology relating to plan view, spatial relationships, interconnections and shape is generally common to all types of microbialites except MISS. Macrostructure also includes the branching pattern; that is, the style, branching mode, frequency, location and angle of divergence and additional smaller-scale features that are part of these categories. Because heads of stromatolites, thrombolites, dendrolites and leiolites are similar structures at the macroscopic level, they can mostly be described using the same terminology for their gross morphology.

Microbialite margins

The relationship between a microbialite and interstitial material can be significant and occurs at several levels regardless of whether the structure is a stromatolite, thrombolite, dendrolite or leiolite. There is a megascopic relationship between the buildup and the sedimentary bed containing it, a macrostructural relationship between a bioherm and the interbiohermal space, and between a head and interspace, and a mesoscopic relationship between fascicles and the interfascicular space and between individual branches (Fig. 11). Terminology for macrostructural margin structures in part overlaps with the mesostructural features of walls and ornament, although these are usually smaller-scale features best described under mesostructure. However, the nature of the macrostructural margin can be significant and should be described.

Describe any characteristic shape or profile shown by the margin. Examine the relationships to the enclosing sediment and how this relates to the bioherm or head margin. For stromatolites, the role of the laminae may be crucial in understanding these relationships.

Thrombolite margins should be described using the same terms used for stromatolite margins. Margins can be smooth, invaginated, wrinkled or lobate. Like stromatolites, the margins of thrombolites can provide information on synoptic profile, but interpretation is much less straightforward. In stromatolites, the column margin is an extension of the laminae, but in thrombolites this is not the case and the dominant mesostructural component does not necessarily play a role. If the thrombolite margins are not smooth, it is important to recognize whether or not the enclosing sediments interfinger with the margin or truncate against the margin (Fig. 18a). Often, keys to possible synoptic profiles can be determined by their relationship to enclosing sediment (drapes, cross-beds). Many Phanerozoic thrombolites were important components of reefs and some thrombolites were major Neoproterozoic reef builders, so it is important to compare thrombolite margins within the reef with those at the margins of the reef.

With regard to composite microbialites, where a thrombolite has a stromatolite rind, synoptic relief can be determined using the stromatolite laminae.

Plan view

The plan view is the shape of the cross-section of the buildup, head, column or branch when viewed in a plane at right angles to the growth direction (Fig. 38). It has been referred to as plan outline (Hofmann, 1969a, fig. 8), as well as transverse section or cross-section, but plan outline should be restricted to an outline. Cross-section can be ambiguous beause the term has been used for vertical views. Plan views can be described using the following terms, based mainly on Hofmann (1969a):

1. *Circular* (subcircular): (Figs 38a, 39a) in which the shape is mostly rounded or subcircular
2. *Ovate* (elliptical, oblong): (Figs 38b, 39b) in which one diameter is much greater than the other
3. *Lanceolate*: (Figs 38c, 39c) shaped like a lance
4. *Linear*: (Figs 38d, 40) in which one axis is narrow and the other axis extends for many times the width of the narrower one. Also referred to as elongate, platy, seif and longitudinal microbialites. Commonly, the long axis is perpendicular to shoreline, but long axis of seif microbialites is parallel to the shoreline (Playford, 1979, p. 16; 1980, p. 74)
5. *Pitted*: (Fig. 38e) circular to ovoidal shape in plan view of sediment filled, deep to shallow, steep-sided pits extending into the structure (Bradley, 1929; Lamond and Tapanila, 2003). Tubestone is an extreme case, where pits are very deep, forming cylindrical, tube-like structures in the rock (Corsetti and Grotzinger, 2005, fig. 1c; Bosak et al., 2013b), but still with a pitted plan view

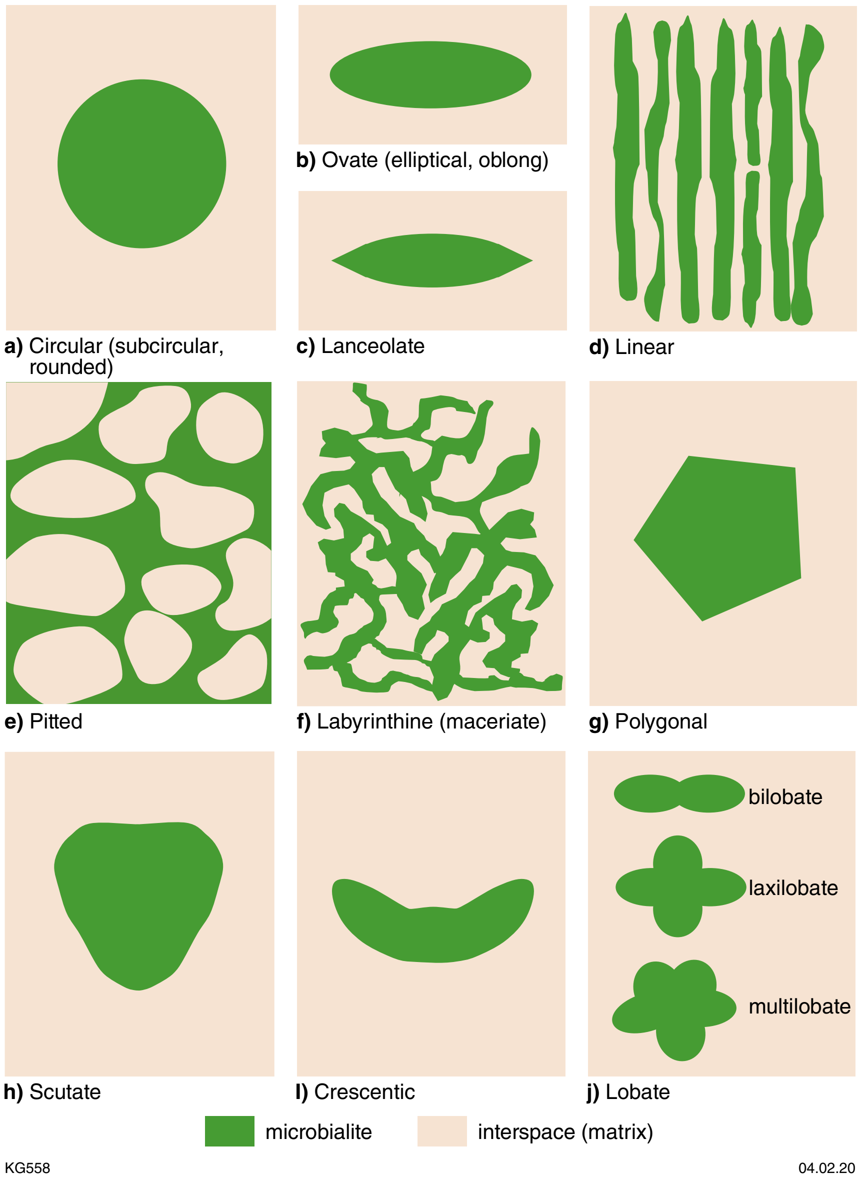

Figure 38. **Microbialite plan views: a) circular (subcircular, rounded); b) ovate (elliptical, oblong); c) lanceolate; d) linear; e) pitted; f) labyrinthine (maceriate, cerebroid); g) polygonal; h) scutate; i) crescentic; j) lobate (bilobate, laxilobate, multilobate). Microbialite, solid green; interspace (matrix), beige**

6. *Labyrinthine*: (Figs 38f, 41) a term introduced by (Shapiro and Aramik, 2006, p. 412) to describe maze-like, linear ridges composed of microbialite, as seen in plan view. Used for the plan view of microbialites that are maceriate microbialites in 3D and cerebroid in surface view
7. *Polygonal*: (Figs 38g, 42a,b) having straight rather than curved sides and the sides subtend angles. Columns are commonly hexagonal or pentagonal in plan view and equal in size with narrow interspaces
8. *Scutate*: (Figs 38h, 42c) shield-like with one straight side and two convex sides
9. *Crescentic*: (Figs 38i, 42d) a thin, curved shape that is thicker in the middle and tapers to thin points or horns at each end
10. *Lobate*: (Figs 38j, 43) having an irregular outline with varying types of lobes:
    - *Laxilobate* (bilobate, trilobate, multilobate): in which adjoining lobe margins are divergent
    - *Densilobate*: in which adjoining lobe margins are parallel and very closely spaced
    - *Brevilobate*: in which the lobes are very short and irregular.

Domical and columnar stromatolites can be distinguished from conical stromatolites in plan view because in a dome or column the laminar spacing diminishes towards the outer margin (Figs 44a,b, 45a), whereas in a cone, the laminae are uniformly spaced in plan view (Figs 44c,d, 45b). Cones appear to have isopachous laminae in plan outline (Fig. 44d) but not necessarily in vertical view (Fig. 44c).

Spatial relationships and interconnections

Bioherms commonly show regularity in their linkage and spacing (Figs 46–50), and there may be a pattern to their distribution on a bedding plane. The following terminology is applicable to both bioherms and to microbialite heads. Measure and describe the spacing together with any interconnections between bioherms or heads.

Linkage

Linkage is the degree of lateral connection between microbialites (Figs 46a–d, 48–50), and is an indication of how many connections are common to adjacent structures. This can be between bioherms or biostromes, or between heads. For stromatolites, this is commonly a connection formed by one or more laminae, such as a bridge (see below). It is not always easy to distinguish the various types but the following terms can be used:

1. *Linked*: (Figs 46a, 48) connections are present between all or most microbialites. Linked cumulate is a variation where domical, often bulbous, microbialites are linked
2. *Locally linked*: (Figs 46b, 49) some adjacent microbialites are linked laterally whereas others are unlinked
3. *Sporadically linked*: (Figs 46c, 49) lateral linkage occurs intermittently and may vary through the vertical profile. Also referred to as partly linked (obsolete term)
4. *Unlinked*: (Figs 46d, 50) there is no linkage.

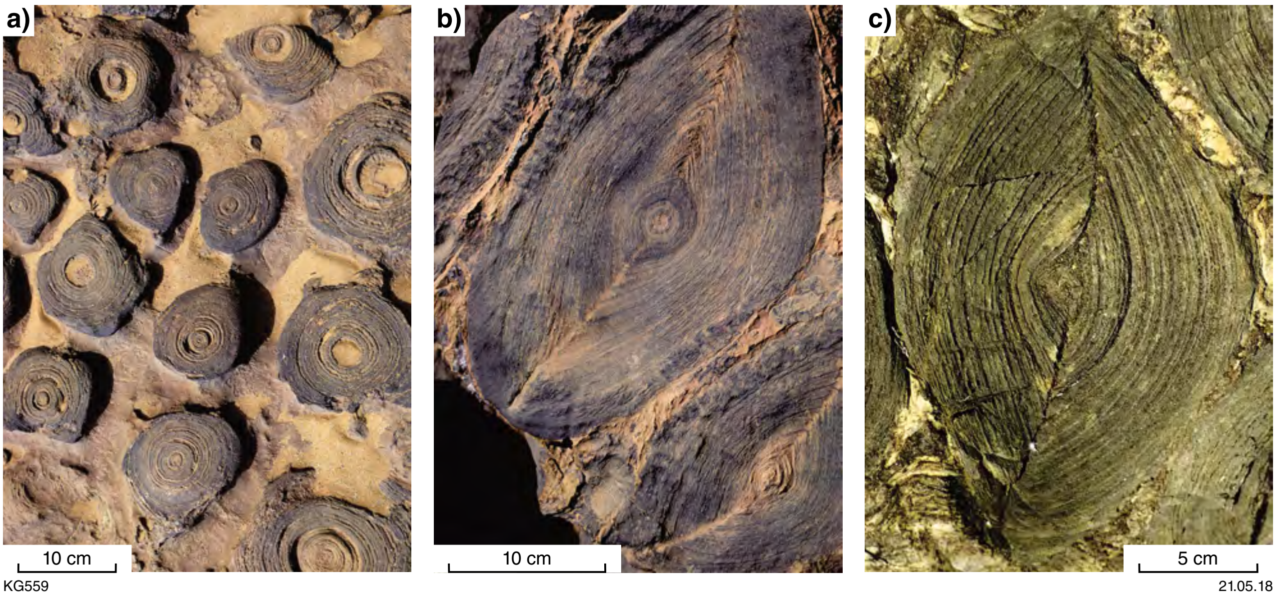

Figure 39. **Examples of plan views: a) circular (subcircular, rounded) and ovate; *Conophyton ressoti*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Lekhleigate Section, Atar region, Mauritania (photo by SM Awramik); b) elliptical; *Conophyton jacquetti*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Lekhleigate Section, Atar region, Mauritania (photo by SM Awramik); c) lanceolate; *Conophyton* new Form; Dungaminnie Formation, Nathan Group; McArthur Basin; Calymmian, Mesoproterozoic; near Heartbreak Hotel airstrip, Bauhinia Downs, Northern Territory, Australia (photo by SM Awramik)**

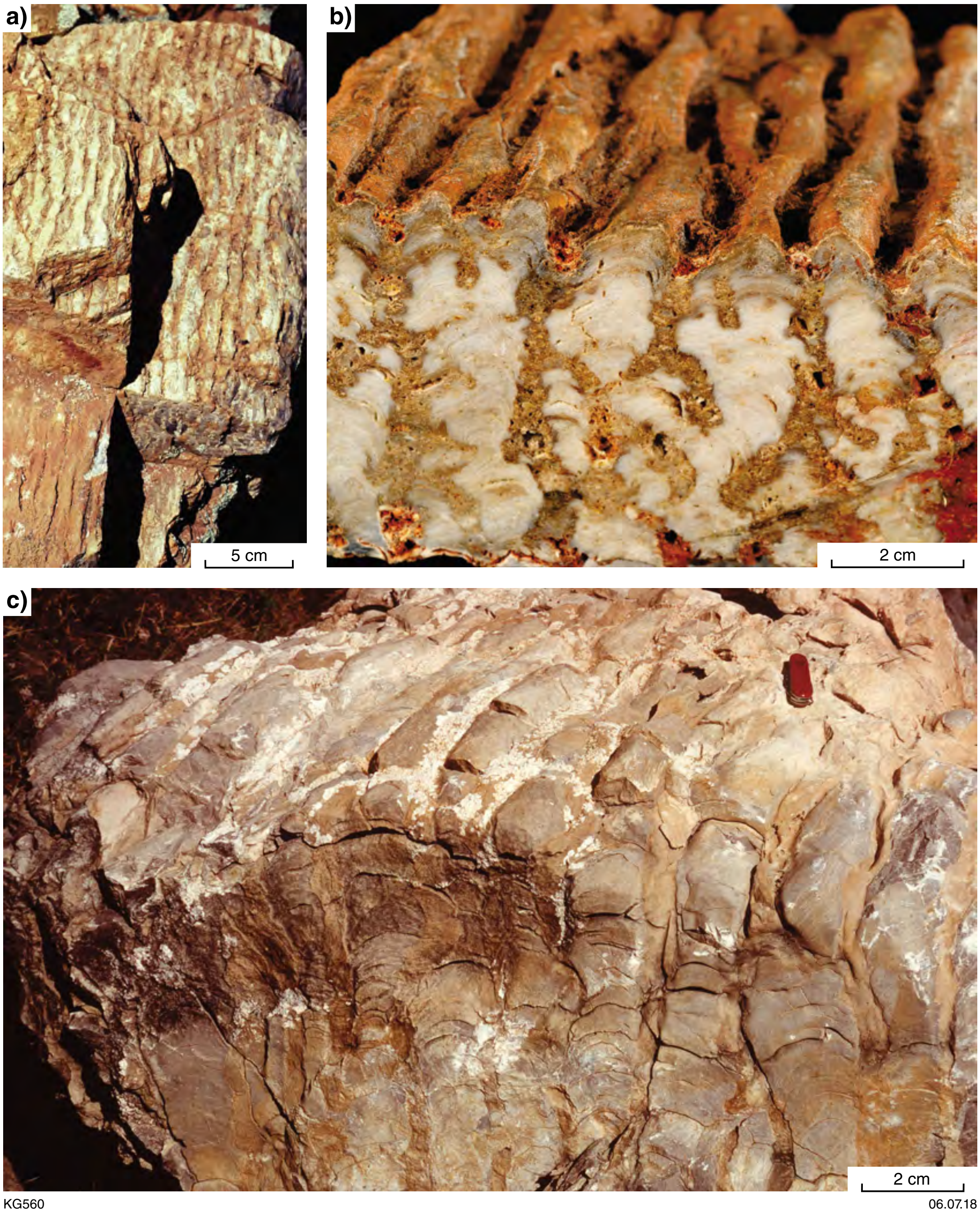

Figure 40. **Examples of plan views – linear: a, b) *Eucapsiphora leakensis*; Mount Leake Formation; Statherian to Stenian, Paleoproterozoic to Mesoproterozoic; Mount Leake, Peak Hill, Western Australia; a) plan and partial vertical view; b) plan view and polished vertical face, GSWA F48393–90507. In linear columns, the complex column shape is seen only in faces cut normal to the lineation. A similar complex shape is present in adjacent columns that are cylindrical in plan view; in faces parallel to the lineation, laminae appear stratiform (photos by K Grey); c) *Scopulimorpha regularis*; Tieling Formation, Jixian Group; North China Craton; Calymmian to Ectasian, Mesoproterozoic; Yanshan Range, Jixian County, Hebei Province, China (photo by SM Awramik)**

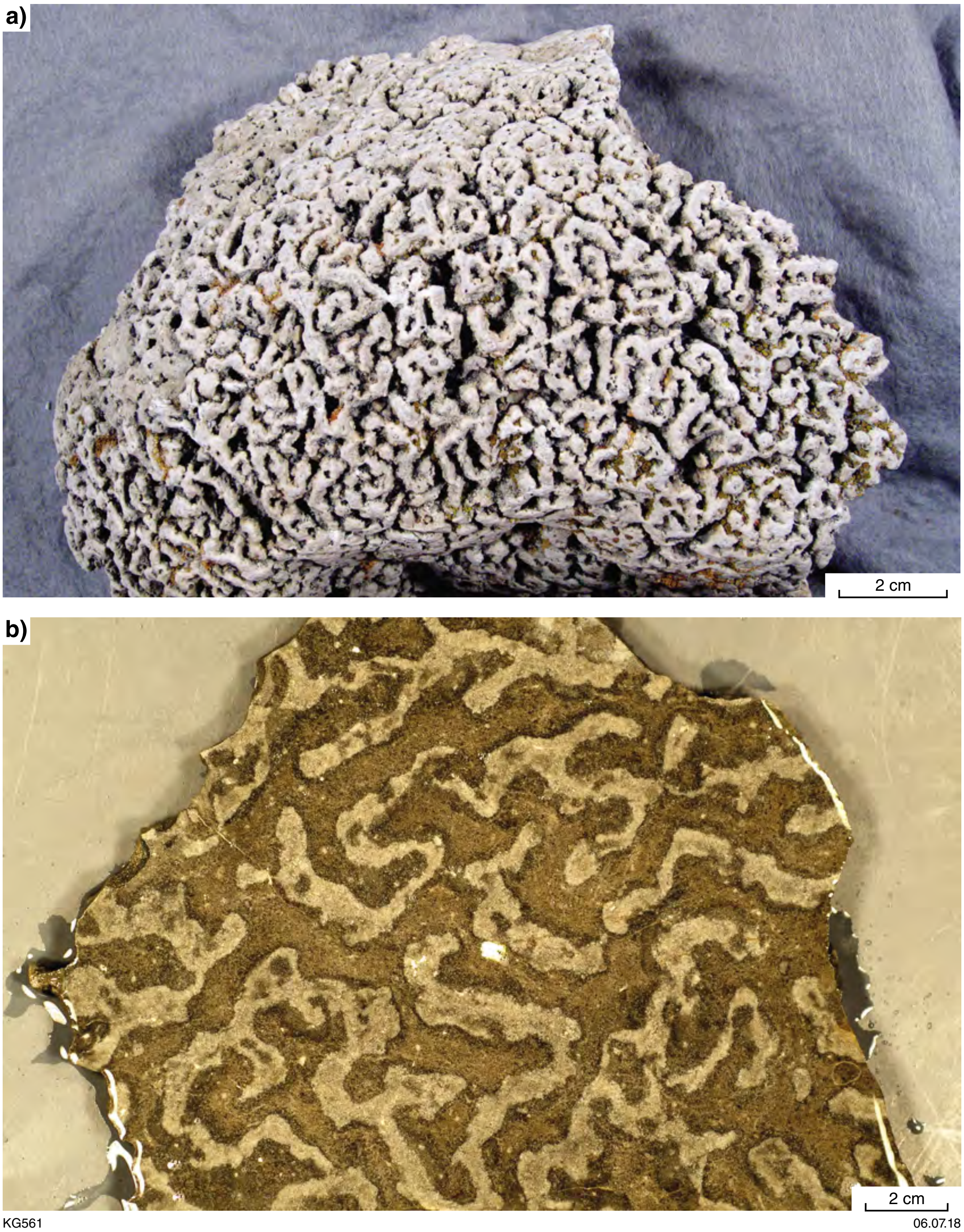

Figure 41. **Examples of plan views – maceriate: a) cerebroid microbialite with maceriate plan view; Pleistocene; Lake Lahontan, precise locality unknown, Nevada, US; UCSB collection (photo by SM Awramik); b) labyrinthine (maceriate); *Favosamaceria cooperi*; Smoky Member, Nopah Formation; upper Cambrian; Mohawk Hill, Clark Mountain Range, San Bernardino County, California, US; Polished slab, UCSB collection. Dark areas are the microbialite (photo by SM Awramik)**

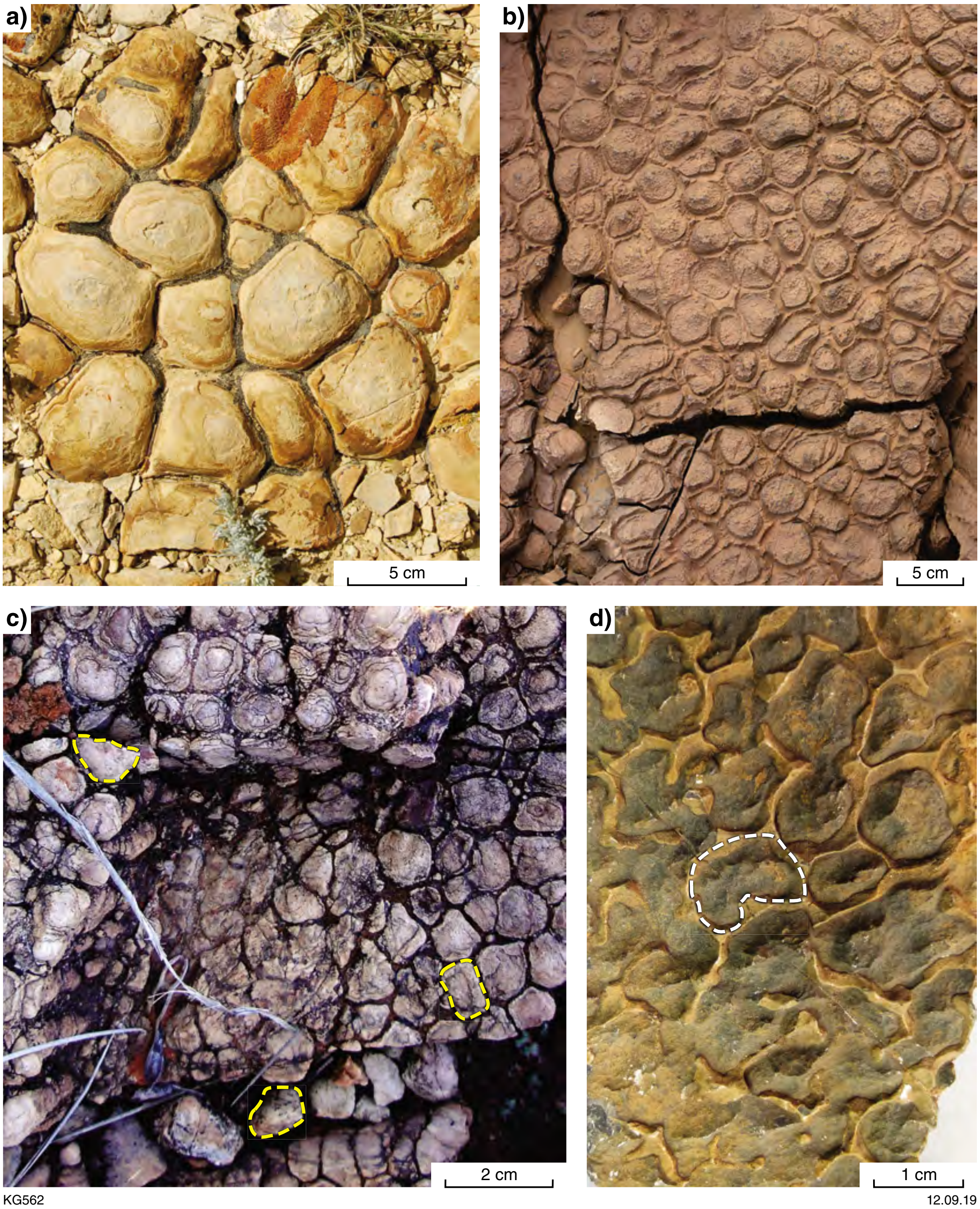

Figure 42. **Examples of plan views – polygonal and scutate: a) polygonal stromatolite; Laney Member, Green River Formation, Washakie Basin; Eocene; Kinney Rim, Sweetwater County, Wyoming, US (photo by SM Awramik); b) polygonal stromatolite; *Inzeria djejimi*; Oued Tarioufet Formation (Unit I.6), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Khang safia, Mauritania (photo by SM Awramik); c) scutate (outlined), rounded and polygonal; *Anabaria juvensis*; cap carbonate above Pioneer Sandstone; Amadeus Basin; Ediacaran, Neoproterozoic; near Ross River Highway, Alice Springs, Northern Territory, Australia (photo by NJ Planavsky); d) crescentic (outlined), polygonal and lobate; *Kulparia alicia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River Highway, Alice Springs, Northern Territory, Australia; holotype, UCSB collection 6 of 3/7/65 (photo by K Grey)**

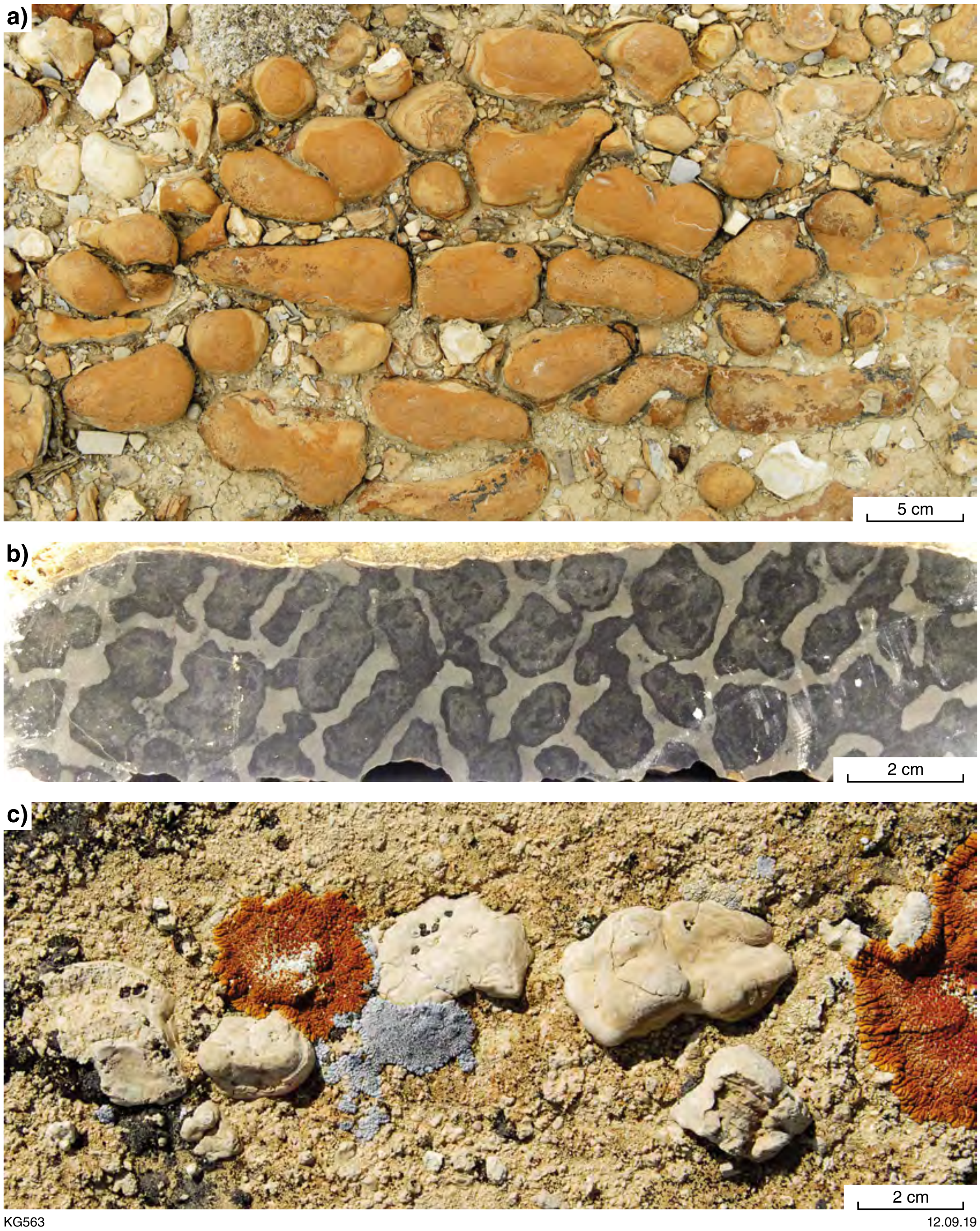

Figure 43. Examples of plan views – lobate; a) bilobate; unnamed stromatolite; Laney Member, Green River Formation; Washakie Basin; Eocene; Kinney Rim, Sweetwater County, Wyoming, US (photo by SM Awramik); b) polylobate; *Kulparia alicia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River Highway, Alice Springs, Northern Territory, Australia; holotype, UCSB collection 6 of 3/7/65 (photo by K Grey); c) polylobate; unnamed stromatolite; Tipton Member, Green River Formation; Bridger Basin; Eocene; White Mountain, Sweetwater County, Wyoming, US (photo by SM Awramik)

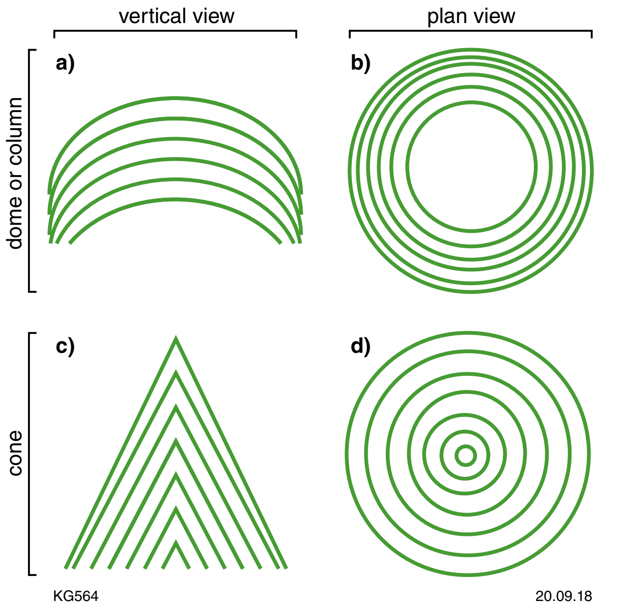

Figure 44. Comparative geometry of dome and cone in vertical and plan view: a) dome or column in vertical view; b) dome or column in plan view; c) cone in vertical view; d) cone in plan view

Spacing

Spacing is an important feature that refers to the relative distance between microbialites (Figs 47–50). Some microbialites occur in clusters. Note any patterns because they may be of paleoenvironmental significance. The following terms (Hofmann, 1969a) may be used to describe spacing (where p = interbiohermal or interhead space and r = radius of the bioherm or head):

1. *Contiguous*: (Figs 47a, 48b, 49) microbialites touching or nearly touching (p = 0)
2. *Closely spaced*: (Figs 47b, 48b, 49b) spacing between microbialites is less than the diameter of the structures (p < r)
3. *Openly spaced*: (Figs 47c, 48a, 50a) spacing between microbialites is about the same as the diameter of the structures (p > 2r)
4. *Isolated*: (Figs 47d, 50b) microbialites are spaced at distances much greater than the diameters of the structures, or are the only microbialite structures present (p > 20r).

Dimensions

Record the dimensions of the microbialite. More than one set of dimensions may be required; the first, those of the overall buildup; the second, those of components in a composite or compound structure. Measurements should include the height, maximum and minimum diameters, and the dimensions of any notable features. For most microbialites it will be necessary to provide a range of measurements. Determine the total relief of the structures; that is, the height of the structure above the substrate at any stage of its growth (Walter, 1972, p.63). This information will be needed for the description of the walls, if present, and the nature of the contact with the flanking sediments.

Lithological variation

Lithological variations can be present throughout a microbialite or in certain parts of it. The differences may consist of marked contrasts between the buildup and the enclosing sediments, or between microbialites and interspaces (interbiohermal space, interhead space, interfascicular space or interspace; Figs 11, 12, 49a, 50), changes in microstructure, or variations in preservation (e.g. patchy dolomitization, phosphatization, or silicification). Describe the nature of any lithological variation.

Microbialite shape

The shape of a microbialite (Figs 51–57) can be described using the following broad categories:

1. *Layered microbialite*: (Figs 51a, 52a) a microbialite that shows little or no positive relief. Laminae, where present, are parallel, nearly planar and continuous. This category includes stratiform and undulatory microbialites, as well as pseudocolumnar, linked-columnar and linked-conical (see below), and encrusting microbialites (Figs 24c, 28, 29)
2. *Domical microbialite*: (Figs 51b, 52b) an individual microbialite that arises directly from the substrate, and has a convex vault
3. *Columnar microbialite*: (Figs 51c, 53) a non-branching microbialite in which height is much greater than the width. This has sometimes been referred to as cylindrical. The terms column or columnar are used somewhat ambiguously to refer to either a single pillar-shaped structure, or to individual branches of fascicles. To avoid confusion, and following dictionary usage, the term column should be retained, but should be restricted to non-branching, pillar-like structures of greater height than diameter that arise directly from the substrate. In describing branched columnar microbialites, the terms branch, branched or branching are preferred to column
4. *Conical microbialite*: (Figs 51d, 54) a non-branching microbialite that commonly has a circular to oval (more rarely polygonal) base, and which tapers to a point. The height is commonly greater than the width. The term coniform is synonymous, but conical is preferred
5. *Branched microbialite*: (Figs 51e, 55) any microbialite that exhibits branching can be referred to as a branched microbialite. However, if an individual microbialite shows complex branching, it forms a fascicle (see below). The terms branching columnar and columnar branching have also previously been used for similar features. Branched is the preferred term. Branched microbialites include stromatolites that have conical laminae (Kah et al., 2009)

Figure 45. Examples of comparative geometry – domes and cones in plan view: a) dome in plan view; domical stromatolite; Stag Arrow Formation, Manganese Group; Collier Basin; Stenian, Mesoproterozoic; Enachedong Creek, BALFOUR DOWNS, Western Australia (photo by K Grey); b) cone in plan view; *Conophyton* new Form (Balfour type); Stag Arrow Formation, Manganese Group; Collier Basin; Stenian, Mesoproterozoic; Enachedong Creek, BALFOUR DOWNS, Western Australia (photo by K Grey)

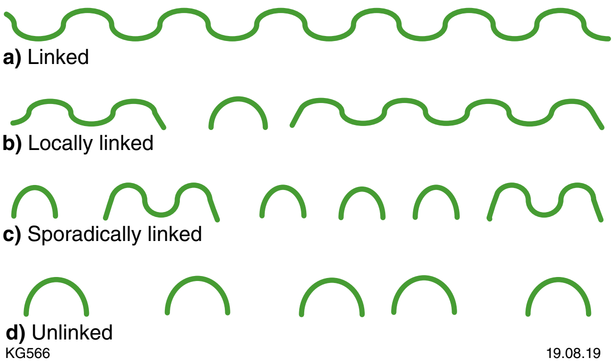

Figure 46. Microbialite linkage – vertical view: a) linked, all buildups are connected laterally; b) locally linked, most buildups are connected laterally; c) sporadically linked, only a few buildups are connected laterally; d) unlinked, no buildups are connected laterally

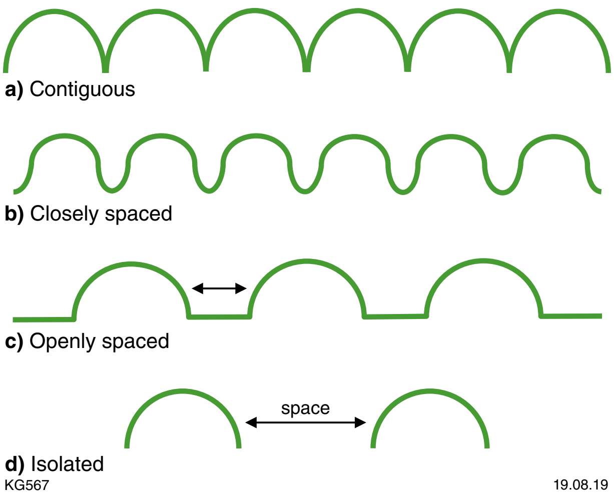

Figure 47. Microbialite spacing: a) contiguous, buildups have little or no interspace areas; b) closely spaced, spaces between buildups are narrow; c) openly spaced, spaces between buildups are broad; d) isolated, spaces between buildups are very wide

6. *Compound microbialite*: (new term) (Figs 51f, 55c, 56) this category includes microbialites that have more than one type of coexisting organization within the same type of microbialite; for example, there may be a combination of geometric shapes, such as conical and branched, as in *Jacutophyton*, or they may be pseudocolumnar, columnar layered, or conical layered, but are all stromatolites. Compound microbialites are particularly common in lacustrine deposits. They differ from composite microbialites in being a combination of morphological shapes of the same type, whereas composite microbialites consist of combinations of different types of microbialites, such as stromatolites, thrombolites and dendrolites, which differ at the highest level of organization, rather than being a combination of shape characteristics of the same microbialite subset at macrostructural level. That is, a combination of a stratiform and branched stromatolite (especially if there is a difference in microstructure), or of a conical and branched stromatolite, would be a compound microbialite; whereas a a combination of a stromatolite with a thrombolite is a composite microbialite

7. *Maceriate microbialite*: (Figs 51g, 57a,b) a term introduced by Shapiro and Awramik (2006, p. 412) for the 3D shape of a microbialite that resembles labyrinthine, hedge-like mazes in plan view and has a cerebroid surface view

8. *Pitted microbialite*: (Fig. 51h) a microbialite with numerous, relatively deep, steep-sided depressions extending into the microbialite and filled with sediment (see Bradley, 1929; Lamond and Tapanila, 2003). Tubestone is an extreme case of a pitted microbialite in which an interconnected network of microbialite is interrupted by very deep (up to 2 m), vertically oriented, mostly cylindrical structures (tubes) filled with sediment (Corsetti and Grotzinger, 2005; Bosak et al., 2013b)

9. *Plumose microbialite*: a microbialite with an apparent central stem (support) and many fine branches that bifurcate and coalesce, producing an overall feathery appearance (Sumner, 1997b, p. 308). Gürich (1906, p. 50–51, pl. XVIII, fig.1) was the first to describe a plumose microbialite, *Malacostroma plumosum*

10. *Oncoid*: (Figs 51i, 57c–e) an unattached stromatolite that is continuously or discontinuously enveloped by the laminae. Although uncommon, some oncoids have small, commonly branching columns in their outer portions (Johnson, 1946) and have been called dendroidal oncolites [sic] (Wade and Garcia-Pichel, 2003). In principle, oncoid could also refer to an unattached structure of microbial origin that is not laminated.

Hofmann (1969a, 1976a,b, 1984) gave detailed accounts of geometrical parameters of idealized microbialite shapes. Geometrical analysis provides a precise determination of shape and can be used to assign microbialites to morphological categories, although such categories can usually be determined by visual inspection. Other types of microbialite shape have been described, but are not well known. If uncommon shapes are encountered, give a detailed description and define any new terms introduced.

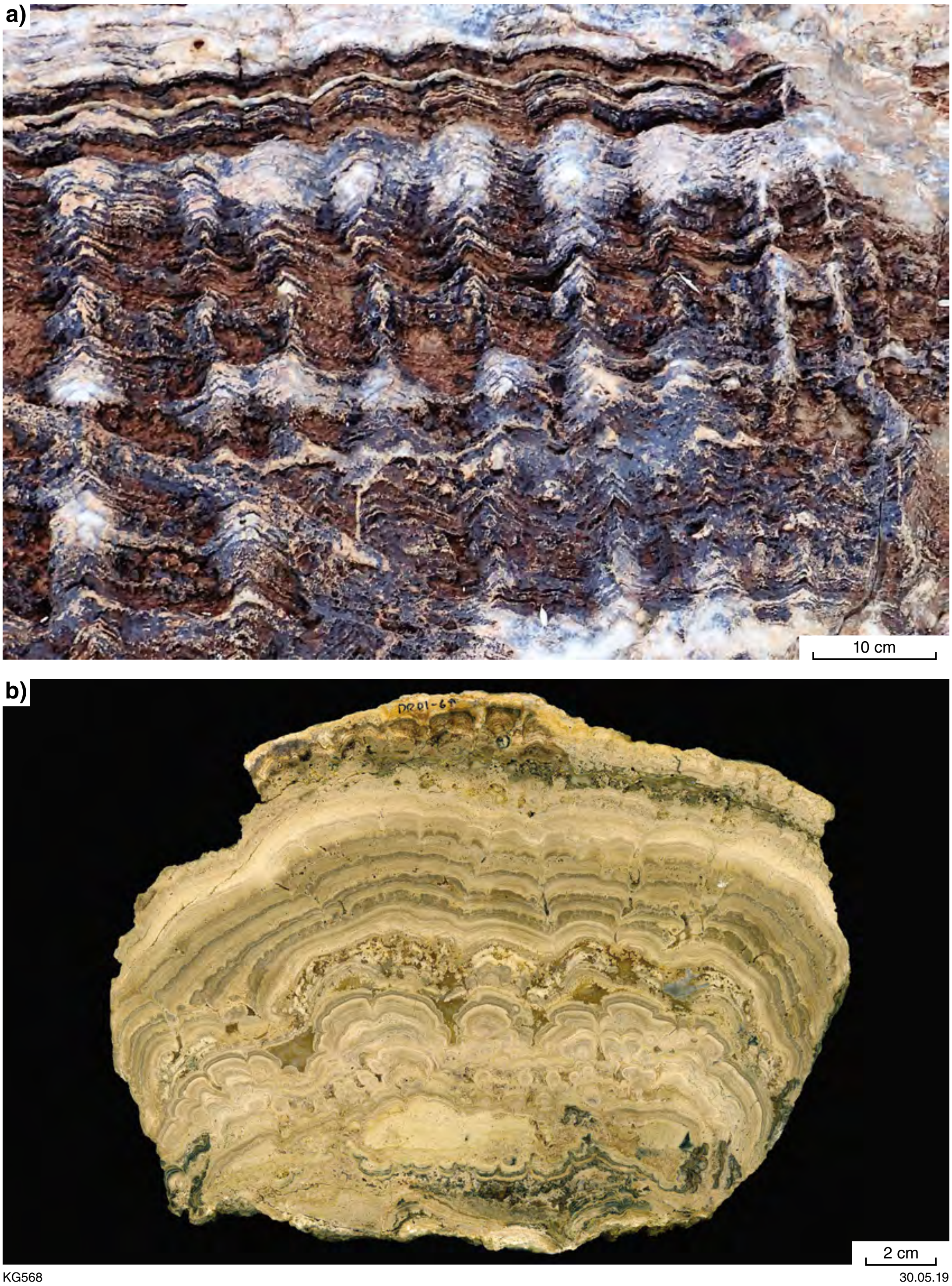

Figure 48. Examples of linkage and spacing: a) linked, openly spaced cones; Duck Creek Dolomite, Wyloo Group; Ashburton Basin; Orosirian, Paleoproterozoic; Duck Creek, WYLOO, Western Australia (photo by HJ Allen); b) linked and locally linked, contiguous and closely spaced stromatolites; Laney Member, Green River Formation; Washakie Basin; Eocene; Delaney Rim, Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik)

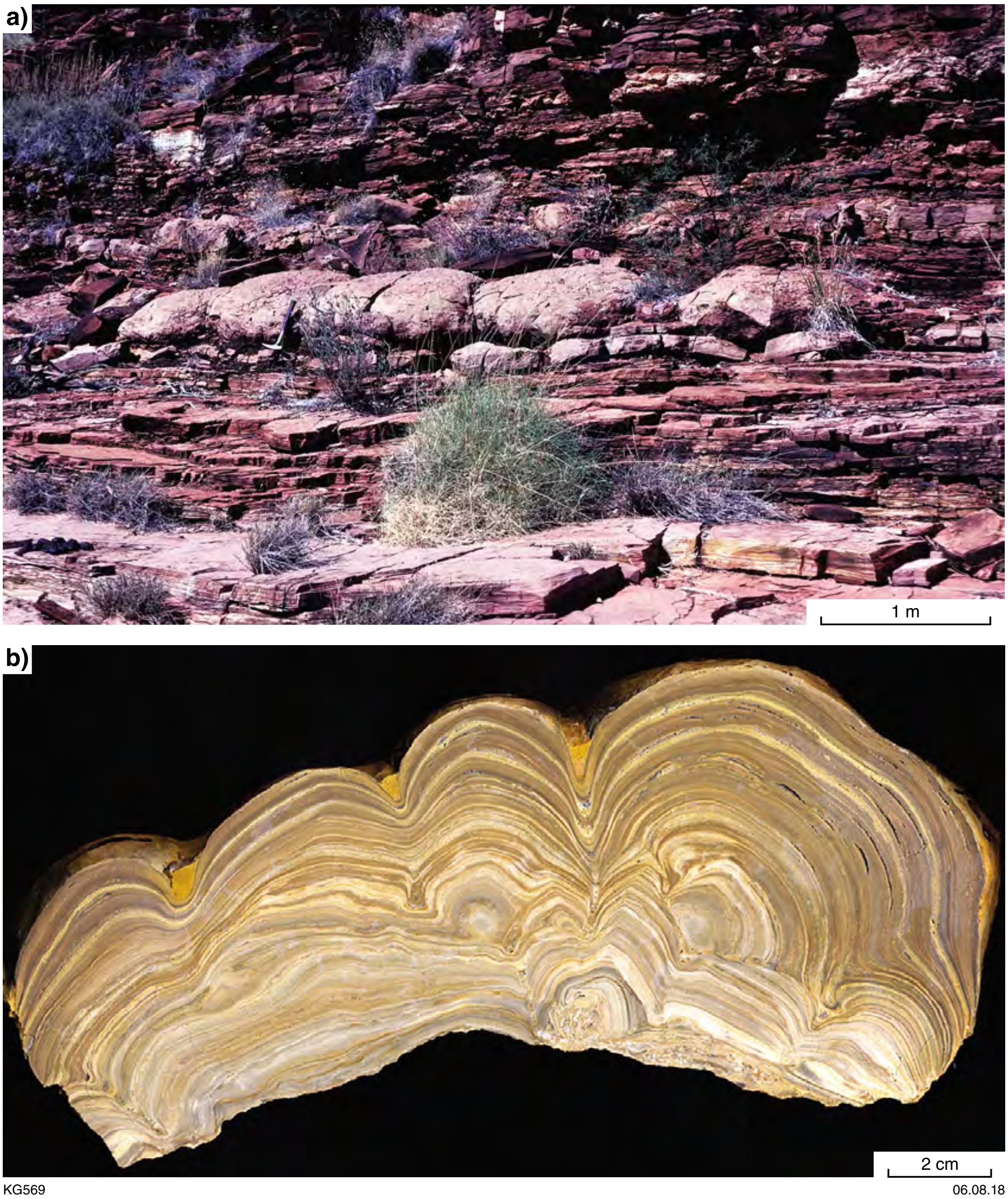

Figure 49. Examples of linkage and spacing: a) linked and sporadically linked, contiguous bioherms, *Tungussia* f. indet.; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; Muddauthera Creek, NULLAGINE, Western Australia (photo by K Grey); b) locally and sporadically linked, contiguous and closely spaced stromatolites; Laney Member, Green River Formation; Washakie Basin; Eocene; Kinney Rim, Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik)

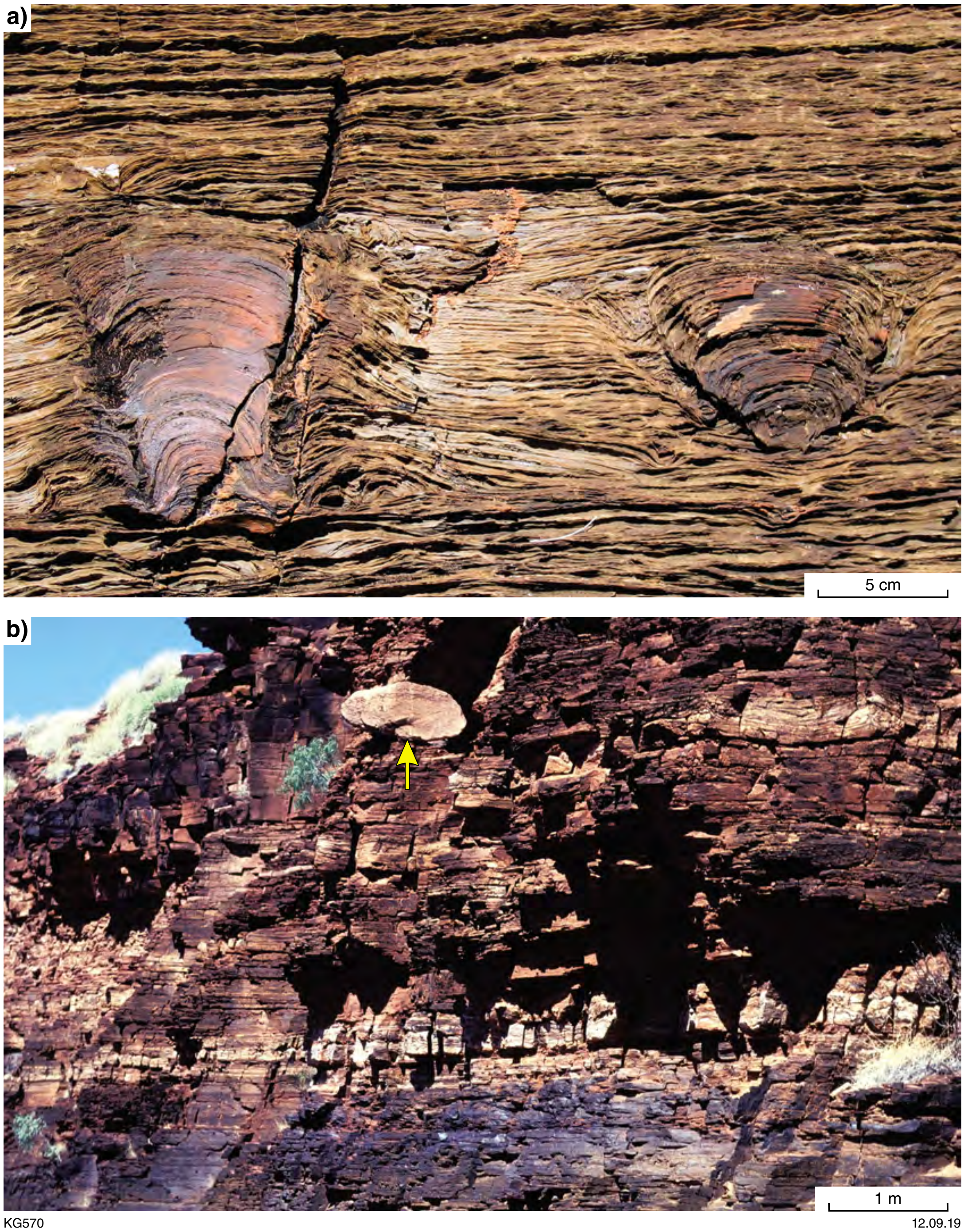

Figure 50. Examples of linkage and spacing: a) unlinked, openly spaced, columnar stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia; micritic microbialite in calcareous siltstone (photo by SM Awramik); b) unlinked, isolated bioherm, *Tungussia* f. indet. (arrow); Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; Muddauthera Creek, NULLAGINE, Western Australia; carbonate microbialite enclosed in laminated mudstone (photo by K Grey)

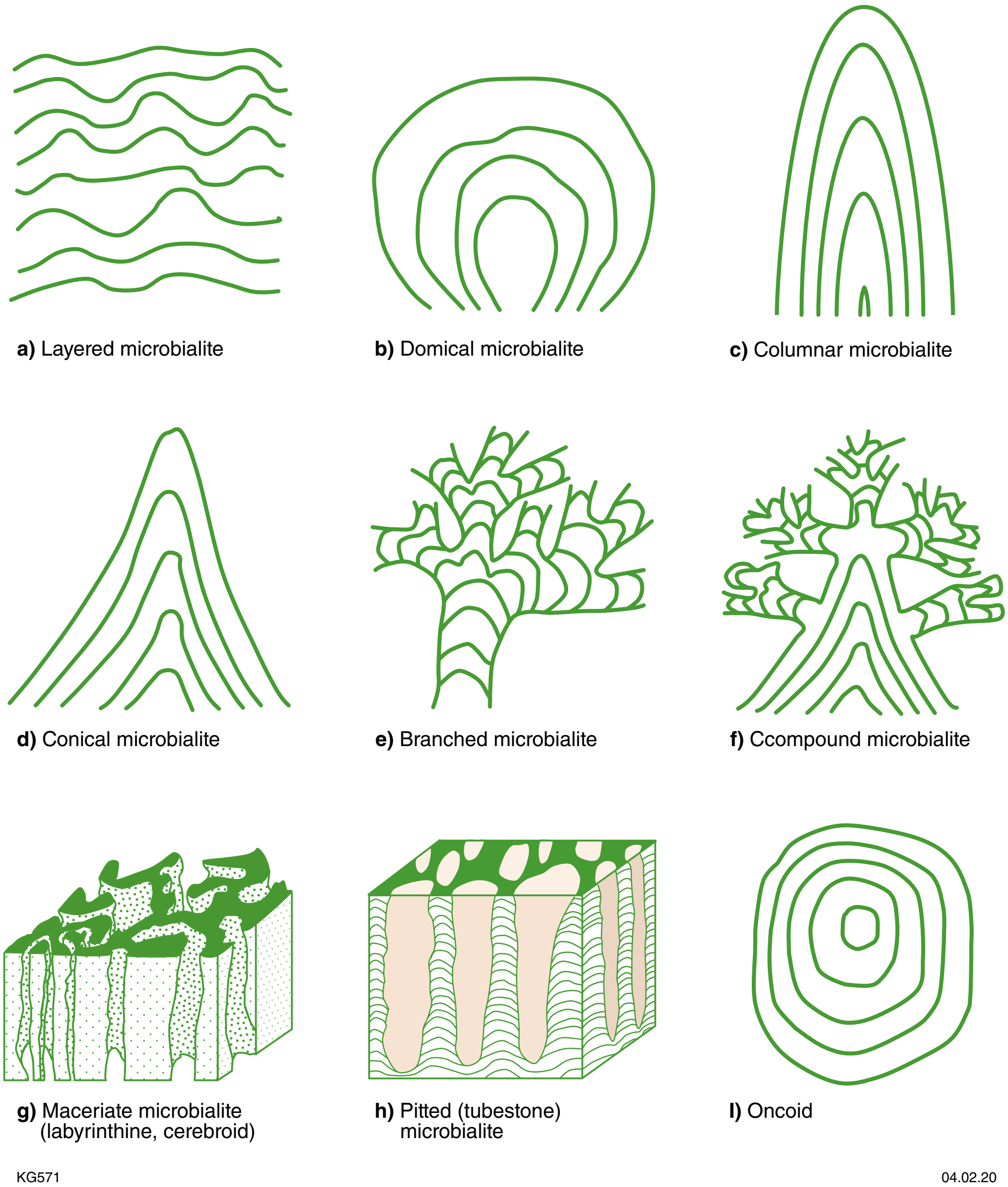

Figure 51. Microbialite shape: a) layered microbialite; b) domical microbialite; c) columnar microbialite; d) conical microbialite; e) branched microbialite; f) compound microbialite; g) maceriate microbialite (labyrinthine, cerebroid), after Shapiro and Awramik (2006, fig. 4); h) pitted (tubestone) microbialite (shaded areas indicate tubes); i) oncoid

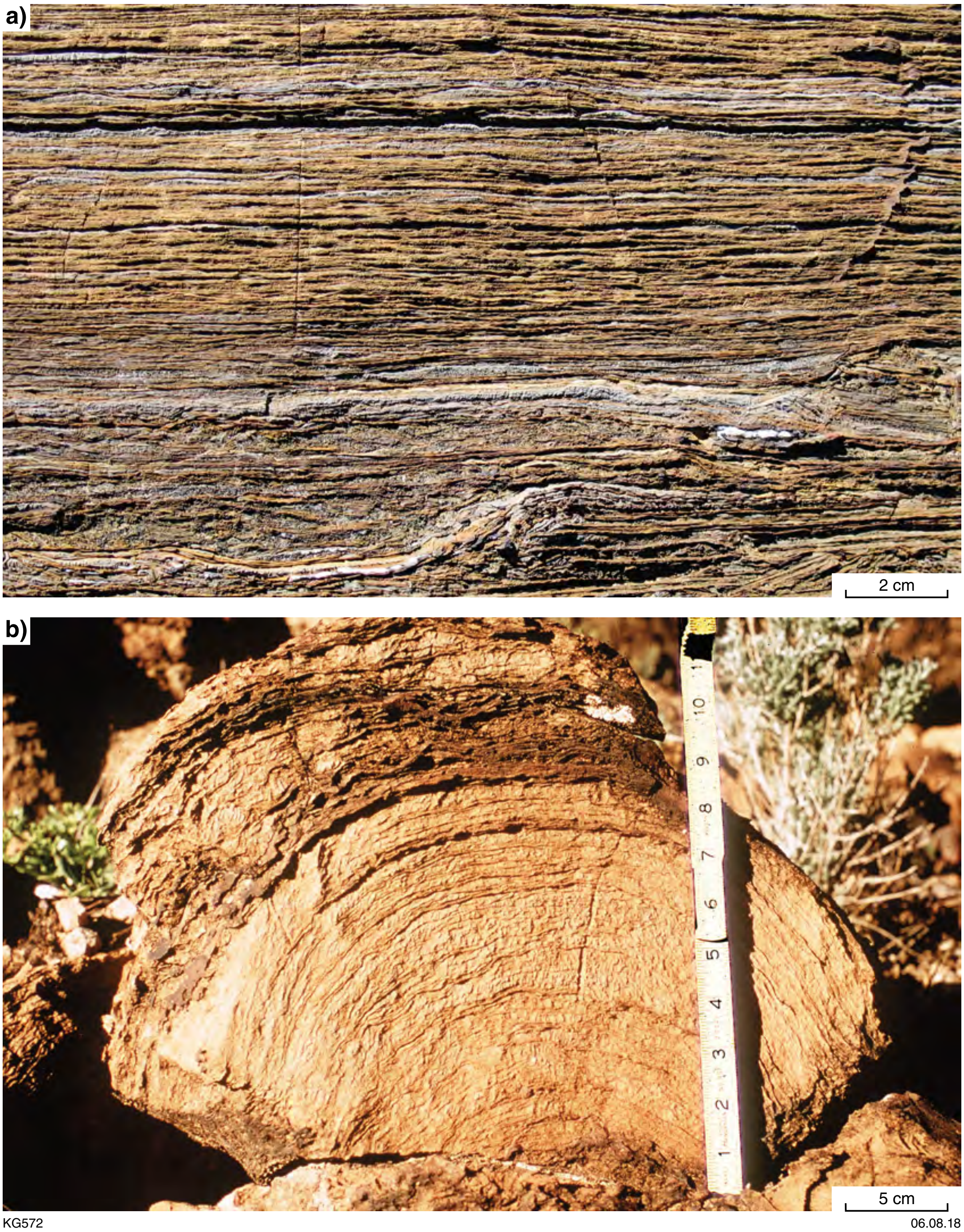

Figure 52. **Examples of shape – layered and domical: a) layered microbialite; Meentheena Member; Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia (photo by SM Awramik); b) domical microbialite; Brighton Limestone, Umberatana Group; Adelaide Rift Complex; Cryogenian, Neoproterozoic; Flinders Ranges, COPLEY, South Australia (photo by SM Awramik)**

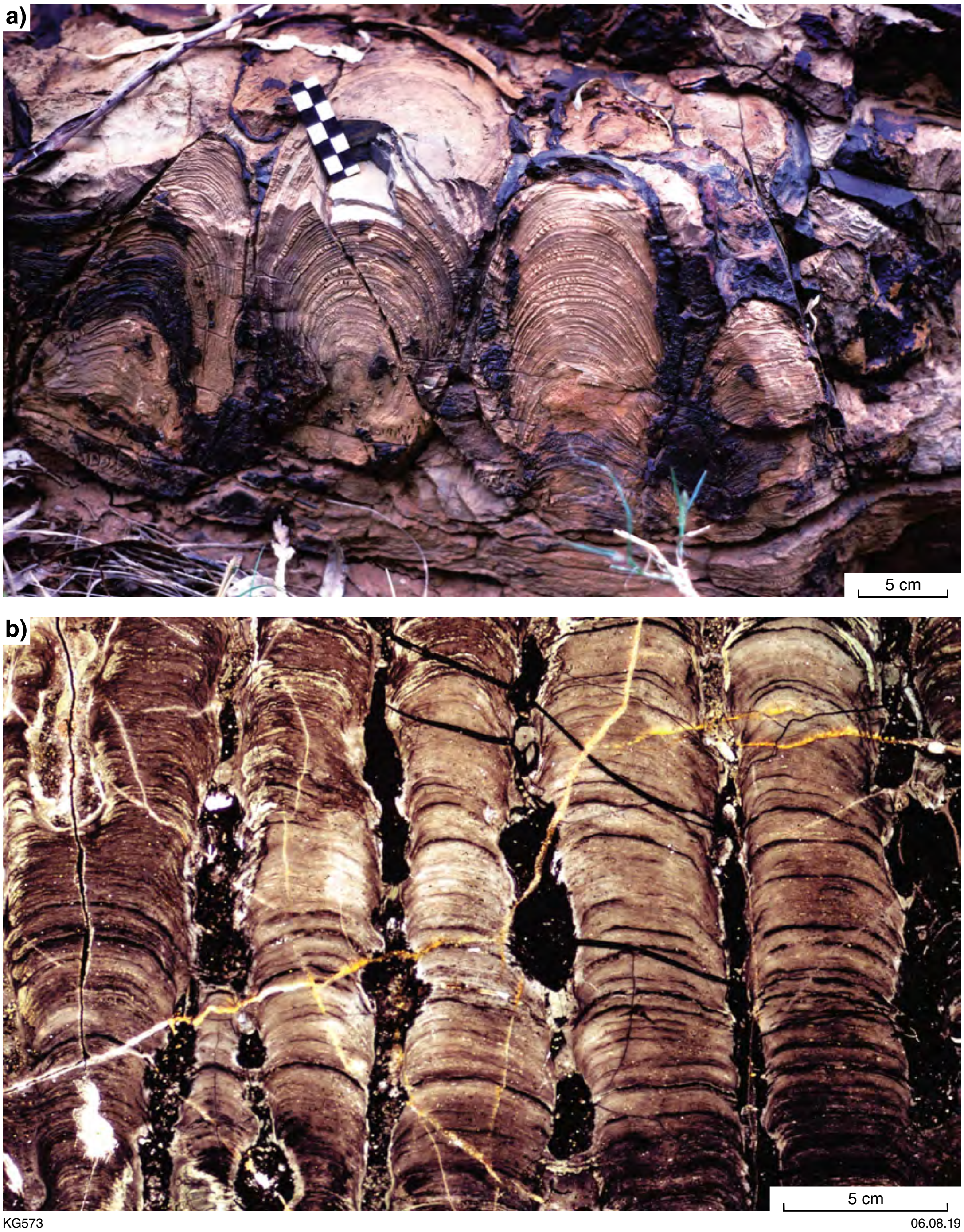

Figure 53. Examples of shape – columnar: a) cf. *Colonella* f. nov.; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, Edmund, Western Australia (photo by K Grey); b) Gunflint Formation, Animikie Group; Animikie Basin; Orosirian, Paleoproterozoic; Winston Point, Lake Superior, Ontario, Canada; polished slab, Peabody Museum of Natural History, Yale University, YPM PB 051800 (photo by SM Awramik)

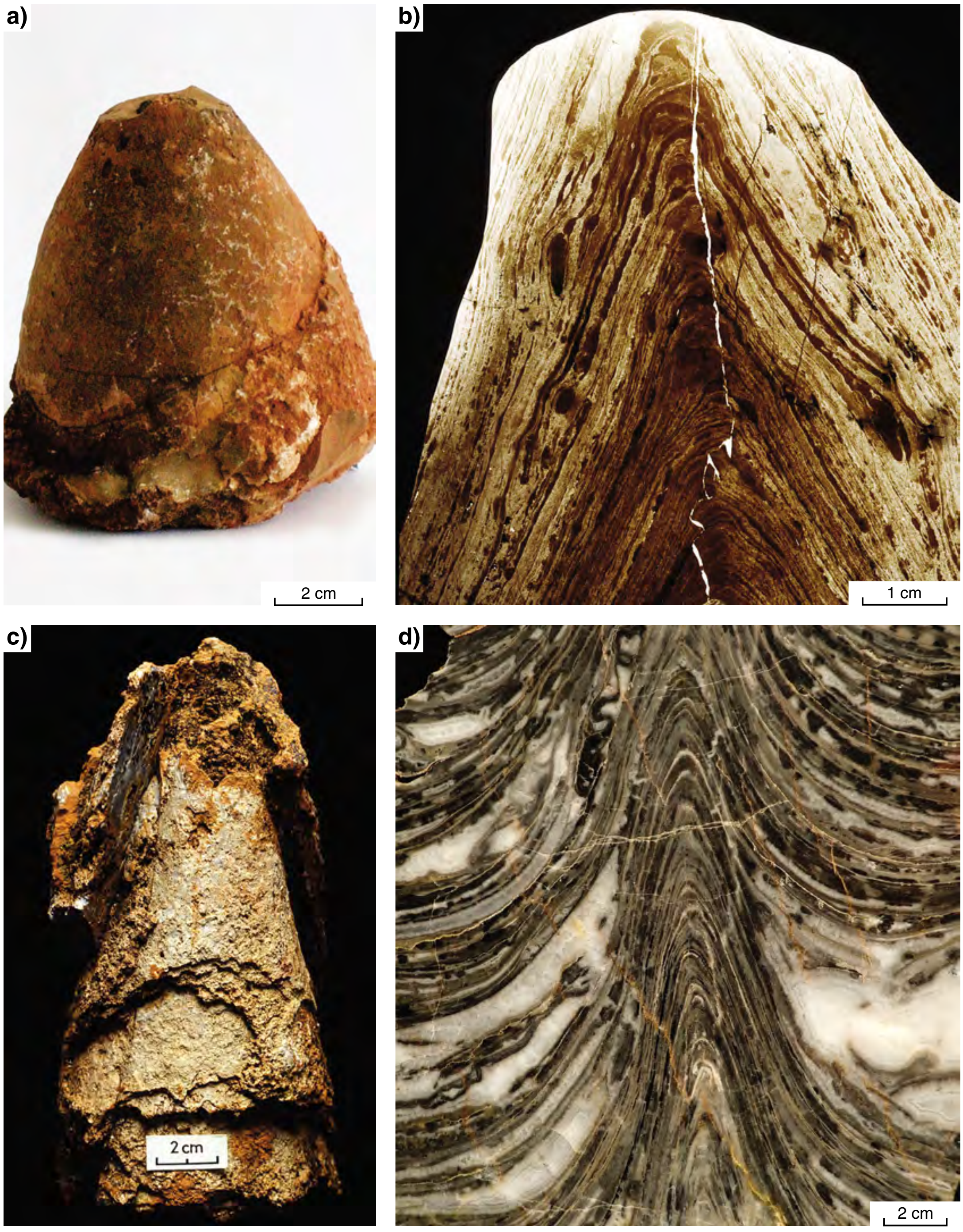

Figure 54. **Examples of shape – conical; a)** ***Conophyton*** **new Form (Throssell type); Kanpa Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; near Lake Throssell, THROSSELL, Western Australia; GSWA F52411D–138968D (photo by SK Martin); b)** ***Conophyton*** **new Form (Balfour type); Stag Arrow Formation, Manganese Group; Collier Basin; Stenian, Mesoproterozoic; near Canning Well, BALFOUR DOWNS, Western Australia; thick section GSWA F53369–31000 (photo by K Grey). c, d)** ***Ephyaltes edingunnensis*****; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; Paroo Station, GLENGARRY, Western Australia: c) whole cone, GSWA F48420–88078A; d) cut face, GSWA F12359–59868 (photo by K Grey)**

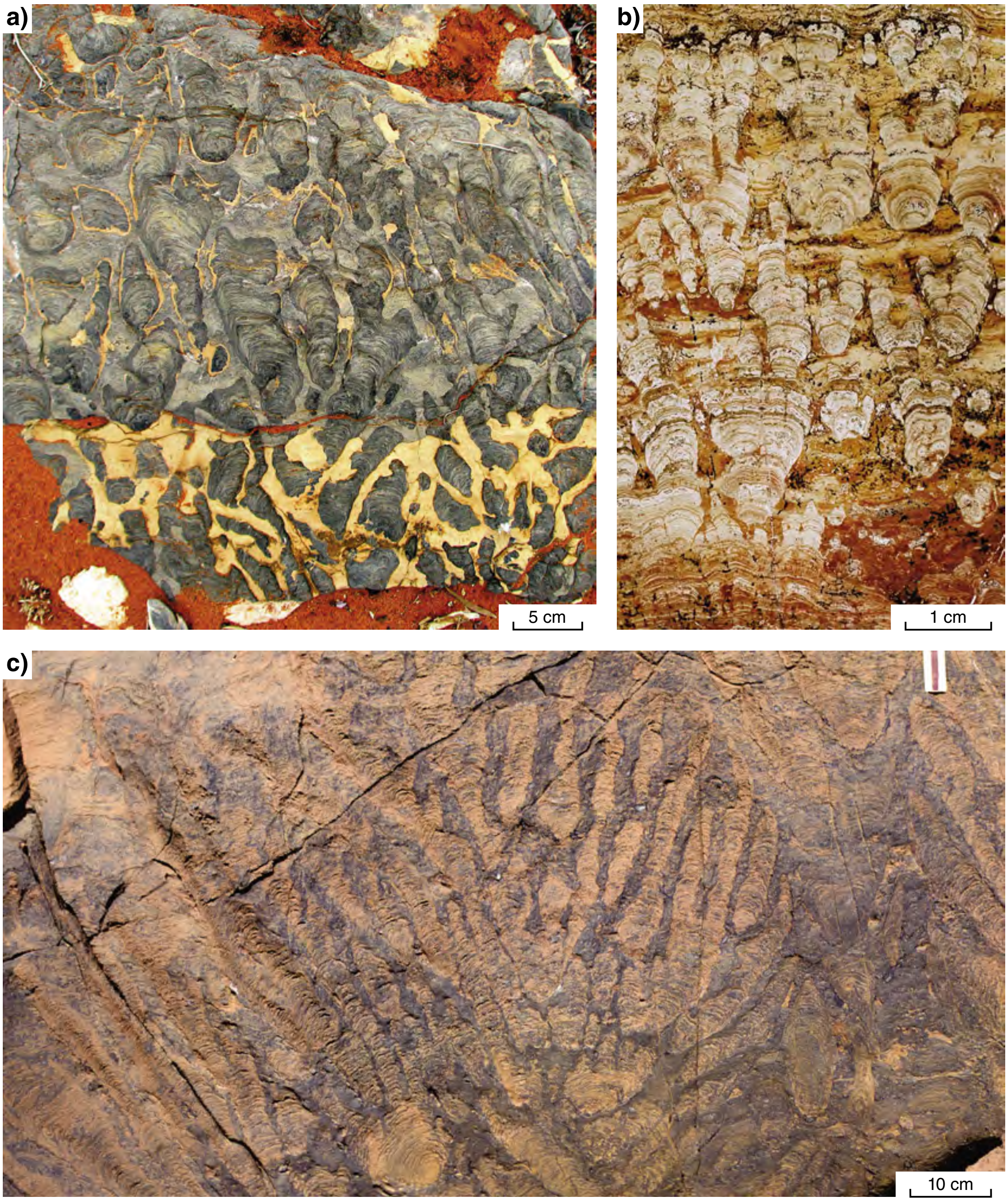

Figure 55. Examples of shape – branched: a) *Linella avis*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Boord Ridges, MACDONALD, Western Australia (photo by PW Haines); b) *Asperia digitata*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, NABBERU, Western Australia; thick section GSWA F12390–46326 (photo by SM Awramik and K Grey); c) *Tilemsina divergens*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania (photo by SM Awramik)

Figure 56. Example of shape – compound; *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania (photo by SM Awramik)

Types of layered microbialites (stromatolites)

Layered microbialites applies only to stromatolites and there are several types: stratiform, undulatory, pseudocolumnar, linked-columnar and linked-conical stromatolites (Figs 58–60). These have more or less continuous, parallel laminae and are mainly planar to undulatory. Some researchers would regard pseudocolumnar and columnar layered as distinct categories, but they are here grouped as layered microbialites with other microbialites that have the feature of laterally continuous, successive layering in common. They can be described as follows:

1. *Stratiform* (planar, flat laminated, planar laminated): (Figs 58a, 59a) Preiss (1972, p. 93) used flat-laminated stromatolite, which he defined as a 'non-columnar stromatolite with flat continuous laminae' (Preiss, 1972, p. 93). Aitken (1967) referred to stratiform stromatolites as cryptalgal laminates. Laminae are continuous and generally flat and parallel. They are usually horizontal, but can occur in other orientations, for example in cavity-encrusting microbialites (Figs 24c, 29b). These variations have been referred to as endostromatolites (Monty, 1982, p. 343) and teicholites (rarely used term). Stratiform stromatolites can be distinguished from abiotic laminated sediments by the alternating dark–light laminae and the gradational boundaries between individual laminae
2. *Undulatory*: (Figs 58b, 59b) Preiss (1972, p. 93) defined undulatory as a 'laterally linked stromatolite in which successive crests are not superimposed'. As the name suggests, the surface is undulose, in contrast to the smoother surface of a stratiform stromatolite
3. *Pseudocolumnar*: (Figs 58c, 59c) this term was used by Hofmann (1969a). Preiss (1972, p. 93) defined it as a 'laterally linked stromatolite in which successive crests are superimposed, forming column-like structures (pseudocolumns)'. A pseudocolumnar stromatolite consists of short lengths of columns interspersed with linked stromatolites, commonly of the same or greater length. Column boundaries cannot be traced in plan view
4. *Linked columnar* (columnar layered, layered columnar): (Figs 58d, 60a) the term columnar layered was used by Nuzhnov in Krylov (1963). Preiss (1972, p. 92) defined a columnar-layered stromatolite as 'a stromatolite in which short columnar and laterally linked (usually pseudocolumnar) portions alternate'. Linked columnar is preferred because it is a parallel term to linked conical. Short sections of columnar microbialites alternate with pseudocolumnar microbialites in vertical section, but where column boundaries can be detected in plan view, they are irregular
5. *Linked conical*: (new term) (Figs 58e, 60b) a microbialite in which short sections of conical microbialite alternate with laterally linked (usually pseudoconical or pseudocolumnar) structures. Plan views can be oblong, elongate, ovoid, or star shaped, and laminae are not necessarily concentric; one side may be larger than the other (note: the name *Conophyton* is reserved for cylindrical-conical stromatolites that have an axial zone; conical microbialites other than linked microbialites should simply be referred to as conical, not as a 'conophyton').

Types of domical microbialites

Domical microbialites are approximately as high as they are wide. They may grade into other shapes (Figs 61a–c, 62) and there are a few common types:

1. *Hemispherical*: (Figs 61a, 62a,b) microbialites that are equal in height and width with the plane of maximum diameter at the base
2. *Bulbous*: (Figs 61b, 62c,d) Raaben et al. (2001, p. 5) used the term picnostromic for mound-like or cabbage-head-like stromatolites but the term bulbous, preferred here, has been used in most cases. A bulbous microbialite generally has height somewhat greater than width with the plane of maximum diameter above the midpoint of the height. The diameter of the base is less than the maximum diameter
3. *Nodular*: (Figs 61c, 62e,f) Nodular is another common term that has been used and is preferred here for a microbialite that is commonly equal in height and width with the plane of maximum diameter generally at mid-height. The diameter of the base is much less than the maximum diameter and the structure may be almost, but not quite, detached from the substrate.

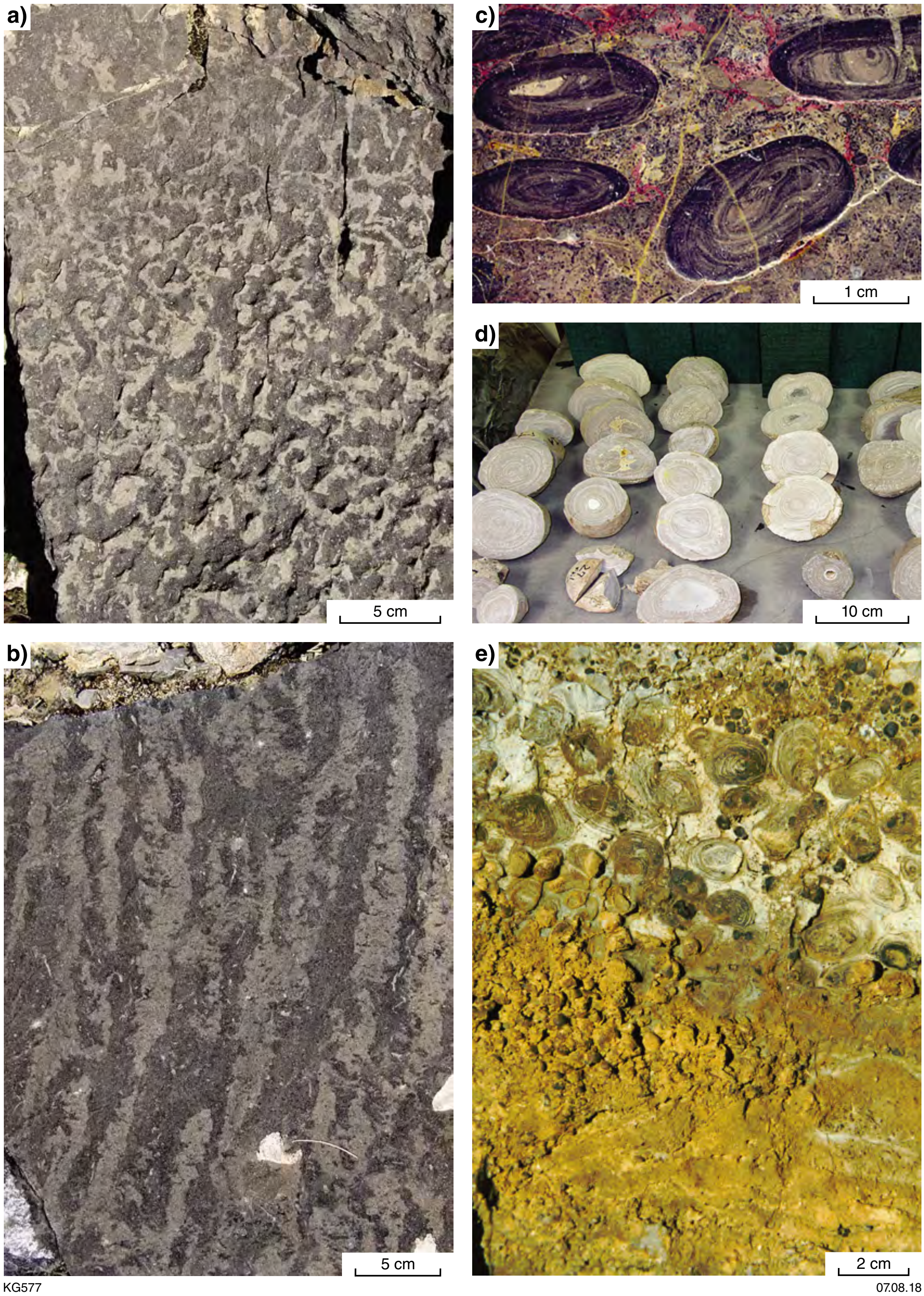

Figure 57. **Examples of shape – maceriate and oncoidal. a, b) Maceriate microbialite; *Favosamaceria cooperi*; Smoky Member, Nopah Formation; upper Cambrian; Mohawk Hill, Clark Mountain Range, San Bernardino County, California, US: a) plan view; b) vertical view. This microbialite is cerebroid in surface view (photo by SM Awramik). c–e) Oncoids: c) Chambless Limestone; lower Cambrian; Marble Mountains, San Bernardino County, California, US; polished slab, UCSB collection (photo by SM Awramik); d) Wasatch Formation; Fossil Basin; Eocene; Sixmile Creek, Rich County, Utah, US; cut surfaces, UCSB collection (photo by SM Awramik); e) Kingston Peak Formation, Pahrump Group; Tonian–Cryogenian, Neoproterozoic; Kingston Range, San Bernardino County, California, US (photo by SM Awramik)**

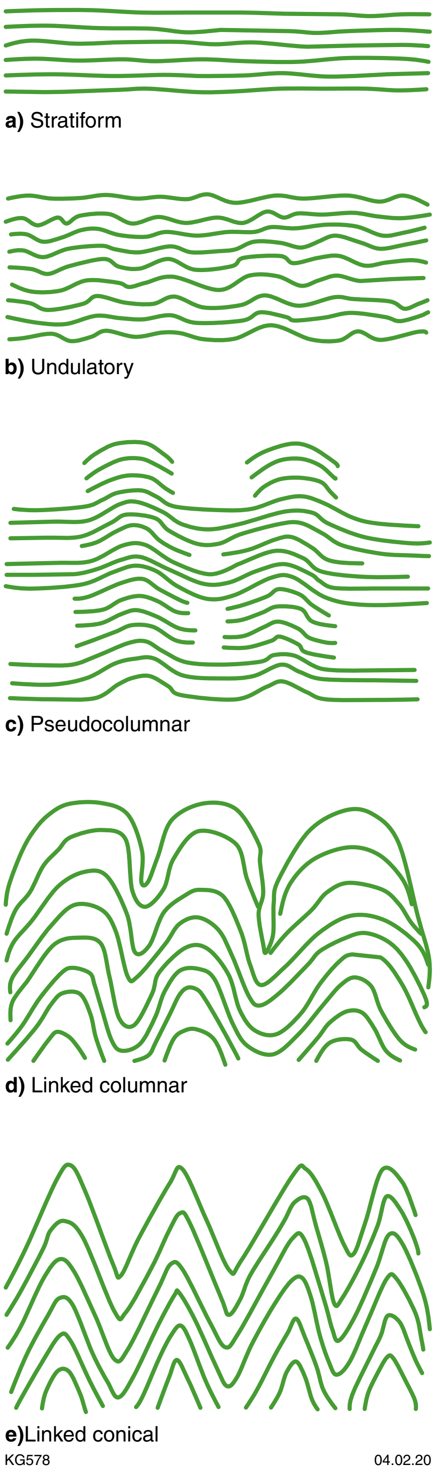

Figure 58. Types of layered microbialites: a) stratiform (planar, flat laminated); b) undulatory; c) pseudocolumnar; d) linked columnar (columnar layered); e) linked conical

Use further descriptors, such as discoidal, ellipsoidal, subspherical, ovoidal, or clavate (club shaped) to elaborate on shapes. The term 'cumulate' (Walter, 1972) is here considered synonymous with domical and bulbous. Raaben et al. (2001, p. 66) referred to cumulate and bulbous shapes as 'nuclear' (a specific type of bulbous or nodular stromatolite in which the central and peripheral laminae differ from one another in texture and microstructure) and also used the term 'picnostromic' for mound-like and cabbage head-like microbialites' (Raaben et al., 2001, p. 5, 30, 69).

Types of columnar microbialites

Columnar microbialites (Figs 61d–f, 63–65) are discrete structures in which the height is greater than the maximum width. Avoid using column if referring to an individual branch, although terms like column margin can be inferred to apply to both columns and branches where both are present. The shape of the column is best determined by 3D reconstruction because a cut face that is slightly tangential can give a false impression that a column has a terete or turbinate termination. Three types can be recognized:

1. *Cylindrical*: (Figs 61e, 63) microbialites in which the diameter is uniform in plan view and remains constant throughout the length of the column, as in the computer-generated growth forms of Hofmann (1969a, p. 12). Microbialites in which the diameter is somewhat variable in plan view and in which the diameter may vary irregularly throughout the length of the column are commonly referred to as subcylindrical, for example *Katavia* in Krylov (1963, p. 94). Some cylindrical microbialites have very acute (reflexed) laminar profiles, for example as illustrated by Hofmann (1969a, fig. 7). These are often assigned to *Conophyton* but this name should only be used for stromatolites that have a distinct axial zone
2. *Terete:* (Figs 61d, 64) microbialites in which the diameter decreases upwards, as in the computer-generated growth forms of Hofmann (1969a, p. 12)
3. *Turbinate*: (Fig. 61f, 65) microbialites in which the diameter increases upwards, as in the computer-generated growth forms of Hofmann (1969a, p. 12). Turbinate microbialites are sometimes described as clavate (club shaped).

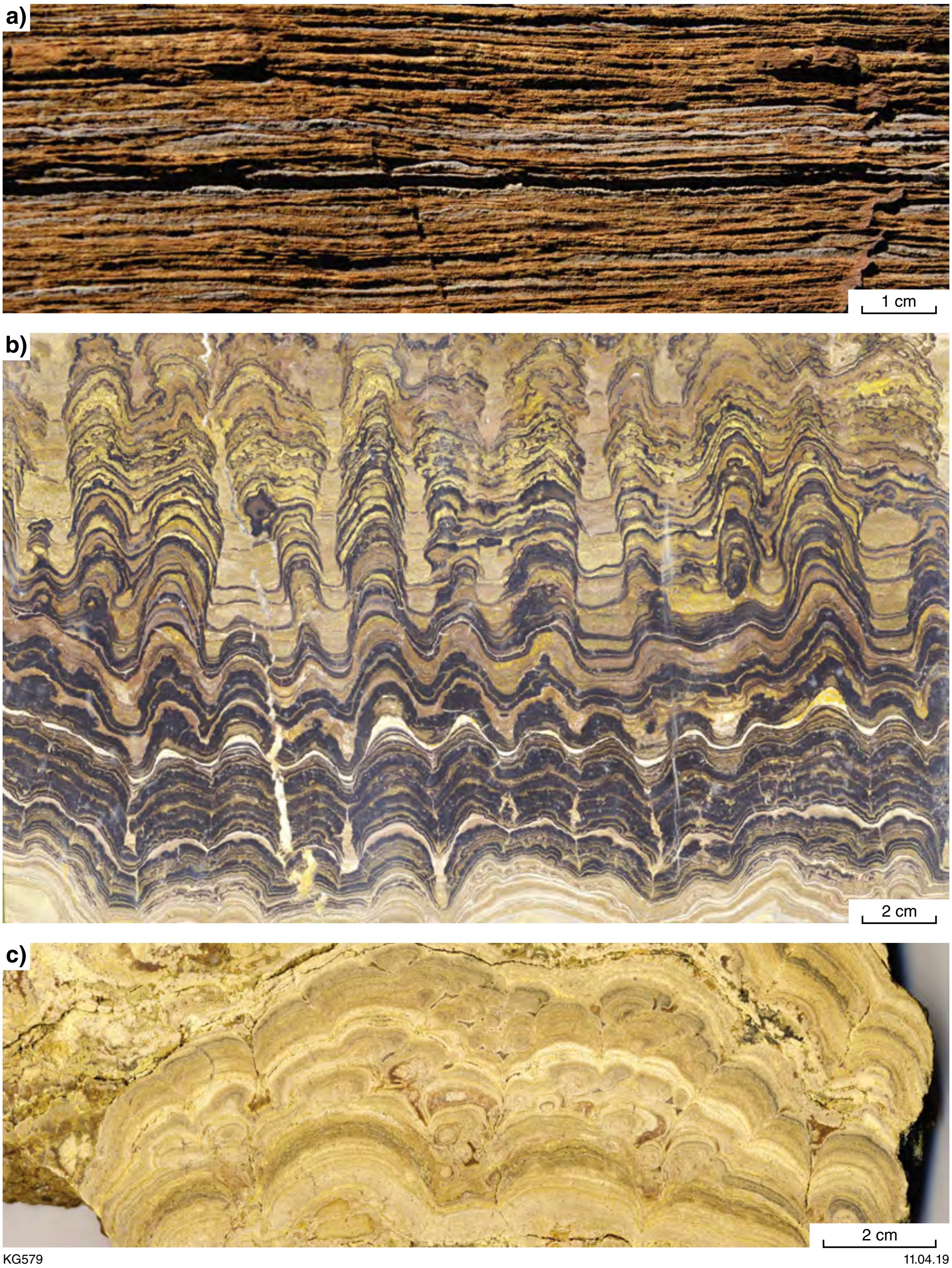

Figure 59. **Examples of layered microbialites: a) stratiform (planar, flat laminated); Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia (photo by SM Awramik); b) undulatory interspersed with pseudocolumnar and linked columnar, developing into columnar; probably from the El Molino Formation; Upper Cretaceous – Paleocene; near Challa Mayu, Bolivia; polished face of commercially available slab, UCSB collection (photo by SM Awramik); c) pseudocolumnar stromatolite; Laney Member, Green River Formation; Washakie Basin; Eocene; Delaney Rim, Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik)**

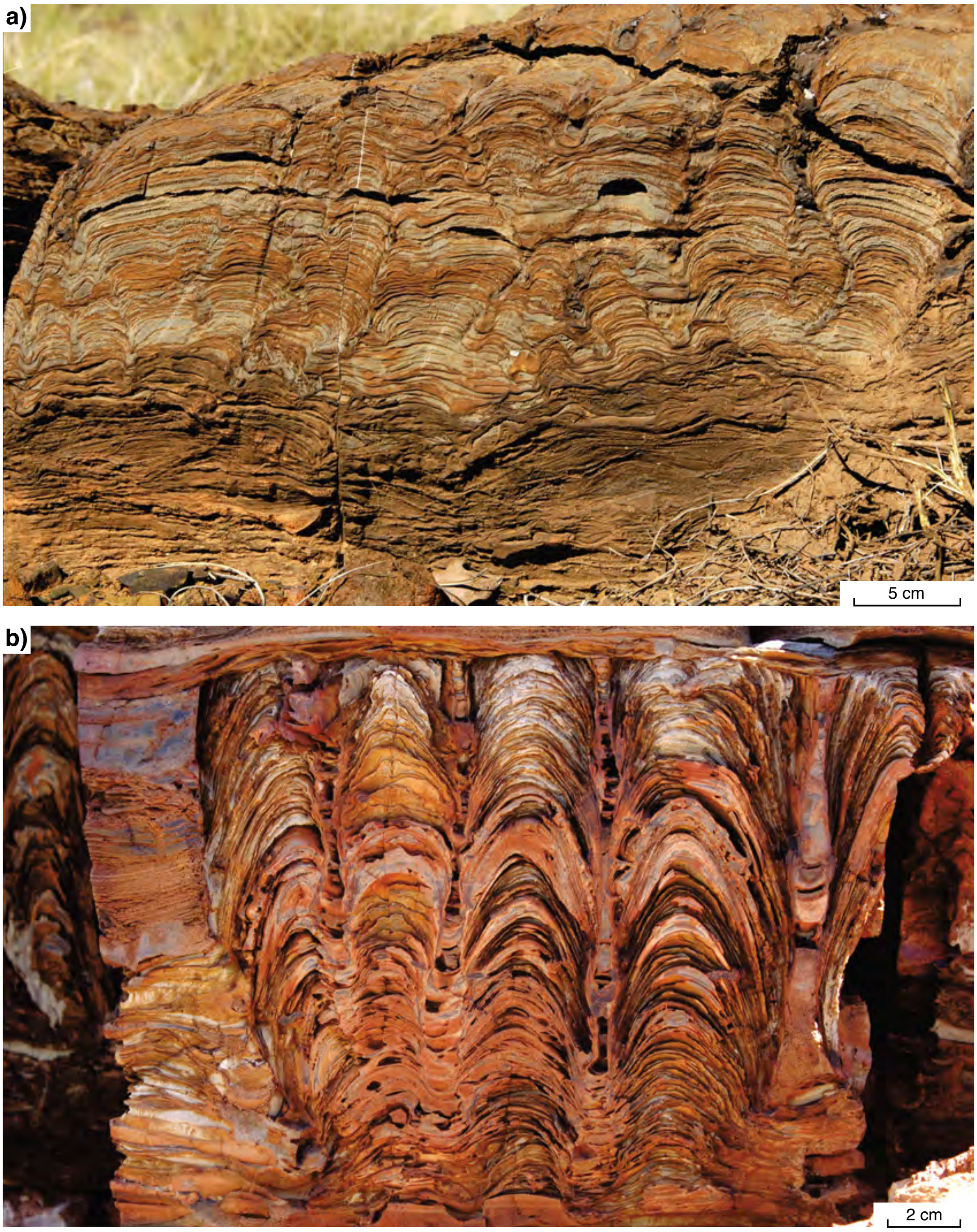

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Figure 60. Examples of layered microbialites: a) linked-columnar (columnar-layered) stromatolite; Meentheena Member; Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia (photo by SM Awramik); b) linked-conical stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Redmont, Pilbara, NULLAGINE, Western Australia (photo by SM Awramik)

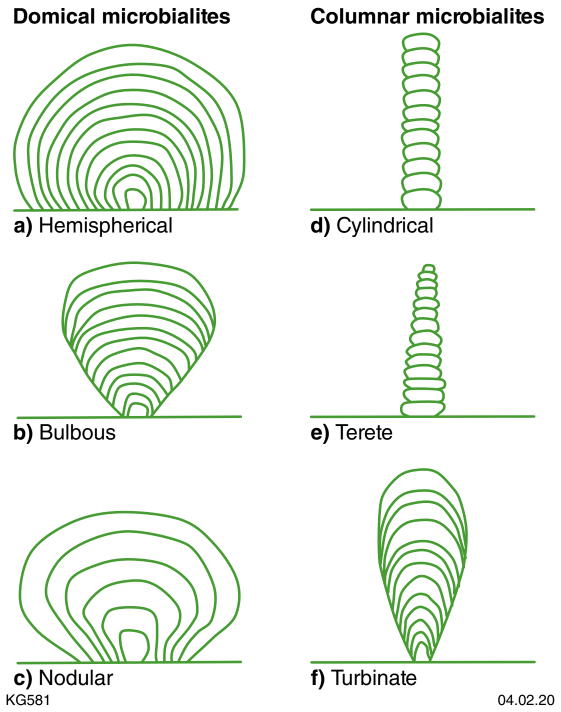

Figure 61. Types of domical and columnar microbialites. a–c) Domical microbialites: a) hemispherical; b) bulbous; c) nodular. d–f) Columnar microbialites: d) cylindrical; e) terete; f) turbinate

Types of conical microbialites

The term conical can be used for any cone-shaped microbialite (Figs 51d, 54, 66–77). The term coniform is synonymous with conical. Most conical microbialites are laminated, but there is no reason why non-laminated microbialites could not be conical. However, many of the features described below are dependent on laminae being present. Some conical microbialites develop highly complex morphologies, in which the central cone may be surrounded by other structures such as branches, ridges, walls and protrusions. Here we introduce the term compound conical (new term) for such structures, and recognize several types of conical microbialites:

1. *Simple conical*: (Figs 66a, 67) where laminae terminate in a distinct apex, are steeply inclined between the base and apex, and do not show curvature in vertical profile. An axial zone may or may not be present
2. *Cylindrical conical*: (Figs 66b, 68, 69) a simple conical microbialite where the column margins are more or less vertical but the laminae are conical. In some cases microbialites may be domical cylindrical (Fig. 69b), where the column begins as a domical stromatolite but transitions to a cone
3. *Concave conical*: (Figs 66c, 70a) similar to simple conical except that the laminae curve inwards in vertical profile
4. *Convex conical*: (Figs 66d, 70b) similar to a simple cone except that the laminae curve outwards in vertical profile
5. *Polygonal conical*: (Figs 66e, 70c,d) where the base of the cone is not circular but is indented, polygonal, or star shaped (stellate) in plan view. The flanks may be planar or concave. Sometimes the plan view is teardrop shaped (68d, 70d). The preferred term is polygonal, although where appropriate, use terms such as star shaped
6. *Inclined conical*: (Figs 66f, 71) any conical microbialite where the axis of the cone is tilted at an angle to the substrate
7. *Ridged conical*: (Figs 66g, 72, 73) a compound microbialite in which lateral ridges connect adjacent cones
8. *Branched conical*: (Figs 66h, 74, 75) a compound microbialite in which a central cone is surrounded by lateral branches
9. *Collared conical*: (new term) (Figs 66i, 76) a compound microbialite in which a central cone is partially encircled by a series of structures resembling a Medici or Elizabethan collar (a fan-shaped collar that stood upright behind the head and sloped down to meet the neckline). Each structure consists of a curved sheet that is vertical or slightly angled away from the central axis and is attached to the cone some distance above its base. The sheets are commonly offset and rarely surround the cone completely
10. *Petaloid conical*: (Figs 66j, 77) a compound microbialite in which a central cone is surrounded by radiating outgrowths that are petal shaped in plan view and that widen outward from where the base of the petals are joined to the cone flank.

Types of branched microbialites

Branched microbialites are structures that divide into discrete branches (for example, Figs 7–9, 11d, 25c, 26d, 32, 35, 36a,c, 37a–c, 40b,c, 55, 63). The terms branching columnar and columnar branching are often used for this feature; however, non-columnar microbialites can branch (for example, Figs 74, 75a,c). A fascicle (Grey, 1984) refers to the structure formed by a multi-branching stromatolite or other form of microbialite (for example, Figs 2, 11d, 31a,b, 32, 35, 36a,c, 37c, 55). Grey (1984, p. 4) defined a fascicle as 'individuals consisting of a group of columns which have a common point of origin, have developed by branching, and which have only minor variation in fabric throughout the structure'. Several closely spaced fascicles may form a bioherm or biostrome. In other words any group of branches that can be traced back to a common locus can be referred to as a fasciculate microbialite. Fascicle is in part equivalent to the term individual as defined by Preiss (1972, p. 93) and Walter (1972, p. 11). Unfortunately, individual has not only been used in the strict sense, but has also been used to refer to individual specimens as well as to parts of specimens, such as a portion of a branch. It has, consequently, become ambiguous, and is here considered obsolete. The term cluster has also been used (Bertrand-Sarfati and Potin, 1994, p. 352) as a similar concept to fascicle. Bertrand-Sarfati (1972b, p. 47) used the term massif to refer to closely spaced fascicles.

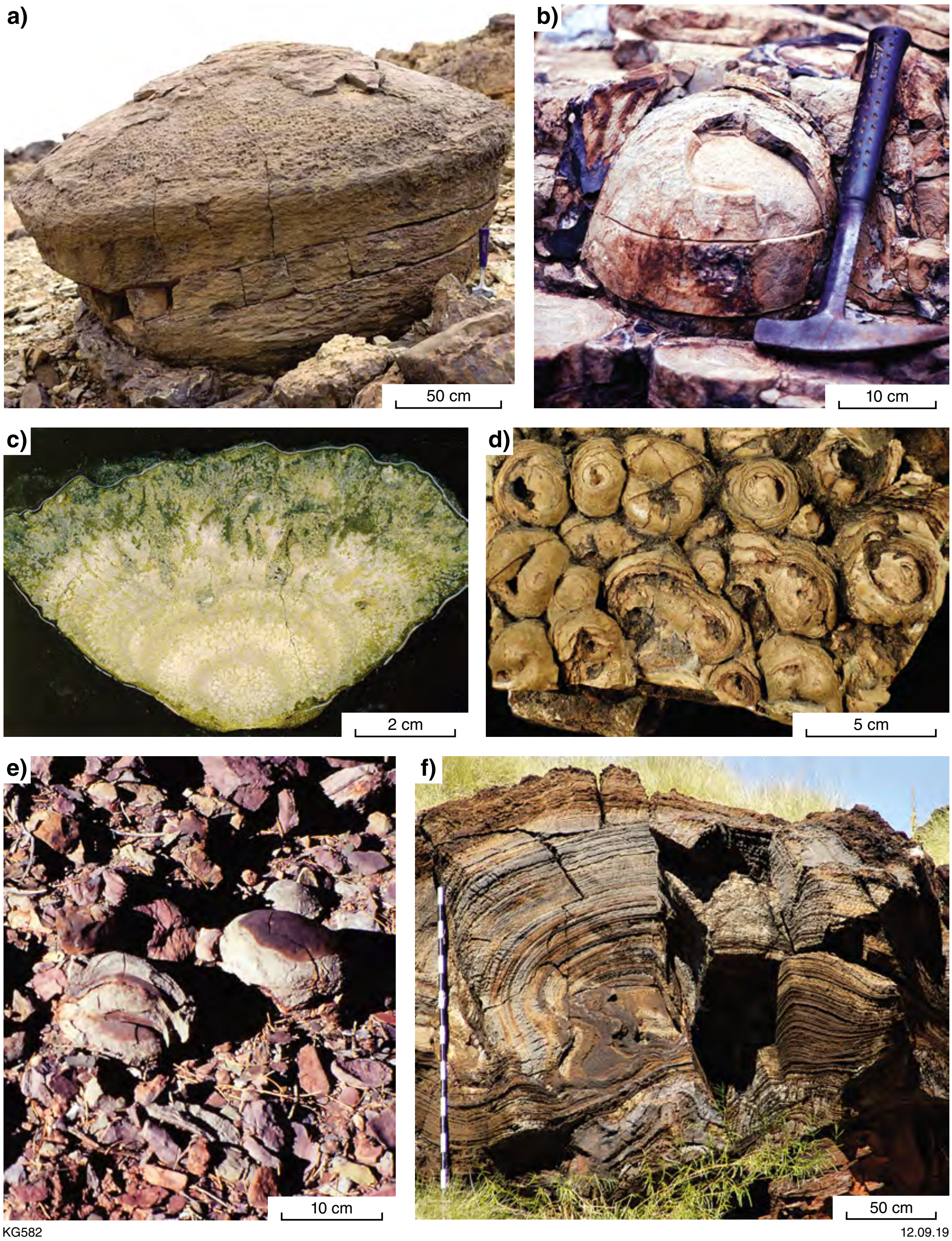

Figure 62. **Examples of domical microbialites: a) hemispherical, walled bioherm; *Jurusania derbalensis*; (Unit I.9), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Aouinet ould bou Derbale, Mauritania (photo by SM Awramik); b) hemispherical stromatolite; cf. *Colonella* f. nov; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, EDMUND, Western Australia (photo by K Grey); c) bulbous stromatolite; Koobi Formation; Turkana Basin; Plio-Pleistocene; east Lake Turkana, Kenya; UCSB collection (photo by SM Awramik); d) domical tops of pseudocolumnar stromatolite; ?Kanpa Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; near Lake Throssell, THROSSELL, Western Australia; GSWA F52408–138961 (photo by K Grey); e) nodular stromatolite; Backdoor Formation, Collier Group; Collier Basin; Stenian, Mesoproterozoic; near Conical Hill, COLLIER, Western Australia (photo by K Grey); f) nodular stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia (photo by SM Awramik)**

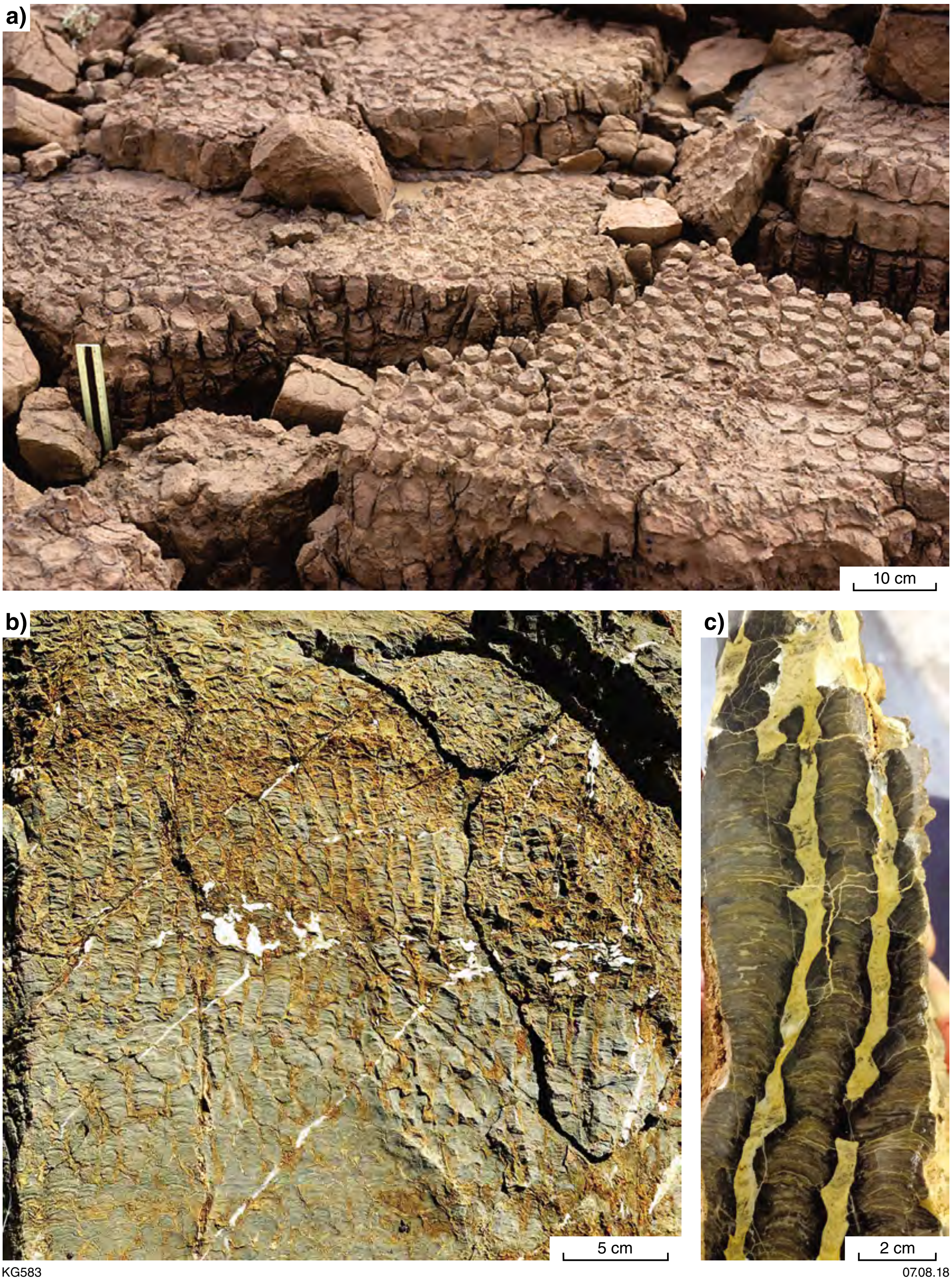

Figure 63. Examples of columnar microbialites – cylindrical columns: a) *Inzeria djejimi*; Oued Tarioufet Formation (Unit I.6), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Khang safia, Mauritania (photo by SM Awramik); b) *Kulparia alicia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; fault block near 'Hidden Valley', Alice Springs, Northern Territory, Australia (photo by PW Haines); c) *Boxonia pertaknurra*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, Alice Springs, Northern Territory, Australia; polished specimen, GSWA F52992–109258 (photo by K Grey)

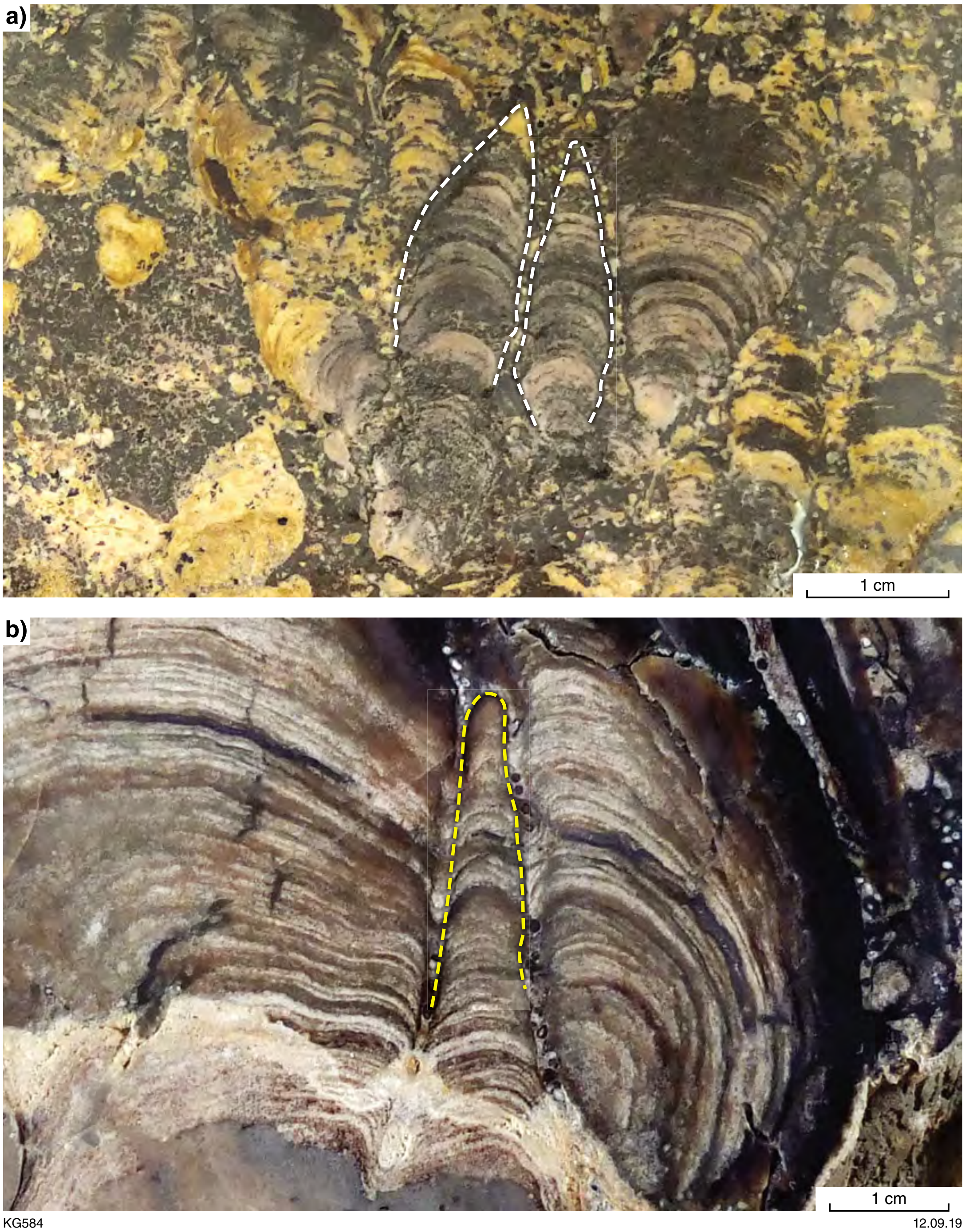

Figure 64. **Examples of columnar microbialites – terete (outlined): a) *Anabaria juvensis*; cap carbonate above Pioneer Sandstone; Amadeus Basin; Ediacaran, Neoproterozoic; near Ross River Highway, ALICE SPRINGS, Northern Territory, Australia; cut face of holotype, UCSB collection 4 of 3/7/65; note the adjacent turbinate columns on either side (photo by K Grey); b) terete column (outline); Laney Member, Green River Formation; Washakie Basin; Eocene; Delaney Rim, Sweetwater County, Wyoming, US; K Grey, private collection. This is not a tangential section but a column that narrows to accommodate widening adjacent columns (photo by K Grey)**

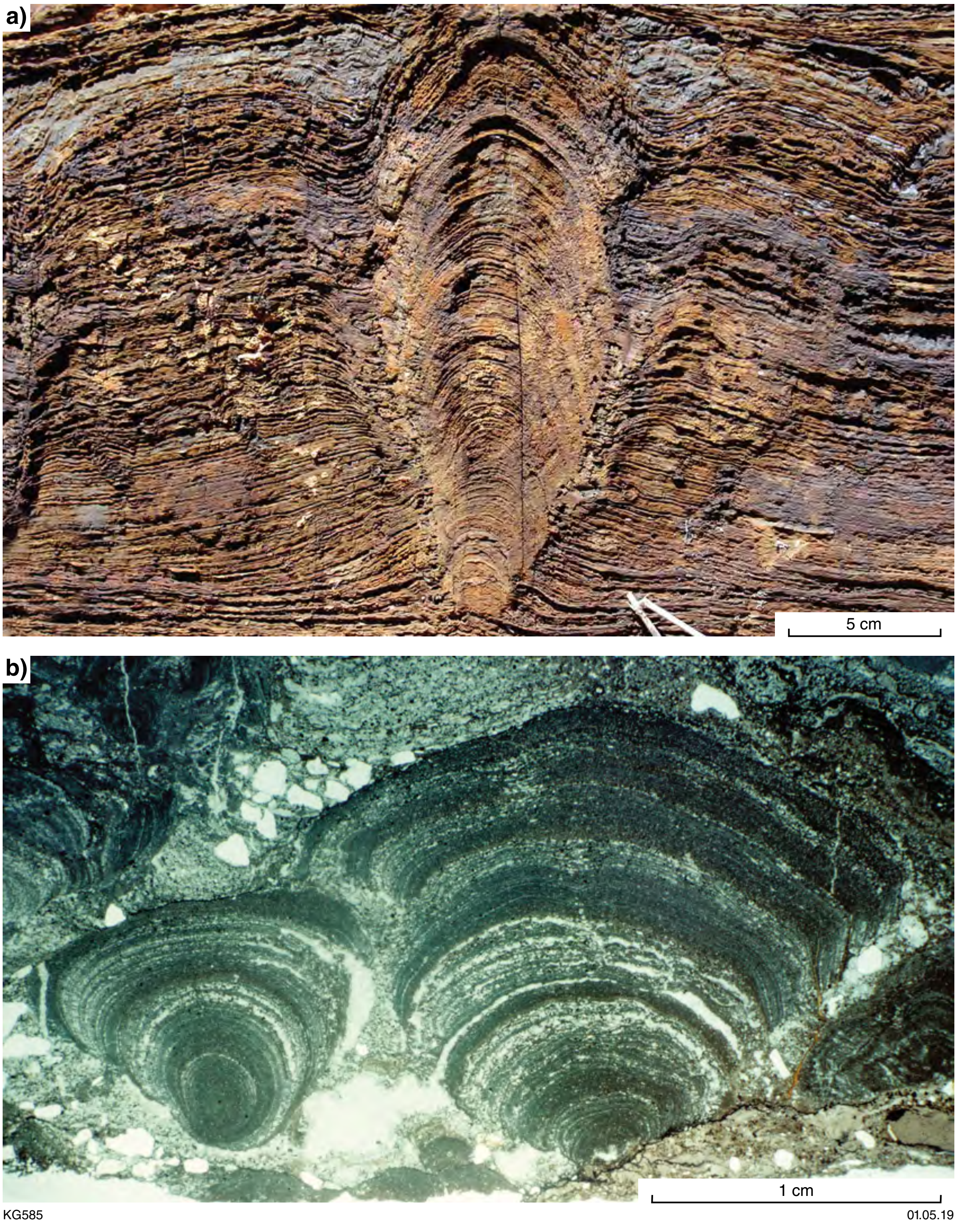

Figure 65. Examples of columnar microbialites – turbinate: a) turbinate stromatolite; Meentheena Member; Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Redmont, Pilbara, Roy Hill, Western Australia (photo by SM Awramik); b) turbinate stromatolite columns; Meentheena Member; Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Redmont, Pilbara, Roy Hill, Western Australia; thick section, UCSB collection (photo by SM Awramik)

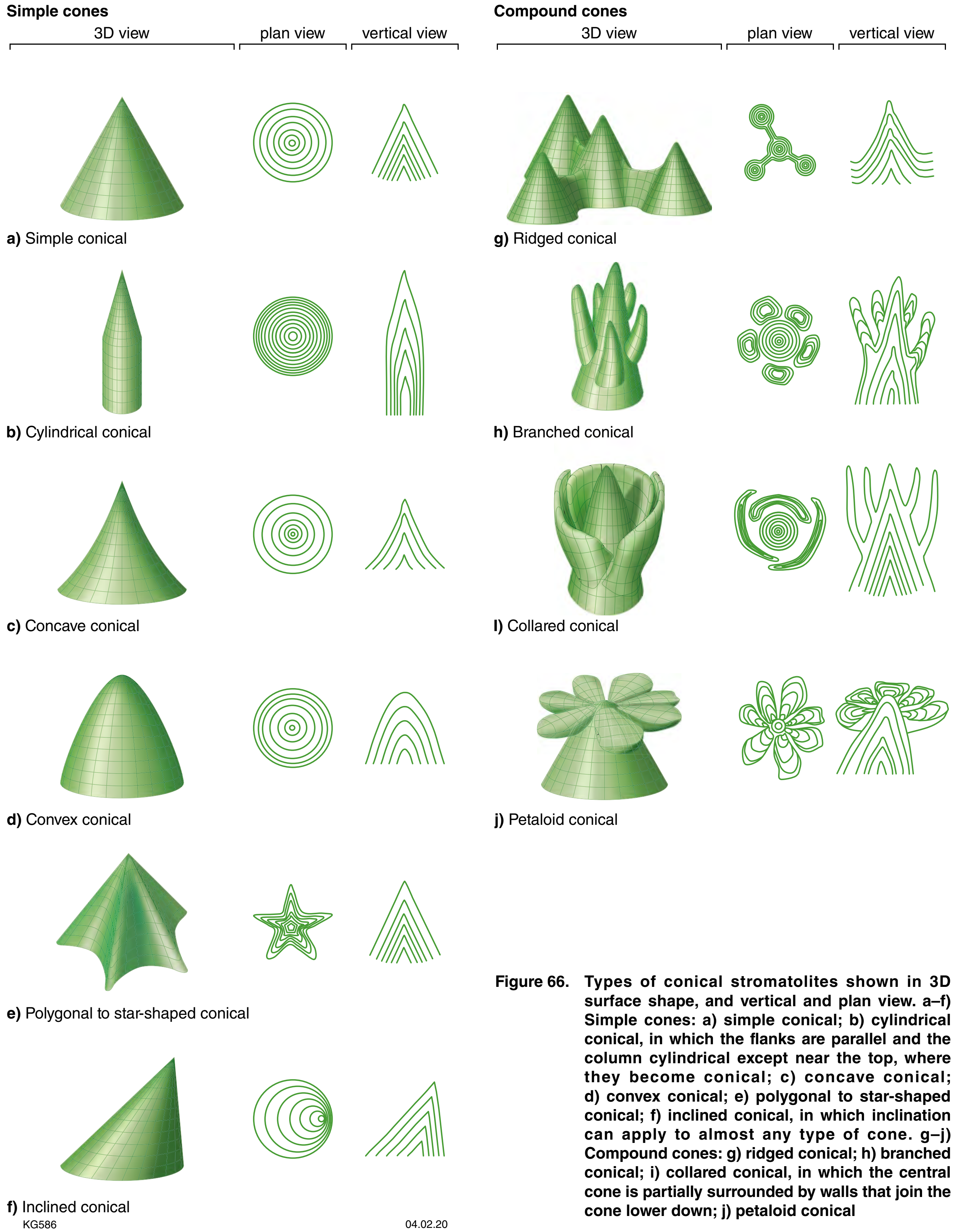

Figure 66. **Types of conical stromatolites shown in 3D surface shape, and vertical and plan view. a–f) Simple cones: a) simple conical; b) cylindrical conical, in which the flanks are parallel and the column cylindrical except near the top, where they become conical; c) concave conical; d) convex conical; e) polygonal to star-shaped conical; f) inclined conical, in which inclination can apply to almost any type of cone. g–j) Compound cones: g) ridged conical; h) branched conical; i) collared conical, in which the central cone is partially surrounded by walls that join the cone lower down; j) petaloid conical**

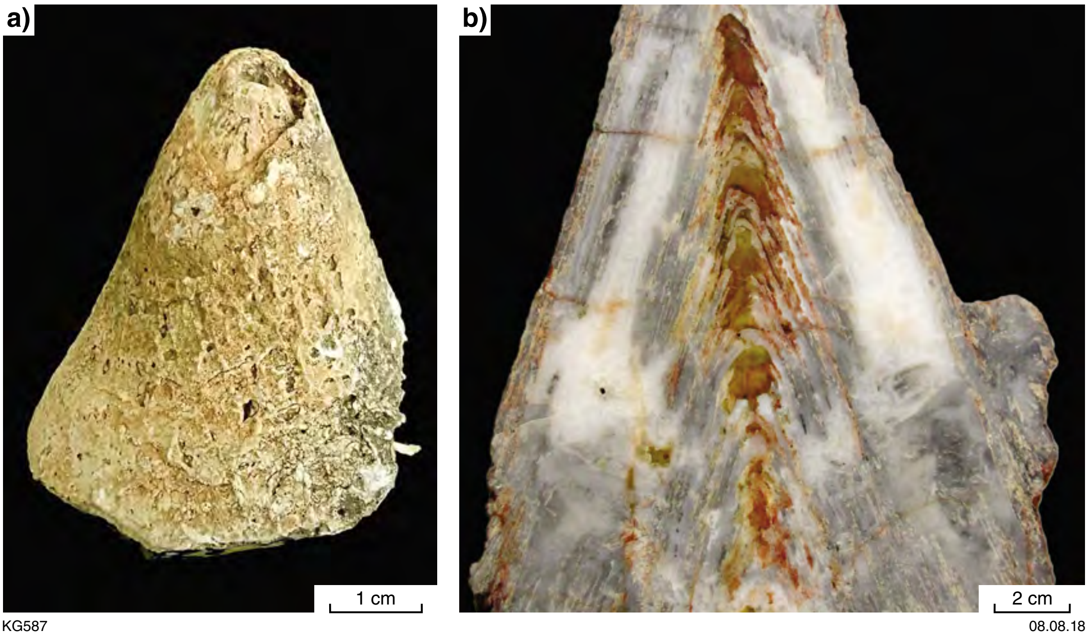

Figure 67. Examples of conical stromatolites – simple conical: a) *Conophyton* new Form (Throssell type); Kanpa Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; near Lake Throssell, THROSSELL, Western Australia; GSWA F52411H–138968H (photo by K Grey); b) *Ephyaltes edingunnensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Cookies Bore, PEAK HILL, Western Australia; vertical section of polished slab, GSWA F48427–90591 (photo by K Grey)

Branched microbialites could also include branched-conical microbialites and compound-conical microbialites, as well as branched-cylindrical microbialites with conical laminae (see 'Types of conical microbialites' above). However, conical microbialites are here described as separate categories because of their distinctive conical component. They include those compound microbialites in which one component is conical and in which there are other types of morphology, such as a conical core and lateral branching, (Figs 51f, 66g–j, 74–77).

Terminology for plan views of branched microbialites is the same as for buildups (see 'Describing microbialite macrostructure – Plan view').

Types of oncoidal microbialites

Oncoidal structures (Figs 51h, 57c–e) (oncoids) are generally spherical to ovoid microbialites that are completely detached from the substrate. Some are discoidal. They are usually laminated.

Vertical profile

The shape of a microbialite in vertical (longitudinal) profile is one of its most distinctive features (Figs 5, 7–11, 17b, 18a, 19, 20a, 23, 25a,c, 26, 27a,c, 28d, 31a,c,d, 32, 33, 34e, 35, 36a,c, 37, 40b,c, 48, 49b, 50, 52, 53, 54b,d, 55–56, 57a,c,e, 58–61, 62c,f, 63b,c, 64–66, 67b, 68a,c, 70a,b, 74, 75a,c, 76c,d). Hofmann (1969a) examined the various growth vectors that control column and branch silhouettes, and used morphometric analysis (Hofmann, 1976b, 1977, 1978) to define features. Describe the overall shape of the microbialite using the previous terminology, but, if required, the shape of individual columns or branches can be further elaborated using the microbialite-shape terminology given below.

Column size

The size or range of sizes of columns and branches are characteristic, can show enormous variation, and need to be described in detail. The length of the columns or branches is an important parameter, and the range of variation in both the height and diameter of individual components should be recorded.

Height-to-width ratio

Record the height-to-width ratio (Figs 78–81) of a column or branch. This was previously referred to by Hofmann (1969a, p. 17) as the accretion vector and defined as 'the upward maintenance or duration of the stacking process.' The term elongation has sometimes been used in a vertical sense, but should only be applied to extension in plan view as a result of current activity (Figs 14, 40). The term height-to-width ratio is preferred when referring to the vertical component. The following descriptors, modified after Hofmann (1969a, p. 17, fig. 10), can be used to specify the relationship of height, H (total relief of the structure), to diameter or width, W:

1. *Crustose*: (Figs 78a, 79a,b) H << W
2. *Stubby:* (Figs 78b, 79c, 80) H ≈ W
3. *Slender*: (Figs 78c, 81) H >> W. Also referred to as digitate (Howe, 1966, p. 65) and microdigitate.

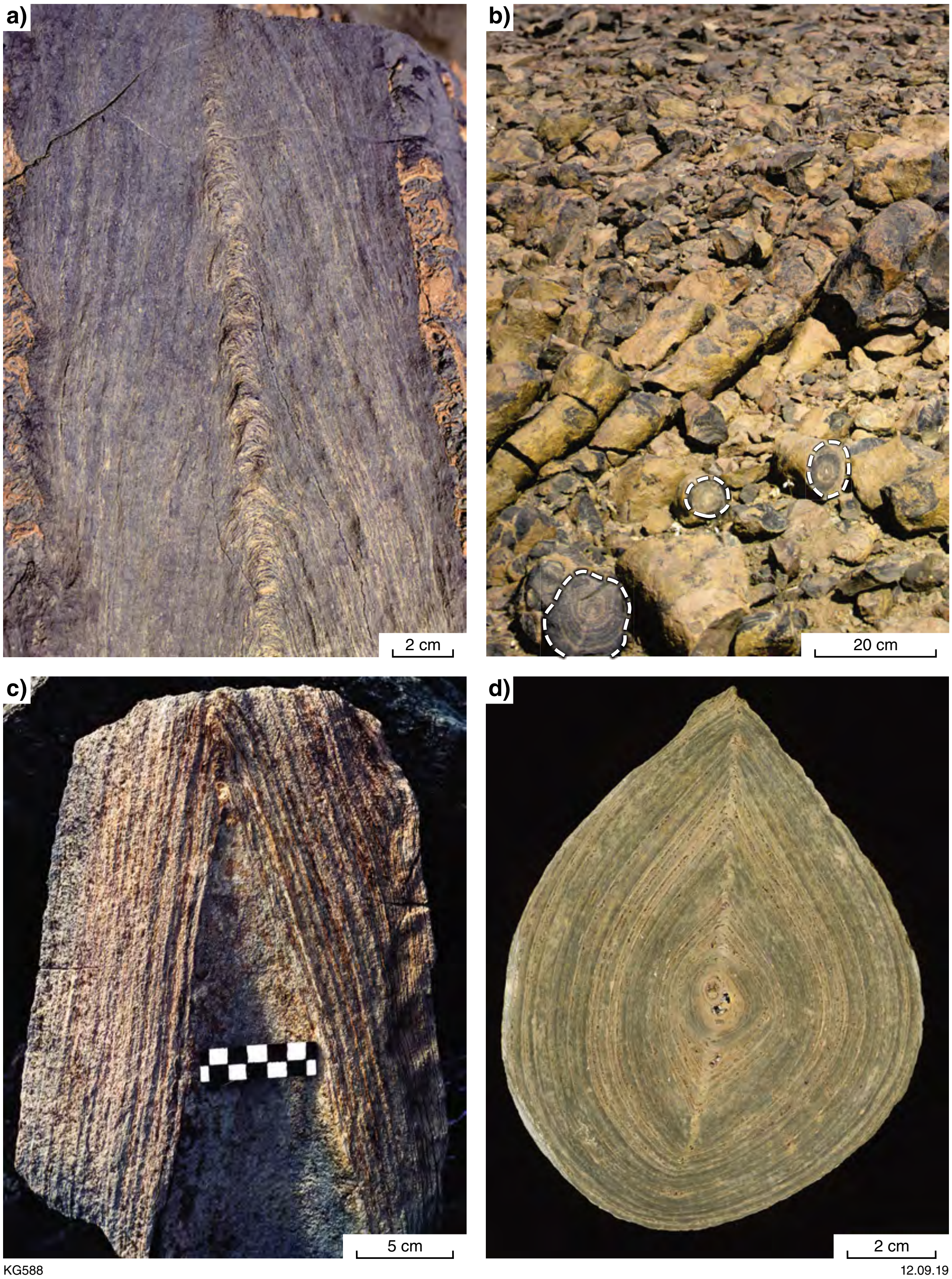

Figure 68. **Examples of conical stromatolites – cylindrical conical: a) near-cylindrical cone; *Conophyton ressoti*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania (photo by SM Awramik); b) fallen and broken *Conophyton*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Lekhleigate Section, Atar region, Mauritania. The cones are cylindrical with a rounded plan view (outlined), and were more than 2 m tall before being toppled by a catastrophic event (Bertrand-Sarfati and Moussine-Pouchkine, 1999; Kah et al., 2009) (photo by SM Awramik). c, d) *Conophyton* new Form; Dungaminnie Formation, Nathan Group; McArthur Basin; Calymmian, Mesoproterozoic; Heartbreak Hotel airstrip, Bauhinia Downs, Northern Territory, Australia: c) cylindrical conical; near-cylindrical cone (photo by K Grey); d) cylindrical-conical stromatolite showing teardrop shape in plan view (photo by SM Awramik)**

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Figure 69. Examples of conical stromatolites – cylindrical conical: a) cylindrical-conical thrombolites, uncovered at a rare low-lake level event; Perth Basin; Holocene; Mount John boardwalk, Lake Clifton, PINJARRA, Western Australia. The cones form around spring seeps and begin with a domical vertical profile. Only forms that are almost permanently submerged develop conical tops. Unlike *Conophyton* and associated taxa, these cones lack an axial zone. Blocky material is microbial mat ripped up from the lake bed, probably by a storm (photo by AJ Mory); b) unnamed cylindrical-conical stromatolites; Laney Member, Green River Formation; Sand Wash Basin; Eocene; near Vermillion Creek, Moffat County, Colorado, US. These microbialites begin with a domical vertical profile. Unlike *Conophyton* and associated taxa, the cones lack an axial zone (photo by DF Cupertino)

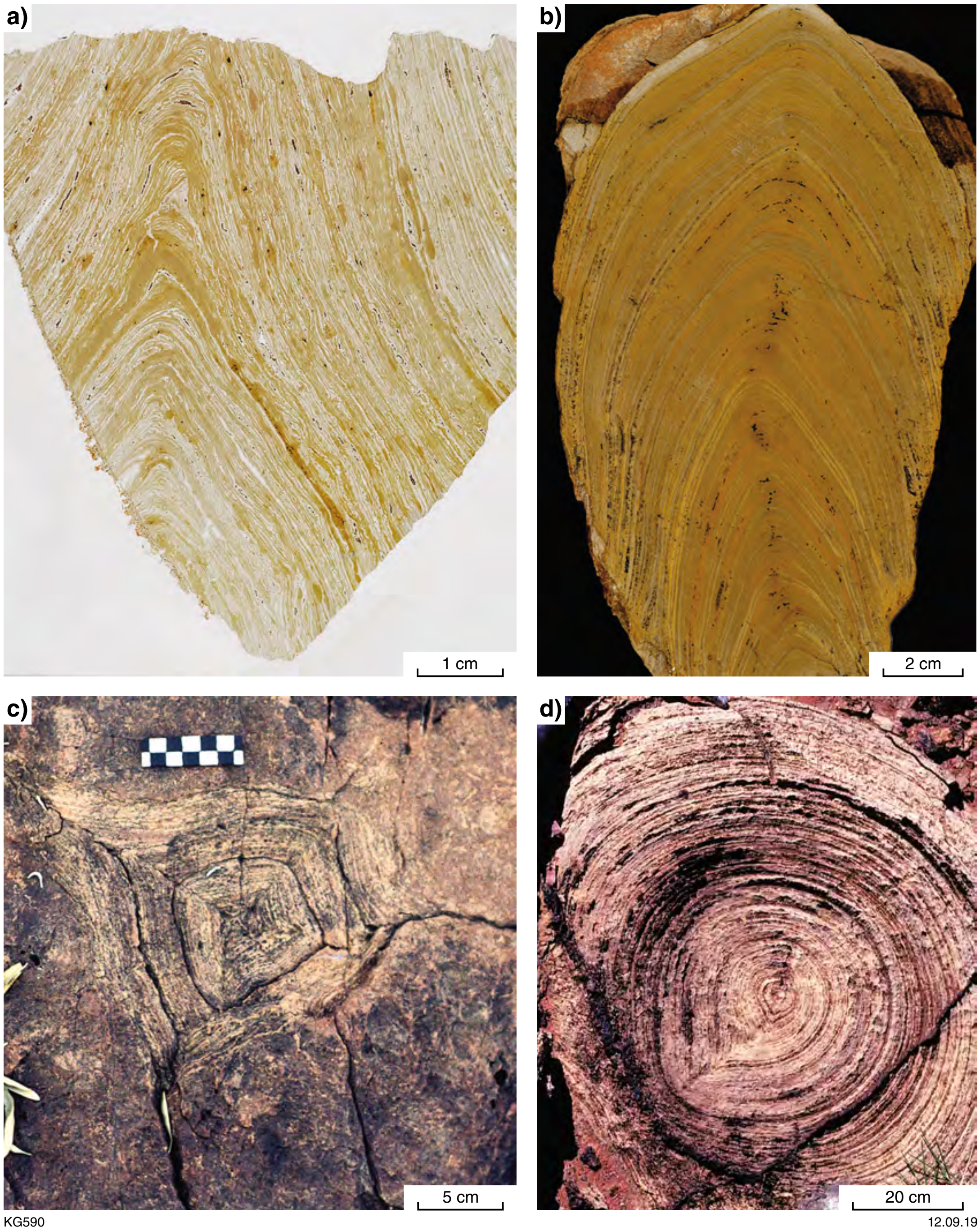

Figure 70. Examples of conical stromatolites – concave, convex and polygonal to star-shaped (stellate) conical: a) concave conical; *Conophyton* new Form (Beyondie type); Backdoor Formation, Collier Group; Collier Basin; Stenian, Mesoproterozoic; near Beyondie Bluff, COLLIER, Western Australia; thick section, GSWA F52632–84747 (photo by K Grey); b) convex conical; *Conophyton* new Form (Throssell type); Kanpa Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; Constance Headland, MADLEY, Western Australia; polished slab, GSWA F52612C–139573C (photo by K Grey); c) polygonal- and star-shaped (stellate) conical stromatolite; Amelia Dolostone, McArthur Group; McArthur Basin; Statherian, Paleoproterozoic; Kilgour River, WALLHALLOW, Northern Territory, Australia. In plan view, the shape ranges from star shaped (stellate) to polygonal (photo by K Grey); d) rounded- to polygonal-conical stromatolite; *Conophyton* new Form (Balfour type); Stag Arrow Formation, Manganese Group; Collier Basin; Stenian, Mesoproterozoic; Enachedong Creek, BALFOUR DOWNS, Western Australia. In plan view, the core is diamond shaped, then becomes concentric and teardrop shaped (photo by K Grey)

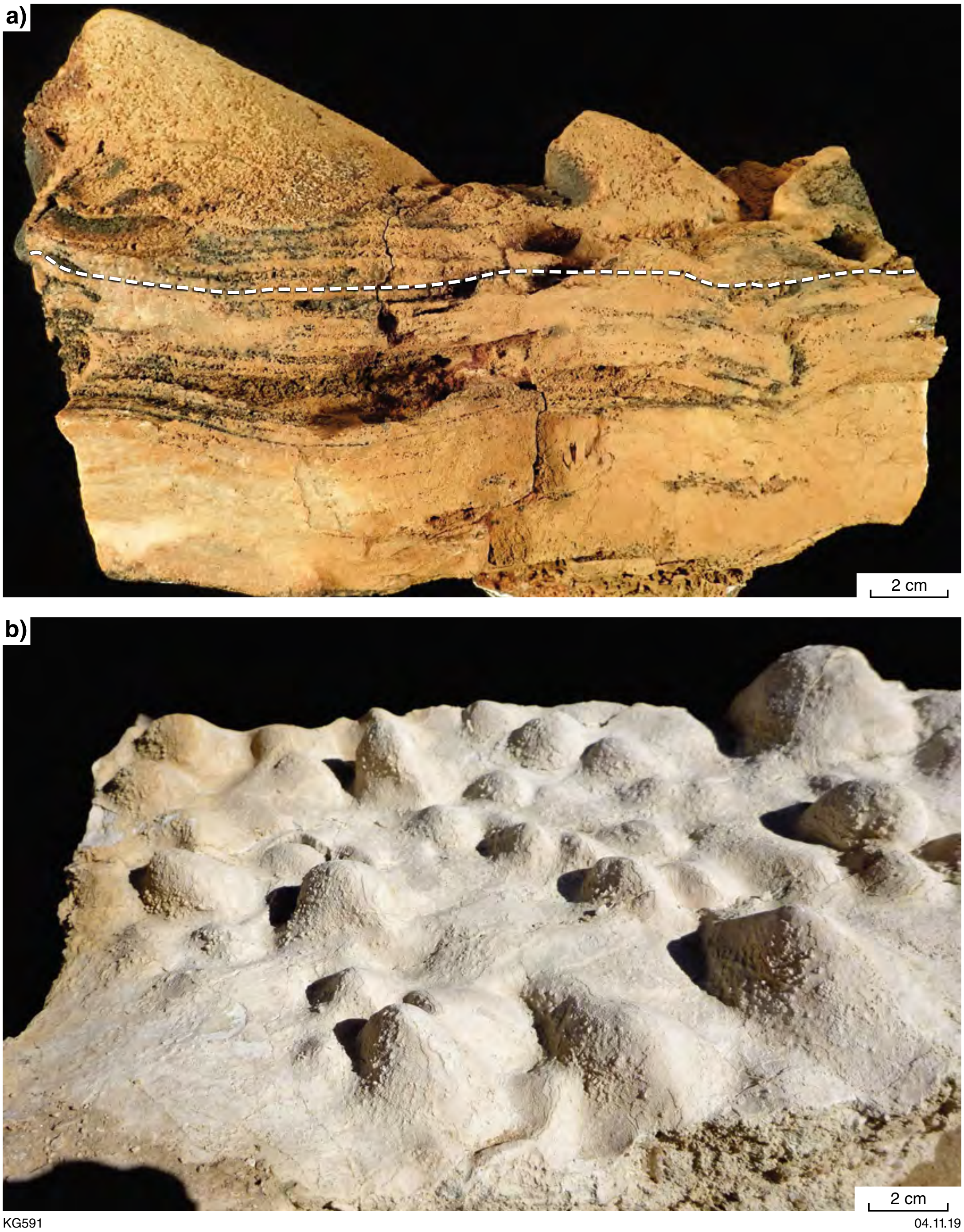

Figure 71. **Examples of conical stromatolites – inclined conical: a) small, conical ('egg-carton') stromatolite inclined to the left; Strelley Pool Formation, Pilbara Supergroup; East Pilbara Terrane; Paleoarchean; Hickman Geoheritage Reserve, east Pilbara, Marble Bar, Western Australia; GSWA F52601–169505, bedding shown by dashed line (photo by SK Martin); b) conical stromatolite inclined to the left; Lovell Wash Member, Horse Spring Formation; Miocene; Lovell Wash, Lake Mead area, Clark County, Nevada, US (photo by SM Awramik)**

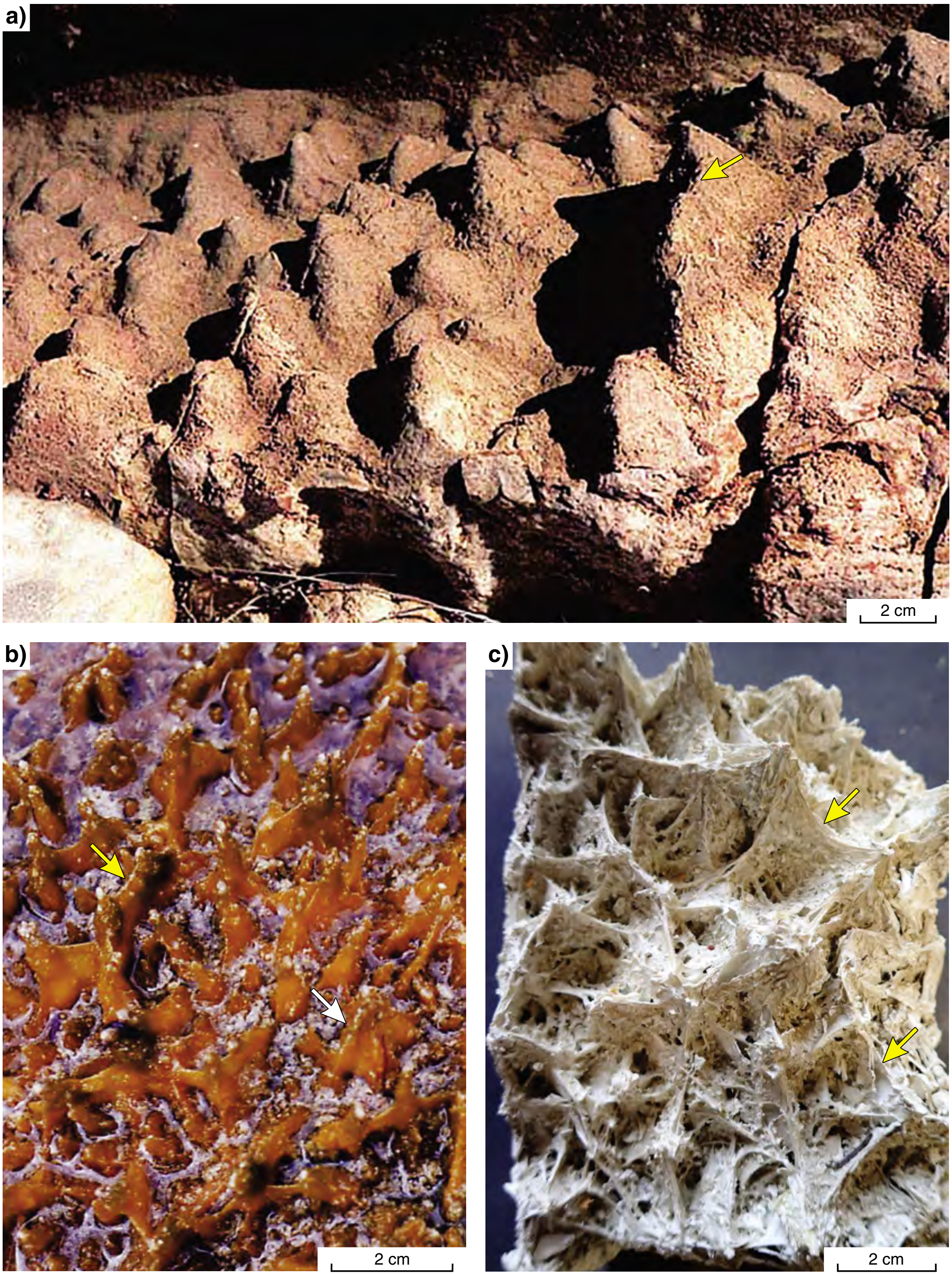

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Figure 72. Examples of compound-conical stromatolites – ridged conical; a) unnamed stromatolite ('egg-carton' type); Strelley Pool Formation; Pilbara Supergroup; East Pilbara Terrane; Paleoarchean; Trendall Geoheritage Reserve, east Pilbara, Marble Bar, Western Australia (photo by K Grey); b) pinnacle-mat stromatolites; Perth Basin; Holocene; 'Pamelup Pond', Lake Preston, Collie, Western Australia (photo by K Grey). ;c) *Conophyton weedii*; Holocene; 'Conophyton Pool', Yellowstone National Park, Teton County, Wyoming, US; USCB collection; cones connected by ridges (arrows) (photo by SM Awramik) Some cones have distinct ridges on their flanks (white arrow); in others, several cones may be connected by sheet-like ridges (yellow arrow)

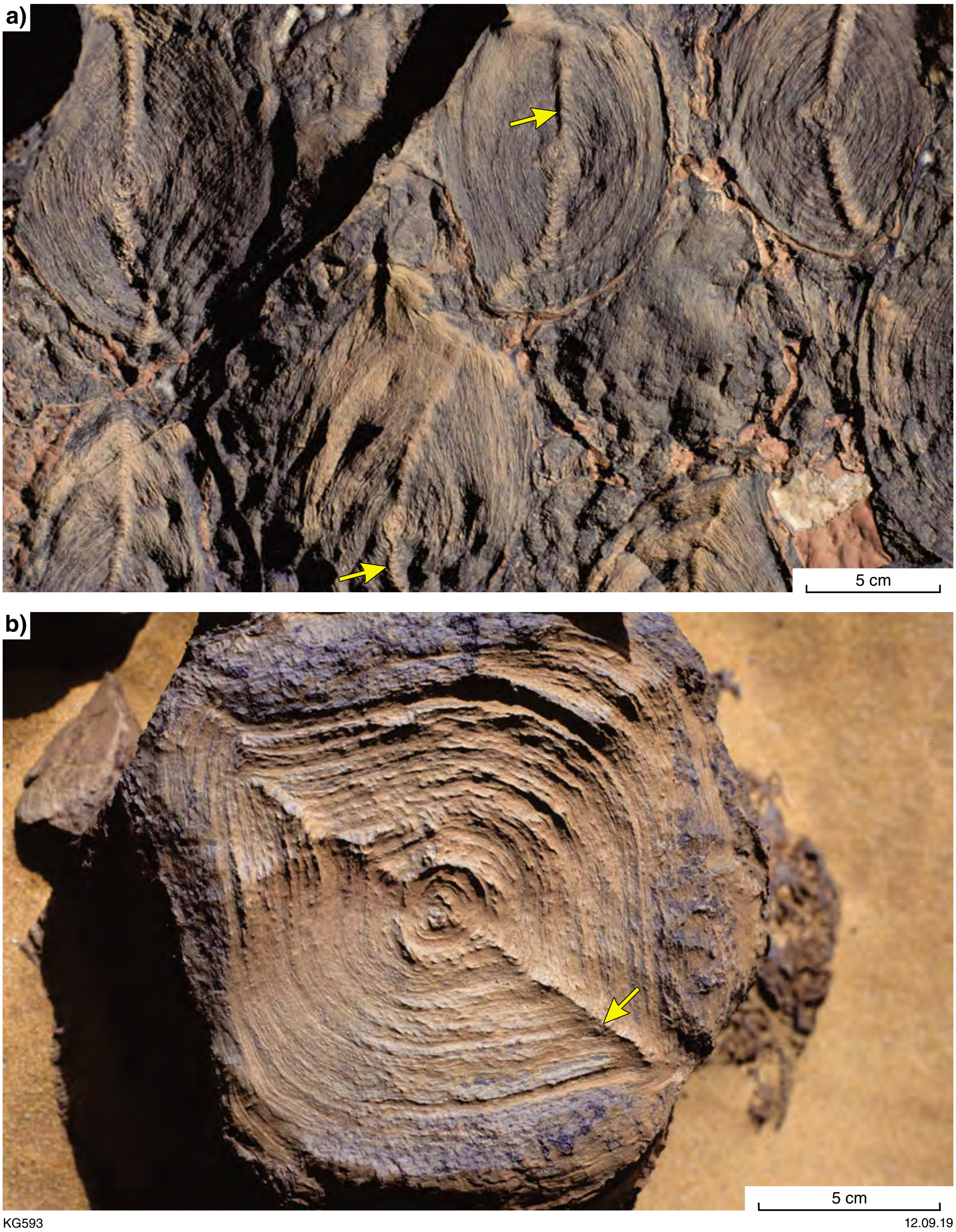

Figure 73. Examples of compound-conical stromatolites – ridged conical: a) parallel sets of elongate cones with lateral ridges (arrows); *Conophyton jacqueti*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania (photo by SM Awramik); b) plan view of ridged cone (ridge arrowed); *Conophyton jacqueti*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania (photo by SM Awramik)

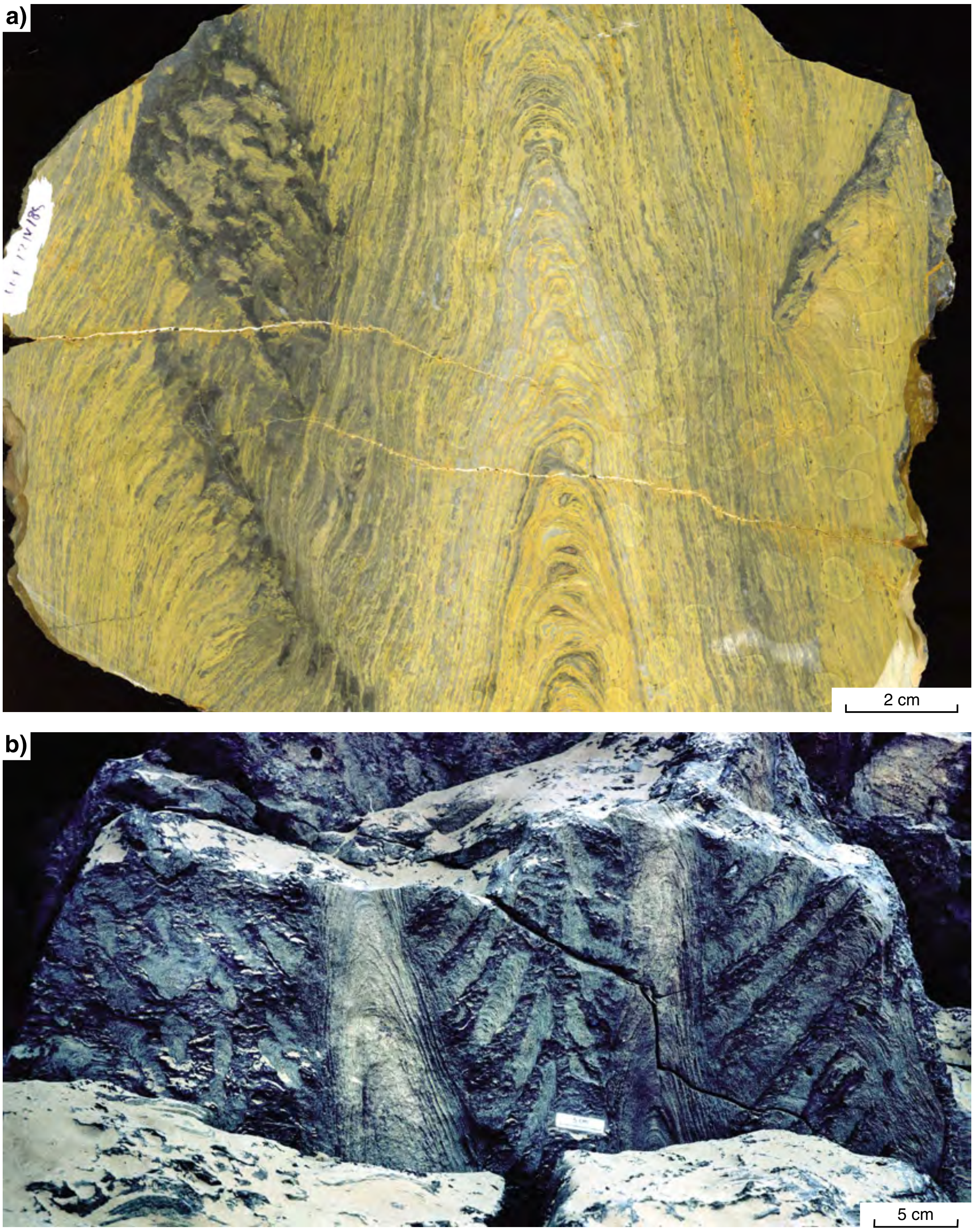

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Figure 74. Examples of compound-conical stromatolites – branched conical: a) *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania; polished slab, vertical view, UCSB collection (photo by SM Awramik); b) *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania; vertical view (photo by K Grey)

Figure 75. Examples of compound-conical stromatolites – branched conical: a) *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania; plan and vertical view; note discrete branches in plan view (photo by SM Awramik); b) *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania; plan view (photo by SM Awramik); c) *Jacutophyton* new Form; Bungle Bungle Dolomite; Osmond Basin; Stenian to Tonian, Mesoproterozoic to Neoproterozoic; Osmand Range, East Kimberley, Dixon Range, Western Australia; GSWA F52406–138931F; half cone showing branches (photo by SK Martin)

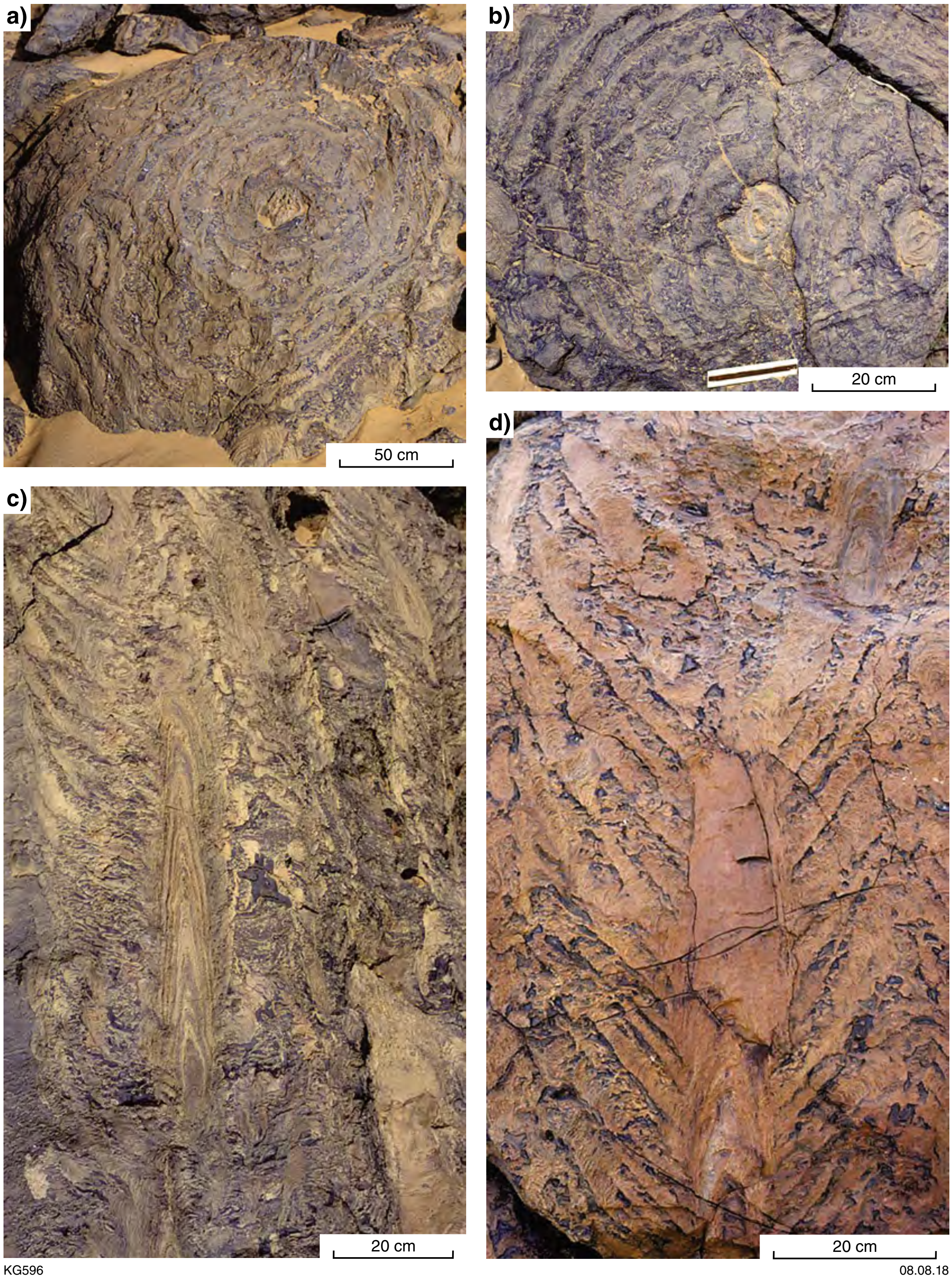

Figure 76. Examples of compound-conical stromatolites – collared conical: a, b) *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania; a, b) plan view; c, d) vertical view (photos by SM Awramik)

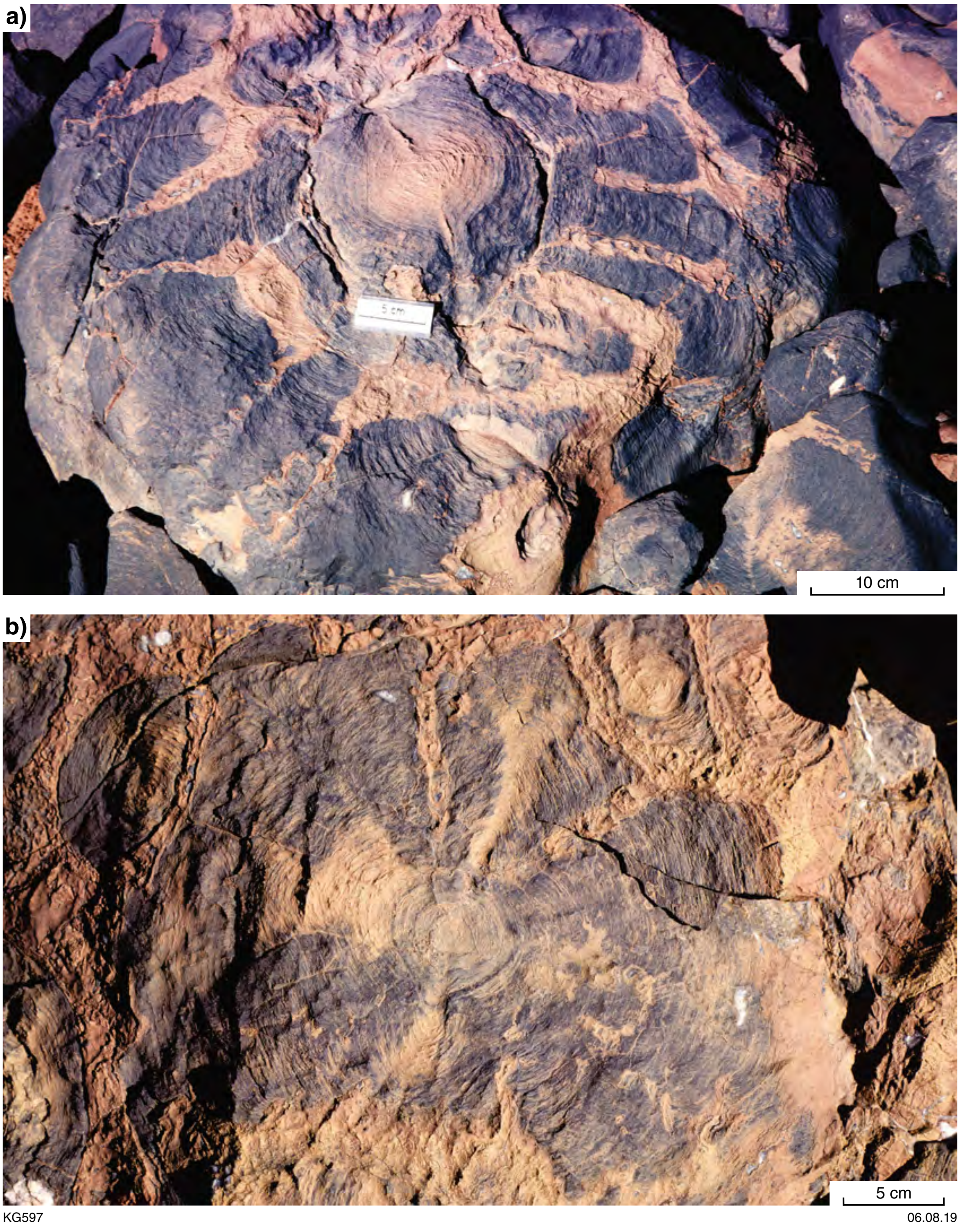

Figure 77. **Examples of compound-conical stromatolites – petaloid conical; *Jacutophyton sahariensis*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania; plan views: a) photo by K Grey; b) photo by SM Awramik**

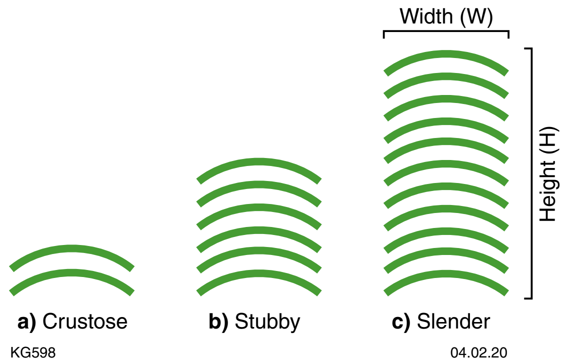

Figure 78. Microbialite height-to-width ratio: a) crustose (H << W); b) stubby (H ≈ W); c) slender (H >> W); H = height of the structure; W = width (diameter)

Variability of growth

Many columnar and branched microbialites do not form perfectly cylindrical columns and branches. The diameter of an individual column or branch can remain constant throughout, or may show variability resulting from lateral expansion or contraction of column diameters (Figs 82–85). The following terms (Hofmann, 1969a, p. 17, fig. 10) describe the degree of variability:

1. *Uniform*: (Figs 82a, 83) the diameter of the column is fairly constant in width
2. *Constringed*: (Figs 82b, 84) the diameter of the column is of variable width, but the changes occur gradually and regularly
3. *Ragged*: (Figs 82c, 85) the diameter of the column is variable, and variations occur frequently and irregularly.

Attitude

Attitude (Figs 86–91) refers to the orientation of a microbialite (especially a column) in relation to bedding and is a function of growth directions and whether the column is straight or curved. Attitude refers to the orientation as seen in vertical profile. Most of the terms are modified after Hofmann (1969a, p. 17, fig. 10).

Hofmann used the term recumbent as an antonym of decumbent. Recumbent referred to a column that bent laterally from an initial vertical growth. Decumbent referred to a column bending upwards from an initial horizontal growth. Dictionary definitions suggest that the two words are very similar in meaning. The bending of columns is similar to bending seen in plant growth, so the terms hyponastic (the bending upwards of a part) and epinastic (the bending downwards of a part from the vertical) here replace decumbent and recumbent respectively. In plants, epinastic growth eventually results in the part pointing downwards, in the opposite direction to the main growth vector. In microbialites, epinastic columns are unlikely to bend far enough for this to happen.

The following terms may be used to describe column attitude:

1. *Erect*: (Figs 86a, 87) columns are perpendicular or normal to the bedding, and are straight and vertical, also referred to as normal
2. *Inclined*: (Figs 86b, 88) columns are straight but at an acute angle (may be up to 45°) to the vertical
3. *Prostrate*: (new term) (Figs 86c, 89) columns are horizontal or lie at an angle of more than 45° to the vertical
4. *Pendant*: (Fig. 86d) columns have a downward accretionary growth habit (Rasmussen et al., 2009, figs 3, 4), particularly common in cavity fill stromatolites (Playford and Wallace, 2001, fig. 7d)
5. *Sinuous*: (Figs 86e, 90) columns have alternating flexuosity; orientation may be in any direction
6. *Hyponastic*: (new term replacing decumbent) (Figs 86f, 91a) a column that initially lies parallel (prostrate) to the substrate but then bends upward producing a tip inclined to the substrate. The initial stage may even dip below the horizontal
7. *Epinastic*: (new term replacing recumbent) (Figs 86g, 91b) a column that is initially erect or slightly inclined to the bedding, which develops a lateral to downwards curvature. Epinastic columns are vertical but eventually become deflected from the vertical
8. *Encapsulated*: (Figs 86h, 91c) spheroidal to ovoidal structure that resulted from growth outward from a central point. This describes the growth form of oncoids and related structures. This was called centrifugal by Hofmann (1969a), however, terms like centrifugal and centripetal are terms associated with forces, whereas the feature referred to is a concentric, geometric pattern.

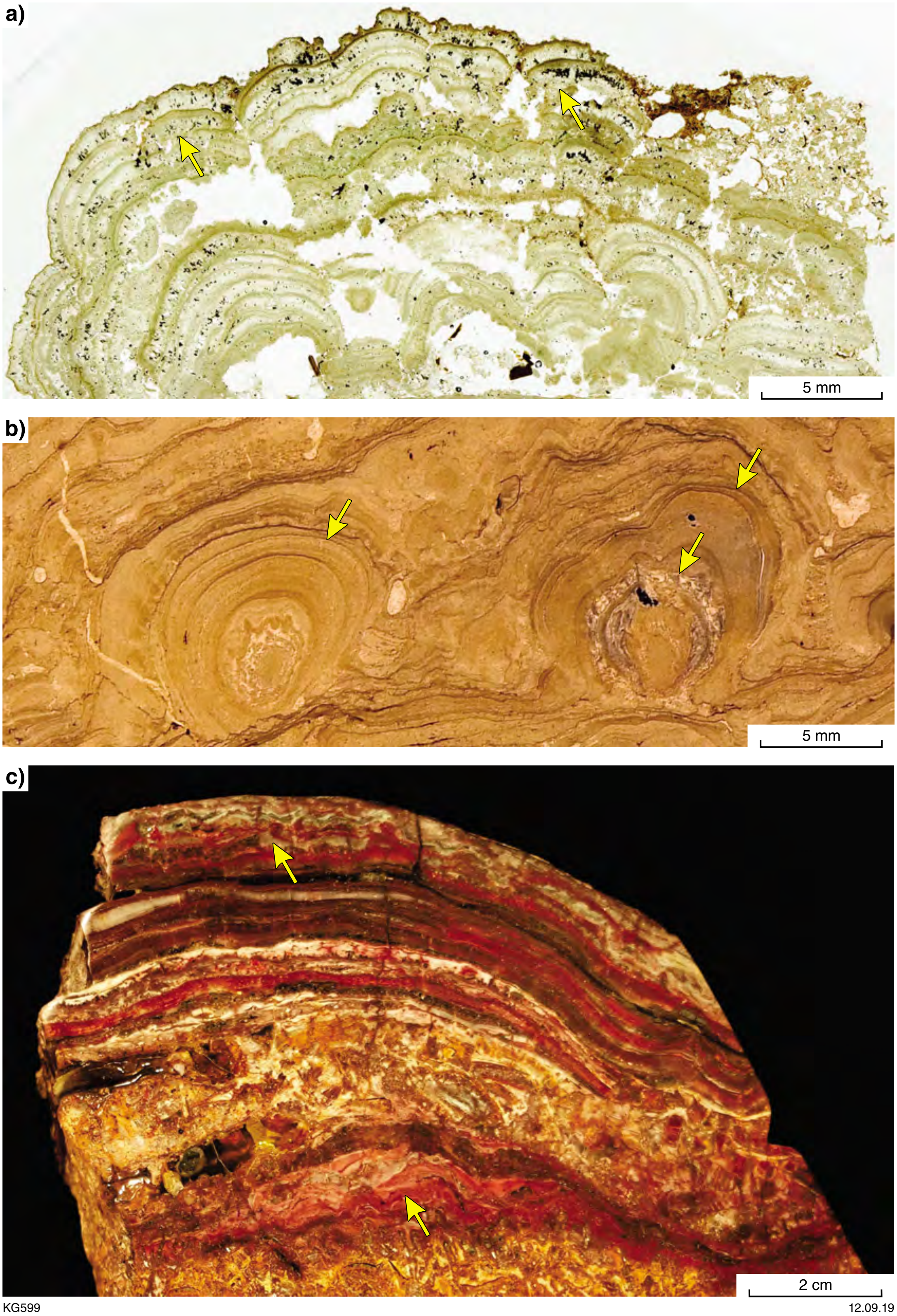

Figure 79. **Examples of height-to-width ratio – crustose and stubby: a) crustose (arrows) and stubby; Holocene; Carrizo Creek, Anza Borrego Desert State Park, San Diego County, California, US; thick section, UCSB collection (photo by SM Awramik); b) crustose (arrows) and stubby; *Alcheringa narrina*; Meentheena Member; Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Mount Herbert, Pilbara, PYRAMID, Western Australia; thick section GSWA F8135–11487 (photo by K. Grey; c) crustose (arrows); thin stromatolitic layers encrusting altered sedimentary layers; Dresser Formation, Warrawoona Group; Warrawoona Large Igneous Province, Pilbara Craton; Paleoarchean; Buick Geoheritage Reserve, Pilbara; MARBLE BAR, Western Australia; polished slab, Western Australian Museum collection, WAM8627a–100649 (photo by K Grey)**

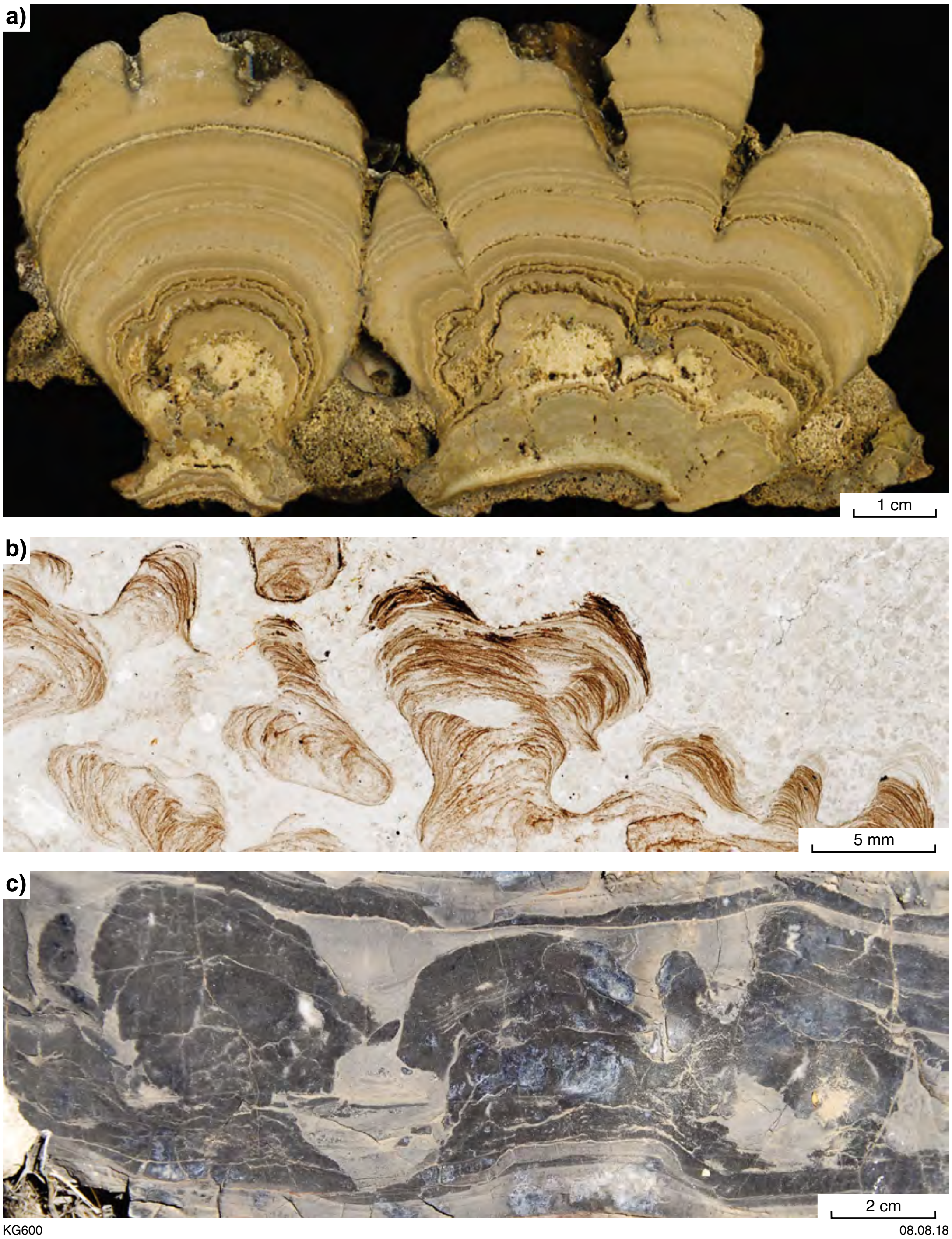

Figure 80. **Examples of height-to-width ratio – stubby: a) stromatolite; Holocene; east shore, Walker Lake, Mineral County, Nevada, US; polished slab, UCSB collection (photo by SM Awramik); b) *Murgurra nabberuensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, NABBERU, Western Australia,; thick section GSWA F12365–46333 (photo by K Grey); c) unnamed stromatolite; Bonanza King Formation; middle to upper Cambrian; near Potosi Mountain, Spring Mountains, Clark County, Nevada, US (photo by SM Awramik)**

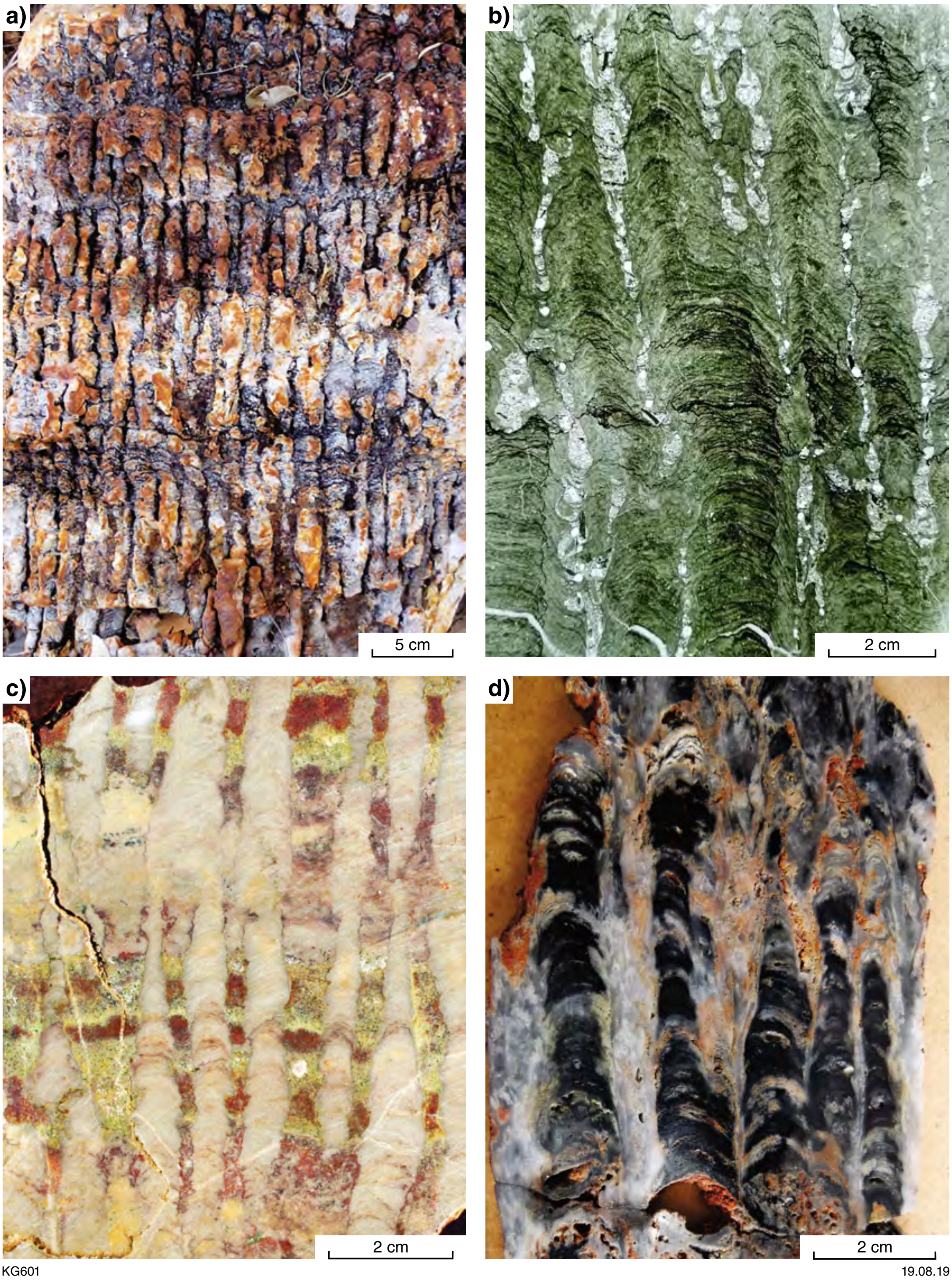

Figure 81. Examples of height-to-width ratio – slender: a) Stromatolite Group indet. new Form; Carson Volcanics, Kimberley Group; Kimberley Basin; Orosirian to Statherian, Paleoproterozoic; Drysdale River area, Drysdale, Western Australia (photo by C Phillips); b) *Kulparia kulparensis*; Etina Formation, Umberatana Group, Adelaide Rift Complex; Cryogenian, Neoproterozoic; near Kulpara, Yorke Peninsula, Adelaide, South Australia; thin section S380, University of Adelaide collection, holotype (photo by HJ Allen); c) *Kulparia alicia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Boord Ridges, Macdonald, Western Australia; cut slab, GSWA F54099–197162 (photo by HJ Allen); d) *Kussoidella karalundensis*; Juderina Formation, Windplain Group; Yerrida Basin; Rhyacian to Statherian, Paleoproterozoic; near Karalundi, Glengarry, Western Australia; thick section GSWA F46658–46289 (photo by K Grey)

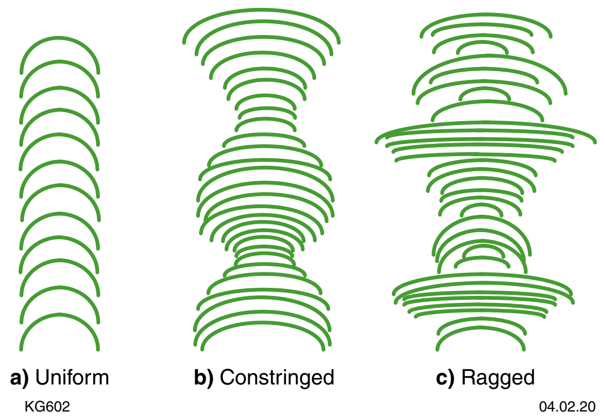

Figure 82. Variability of microbialite growth: a) uniform; b) constringed; c) ragged

Characteristics of branched microbialites

Branched usually refers to subdivision of a column, but can occur with other microbialite shapes. There are several aspects of branching to be considered.

Branching style

Branching style (Figs 92–95) refers to the position of filial branches in relation to the parent column, and the nature and number of branches resulting from division from a parent column (Hofmann, 1969a, p. 17–18, fig. 16). The terminology used here is adapted from Hofmann (1969a). Branching style can be described as:

1. *Furcate* (bifurcate, trifurcate): (Figs 92a,b, 93a,b) a type of equal subdivision 'in which columns branch into smaller ones without increase in total width of the structure' (Hofmann, 1969a, p. 10). Furcate is now used to refer to an equal subdivision without expansion of total width, and can be further refined by the use of terms such as bifurcate and trifurcate. In part, this was previously referred to as passive or false branching. Most furcate branching is alpha parallel
2. *Multifurcate*: (Figs 92b, 93c,d) Hofmann (1969a, p. 18, fig. 10) described multifurcate as branching in which structures 'at a certain level, pass into several considerably smaller, diverging branches'. Columns divide into more than three smaller (filial) columns without increase in the total width of the structure
3. *Dichotomous*: (Figs 92c, 94a,b) Walter (1972, p. 13) defined dichotomous branching as branching into two new columns (Walter, 1972, p. 13) in which the point of division occurs more or less at the centre of the parent column to give rise to two almost mirror-image filial columns
4. *Lateral*: (Figs 92d, 94c,d) branching in which a filial column or branch develops on the side of the parent column. Filial branches may result from an equal division in which filial columns are approximately the same diameter; or an unequal division, in which one filial column is considerably larger than the other. (Remember that equally divided branches may apparently have unequal widths if the plane of observation passes near the margin of one of the branches, but is near the middle of the other).

Branches sometimes recombine into a single column, a feature known as convergence. Convergence (Figs 92e,f, 95) is a more extensive feature than lateral linkage or bridging, which usually only involves a connection between columns over a few centimetres. Hofmann (1969a) recognized two types of convergence, coalesced and anastomosed. It may be difficult to distinguish the difference between the two in some cases:

1. *Coalesced*: (Figs 92e, 95a,b) Hofmann (1969a, fig. 10) described this as convergence in which two or more adjacent columns or branches increase in diameter until they merge to form a single, larger column or branch
2. *Anastomosed*: (Figs 92f, 95c,d) Hofmann (1969a, fig. 10) described this as convergence in which two or more adjacent columns or branches are overgrown by a third larger column or branch, so that the whole structure exhibits both branching and fusion.

Branching is sometimes referred to as digitate (Howe, 1966, p. 65), but the more specific terms used above are preferred. Microdigitate has been used as a general term for any small (one to several millimetres in diameter), columnar stromatolite (Grotzinger and Reed, 1983, p. 712; Grotzinger, 1986a,b; Hofmann and Jackson, 1987, p. 963). Some microdigitate stromatolites have been called microdigitate tufa (Grotzinger, 1986a, p. 1215; Sami and James, 1996, p. 216). The term is synonymous with ministromatolite.

Branching mode

Branching mode (Figs 96–98) refers to the changes, if any, in the parent columns just prior to branching. Previously, there has been a tendency to treat branching mode and angle of divergence as the same characteristic, but they are distinctive features. Branching mode refers to the degree of widening of columns prior to branching and can be described using the following terminology:

1. *Alpha branching*: (Figs 96a, 97) a division in which the width of the parent remains constant before branching
2. *Beta branching*: (Figs 96b, 98a,b) a division in which the parent column widens gradually before branching
3. *Gamma branching*: (Figs 96c, 98c,d) a division in which the parent column widens abruptly before branching.

The terms active and passive (here considered obsolete) were originally used to denote the method of branching, but proved impractical (Krylov, 1967) and for the most part they have been abandoned (Walter, 1972), as have the terms true and false (Hofmann, 1969a). In the diagrams and glossaries given by Preiss (1972) and Walter (1972), alpha, beta and gamma branching were linked to parallel branching (see angle of divergence), but variations in thickness can also occur in slightly divergent and markedly divergent branching microbialites.

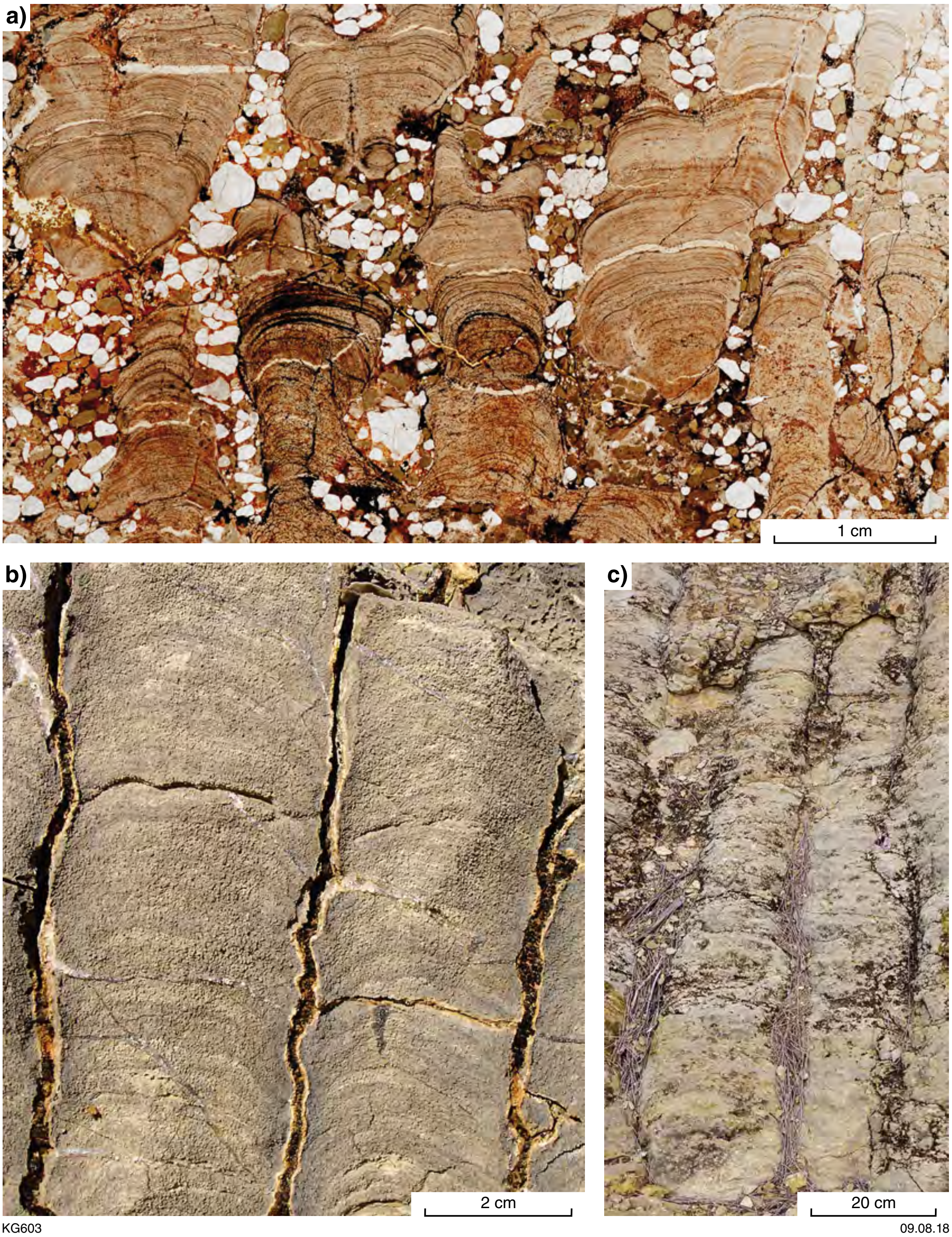

Figure 83. Examples of variability of growth – uniform column width: a) *Anabaria juvensis*; cap carbonate above Pioneer Sandstone; Amadeus Basin; Ediacaran, Neoproterozoic; near Ross River Highway, ALICE SPRINGS, Northern Territory, Australia; thick section GSWA F52665–109263 (photo by SM Awramik and K Grey); b) *Inzeria intia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, ALICE SPRINGS, Northern Territory, Australia (photo by NJ Planavsky); c) thrombolite; Wirrealpa Limestone, Moralana Supergroup; early Cambrian; Arrowie Basin; near Old Wirrealpa Mine, Flinders Ranges, PARACHILNA, South Australia (photo by PD Kruse)

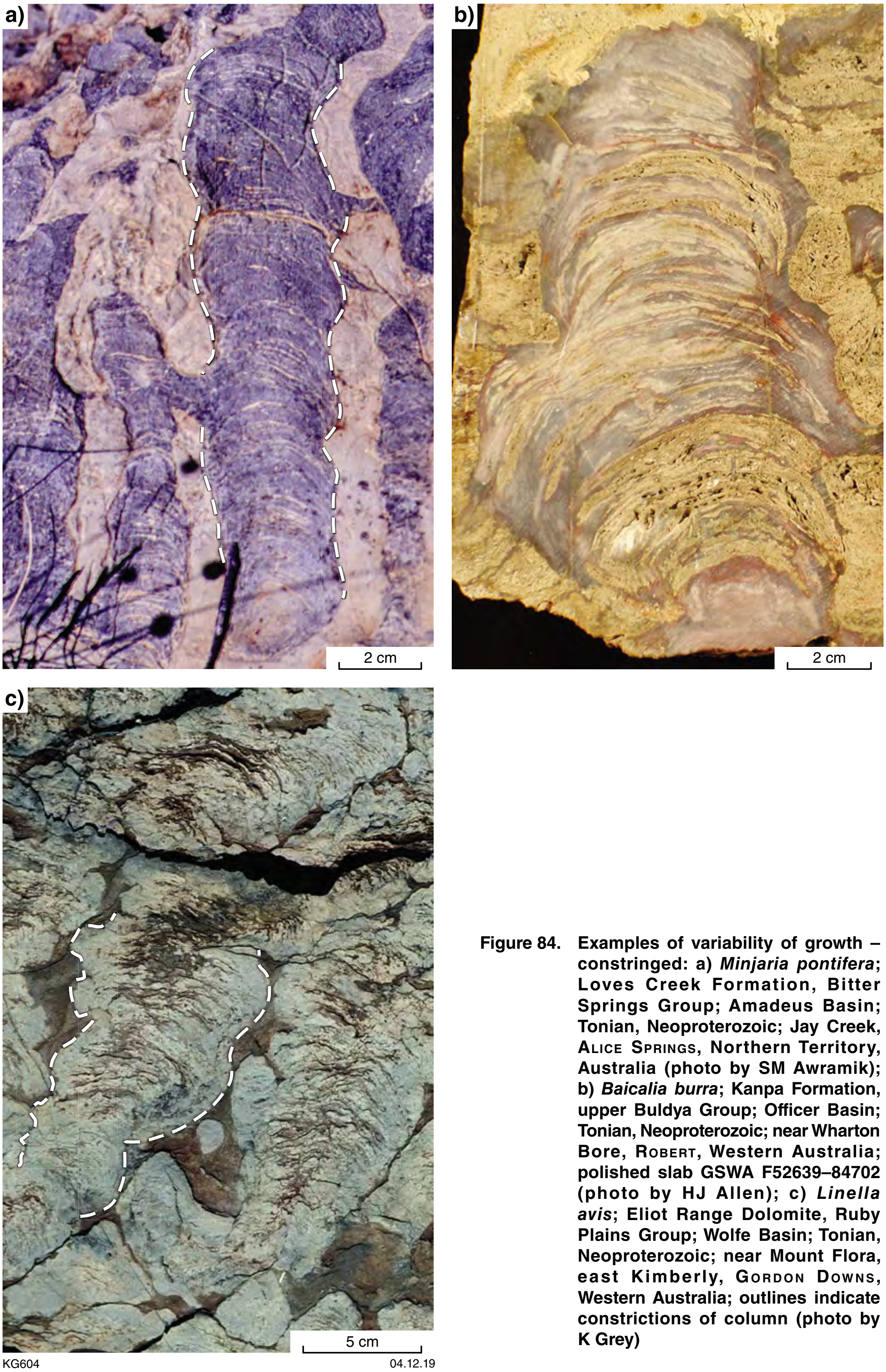

Figure 84. **Examples of variability of growth – constringed: a) *Minjaria pontifera*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Jay Creek, ALICE SPRINGS, Northern Territory, Australia (photo by SM Awramik); b) *Baicalia burra*; Kanpa Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; near Wharton Bore, ROBERT, Western Australia; polished slab GSWA F52639–84702 (photo by HJ Allen); c) *Linella avis*; Eliot Range Dolomite, Ruby Plains Group; Wolfe Basin; Tonian, Neoproterozoic; near Mount Flora, east Kimberly, GORDON DOWNS, Western Australia; outlines indicate constrictions of column (photo by K Grey)**

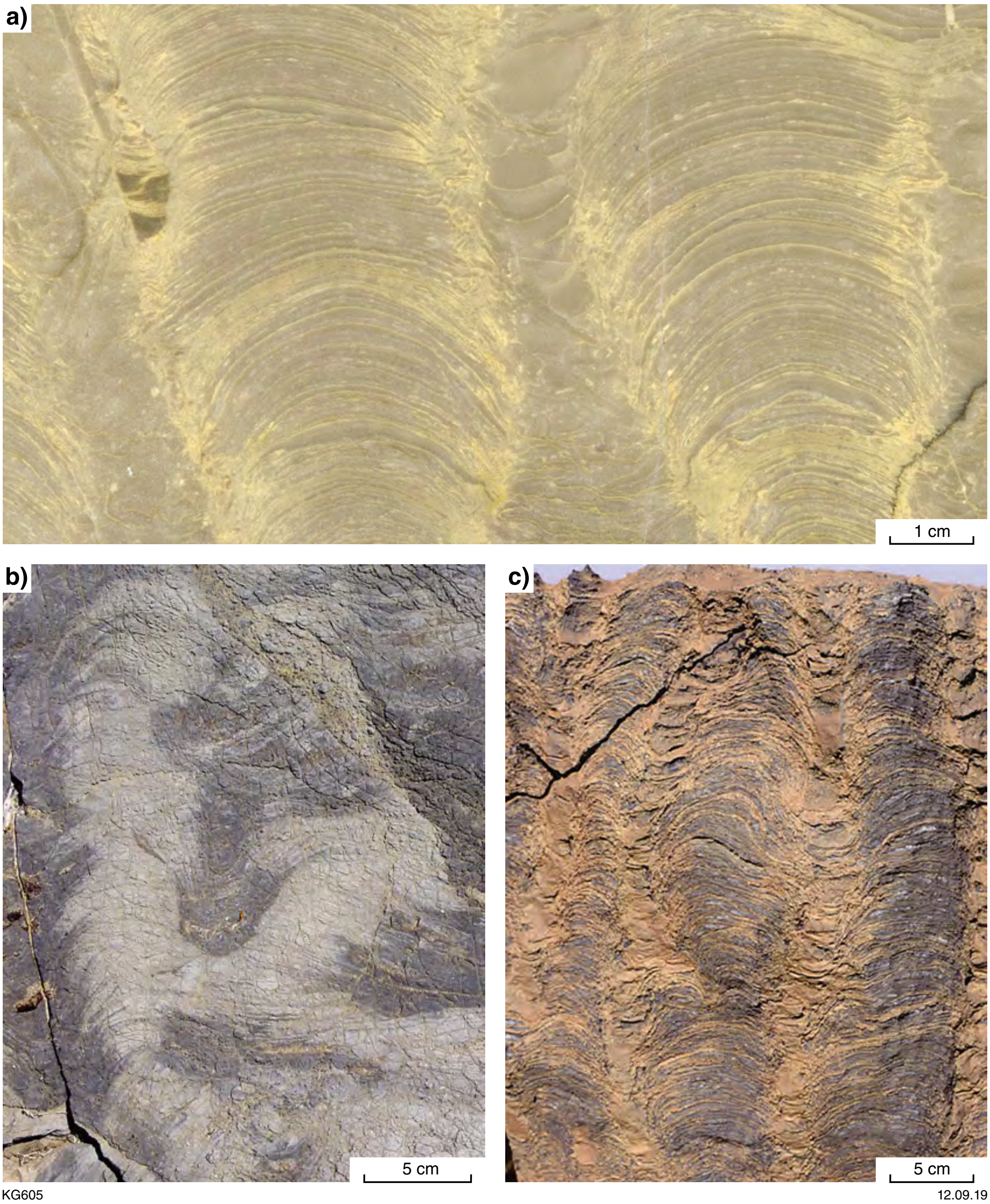

Figure 85. Examples of variability of growth – ragged; a) '*Baicalia*'; Tieling Formation, Jixian Group; North China Craton; Calymmian to Ectasian, Mesoproterozoic; Yanshan Range, Jixian County, Hebei Province, China; polished slab, UCSB collection (photo by SM Awramik); b) unnamed stromatolite; Beck Spring Dolomite, Pahrump Group; Tonian, Neoproterozoic; Alexander Hills, San Bernardino County, California, US (photo by SM Awramik); c) *Inzeria djejimi*; Tawaz Formation (Unit I.7), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; near Atar, Mauritania (photo by SM Awramik)

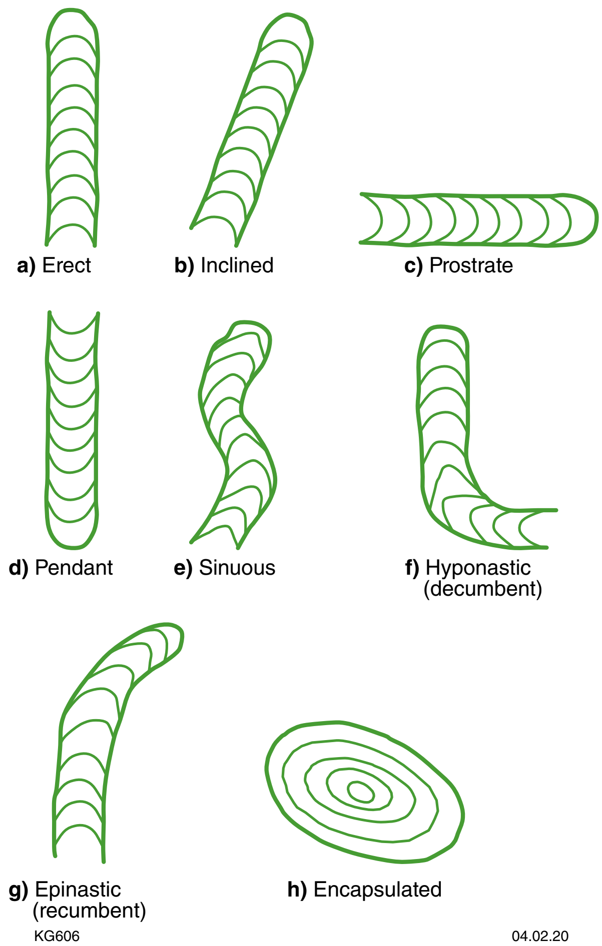

Figure 86. Microbialite attitude: a) erect; b) inclined; c) prostrate; d) pendant (Rasmussen et al., 2009); e) sinuous; f) hyponastic (decumbent); g) epinastic (recumbent); h) encapsulated

Frequency, location and spacing of branching

The frequency and location of branching and its spacing are significant characteristics and quantitative data should be provided on the actual spacing. Branching may be irregularly spaced, or may be more consistently or equally spaced. It can be concentrated on one side of the structure or occur evenly throughout. Branching may occur in all adjacent branches in one particular plane, or be erratic. The overall shape created by the branching pattern can be further described by the use of terms such as arborescent, dendriform (both meaning tree-like in form), fastigiate (with conical or tapering outline, like a lombardy poplar tree), or bushy (shrub like).

Angle of divergence

The angle of divergence (Figs 99–101) is the angle at which branches diverge from one another and is an important feature. Angle of divergence has often been linked to branching mode, but divergence is unrelated to whether a column widens or not before branching. The angle of divergence is measured in the plane of branching, and can either be treated quantitatively, or can be qualitatively with the following terms:

1. *Parallel*: (Figs 99a, 100a,b) in which the filial branches are parallel or subparallel
2. *Moderately divergent*: (Figs 99b, 100c) in which the filial branches diverge at acute angles (less than or equal to 45°)
3. *Markedly divergent*: (Figs 99c, 101a,b) in which branches diverge at broad angles (more than 45°)
4. *Horizontal* or *subhorizontal*: (Figs 99d, 101c) branches diverge perpendicularly to axis of growth.

Characteristics of conical microbialites

Conical microbialites can, to a large extent, be described using the same terminology as for domical and branched microbialites, but their laminae often have additional characteristics. In many conical microbialites, the vertical height is considerably greater than the radius of the base and the slope of the flank is very steep, and well above the angle of repose for sedimentary grains. Because of the special morphology of conical stromatolites, certain parameters are significant for distinguishing different types and should be described or measured (Semikhatov, 1962; Komar, 1966; Komar et al., 1965a,b).

Even where a cone is weathered, the minimum height of the cone can be calculated if the maximum diameter and the axial angle are known by using the cosine rule. Some conical stromatolites can reach heights of several metres and individual laminae can extend the full height of the flank (Donaldson, 1976).

Conical stromatolites are common in many stratigraphic units and range from the early Archean to the present day. A variety of shapes have been recognized, ranging from true cones to polygonal structures (Fig. 66a–f) and including more complex structures that may be ridge-like or incorporate a variety of appendages attached to the cone (Fig. 66g–j; Vlasov, 1977; Raaben et al., 2001). Some appear to be free-standing cones, linked only at the base, whereas others are laterally linked, in some instances throughout the height of the cone. All such features should be described.

Some conical stromatolites have an axial zone, a narrow region in the centre of the cone where laminae display a distinct change in slope and are commonly lensoidal with one or more laminae laterally offset as they are stacked. Axial zones are diagnostic of several taxa and show several variations that need to be described. These include the type of axial zone, the axial angle, the type and continuity of the laminae, and the ratio of light to dark laminae (see sections ‘Describing microbialite mesostructure’ and ‘Describing microbialite microstructure’).

Linkage

Like other microbialites, conical microbialites can be laterally linked, and the same terminology is used to describe the linkage and spacing as in regular columns (Figs 46–50). Alternatively, they can be connected by bridges (see ‘Describing microbialite mesostructure’).

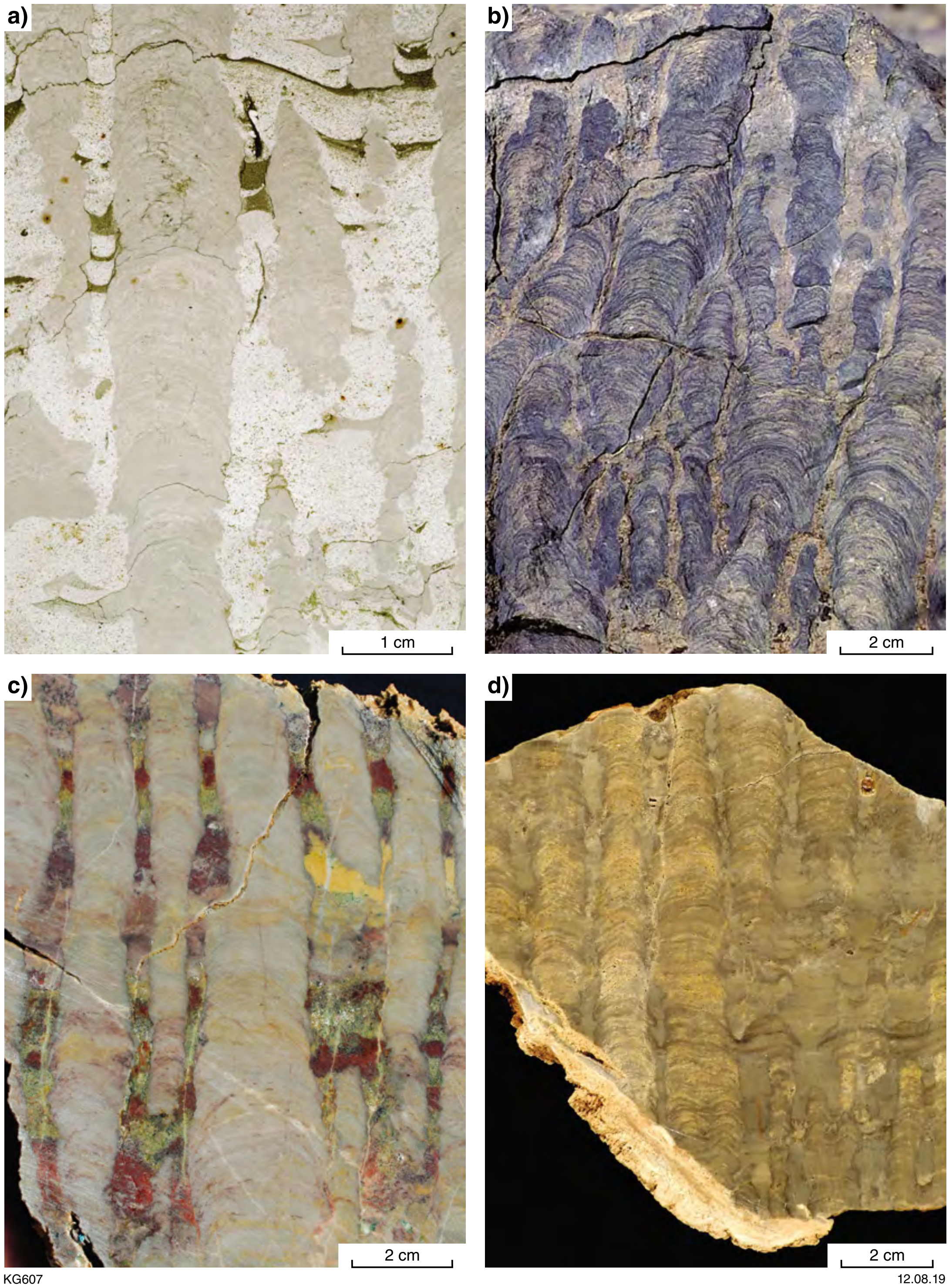

Figure 87. Examples of attitude – erect: a) *Kussoidella* cf. *limata*; Elgee Siltstone, Kimberley Group; Kimberley Basin; Statherian, Paleoproterozoic; near Margaret River, Kimberley, Mount Ramsay, Western Australia; thick section, GSWA F52396–138903 (photo by K Grey); b) *Tungussia nodosa*; Tawaz Formation (unit I.7), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; east of Atar, Mauritania (photo by SM Awramik). c, d) *Kulparia alicia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic: c) Boord Ridges, western Amadeus Basin; Macdonald, Western Australia; cut face GSWA F54099–197162 (photo by HJ Allen); d) near Ross River Highway, Alice Springs, Northern Territory, Australia; cut face, GSWA 207455 (photo by HJ Allen)

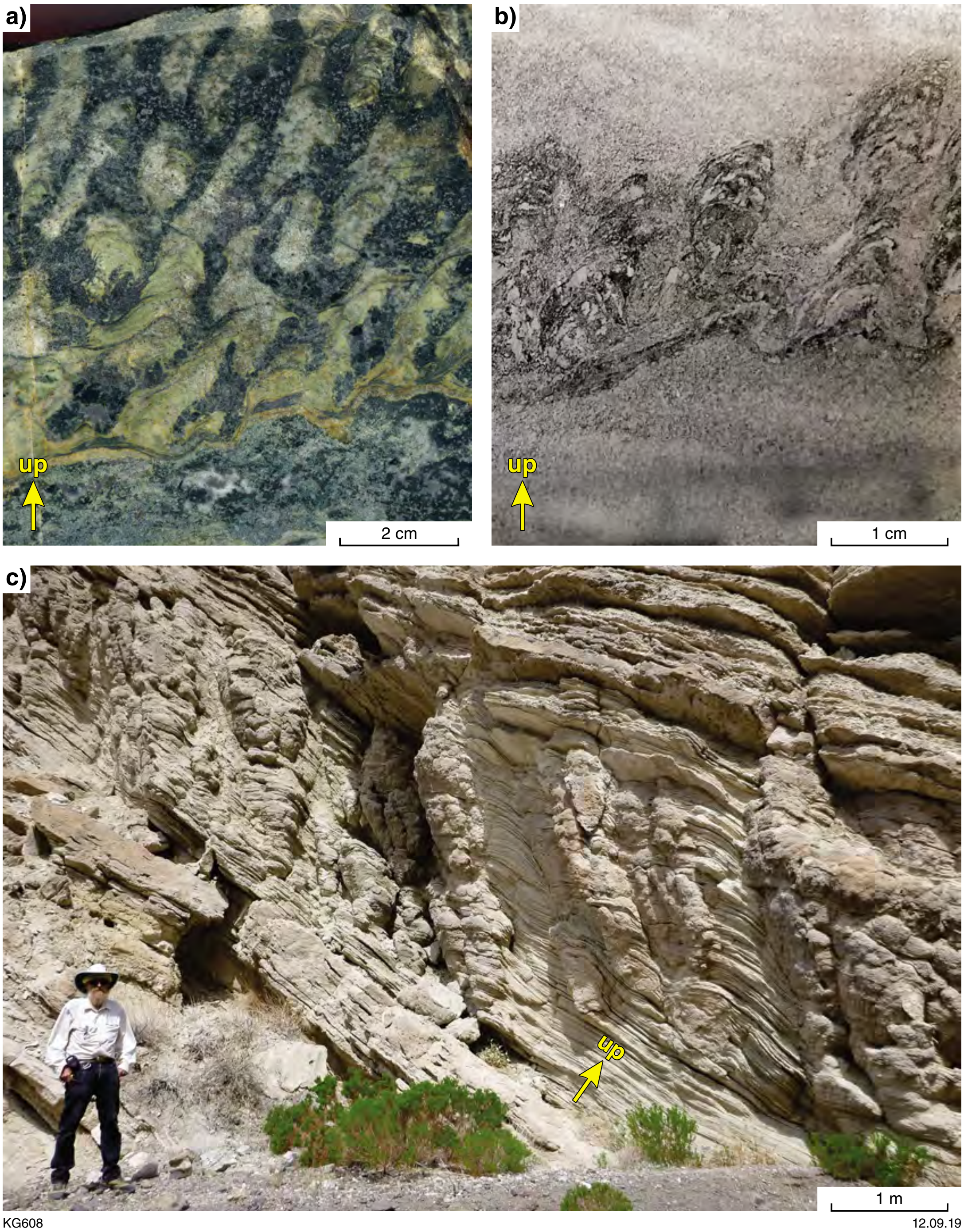

Figure 88. Examples of attitude – inclined (arrows indicate vertical): a) unnamed stromatolite; Biwabik Formation, Animikie Group; Animikie Basin; Orosirian, Paleoproterozoic; Hoyt Lake, Saint Louis County, Minnesota, US; polished slab, UCSB collection (photo by SM Awramik); b) small, unnamed, inclined columns on climbing-ripple substrate; Duck Creek Dolomite, Wyloo Group; Ashburton Basin; Orosirian, Paleoproterozoic; Miningee Well, Ashburton region, Wyloo, Western Australia (photo by K Grey); c) inclined, offset, stacked buildups composed of unnamed ministromatolites; Furnace Creek Formation; Pliocene; Black Mountains, Death Valley National Park, Inyo County, California, US. As the lake transgressed in an episodic manner, the nearshore site, where the buildups grew, migrated along with the transgression, forming a succession of offset buildups. Subsequent tilting of the Furnace Creek Formation produced this interesting geometry (photo by SM Awramik)

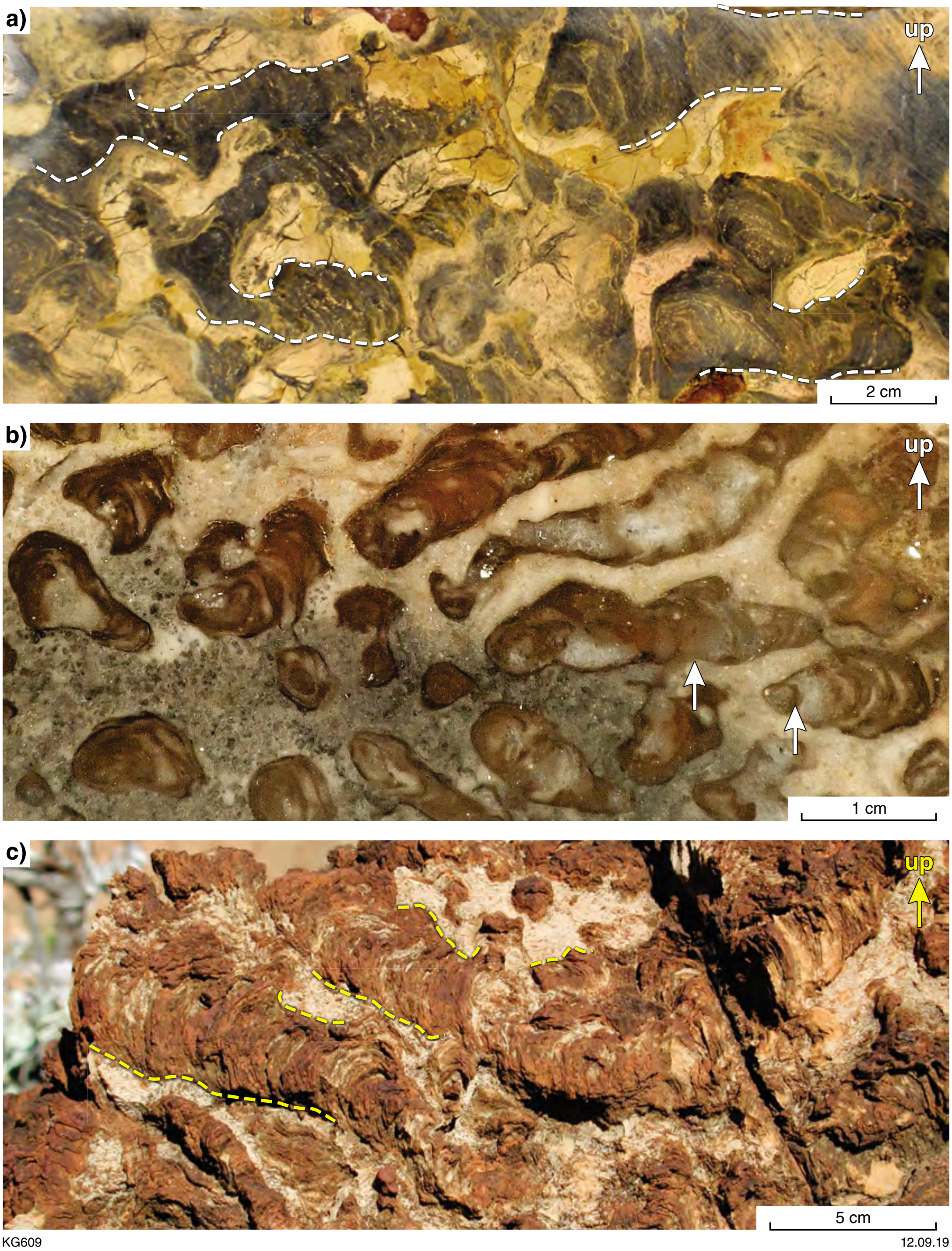

Figure 89. Examples of attitude – prostrate: a) *Tungussia julia*; Egan Formation, Louisa Downs Group; Halls Creek Orogen; Ediacaran, Neoproterozoic; Margaret River, Mount Ramsay, Western Australia; cut slab GSWA F49859–138907. Some branches are horizontal, i.e. prostrate (outlined), but become hyponastic towards their tips (photo by HJ Allen); b) *Murgurra nabberuensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, Nabberu, Western Australia; prostrate branches arrowed (photo by SK Martin); c) unnamed stromatolite; Kiangi Creek Formation, Edmund Group; Edmund Basin; Calymmian, Mesoproterozoic; Peedawarra Creek, Edmund, Western Australia; prostrate branches outlined (photo by DMcB Martin)

Figure 90. Examples of attitude – sinuous; a) sinuous columns (outlined) (incorrectly identified as '*Kotuikania juvensis*'); Johnnys Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; northeast of Ross River, Alice Springs, Northern Territory, Australia (photo by SM Awramik); b) sinuous column (outlined); *Gruneria* f. indet.; Gunflint Formation, Animikie Group; Animikie Basin; Orosirian, Paleoproterozoic; Winston Point, Lake Superior, Ontario, Canada; thick section from slab, Peabody Museum of Natural History, Yale University, YPM PB 051800 (photo by SM Awramik); c) sinuous branching columns (outlined); *Anabaria juvensis*; cap carbonate above Pioneer Sandstone; Amadeus Basin; Ediacaran, Neoproterozoic; near Ross River Highway, Alice Springs, Northern Territory, Australia; cut face (Vanyo and Awramik, 1982), UCSB collection 4 of 3/7/65 (photo by SM Awramik)

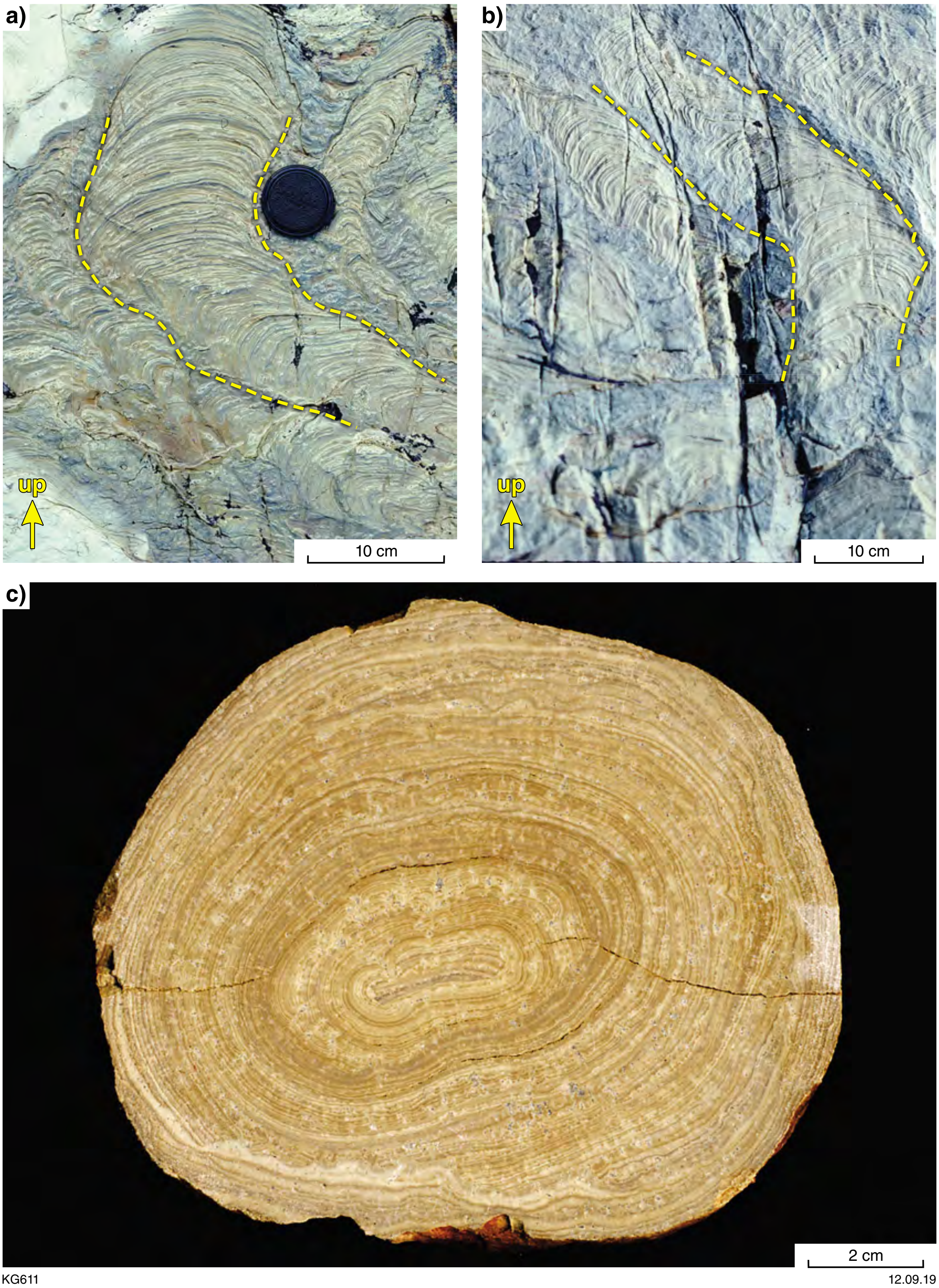

Figure 91. **Examples of attitude – hyponastic, epinastic, encapsulated: a) hyponastic (decumbent), outlined, and b) epinastic (recumbent), outlined; '*Collenia columnaris*'; Altyn Formation, Belt Supergroup; Belt Basin; Calymmian to Ectasian, Mesoproterozoic; Apikuni Falls, Glacier National Park, Glacier County, Montana, US (arrows indicate way up) (photos by K Grey); c) encapsulated; oncoid; Wasatch Formation; Fossil Basin; Eocene; Sixmile Creek, Rich County, Utah, US; polished slab, UCSB collection (photo by SM Awramik)**

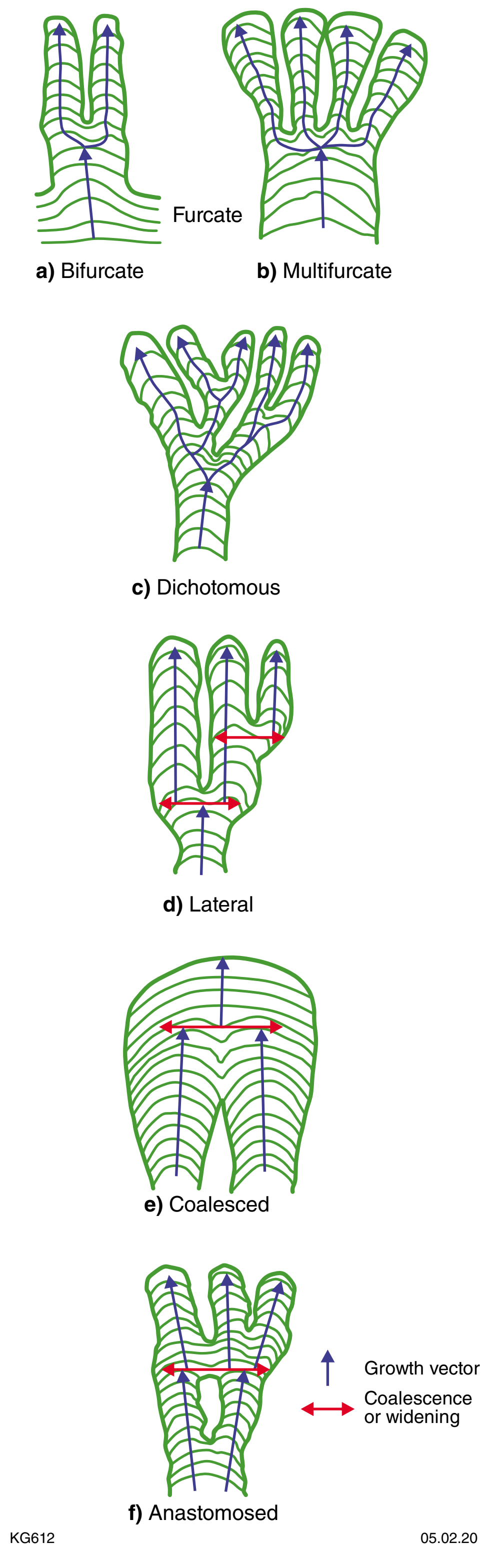

Figure 92. Microbialite branching style: a, b) furcate, branches more or less equal and parallel; a) bifurcate, b) multifurcate; c) dichotomous, branches usually unequal and at a divergent angle from parent; d) lateral, branches unequal, diverging at right angles to parent and parallel to parent; e) coalesced, initial columns parallel, then converge into a single column; f) anastomosed, initially parallel or slightly divergent columns overgrown by a new column; new columns may develop from anastomosed area. In each, blue line indicates growth vector, red line is coalescence or widening

Coefficient of thickening

The coefficient of thickening indicates the thickening of the lamina at the apex relative to the thickness of the lamina at the flank. It is expressed as h/H, where h is the thickness of the lamina on the flank and H is the thickness of the same lamina at the axis (Fig. 102). It is best to make enough measurements to determine a statistical mean (commonly at least 15).

Axial angle

The steepness of the lateral slope can be expressed as a measurement of the angle between the axis and the flank (Fig. 102). Komar et al. (1965a) used angle α in the apex of a triangle inscribed between the margins of adjacent laminae in the crestal zone (Fig. 102a). As Walter (1972) pointed out, this angle depends on the dimensions of H and d (where d is the width of the axial zone); d often depends on the slope of the lamina away from the crest. Because of the thickness variability and offset of the lamina in the axial zone, Walter regarded this parameter to be of doubtful taxonomic value. Walter (1972) suggested using the coefficient of crestal zone thickening, h/H, and the crestal zone width. In most axial zones, the laminae become nearly vertical and parallel in the axial zone at a break of slope. The width of the axial zone is generally constant at the break of slope, even though within the zone the lamina may become lensoid and offset. It is therefore best to measure the axial zone width, w, at the break of slope (Fig. 102b). Enough measurements should be made to determine a statistical mean. Grey (1994a) suggested that the axial angle could best be measured by drawing a line through the axial zone along the line of best fit, and another line subtended by the most constant part of the lateral slope, the tangential lateral slope (ignoring the axial zone) and measuring the axial angle where the two lines meet (Fig. 102b).

Types of axial zone

Many conical stromatolites are characterized by an axial zone, a narrow region in the centre of a conical stromatolite formed at the apex of the laminae (Figs 103). There is a distinct steepening of the slope just below the laminar apex, and the apex itself is commonly lensoid with one or more laminae laterally offset as they are stacked. The axial zone is sometimes referred to as a crestal zone, particularly in the case of a ridged stromatolite.

Three types of axial zone (I–III) (Figs 103, 104) were recognized by Komar et al. (1965a,b) and Walter (1972):

1. *Type I*: (Figs 103a, 104a,b) in which the laminae are not offset or contorted and have uniform thickness
2. *Type II*: (Figs 103b, 104c,d) in which laminae are not offset, but have variable thickness
3. *Type III*: (Figs 103c, 104e,f) in which the laminae are offset and have uneven thickness.

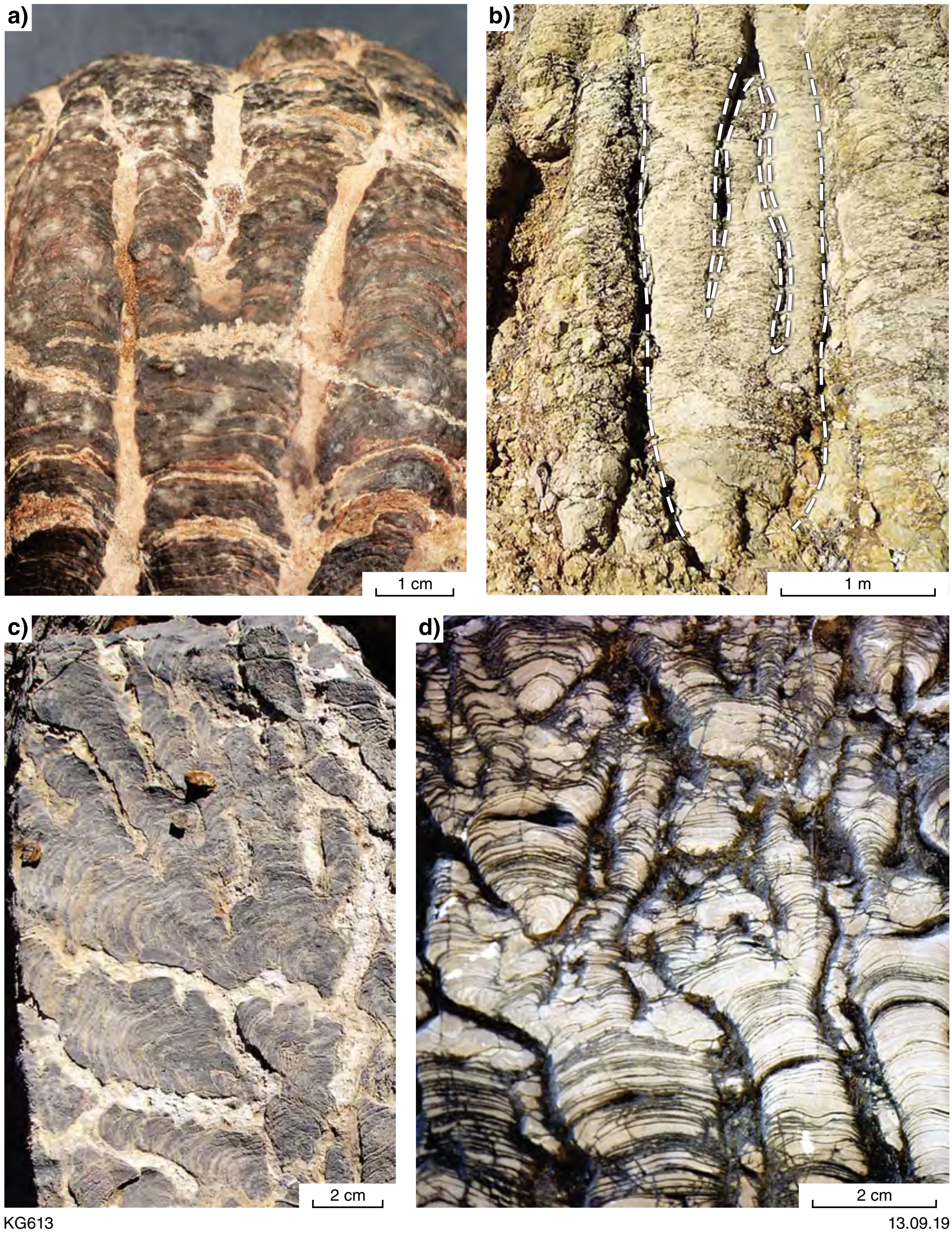

Figure 93. Examples of branching style – furcate, bifurcate, multifurcate: a) bifurcate; *Boxonia pertaknurra*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; unknown locality, Northern Territory, Australia; detail of columns, polished specimen, SMA private collection (photo by K Grey); b) trifurcate; thrombolite (outlined); Wirrealpa Limestone, Moralana Supergroup; lower Cambrian; Arrowie Basin; near Old Wirrealpa Mine, Flinders Ranges, PARACHILNA, South Australia (photo by PD Kruse); c) multifurcate; *Inzeria intia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, ALICE SPRINGS, Northern Territory, Australia (photo by NJ Planavsky); d) multifurcate; *Anabaria chisienensis*; Tieling Formation, Jixian Group; North China Craton; Calymmian to Ectasian, Mesoproterozoic; Yanshan Range, Jixian County, Hebei Province, China (photo by SM Awramik)

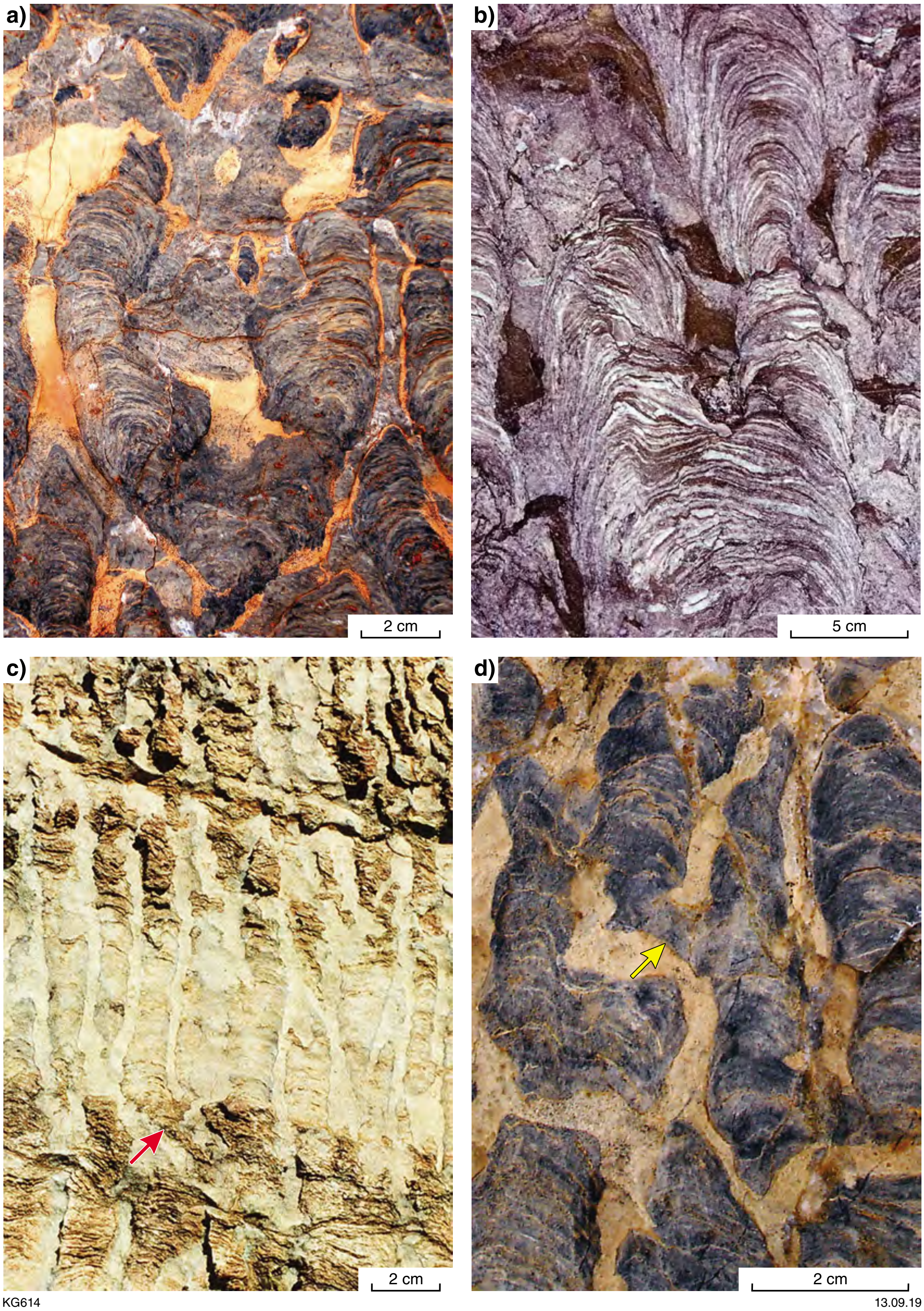

Figure 94. Examples of branching style – dichotomous, lateral: a) dichotomous; *Linella avis*; Bitter Springs Group; western Amadeus Basin; Tonian, Neoproterozoic; Boord Ridges, MACDONALD, Western Australia (photo by HJ Allen); b) dichotomous: '*Baicalia*'; Shisanlitai Formation, Jinxian Group; North China Craton; Tonian, Neoproterozoic; Jixian County, Liaoning Province, China (photo by SM Awramik); c) lateral (arrow); *Acaciella australica*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Ross River, ALICE SPRINGS, Northern Territory, Australia; detail of columns (photo by SM Awramik); d) lateral (arrow); *Linella avis*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, Amadeus Basin; ALICE SPRINGS, Western Australia (photo by NJ Planavsky)

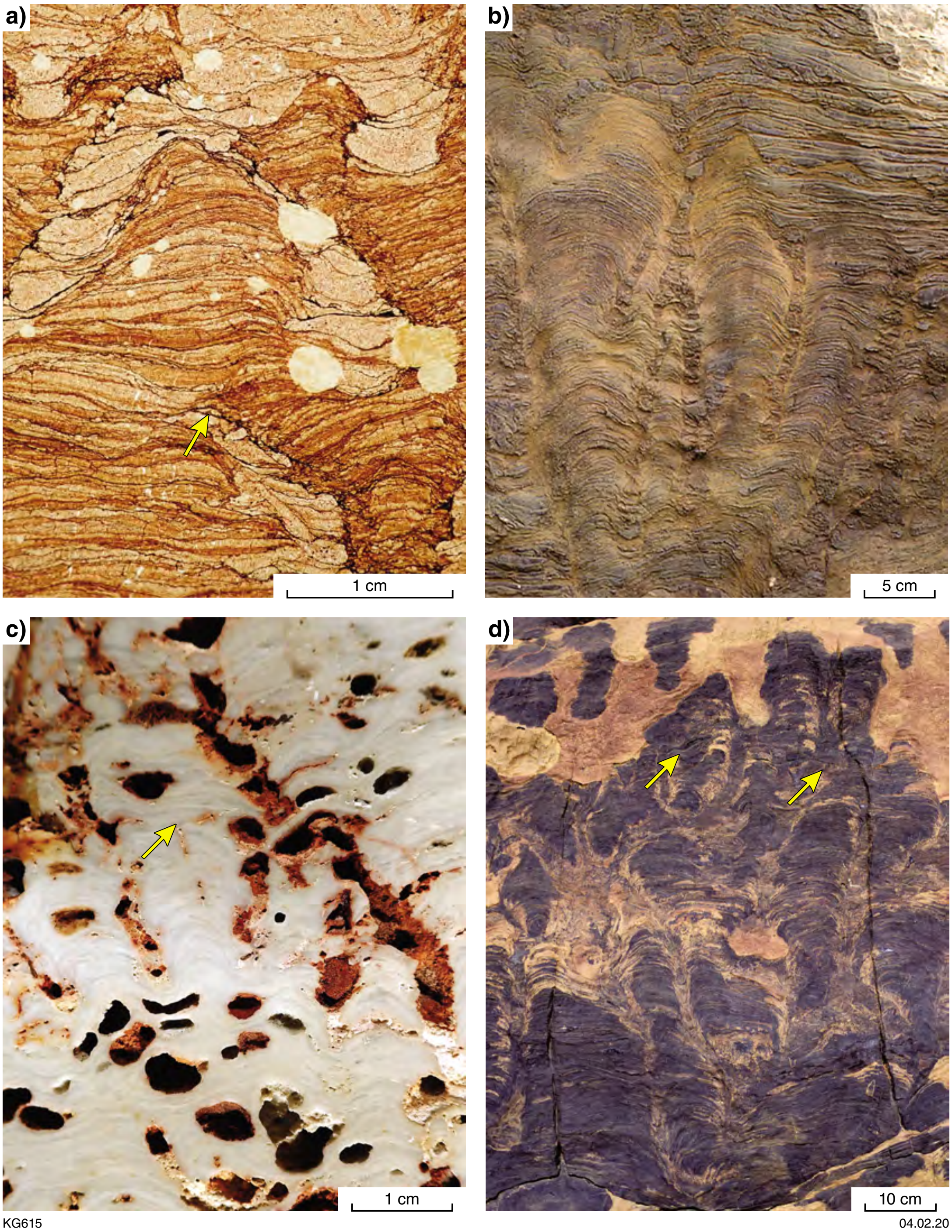

Figure 95. Examples of branching style – coalesced and anastomosed: a) coalesced (arrow); *?Inzeria conjuncta*; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; Muddauthera Creek, eastern Pilbara, Nullagine, Western Australia; thick section, GSWA F52552–109251C (photo by SK Martin); b) coalesced; *Nouatila frutectosa*; Tifounke Formation (Unit I.12), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Guelb Nouatil, Atar region, Mauritania (photo by SM Awramik); c) anastomosed (arrow); *Wilunella glengarrica*; Bubble Well Member, Juderina Formation, Windplain Group; Yerrida Basin; Rhyacian to Statherian, Paleoproterozoic; south of Mount Russell, Glengarry, Western Australia; polished face GSWA F48470–84606 (photo by K Grey); d) anastomosed (arrows); *Tungussia* aff. *confusa*; Atar Formation (unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania (photo by SM Awramik)

Figure 96. **Microbialite branching mode: a) alpha branching, width of parent remains constant before branching; b) beta branching, parent column widens gradually before branching; c) gamma branching, parent column widens abruptly before branching**

Figure 97. **Examples of branching mode – alpha branching: a) bifurcating column which remains the same width after branching (outlined); part of an extensive thrombolite biostrome; Wirrealpa Limestone, Moralana Supergroup; early Cambrian; Arrowie Basin; near Old Wirrealpa Mine, Flinders Ranges, PARACHILNA, South Australia (photo by PD Kruse); b) column with bifurcate branching but retaining uniform width throughout; *Acaciella australica*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; northeast of Ross River, ALICE SPRINGS, Northern Territory, Australia (photo by NJ Planavsky)**

Describing microbialite mesostructure

Mesostructure (Figs 2, 3) comprises the internal features of a microbialite that are commonly visible to the unaided eye, although use of a hand lens (loupe) or low-powered microscope may be needed to help characterize the feature. The term mesostructure in this handbook includes some features previously included in microstructure, such as the distinctness, continuity, thickness and composition of the laminae (Preiss, 1972, p. 93). These features are different in scale to features such as texture and fabric (which are microscopic and discussed under ‘Describing microbialite microstructure’). In stromatolites, it deals principally with various aspects of the laminae (Fig. 105a); in thrombolites, with various aspects of the mesoclots (Shapiro, 2000) (Fig. 105b); and in dendrolites, with the finer detail of the dendrolitic structures (Fig. 105c). It does not apply to leiolites because these do not have an internal structure. Many MISS have mesostructure, such as lamination and there are descriptions in Schieber et al. (2007a) and Noffke (2010).

It has become obvious that one of the difficulties in relating features of living microbialites to those observed in fossil microbialites lies in the differing approaches of microbiologists, sedimentologists, paleontologists and biostratigraphers. Research into living microbialites has often concentrated on the microorganisms and sediment composition, and tended to ignore how these elements are organized into the shapes and patterns of laminar, thrombolitic and dendritic architecture or mesostructure — but see Walter et al. (1976), Reid et al. (2000), Jahnert and Collins (2012), and Suosaari et al. (2016, 2018) for examples of studies that describe mesostructure in living microbialites. In living mats, mesostructure has sometimes been referred to as mat topography, which refers primarily to the surface features (Bauld et al., 1992, p. 262). To facilitate comparisons between living and fossil stromatolites, the term architecture is proposed here for fossil counterparts, and is defined as the product of the laminar shape, laminar boundaries, stacking of individual laminar elements, and 3D laminar structure and its relationship to underlying or overlying laminae.

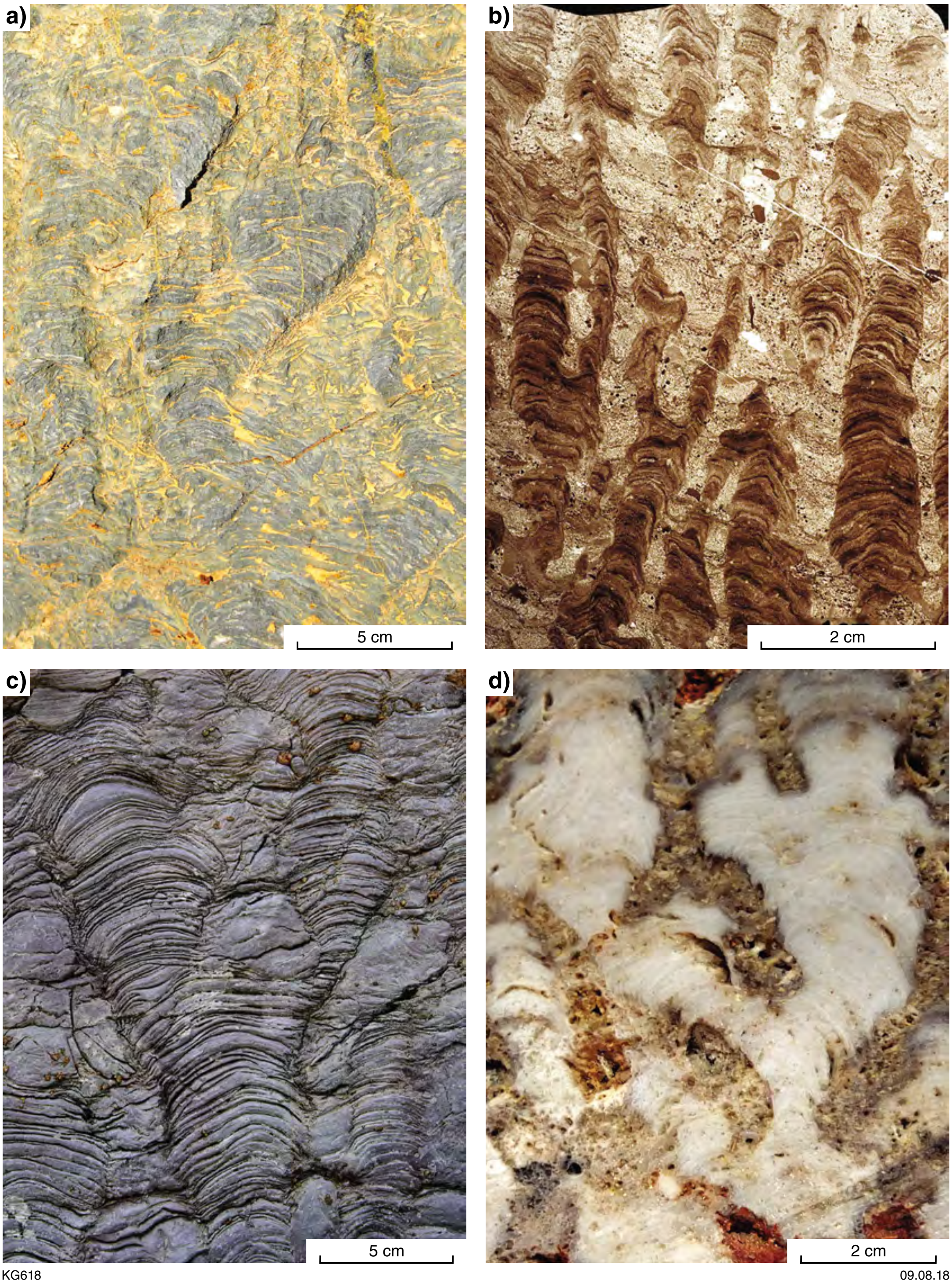

Figure 98. **Examples of branching mode – beta and gamma branching; a) beta branching; *Linella avis*; Loves Creek Formation, Bitter Springs Group; western Amadeus Basin; Tonian, Neoproterozoic; Pollock Hills, WEBB, Western Australia (photo by CV Spaggiari); b) beta branching, note the gradual expansion of the columns before branching; ?*Acaciella augusta*; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; near Tooma Stockyard, NULLAGINE, Western Australia; thick section, GSWA F52562–84678B (photo by K Grey); c) gamma branching; *Anabaria chisienensis*; Tieling Formation, Jixian Group; North China Craton; Calymmian to Ectasian, Mesoproterozoic; Yanshan Range, Jixian County, Hebei Province, China (photo by SM Awramik); d) gamma branching; *Eucapsiphora leakensis*; Mount Leake Formation; Statherian to Stenian, Paleoproterozoic to Mesoproterozoic; Mount Leake, PEAK HILL, Western Australia; polished vertical face, GSWA F48393–90507 (photo by K Grey)**

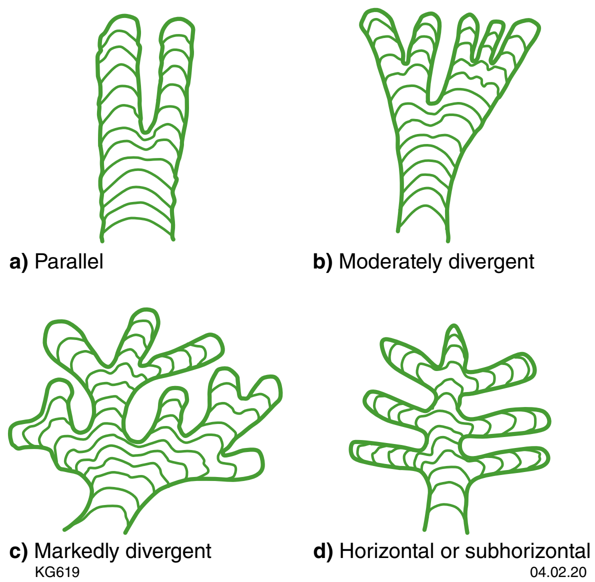

Figure 99. Microbialite angle of divergence: a) parallel; b) moderately divergent; c) markedly divergent; d) horizontal or subhorizontal

In non-laminated microbialites, mat architecture is any relationship visible between a microbially constructed element and the surrounding matrix. From the genetic viewpoint, this represents the product of specific combinations of sediment, cement, and other components, under the influence of microbial activity.

Mat topography and architecture have been the subject of investigations of MISS in siliciclastic systems. These primarily manifest themselves on sediment surfaces in modern situations and on bedding plane surfaces in fossil examples, and the terminology that has been developed largely from a genetic perspective is different from that used for microbialites. Much of this work is summarized in Hagadorn et al. (1999), Schieber et al. (2007a), Noffke (2010), and and Davies et al. (2016).

Features to be described under microbialite mesostructure include:

- for stromatolites, all aspects of the lamina, such as shape, waviness, synoptic relief, degree of inheritance, lateral continuity, thickness and its variation, mode of stacking, development of macrolaminae, and structures associated with the termination of laminae such as column–surface characteristics and walls
- for thrombolites, all aspects of the mesoclot including shape, profile, outline, orientation, size, spatial relations, and arrangement
- for dendrolites, shape and orientation of the shrub, and the shape and orientation of any components that comprise the mesostructure
- for MISS, the geometry of the surface topography.

Diagenesis can obliterate or nearly obliterate original mesostructure and microstructure, possibly producing a post-depositional microbialite. It is important to determine, if possible, the original mesostructural type. The nature of the diagenesis would be described under microstructure. Determining original features is important for descriptions and other analyses.

Describing stromatolite mesostructure

Lamination (Figs 2, 3, 105a) is the distinctive mesostructural characteristic of a stromatolite and includes the laminar architecture. Architecture is an order of magnitude greater than microstructure and is therefore grouped with other elements of mesostructure. Terms such as banded (relating to laminar thickness, stacking and regularity of laminae), streaky (referring to lateral continuity), and filmy (referring to continuity and comparative thickness of laminae) are all mesostructural features. By contrast, a term such as micritic is of a different level of organization and is a microstructural term referring to grain or crystal size and composition.

The basic component of architecture is the lamina (Figs 105a, 106–110). The nature of the laminae is a fundamentally significant characteristic of stromatolites (Lee et al., 2000) and controls the architecture, which in turn gives rise to the macrostructure (sublaminar features comprise the microstructure). A lamina is 'the smallest unit of layering' (Preiss, 1972, p. 93; Walter, 1972, p. 13). The term lamina is here used for a single layer (not a couplet), and is normally defined by distinctive upper and lower boundaries (Fig. 106a). Stromatolitic laminae commonly consist of alternating dark and light laminae (Figs 105a, 107–109), here referred to as a couplet (Fig. 106a), an equivalent to the term 'lamina' as used by Hofmann to describe one light plus one dark lamella (Hofmann, 1969a, p. 4, fig. 1). It has also been referred to as a doublet (Trompette, 1969, p. 136).

Hofmann (1973, p. 357), in a discussion of rhythmicity of lamination, viewed the transition from a dark lamina to a light lamina as a continuous process. From the descriptive point of view, it is often difficult to tell whether a couplet consists of a basal dark lamina that grades into a light lamina, or a basal light lamina that grades into a dark lamina. Although in some cases contacts are sharp (Figs 107, 108, 109a), boundaries between the two components do not necessarily consist of alternating sharp and gradational contacts (Figs 109, 110b–c). Although it would seem logical to place the base of a couplet at a sharp boundary, this is not always practical. Both boundaries may be sharp, both gradational, or comprise more complex types of accretion than simple couplets. There can be intermediate-coloured laminae in addition to the dark and light laminae (Fig. 110a,b), or highly complex lamination and microstructure with numerous voids (Fig. 110c). Lacustrine stromatolites (Fig. 110b,c) generally have more complex laminae than marine ones. In practical terms, it is usually simplest to measure each category of lamina independently and comment on the nature of the boundaries separating each category.

While some stromatolites have uniform mesostructure, in others the mesostructure may vary in different parts of the stromatolite, or different types of laminae may be intercalated. The descriptive terminology is not mutually exclusive. In practice, many of the categories coexist and intergrade.

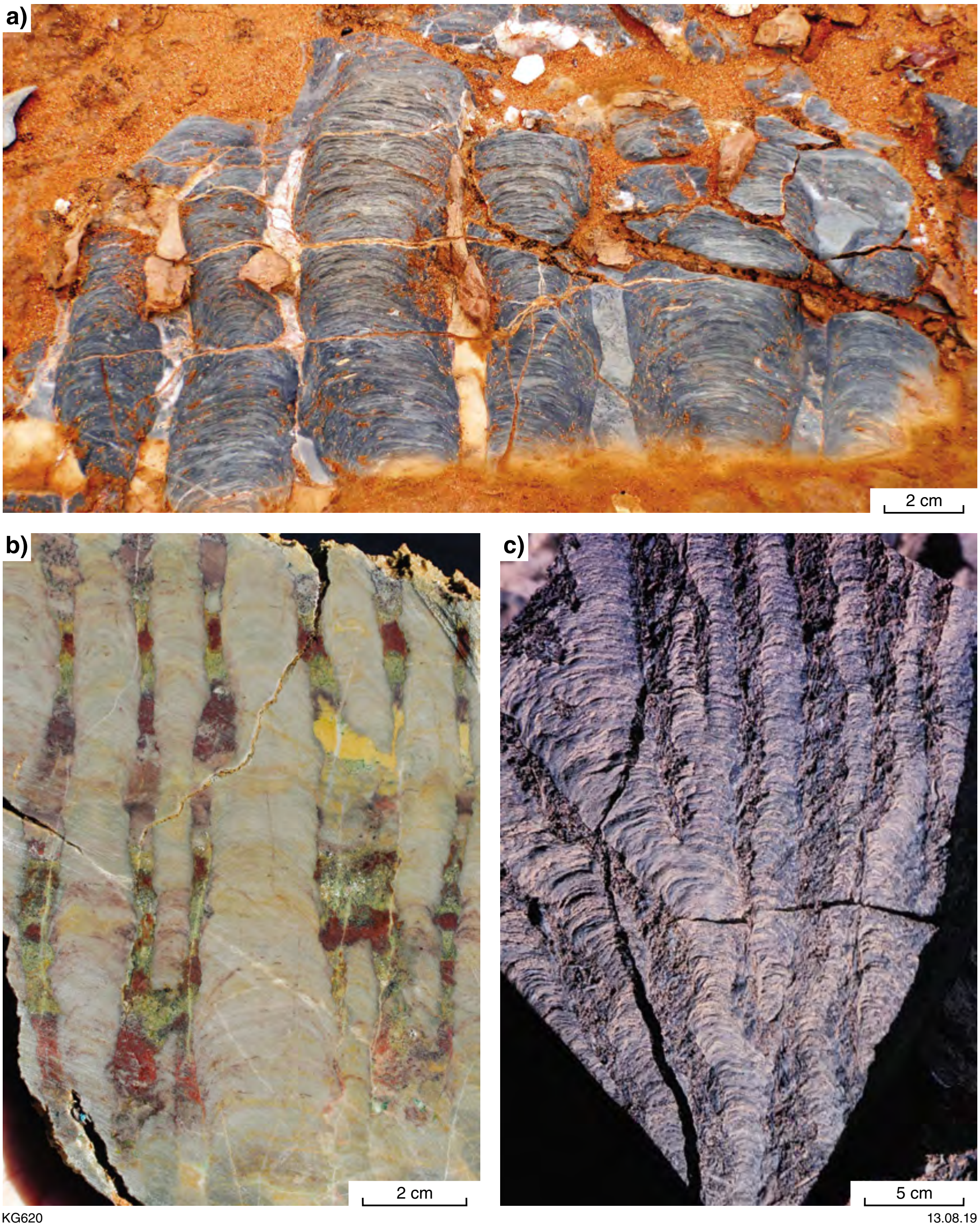

Figure 100. Examples of angle of divergence – parallel to moderately divergent: a) parallel; *Boxonia pertaknurra*; Loves Creek Formation, Bitter Springs Group; western Amadeus Basin; Tonian, Neoproterozoic; Boord Ridges, MACDONALD, Western Australia (photo by HJ Allen); b) parallel; *Kulparia alicia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Boord Ridges, MACDONALD, Western Australia; cut slab, GSWA F54099–197162 (photo by HJ Allen); c) moderately divergent; *Serizia radians*; Tawaz Formation (unit I.7); Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Serize camel pass, Atar, Mauritania (photo by K Grey)

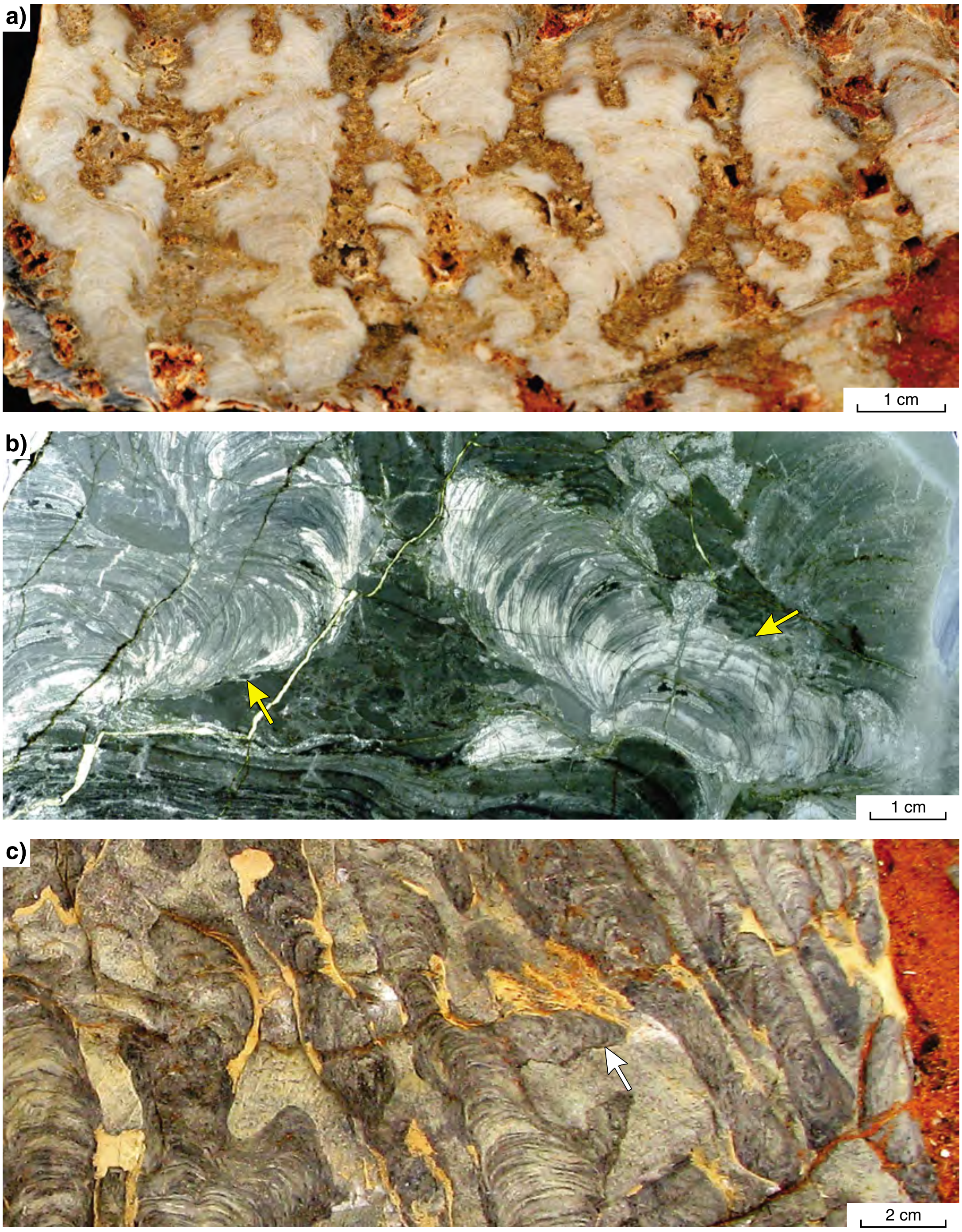

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Figure 101. **Examples of angle of divergence – markedly divergent to horizontal: a) moderately to markedly divergent; *Eucapsiphora leakensis*; Mount Leake Formation; Statherian to Stenian, Paleoproterozoic to Mesoproterozoic; Mount Leake, Peak Hill, Western Australia; polished face GSWA F48393–90507 (photo by K Grey); b) markedly divergent (right arrow) and horizontal (left arrow); *Tungussia wilkatanna*; Skillogalee Dolomite, Burra Group; Adelaide Rift Complex; Tonian, Neoproterozoic; Depot Creek, Flinders Ranges, Port Augusta, South Australia; thick section (holotype) S412, University of Adelaide collection (photo by SM Awramik); c) horizontal (arrow), *Linella avis*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Boord Ridges, Macdonald, Western Australia (photo by PW Haines)**

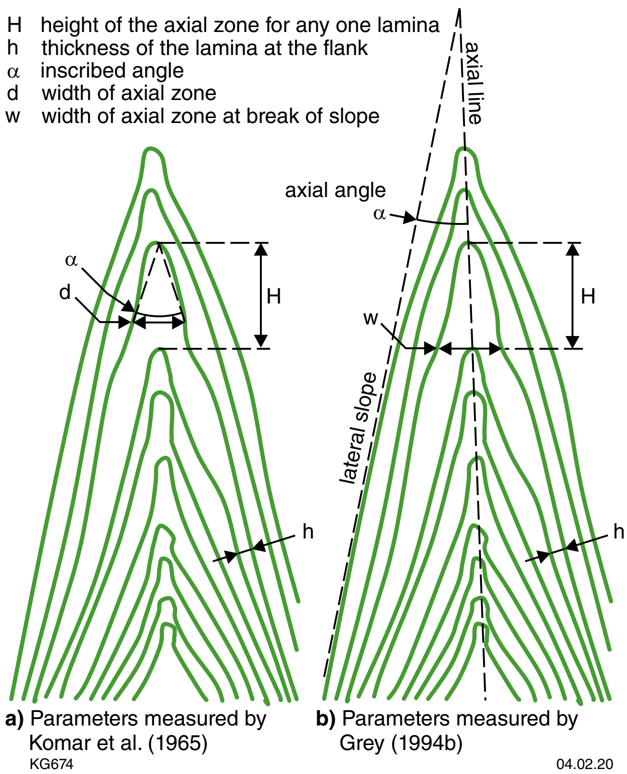

Figure 102. Measurable parameters related to the microbialite axial zone. H/h, coefficient of thickening, where H is the height of the axial zone for any one lamina, and h is the thickness of the lamina at the flank: a) parameters measured by Komar et al. (1965a); α, inscribed angle; d, width of axial zone; b) parameters measured by Grey (1994a); α, inscribed angle between axial line and tangential lateral slope; w, width of axial zone at break of slope

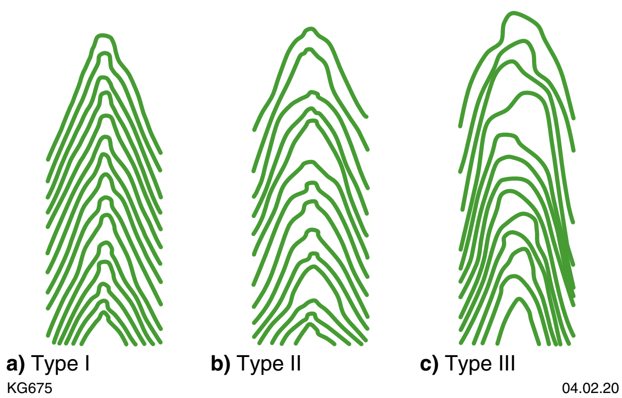

Figure 103. Axial zones in conical stromatolites: a) Type I, laminae of regular thickness and not distorted; b) Type II, laminae of variable thickness and not distorted; c) Type III, laminae of variable thickness and distorted (adapted from Komar et al., 1965a; Walter, 1972)

Features of the lamina requiring description include laminar patterns, mode of stacking, shape, waviness, synoptic relief, degree of inheritance, lateral continuity, thickness, development of macrolaminae, and structures associated with the termination of laminae, such as column-surface characteristics and walls (see below). These features, in combination with the microstructure (in the more limited interpretation provided here), produce the laminar architectural types discussed below. The proportion of dark to light laminae may vary throughout the stromatolite, and changes may be abrupt or gradual. Note any significant changes and whether they are progressive.

Lamination should be characterized as rigorously as possible because it is a key feature in differentiating stromatolite types. Diagenetic alteration can severely modify some aspects of the laminae at the mesostructural level; this needs to be taken into consideration and the extent of alteration recorded in descriptions.

Laminar patterns

Laminar pattern (Figs 106a, 107–108) refers to how many types of laminae are present and how the types relate to each other. Determine whether the laminae form couplets, i.e. a simple alternation of a light and a dark lamina (Hofmann, 1969a), or non-couplets, where there is no simple alternation couplets (Figs 106b, 109–110). This may be because more than two types of laminae are present (Riding, 2008; Planavsky and Ginsburg, 2009).

Stacking pattern

The stacking pattern (Figs 111, 112) of the laminae refers to the way in which laminae relate to each other vertically and the patterns produced by this relationship. It includes the manner in which laminae relate to each other at the margins. It is the combination of these attributes that produces distinctive laminar stacking patterns (Monty, 1976, p. 195).

There are three basic ways in which laminae may overlap (Figs 111, 112). Laminae may be parallel (Figs 111a, 112a), in which each lamina terminates against the column margin with no overlap; they may be overlapped, where a single lamina overlaps the terminations of other laminae, either with the overlap predominantly by light laminae (Figs 111b, 112b) or predominantly by dark laminae (Figs 111c, 112c); or they may be walled, in which continuous overlapping by successive laminae gives rise to walls and produces various types of wall structure discussed below. Laminae may be stacked together to form specific patterns, and different types and different numbers of laminae may be involved in the formation of each pattern. Such patterns are referred to as macrolaminae (see below). Alternating laminae may have very different textures and microstructures, and any recurring patterns and range of variation should be described.

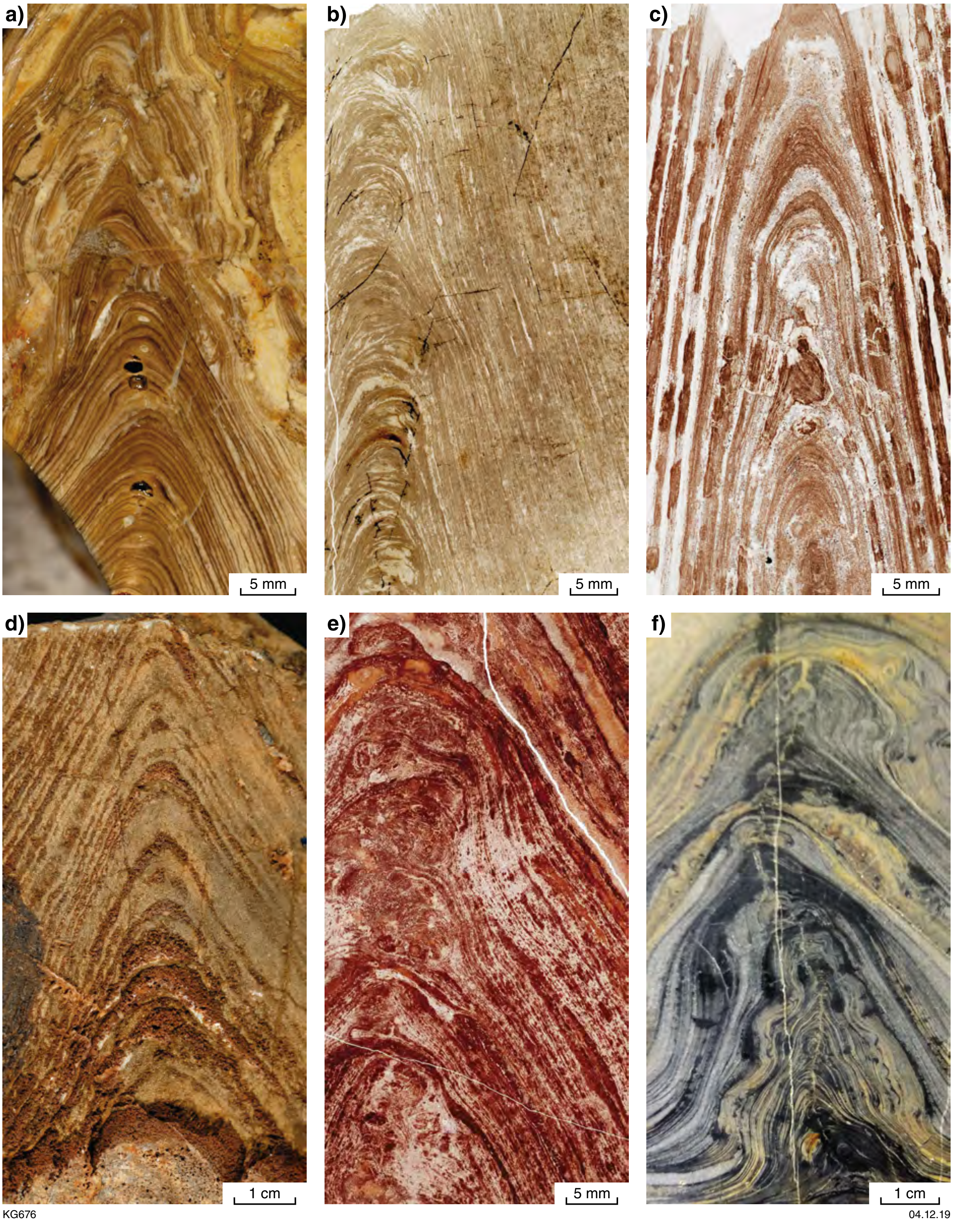

Figure 104. Examples of axial zones. a, b) Type I: a) *Conophyton* new Form (Throssell type); Kanpa Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; Lake Throssell, THROSSELL; polished face GSWA F52674A–76598 (photo by SM Awramik and K Grey); b) *Conophyton* new Form; Muntharra Formation, Edmund Group; Edmund Basin; Calymmian, Mesoproterozoic; Pingandy Creek, MOUNT EGERTON, Western Australia; thick section F9932–46009F (photo by SM Awramik and K Grey). c, d) Type II: c) *Conophyton* new Form; Pear Tree Dolostone, Limbunya Group; Birrindudu Basin; Statherian, Paleoproterozoic; Swan Yard, LIMBUNYA, Northern Territory, Australia; thick section GSWA F52403–138930G (photo by SM Awramik and K Grey); d) *Conophyton* new Form (Trendall type); Strelley Pool Formation, Pilbara Supergroup; East Pilbara Terrane; Paleoarchean; Trendall Geoheritage Reserve, MARBLE BAR, Western Australia; hand specimen GSWA F46708–54977 (photos by SM Awramik and K Grey). e, f) Type III: e) *Conophyton* new Form (Balfour type); Stag Arrow Formation, Manganese Group; Collier Basin; Stenian, Mesoproterozoic; Enacheddong Creek, BALFOUR DOWNS, Western Australia; thick section, GSWA F52619A–84664A (photo by SM Awramik and K Grey); f) ridged stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; Meentheena Conservation Reserve, NULLAGINE, Western Australia; thick section, UCSB collection (photo by SM Awramik)

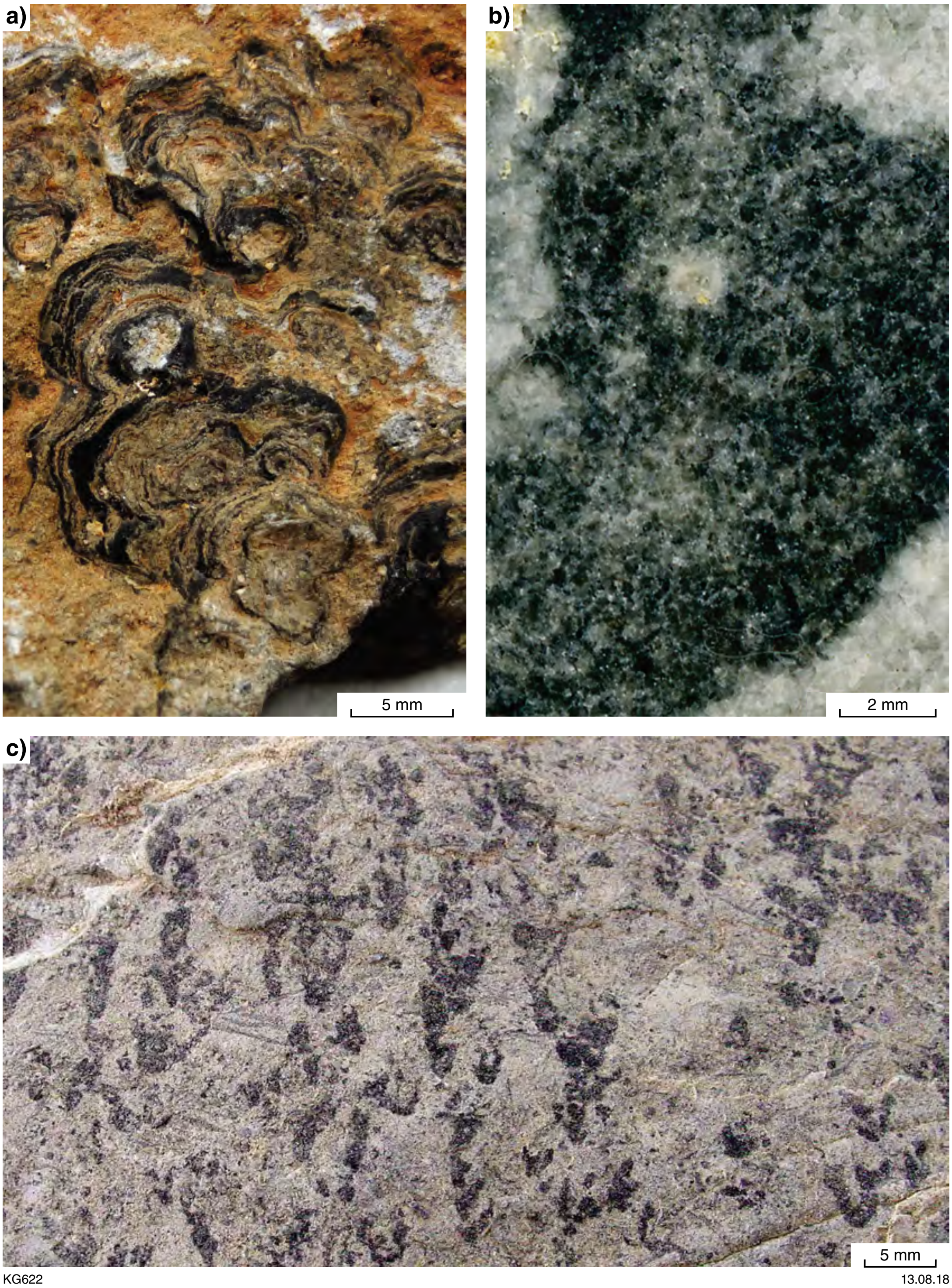

Figure 105. Types of microbialite mesostructure: a) stromatolite (laminae); contact between Maddina Formation and Woodiana Member, Jeerinah Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Mount Florance Homestead, Pilbara, PYRAMID, Western Australia; cut face GSWA F52421–76591 (photo by K Grey); b) thrombolite (mesoclots); *Favosamaceria cooperi*; Smoky Member, Nopah Formation; upper Cambrian; Mohawk Hill, Clark Mountain Range, San Bernardino County, California, US; polished slab, UCSB collection; dark areas are the mesoclots (photo by SM Awramik); c) dendrolite (shrubs); Desert Valley Formation; upper Cambrian; Delamar Mountains, Lincoln County, Nevada, US (photo by SM Awramik)

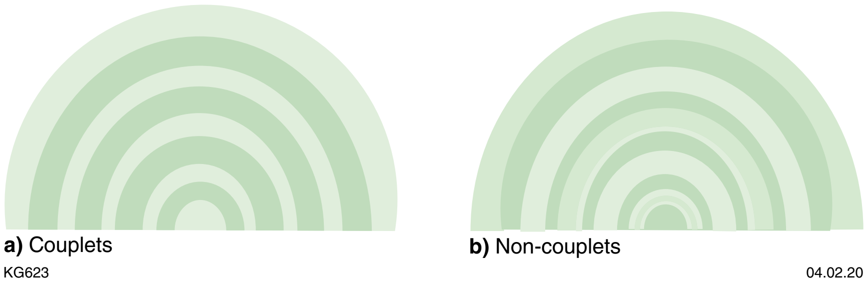

Figure 106. Stromatolite laminar patterns: a) couplets; b) non-couplets

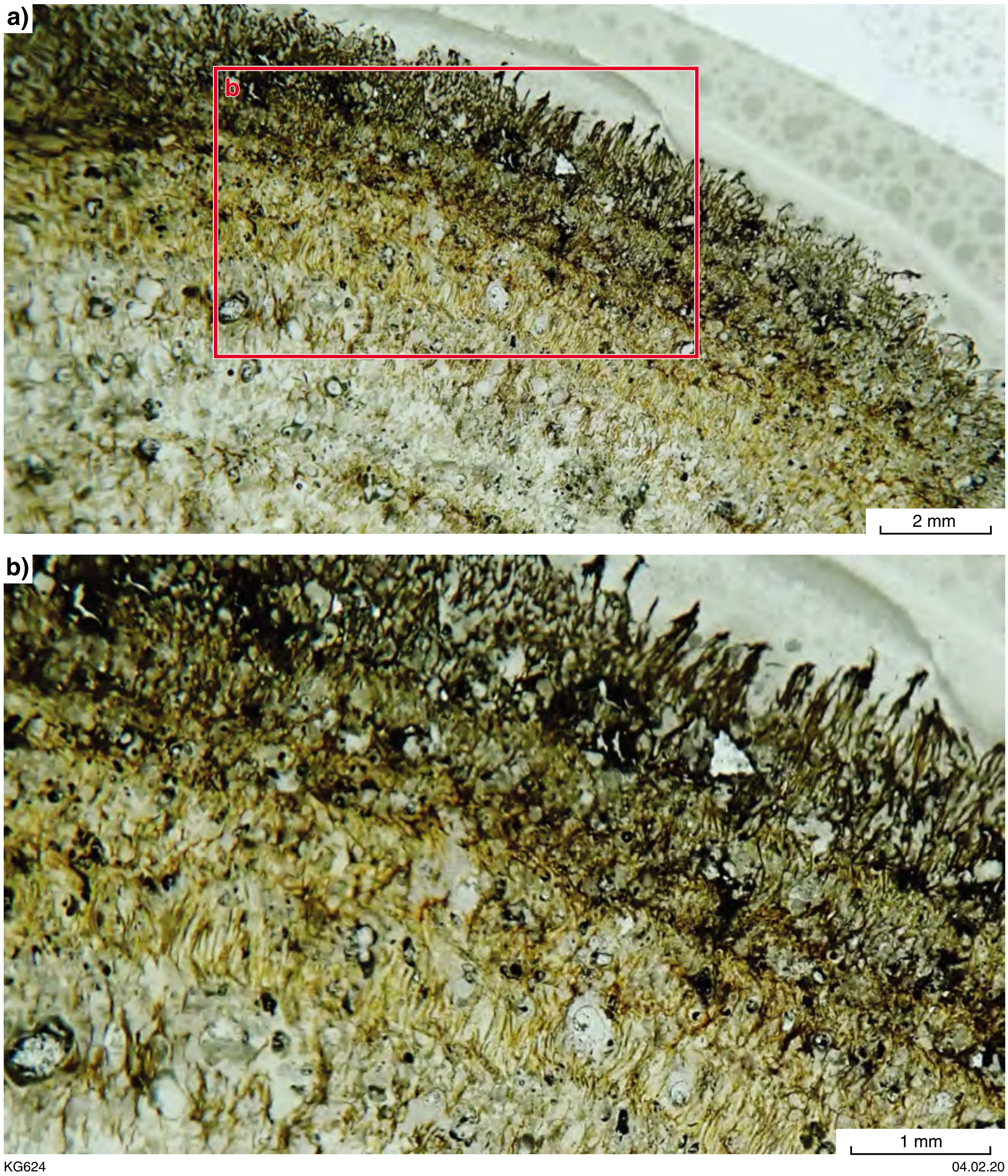

Figure 107. Examples of laminar patterns – 'pincushion' stromatolite, Perth Basin; Holocene; Lake Clifton south, Pinjarra, Western Australia; thick section GSWA F46713–76517: a) specimen showing alternating light and dark laminae; b) detail of filaments and laminae with filaments projecting at the surface (Grey and Thorne, 1985) (photos by SK Martin)

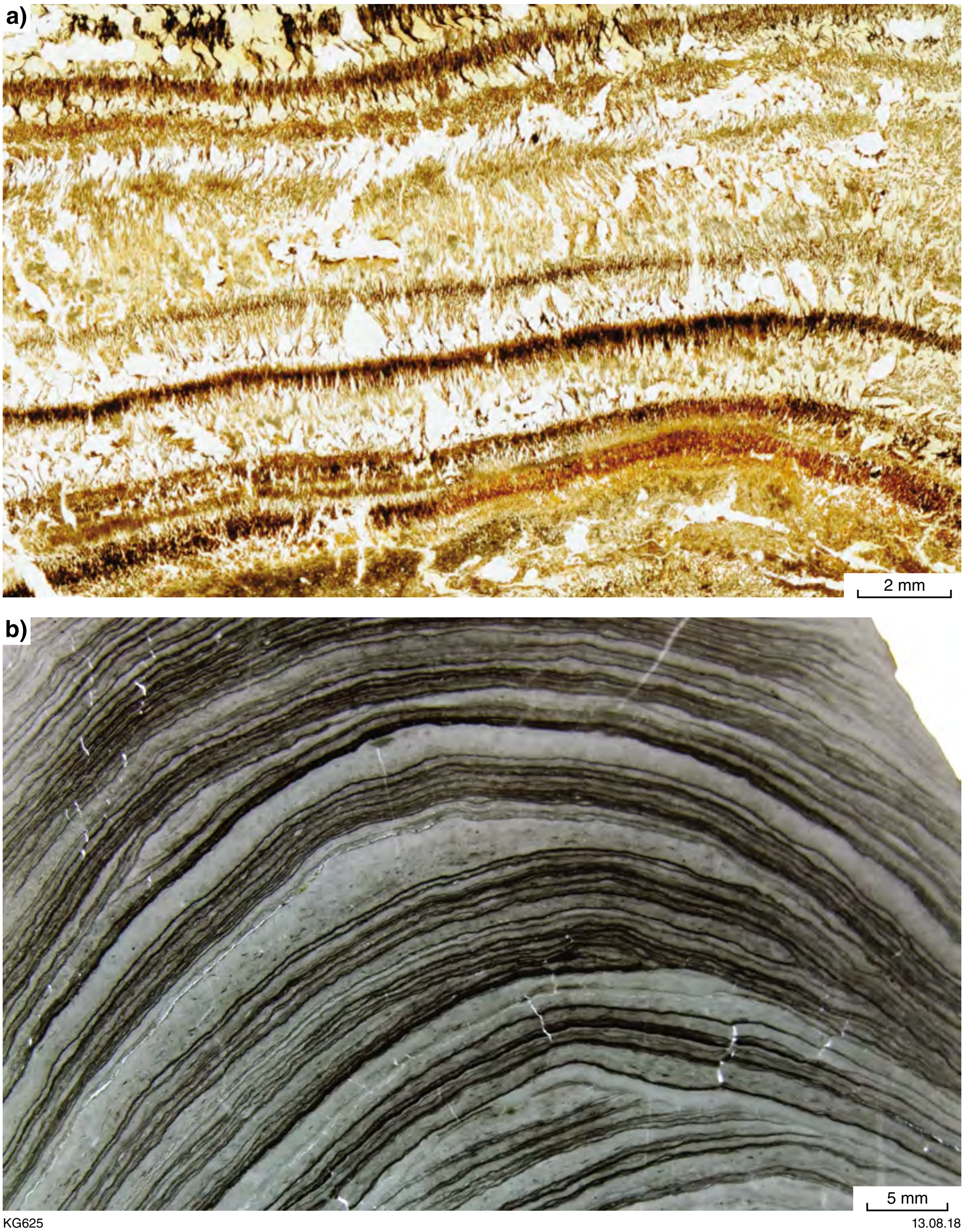

Figure 108. Examples of laminar patterns – alternating light and dark laminae: a) alternating laminae with vertical filaments; stromatolite; Holocene; Keene Wonder Springs, Death Valley National Park, Inyo County, California, US; thick section, UCSB collection (photo by SM Awramik); b) cf. *Colonella* f. nov.; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, EDMUND, Western Australia; thick section GSWA F9915–46073B (photo by M Ang)

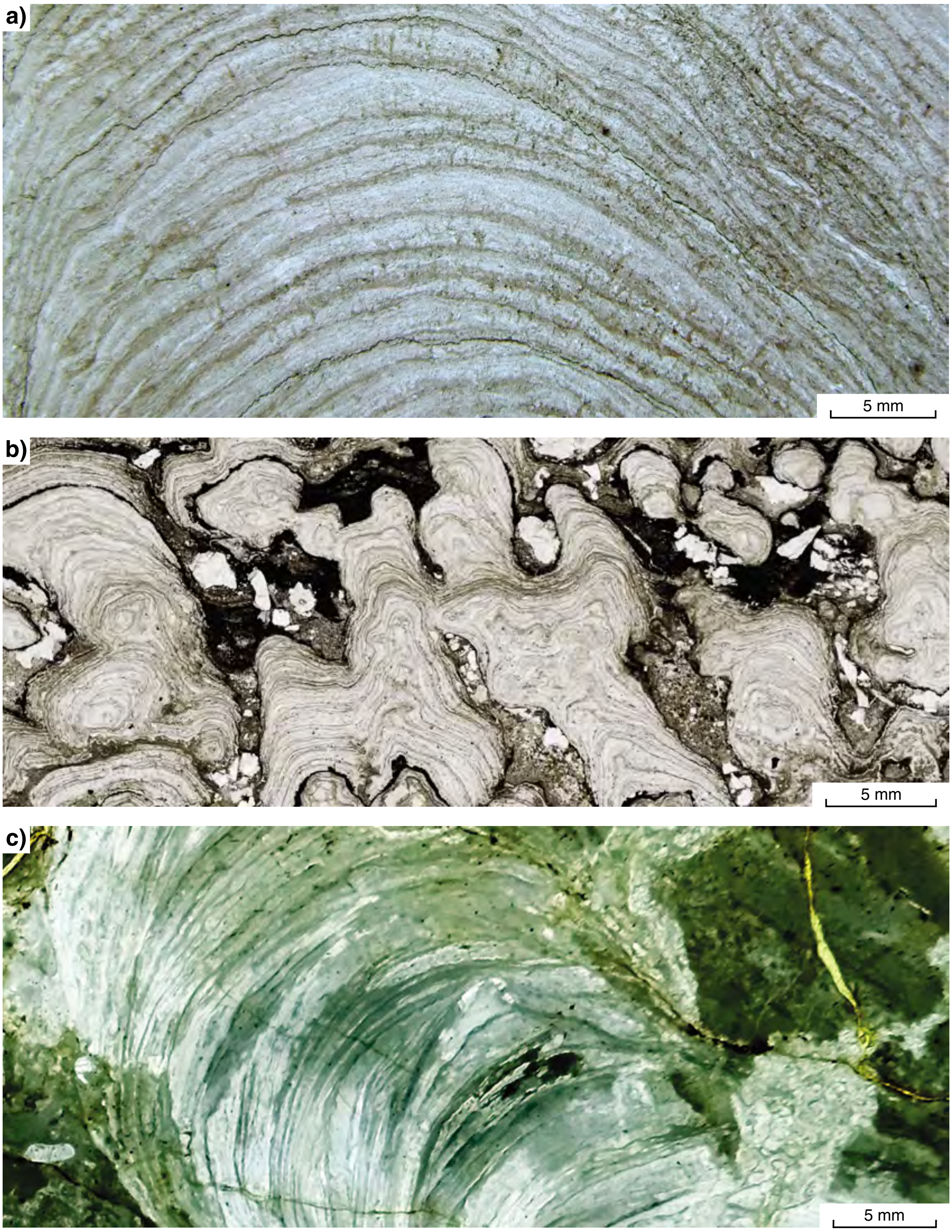

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Figure 109. Examples of laminar patterns – alternating light and dark laminae: a) stromatolite; Trezona Formation, Umberatana Group; Adelaide Rift Complex; Cryogenian, Neoproterozoic; Enorama Creek, Flinders Ranges, PARACHILNA, South Australia; thick section GSWA F53602–46179 (photo by M Ang); b) columnar stromatolite '*Gruneria biwabikia*' in Cloud and Semikhatov (1969, R2422); Maddina Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Redmont; MARBLE BAR, Western Australia; thick section GSWA F52218–109292 (photo by SM Awramik and K Grey); c) *Tungussia wilkatanna*; Skillogalee Dolomite, Burra Group; Adelaide Rift Complex; Tonian, Neoproterozoic; Depot Creek, Flinders Ranges, PORT AUGUSTA, South Australia; thick section (holotype) S412, University of Adelaide collection (photo by HJ Allen)

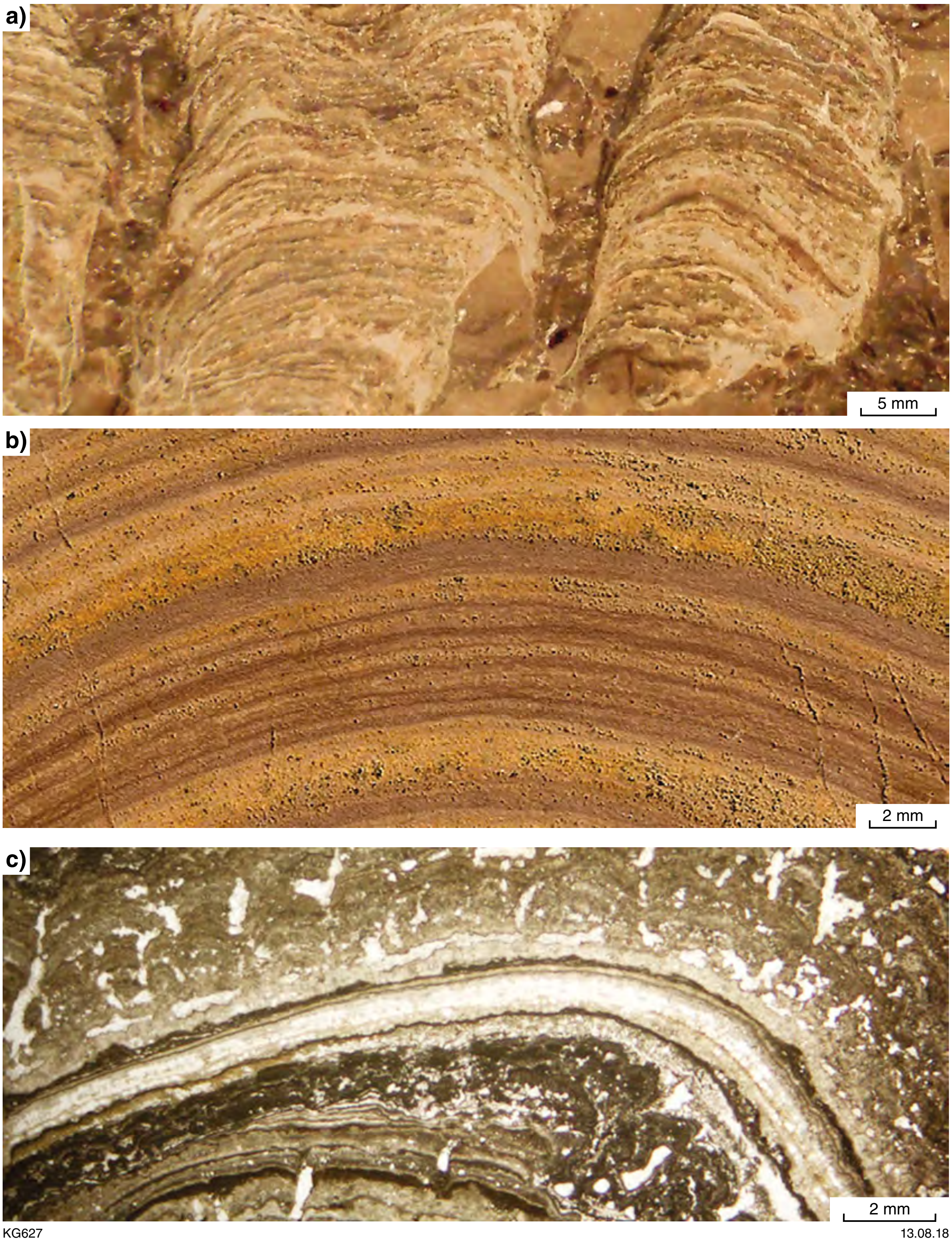

Figure 110. Examples of laminar patterns – non-couplets and complex laminae: a) non-couplets, light, dark and intermediate laminae; *Acaciella australica*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Katapata Gap, HERMANNSBURG, Northern Territory, Australia; polished slab, GSWA F9976–46062 (photo by HJ Allen); b) non-couplets, alternation of a few lamina types; unnamed stromatolite; Fossil Butte Member, Green River Formation; Fossil Basin; Eocene; Soda Hollow area, Uinta County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik); c) complex laminae and microstructure with numerous voids; unnamed stromatolite; Dove Spring Formation, Ricardo Group; El Paso Basin; Miocene; El Paso Mountains, Kern County, California, US; thick section, UCSB collection (photo by SM Awramik)

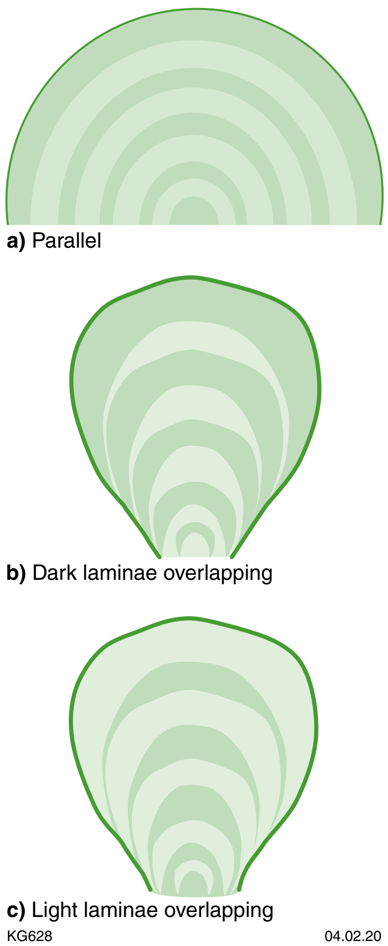

Figure 111. Stacking patterns and overlap of laminae: a) parallel; b) dark laminae overlapping; c) light laminae overlapping

Macrolaminae

The term macrolamina (Figs 113–115) is here used to describe any higher-order pattern of banding produced by a grouping of laminae. For example, a macrolamina may consist of thin bands of fine, dark laminae juxtaposed against bands of light laminae that are thicker and perhaps have different grain size (Figs 113a, 114). Alternatively, a macrolamina may consist of a set of light laminae with rarer dark lamina bundles that are thinner (Figs 113b, 115a). Laminae may show a progressive increase or decrease in thickness (Figs 113c, 115b) and such sets may be cyclic. Macrolaminae can be produced by many different combinations of laminae. Any recognizable or repeated patterns, such as rhythmicity, should be described in detail. Macrolaminae are more common in lacustrine stromatolites than marine stromatolites.

Intercalations

In addition to macrolaminae formed by normal microbial growth, intercalations (Figs 113d, 116f,g) may be present. These normally consist of interspersed layers of detrital grains, but could also be late infills of sediment injected between laminae, growth of new laminae between existing laminae, or mineral deposition between laminae.

Laminar alternation

Laminar alternation (Figs 116–119) is the variation in texture and microstructure between successive laminae. The following terminology (based on Monty, 1976) can be used to describe the alternation of laminae:

1. *Even*: (Figs 116a, 117a) all adjacent laminae consist of similar microstructural types, normally of couplets; boundaries between laminae are commonly distinct and have sharp contacts
2. *Composite*: (Fig. 116b,c, 117b) adjacent laminae consist of different microstructural types, normally of non-couplets; some boundaries are sharp (Fig. 116b), others have no sharp boundaries (Fig. 116c), and both dark and light laminae can be gradational (Fig. 117b)
3. *Film bounded*: (Fig. 116d,e, 118) adjacent laminae consist of a couplet; one of the laminae in the couplet (generally the dark one) consists of a thin film and may have a finer texture than the other lamina. Typically, a film-bounded microstructure consists of a light lamina with a sharp lower boundary and coarse-grained texture, which grades upward into a much thinner, fine-grained, dark lamina with a sharp, and typically irregular, undulose or wispy upper boundary (Zhang, 1986). This type of alternation gives rise to filmy architecture (see below). The film may be smooth (Fig. 116d) or wavy (Figs 116e, 118)
4. *Void intercalated*: in which any of the laminar types described above have fenestrae in laminae filled with sediment or cement (Fig. 116f, 119a,b); later infilling of fenestrae may push laminae apart (Figs 116g, 119a,c).

Laminar profile (laminar shape)

The 3D conformation of a lamina is referred to as the laminar shape (Figs 120–123). The geometric attributes of laminar shape were discussed at length by Hofmann (1969a, p. 6–16). Most laminae are convex upward. Since laminar shape is 3D, it has to be inferred from the laminar profile (the 2D expression of the laminar shape) or determined from 3D reconstruction. Laminar profile seems to have been first used by Hofmann (1976b, p. 48), who discussed and illustrated the various parameters that make up the profile of the lamina (Hofmann, 1976b, p. 51, 52, fig. 5). It is common practice to illustrate the laminar shape by means of the laminar profile (e.g. see Walter, 1972, p. 20, fig. 6). Hofmann (1977) and Zhang and Hofmann (1982) carried out morphometric analysis of the laminar profile to show how this feature could be used to characterize stromatolite taxa.

Because the laminar profile is the 2D expression of a 3D feature, it is best characterized by 3D reconstruction. The laminar profile needs to be examined in sections cut as close as possible to the growth axis of the stromatolite. It can show considerable variation throughout an individual stromatolite, or vary either from column to column, or individual to individual, and the range of variation in itself might be diagnostic. However, the laminae may be nearly obliterated in poorly preserved specimens.

The range of variation should be given either from visual inspection, or by the use of morphometric analysis (Hofmann, 1976b, 1977; Zhang and Hofmann, 1982).

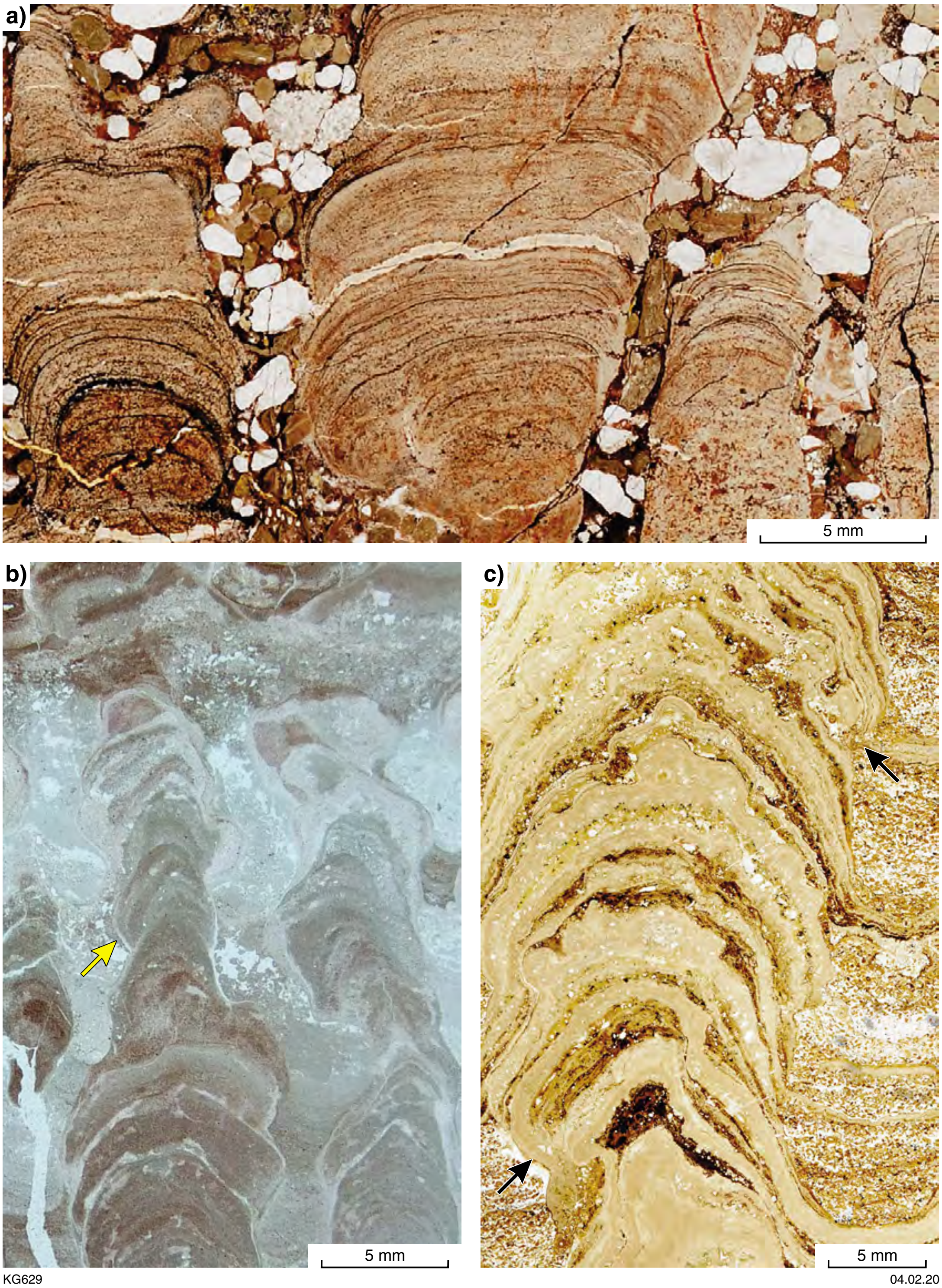

Figure 112. Examples of parallel and overlapping laminae: a) parallel; *Anabaria juvensis*; cap carbonate above Pioneer Sandstone; Amadeus Basin; Ediacaran, Neoproterozoic; near Ross River Highway, ALICE SPRINGS, Northern Territory, Australia; thick section, GSWA F52665–109263 (photo by SM Awramik and K Grey); b) light laminae overlapping dark laminae (arrow); *Segosia finlaysoniensis*; Bubble Well Member, Juderina Formation, Windplain Group; Yerrida Basin; Rhyacian to Statherian, Paleoproterozoic; Quartermaine Well, PEAK HILL, Western Australia; thick section GSWA F48460–76593 (photo by K Grey); c) light laminae overlapping dark laminae (arrows); stromatolite; probably from the El Molino Formation; Upper Cretaceous – Paleocene; near Challa Mayu, Bolivia; thick section from commercially available slab, UCSB collection (photo by SM Awramik)

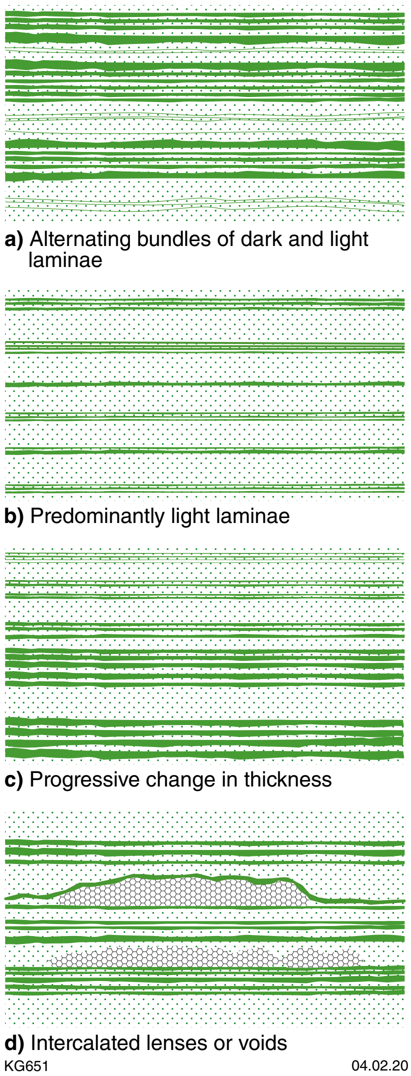

Figure 113. Microbialite macrolaminae and intercalations: a) macrolaminae formed by alternating bundles of dark and light laminae; b) macrolaminae formed by predominantly light laminae with rarer dark laminae; c) laminae showing a progressive change in thickness; d) intercalated lensoid detrital or void-filling minerals

Laminar profile (as a proxy for laminar shape) (Figs 120–122) can be of the following types:

1. *Concave*: (Figs 120a, 121a) used by Hofmann (1969a, p. 15; fig. 8) for a lamina in which the curvature is downward
2. *Flat*: (Figs 120b, 121b) a horizontally continuous lamina. Sometimes referred to as planar (obsolete term)
3. *Gently convex*: (Figs 120c, 121c) used by Preiss (1972, p. 93) for a 'lamina whose height to width ratio is less than or equal to 0.5'
4. *Steeply convex*: (Figs 120d, 122a) used by Preiss, 1972, p. 93) for a 'lamina whose height-to-width ratio is greater than 0.5'
5. *Parabolic*: (Figs 120e, 122b) Hofmann (1969a, p. 15, fig. 8) designated various types of parabolic laminae, such as acute or prolate. However, these are not readily distinguished and we prefer to use the single term parabolic defined by (Preiss, 1972, p. 93) as a 'lamina whose axial longitudinal (usually the vertical) section approximates a parabola'
6. *Penecinct*: (Figs 120f, 122c) a lamina that almost completely encloses a body. Such forms can also be described as nodular with a narrow base, or as a pedestal. Unless the vertical profile passes through the area of attachment (Figs 120f, 122c), the form may appear as in an oncoid (Hofmann, 1969a, fig. 8). Hofmann (1969a) referred to this as globoidal (obsolete term)
7. *Plenicinct*: (Figs 57c–e, 120g, 122d) a lamina that completely encloses a body, as in an oncoid. Also sometimes referred to as an inflated lamina (obsolete term), Hofmann (1969a, fig. 8) also referred to this as globoidal
8. *Rectangular*: (Figs 120h, 123a) Defined by Preiss (1972, p. 93, fig. 1) and Walter (1972, p. 14, text-fig. 3) as a lamina that 'in a longitudinal section (usually the vertical profile) of a column is flat topped with edges deflexed at about 90°'
9. *Rhombic*: (Figs 120i, 123b) Defined by Preiss (1972, p. 93, fig. 1) and Walter (1972, p. 14, text-fig. 3) as a lamina that 'in a longitudinal (usually the vertical) section of a column is flat topped with subparallel edges not perpendicular to the top'
10. *Conical*: (Figs 120j, 123c) a lamina with a pointed profile. The term has been widely used in the literature, but should be restricted to a lamina that is cone-shaped in 3D. The presence of conical laminae does not necessarily produce a cone-shaped stromatolite. Cylindrical columns can be composed of conical laminae in which the lower parts of the laminae are sub-vertical and parallel to each other and to the column walls, as in some forms of *Conophyton*. Conical laminae with steep vertical profiles commonly have a small, second-order, even more acute cone at their peak, and these superimposed structures form an axial zone (see below), as typified by *Conophyton*. Hofmann (1969a, p. 14, fig. 8) referred to an inflexed lamina with a pointed crest, which is convex on either side of the crest, as geniculate (obsolete term)
11. *Angulate*: (Figs 120k, 123d) (also referred to as tented, crested or cuspate) used to describe a lamina that is not conical but which is angular in profile. Hofmann (1969, p. 15, fig. 8) used the term for a lamina that is angular in profile but which forms a ridge, crest or cusp, rather than a cone, in 3D. Tented is when planar, filmy laminae drape over a single vertically oriented support (Sumner, 1997b, p. 306). Cuspate tends to be lower in profile than either crested or ridged and the profile is concave on both sides of the crest (Hofmann, 1969, p. 15, fig. 8). Hofmann (1969) and Allwood et al. (2006) used the term in a somewhat different sense to Sumner (1997a,b), Schröder et al. (2009) and Bartley et al. (2015). Until this aspect of terminology is standardized, make sure the feature is adequately described and cite the usage being followed.

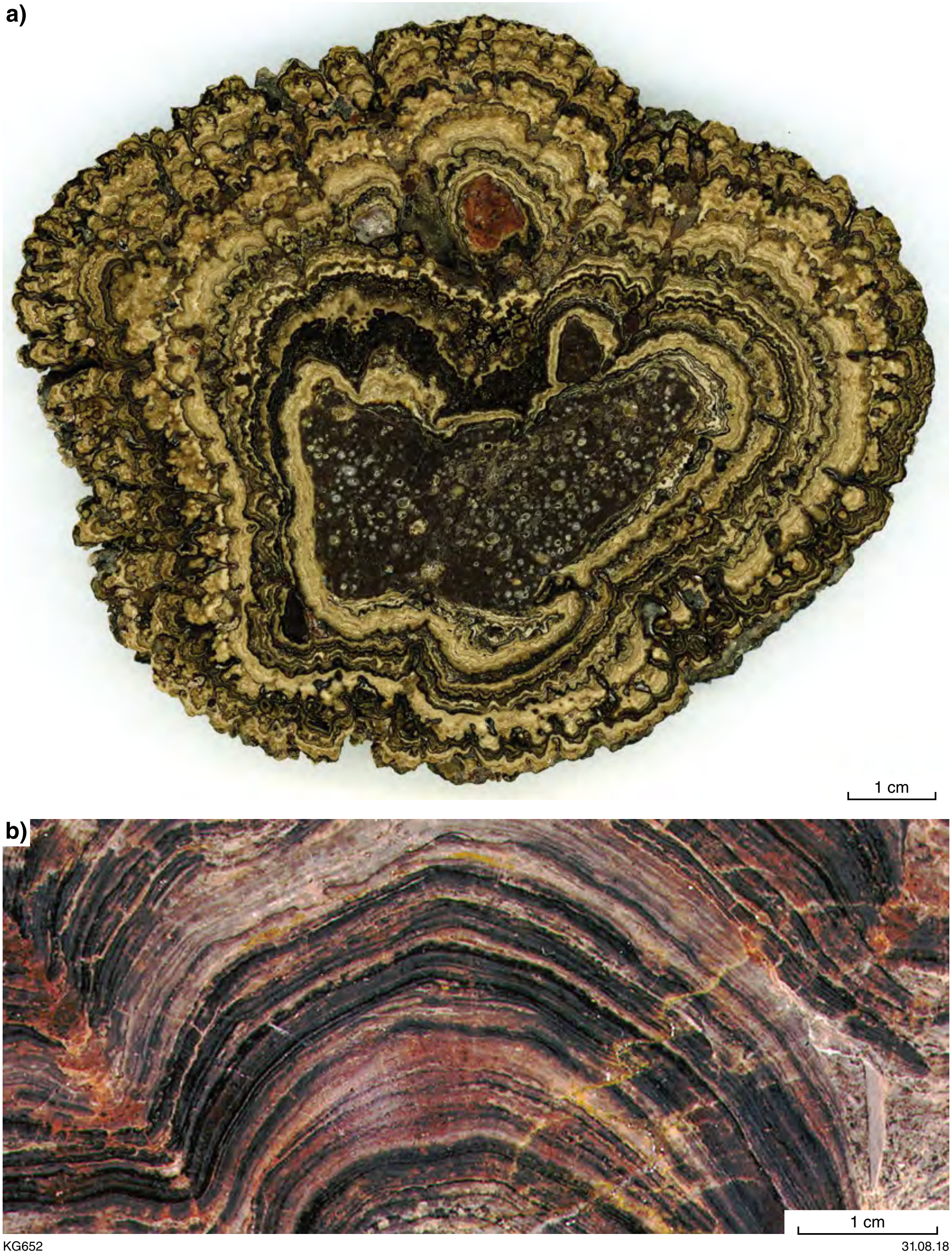

Figure 114. Examples of macrolaminae: a) macrolaminae with predominantly light laminae in an oncoid; unknown formation; Upper Cretaceous; Lady of Angels Lake, Chihuahua, Mexico; commercially available slab, UCSB collection (photo by SM Awramik); b) dark macrolaminae with thin light laminae and light laminae with thin dark laminae; *Collenia undosa*; Spokane Formation, Belt Supergroup; Belt Basin; Calymmian, Mesoproterozoic; near White Sulphur Springs, Meagher County, Montana, US; polished slab, UCSB collection (photo by SM Awramik)

Figure 115. Examples of macrolaminae: a) laminae that show a progressive change in thickness, appearing to thin towards top right (away from axial zone); *Conophyton* new Form (Pingandy form); Muntharra Formation, Edmund Group; Edmund Basin; Calymmian, Mesoproterozoic; Pingandy Creek, Mount Egerton, Western Australia; thick section GSWA F9932–46009F (photo by SM Awramik and K Grey); b) macrolaminae formed by predominantly light laminae with rarer dark laminae (l) and predominantly dark lamine with rarer light laminae (d); cf. *Colonella* new Form; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, Edmund, Western Australia; thick section GSWA F9915–46013 (photo by M Ang)

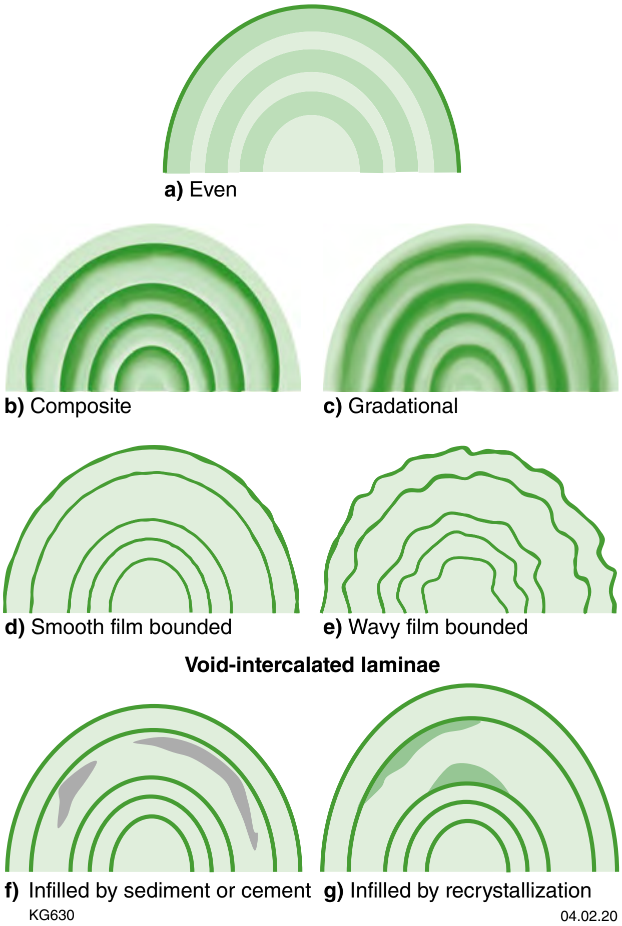

Figure 116. Stromatolite laminar alternation: a) even; b) composite with some sharp boundaries, others are gradational; c) both light and dark laminae gradational; d, e) film bounded with d) smooth or e) wavy laminae; f, g) void-intercalated laminae, either f) an original fenestrate lamina infilled by sediment or cement, or g) later infill which may push the laminae apart

Laminar waviness

Laminar waviness (Figs 124, 125) is the degree of evenness of the laminae, and is a measure of the density of second-order curvatures. Hofmann (1969a, p. 14–16) characterized laminae according to the order of curvature and crinkling. Order of curvature addresses whether a lamina is smooth (first order), or has second or third orders of curvature imposed on it. Walter (1972, p. 14, text-fig. 3) substituted the terms wavy and wrinkled, which are preferred here. The degree of laminar waviness and wrinkling varies from no wrinkling (smooth), to specific types of waviness and wrinkling (wavy and wrinkled). Where the waviness is regular, the simplest method is to describe it using the following terms:

1. *Smooth*: (Figs 124a, 125a) with no second-order curvature or flexures
2. *Wavy*: (Figs 124b, 125b) a lamina having a second-order curvature with wavelengths commonly greater than 2 mm; Walter (1972, p. 14, text-fig. 3) defined wavy lamina as having 'flexures of wavelength greater than 2 mm'. Waviness should not be confused with pseudocolumns, in which the flexures are formed by the full width of a lamination across a column or pseudocolumn
3. *Wrinkled*: (Figs 124c, 125c) a second-order curvature or flexures of wavelengths less than or equal to 2 mm (Preiss, 1972, p. 93, fig. 1; Walter, 1972, p. 14).

Where the wrinkles or waviness are less regular, terms such as corrugate, crenate, crenulate, crinkled and dentate have sometimes been used as desciptors (Hofmann, 1969a, p. 14, fig. 8).

In addition to showing waviness, the laminar profile may show a modality (Fig. 126), which is the number of crests in a laminar profile. For example, the profile may be unimodal, with a single crest (Figs 126a, 127a), bimodal, with two crests (Figs 126b, 127b), or multimodal, if more than two crests are present. Bimodality frequently occurs just prior to branching. The axis of the profile may be symmetrical or asymmetrical (Figs 126c, 127c), that is, it may be skewed to the left or right of the midline.

Synoptic relief of laminae

The synoptic relief (Figs 128–129) is the amplitude of the laminar profile in 3D. It is the feature sometimes referred to as the relief of the lamina or the synoptic profile, and was discussed and illustrated by Hofmann (1969a, p. 9, and fig. 18) and Walter (1972, p. 61, text-fig. 22). The 2D synoptic profile is commonly described and measured as a proxy for the synoptic relief. The synoptic relief can be characterized as follows, modified from Hofmann (1969a, p. 9), where W is the width of the hemispheroid fitted to the laminar shape, and H is the relief or height of the lamina:

1. *Low*: (Figs 128a, 129a) W >> H
2. *Moderate*: (Figs 128b, 129b) W ≈ H
3. *High*: (Figs 128c, 129c) W << H

The synoptic relief may vary throughout the height of the head or individual structure, or may show regular patterns of variation.

Degree of inheritance of laminae

Inheritance (Figs 130–131) refers to the degree to which a lamina conforms in shape to underlying laminae and is equivalent to the term serial development of Hofmann (1969a, p. 17, fig. 13). There are three terms to describe inheritance:

1. *Low*: (Figs 130a, 131a) successive laminae rarely conform to the shape of the underlying laminae
2. *Moderate*: (Figs 130b, 131b) some but not all laminae conform to the shape of the underlying laminae
3. *High*: (Figs 130c, 131c) most laminae conform to the shape of the underlying laminae.

Figure 117. Examples of laminar alternation: a) even alternation (bracketed); stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; 'Mycenae' locality, Meentheena Conservation Reserve, Pilbara, NULLAGINE, Western Australia; thick section, GSWA F12515–46196 (photo by M Ang); b) composite; stromatolite; Copper Harbor Conglomerate, Oronto Group; Keweenawan Trough; Stenian, Mesoproterozoic; Keweenaw Peninsula, Keweenawa County; Upper Peninsula, Michigan, US; thick section, UCSB collection (photo by SM Awramik)

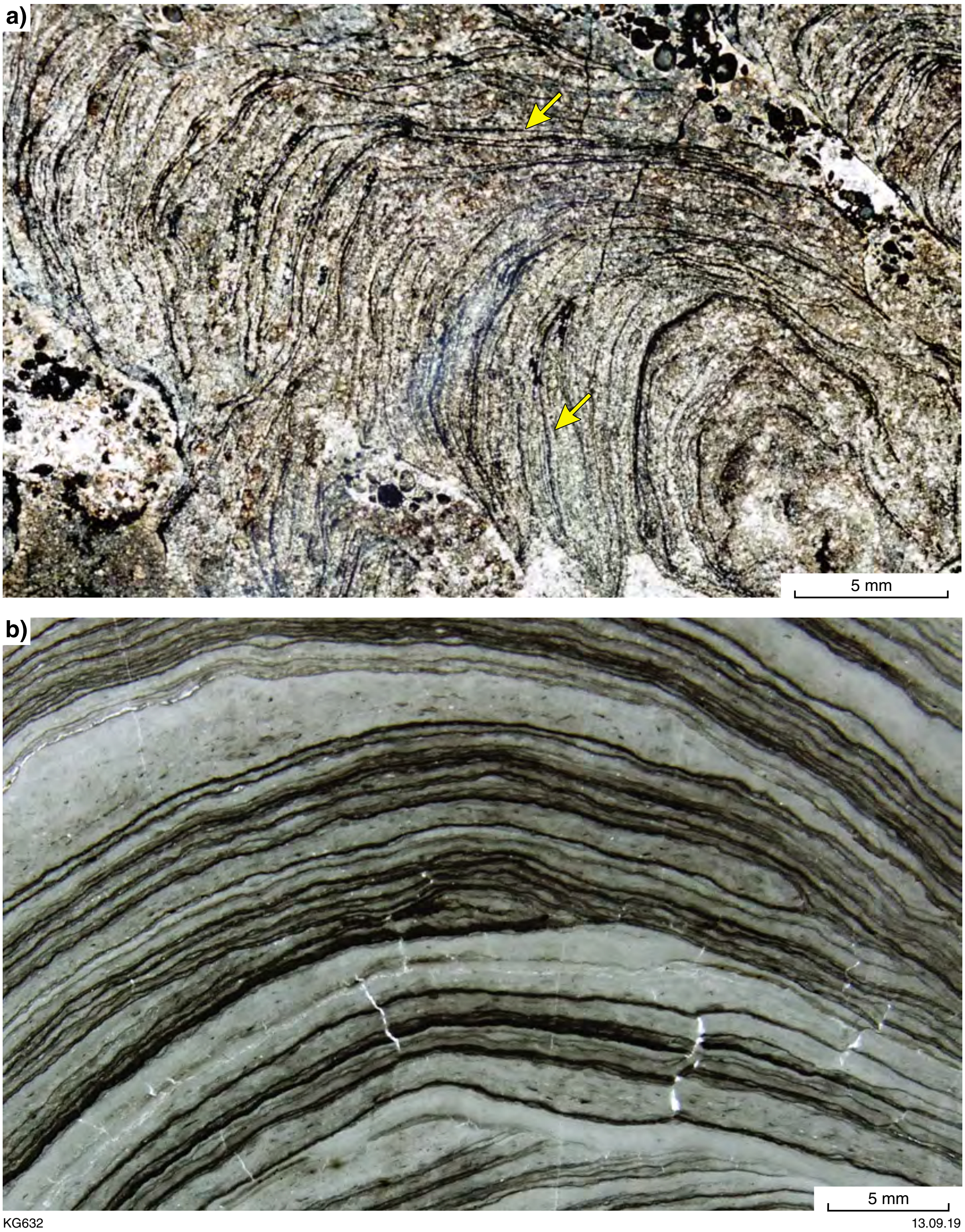

Figure 118. Examples of laminar alternation – film bounded (arrows): a) *Carnegia wongawolensis*; Windidda Member, Frere Formation; Earaheedy Basin; Orosirian, Paleoproterozoic; near Wongawol Homestead, KINGSTON, Western Australia; thick section GSWA F12350–46595 (photo by K Grey); b) alternating light and dark laminae; cf. *Colonella* new Form; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, EDMUND, Western Australia; thick section GSWA F9916–46073B (photo by M Ang)

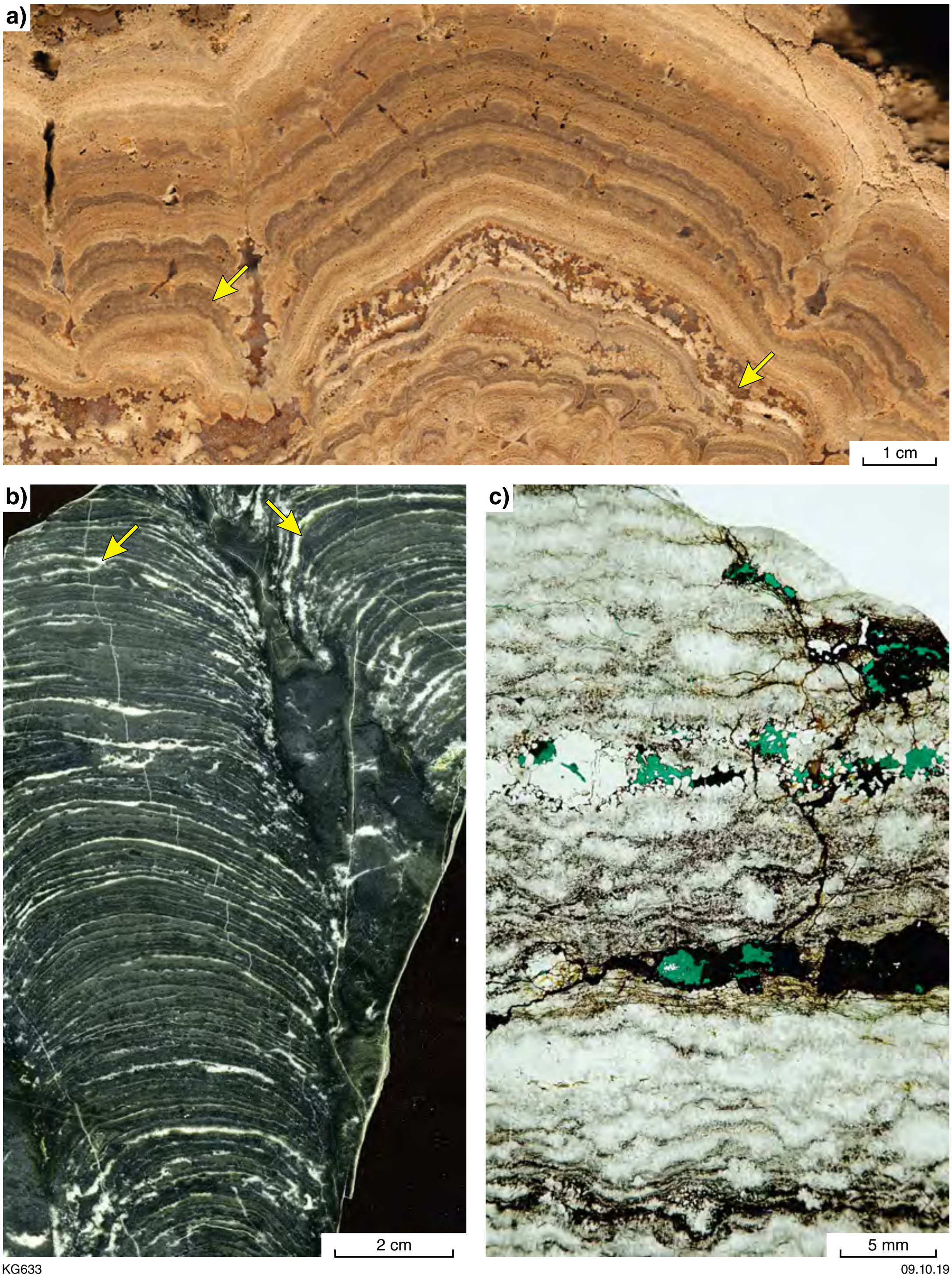

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Figure 119. Examples of laminar alternation – void intercalated: a) intercalated sediment; stromatolite; Laney Member, Green River Formation; Washakie Basin; Eocene; Delaney Rim, Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik); b) intercalated dolomicrite and dolosparite; *Minjaria uralica*; Min'yar Formation, Karatau Group; Tonian, Neoproterozoic; Belaya River, near Belskaya, Bashkortostan, South Urals, Russia; UCSB collection, Preston Cloud sample 1a of 10/8/71. The dolosparite is filling fenestrae that developed along laminae (photo by SM Awramik); c) intercalated cement, silica and mineral (copper) infilling fenestrae; Broadhurst Formation, Throssell Range Group; Tonian, Neoproterozoic; Nifty Copper Mine, Paterson Range, Western Australia; drillcore thick section GSWA F52426–84700 (photo by SK Martin)

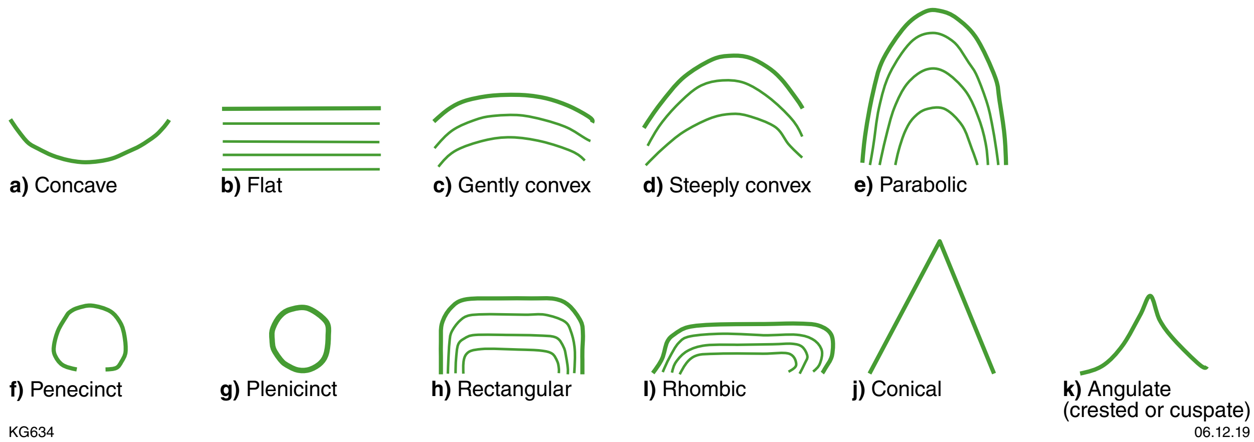

Figure 120. Laminar profile (laminar shape): a) concave; b) flat; c) gently convex; d) steeply convex; e) parabolic; f) penecinct; g) plenicinct; h) rectangular; i) rhombic; j) conical; k) angulate (crested or cuspate) (after Hofmann, 1969a). Laminar shape is 3D and either has to be inferred from the laminar profile (the 2D expression of the laminar shape) or determined from 3D reconstruction

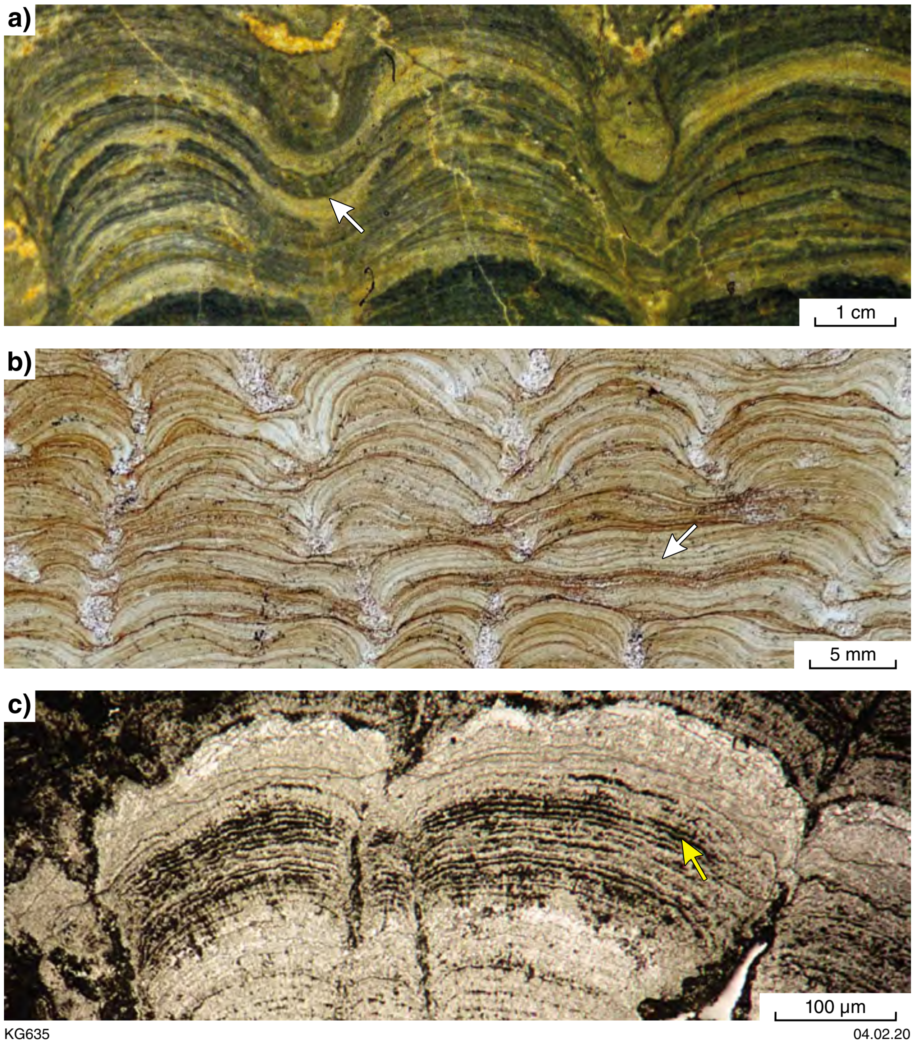

Figure 121. Examples of laminar profile (shape): a) concave; in pseudocolumn of *Omachtenia teagiensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; Sweeney Creek, Nabberu, Western Australia; polished slab GSWA F12369–46580 (photo by K Grey); b) flat; *Acaciella savoryensis*; Boondawari Formation; Officer Basin; Ediacaran, Neoproterozoic; Boondawari Creek, Gunanya, Western Australia; thick section (Holotype) GSWA F49036–91651G (photo by K Grey); c) gently convex; stromatolite; Tipton Member, Green River Formation; Bridger Basin; Eocene; Essex Mountain, Sweetwater County, Wyoming, US; acetate peel, UCSB collection (photo by SM Awramik)

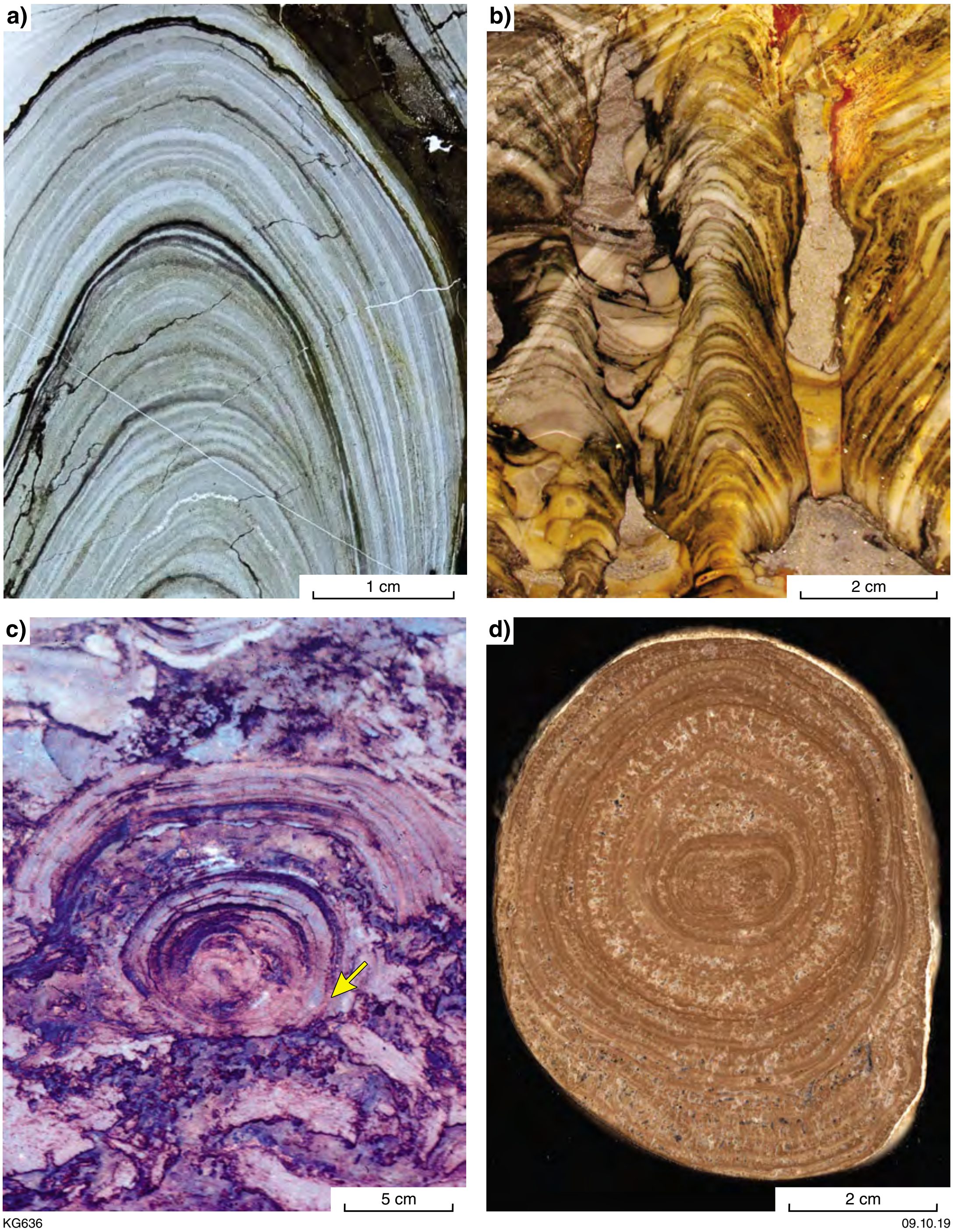

Figure 122. Examples of laminar profile (shape): a) steeply convex; stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; 'Mycenae' locality, Meentheena Conservation Reserve, NULLAGINE, Western Australia; thick section GSWA F12515–46196 (photo by M Ang); b) parabolic; conical-columnar stromatolite; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Redmont, ROY HILL, Western Australia; cut face, GSWA F52672–139033 (photo by DTO Flannery); c) penecinct (arrow) stromatolite; Duck Creek Dolomite, Wyloo Group; Ashburton Basin; Orosirian, Paleoproterozoic; Duck Creek, Ashburton region, WYLOO, Western Australia (photo by K Grey); d) plenicinct oncoid; Wasatch Formation; Fossil Basin; Eocene; Sixmile Creek, Rich County, Utah, US; polished slab, UCSB collection (photo by SM Awramik)

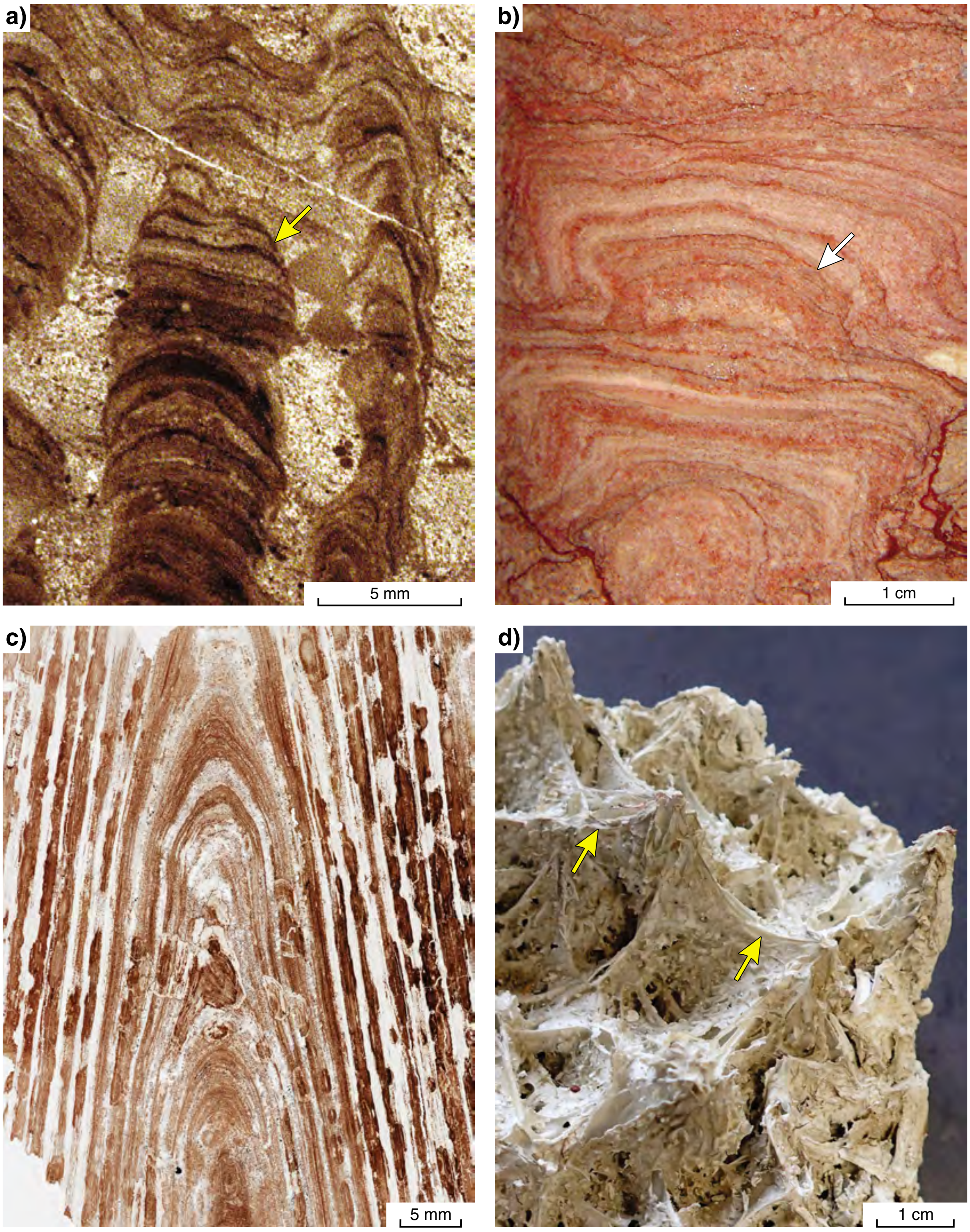

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Figure 123. Examples of laminar profile (shape): a) rectangular (arrow); ?*Acaciella augusta*; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; near Tooma Stockyard, Nullagine, Western Australia; thick section GSWA F52562–84678B (photo by K Grey); b) rhombic (arrow); *Basisphaera irregularis*; Woolnough Member, Browne Formation, lower Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Lancer 1, 1335.2 m, Gibson Desert, Herbert, Western Australia (photo by K Grey); c) conical, *Conophyton* new Form; Pear Tree Dolostone, Limbunya Group; Birrindudu Basin; Statherian, Paleoproterozoic; Swan Yard, Limbunya, Northern Territory, Australia; thick section GSWA F52404–138930 (photo by SM Awramik and K Grey); d) angulate (cuspate) (arrows); *Conophyton weedii*; 'Conophyton Pool', Yellowstone National Park, Teton County, Wyoming, US; UCSB collection (photo by SM Awramik)

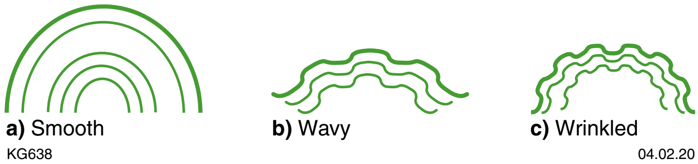


Figure 124. Laminar waviness: a) smooth; b) wavy; c) wrinkled

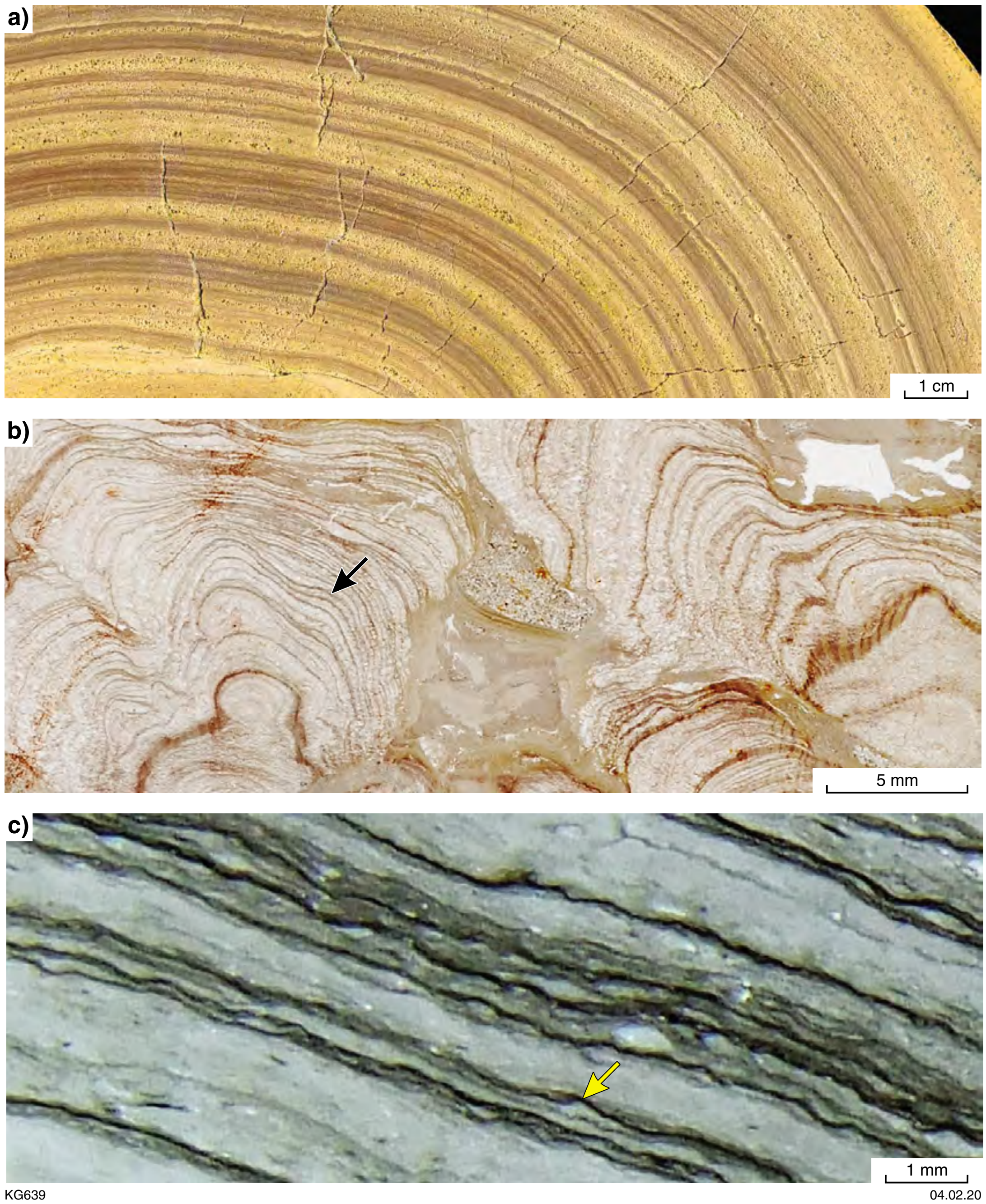


Figure 125. Examples of laminar waviness: a) smooth laminae; stromatolite; Fossil Butte Member, Green River Formation, Fossil Basin; Eocene; Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik); b) wavy laminae (arrow); stromatolite; Woodiana Member, Jeerinah Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Tambrey ruins, Pilbara, PYRAMID, Western Australia; thick section GSWA F52635A–90538B (photo by SM Awramik and K Grey); c) wrinkled laminae (example arrowed); columnar stromatolite; cf. *Colonella* new Form; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, EDMUND, Western Australia; thick section GSWA F9915–46013 (photo by M Ang)

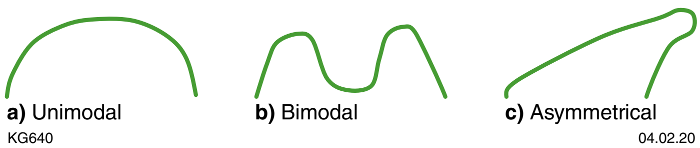


Figure 126. Laminar modality: a) unimodal; b) bimodal; c) asymmetrical

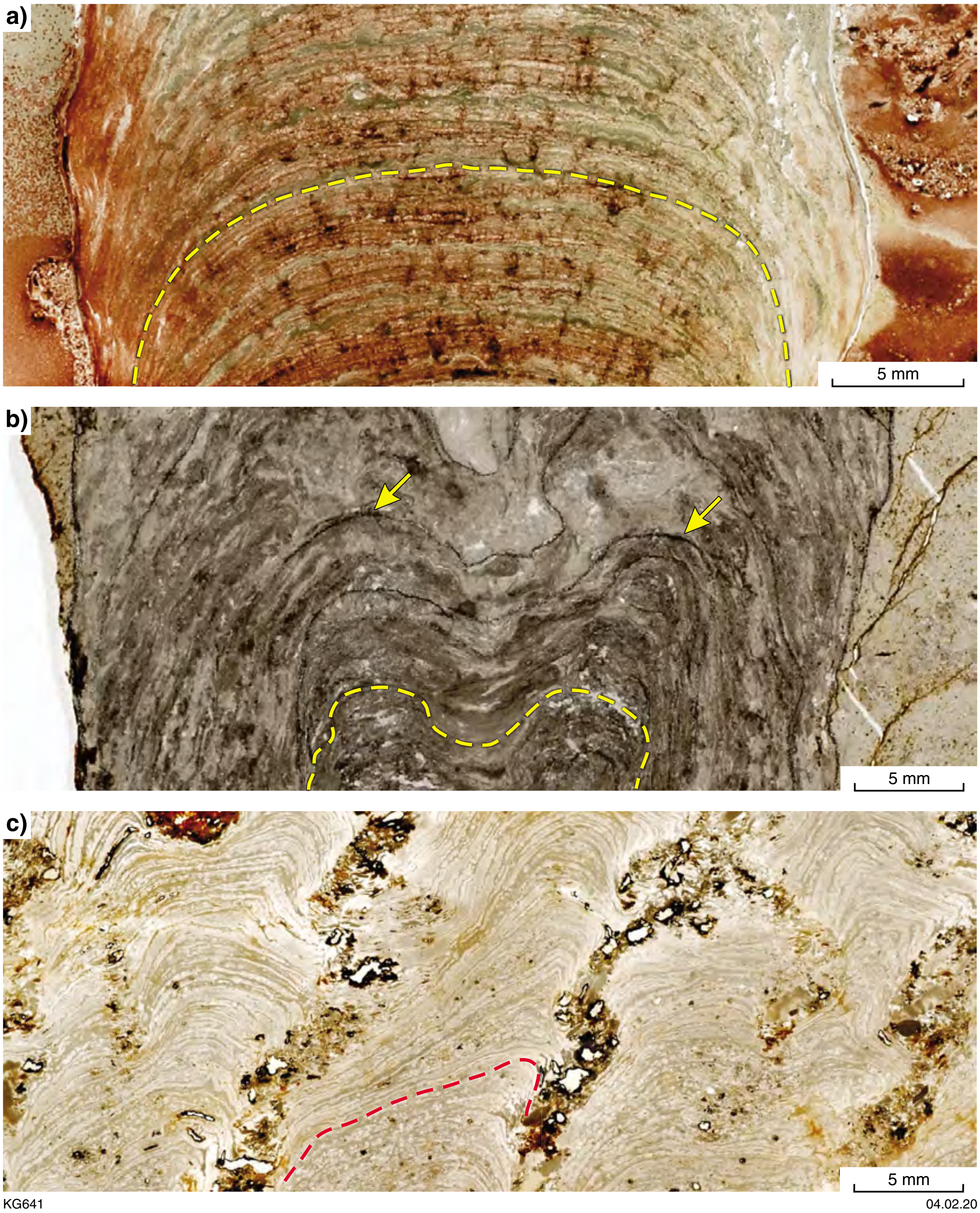


Figure 127. Examples of laminar modality: a) unimodal (outlined); *Externia yilgarnia*; Frere Formation; Earaheedy Basin; Orosirian, Paleoproterozoic; near Lake Wells, DUKETON, Western Australia; thick section GSWA F12360–46075 (photo by SM Awramik and K Grey); b) bimodal (outlined); *Pilbaria deverella*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; Sweetwaters Well, NABBERU, Western Australia; thick section GSWA F12378–46583 (photo by SM Awramik and K Grey); c) asymmetrical (outlined), *Eucapsiphora leakensis*; Mount Leake Formation; Statherian to Stenian, Paleoproterozoic to Mesoproterozoic; Mount Leake, PEAK HILL, Western Australia; thick section GSWA F12521–59816 (photo by SM Awramik and K Grey)

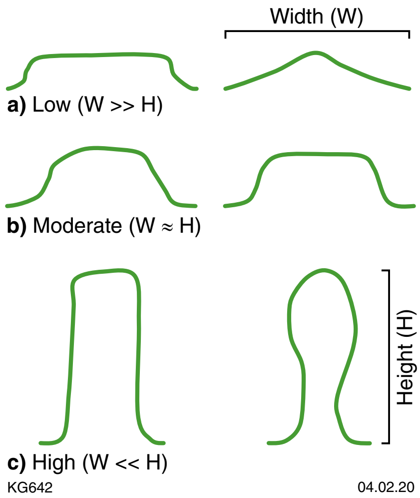
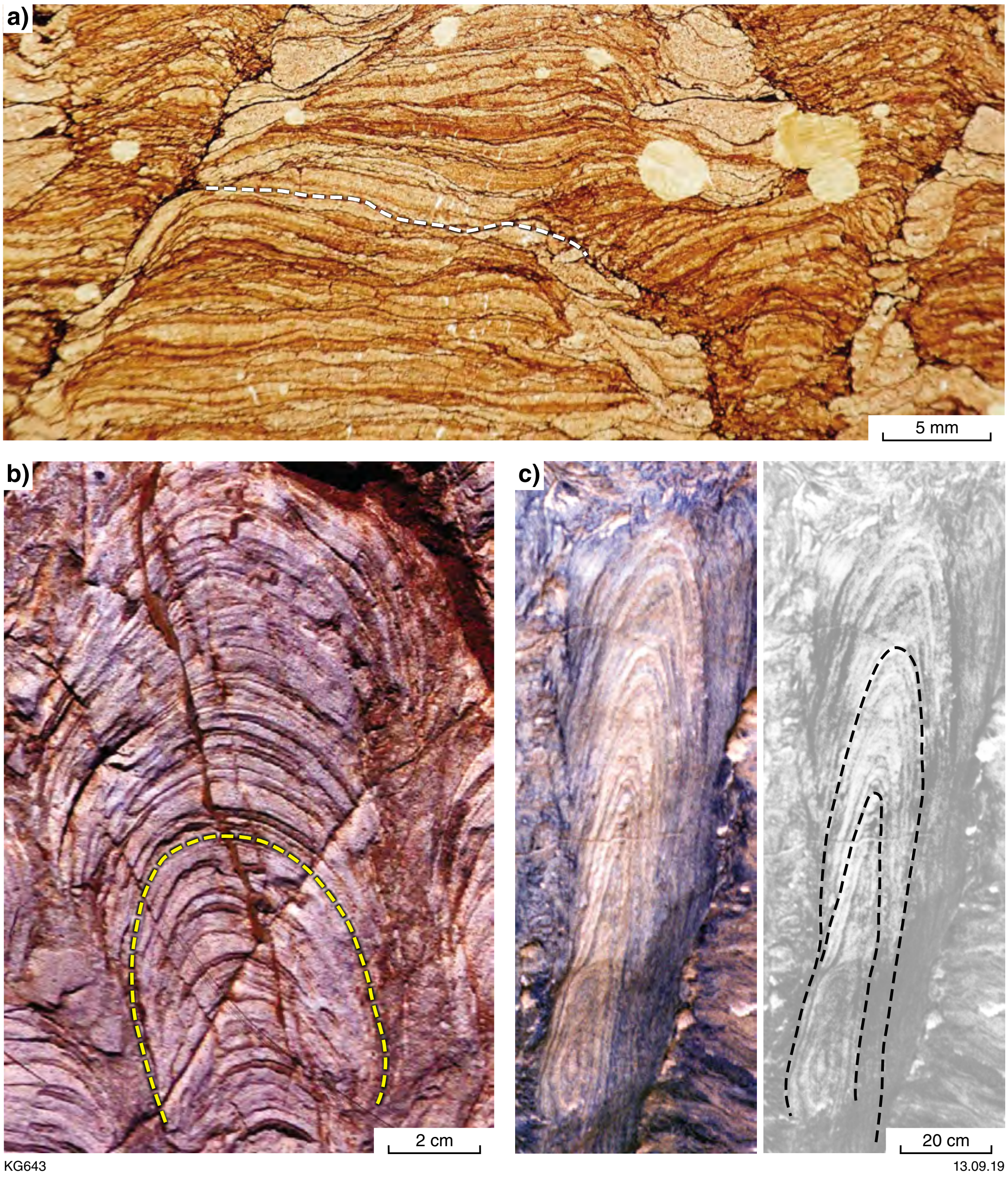


Figure 128. (left) Synoptic relief: a) low: W >> H; b) moderate: W ≈ h; c) high: W << h; where W is the span of the structure and H is relief of the lamina (after Hofmann, 1969a)

Figure 129. (below) Examples of synoptic relief (outlined): a) low; ?*Inzeria conjuncta*; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; Muddauthera Creek, eastern Pilbara, NULLAGINE, Western Australia; thick section GSWA F52552–109251C (photo by SK Martin); b) moderate; unnamed stromatolite, Coomberdale Chert, Moora Group (age uncertain); ?Mesoproterozoic; near Coorow, PERENJORI, Western Australia (photo by K Grey); c) high; *Conophyton ressoti*; Atar Formation, (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Tod-Oued Tenkharada, Atar region, Mauritania. Lamina shape outlined in adjacent sketch (photo by K Grey)



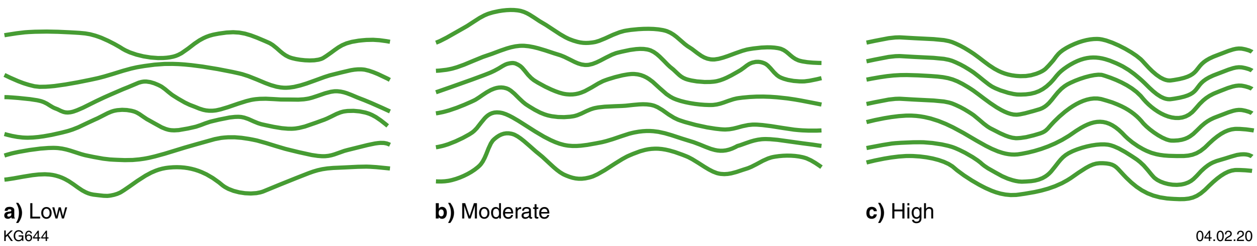


Figure 130. Degree of laminar inheritance of laminae: a) low; b) moderate; c) high

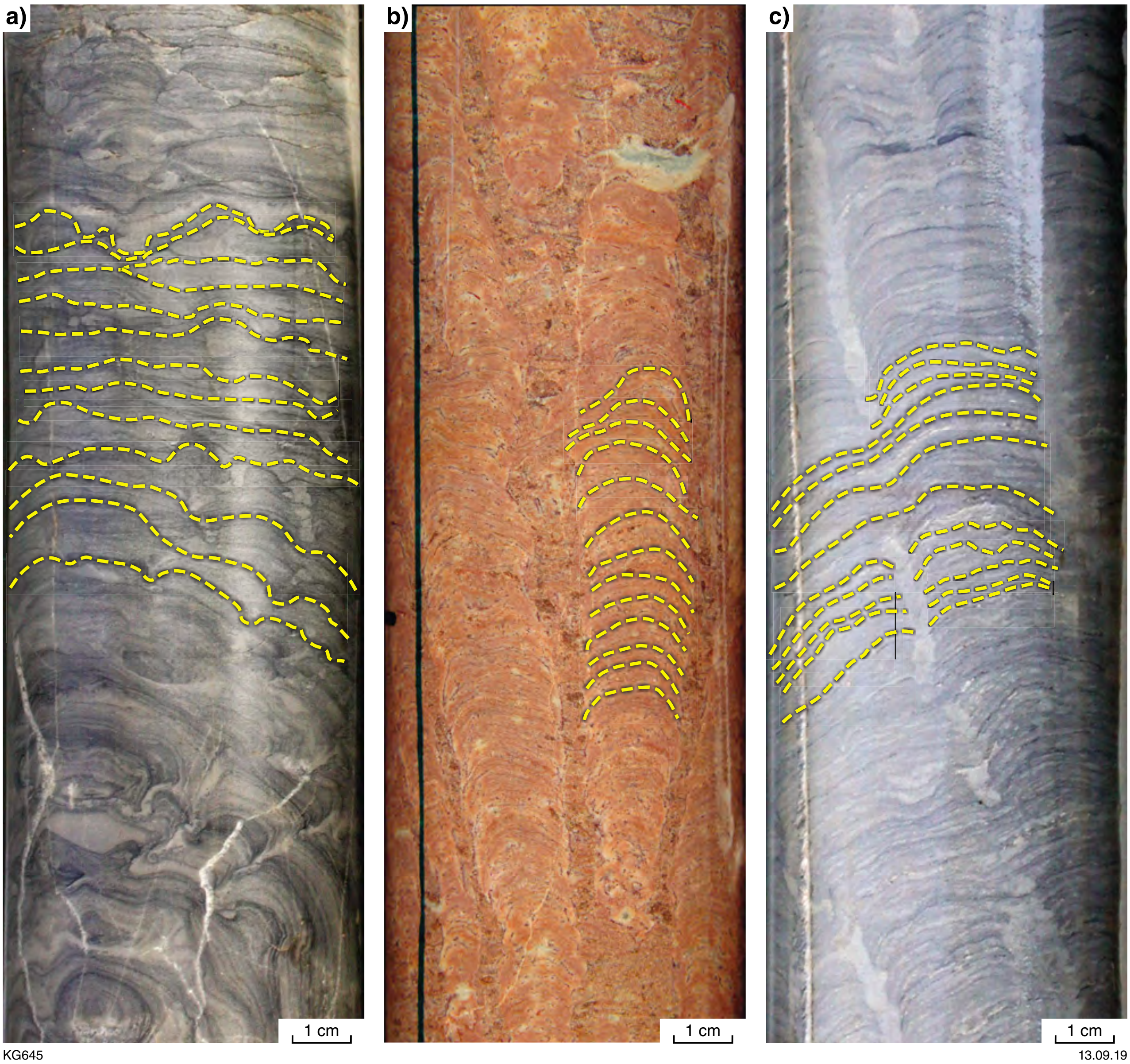


Figure 131. Examples of degree of laminar inheritance (outlined): a) low inheritance; *Inzeria intia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Wallara 1, 1987 m, Henbury, Northern Territory, Australia; core (photo by AC Hill); b) moderate inheritance; *Boxonia pertaknurra*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Wallara 1, 1986 m, Henbury, Northern Territory, Australia; core (photo by AC Hill); c) high inheritance; *Minjaria pontifera*; Woolnough Member, Browne Formation, lower Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Lancer 1, 1332.5 m, Gibson Desert, Herbert, Western Australia; core (photo by K Grey)

Lateral continuity and thickness

Lateral continuity (Figs 132–136) refers to the degree of continuity of a lamina across the individual stromatolite structure, its variability in thickness, and the uniformity of the lithology across the structure. The lateral continuity of a lamina within the head, column or branch may closely reflect the original texture of the lamina, or may be a result of secondary alteration (and thus may require microstructural considerations). Choose from the following terms to describe lateral continuity:

1. *Continuous*: (Figs 132a, 133a,b) a lamina that extends continuously across the stromatolite, the lithology is consistent, and there are only slight changes in thickness, with possible thinning at the margins. The upper and lower boundaries are more or less parallel
2. *Discontinuous*: (Figs 132b, 133c) a lamina that extends from one side of the stromatolite to the other, but forms a series of discontinuous, aligned lenses. The lithology within the lenses is consistent
3. *Lenticular*: (Figs 132c, 134) a lamina that extends continuously and the lithology is consistent, but the thickness varies considerably across the curvature. The lamina is relatively thick at the centre but thins regularly towards the stromatolite's margins
4. *Microcross-laminated* (offset lenticular, offset lensoid): (Figs 132d, 135a) a lamina that does not extend from one side of the stromatolite to the other, but forms a series of discontinuous and offset lenses that may be truncated by succeeding laminae. The lithology within the lenses is consistent
5. *Irregular*: (Figs 132e, 135b) a lamina that extends continuously and the lithology is consistent, but the thickness varies irregularly across the stromatolite
6. *Heterogeneous*: (Figs 132f, 135c) a lamina that is different at the centre from the margins of the stromatolite (a characteristic that can also be considered a feature of the microstructure). The thickness can also be variable
7. *Harmonized* (new term) (matched, coordinated, synchronized): (Figs 132g, 136) a lamina in one column that can be matched with corresponding laminae in neighbouring columns, even though the lamina does not necessarily extend across the interspace area. The opposite case, a lamina that is not matched across adjacent columns, can be referred to as discordant (new term).
8. *Isopachous:* all laminae in the structure are of equal thickness along their full length.

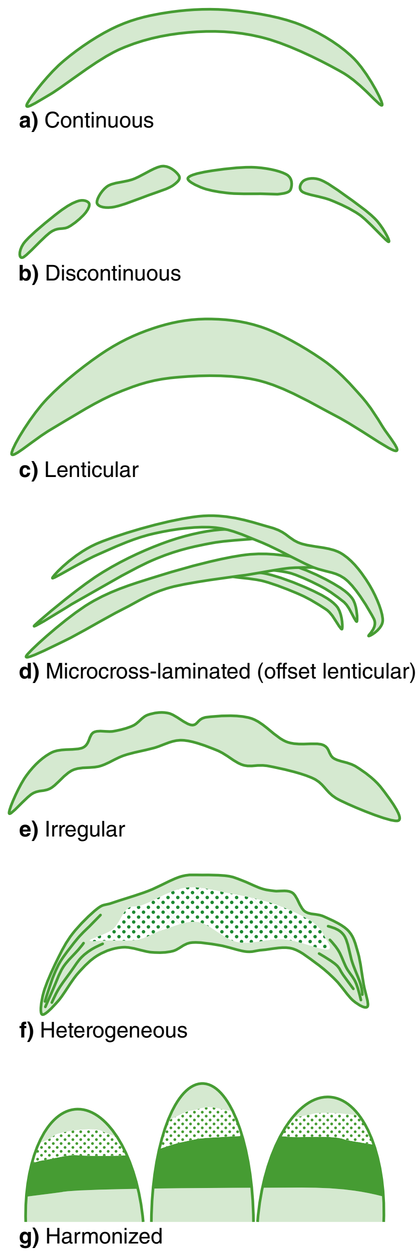


Figure 132. Laminar lateral continuity and thickness: a) continuous; b) discontinuous; c) lenticular; d) microcross-laminated (offset lenticular); e) irregular; f) heterogeneous; g) harmonized (each lamina can be recognized across many columns)

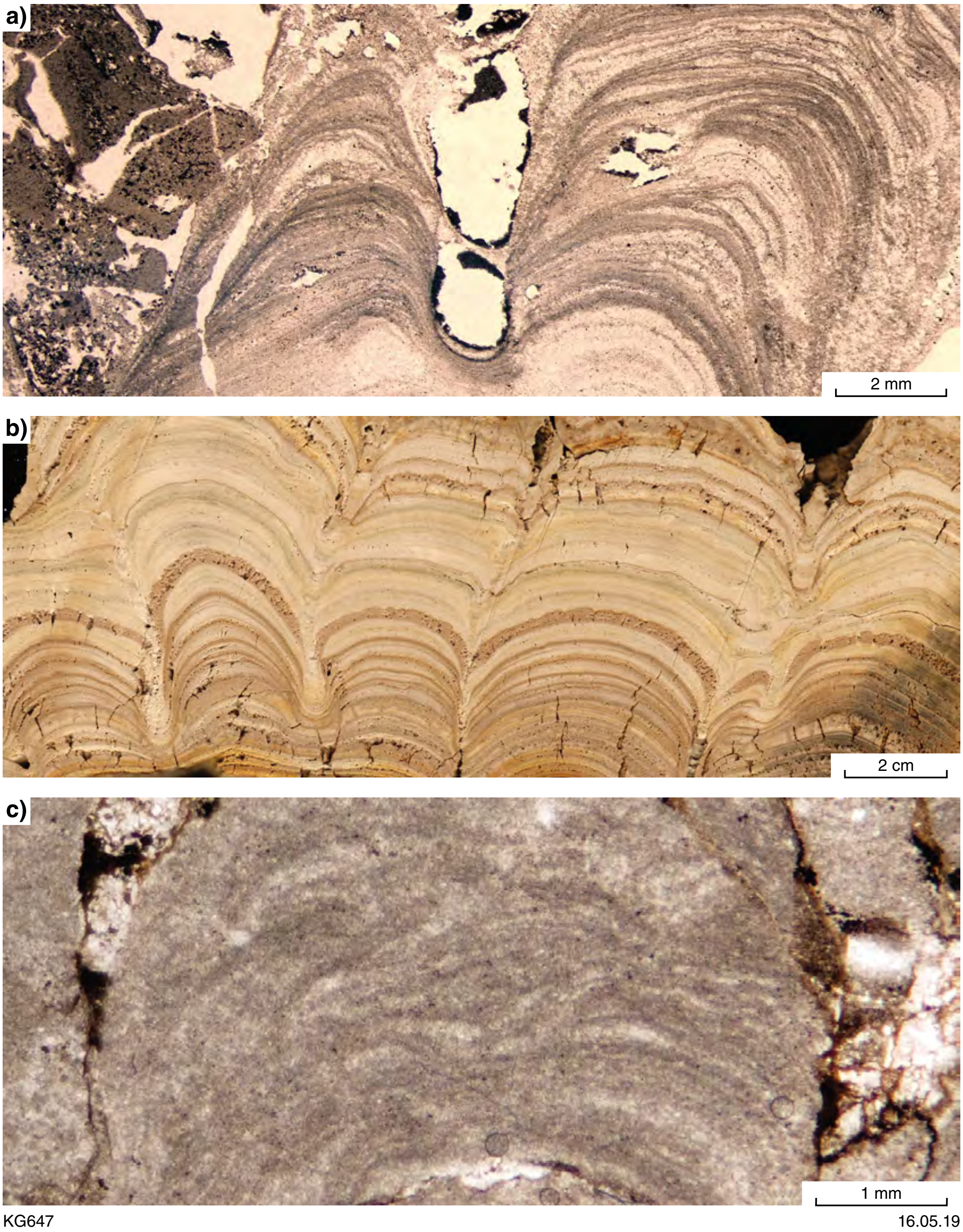


Figure 133. Examples of lateral continuity and thickness: a) continuous; columnar stromatolite; Woodiana Member, Jeerinah Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Tambrey ruins, Pyramid, Western Australia; thick section GSWA F52636–90539 (photo by SK Martin); b) continuous; pseudocolumnar stromatolite; Douglas Creek Member, Green River Formation; Piceance Creek Basin; Eocene; Douglas Pass, Garfield County, Colorado, US; polished slab, UCSB collection (photo by SM Awramik); c) discontinuous; columnar stromatolite; Wollogorang Formation, Tawallah Group; McArthur Basin; Statherian, Paleoproterozoic; Calvert Hills, Northern Territory, Australia; thick section, UCSB collection (photo by SM Awramik)

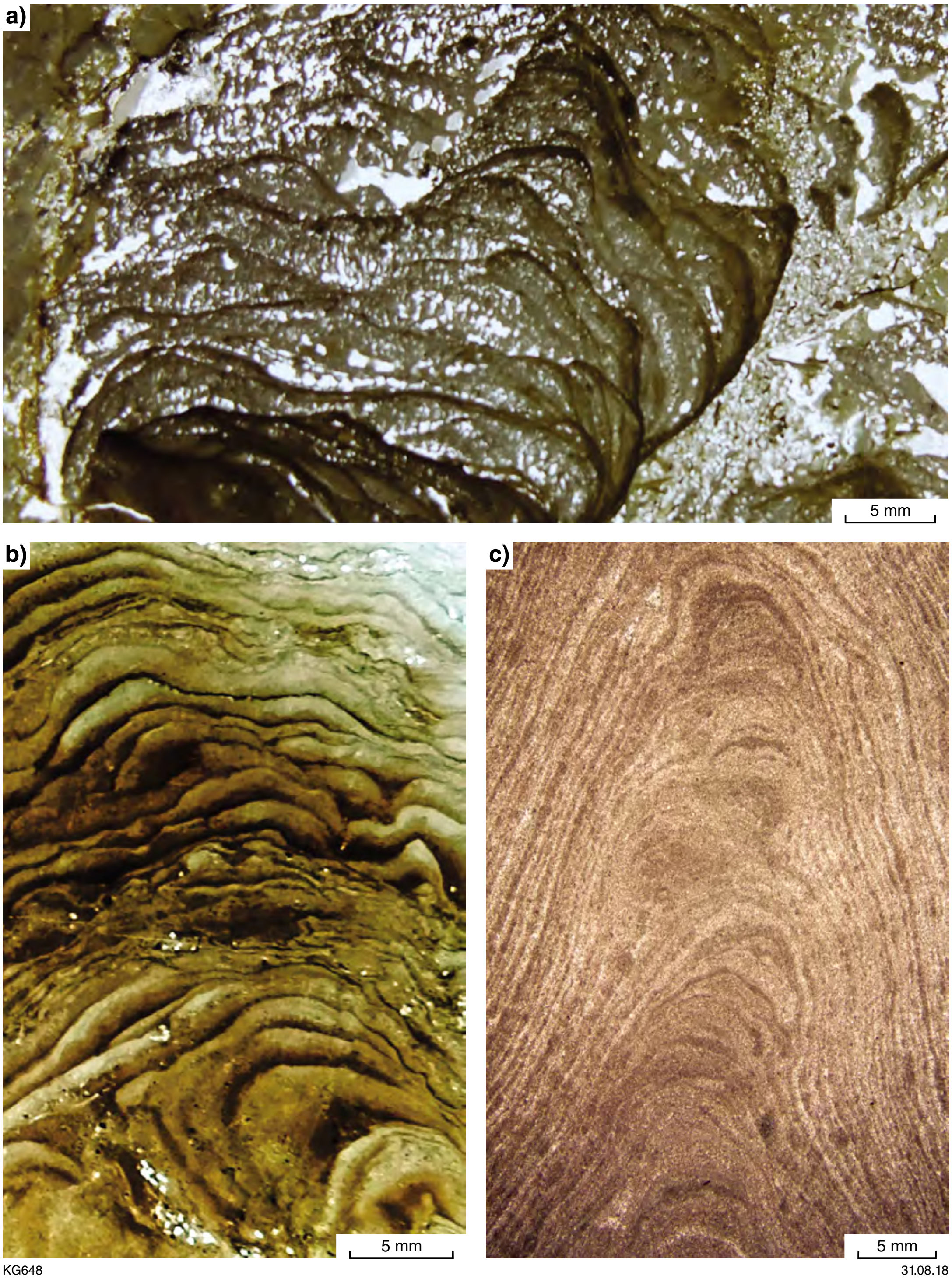


Figure 134. Examples of lateral continuity and thickness – lenticular; a) *Tesca stewartii*; Julie Formation; western Amadeus Basin; Ediacaran, Neoproterozoic; Boord Ridges, MACDONALD, Western Australia; thick section, CPC 19004 (photo by K Grey; b) *Tungussia etina*; Etina Formation, Umberatana Group; Adelaide Rift Complex; Cryogenian, Neoproterozoic; near Blinman, Flinders Ranges, PARACHILNA, South Australia; thick section S158, University of Adelaide collection (photo by HJ Allen); c) *Conophyton* new Form; unnamed carbonate below Pentecost Sandstone, Kimberley Group; Kimberley Basin; Statherian, Paleoproterozoic; Marndungum Island, High Cliffy Islands, Montgomery Reef, CAMDEN SOUND, Western Australia; GSWA F52601–139014 (photo by HJ Allen)

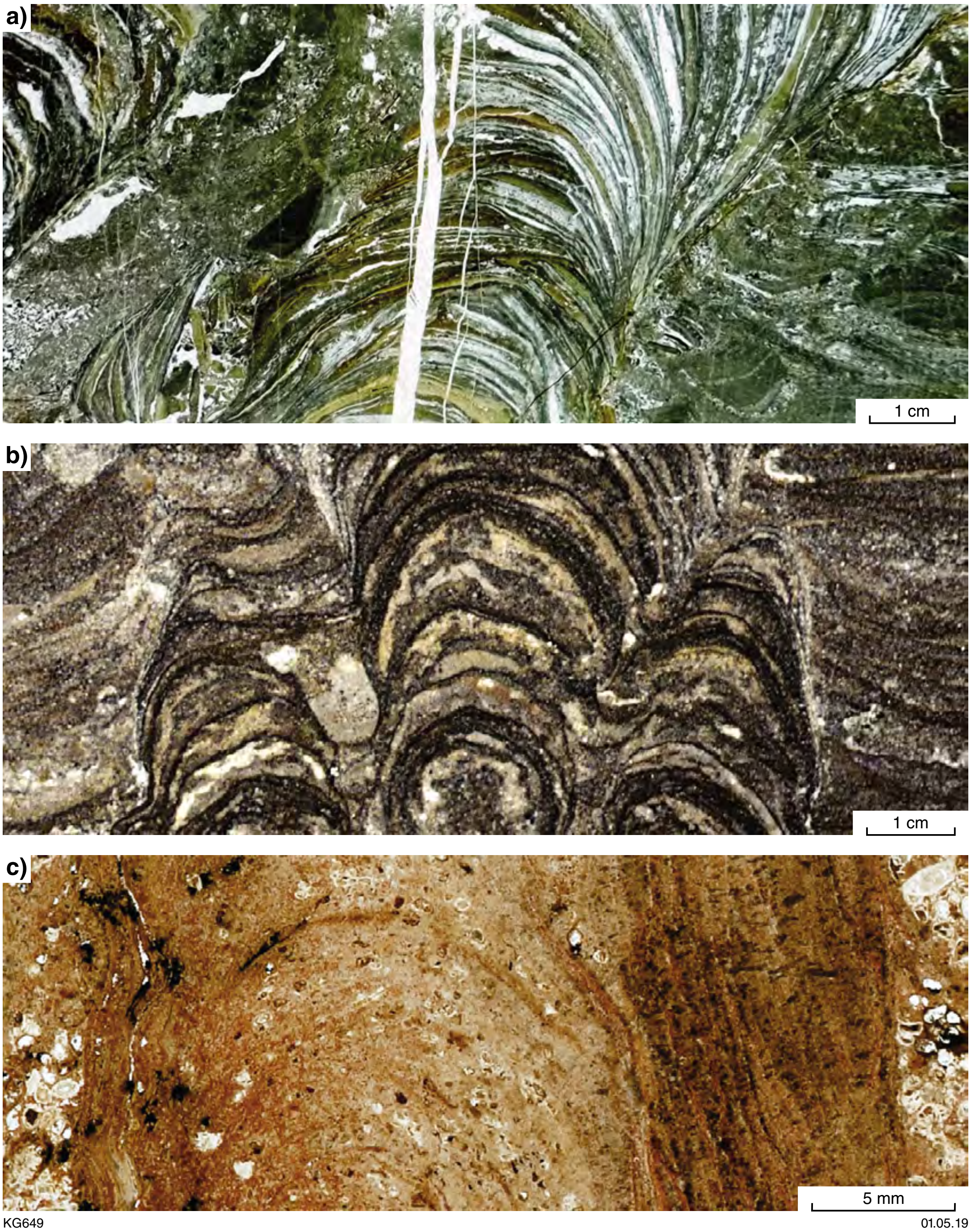


Figure 135. Examples of lateral continuity: a) microcross-lamination (offset lenticular); *Baicalia burra*; ?Skillogalee Dolomite, Burra Group; Adelaide Rift Complex; Tonian, Neoproterozoic; near Mount Hut, ANDAMOOKA, South Australia; thick section S305, University of Adelaide collection (photo by HJ Allen); b) irregular; *Cryptozoon proliferum*; Hoyt Limestone; upper Cambrian; near Lester Park, Saratoga County, New York, US; UCSB collection (photo by SM Awramik); c) heterogeneous laminae that differ across the width of the column; *Windidda granulosa*; Windidda Member, Frere Formation; Earaheedy Basin; Orosirian, Paleoproterozoic; Mount Elisabeth, ROBERT, Western Australia; thick section GSWA F12380–46598 (photo by K Grey)

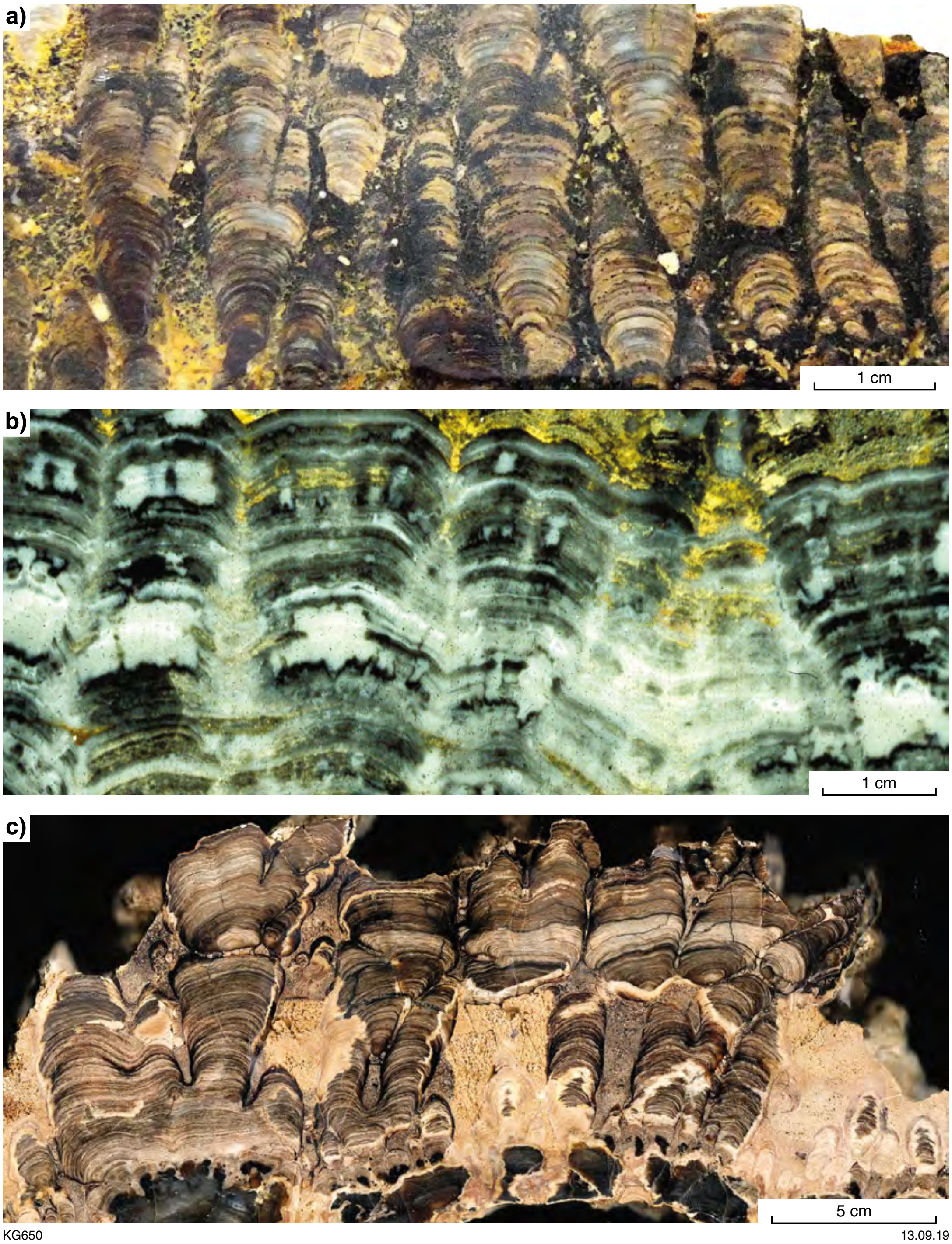


Figure 136. **Examples of lateral continuity – harmonized; a) *Anabaria juvensis*; cap carbonate above Pioneer Sandstone; Amadeus Basin; Ediacaran, Neoproterozoic; near Ross River Highway, Alice Springs, Northern Territory, Australia; cut face of holotype, UCSB collection 4 of 3/7/65 (photo by K Grey); b) *Asperia digitata*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Cookies Bore, Glengarry, Western Australia; polished slab GSWA F48445–88081 (photo by K Grey); c) stromatolite; Laney Member, Green River Formation; Washakie Basin; Eocene; Delaney Rim, Sweetwater County, Wyoming, US; polished slab, UCSB collection (photo by SM Awramik)**

Column margins of stromatolites

Extensions of laminae beyond the column give rise to a range of subsidiary mesostructures at column margins, including walls (Figs 137–142) and ornament (column-surface characteristics, surface ornamentation) (Figs 143–149). A lamina or laminae may terminate abruptly at the column margin or the terminations may turn downward, overlap, and lie parallel to each other to form walls. Ornament results from laminae that extend beyond the main column margin to form second-order characteristics of the vertical profile, or extend into the interspace areas to form a variety of ornamental features or linking structures, such as bridges.

Walls

A wall (Figs 137–142) (or envelope) was described by Korolyuk (1960b, p. 117, fig. 4) as being 'formed as a result of the connection of microlayers with each other in the marginal part of the structure.' She pointed out that the laminae can change their character near the column margin and that the walls are thin and single layered, or complex and multi-layered, although not all columns have walls. Hofmann (1969a, p.18) described a wall as containing 'the marginal, downwardly directed, encrusting portions of the laminae which are in contact with a matrix whose accumulation postdates that of the lamina with which it is in contact.' Both Preiss (1972, p. 93) and Walter (1972, p. 14) described a wall as a structure 'at the margin of a column formed by one or more laminae from within the column bending down and coating the margin for at least a short distance.'

Note the presence or absence of walls. The nature of the wall may vary along the length of a column, or from branch to branch within a fascicle. For example, they can either coat the entire structure, referred to as a continuous wall, or may cover only short segments of it, in which case they are referred to as patchy walls. Walls are commonly features found only in stromatolites because other microbialites lack laminae. The term selvage or rind is used when there is a distinctive coating enveloping either a stromatolite or other type of microbialite. Sometimes this may consist of a coating formed by one type of microbialite that encases another kind.

The following wall types can be recognized:

1. *Unwalled*: (Figs 137a, 138) where the laminae terminate abruptly at the column or dome margin and may be of even or uneven length. If laminae end unevenly or with only a slight down turning, the edge of the structure commonly has a ragged appearance
2. *Simple wall*: (Figs 137b, 139) where a wall is formed by only one or two overlapping laminae, each continuing parallel to the sides of the structure for some distance and then tapering out
3. *Multilaminate wall*: (Figs 137c, 140, 141a) where several laminae overlap the structure's margin and continue parallel to each other, coating the sides of the structure over most of its length
4. *Patchy wall*: (Figs 137d, 141b) where parts of a column are walled, and other parts are unwalled
5. *Complex wall*: (Figs 131e, 142a,b) where one or more laminae overlap the edges of several underlying laminae to give a nested appearance. In this case the enveloping laminae tend to terminate abruptly where they turn in against the structure's margin, and the laminae that have been overlapped tend to be truncated.

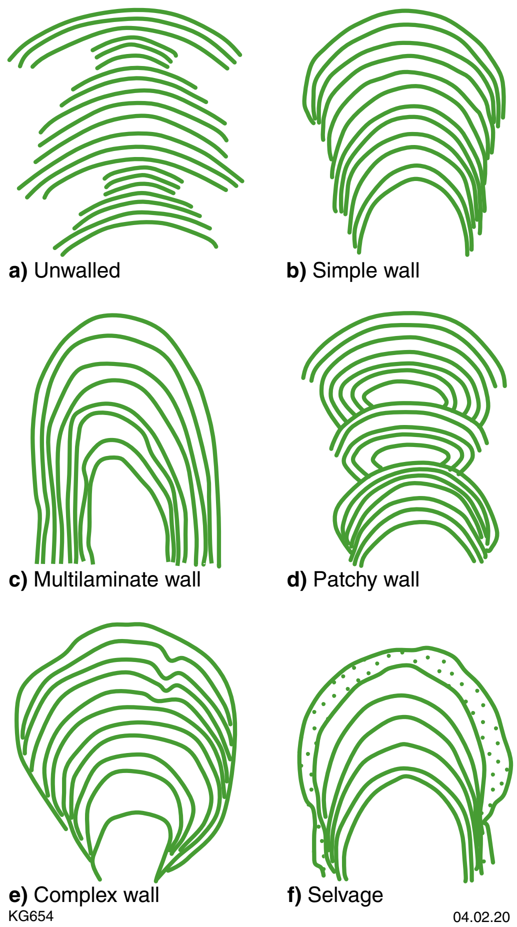


Figure 137. Microbialite walls: a) unwalled; b) simple wall; c) multilaminate wall; d) patchy wall; e) complex wall; f) selvage

The significance of walls has not been satisfactorily determined, and erosion can sometimes remove them. Nevertheless, in many microbialites the nature of the column margin is consistent and appears to be a diagnostic characteristic. Detailed examination of the wall can also help determine the amount of synoptic relief and growth history.

Selvage and rind

Some microbialites have an outer coating known as a selvage or mantle (Fig. 137f, 142c). Although both terms have been used in the literature, mantle seems to have been introduced as a mistranslation from the Russian (Hofmann, 1969a, p. 18) following Raaben (1964) and Komar et al. (1965a, p. 18). Selvage seems to be a more accurate translation, and is more commonly used (Preiss, 1971, p. 93; Walter, 1972, p.14; Hofmann, 1969a, p. 18; Raaben et al., 2001) and is the term preferred here. Hofmann described the feature as 'a narrow peripheral zone of a nonlaminated microfabric different from the laminated central portion of the stromatolite'.

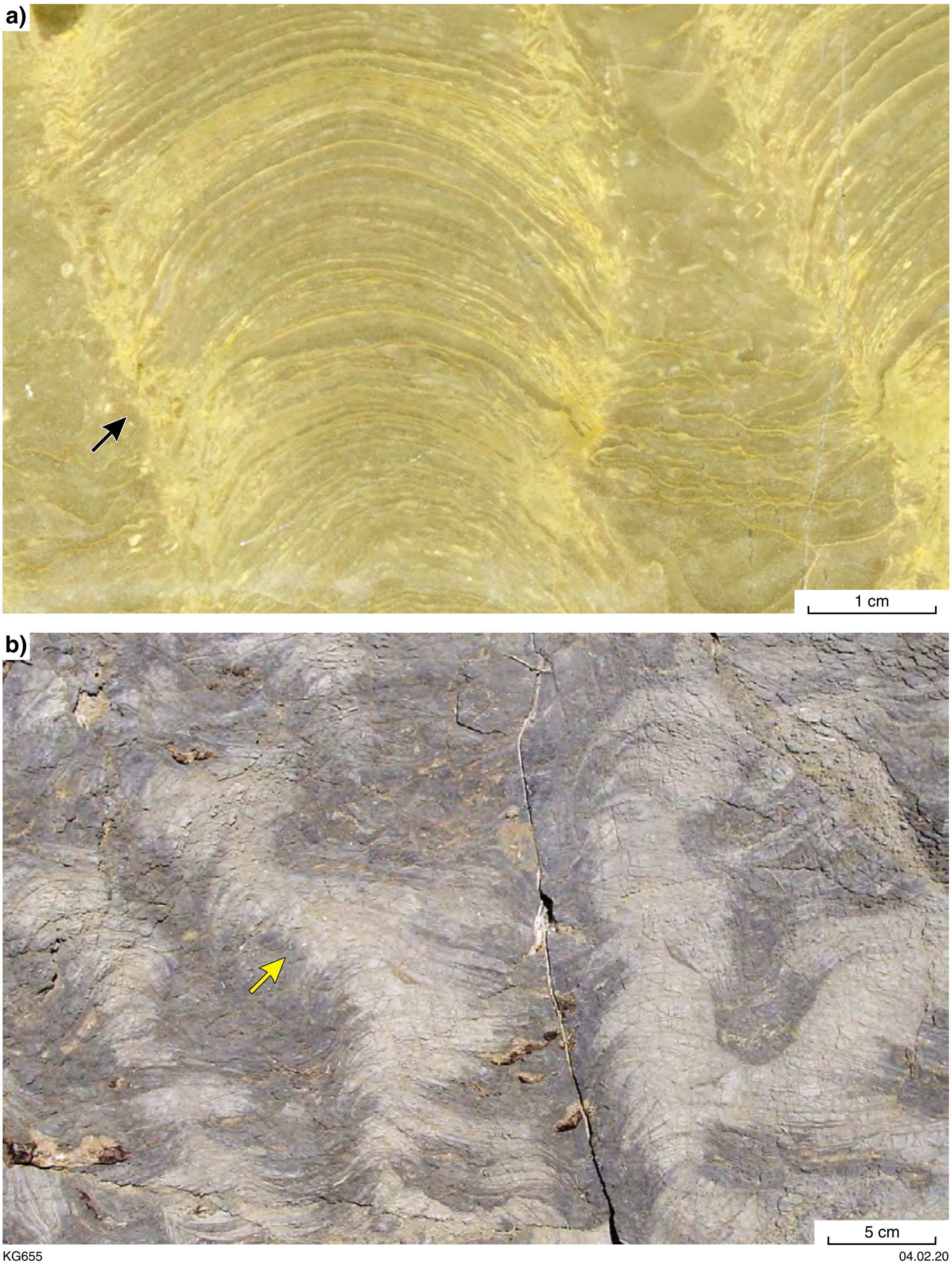


Figure 138. Examples of walls – unwalled (arrow); a) '*Baicalia*'; Teiling Formation, Jixian Group; North China Craton; Calymmian to Ectasian, Mesoproterozoic; Yanshan Range, Jixian County, Hebei Province, China; polished slab, UCSB collection (photo by SM Awramik); b) columnar stromatolite; Beck Spring Dolomite, Pahrump Group; Tonian, Neoproterozoic; Alexander Hills, San Bernardino County, California, US (photo by SM Awramik)

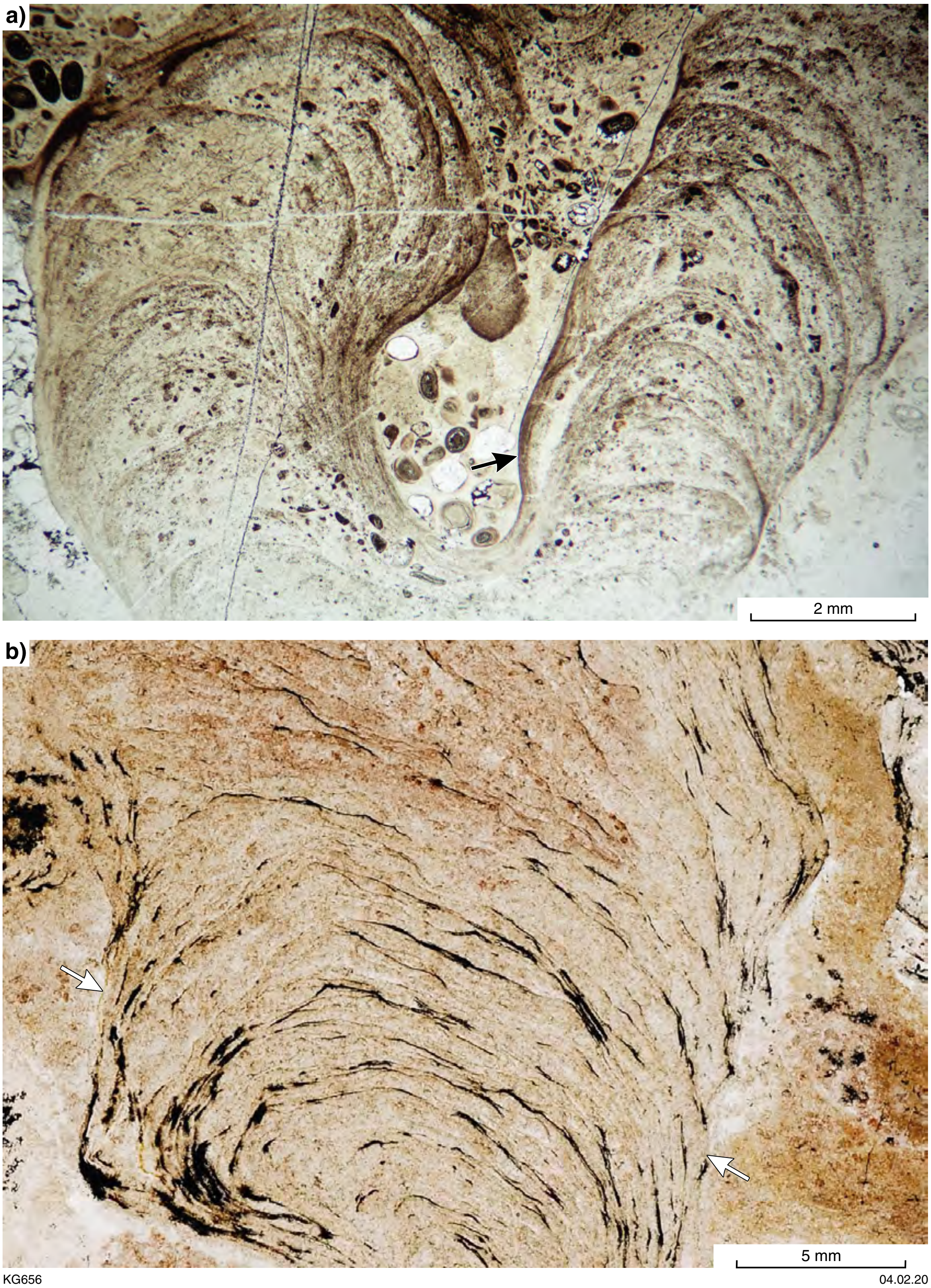


Figure 139. Examples of walls – simple wall (arrow): a) *Gruneria* f. indet.; Gunflint Formation, Animikie Group; Animikie Basin; Orosirian, Paleoproterozoic; Winston Point, Lake Superior, Ontario, Canada; thick section from slab, Peabody Museum of Natural History, Yale University, YPM PB 051800 (photo by SM Awramik); b) *Carnegia wongawolensis*; Windidda Member, Frere Formation; Earaheedy Basin; Orosirian, Paleoproterozoic; Wongawol Creek, Kingston, Western Australia; thick section GSWA F12349–46594 (photo by SM Awramik and K Grey)

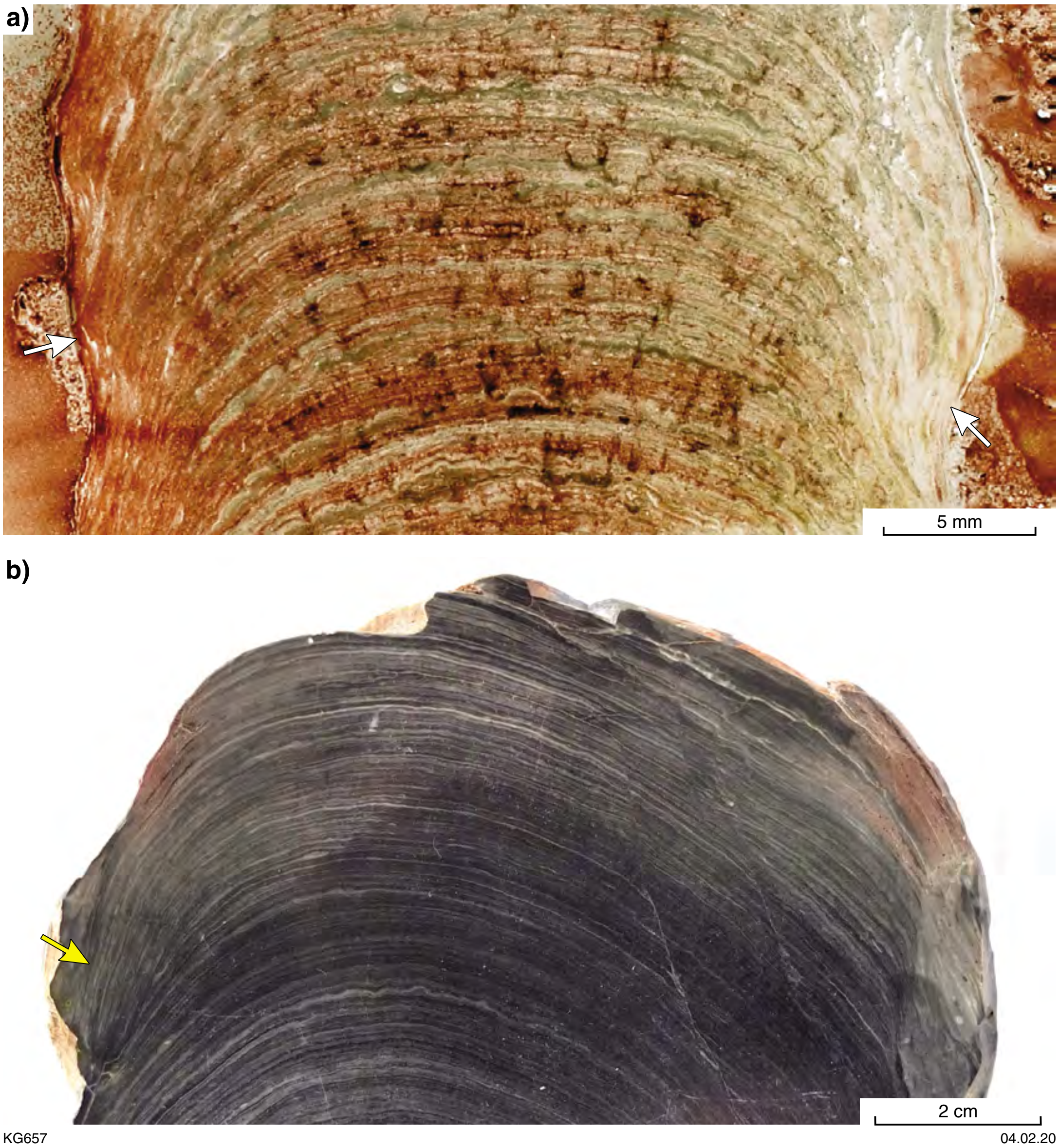


Figure 140. Examples of walls – multilaminate wall (arrow): a) *Externia yilgarnia*; Yelma Formation, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; Wongawol Creek, near Lake Wells, DUKETON, Western Australia; thick section GSWA F12360–46075 (photo by SM Awramik and K Grey); b) cf. *Colonella*; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, EDMUND, Western Australia; polished face, GSWA F9914-46016 (photo by K Grey)

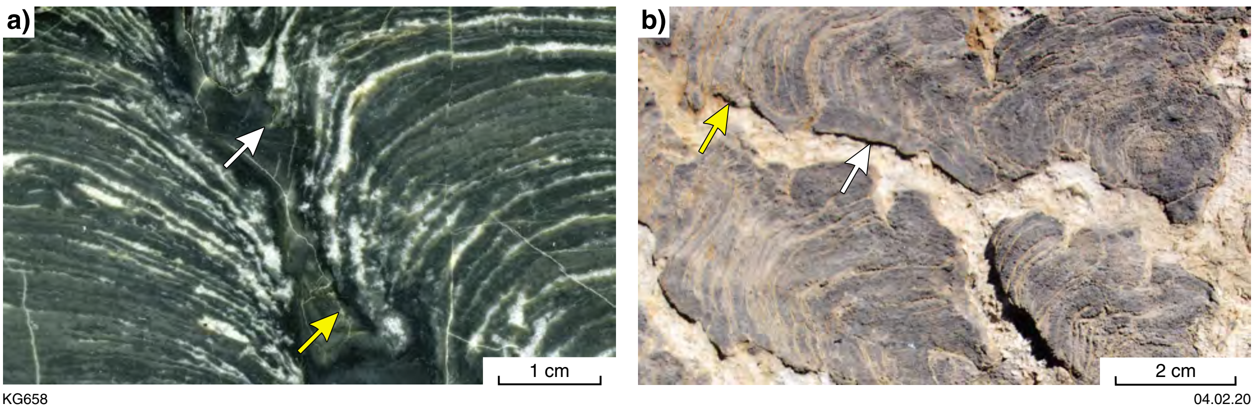


Figure 141. Examples of walls – patchy wall (wall present, yellow arrow; wall absent, white arrow): a) *Minjaria uralica*; Min'yar Formation, Karatau Group; Tonian, Neoproterozoic; Belaya River, near Belskaya, Bashkortostan, South Urals, Russia; UCSB collection, Preston Cloud sample 1a of 10/8/71 (photo by SM Awramik); b) unnamed stromatolite; Johnnys Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, Alice Springs, Northern Territory, Australia (photo by NJ Planavsky)

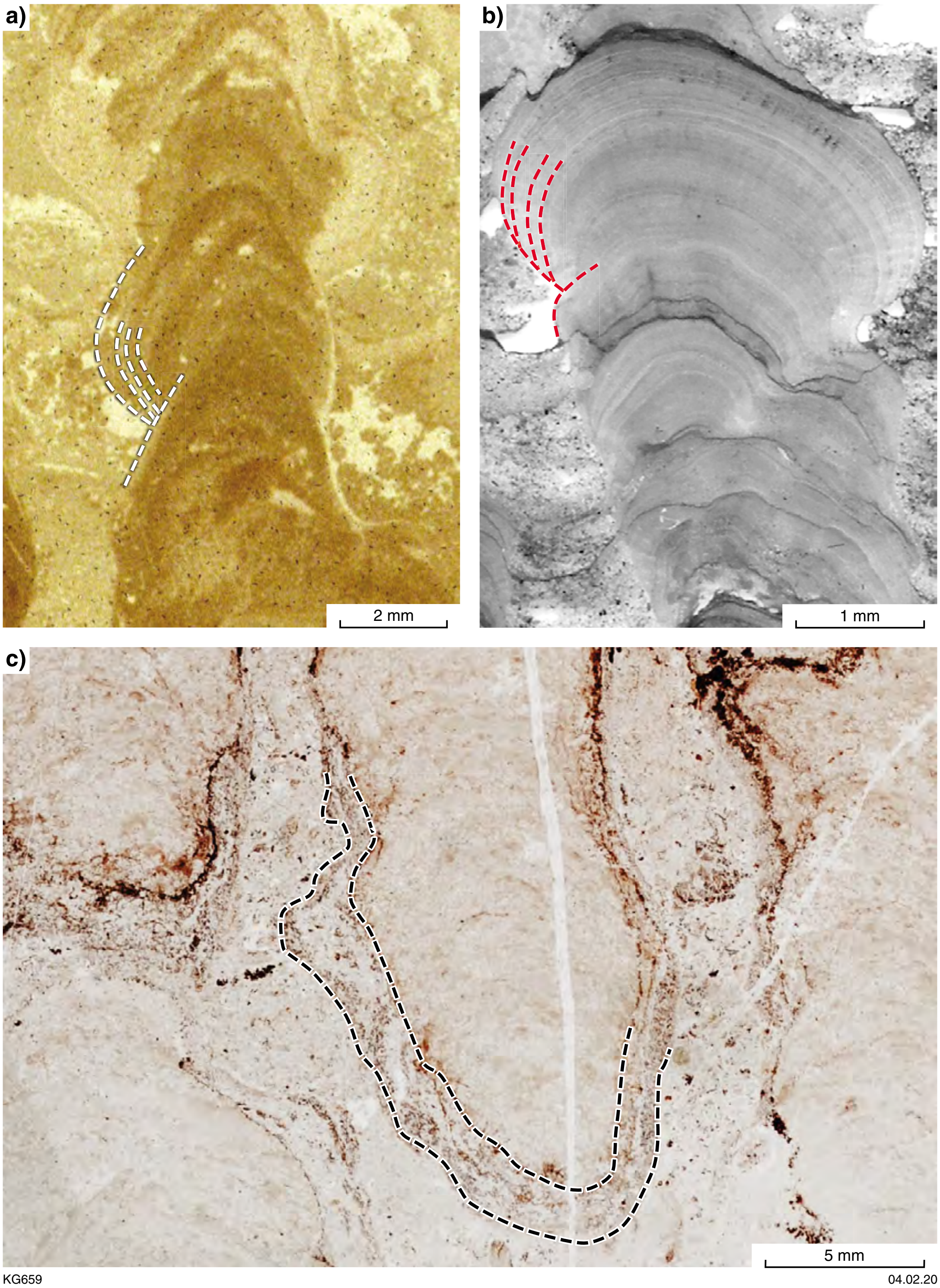


Figure 142. Examples of walls – complex wall and selvage: a) complex wall (outlines); *Segosia finlaysoniensis*; Bubble Well Member, Juderina Formation, Windplain Group; Yerrida Basin; Rhyacian to Statherian, Paleoproterozoic; Amoco-Duval Quartermaine Well 1, Peak Hill, Western Australia; thick section GSWA F48460–76593 (photo by K Grey); b) complex wall (outlines); ?*Alcheringa narrina*; Meentheena Member, Tumbiana Formation, Fortescue Group; Fortescue Basin; Neoarchean; 'Knossos', near Redmont, Pilbara, Roy Hill, Western Australia; thick section UCSB collection (photo by SM Awramik); c) selvage (outline); *Gymnosolen* f. indet.; Johnnys Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; east of Ross River, Alice Springs, Northern Territory, Australia; thin section GSWA F52673–109260 (photo by SM Awramik and K Grey)

Preiss (1972, p. 93) described a selvage as

> [an] unlaminated coating on column margins. Possible explanations for this include (a) micritization by algal boring; (b) inorganic precipitation of lime; (c) a thin algal film on column margins during growth. In some forms a selvage-like structure is probably the result of differential recrystallization of a wall.

A selvage is not a wall, but a layer that envelops the entire margin. It is not necessarily microbial in origin, but is usually a micritic layer that is, or was, probably precipitated; it may or may not be laminated. Selvage has principally been used for this feature for Precambrian microbialites. The term rind has been used in describing Phanerozoic microbialites, for both unlaminated (Ahr, 1971, p. 215) and laminated coatings (Shapiro and Awramik, 2000, p. 176), in some instances producing composite microbialites. The relationship between the selvage or rind and the coated structure should be described as it can provide valuable evidence about changes in environmental conditions.

Ornament

The most conspicuous element found on column surfaces is ornament (Figs 143–149), an irregularity of the surface that has a consistent shape. In many cases, ornament results from the terminal development of laminae. However, other microbialites beside stromatolites may develop surface irregularities of this type, and the terminology given below can also be applied to any microbialite.

Ornament has a variety of shapes and sizes that is best portrayed by 3D reconstruction. However, outcrop silhouettes, slabs, peels and thin sections can provide valuable information. A line drawing showing the ornament is recommended if 3D reconstructions are not possible. Many terms have been used in the literature. The basic types listed here are the most commonly encountered, and terminology is based mainly on Hofmann (1969a, p. 18, fig. 12), Preiss (1972, p. 92–93, fig. 1) and Walter (1972, p. 12–14, text-fig. 3). Other terms may apply in specific cases, in which case the usage of the term should be explained:

1. *Smooth*: (Figs 143a, 144) having no irregularities (Hofmann, 1969a, p. 18, fig. 12)
2. *Bumpy*: (Figs 143b, 145a) in which there are low, rounded protrusions
3. *Tuberous*: (Figs 143c, 145b) similar to bumpy but the protrusions are smooth and have a downward extension
4. *Fimbriate*: (Figs 143d, 146a) with fringes or lips hanging down. These may consist of several thin peaks horizontally aligned or be more like a thin cornice
5. *Lobate*: (Figs 143e) similar to fimbriate, but with more rounded protrusions that hang downwards. Also includes an ornament of small bumps referred to as tuberculate by Hofmann (1969a, p. 18, fig. 12)
6. *Peaked*: (Figs 143f, 146b) protrusions that have sharp points

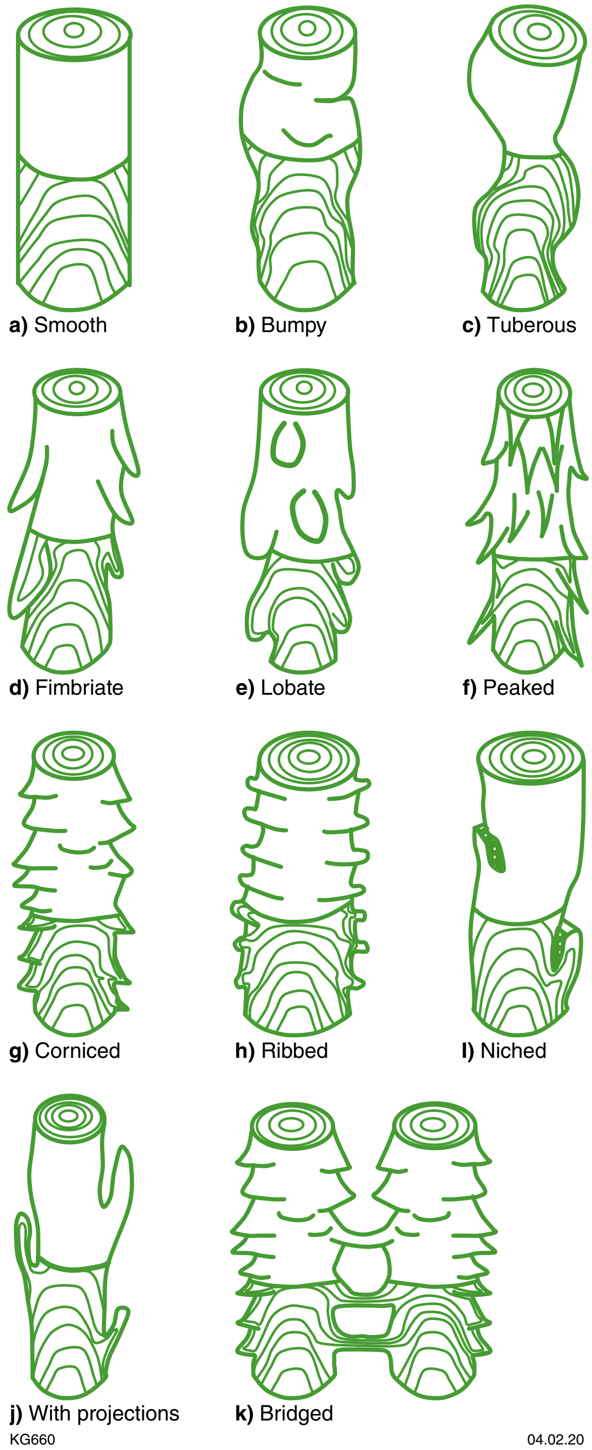


Figure 143. Microbialite ornament (after Walter, 1972): a) smooth; b) bumpy; c) tuberous; d) fimbriate; e) lobate; f) peaked; g) corniced; h) ribbed; i) niched; j) with projections; k) bridged

7. *Corniced*: (Figs 143g, 147a) with an overhanging lamina or set(s) of elongated laminae that are rhythmically constringed to produce concentric, sharp-edged corrugations (for practical purposes this can be considered equivalent to the obsolete term rugate). It may be difficult to distinguish between fimbriae and cornices without a 3D reconstruction

Figure 144. Examples of ornament – smooth; a) columnar microbialite; cf. *Colonella*; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Irregully Gorge, EDMUND, Western Australia (photo by K Grey); b) stromatolites; sub-fossil to Holocene; Marion Lake, Yorke Peninsula, MAITLAND SPECIAL 1:250 000 sheet, South Australia (photo by K Grey)

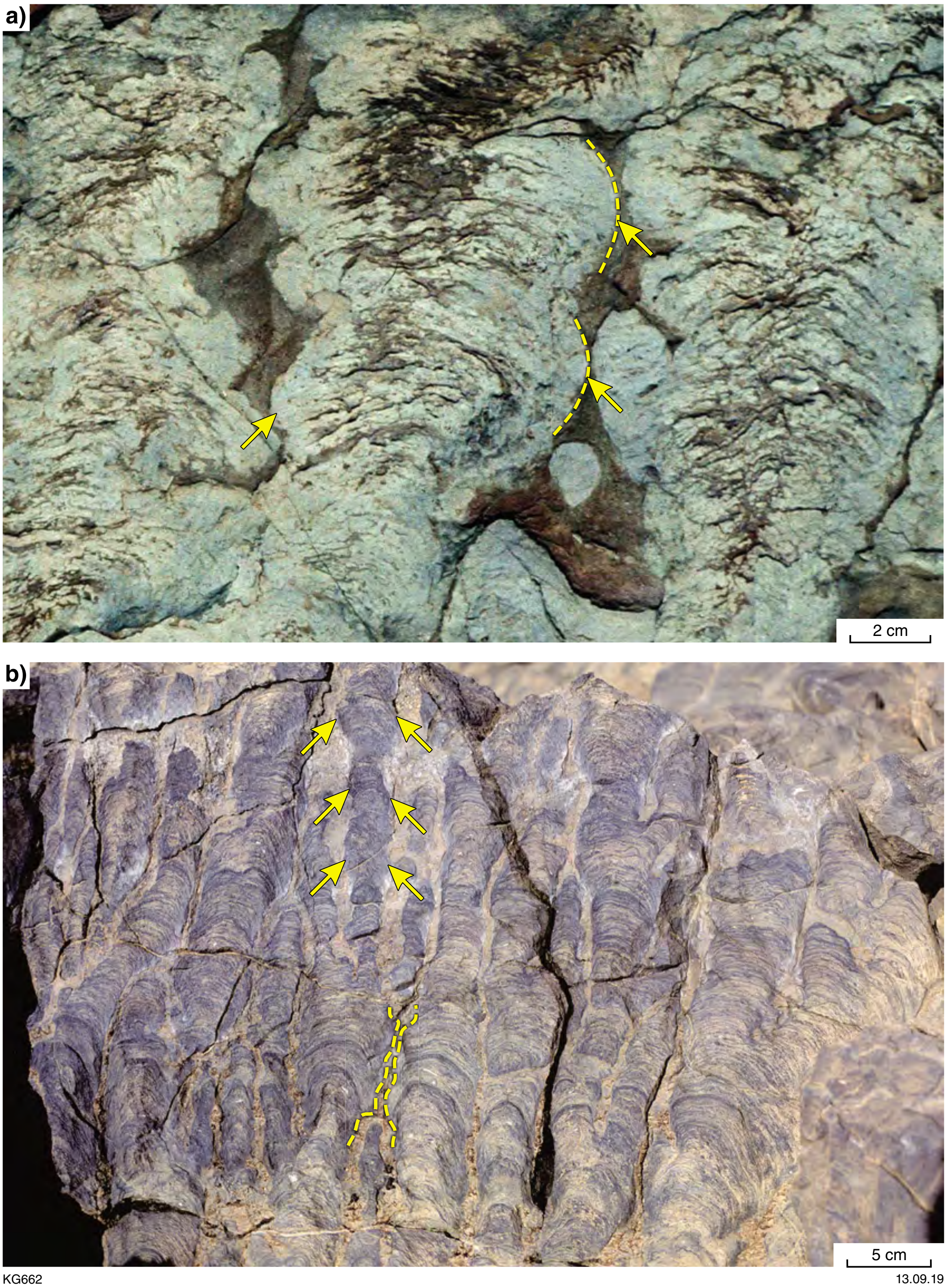


Figure 145. Examples of ornament: a) bumpy (arrows and outline); *Linella avis*; Eliot Range Dolomite, Ruby Plains Group; Wolfe Basin; Tonian, Neoproterozoic; near Mount Flora, east Kimberly, GORDON DOWNS, Western Australia (photo by K Grey); b) tuberous (arrows and outline); *Tungussia nodosa*; Tawaz Formation (unit I.7), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; east of Atar, Mauritania (photo by SM Awramik)

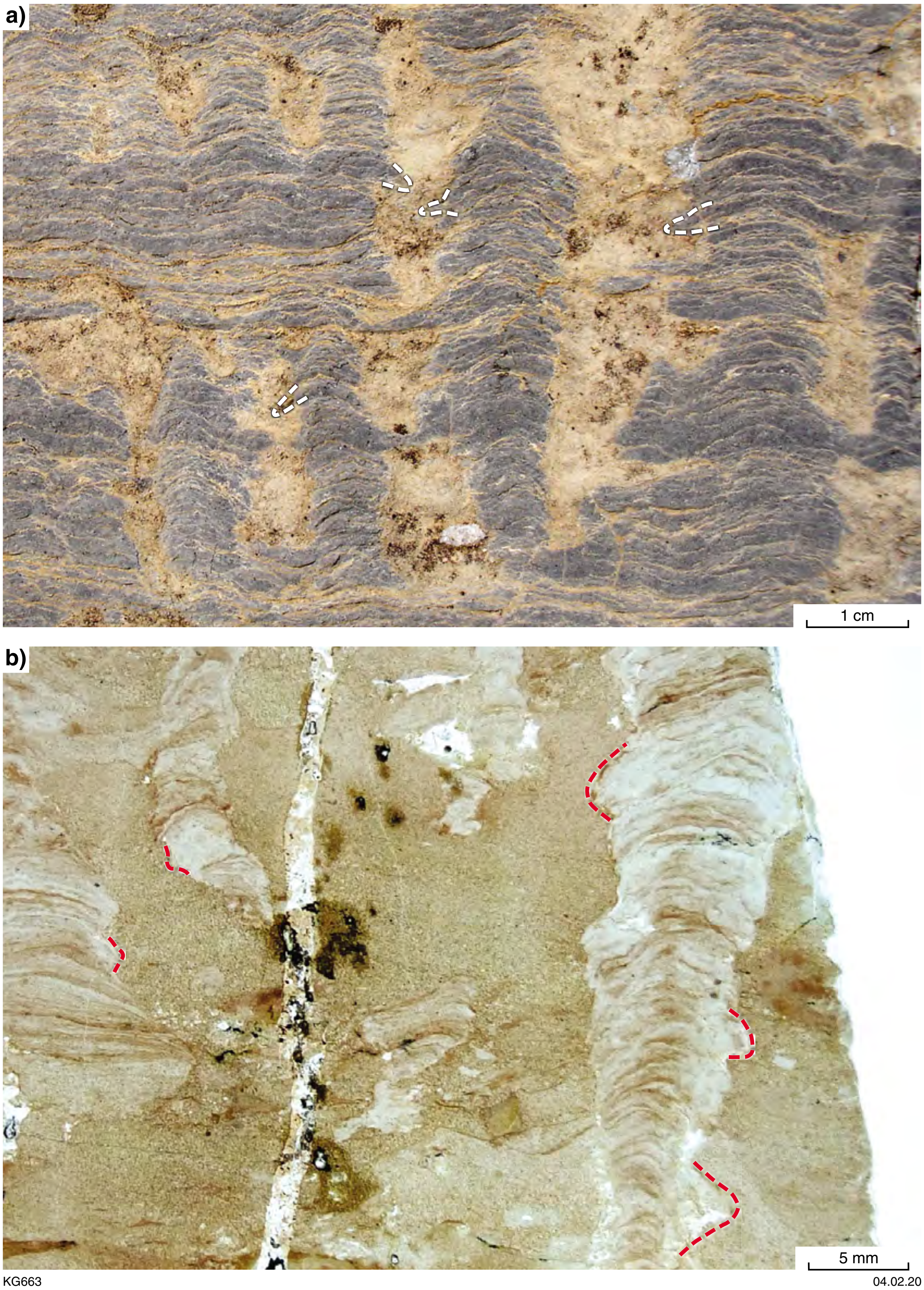


Figure 146. Examples of ornament: a) fimbriate (outlines); unnamed stromatolite; Johnnys Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, ALICE SPRINGS, Northern Territory, Australia (photo by NJ Planavsky); b) peaked (outlines); ?*Inzeria multiplex*; Waltha Woora Formation, ?Tarcunyah Group; Officer Basin; Cryogenian, Neoproterozoic; east of Cape Wharton, east Pilbara, BALFOUR DOWNS, Western Australia; thick section GSWA F52537–84632 (photo by K Grey)

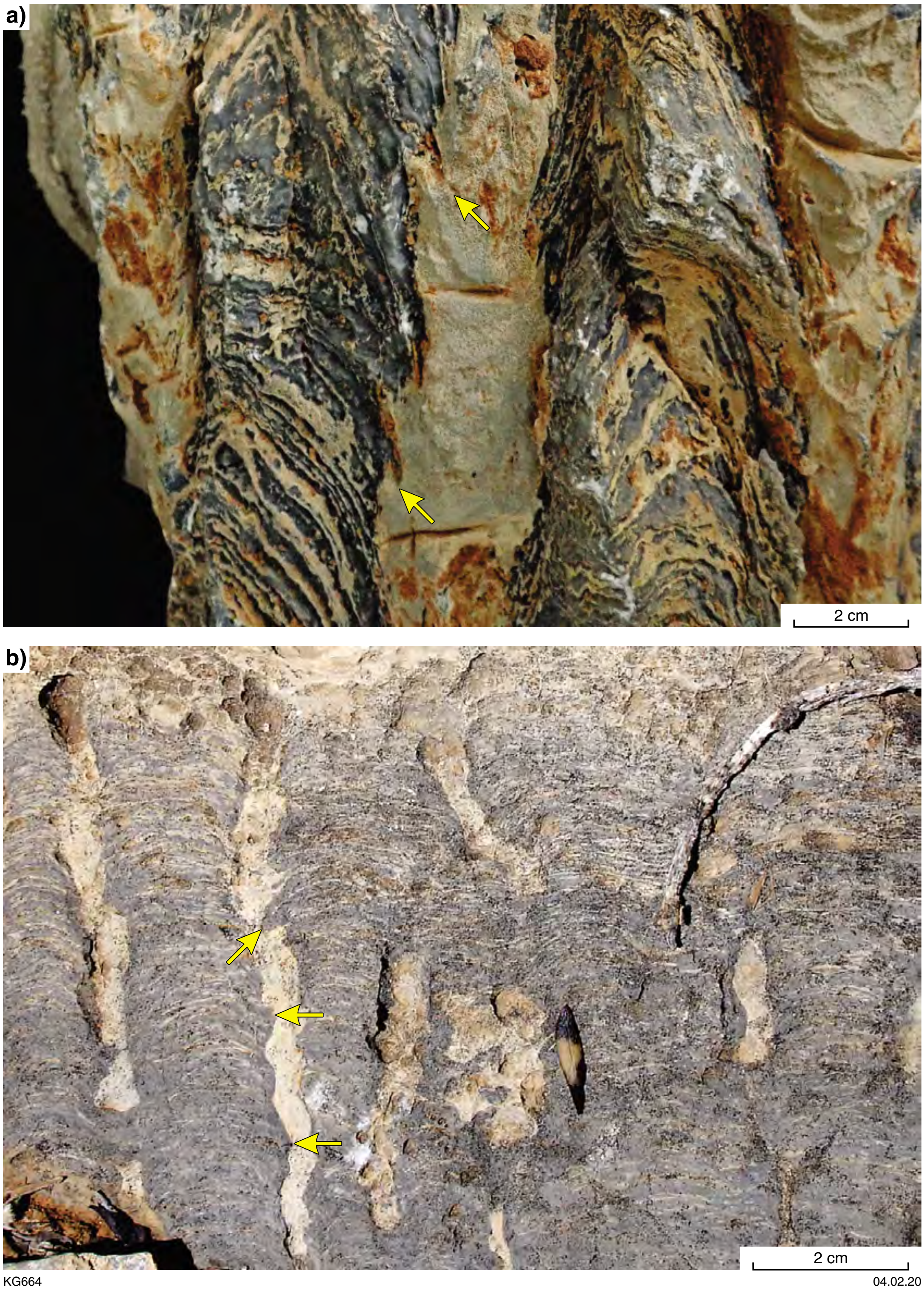


Figure 147. Examples of ornament: a) corniced (arrows); *Baicalia capricornia*; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Peedawarra Flats, Mount Phillips, Western Australia; hand specimen GSWA F9905–46033 (photo by SK Martin); b) ribbed (arrows), ribs emphasized by weathering; *Inzeria intia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; near Ross River, Alice Springs, Northern Territory, Australia (photo by NJ Planavsky)

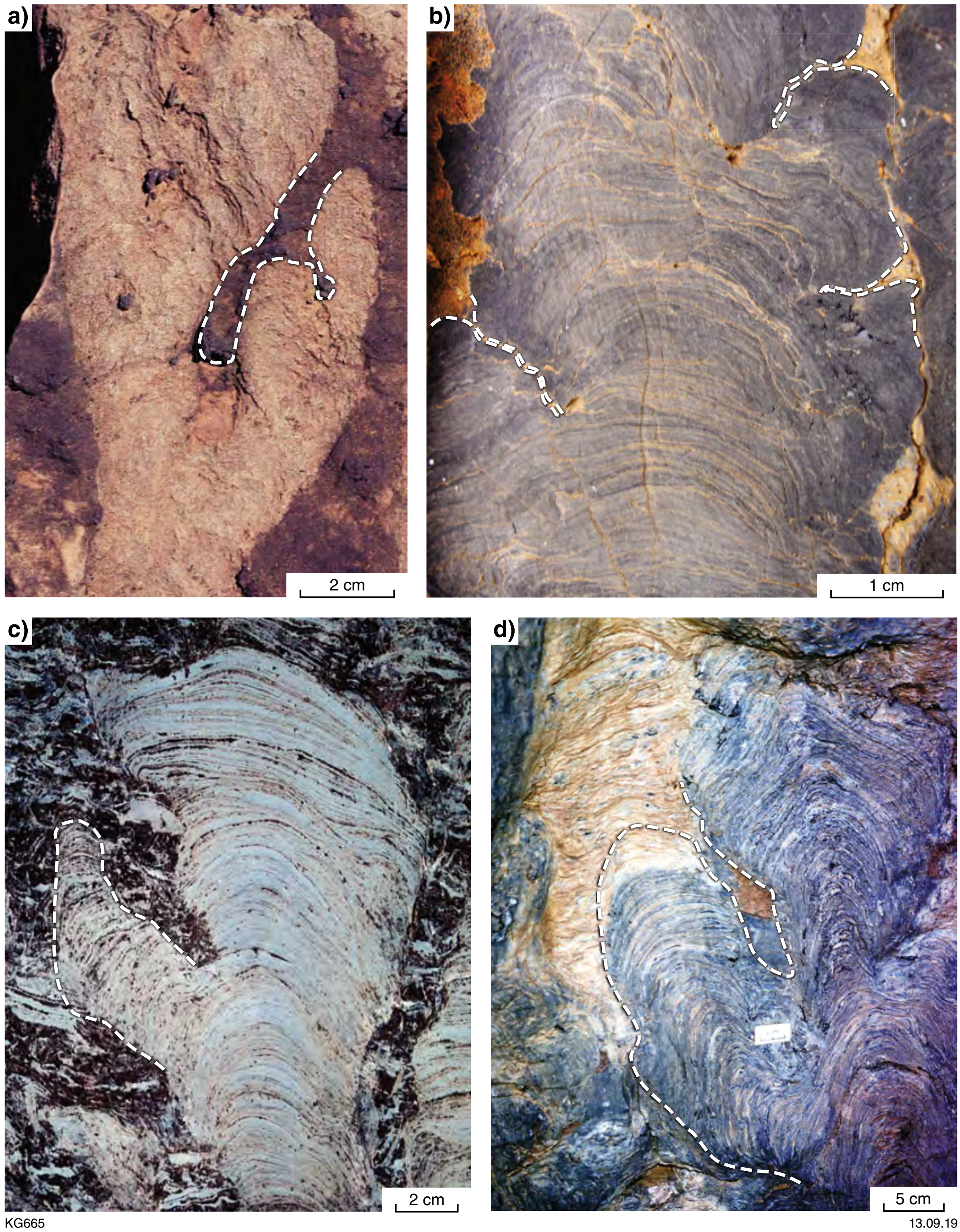
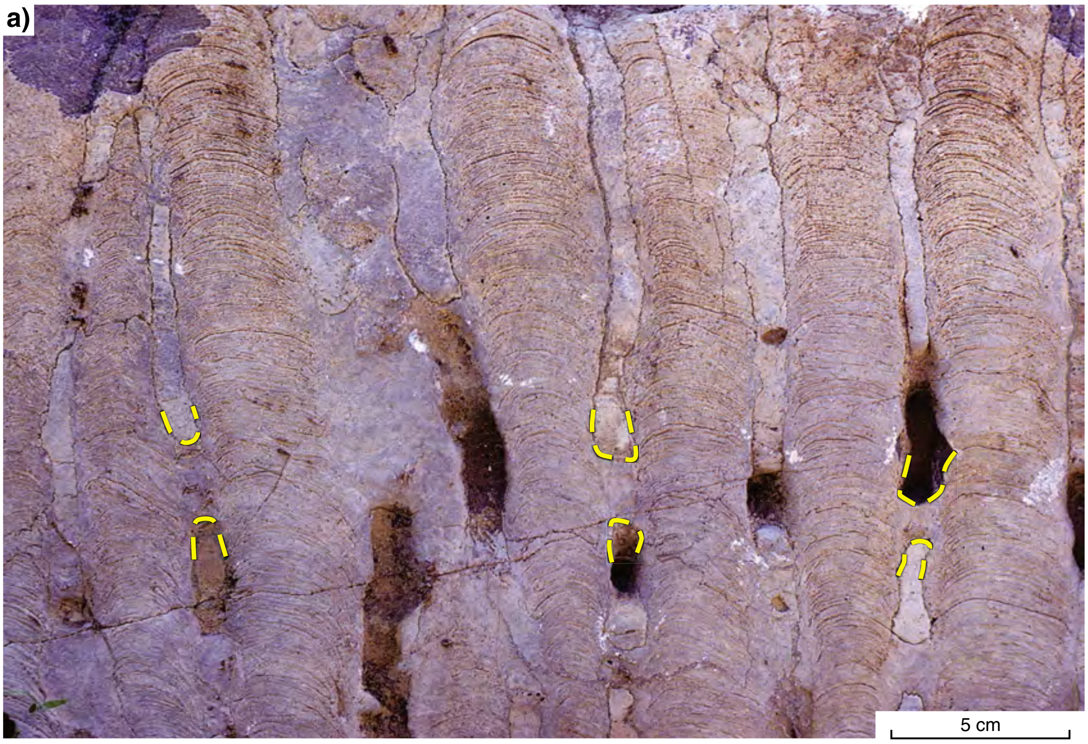


Figure 148. Examples of ornament – niches and projections: a) niched (outline); *Pilbaria deverella*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Simpson Well, NABBERU, Western Australia (photo by K Grey; b) narrow niches (outlines); *Inzeria intia*; Loves Creek Formation, Bitter Springs Group; Amadeus Basin; Tonian, Neoproterozoic; Ross River, ALICE SPRINGS, Northern Territory, Australia (photo by NJ Planavsky); c) projection (outline); stromatolite; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Henry River, Irregully Gorge, EDMUND, Western Australia (photo by DMcB Martin); d) projection and niche (outline); *Baicalia safia*; Atar Formation (Unit I.5), Atar Group; Taoudenni Basin; Stenian, Mesoproterozoic; Lekhleigate Section, Atar region, Mauritania (photo by K Grey)

a)



b)

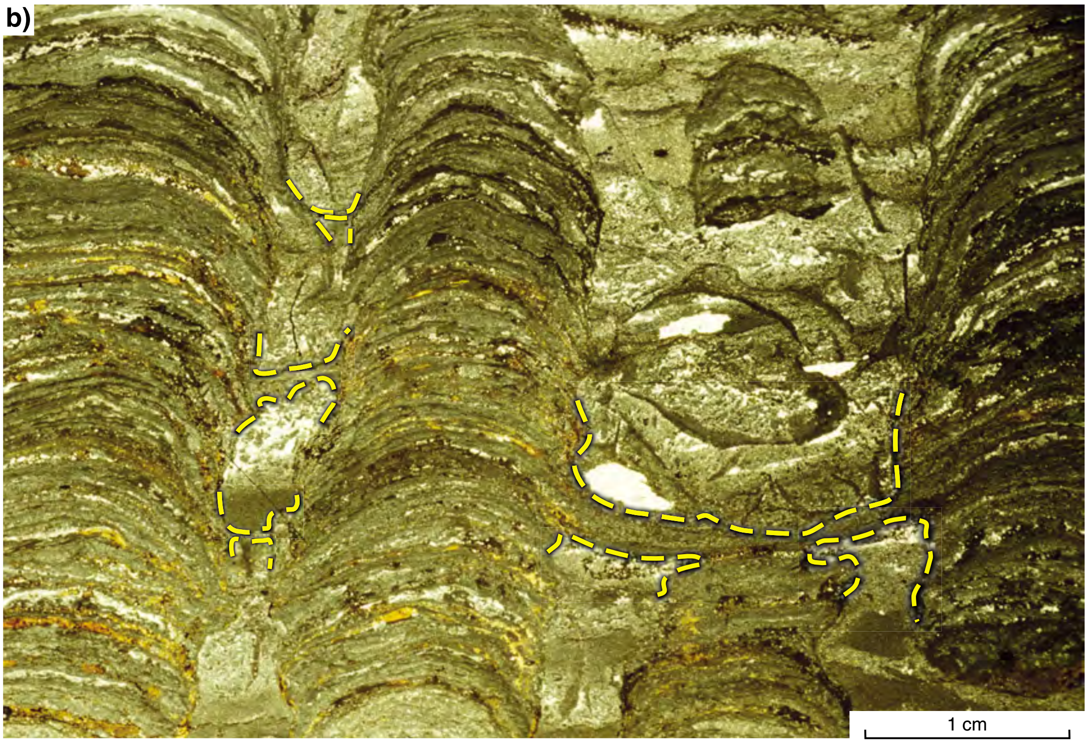


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Figure 149. Examples of ornament – bridged: a) columns connected by massive bridges (outlines); ?*Chihsienella chihsienensis*; Tieling Formation, Jixian Group; North China Craton; Calymmian to Ectasian, Mesoproterozoic; Yanshan Range, Jixian County, Hebei Province, China (photo by SM Awramik); b) columns connected by delicate bridges (outlines); *Acaciella australica*; Skates Hills Formation, Sunbeam Group; Officer Basin; Tonian, Neoproterozoic; Skates Hills, TRAINOR, Western Australia; thick section GSWA F49235–90599 (photo by K Grey)

8. *Ribbed*: (Figs 143h, 147b) with projections at the column margin formed by abrupt and regular increases and decreases in diameter that produces horizontal projections at the column margin. To some extent ribs are a small-scale version of constringed, but their influence is mainly restricted to the column margin
9. *Niched*: (Figs 143i, 148a,b) elongate, vertical or near vertical depressions at the column margins that extend into the column body
10. *Projections*: (Figs 143j, 148c,d) small, upward protrusions from the column margins. These could be considered to be a special form of branching, but they are not large enough for branches. Moreover, they are generally separated from the column by niches, and there may be a rim around the niche (attached to the column at the sides) rather than a discrete projection. It may be difficult to distinguish this type of feature without a 3D reconstruction
11. *Bridged*: (Fig. 143k, 149) laminae that cross the interspaces and connect adjacent columns. It is important to describe the degree of bridging and its frequency. Massive bridges consist of numerous laminae (Fig. 149a). Delicate bridges consist of only one or two laminae (Fig. 149b).

Combinations of several ornament types can occur on the same head. For example, niches may be bordered by a projection, or protrusions may be of several different types. 3D reconstruction is particularly important for recognizing niches as hollows or pockets, extending from the column surface into the main body of the column, rather than as spaces between branches.

Laminar architecture

Laminar architecture (Figs 150–156) is here defined as the 3D structure of a lamina and its relationship to underlying and overlying laminae. Its characteristics depend on the shape, lateral continuity, nature of boundaries, and stacking of individual laminar elements. Architecture straddles mesostructure and microstructure (in the sense that microstructure implies that it needs to be viewed microscopically). Mesostructure, as used here, does not include features of individual grains or petrographic elements that have sometimes previously been grouped with architectural features. Microstructure is a sublaminar feature, so technically is not mesostructure, but it sometimes finds expression in the nature of the laminae; for example, pillared laminar architecture may show up as a distinct wrinkling of the laminae as viewed at mesostructural level, and in some cases is reflected at macrostructural level. It is best to describe laminar features and sublaminar features under mesostructure and microstructure, respectively, but document any interdependence between the two. Laminar architecture also differs from features of individual grains or petrographic elements that have sometimes previously been grouped with architectural features. It is studied mainly in 2D (for example, on slabbed faces or in thin sections), although attempts should be made to determine the 3D shape. Slabs cut normal to vertical surfaces can provide the most definitive information. Architecture is the product of specific combinations of microorganisms, sediment, cement and any other components, formed within a limited timeframe. It also includes the manner in which successive combinations are related to each other. However, architecture can be altered by compaction.

Komar et al. (1965a, fig. 4; 1965b, fig. 2) recognized seven types of microstructure, which were renamed by Hofmann (1969b, fig. 9), as ‘fragmentary-ribboned’, ‘uniformly wavy-ribboned’, ‘non-uniformly ribboned’, ‘linearly striated’, ‘irregularly striated’, ‘fragmentary-lumpy’ and ‘irregularly lumpy’. Preiss (1972, p. 93) used a simpler terminology, recognizing only three types: ‘banded’, ‘streaky’ and ‘vermiform’. Walter (1972, p. 14) introduced ‘striated microstructure’ in addition to the other three terms. Two more types, ‘film’ and ‘tussock’ microstructures, were described by Bertrand-Sarfati (1976, p. 253–255). Hoffman (1976, p. 266) referred to stromatolites with voids parallel to the laminae as ‘fenestrate stromatolites’. However, the term has been applied to different structures — for example, by Sumner and Grotzinger (2004) and Stevens et al. (2011) — so we prefer the term ‘alveolar laminar architecture’. Another type of laminar architecture is ‘pillared’ (Hofmann, 1969b, Raaben et al., 2011; Allen et al., 2016) in which laminae contain small, micro-columnar structures.

Restricting microstructure to sublaminar features, as this handbook does, differentiates the following categories of laminar architecture: banded, filmy, striated, streaky, tussocky pillared, vermiform and alveolar, which are distinct from categories of microstructure, with which they were previously included. The list is far from comprehensive and further recognition and cataloguing of types is expected once the significance of mat architecture in both fossil and recent microbialites becomes more clearly appreciated:

1. *Banded laminar architecture*: (Figs 150a, 151a,b) Hofmann (1969b, fig. 9), following Komar et al. (1965a, Fig. 4), called this type ribboned and identified the subcategories fragmentary ribboned, uniformly wavy-ribboned and non-uniformly ribboned. In practice, it can be difficult to distinguish the subcategories, and we prefer to follow Preiss (1972) and Walter (1972) in using the term banded for all three. Preiss (1972, p. 93) stated that banded laminar architecture ‘is characterized by very continuous laminae with sharp, distinct, more or less parallel boundaries’. The alternating stacking pattern is very distinctive and the boundaries are commonly well defined and equidistant. Banded architecture differs from striated and streaky types, which have laminae that are less continuous and distinct, and which commonly grade into one another.

   Examples: *Baicalia burra*, which is evenly banded (Preiss, 1972, fig. 14c); *Omachtenia ‘utschurica’*, which is broadly banded (Preiss, 1974, fig. 10c); *Tungussia etina*, which is wavy banded (Preiss 1974, fig. 11d).

2. *Filmy laminar architecture*: (Figs 150b, 151c,d) characterized by regularly alternating laminae of very different thicknesses. Bertrand-Sarfati (1976, p. 253) referred to this as film microstructure and described it as ‘regularly banded dark, thin (mode 0.003 mm), micritic films’. A thick, usually lensoid, light lamina (sometimes consisting of spar or microspar) is bounded on the upper surface by a very thin, dark, micritic film. The continuity, thickness, and straightness of the dark film are usually consistent

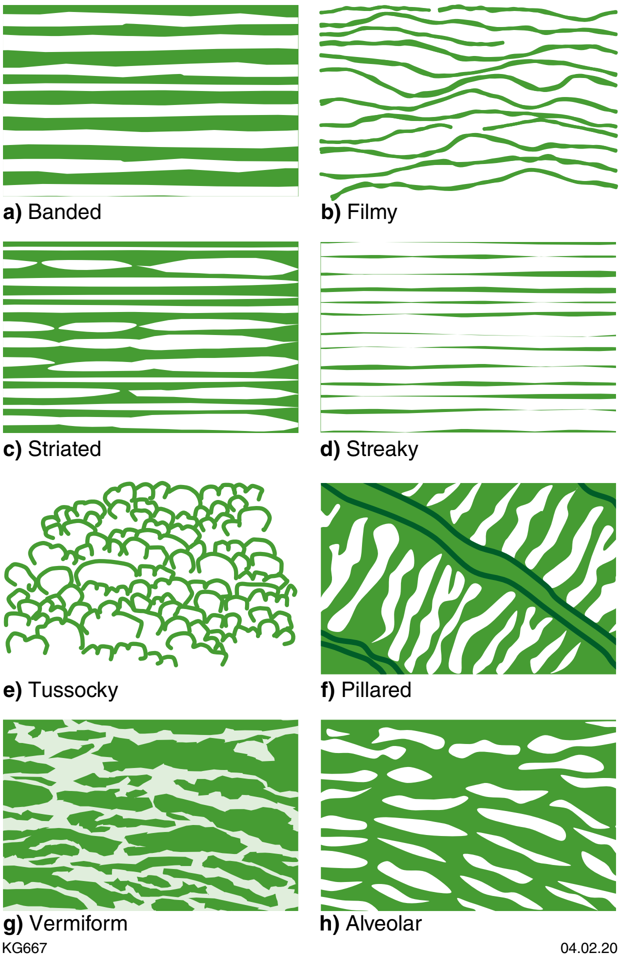

Figure 150. Laminar architecture: a) banded; b) filmy; c) striated; d) streaky; e) tussocky; f) pillared; g) vermiform; h) alveolar

for any particular head. The upper boundary of the dark lamina is clearly defined, whereas the contact between the base of the dark lamina and the top of the light lamina is gradational. In what resembles a filmy laminar architecture, Zhang (1986) described microfossils that suggested day–night cycles. Some examples previously included as micritic-mat microstructure (Bertrand-Sarfati, 1976) can be included as filmy architecture.

Examples: *Conophyton jacqueti* has distinctive dark films (Bertrand-Sarfati and Moussine-Pouchkine, 1985); *Baicalia mauritanica* does not have distinctive couplets, but instead consists of groups of films (Bertrand-Sarfati, 1976, p. 252, fig. 1b). Bertrand-Sarfati (1976, p. 253) also noted *Baicalia lacera*, which has sporadic clear layers containing peloids, as having film architecture.

3. *Striated laminar architecture*: (Figs 150c, 152) striated microstructure was illustrated by Komar et al. (1965a, fig. 4; 1965b, fig. 2) and was recognized as two distinctive types of microstructure by Hofmann (1969b, fig. 9), which he called 'linearly striated and irregularly striated'. Preiss (1972, p. 93) described striated microstructure as consisting of 'primary chains of lenses, oriented parallel to the lamination' but excluding 'cases where originally continuous laminae are disrupted by recrystallization', and Walter (1972, p. 12, 14) described it as a microstructure 'in which the laminae originally formed as chains of lenses'. Striated laminar architecture can consist of either chains of light lenses within dark laminae or dark lenses within light laminae.

   Example: *Conophyton garganicum australe* in Walter (1972, p. 12, 14).

4. *Streaky laminar architecture*: (Figs 150d, 153) streaky architecture was not differentiated from striated by Komar et al. (1965a, fig. 4; 1965b, fig. 2), Hofmann (1969b, fig. 9) or Preiss (1972, p. 93), although a similar type has sometimes been referred to as platy in the Russian literature (Walter, 1972, p. 11). The term streaky microstucture was proposed by Walter (1972, p. 11–12) for laminae that are 'moderately distinct and continuous; those which are darker are usually the most distinct and they are set in a matrix of pale carbonate, into which they frequently grade vertically'. Walter (1972, p. 12) also recognized a subsidiary type, in which the laminae are discontinuous and have jagged margins and the laminar boundaries tend to be graded and indistinct. He referred to this type as 'irregular streaky' and thought it might be comparable to the fragmentary ribboned type of Hofmann (1969b, fig. 9).

   Examples: *Acaciella augusta*, which is regularly streaky (Preiss, 1972, p. 1, fig. 11e); *Gymnosolen* cf. *ramsayi* (now *Gymnosolen* new Form), which has a distinctive streaky architecture (Preiss, 1973a, fig. 12a); *Inzeria conjuncta*, which is also distinctly streaky (Preiss, 1973a, fig. 14a); ?cf. *Kulparia* f. indet., which has streaky architecture (Preiss, 1976b, fig. 46).

5. *Tussocky laminar architecture*: (Figs 150e, 154) this term was introduced by Bertrand-Sarfati, (1972b, p. 255; 1976, p. 253) and in many ways is representative of the concept of laminar architecture. It consists of an irregular lamination defined by the juxtaposition of separate hemispherical tussocks of different size usually composed of radiating elements (Bertrand-Sarfati, 1976, p. 253; Bertrand-Sarfati and Pentecost, 1992; Bertrand-Sarfati et al., 1994). Tussocks may be a primary feature formed by radiating filaments or a diagenetic overprint, where radiating filaments have been replaced by radiating crystals. The sedimentary element is commonly detrital quartz embedded in cement and overgrown by a dark, filmy lamina that may in turn be overlain by pure sparite cement.

   Examples: *Tungussia globulosa*, which has filamentous tussocks commonly overgrown by a cement of pure sparite (Bertrand-Sarfati, 1976, p. 256, fig. 2a); *Tungussia hemispherica*, in which the tussocks are commonly overgrown by a dark film (Bertrand-Sarfati, 1976, p. 253); *Serizia radians*, in which the tussocks are embedded in laminae of detrital quartz set in carbonate cement (Bertrand-Sarfati, 1976, p. 253); *Alternella hyperboreica*, in which the tussocks lack filaments and occur as flat pillows superimposed randomly with dark films that are moulded onto the surface of the pillows (Bertrand-Sarfati, 1972b, p. 255); *Rivularia*-like, which forms tussocks that encrust various hard

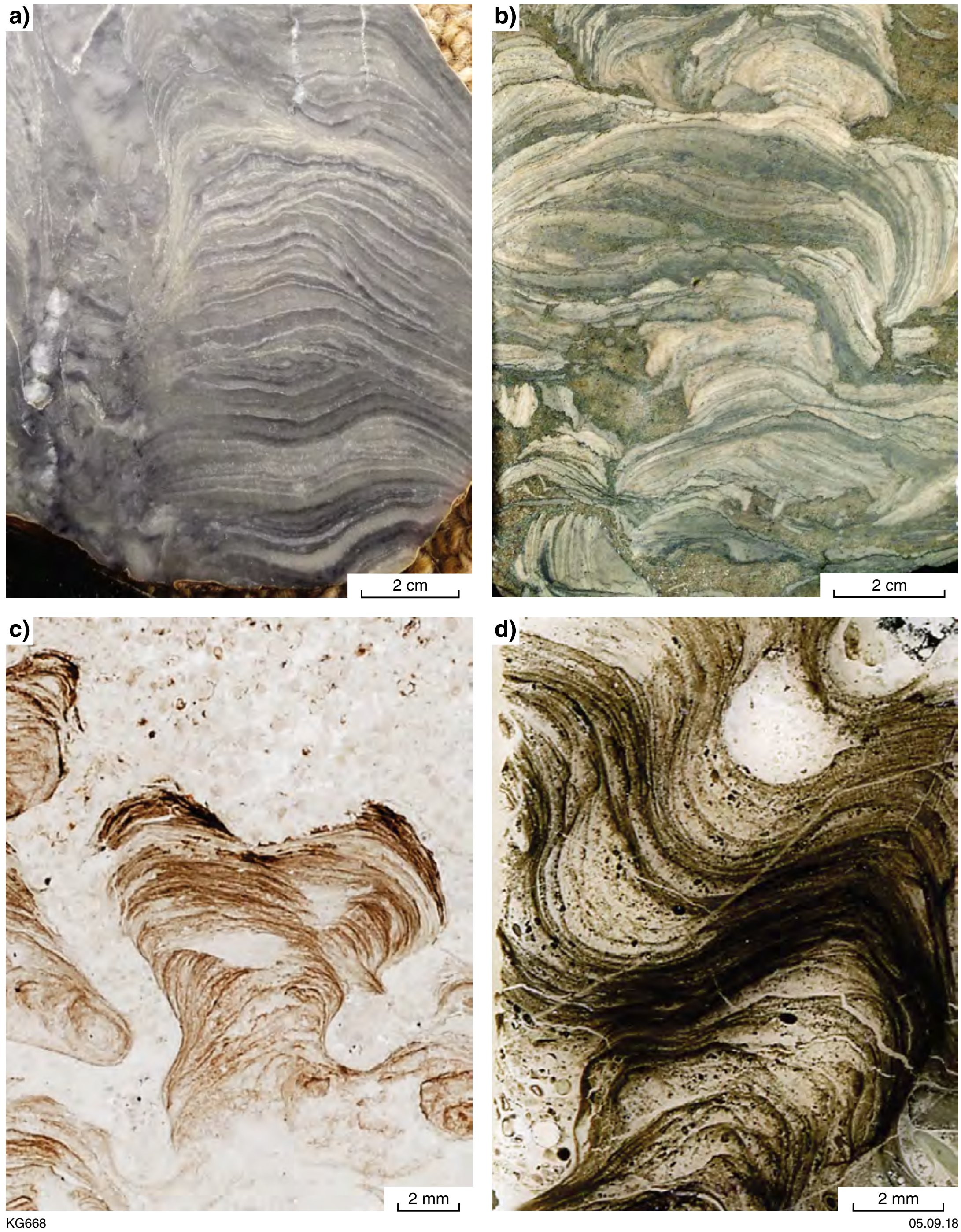

Figure 151. Examples of laminar architecture: a) banded; *Baicalia capricornia*; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Peedawarra Flats, MOUNT PHILLIPS, Western Australia; polished face GSWA F9908–46036 (photo by K Grey); b) banded; *Tungussia wilkatanna*; Steptoe Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Empress 1A, 510.8 – 513.5 m, Gibson Desert, WESTWOOD, Western Australia; split core (photo by K Grey); c) filmy; *Murgurra nabberuensis*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, NABBERU, Western Australia; thick section GSWA F12365–46333 (photo by SM Awramik and K Grey); d) filmy; *Gruneria* f. indet.; Gunflint Formation, Animikie Group; Animikie Basin; Orosirian, Paleoproterozoic; Winston Point, Lake Superior, Ontario, Canada; thick section from slab, Peabody Museum of Natural History, Yale University, YPM PB 051800 (photo by SM Awramik)

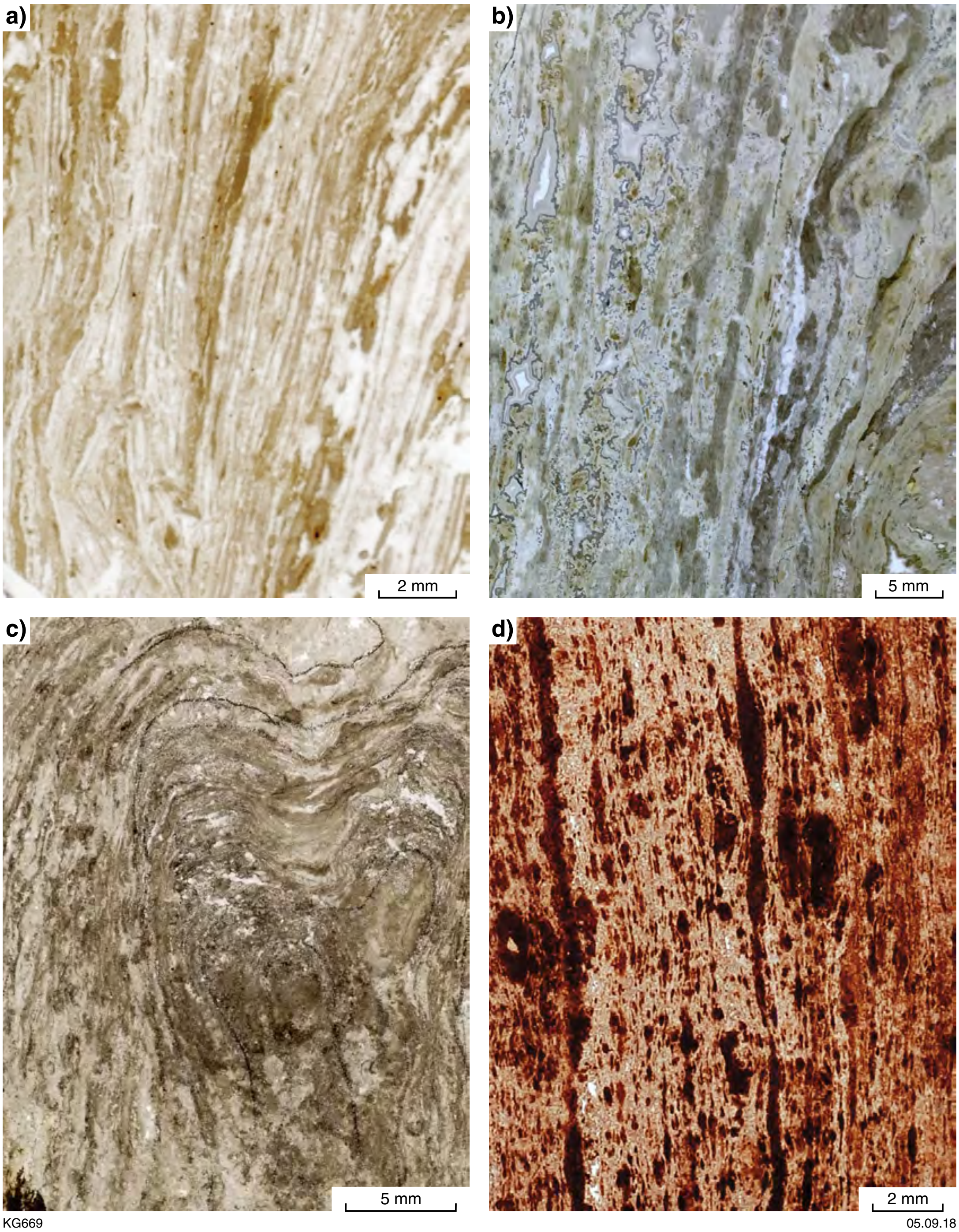

Figure 152. Examples of laminar architecture – striated; a) *Conophyton garganicum australe*; Irregully Formation, Edmund Group; Edmund Basin; Statherian, Paleoproterozoic; Fords Creek, TUREE CREEK, Western Australia; thick section GSWA F53603–84727 (photo by SM Awramik and K Grey); b) *Australoconus abnera*; Balbirini Dolostone, Nathan Group; McArthur Basin; Statherian to Calymmian, Paleoproterozoic to Mesoproterozoic; near Balbirini, BAUHINIA DOWNS, Northern Territory, Australia; thick section GSWA F53604–90518 (photo by M Ang); c) *Pilbaria deverella*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, NABBERU, Western Australia; thick section GSWA F12378–46583 (photo by SM Awramik and K Grey); d) striated to streaky; *Conophyton* new Form; Stag Arrow Formation, Manganese Group; Collier Basin; Stenian, Mesoproterozoic; Enachedong Creek, BALFOUR DOWNS, Western Australia; thick section GSWA F52619–84664A (photo by SM Awramik and K Grey)

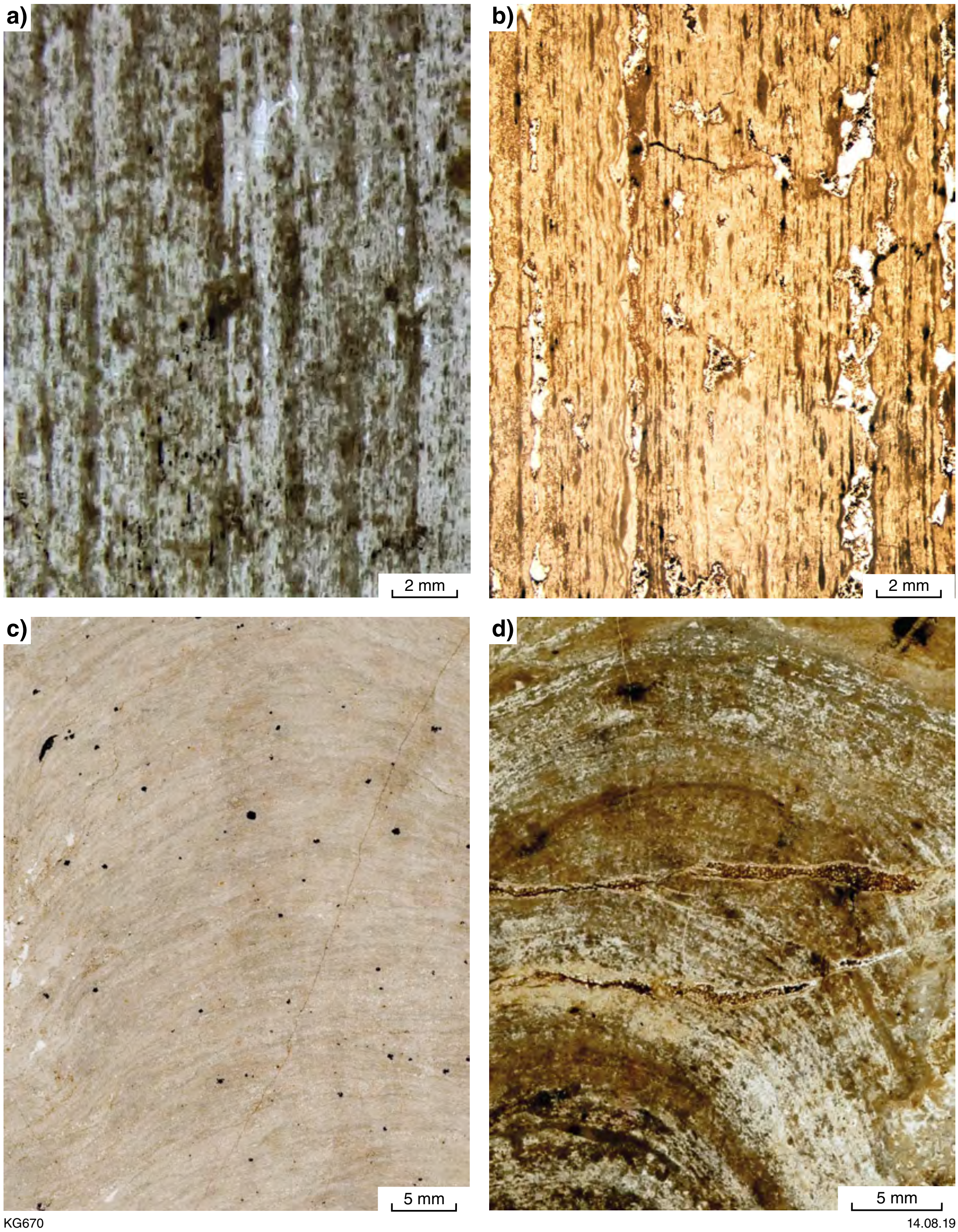

Figure 153. Examples of laminar architecture – streaky: a) *Conophyton* new Form (Pingandy type); Muntharra Formation, Edmund Group; Edmund Basin; Calymmian, Mesoproterozoic; Pingandy Creek, Mount Egerton, Western Australia; thick section GSWA F9932–46009 (photo by M Ang); b) *Conophyton* new Form; Dungaminnie Formation, Nathan Group; McArthur Basin; Calymmian, Mesoproterozoic; near Heartbreak Hotel airstrip, Bauhinia Downs; Northern Territory, Australia; thick section GSWA F53701–90524 (photo by SK Martin); c) *Pilbaria deverella*; Sweetwaters Well Dolomite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Sweetwaters Well, Nabberu, Western Australia; thick section GSWA F12376–46333 (photo by SM Awramik and K Grey); d) *Omachtenia teagiana*; Sweetwaters Well Dolerite, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; Sweeney Creek, Nabberu, thick section GSWA F12371–46582 (photo by SM Awramik and K Grey)

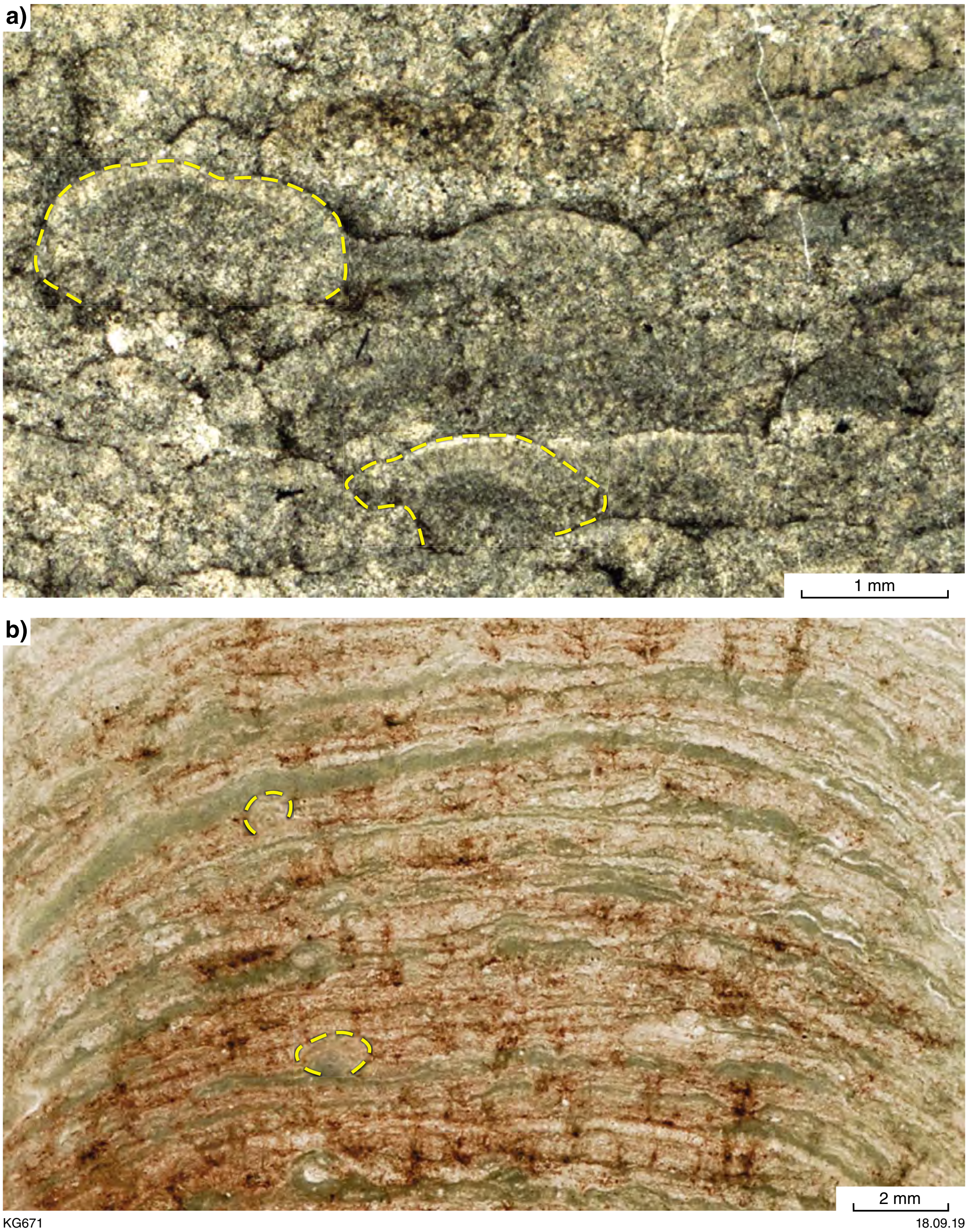

Figure 154. Examples of laminar architecture – tussocky (outlines): a) *Externia yilgarnia*; Yelma Formation, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; near Lake Wells Homestead, THROSSELL, Western Australia; thick section GSWA F52286–193359 (photo by K Grey); b) *Externia yilgarnia*; Yelma Formation, Tooloo Group; Earaheedy Basin; Orosirian, Paleoproterozoic; Wongawol Creek, near Lake Wells, DUKETON, Western Australia; thick section GSWA F12360–46075 (photo by SM Awramik and K Grey)

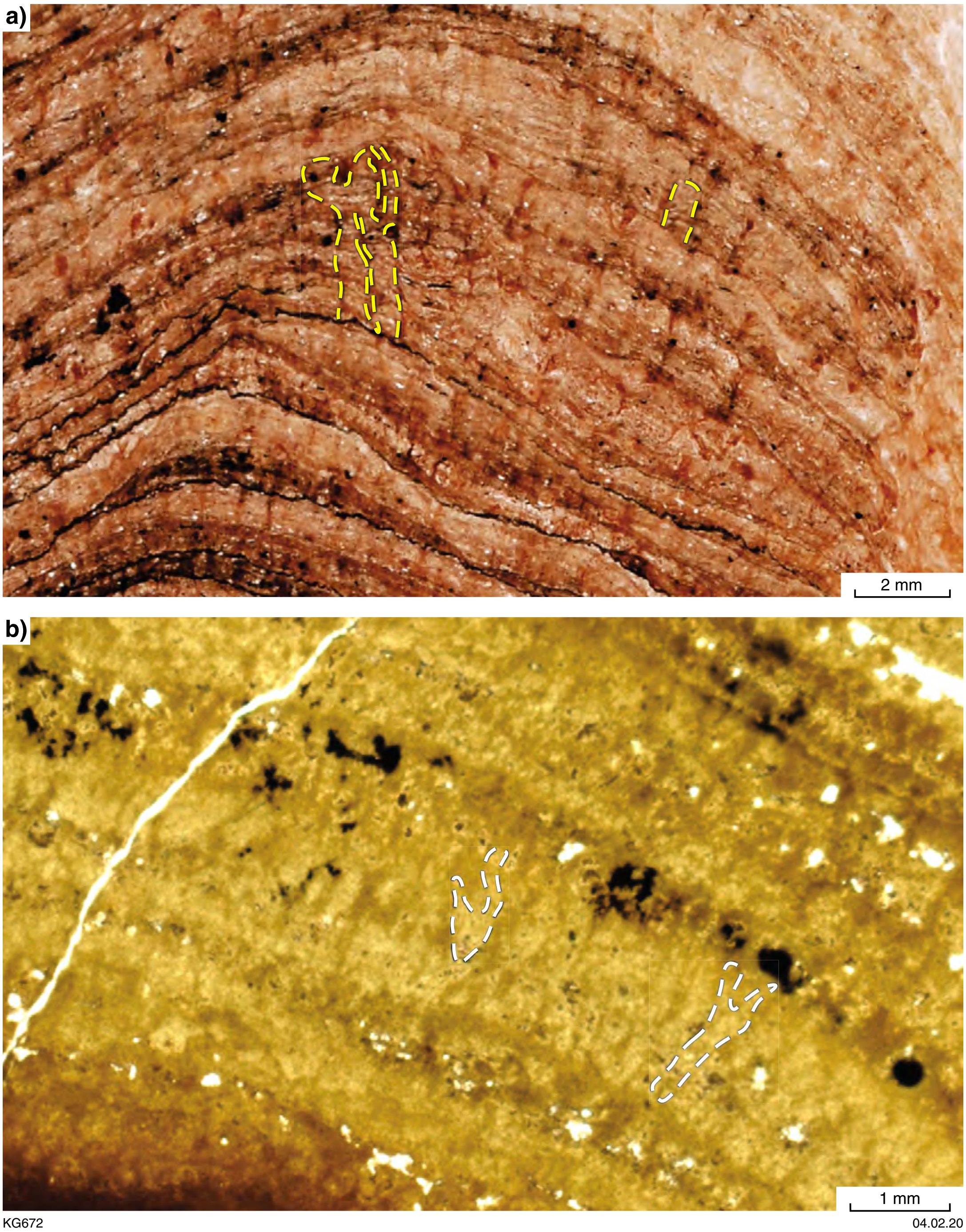

Figure 155. Examples of laminar architecture – pillared (outlined): a) *Earaheedia kuleliensis*; Kulele Limestone, Miningarra Group; Earaheedy Basin; Orosirian to Statherian, Paleoproterozoic; Thurraguddy Bore, THROSSELL, Western Australia; thick section GSWA F12356–42896 (photo by SM Awramik and K Grey); b) *Atilanya fennensis*; Aralka Formation; western Amadeus Basin; Cryogenian, Neoproterozoic; Boord Ridges, MACDONALD, Western Australia; thick section GSWA F52346–197130 (photo by HJ Allen)

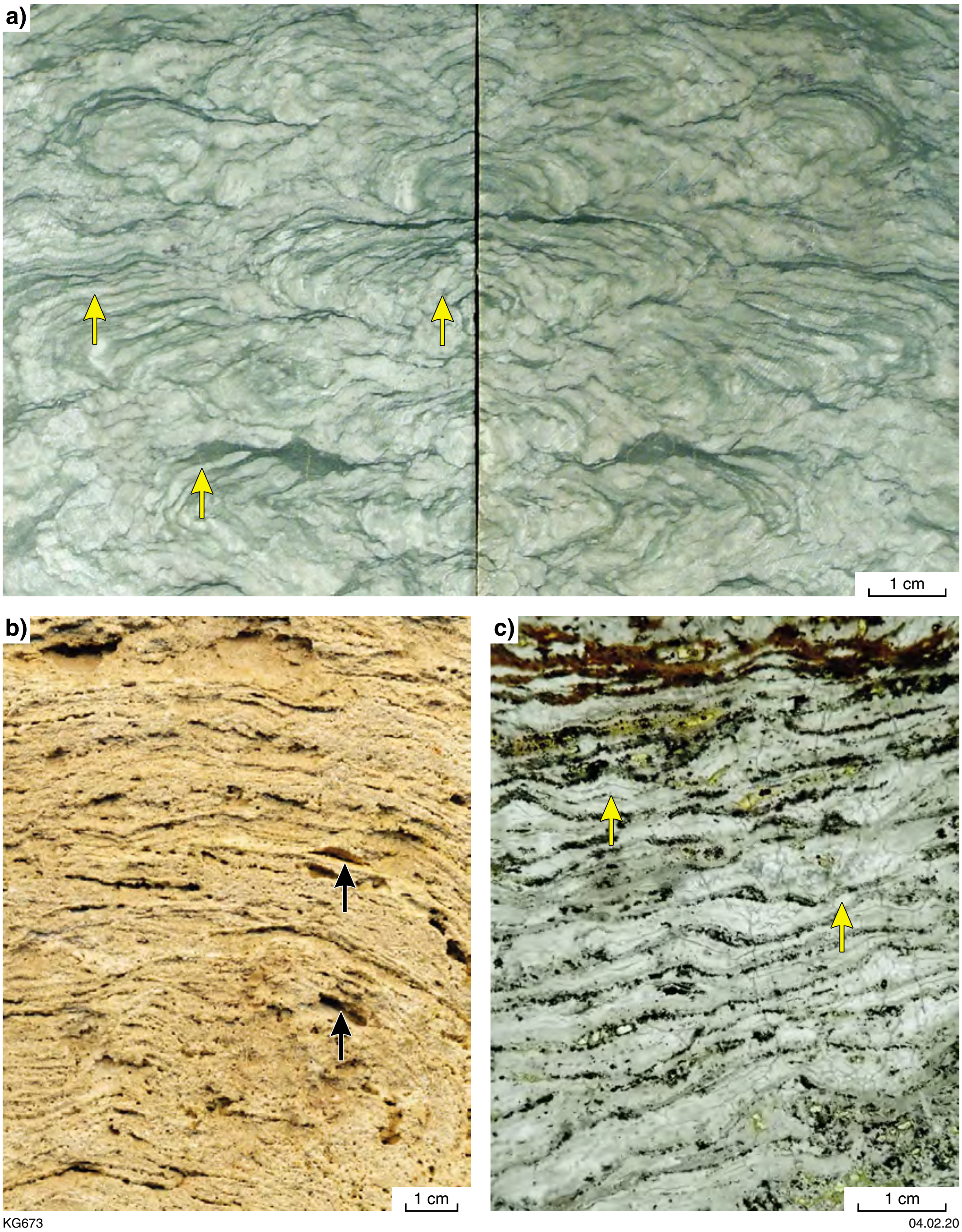

Figure 156. **Examples of laminar architecture – vermiform and alveolar; a) vermiform (arrows); *Tungussia* new Form; Hussar Formation, upper Buldya Group; Officer Basin; Tonian, Neoproterozoic; GSWA Empress 1A, 1077.4 m, Gibson Desert, Westwood, Western Australia; split core (photo by K Grey); b) alveolar (arrows); microbialite; Holocene; Carnarvon Basin; Carbla Point, Hamelin Pool, Shark Bay, Yaringa, Western Australia; cut face, UCSB collection (photo by SM Awramik); c) alveolar (fossil microbialite with spaces infilled by silica – arrows); Broadhurst Formation, Throssell Range Group; Tonian, Neoproterozoic, near Lochinvar ruins, Yarrie, Western Australia; thick section, GSWA F52600–88054 (photo by SK Martin)**

substances in streams, and has an architecture of juxtaposed hemispherical tussocks (Bertrand-Sarfati, 1976); *Externia yilgarnia*, which is composed of small tussocks arranged in a linear pattern (Preiss, 1976b, fig. 51; Grey, 1984).

6. *Pillared laminar architecture*: (Figs 150f, 155) a term used by Raaben et al. (2001) and Allen et al. (2016) for an architecture that consists of small columnar structures normal to the lamina curavature, and usually within a single lamina. The micro-columns can be quite variable. They are generally light in colour and are separated from each other by a narrower, darker interspace. The pillars may branch and, where well preserved, develop internal laminae of their own. In some cases, pillars extend through several successive laminae. They can also be referred to as micropillared.

   Examples: *Atilanya fennensis*, which shows good development of this internal architecture that is reflected by a distinctive wrinkly appearance of the laminae at macrostructural level (Allen et al., 2016); *Calevia olenica*, which reportedly has pillared 'microstromatoid' structures in the laminae (Raaben et al., 2001, p. 17); *Tysseria voronova* as illustrated in Raaben (2003, pl. 2, fig. 8).

7. *Vermiform laminar architecture*: (Figs 150g, 156a) probably equivalent to clotted in the sense of Komar et al. (1965a, Fig. 4; 1965b, fig. 2) and lumpy in the sense of Hofmann (1969b, fig. 9). According to Preiss (1972, p. 93), vermiform architecture 'consists of narrow, sinuous, pale-coloured areas (usually of sparry carbonate) surrounded by darker, usually finer grained areas'. Walter (1972, p. 14) gave a similar definition except he mentioned that the fine-grained areas are also carbonate, as did Bertrand-Sarfati (1976, p. 255). The boundaries may be poorly defined.

   Examples: *Madiganites mawsoni* in Walter (1972) and Bertrand-Sarfati (1976, p. 256–255); *Acaciella angepena*, which is regularly laminated; *Boxonia gracilis*, which has rounded granules; *Uricatella urica*, which has a polygonal network; *Boxonia divertata*, which has a variable network; *Minjaria procera*, which sporadically shows a polygonal structure.

8. *Alveolar laminar architecture*: (Figs 150h, 156b,c) consists of solid laminae separated by sub-parallel voids. These voids may have been infilled by later mineralization. The voids are commonly referred to as fenestrae and the architecture type 'fenestrate stromatolites'; for example, see Hoffman (1976, p. 266). However, Sumner and Grotzinger (2004) and Stevens et al. (2011) have used the term for a different type of structure. To avoid confusion, we prefer the term alveolar laminar architecture. Examples can be found in living (Figs 23d, 26, 33, 156b) and fossil (Figs 119c, 156c) stromatolites.

Describing thrombolite mesostructure

Thrombolites are not as well studied as stromatolites and this has resulted in numerous ambiguities and confusion. As noted, there are fundamental differences between thrombolites and stromatolites at the mesostructural level and it is here that separate terminology is required to differentiate the two types of microbialites. However, terminology is currently in disorder. The same terms, such as mesoclot, have been used to describe different features, and different terms have been used for the same features. Supposedly, the distinguishing mesostructural component of a thrombolite is the mesoclot (Shapiro, 2000). The term mesoclot was introduced by Kennard and James (1986, p. 493) as a modification of the original description of a thrombolite by Aitken (1967, p. 1164) that referred to a 'macroscopic clotted fabric'. Riding (2011a, p. 641) observed that 'Aitken's (1967) seemingly straightforward definition of thrombolite contained the seeds of more confusion than might have been anticipated.' Kennard and James in their coining of mesoclot wanted to avoid confusion with submillimetre-size clots (peloids, grumeaux) common in many microbialites. However, Aitken (1967) intended thrombolite to be a field term and hence stressed the visible or macroscopic aspect.

Besides mesoclots, other terms have been used for the characteristic mesostructure: clots (Aitken, 1967), fenestrae (Pratt and James, 1982); mesoclots (Kennard and James, 1986; Shapiro, 2000; Turner et al., 2000); microclots (Armella, 1994; Harwood and Sumner, 2012); thromboids (Armella, 1994; Kennard, 1994; Turner et al., 2000); also macroscopic clotted fabric (Aitken, 1967) and clotted macrofabrics (Riding, 1991), in which macrofabric is equivalent to mesostructure.

In addition to the perspective provided by Shapiro (2000), discussed under 'Microbialites and their constituents', Riding (2011a, p. 642) pointed out that:

> At present, it is safe to say that 'clot' (and the equivalent terms mesoclot and thromboid) has not been used consistently in thrombolite studies. It has been applied to millimetric patches within microbial carbonate, to centimetric lobate patches and also extended columns of microbial carbonate surrounded by detrital carbonate sediment, to transverse sections of these columns (here termed pseudoclots), and to diffuse patches of trapped sand, as well as to secondarily enhanced clots.

Additionally, some arborescent mesoclots in thrombolites superficially resemble branching calcimicrobes (Lee et al., 2014).

Shapiro (2000) rejected terms he considered confusing, such as fenestrae (Pratt and James, 1982), thromboid (Kennard, 1994) and macroclot, and favoured mesoclot. Shapiro (2000) reviewed the terminology and recommended using mesoclot, which is followed in this handbook (Figs 1, 3, 16–18, 23, 33a,c,e, 157–161). However, we also use the general term 'clot' as discussed below.

Riding (2000, p. 194) introduced the concept of post-depositional microbialites (for thrombolites) whereby 'clotted macrofabrics can be syndepostionally produced, diagenetically enhanced, or diagenetically created…', altering the original mesostructure so that clotted fabrics 'in carbonates appear in some cases to develop secondarily'.

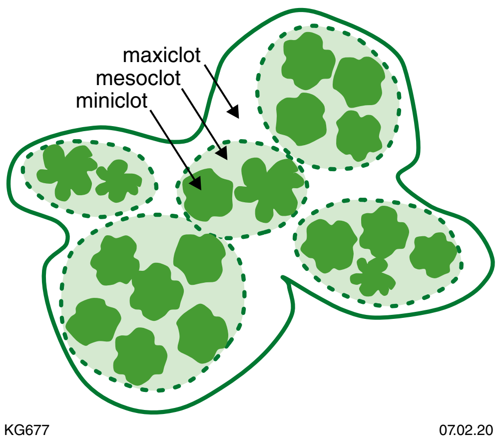

Figure 157. Thrombolite clot hierarchy – some, but not all, clots are compound structures. Components can be referred to as maxiclots, mesoclots and miniclots. Mesoclots are millimetre to centimetre in scale

Hierarchy of mesostructural organization

Laminae and mesoclots can be regarded as occupying parallel positions in the hierarchy of descriptive terminology, but whereas laminae are layers, mesoclots are not. Nevertheless, mesoclots display a range of characteristics of size, shape and organization, just as laminae do. Megascopic and macroscopic features of a thrombolite should be described using terminology common to stromatolites and thrombolites. Microscopic features of a mesoclot (miniclots and other sub-mesoclot features) should be described under microstructure using similar terminology to that employed for stromatolites.

From examination of published images, we have concluded that:

- thrombolites of different ages appear to show different types of mesostructure (see 'Microbialites and their constituents')

and

- the mesostructure of many thrombolites consists of two or more levels of organization.

These different levels and their associations have not necessarily been recognized or fully described, possibly because of the lack of appropriate terms for each hierarchical level. A number of authors have illustrated, but failed to comment on, this hierarchy and have applied the term mesoclot (or one of its equivalents) to different structural levels. For example, Lee et al. (2014, fig. 3d) showed dark grey, centimetre-scale structures, each composed of several millimetre-scale structures that are, in turn, composed of several submillimetre-scale structures and matrix. They refer to the largest of these structures as mesoclots. Turner et al. (2000, p. 90) recognized three scales of micritic clots, which they referred to as grumeaux (~25 to 100 µm), stromatolite-margin clots (~80 to 1000 µm) and thromboids (~500 to 5 mm). Examples such as the above suggest that some, but not all, thrombolites show a higher level of organization that comprises amalgamated clots. Additionally, some thrombolites may preserve a lower level of organization, in which individual mesoclots are composed of smaller components. These components may consist of several smaller clots, or calcimicrobes, or peloids, or sedimentary grains, or cements, or a combination of the above. Component clots are often poorly defined and diffuse, and consist of darker patches that mark where smaller clots have amalgamated into larger, usually better defined clots.

In order to better comprehend the complexities of thrombolites we recommend a three-tiered approach by using the terms maxiclot, mesoclot and miniclot (Figs 157–161). We suggest using maxiclot where several mesoclots have amalgamated into a larger structure, most commonly at the scale of a several millimetres to a few centimetres, and miniclot for sub-millimetre clots that are constituents of a mesoclot or isolated small clots. The term clot can be used in a general sense to refer to all three types. Not all clotted mesostructure displays all three components. This three-tiered approach should help in a better understanding of thrombolite mesostructure, at least until a more inclusive and comprehensive analysis of thrombolite mesostructure has been undertaken. Mesoclots are still the distinguishing feature of a thrombolite.

Maxiclots

We introduce the term maxiclot (Figs 157–160) for an amalgamation of several mesoclots into a larger structure, commonly about a centimetre in scale. This is preferred to using macroclot or macroscopic clotted texture, which has been used infrequently and inconsistently in the literature, often being applied to structures of differing scales. Aitken (1967) introduced the terms macroscopic clotted fabric as a distinguishing characteristic of thrombolites and clots for centimetre-sized patches of microcrystalline limestone. Kennard (1989) referred to macroscopic clots as the main component of a thrombolite; however, the same feature was called a thromboid by Armella (1994). Pickard (1996, p. 68, caption to fig. 2b) described macroclots as 'composed of peloidal micrite (pm) and…are cemented by radiaxial calcite cement'. Riding (2011) used the term macroclot, referring to the patchy recrystallization of the clotted fabric in Aitken (1967), but did not define the nature of a macroclot. Because of these uncertainties, we have introduced the new term maxiclot with the specific definition given above and applying to the larger structures (solid outline) in Figs 158–160.

Mesoclots

A mesoclot (dotted outline in Figs 157–158, 159c, 160) is the basic structure of a thrombolite. Many authors have used the term, but not necessarily consistently (see above). We define mesoclot as a millimetre- to centimetre-scale mesostructural component that consists of spheroidal to polylobate masses, composed of one to a variety of components within the groundmass of the unlaminated microbialite. We use the term mesoclot in the sense of Shapiro (2000) because it has become the most widely adopted of the proposed terms, and because it is the term most readily adapted to handle complexities of organizational levels within thrombolites that have not previously been fully recognized.

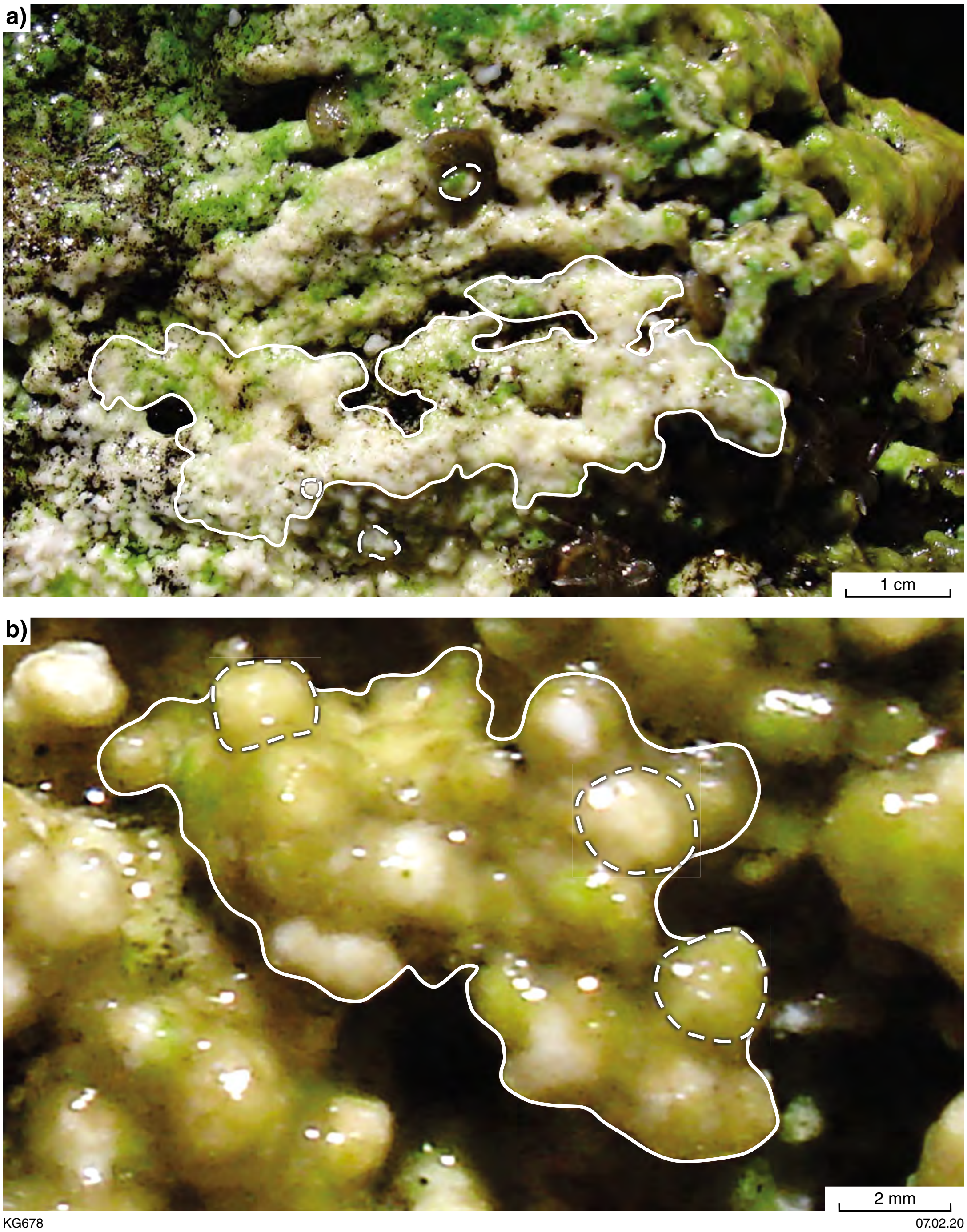

Figure 158. Examples of clot hierarchy in living thrombolites: a) maxiclots (solid line) and some isolated mesoclots (dashed outline) in a thrombolite; Perth Basin; Holocene; Lake Thetis, Cervantes, Hill River, Western Australia (after Grey and Planavsky, 2009, fig. 22) (photo by NJ Planavsky); b) thrombolite (see Fig. 27) formed of mesoclots (dashed outline) amalgamating into maxiclots (solid outline); Perth Basin; Holocene; Lake Thetis, Cervantes, Hill River, Western Australia (photo by NJ Planavsky)

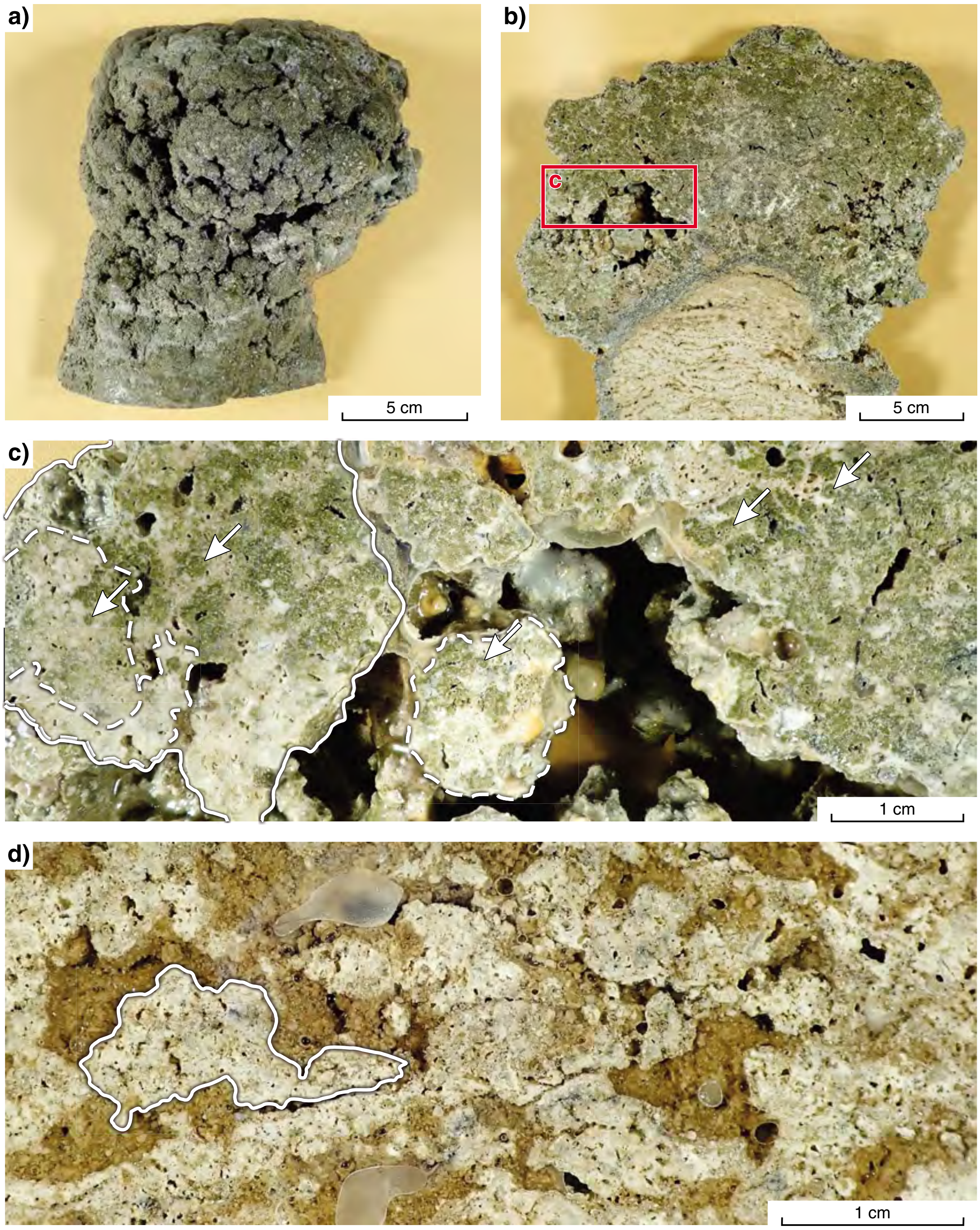

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Figure 159. Examples of clot hierarchy in living thrombolites; Carnarvon Basin; Holocene; Hamelin Pool, Shark Bay, EDEL and YARINGA, Western Australia; samples collected by RP Reid and EP Suosaari (photos by SK Martin and K Grey): a) thrombolite composed of *Entophysalis* (see Fig. 27c); GSWA F54144; b) similar to a) showing the internal structure, consisting of a stromatolitic core (cream-coloured area with laminations) capped by a thrombolite (greenish area with maxiclots composed of mesoclots); GSWA F54145; c) detail of thrombolitic cap in b); the specimen consists mainly of large mesoclots (dashed outline). The small, dark, submillimetric patches within the mesoclots (arrows) may be miniclots and some mesoclots appear to be in the process of amalgamating to form maxiclots (solid outline); GSWA F54145; d) thrombolite formed of maxiclots; the specimen is at a more advanced stage of lithification than previous specimens and consists mainly of maxiclots (solid outline), although the mesoclots which make up the maxiclots can still be recognized; GSWA F54106

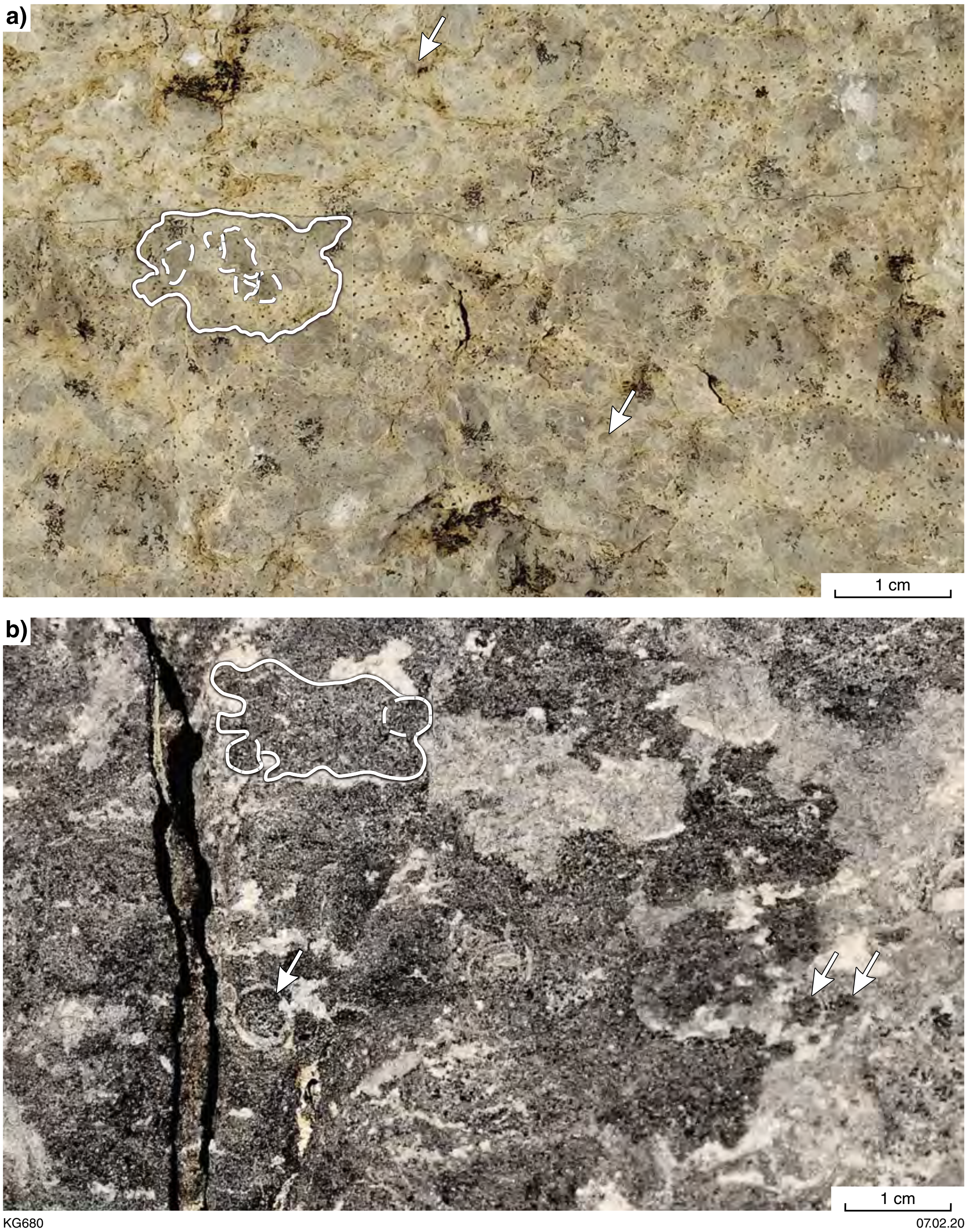

Figure 160. Examples of clot hierarchy in fossil thrombolites: a) mesoclots (dashed outline), with some traces of miniclots, amalgamating into maxiclots (solid outline) and isolated miniclots (arrowed); thrombolite; Wirrealpa Limestone, Moralana Supergroup, Arrowie Basin; Cambrian; near Old Wirrealpa Mine, Flinders Range, Parachilna, South Australia (photo by HJ Allen); b) thrombolite formed by small mesoclots (dashed outline) amalgamating into maxiclots (solid outline); isolated miniclots are also present (arrows); Desert Valley Formation (lower dark dolomite member); upper Cambrian; Delamar Mountains, Lincoln County, Nevada, US (photo by SM Awramik)

Mesoclots are usually dark in colour, of variable shape and composition; they can be isolated, interconnected, or coalesced, and separated from one another by sediment or cement, or some combination of both. According to Shapiro (2000, p. 169), they are composed of a variety of microstructural elements. These include dense micrite (Glumac and Walker, 1997), peloids (Pratt and James, 1982; Shapiro, 1998), and various calcimicrobes (Moore et al., 1984; Kennard and James, 1986; Latham and Riding, 1990; Lee et al., 2014). The distribution of mesoclots across the 2D surface of the thrombolite imparts the characteristic clotted appearance and composition. Amalgamated mesoclots form maxiclots and can, in turn, be composed of miniclots.

Miniclots

A miniclot is the smallest example of a clot (Fig. 160b). A miniclot is a sub-millimetre clot that is commonly a constituent of a mesoclot but can also occur independently of other types of clot. Miniclots have also been called grumeaux (Turner et al., 2000) and microclots Harwood and Sumner (2012). However, the term grumous is here used to describe a type of stromatolitic microstructure, so is best avoided for thrombolite terminology. There is some overlap between miniclots and the application of the terms mesoclot and microclot, although these terms have often been vaguely defined. For example, although authors such as Armella (1994), Johnson et al. (2012) and Le Ber et al. (2015) mentioned microclots, or some variation of the term, they did not define or adequately describe them. One of the more informative descriptions was that of Fraiser and Corsetti (2003), who mentioned micrite clumps ~70 μm in diameter encased in cement, which presumably are the same as microclots illustrated in their figure 2C. Even in this case, there is ambiguity as to the specific term to be used, and which structures within a photomicrograph are referred to in the captions. Microclot implies the clot is not visible to the unaided eye and would therefore be a microstructural component. For these reasons, we prefer the term miniclot, which we define as a clot a millimetre or less in size occurring as a component within a mesoclot or as an isolated clot (Figs 157, 159c). Miniclots are usually dark, poorly defined masses of variable shape, but commonly spheroidal. Some miniclots are peloids. Amalgamated miniclots can form mesoclots (Zhang et al., 2016, fig. 8j) or may comprise more complex structures, such as peloidal miniclots embedded in micritic mesoclots (Figs 158–160).

The shapes and other characteristics of maxi- meso- and miniclots are similar, although the shape of a combined structure is not necessarily the same as its components. The characteristics of all three clot types can be described using common terminology. Clots are best studied by tracing their outline digitally or on acetate paper. These tracings emphasize details and patterns (Shapiro and Awramik, 2006, fig. 7.2).

Clot shape

The 3D morphology of a clot is referred to as the clot shape (Fig. 161). Shape is usually polymorphic and quite variable in both ancient (Kennard, 1994, p. 450) and living thrombolites (Moore and Burne, 1994, p. 23). No universal scheme has been proposed for the study of clots, so provide clear and well-illustrated explanations of the methods used. Qualitative descriptions of 2D surfaces are potentially useful in the field and for comparative studies, but it is critical that the 3D nature of clots be considered. The relatively small size of clots makes study of their 3D morphology difficult. Most studies have relied on the 2D vertical (longitudinal) profiles of mesoclots (Aitken and Narbonne, 1989; Kennard, 1994), best determined from a vertically oriented thrombolite. There has been no geometric (morphometric) analysis of clot shapes, profiles, or outlines, although this should be possible using ImageJ or other morphometric software. The use of micro-CT scans should be explored for investigating 3D clot shape.

Clot morphology has been characterized in the literature, but in practice it is often difficult to identify specific categories or provide adequate illustrations. Very few shape categories have been formally defined or described (Fig. 161), and many of the terms are used inconsistently; for example, pendant, as used by Kennard (1994), seems to have little in common with the usage by Kahle (2001). Some terms that purportedly refer to shape, also depend on position and orientation within the thrombolite. Until the terminology is standardized, it will be difficult to provide a rational list of terms to use. Some of the more common terms that have seen consistent usage are listed below. Generally, shapes are poorly illustrated and it is difficult to find good examples of many of them; references to suitable images are cited where possible. Note that most are 2D not 3D:

1. *Rounded*: (Fig. 161a) margins are more or less equidistant from the centre (Kahle, 2001, fig. 5a,b)
2. *Subrounded*: (Fig. 161b) margins are at an irregular distance from the centre (Kahle, 2001, fig. 5a,b)
3. *Oblong*: (Fig. 161c) one axis is much longer than the other
4. *Lanceolate*: (Fig. 161d) one axis is significantly longer than the other and terminates in pointed tips. The direction of elongation should be noted
5. *Crescentic*: (Fig. 161e) elongate with a pronounced curvature of the major axis
6. *Scutate*: (Fig. 161f) shaped like a shield. Note the orientation of the flat side relative to the growth direction
7. *Pendant*: (Fig. 161g) the flat surface forms the upper margin and the lower margin is lobate (Kennard, 1994, fig. 7b)
8. *Lobate*: (Fig. 161h) having several protrusions of the clot margin (Kennard, 1994, fig. 7e)
9. *Saccate*: (Fig. 161i) hollow with a distinct rim. Though often lobate, they can form a variety of external shapes (Kennard, 1994, fig. 7e)
10. *Arborescent*: (Figs 18a, 161j) having a bushy shape (Kennard, 1994, fig. 7a; Riding, 2011a, fig. 8) with a flat base and lobate or branched upper portion
11. *Diffuse*: (Fig. 161k) with indistinct borders (Harwood and Sumner, 2012, fig. 7C).

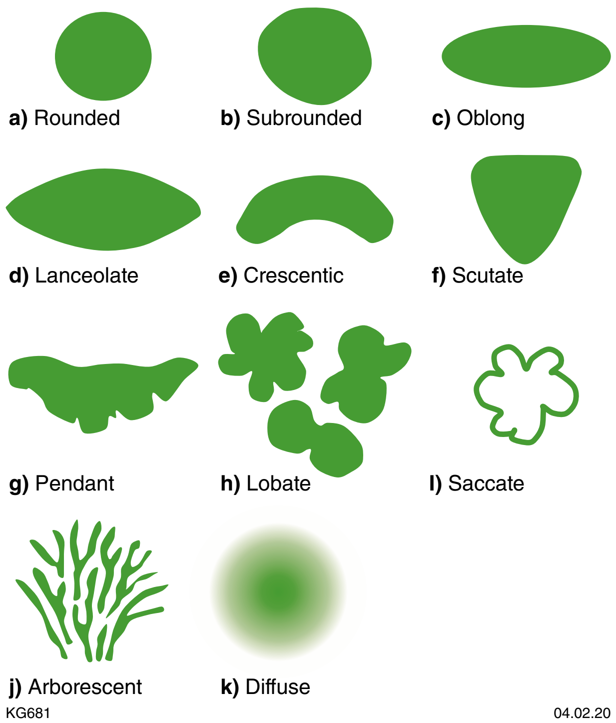

Figure 161. **Thrombolite clot shape: a) rounded; b) subrounded; c) oblong; d) lanceolate; e) crescentic; f) scutate; g) pendant; h) lobate; i) saccate; j) arborescent; k) diffuse**

Clot orientation

Care should be taken to distinguish between thrombolite orientation (see macrostructure) and clot orientation. Clots can be oriented in a regular pattern either locally or throughout the entire thrombolite. Orientations should be noted and patterns described. A handful of terms can be applied to mesoclot orientation:

1. *Normal*: the major axes of the clots lie parallel to the thrombolite growth axis and generally normal to bedding
2. *Prostrate*: the major axes of the clots lie horizontal or at an oblique angle to the vertical. Angles should be noted
3. *Radial*: the major axes of the clots radiate from parallel to the growth axis at the centre of the thrombolite (i.e. generally normal to the bedding) to more divergent angles near the margin
4. *Random*: there is no regular orientation to the clots.

Clot size

Clot height, length, and width should be measured on vertically and horizontally oriented samples (vertical profile and outline). This should be done on several thrombolite samples in different parts of the buildup (centre to margins) and within the thrombolites going from the base towards the top and from the centre towards the margins. Note if there are any patterns in size variation among the different samples.

Clot spatial relations and arrangement

One of the many complexities of clots is that they can be isolated, interconnected, or coalesced (see 'Hierarchy of mesostructural organization'). This complicates shape, profile and outline descriptions. For coalesced and interconnected clots, descriptors such as slightly, moderately and highly can be used. Determine if clots are randomly arranged in the thrombolite, radially arranged, or if there are other arrangements. Note if the clots are polymorphic — that is, they have variable or inconsistent shape throughout the thrombolite. Clots can also be more concentrated in certain regions of the head, such as in the outer portions of the head. Determine the percentage of the thrombolite composed of clots.

Other aspects of thrombolites

Phanerozoic thrombolites often have invertebrates within the thrombolite (associated with mesoclots) as well as invertebrates in the enclosing sediment (Webb, 1987; Leinfelder et al., 1993; Tomás et al., 2013). The invertebrates in and associated with the thrombolite buildup should also be identified and spatial relations to the thrombolite itself described.

At times, microbialites can be a combination of thrombolites and stromatolites, thrombolites and dendrolites, or all three, defined above as 'composite microbialites' (Fig. 23). Any laminae present should be described using stromatolitic mesostructural terminology. Care should be taken to note the relationship of the laminae to the thrombolitic portions of the microbialite and whether the relationships are gradational, alternating, or have some other association.

Describing dendrolite mesostructure

Dendrolites, as the name suggests, have a dendritic mesostructure. The mesostructural components are shrub like and occur in a structureless matrix (Fig. 19). Individual shrubs can be composed of micrite (Ibarra et al. 2014), calcimicrobes (some in clusters; Riding, 1991), radiating crystals (Chafetz and Folk, 1984) or peloids (Della Porta et al., 2011). Shapiro and Awramik (2000, p. 173) pointed out that, whereas stromatolites are characterized by a laminated mesostructure and thrombolites by a clotted mesostructure, dendrolites 'are characterized by a dendritic fabric of calcimicrobes.' As discussed under 'Microbialites and their constituents' this dendritic fabric can be referred to as 'shrubs'.

Shrubs should be described in terms of their overall shape, size, style of branching, intershrub sediment (equivalent of interspace) and composition, using terms recommended for similar structures elsewhere in this handbook. Because they are so poorly documented and so variable, suitable terms are not listed here and need to be developed. It is critical that definitions are clear and unambiguous. The study of dendrolites is an emerging field, thus it is important to adequately illustrate them with drawings, images, and labels.

Some shrubs can superficially resemble arborescent mesoclots in thrombolites, but are distinguished from them by being composed of branching clusters of calcimicrobes (Lee et al., 2014), rather than micritic mesoclots.

Describing leiolite mesostructure

Leiolite, introduced by Braga et al. (1995), refers to a microbialite in which the mesostructure is structureless; it has no lamination, mesoclots or shrubs (Fig. 20a). Riding (2000) used the term aphanitic in discussing leioloites, implying that components (grains) are too small to be seen with the unaided eye. The leiolites described by Braga et al. (1995) were domes composed of ooids (a structureless microbial boundstone). We recommend that leiolite be used for a microbialite with a structureless mesostructure regardless of grain size.

As Lee et al. (2000, p. 16) pointed out, a 'model envisioning continuous microbial growth under constant sedimentation would produce no laminae.' In other words, this would produce a leiolite. Also, because they are structureless at the mesoscopic scale, there is little to describe and descriptions should be based on microstructure using similar terms to those associated with stromatolites, thrombolites and dendrolites. We also note that it is difficult to distinguish a structureless microbialite from one in which any detail of internal structure has been lost through diagenesis or recrystallization.

Describing microbialite microstructure

Microstructure is here restricted to the fine-scale features present in the mesostructure that are best studied under the microscope. This is a different concept from some earlier uses. Previously, microstructure commonly referred to features that we include in mesostructure, especially the distinctness, continuity, thickness and laminar architecture of stromatolites (for example, as used by Preiss, 1972, p. 93). Although architecture could be considered to straddle both meso- and microstructure, it is here categorized under mesostructure. In previous usage, microstructure also included the composition of the laminae, and this is the sense in which we use it. In the case of thrombolites and dendrolites, microstructure refers to the internal nature of the mesoclot or dendritic structure, as well as areas between the mesoclots or dendritic structures ('shrubs') within the head. In the case of leiolites, there may some confusion with regard to microstructure. When first defined and described (Braga et al., 1995), leiolites were reported to have unorganized grainstone as the microstructure. This is essentially the same definition of Kennard and James (1986, p. 492) who recognized 'undifferentiated microbial boundstone' as a third category of microbial structures in addition to stromatolites and thrombolites.

Microstructure (Figs 162–170) includes constituents such as sedimentary grains, fabric, texture, precipitates, and any preserved microbial components. In some cases, only traces of previous microbial structures remain (Schopf and Walter, 1982, p. 558). These were defined by Schopf (1983b, p. 453) as palimpsest stromatolitic microstructures; a microstructure 'in a stromatolitic sediment in which the distribution of kerogen, iron oxide, pyrite, or some other pigmenting material indicates the former distribution of microbial remains'. Such microstructures are not restricted to stromatolites, but can also be present in other types of microbialite.

There is evidence that different kinds of microbial mats produce specific microstructures and they can be preserved in ancient microbialites (Gebelein, 1974; Monty, 1976; Awramik and Semikhatov, 1979; Semikhatov et al., 1979; Walter, 1983; Awramik, 1991, 1992a; Walter et al., 1992; Zhang and Hofmann, 1992; Omelon et al., 2013; Bartley et al., 2015; Harwood Theisen and Sumner, 2016). Characteristic features of the original mat and associated matrix can be preserved and survive diagenetic alteration. However, diagenesis can obliterate or nearly obliterate original microstructure. It is important to determine, if possible, the original microstructure and characterize the diagenesis. Original microstructure, such as grain size, fabric and mineralogy, are important for description, paleoenvironmental interpretations and other analyses.

Microstructure must be considered as an important factor in microbialite descriptions and classification. Although there have been several studies of living microbialite microstructure, microstructure (for example, Gebelein, 1974; Monty, 1976; Dupraz et al., 2013; Suosaari et al., 2016), there have been only a few comprehensive reviews of fossil types (Bertrand-Sarfati, 1972a,b, 1976; Komar, 1989; Bertrand-Sarfati et al., 1994; Zhu, 1982). Much of the terminology that has developed over the years does not adequately reflect what is presently known about the microbiology, sedimentology and petrography of microbialites. As microbialite descriptions have amassed, recurring styles of microstructure have been observed and even in examples where low-grade alteration has occurred, many still seem to reflect their original structure. However, care must be taken when analysing these patterns; alteration of an original laminated fabric to a clotted, thrombolitc fabric has been described for living Bahamian stromatolites (Planavsky and Ginsburg, 2009). Appreciation of the biogenic influence on microstructure must be tempered by a familiarity with the petrographic aspects of secondarily recrystallized and replaced textures (including fabrics).

There have been inconsistencies with regard to the term fabric as applied to microbialites. Monty (1976, p. 193) stated that fabric 'refers to internal spatial properties of these structures [stromatolites] such as the development of a lamination', whereas microstructure 'refers to the microscopic characteristics of the internal properties.' However, Bertrand-Sarfati and Walter (1981, p. 355) referred to the combination of laminar shape and microstructure as 'fabric'. Harwood (2009, p. 19) referred to composite fabric as a mixture of mesofabric types, such as mesoclots, laminae and their intergradation, although use of fabric in this way is questionable as fabric is a microstructural feature and a component of texture. Riding (2011a, p. 636) used macrofabric in the same sense that mesostructure is used in this handbook to identify the different types of microbialites (Fig. 1).

It is difficult to reconcile these different viewpoints. Instead, it is better to restrict the use of terms such as texture and fabric to their sedimentological meanings. Texture is the 'size, shape and arrangement (packing and fabric) of the component elements of a sedimentary rock' (Pettijohn, 1957, p. 13) and fabric is the 'orientation (or lack of it) of discrete particles, crystals and cement...' (Neuendorf et al., 2011, p. 227). We recommend that fabric be used in the sedimentological (microstructural) sense, so that fabric and texture are treated as components of microstructure. Care must be used when the term fabric is used above the microstructural level and it should be identified with the proper prefix.

In this handbook, the terms mesostructure and microstructure have been modified to indicate more clearly the hierarchical level being described. At present several broad types of microstructure can be distinguished (Figs 162–170) but the list is far from comprehensive and further recognition and cataloguing of types is required. For descriptive purposes, terms suggesting a genetic origin should be avoided. Some microstructures may intergrade with each other. Researchers should attempt to distinguish between primary and secondary fabrics. The taphonomy of the microbialite (including the degradational history of the constructing organisms or biostratinomy) and its subsequent diagenetic (secondary) alteration may need to be considered in analysing the microstructure. The aim should be to estimate what changes have taken place that might have altered the microstructure.

Types of microstructure

Maslov (1960), Semikhatov (1962) and Komar (1989) each suggested classifying microbialites on the basis of microstructure, but this approach, as discussed by Semikhatov and Raaben (2000), has not been widely adopted, mainly because it is still unclear whether or not microstructure shows consistent and concurrent variation as diagenesis progresses. However, examination of numerous descriptions in the literature indicates that there are consistent associations between mesostructural and microstructural types. Despite this, Turner et al. (2000) and Planavsky and Ginsburg (2009) noted that some thrombolites have their origin from taphonomic differentiation of previously existing microstructures. Until the relationship between microstructure, mesostructure and other aspects of gross morphology is better understood, microstructure and any possible diagenetic variants should be described along with other microbialite characteristics.

The following microstructural terms are the ones most commonly used:

1. *Micritic*: (Figs 162a, 163) refers to structureless micrite, as in the sense of Folk (1959), where it is the principal component of a lamina or comparable structure. It may have been precipitated or sedimented or both. Care should be taken with the term dolomicrite. If used, it would be helpful to make clear whether the dolomite contributed to the primary microstructure or is diagenetic in origin. Some microbialites in lacustrine systems have been interpreted to have fine-grained, primary dolomite; hence, dolomicritic would be a valid microstructural term (Last et al., 2010)
2. *Microsparry*: (Figs 162b, 164) refers to a microstructure composed of microspar, which is 5–30 μm in grain size (Folk, 1965, p. 7). Most microspar forms as a result of the recrystallization of micritic calcite or aragonite crystals (Flügel, 2004)
3. *Grumous*: (Figs 162c, 165) refers to a microstructure composed of micritic peloids or clots (commonly between 0.1 and 0.5 mm in diameter) that can be clumped together in an irregular manner, with interparticle and fenestral pores between them. This microstructure has also been called spongioform (Pratt, 1982), structure grumeleuse (grumeaux, grumelous; Cayeux, 1935; Bathurst, 1971; Turner et al., 2000), clotted (Schwarzacher, 1961), and peloidal (Bahniuk et al., 2015). Grumous microstructure is common in, although not restricted to, many Phanerozoic marine thrombolites and stromatolites
4. *Granular*: (Figs 162d, 166) refers to a microstructure composed of silt-sized or larger detrital sediment incorporated into the microbialite (Frantz et al., 2015). This includes ooids, peloids (where they are subordinate), bioclasts and catagraphs. The exact nature of these particles should be described
5. *Spherical*: (Figs 162e, 167a) refers to spheres, in some cases hollow, in others filled with mineral matter, with a well-defined outer boundary, and incorporated into the microbialite. Bradley (1929, p. 207, plate 32a,b) discussed and illustrated a stromatolite with a microstructure of carbonate-filled spheres (*Chlorellopsis*), from the Eocene Green River Formation, Utah, US
6. *Fibrous*: (Figs 162f, 167b) refers to a microstructure composed of fibrous or radiating crystals oriented perpendicular to the lamina or other surface. In lacustrine stromatolites, fibrous laminae often alternate with micritic laminae
7. *Tubular*: (Figs 162g, 168–169) refers to a microstructure composed of hollow tubules with micritic walls interpreted to be calcimicrobes (Batten et al., 2004, fig. 9B; Riding, 2000, fig. 3). The size, shape, and orientation of the tubules should be noted. Some may be filament moulds or even minute burrows. This microstructure has also been called skeletal microstructure and vermiform (Pratt, 1982, p. 88), but this term already exists for a type of laminar architecture (see above). Riding (1977, p. 57) used the term ‘skeletal stromatolite’ where skeletal calcification is produced by calcified microbes (calcimicrobes), generally cyanobacteria. (Such microstructures can be present in other types of microbialite besides stromatolites.) Pia (1927, p. 37) used the term porostromata for a microstructure with tubular calcimicrobes. The taxonomic name(s) of the microfossils should be given in the description if possible. Orientation of tubules can be random, as in some *Girvanella* (Riding, 2000, fig. 3), or radiating as in *Rivularia* (Pentecost, 1987)
8. *Microfossiliferous*: (Figs 162h, 170) refers to a microstructure or portions of a microbialite composed of recognizable, organic-walled microfossils (Schopf and Sovietov, 1976; Schopf et al., 1977; Awramik and Semikhatov, 1979; Cao and Yin, 2011). These are only rarely preserved in microbialites.

Record other features in addition to the types or combinations of microstructure; for example, the presence of cavities or fenestrae, which may be irregularly distributed or, in the case of stromatolites are consistently parallel to the laminae.

Describing other features associated with microbialites

Petrography

Describe other features such as mineralogy, grain shape and size, and grain relationships that occur in the specimens both within the microbialite and the surrounding matrix using standard petrological techniques and terminology. This information is useful for describing the texture and fabric.

Interspace filling

The interspace (Fig. 11) is the area between structural elements, such as buildups, bioherms, biostromes, heads, fascicles, columns, branches, and oncoids. Interspace filling is the material that occupies the interspace. The filling provides valuable information on lithofacies and paleoenvironment, and commonly contains features that relate to the growth history of the adjacent microbialites. Interspace sediment should be compared and contrasted with sediment in the microbialite. Note whether the fill intergrades with, or terminates abruptly at, the microbialite margin, whether or not there is evidence of erosion, and whether laminae extend across the interspace areas as faint traces or even as robust bridges.

Secondary alteration

Secondary alteration refers to diagenetic and metamorphic features including recrystallization, silicification, deformation, and phosphatization that may be present in a microbialite. Although microstructure was recognized by Maslov (1960) as a diagnostic characteristic, as discussed above, this has not been widely accepted because of concerns about overprinting by diagenesis. Generally, petrographic characteristics of microbialites have been inadequately described. Where possible, determine the diagenetic history of a microbialite and describe the extent of any alteration. Note the presence of features such as stylolites and veins.

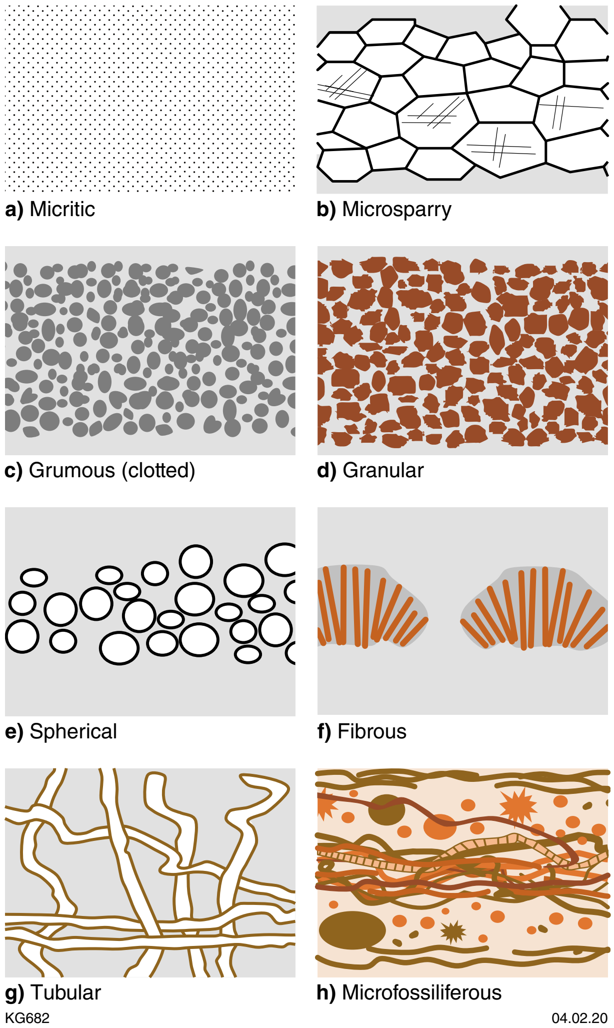

Figure 162. Microbialite microstructure: a) micritic; b) microsparry; c) grumous (clotted); d) granular; e) spherical; f) fibrous; g) tubular; h) microfossiliferous

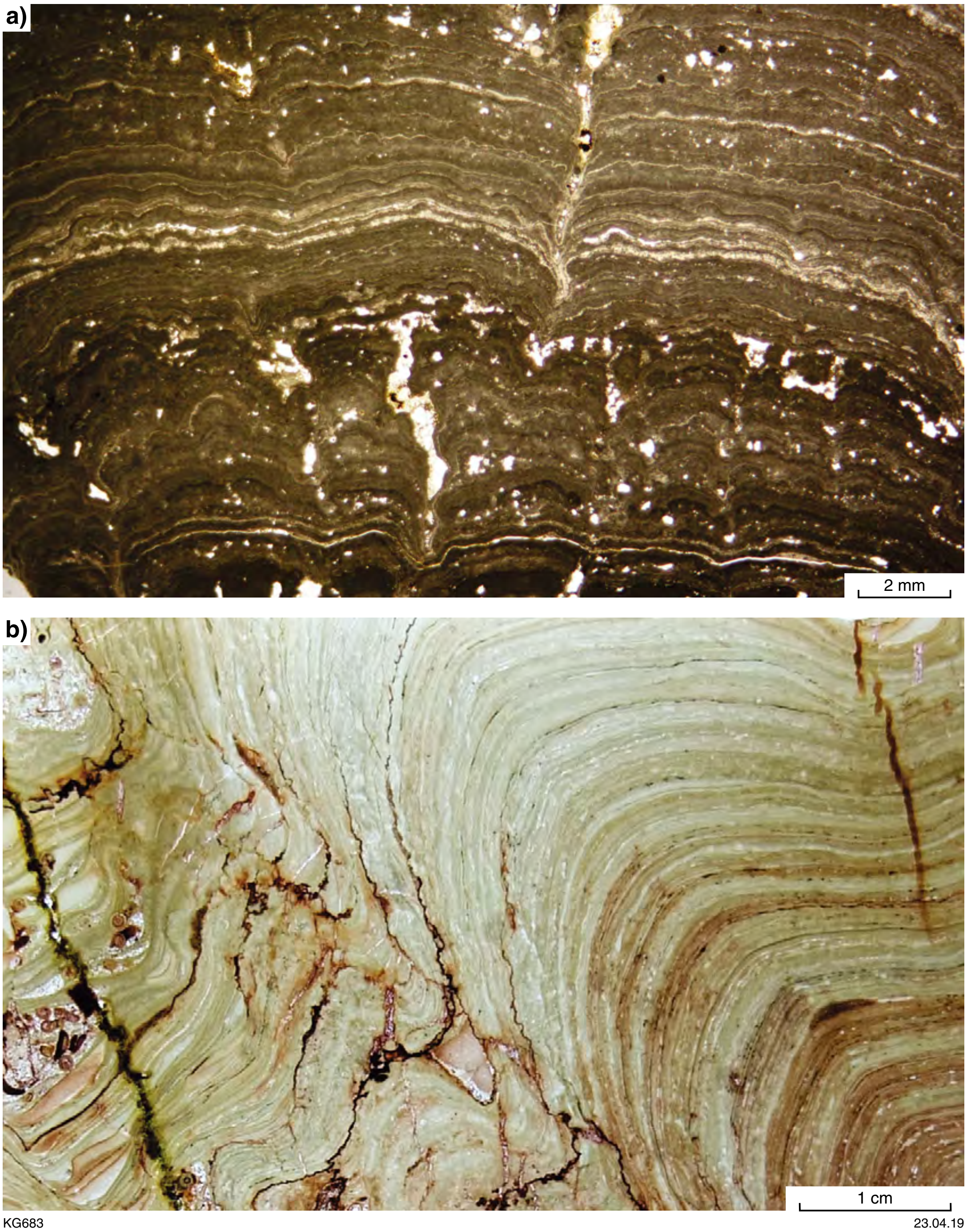

Figure 163. Examples of microstructure – micritic: a) stromatolite; Manix Formation; Manix Basin; Pleistocene; near Afton, San Bernardino County, California, US; thick section UCSB collection (photo by SM Awramik); b) *Acaciella* f. indet.; Ord Basin; ?Cambrian; Lacey Creek, Gordon Downs, Western Australia; thick section GSWA F5020–0. Dark laminae are micritic (photo by K Grey)

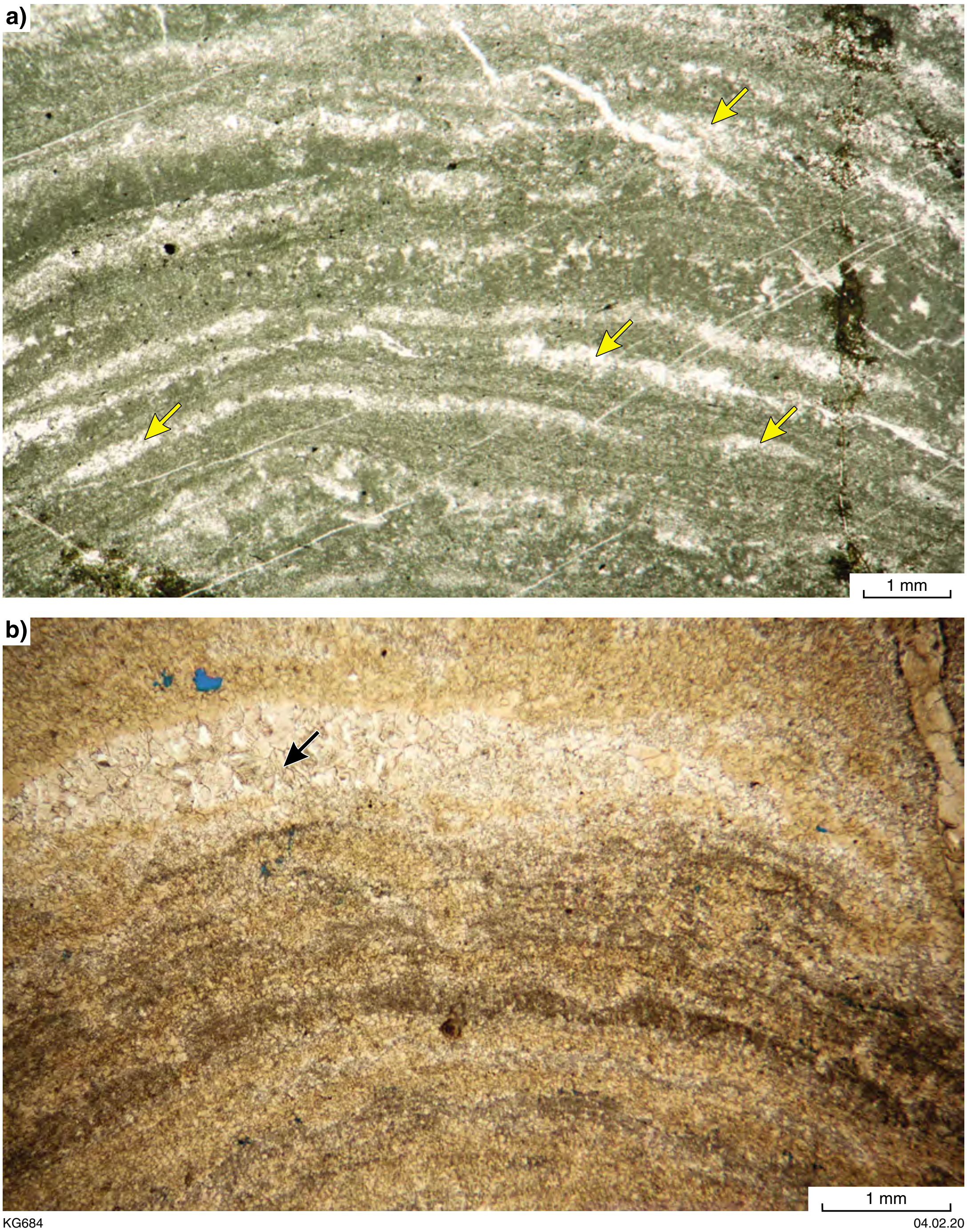

Figure 164. Examples of microstructure – microsparry (arrows): a) stromatolite; upper Tuanshanzi Formation, Changcheng Group; North China Craton; Statherian, Paleoproterozoic; Yanshan Range, Hebei Province, China (photo by SM Awramik); b) microspar interspersed with micrite (arrow); stromatolite; Antero Formation; South Park Basin; Oligocene; South Park area, Park County, Colorado, US; thick section, UCSB collection (photo by SM Awramik)

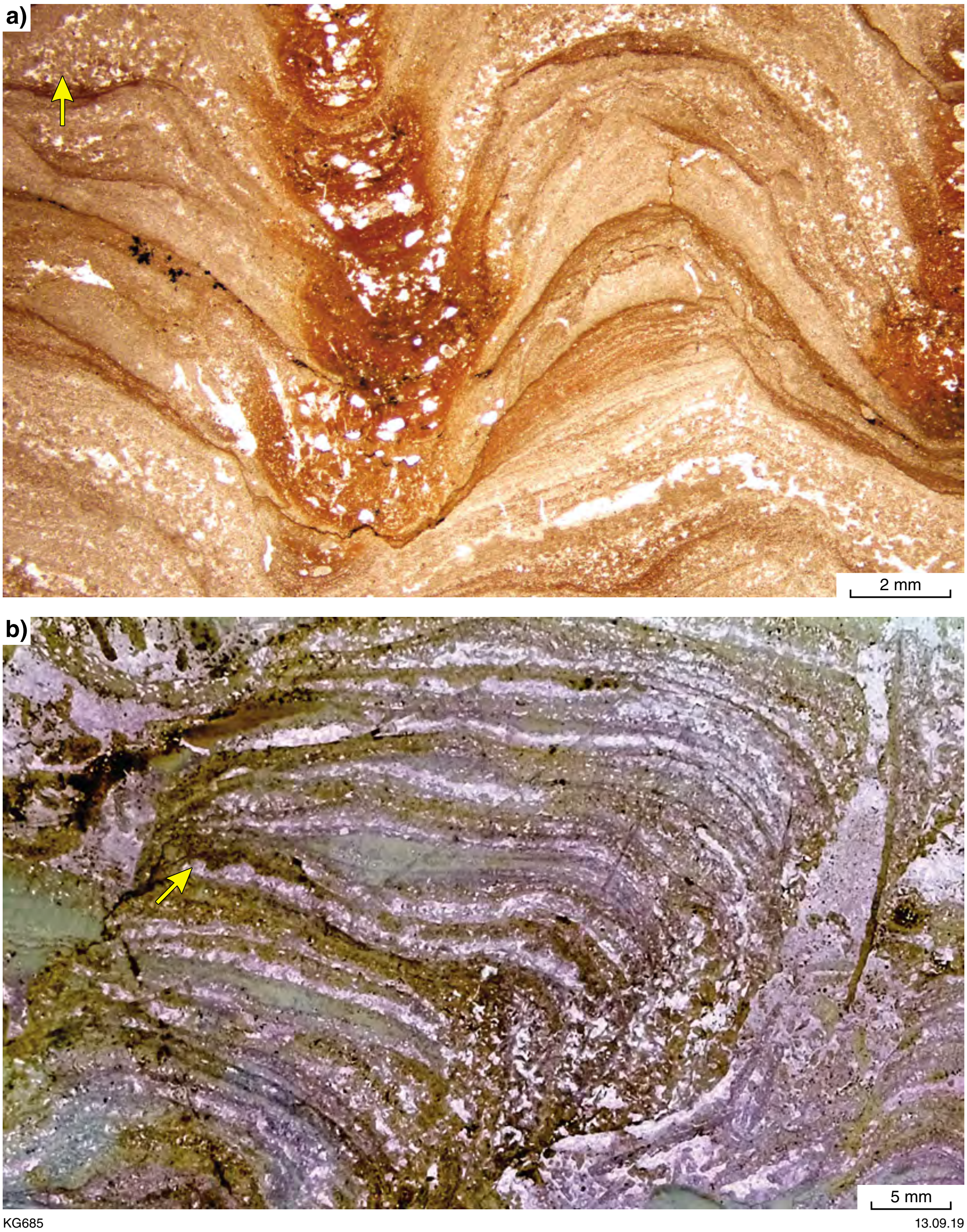

Figure 165. Examples of microstructure – grumous (clotted): a) columnar-layered stromatolite that occurs with *Tesca stewartii*; Julie Formation; Amadeus Basin; Ediacaran, Neoproterozoic; Boord Ridges, Western Australia; thick section, GSWA 197139. Light, grumous laminae (arrow) interspersed with more homogeneous, banded laminae (photo by HJ Allen); b) *Omachtenia* f. indet. ex *utschurica*; Brighton Limestone equivalent, Umberatana Group; Adelaide Rift Complex; Cryogenian, Neoproterozoic; near Depot Flat Road, Flinders Ranges, PORT AUGUSTA, South Australia; thick section, S166, University of Adelaide collection; arrow points to grumous lamina, pink stain is Alizarin Red (photo by HJ Allen)

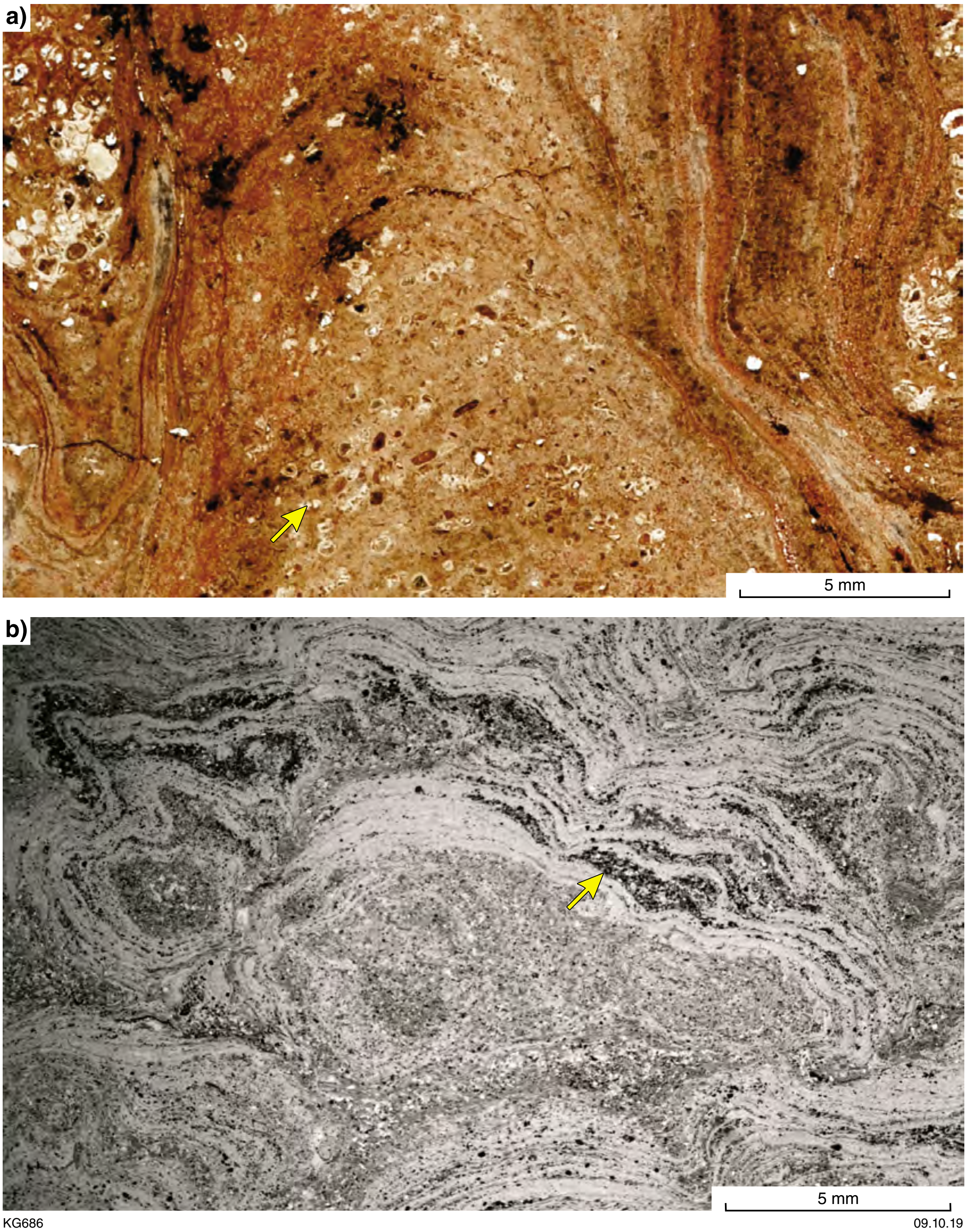

Figure 166. Examples of microstructure – granular: a) granular column centre (arrow); *Windidda granulosa*; Windidda Member, Frere Formation; Earaheedy Basin; Orosirian, Paleoproterozoic; Mount Elisabeth, ROBERT, Western Australia; thick section GSWA F12380–46598 (photo by SM Awramik and K Grey); b) granular laminae (arrow) interspersed with fine silica laminae; ?*Alcheringa narrina*; Jeerinah Formation, Fortescue Group; Fortescue Basin; Neoarchean; near Millstream, PYRAMID, Western Australia; GSWA F52633–80790 (photo by SK Martin)

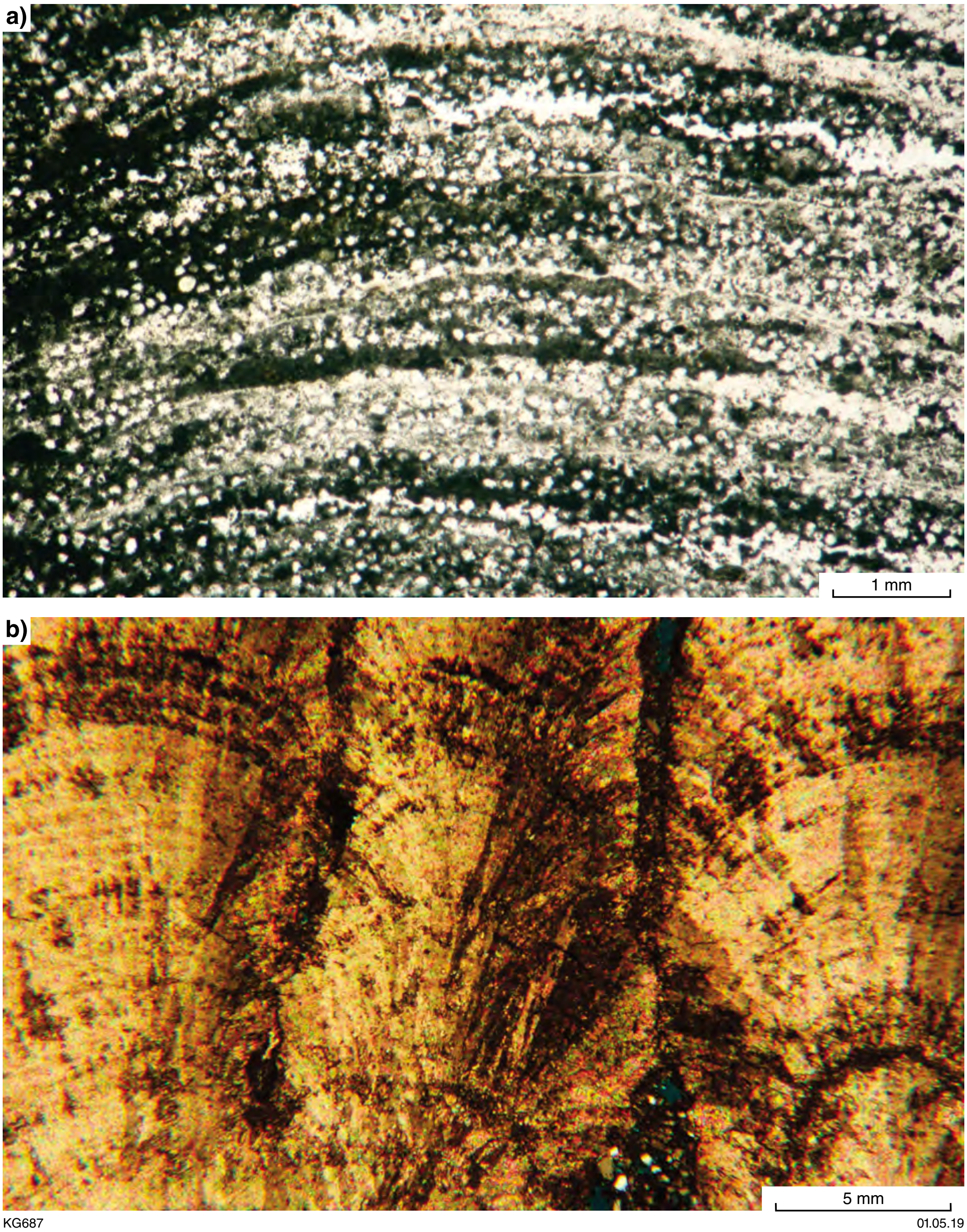

Figure 167. Examples of microstructure – spherical and fibrous: a) spherical; *Chlorellopsis coloniata* in stromatolite; Laney Member, Green River Formation; Bridger Basin; Eocene; Little Mesa, near La Barge, Lincoln County, Wyoming, US; thick section, UCSB collection (photo by SM Awramik); b) fibrous; stromatolite; Tipton Member, Green River Formation; Bridger Basin; Eocene; Essex Mountain, Sweetwater County, Wyoming, US; thick section, UCSB collection (photo by SM Awramik)

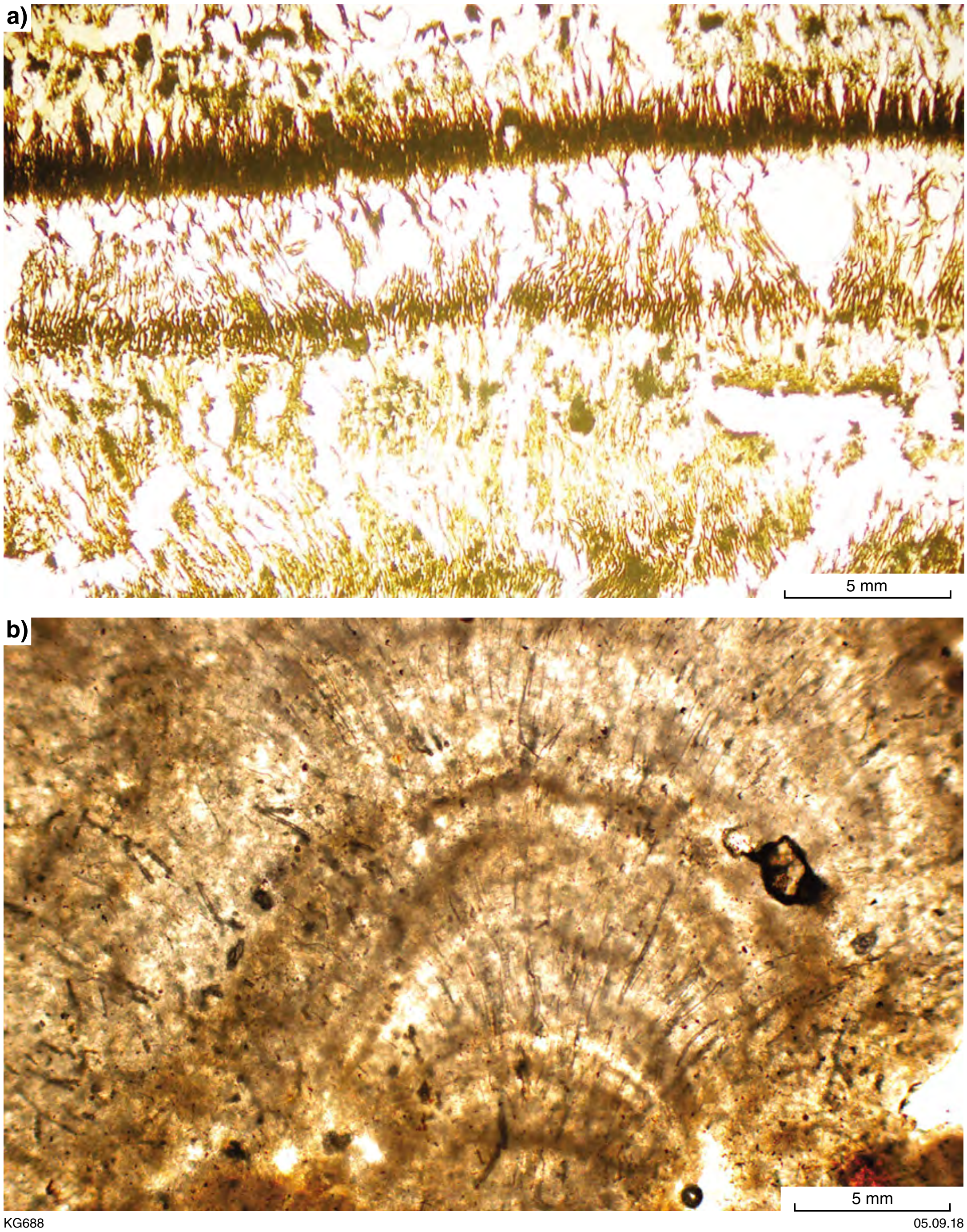

Figure 168. **Examples of microstructure – tubular: a) vertical filaments of *Rivularia*; Holocene; Keene Wonder Springs, Death Valley National Park, Inyo County, California, US; thick section, UCSB collection (photo by SM Awramik); b) filaments; stromatolite; Holocene; Hayk Basin; Lake Hayk, Southern Wollo, Ethiopia; thin section, UCSB collection (photo by SM Awramik)**

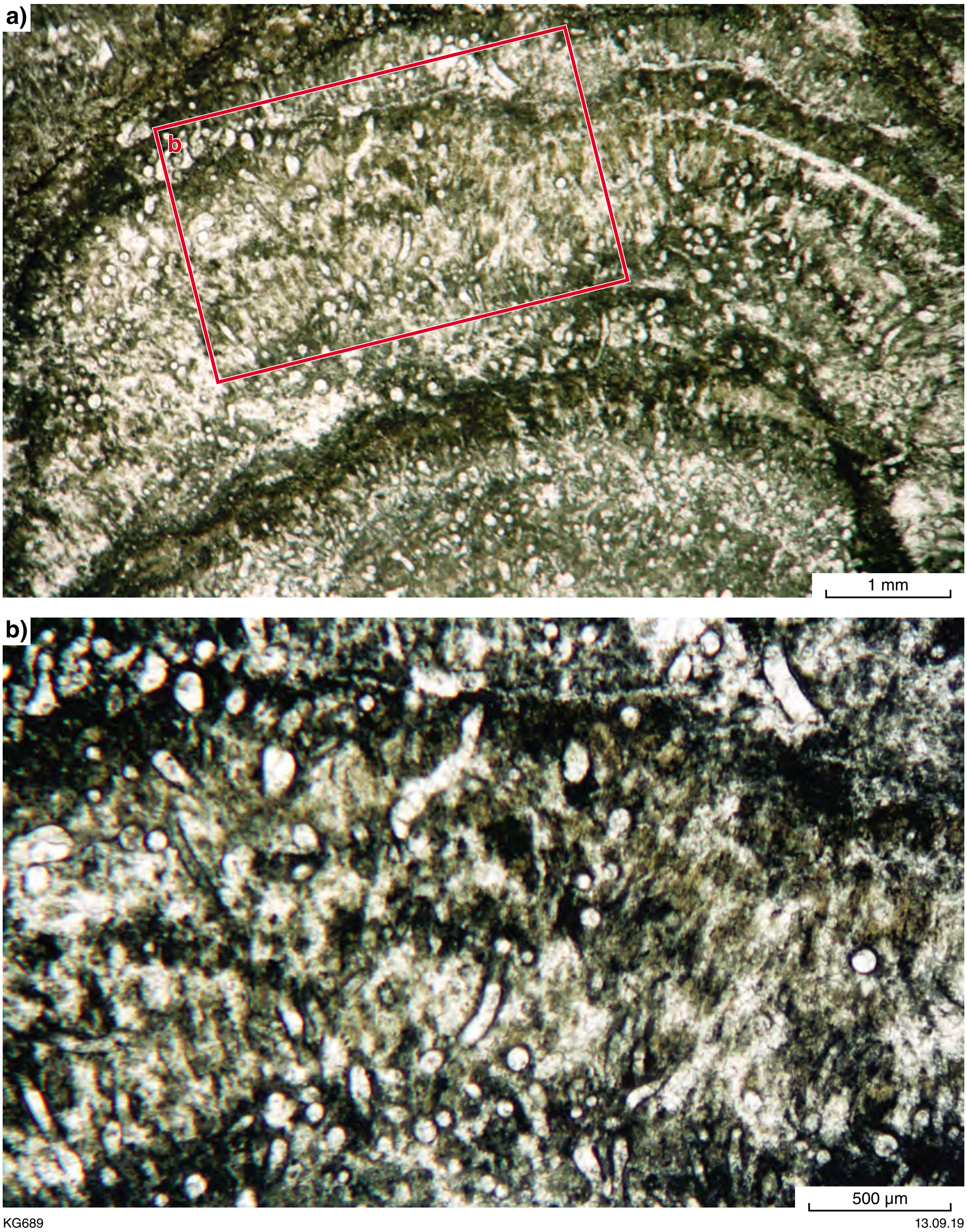

Figure 169. Examples of microstructure – tubular: a) oncoid laminae composed of tubular calcimicrobes; b) magnified detail of area indicated in (a); Green River Formation; Uinta Basin; Eocene; Uintah County, Utah, US; thin section, UCSB collection (photo by SM Awramik)

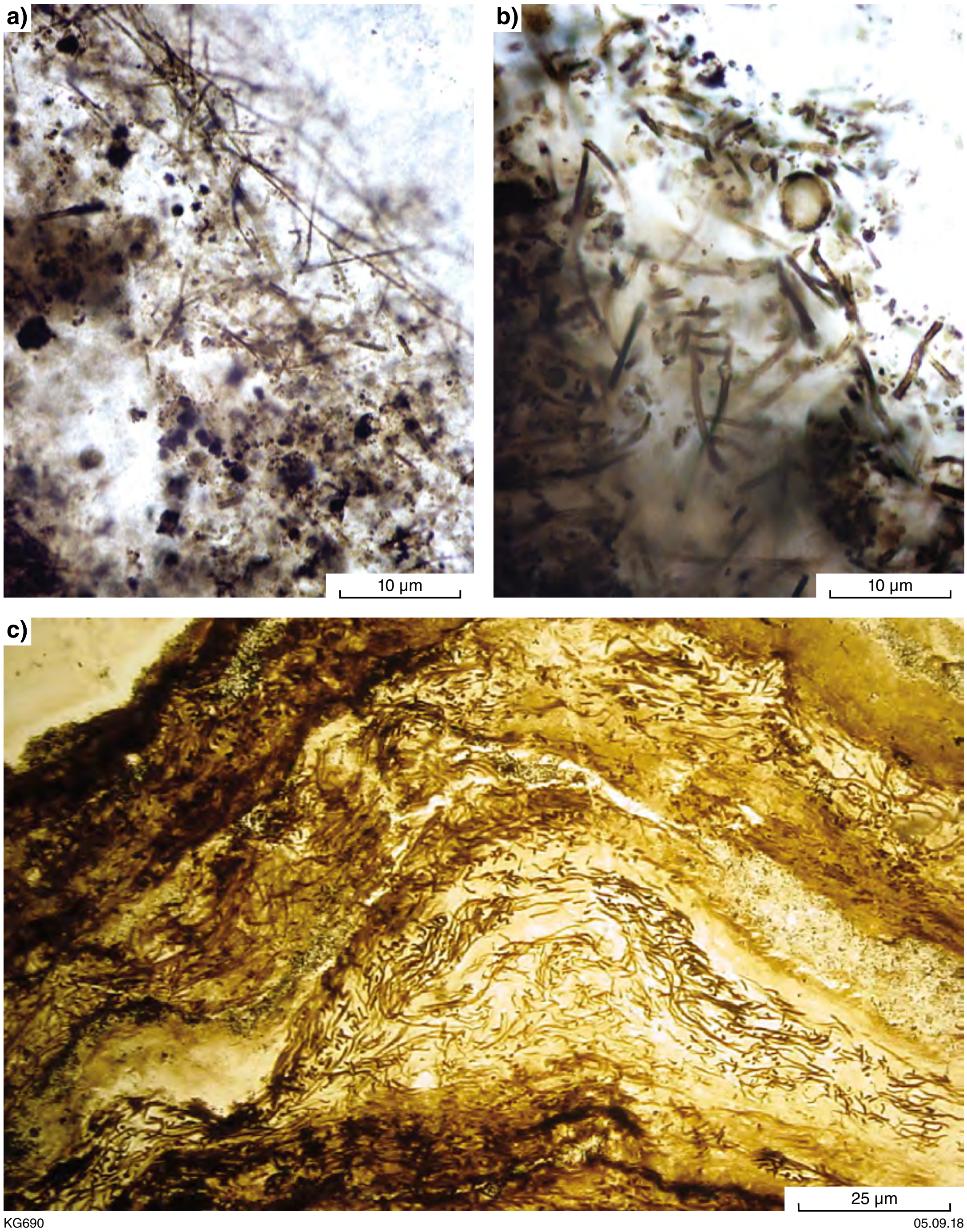

Figure 170. Examples of microstructure – microfossiliferous: a, b) Gunflint Formation, Animikie Group; Animikie Basin; Orosirian, Paleoproterozoic; Flint Point, Lake Superior, Ontario, Canada (photos by K Grey); a) thin section, GSWA F53699/1–76588A, coccoids and filaments in a stromatolitic lamina; b) thin section, GSWA F53699/2–76587A, coccoids and filaments at the margin of a stromatolitic lamina; c) filamentous microfossils in laminae of conical stromatolite; Jiudingshan Formation; North China Craton; Neoproterozoic; Liulou Village, Suining County, northern Jiangsu Province, China; thin section su-10, Nanjing Institute of Geology and Palaeontology (Cao and Yin, 2011) (photo by SM Awramik)

Recommendations for microbialite nomenclature

IGCP Project 261 in the 1980s recognized that controversies surrounding microbialite naming had resulted in a lack of communication among researchers. More than three decades later, the situation has not improved. There is still a need for researchers to adopt standard descriptive methods and a well-defined, readily applicable terminology, regardless of whether a microbialite is formally named or not. A standard description can be independent of formal nomenclature, but should also be capable of being used in formal taxonomy. Cao (2003) called for a unified international code for stromatolite nomenclature and in the following section we examine the development of naming systems, the need for a unified code, what form this could take, and why there is now a pressing need for such a code to be developed.

The long-held tradition of naming microbialites under the International Code of Botanical Nomenclature (Krylov, 1976) has suffered a setback that indicates all microbialite names are invalid (McNeill and Turland, 2011). The latest versions of the International Code of Botanical Nomenclature, now called the International Code of Nomenclature for algae, fungi, and plants (ICNafp), here referred to as ICN, beginning with the Melbourne Code (McNeill et al., 2012) and perpetuated by the Shenzhen Code (Turland et al., 2018), invalidates naming practices that for over 100 years have applied to microbialites, in particular to stromatolites. This has led to the development of an alternative approach suggested here.

Historical perspective on naming microbialites

Microbialites are viewed by many researchers as organo-sedimentary structures produced by the sediment trapping, binding or precipitation activity of microbes, principally photosynthetic microbes. Cyanobacteria are considered the primary organisms involved. Living analogues, principally from from the following locations, have provided some understanding of the complex biological and sedimentological processes operating:

- Shark Bay, Western Australia (Logan, 1961; Logan et al., 1974; Papineau et al., 2005; Jahnert and Collins, 2011, 2012; Suosaari et al., 2016)
- Lake Clifton, Lake Thetis and other Western Australian lakes (Burne and Moore, 1987; Moore, 1987; Moore et al., 1984; Grey et al., 1990; Reitner et al. 1996; Grey and Planavsky, 2009; Lluesma Parellada, 2015; Warden et al., 2016; Wacey et al., 2018)
- the Bahamas (Monty, 1967; Dravis, 1983; Dill et al., 1986; Riding et al., 1991; Reid et al., 1995, 2000; Macintyre, 2000; Dupraz et al., 2004; Andres and Reid, 2006)
- thermal springs such as those at Yellowstone (Walter et al., 1976) and the North Island of New Zealand (Jones et al., 1997a, 1997b, 2000, 2002, 2004, 2005)
- permanently ice-covered Antarctic lakes (Love et al., 1983; Wharton, 1994; Andersen et al., 2011; Hawes et al., 2013).

Although a single species of cyanobacterium might be involved in some cases (Golubic and Focke, 1978), more often communities containing a few to many species are involved (Bauld et al., 1992; Papineau et al., 2005; Ley et al., 2006; Foster and Green, 2011). In addition to cyanobacteria, a variety of other microbes are found, such as diatoms (Winsborough and Golubić, 1987). Metagenomics has revealed great diversity of bacteria, archaea and eukaryotes in some microbialites (Mobberley et al., 2015). Viruses are also known (Desnues et al., 2008) but their role and effect in microbialite construction is unexplored. Macroscopic organisms can also participate in construction; for example, caddisfly larvae (Leggitt and Cushman, 2001). In rare cases, microbial fossils are found preserved in ancient stromatolites (Barghoorn and Tyler, 1965; Licari et al., 1969; Nyberg and Schopf, 1984; Cao et al., 2001; Kempe et al., 2002) and such examples provide important insight into how fossil microbialites were constructed and how they compare with living examples.

As discussed in 'Aims and approach', many researchers have pointed out the problems of identifying whether or not microbes were involved in the formation of a microbialite (Brasier et al., 2006; McLoughlin et al. 2008; Allwood et al., 2009). As a result, some researchers prefer to restrict the term stromatolite to laminated, lithified structures without invoking microbial activity, as defined by Semikhatov et al. (1979). This broad definition implies that any layered structure could technically be classified as a stromatolite, regardless of whether microbial activity was involved, and diverges from the original concept of stromatolite.

The term stromatolite (Stromatolith in German) was coined by Kalkowsky (1908), although there is considerable disagreement over what Kalkowsky originally meant and it becomes more difficult when dealing with the translations of Kalkowsky's paper into English (Hofmann, 1969a; Monty, 1977; Krumbein, 1983; Riding, 1999; Paul and Peryt, 2000). A comprehensive translation of portions of Kalkowsky was given by Paul et al. (2008, 2011). Of several statements about stromatolites by Kalkowsky, the following appear to be most pertinent (Paul et al., 2008, p. 151–152; 2011, p. 13–28):

> The new term 'Stromatolite' is proposed for limestones with unique organization and structures that occur associated with 'roe-stone' (oolites). Stromatolites have a fine, more or less even layered fabric that contrasts with the concentric fabric of oolite grains (Paul et al., 2011, p. 15)

> Stromatolites are composed of thin, more or less flat laminae of calcite with a specific texture. These thin laminae are termed 'Stromatoids'. Stromatolites, unlike oolites, are not formed by limited individual colonies of constructing organisms; rather layers or mats of constructing organisms form them (Paul et al., 2011, p. 20–21)

> Vertical sections of all stromatolites show a distinct layered texture that is accentuated by weathering. In polished sections and thin sections, these basic stromatoid layers are seen to be composed of fine filaments which sometimes have a weak fan-like arrangement and a tendency to a radial structure (Paul et al., 2008, p. 151)

> Stromatolites may have many different forms but these are only variations of a common theme. All were created by the same type of organism and different species cannot be distinguished (Paul et al., 2008, p. 152)

> We have to assume that simple plants gave rise to limestone precipitation (Paul et al., 2011, p. 25)

> My aim has been to show that the oolites and stromatolites of the north German Bunter Sandstone are inherently of organic origin (Paul et al., 2011, p. 25).

From these statements, there can be little doubt that Kalkowsky intended the term stromatolite to refer to biogenic constructions and he may have even recognized the presence of fine filaments that he regarded as being responsible for precipitation of the limestone. In this handbook, we accept that stromatolites are biogenically induced and follow the definitions introduced by Awramik and Margulis (1974, p. 5) and Awramik and Margulis (cited in Walter, 1976, p. 1) and subsequently modified by Burne and Moore (1987, p. 249), although we have also attempted to select non-generic descriptive terms that can be applied equally to abiogenic structures resembling stromatolites.

We have chosen to use a slightly modified version of 'stromatolite', recognizing it may be imperfect and controversial (see 'Aims and approach'), because of its widespread usage and transliteration into many languages.

Burne and Moore (1987, p. 241) introduced the term 'microbialite' to encompass all microbially produced sedimentary constructions, and the term stromatolite was reserved for laminated varieties. The important concept here is that the deposit or structure formed as a direct result of microbial activity, and that the term not be applied to sediments that accumulated without microbial activity and were then later cemented by microbially influenced processes. Consequently, as discussed above, we regard the term stromatolite, together with thrombolite, dendrolite, leiolite and MISS, to be a subset of microbialite (Fig. 1) and, as such, a structure of microbial origin. A term such as 'abiogenic stromatolite' is accordingly an oxymoron and should not be used. The correct term for a laminated structure that has formed by some method other than a biogenic one is a pseudostromatolite or, if neither a biogenic or abiogenic origin can be determined, a dubiostromatolite (Awramik and Grey, 2005).

The term 'microbolite' was introduced by Riding (1991, p. 22), who argued that it was etymologically more correct, and was subsequently used by Schmid (1996), but has not been widely accepted and negates the original intention of Burne and Moore (1987), which was to emphasize the role of microbial mats.

The debate about whether or not to give identifying names to microbialites (and if so, what type of name) has gone on for a long time (see 'History of naming'). In large part, the controversy has resulted from the recognition that microbialites are not the products of a single organism. Significant features used to identify taxa are commonly a combination of various characteristics at multiple levels of organization and include the range of variation of those characteristics, rather than single, unique characteristics. The range of variation differs between microbialite taxa. Some may show only a narrow range of variation; in others it can be quite broad. Within a single taxon, some characters may be very consistent, whereas other features vary widely. Both the commonest variants and the end members of variation are significant in characterizing categories of microbialites.

Proposed classification schemes

The development of an effective method of classifying different types of microbialites has been extensively debated (Aitken, 1967, p. 1166). Various schemes have been proposed, as reviewed by Hofmann (1969a) and Walter (1972), but only the application of a system based on Linnean nomenclature has found wide application. None of the proposed alternatives (Maslov, 1953, 1960; Donaldson, 1963; Logan et al., 1964; Johnson, 1966; Aitken, 1967; Szulczewski, 1968; Krylov, 1976; Cao and Bian, 1985; Komar, 1989) has been entirely satisfactory or universally adopted.

The polynomial system proposed by Maslov (1953, 1960, p. 54), although uniquely descriptive, was criticized by Walter (1972, p. 15) and Semikhatov and Raaben (2000, p. 299) because it resulted in unwieldy terminology such as 'collenia planolaminaris minutocolumnaris microstylostromica granulosa' (Maslov, 1960, p. 70). Hofmann (1969a) suggested that quadrinomials be considered. Two of the epithets should refer to the meso- to macromorphology and two epithets should refer to the microstructure. Suggestions to use polynomials embodied a return to pre-Linnean polynomial plant taxonomy (Moore, 2003; Winston, 1999). The polynomial system was abandoned (along with the concept of numerical taxonomy) after the publication of Species Plantarum (Linnaeus, 1753; Stearn, 1957; Koerner, 1999).

The use of descriptive formulae, as proposed by Logan et al. (1964), can be applied to simple geometric patterns found in many Holocene microbialites and to some ancient stromatolites. Hofmann (1969, p. 28–29, table 10) summarized the scheme as being based on formulae constructed from a 'combinations of intials of adjectives, adverbs, and nouns' that rested 'on the arrangement of basic geometric units (hemispheroids and spheroids), their lateral linkage, and their stacking.' Although several hundred publications cite the classification of Logan et al. (1964), only a handful of researchers has adopted their formulaic system and often the nomenclature has not been comprehensively applied. Examples of its use include Kaufmann (1964), Aitken (1967), Harris (1967), Mohan (1968), Pugh (1968), Kruger (1969), O'Connor (1972), Marchese (1974), Peryt (1975), Ordóñez and García del Cura (1977), Elmore (1983), Bekker et al. (2003), Flügel (2004), Altermann (2008), Massari and Westphal (2011), Préat et al. (2011), Roemers-Oliveira et al. (2015), and Barlow et al. (2016). This system becomes cumbersome and too simplistic when applied to highly polymorphic, complexly branching forms typically found in Proterozoic rocks (Bertrand, 1968; Walter, 1972, p. 15; Semikhatov and Raaben, 2000, p. 299).

A system of using gross structure and descriptive adjectives proposed by Donaldson (1963, p. 7) and supported by Aitken (1967, p. 1167) suffers from being too simplistic, and is difficult to use for direct comparison. Terms such as 'Hemispherical stromatolites (Collenia Walcott)' include dozens of forms with very different associations of characteristics.

Use of the shape and lateral extension of laminae (Szulczewski, 1968) highlights a significant characteristic, but the feature needs to be used in conjunction with many others in order to characterize a particular stromatolite.

Cao and Bian (1985) proposed an eleven-category numerical code based on mesostructural to microstructural morphological attributes to produce a digit-descriptive way to describe microbialites.

These alternate systems, except for Cao and Bian's, only allow comparison at a superficial level, and do not facilitate comparisons at a level necessary for detailed morphological comparisons and biostratigraphy.

Numerous researchers for over 100 years have utilized binomial nomenclature (Hall, 1883; Hofmann, 1969a; Maslov, 1960; Korolyuk, 1960a,b; Semikhatov, 1962; Logan and Chase, 1961; Krylov, 1963, 1967; Komar, 1966; Nuzhnov, 1967; Raaben, 1964, 1969a,b; Shapovalova, 1968, 1974; Cloud and Semikhatov, 1969; Bertrand-Sarfati, 1972a,b; Preiss, 1972, 1973a,b, 1974, 1976b, 1987; Walter, 1972; Zhu et al., 1978; Grey, 1984; Raaben and Sinha, 1989; Komar, 1990; Jackson and Southgate, 2000; Shapiro and Awramik, 2000; Sergeev, 2001; Bian et al., 2005; Allen et al., 2016), although there have been differences in opinion about how to apply the names.

Although morphological variability is common in microbialites, often a morphological theme is observed. These were referred to as 'clusters of characters' by Bertrand-Sarfati and Walter (1981, p. 363). Hall (1883) appears to have recognized this in his establishment of the taxon *Cryptozoon*. Seely (1906, p. 170) named three taxa of *Cryptozoon*, concluding that the varieties were sufficiently distinctive and defined by diagnostic characteristics. Fenton and Fenton (1931, p. 682) pointed to three stromatolite taxa 'all forming sharply delimited masses, all as stable in their characters as any coral, all readily recognizable in the field'. Maslov (1937a,b, 1938) demonstrated the applicability of some morphological features for the delimitation of discrete taxa and described several Groups and Forms of Siberian stromatolites. Later, a number of researchers in the former USSR (IN Krylov, VA Komar, ME Raaben, SV Nuzhnov, MA Semikhatov, and others) contributed to the debate, arguing for the use of a binomial nomenclature and describing several dozen taxa and using them in biostratigraphy, as reviewed by Krylov (1975) and Semikhatov (1976). Krylov (1976, p. 32) summarized the viewpoint of these researchers that '...stromatolites could and should be classified within the framework of formal paleontological classifications including strict observance of the nomenclatural codes'. Updated diagnoses of Precambrian Indian and Russian 'Type-Form-Genera' were published (in English) by Raaben et al. (2001), and this reflected the advanced state of stromatolite taxonomy in Russia. Likewise, in China, researchers concluded that stromatolites showed non-repeated and unidirectional characteristics (Zhu et al., 1978, 1987; Zhu, 1982; Zhu and Chen, 1992) consistent with evolutionary succession (Cao and Yuan, 2003) and gave numerous names to formally described taxa. As discussed below, the experiences of researchers in Russia, China, India and Australia demonstrate how a naming system can be applied in a practical and consistent manner.

Proposed naming schemes

Almost all microbialites that have been named are stromatolites, only a few thrombolites have been named, and to the best of our knowledge, no dendrolites or leiolites have been named. Although fossil microbialites are the ones most often named, in a few cases, living microbialites have been named; for example, *Cryptozoon* in Logan (1961), *Vacerrilla walcotti* and *Conophyton weedii* in Walter et al. (1976, p. 278–284). Some MISS have names, such as 'Kinneyia', 'Manchuriophycus' and 'Arumbaria' (Davies et al., 2016).

The formal naming of microbialites began in 1883 when James Hall applied the binomial *Cryptozoon proliferum* to upper Cambrian stromatolites of New York State, US (Hall, 1883). Unfortunately, he did not provide a proper diagnosis. Hall (1883) followed the time-honoured tradition of establishing a Linnean-style, binomial name for an entity that he interpreted as a fossil. Since then, more than one thousand taxa have been named with binomials (Awramik and Sprinkle, 1999). Hall (1883) thought *Cryptozoon* was the remains of some unknown animal (Gr. *kryptos*, hidden; Gr. *zoon*, animal).

Later, others speculated on the identity of the organism(s) responsible for stromatolite construction and ideas included protozoans (Dawson, 1896), stromatoporoids (Seely, 1906), and coelenterates (Steinmann, 1911). Cohn (1862, 1864), Tilden (1897), and Kalkowsky (1908), among others, suggested the role of algae and cyanobacteria in the precipitation of calcium carbonate and construction of what are now called microbialites. In Australia, Saint-Smith in Maitland (1913, p. 12), although not using the term stromatolite, observed that 'small circular patches of fairly compact lime are forming as the result of growth of colonies of small organisms' along the eastern shore of Lake Clifton. These structures were later described as thrombolites by Moore (1987). Nevertheless, the origin of *Cryptozoon* and similar fossil structures remained uncertain until 1914 when Walcott and Wieland independently suggested they were the products of 'algae'. Wieland (1914) interpreted *Cryptozoon* as an originally calcareous alga ('seaweed') and Walcott (1914) compared *Collenia* and other structures in the Belt Supergroup (Montana, US) to fresh water 'algal biscuits' built by cyanobacteria.

Holtedahl (1919, p. 95) did not regard stromatolites as 'real fossils' that deserved generic and specific names. On the other hand, in the same paper Holtedahl (1919, p. 100) successfully correlated strata in Finmark, northern Norway, with strata in the Kanin Peninsula, Russia, using the stromatolite *Gymnosolen,* which was named and described by Steinmann (1911) from the Kanin Peninsula. Similarly, Høeg (1929) rejected binomial names because he was uncertain whether identical stromatolites could be built by different organisms and thought the same stromatolite might be built by several species. An early criticism was expressed by Høeg (1929, p. 8) who considered it to be 'preposterous to create binomial names for these structures, however useful such names may be.' Young (1933, p. 32), although contributing greatly to the understanding of South African stromatolites, nevertheless commented that 'the generic and specific names sometimes applied to stromatolites have little or no systematic value.' At about the same time, some workers insisted on both the naming and use of binomials for taxa; for example, Fenton and Fenton (1931).

The naming of stromatolites proceeded slowly at first after the naming of *Cryptozoon proliferum* by Hall (1883). The first Precambrian stromatolite, a branched-columnar type, was named *Archaeozoon acadiense* by Matthew (1890). In total, at least 23 Forms of *Cryptozoon* have been named. Gürich (1906) named five new 'genera' and 14 'species' of stromatolitic structures (he called them spongiostromes); however, unlike others naming stromatolites, he based his taxa on the microstructure as seen in thin section. It was not until 1911 that a third 'genus', *Gymnosolen*, based on macrostructure, was established by Steinmann (1911). Walcott (1914) named a fourth stromatolite Group, *Collenia* (which has over 80 Forms named). *Carelozoon* was named by Metzger (1924), and Maslov (1937b) named the distinctive, conically laminated, cylindrical stromatolite *Conophyton*. Since then, more than 311 Groups have been named.

The most important and influential contributions to the late 1920s and 1930s stromatolite nomenclature were by Pia (1927), Fenton and Fenton (1931, 1933, 1936, 1937, 1939), and Maslov (1937a,b, 1938, 1939a,b). These contributions presented formal descriptions of several dozen taxa, including *Conophyton* and several of its Forms (Maslov, 1937b, 1938). However, the idea of formal naming was not supported by other researchers. Cloud (1942) suggested that stromatolites not be named, but as a matter of convenience, those names already in the literature could be retained and used in the vernacular (although he expressed a different view in Cloud and Semikhatov, 1969). Aitken (1967, p. 1166) concluded that stromatolites should not be named and that it remained to be seen if biostratigraphy worked. Logan et al. (1964) concluded that stromatolites should not receive binomial names because, to them, stromatolites did not appear to have the limited morphological variability of strict biological species. They proposed a nomenclature using letters that reflected the large-scale geometric attributes of the stromatolites. However, Logan had previously used Linnean names for stromatolites (Logan and Chase, 1961). There is thus considerable ambiguity among authors about using binomials for stromatolites. On occasions they have been critical of the practice, but the same authors have resorted to binomials at other times, possibly because of the convenience of the naming system.

Rezak (1957) and Aitken (1967) summarized the previous differences in opinion regarding the use of generic and specific names for stromatolites. Opinions remained divided in the 1970s (Krylov, 1976) and little has changed over the last several decades. Grotzinger and Knoll (1999, p. 345) referred to the use of a 'quasi-Linnean system' and concluded that although biology played a role in the accretion of most stromatolites, this 'does not equate to a statement that secular changes in stromatolite form or microstructure reflect changes in the mat-building biota' but reflected 'how environmental change has contributed to the stratigraphic distribution of stromatolitic forms and textures' (Grotzinger and Knoll, 1999, p. 353). Altermann (2004, 2008) was sceptical of claims of biostratigraphical usefulness, in part because of the difficulties of applying names, and in part because he considered claims of stratigraphic value as 'illusive', being 'grounded in the evolution of sedimentary facies belts and cyclicity of sediments' (Altermann, 2004, p. 569).

Much of the criticism about naming microbialites and using them for biostratigraphy has come from North America and western Europe, and this perhaps explains why their use for correlation has never been thoroughly tested in those parts of the world, whereas it has been accepted elsewhere. Relatively few taxonomic studies have been published in North America compared to other continents. Only about 75 taxa, including only a handful at Form level, have been named for all of geological time in North America and many names need revision (Awramik, unpublished data). Although Hofmann (1972, 1981, 1998) compiled inventories of Canadian fossils, he did not investigate their comparative stratigraphic distributions. Other reports that place stromatolites in their stratigraphic context have rarely described or named them. For example, there are several papers in Campbell (1981), especially one on the Little Dal Group by Aitken (1981), that showed the stratigraphic distributions of microbialites in Canadian Proterozoic Basins, but there was no comprehensive attempt to plot comparative stratigraphic distributions. Consequently, conclusions about the utility of microbialite biostratigraphy have not been arrived at through critical analysis or empirical testing. The net result of incomplete studies coupled with adverse criticism has been an almost complete abandonment of microbialite biostratigraphy as a valid method for chronostratigraphy of Proterozoic successions, and a perception that microbialite biostratigraphy has not been proven in terms of North American geology.

By contrast, more than 100 Groups and 380 Forms were listed by Raaben et al. (2001) as being recorded in India and Russia, and 205 Groups and 727 Forms have been described from China (Cao and Yuan, 2003), where biostratigraphy has been widely applied. In Australia, some 45 Groups and 80 Forms have been recorded, and several distinctive taxa await description. In particular, distributions in the late Tonian, Cryogenian and Ediacaran have been documented from several hundred localities and provide robust correlations when tested against other methods such as lithostratigraphy, isotope chemostratigraphy, palynology and well-log correlations (Hill et al., 2000; Grey et al., 2005, 2011, 2012; Grey, 2007, 2008 and references therein, and unpublished data). Moreover, predicted distributions are confirmed whenever new areas, such as the western Amadeus Basin, are documented (Haines et al., 2010a,b, 2012; Allen et al., 2012, 2016; Grey et al., 2012). Thus, detailed documentation of stratigraphic distributions, particularly in Russia, China and Australia, provides persuasive evidence that microbialites are an effective correlation tool.

Current status of microbialite names

The potential use of microbialites for biostratigraphy accelerated their naming. For the Phanerozoic, conventional fossils were useful biostratigraphically and there did not appear to be a need to resort to microbialites, although they can be used (Shapiro and Awramik, 2000). For the Precambrian, it was a different matter. Before the widespread use of reliable geochronological techniques, the Precambrian was terra incognita with regard to age determination because its paleontological record was so poorly understood. Early in microbialite studies, it was known that they are abundant in strata beneath known Cambrian rocks, as pointed out by Matthew (1890), Steinmann (1911) and Walcott (1914), and thus were candidates for biostratigraphic analysis.

The possibility that microbialites could be used to tell geological time was suggested by Walcott (1906, p. 19). Howchin (1914), however, felt that the variations of *Cryptozoon* known to him (most stromatolites were called *Cryptozoon* or Cryptozoan at this time) appeared to be of little value in biostratigraphy. Maslov (1939) made the first serious attempt to use stromatolites in biostratigraphy by defining a succession in the Urals and correlating it to similar microbialite successions in eastern Siberia and China. Kao et al. (1934, p. 248) suggested certain '*Collenia*' in the Tieling Formation of China might be unique. It was not until the 1950s that the application of stromatolites to biostratigraphy was tested in a systematic manner. An ambitious program in the then USSR was established to evaluate and use, where possible, stromatolites in biostratigraphy; for example, see the review by Semikhatov (1976). It was found that there are several time-dependent and consistent associations of stromatolites in late Proterozoic rocks over vast regions of the former USSR (Keller et al., 1960; Semikhatov, 1962; Krylov, 1963). This research resulted in the discovery and documentation of abundant, morphologically distinct and diverse stromatolites, and necessitated the naming of new taxa. New methods were developed to study stromatolites; in particular, the graphical reconstruction of stromatolite morphology from serially sectioned specimens (Krylov, 1959). Similar stromatolites and temporal patterns were later observed in Australia, Canada, the United States, India, Africa, and China (Cloud and Semikhatov, 1969; Glaessner et al., 1969; Raaben, 1969b, 1978; Valdiya, 1969; Bertrand-Sarfati, 1972a,b; Hofmann, 1972, 1981, 1998; Preiss, 1972, 1973a,b, 1974, 1976a,b, 1987; Walter, 1972; Cao and Liang, 1974; Semikhatov, 1978). As more stromatolites became known, the number of taxa increased and more than 1187 taxa have been described (Awramik and Sprinkle, 1999).

Another debate about naming microbialites has revolved around which is the most appropriate code of nomenclature to use. Although the International Code of Zoological Nomenclature (ICZN) was used in early naming, once the role of cyanobacteria was recognized it became clear that the structures should not be named under that code. Because extant stromatolites are built primarily by prokaryotes, the International Code of Nomenclature of Bacteria (Lapage et al., 1992; now International Code of Nomenclature of Prokaryotes) might appear to be suitable. However, it is inappropriate for microbialites since many of the properties used to typify bacteria employ biochemical and other methods on living cultures (Sneath, 1986). To confound matters further, the principle microorganisms responsible for forming most microbialites are cyanobacteria, and although prokaryotic and seemingly appropriate to fall under the jurisdiction of the International Code of Nomenclature of Prokaryotes, most have been named following the International Code of Botanical Nomenclature (ICBN), now replaced with the International Code of Nomenclature for algae, fungi, and plants (ICN), the Melbourne Code (McNeill et al., 2012) and the Shenzhen Code (Turland et al., 2018). This is based historically on their being called 'blue-green algae' and studied along with algae, as discussed by Fogg et al. (1973) and Whitton and Potts (2012). Consequently, the ICBN and now the ICN, developed under the auspices of the International Association for Plant Taxonomy (IAPT), has been the preferred Code because it deals notably with free-living organisms, includes algae, and it has been the code of choice for most practitioners of stromatolite nomenclature. Krylov (1976, p. 32) stated that 'It is most convenient to use the provisions for fossils in the International Code of Botanical Nomenclature (ICBN), as is the current practice of the majority of Soviet and many foreign researchers.'

In a sense, researchers who name microbialites have been working under an honour system in following the Botanical Code (ICN) to the best of their ability, but working outside of the Code's jurisdiction. Cloud and Semikhatov (1969) urged the next revisers of the then Botanical Code to consider including stromatolites.

However, this was not done, although a glimmer of hope was presented in the Saint Louis Code (Greuter et al., 2000), Article 1.2 which stated that:

> Fossil taxa may be treated as morphotaxa. A morphotaxon is defined as a fossil taxon which, for nomenclatural purposes, comprises only the parts, life-history stages, or preservational states represented by the corresponding nomenclatural type.

Using this article, a fossil microbialite could be regarded as a preservational state. It could also be argued that the name represented a temporary application to a structure that was only partially known or poorly preserved pending the discovery of more definitive material (in this case, the preservation of the constructing species of fossilized bacteria or algae).

Regardless of whether microbialites should be given names, the status of such names under the provisions of the ICBN and ICN has frequently been questioned because the structures are not representative of an individual species. Cloud and Semikhatov (1969) pointed out that lichens are the products of associations of fungi and algae (green algae and cyanobacteria), yet lichens were included under the ICBN and ICN. As a result of these arguments, most researchers who elected to name microbialites did so under the provisions of the ICBN. This expediency was dealt a serious blow that made all microbialite taxa invalid following the adoption of the ICN or Melbourne Code (McNeill et al., 2012), particularly because of provisions eliminating morphotaxa (McNeill and Turland, 2011, p. 245). Thus, microbialites are nomenclatural orphans.

The current difficulties with regard to the naming of microbialites began in 2006 when James Brooks, Thesaurus Manager, CABI Head Office, Nosworthy Way, Wallingford, Oxfordshire, OX10 8DE, United Kingdom, pointed out to one of us (KG) that the stromatolite name *Acaciella* Walter 1972, with type species *Acaciella australica* (Howchin 1914) Walter 1972, was a homonym (a name spelled exactly like a name based on a different type) for *Acaciella* Britton and Rose 1928, a genus of acacia, with type species *Acaciella villosa*.

The stromatolite *Acaciella* Walter 1972 is widespread in Australia, contains several 'species' and has a fossil assemblage named after it (Hill et al., 2000). If stromatolite names were valid under the ICN, *Acaciella* Walter would be a junior homonym and it would be necessary to rename the stromatolite. Before embarking on a major systematic publication to rename *Acaciella* and associated taxa, Grey sought a ruling from Professor John McNeill, Royal Botanic Garden, Edinburgh, senior author of the ICBN (Vienna Code), seeking clarification.

As a result of the ensuing correspondence, several points became clear:

1. Names of stromatolites (microbialites) are not being included in the Index Nominum Genericorum (although a number have been maintained for reasons of homonymy), and names will only be included if they involved a stromatolite (microbialite)-building organism that was itself named
2. In the opinion of J McNeill (written comm., 15 November 2006):

   The basic problem with naming stromatolites under the ICBN is that they cannot apparently be described as 'organisms' or even representations of organisms in the way that fossil impressions are — names of stromatolites cannot, I understand, be thought of as the names of the organisms responsible for the stromatolite, as can names applied to organisms falling under the ICBN only known through some representation of their structure.

   Unlike the International Code of Zoological Nomenclature, which provides for the naming of ichnotaxa', the fossil work of animals, the ICBN has no history of providing for the naming of the 'work' of organisms falling under its mandate — probably just because such structures rarely exist — stromatolites, if they can be so construed, being perhaps the only example. [Lichens are a bit like this in that a fungus utilizes its algal symbiont to create a unique structure, but we get around this by applying the name to fungal symbiont]
3. It will only be possible to get stromatolite names accepted under the ICBN by seeking an amendment to the Code 'that would parallel the ICZN's provision for ichnotaxa' (J McNeill, written comm., 15/11/2006).

It is difficult to argue with the above statements, particularly the second one. It is a self-evident statement of the facts as most microbialite taxonomists have understood them for years, although it goes further in rejecting the assumptions under which microbialite nomenclature has operated for more than a century.

Under the the Melbourne Code (McNeill et al., 2012), the provisions became even more exclusive of fossil structures that fall into the grey area of parataxonomy — the practice of sorting samples into recognizable taxonomic units, generally known as morphospecies (Krell, 2004, p. 795–796; Abadie et al., 2008) — through changes to Article 1. The concept of morphotaxa was removed from the Code, and without this concept, there is no home for microbialite nomenclature under the Code. Moreover, as microbialite names are no longer included in the Index Nominum Genericorum, many indexing systems, like AlgaeBase, now list many microbialite names as invalid. These restrictions impose impossible conditions on researchers attempting to publish formal descriptions or trying to investigate stratigraphic distributions of named stromatolite taxa. The situation did not change under the subsequent version, the Shenzhen Code (Turland et al., 2018).

Obtaining an amendment to the ICN would be very difficult given the small number of microbialite taxonomists who operate today. Microbialite researchers are unlikely to get a sympathetic hearing from the majority of botanists and paleobotanists. Microbialites are probably insignificant to mainstream plant taxonomists, who would most probably argue for maintaining the 'purity' of the Code. The example of what happened when the issue of adopting parataxa under the provisions of the ICZN was raised was not encouraging (see below).

A proposed BioCode (IBN), prepared under the auspices of the International Committee on Bionomenclature (ICB), might have addressed issues of fringe groups such as microbialites under Article 31.2 (Greuter et al., 2011), because it recognized parataxa and ichnotaxa, 'the fossilised work of organisms', but agreement could not be reached and there will be considerable debate before an overarching Code is adopted. Microbialites remain in limbo; unable to be named under the provisions of the International Code of Nomenclature of Bacteria, not appropriately placed as ichnotaxa under the ICZN, and not acceptable under the ICN.

Setting aside the debate about whether microbialite biostratigraphy succeeds, this leaves the question of whether there is any purpose in naming microbialites at all.

Do microbialites need names?

It may be possible to do without names, but much would be lost in the process. The issue is one of scientific communication. It is not only taxonomists who use names; names act as a shortcut to a defined range of variation for researchers approaching microbialites from many disciplines. The use of names is acknowledged in an indirect way: most non-taxonomic researchers will use a term like '*Conophyton*' to indicate a particular type of conical or coniform structure. For example, Cao et al. (2001), Jones et al. (2002) and Sherman et al. (2002) are among the many who have used the name *Conophyton* to convey a distinctive shape. However, a downside in many of the examples is the lack of a proper discussion of the systematic status of the name or whether a key diagnostic feature, the axial zone, was recognized in applying the name. Nevertheless, it can be argued that the name communicates the presence of a cone-shaped stromatolite and it can be easily searched in reference databases. There are many other examples of the informal use of Group names, such as Boxonia (Corsetti and Storrie-Lombardi, 2003), Stratifera (Tapanila et al., 2004), and Kussiella (Halverson et al., 2004). None of these authors attempt to treat the microbialites systematically, and they did not italicize the name, indicating an informal usage, but it is obvious that they required a name to further their discussions, and that a name is helpful. However, for microbialites that show a great deal of morphological variability within short distances (decimetre to metre scales), as found in many lacustrine examples, it is probably best to just describe them without naming.

Debate about the acceptability of microbialite biostratigraphy has continued over the decades but it is difficult to see how the investigation of claims and counter claims can be conducted without a naming framework, which is why the issues raised by the correspondence with McNeill (written comm., 15 November 2006) are so troublesome.

From a pragmatic point of view, and because microbialite nomenclature has to a large extent operated outside of but employed the rules of the ICBN (or ICN), we see no reason to abandon practices that have been followed for more than a century. Indeed, our correspondence in relation to the status of microbialites under the ICN suggested that there is nothing to prevent microbialite researchers from just going on using the relevant provisions of the ICN, although microbialites, not being organisms, would be outside the mandate of the ICN and new names given to microbialites would have no protection under the code's current rules on homonymy.

Microbialite researchers need to consider whether the most effective way forward for scientific communication about microbialites, in particular for their use in basin analysis and stratigraphy, is to use a naming system.

To many microbialite scholars, the names signify particular combinations of shapes and characteristics and are useful in communication — which is one of the goals of this handbook. The descriptive process requires that types be established and housed in public institutions; the system facilitates comparative research; there is immense archival value invested in named and properly housed type specimens; and many of the taxa named appear indispensable to microbialite biostratigraphy. The current, viable, operating nomenclature is destabilized because microbialites now fall outside the ICN. New taxonomic names given to microbialites will not be protected under rules on homonymy, and it will be extremely difficult for biostratigraphers and others looking for patterns to build on previous work if all existing names have to be abandoned. It will be equally impossible to disprove biostratigraphic interpretations if the use of names is also denied for this purpose.

However, it seems that the long history of naming stromatolites and the large number of names currently in the literature require a naming method and nomenclatural rules will still be needed, even if microbialites do not fall under the mandate of current codes. The most feasible solution is to develop a 'Microbialite Code' based on practices currently used, but tailored specifically to the special uses of microbialites.

There would be advantages in adopting such an approach. All names up to a certain date (yet to be decided) could be validated. This means that problematic names like those erected by Krylov (1962) in his unpublished thesis, and later widely used by others, could be attributed to their original author. Despite a vote by Soviet geologists to accept the thesis names as being published by Krylov in 1962, this ruling remains questionable under the provisions of existing codes. However, from a pragmatic position, these names are now widely entrenched in the literature, and were attributed to Krylov in the comprehensive catalogue of Russian and Indian Groups (Raaben et al., 2001). It may be simpler to retain them by simply declaring them to be a conserved name at the date specified.

Microbialite names like *Acaciella* (a widely used and significant taxon) could be retained because it would no longer be a homonym with the extant plant of that name because the same names can coexist under separate codes. The microbialite use of several other names, such as *Baicalia* (a moth and a chrysophyte) and *Plumaria* (an extant plant), would be acceptable. Names only need to be changed if they are transferred from one code to another and consequently become homonyms.

A separate microbialite code would enable provisions to be made to name structures deemed to be microbial in origin while acknowledging that the constructs are the products of ecosystems rather an individual or individual species. Because there is generally no possibility of finding the individual organisms involved in the construction of most fossil microbialites, the classification would be purely morphological and there would be no need to try to show relationships to microbial constructors.

There are many other issues that should be addressed in the process of adoption of a microbialite-specific code, not the least of which is whether it is still appropriate to use a Linnean system of nomenclature. The Linnean system of naming has many advantages, one of them being that it is essentially a set of rules for naming, as both the ICN and ICZN point out. The main purpose of the codes is to regulate the system of naming; the use of names to show any relationship between taxa is not the function of a nomenclatural code. The Linnean system is simple to use and familiar to paleontologists and other natural scientists, and the names are already well established in the case of many fossil microbialites. As discussed under 'Retaining Linnean nomenclature', taxa need not be classified as genera or species and the cumbersome use of Group and Form could be abandoned in favour of newly coined terms that indicate clearly that the names do not imply genera and species in the sense of the existing codes.

Before adopting a new code, several possibilities about how a microbialite code would operate could be considered. One possibility is that a new code need not necessarily be tied to grammatically correct Latin endings. Although incorrect endings will probably grate with an older generation of paleontologists, a system that does not defer to rules of agreement and declension unknown to the majority of modern practitioners would be easier for computing and database management. Wherever the debate goes from here, microbialite researchers should aim for a naming system that ensures stability and allows comparative studies of both morphology and stratigraphic and geographic distribution to continue.

There are numerous examples in the literature that exemplify the need for a nomenclature code. Among the most serious problems that have arisen because authors have not followed any of the established international codes are these:

1. The formal description of the same new Group and Form more than once. Example: Liang (1980) described *Anabaria chihsienensis* as a new Form, yet the stromatolite was first formally described by Cao and Liang (1974)
2. The use of a new Group and, or Form name by the author of the name before it is formally published. Examples: a) Korolyuk (1959) used the name *Stratifera*, both italicized (e.g. figure 1 of plate I on p. 81) and non-italicized (e.g. p. 76); however, the formal diagnosis did not appear until 1960; b) Tewari (1988, p. 3) used the name *Rahaella* g. nov.; however, the formal description of the new Group was not published until 1989 (Tewari, 1989)
3. The use of n.g. and n.f. and other variants of 'new Group' or 'new Form' in publications other than the one that formally describes the new taxon. Example: Du and Li (1980, p. 344) listed stromatolites that occur in the Yanshan Ranges and included *Scyphus yanshanensis* f. nov., *Microstylus radiola* f. nov., and *Colonnella crassibrevis* f. nov., yet they apparently were never described
4. Use of a Group or Form name that appeared in an unpublished manuscript. Example: Qiu and Liu (1982) further described three taxa (*Jacutophyton luonanensis*, *Paracolonella shimenensis*, and *Litia dongqinlingensis*) that were first named and described in an unpublished 1977 manuscript
5. The introduction of new Group or Form names without formal descriptions. Example: Kumar introduced four new stromatolite names, '*Crossia*', '*Krolia*', '*Nainitalia*', and '*Plumia*', in an abstract (Kumar, 1979) and published paper (Kumar, 1980). The published paper gave a brief description, did not provide a diagnosis, and only indicated that 'detailed study of these fossils is underway and brief descriptions are given' (Kumar, 1980, p. 265).

Using open nomenclature

It is clear from many publications and discussions that a number of geologists, sedimentologists, microbiologists, and even some paleontologists, will never wish to use binomial nomenclature for microbialite (stromatolite) structures. For example, very few attempts have been made to classify or name Phanerozoic and Holocene microbialites (stromatolites). That is because:

- Phanerozoic microbialites (stromatolites) often coexist with other fossils that are capable of providing more refined stratigraphic or environmental interpretation than microbialites
- researchers do not think microbialites should be named
- complex, morphologically distinctive microbialites with a morphological theme, relatively common in the Precambrian, are less common in Phanerozoic
- Phanerozoic microbialites often exhibit lateral variability among nearest neighbours making unifying descriptions of the microbialites difficult. This is despite the fact that microbialites are ideal candidates to test the relative influences of paleoenvironmental and evolutionary controls (Shapiro and Awramik, 2000), but the lack of systematic description has limited this type of study.

Despite the success in naming and describing Proterozoic stromatolites, and the mounting evidence that stromatolite biostratigraphy is a useful correlation tool — for example, see Hill et al. (2000), Medvedev et al. (2005), and Filho and Fairchild (2011) — some researchers consider formal names unnecessary, and if names exist, they are often ignored. For example, a study of stromatolites in relation to environmental controls in the Bitter Springs Group of central Australia (Southgate, 1989, 1991) did not refer to the existing names in Walter (1972). It is unclear whether Southgate's conclusions apply to all taxa from the Bitter Springs Group, or only to one or two taxa. Because of this, the observations, while valid for the described area, are difficult to apply to stromatolites in other basins. If an author is not a supporter of naming microbialites, it would still be useful to give an indication that structures have previously been named.

Even researchers in a variety of fields who do not intend to name microbialite structures need to describe distinctive stromatolites in a manner that presents the most useful information and allows comparisons to be made. For those who have reservations about binomial nomenclature, yet wish to discriminate between morphological variations, a system of 'open nomenclature' (Matthews, 1973; Bengtson, 1988) is appropriate, especially if extended to include terms such as Group 1 and Form 1 to accommodate undescribed entities. In this method, each described entity is designated by a term such as 'Stromatolite Form 1', 'Stromatolite Form 2', etc. followed by the author's name and date, although some authors such as Filho and Fairchild (2011) used 'morphotype' instead. The description then follows the same pattern as that for a formally designated taxon. This approach is preferable to putting a formal name (often italicized) on a structure that has not been properly identified. Such informal classification can be used by researchers who feel it is inappropriate (or who do not wish) to name microbialites. Open nomenclature can be used parallel to the Linnean system, and still allows comparisons with formally named microbialites.

Open nomenclature (if applied rigorously enough) should allow non-taxonomic descriptions to be compared readily with taxonomic ones, and reduce problems arising from lack of familiarity with the taxonomic literature. It provides non-taxonomists with a system for describing microbialites (stromatolites) using a detailed, standardized description and adopting open nomenclature. This, in turn, will facilitate future taxonomic assignment and aid biostratigraphic studies, even if that was not the original purpose of the description. A further advantage is that the description can be readily cited in synonymy. In addition, open nomenclature can be used in taxonomic studies as an interim measure for dealing with microbialites (stromatolites) that cannot confidently be assigned to named taxa, perhaps because of poor preservation, inadequate or unrepresentative sampling, dissimilarity to previously described taxa, or reluctance to name the structure. Open nomenclature provides both taxonomist and non-taxonomist with a 'halfway stage' to formal nomenclature.

The informal name should be followed by a description of the distinctive features of the microbialite. The level of description will depend on the purpose for which the description is being used. For example, a field geologist will probably find that the guidelines in this handbook (Appendices 1, 2) provide sufficient information for a brief description, while taxonomists will need to follow a more rigorous descriptive structure and terminology. Whatever the approach, the greatest benefits result if informal descriptive methods parallel as much as possible those used for formal taxonomy. Most importantly, described specimens should be adequately illustrated. Where possible, one specimen should be nominated to typify the morphology. This will reduce confusion should the informal category be incorporated in a formal taxon at a future date. It would be advantageous, especially for future descriptive treatment, if specimens were deposited in an institution, even if Linnean nomenclature is not adopted.

The naming of microbialites is such a controversial issue that for the purposes of this handbook the nomenclatural procedure adopted is left entirely to the discretion of individual researchers. Authors may choose to adopt Linnean nomenclature with all its rules (see below), or they may decide not to apply names at all and use an informal system. In either case, some method of rigorously describing different morphological examples needs to be applied and it is hoped that by following the methodology, terminology and descriptive formats suggested in this handbook, some consistency will be reintroduced into microbialite analysis. Claims and counterclaims about biological versus environmental control will not be resolved until descriptions of relevant morphologies are placed on an equal footing.

Is an independent Microbialite Code feasible?

Results were discouraging when the issue of adopting parataxa and other problematical fossils (an artificial classification) under the provisions of the ICZN was raised (Moore and Sylvester-Bradley, 1957; Schindewolf, 1957; Sarjeant and Kennedy, 1973; Melville, 1979, 1981a,b,c, 1995; Sarjeant, 1979; Bengtson, 1985; Rasnitsyn, 1987; Bromley, 1996; Bertling, 2007) and the situation has never been satisfactorily resolved from the paleontological viewpoint. Trace fossil researchers face similar problems (Bertling, 2007), and even though ichnotaxa currently come under the umbrella of the ICZN, the arrangement is an uncomfortable one. Microbialite-building organisms are rarely preserved. Consequently, fossil microbialites could be regarded as trace fossils (Sarjeant and Kennedy, 1973, p. 461; Pickerill, 1994; Golubic and Lee, 1999, p. 341; Shapiro, 2007). Shapiro (2007) discussed the idea of including microbialites with other ichnofossils under the ICZN, but there is a reluctance for this to happen, both among microbialite researchers, conscious of the botanical affinities, and among zoologists, who are reluctant to include them within the framework of the Zoological Code.

Microbialite (stromatolite) researchers are not alone in facing the dilemma of naming fossils of uncertain taxonomic status. Paleontologists working on groups such as trace fossils, conodonts, spores and pollen, chitinozoa, and other fossils whose precise relationships to extant organisms were not clear, have (to varying degrees) tried to either obtain acknowledgment of their particular problems, or some modification of existing codes (usually the Zoological Code) that would have allowed them a more pragmatic approach. However, propositions for fossil groups, such as trace fossils (Sarjeant and Kennedy, 1973; Sarjeant, 1979), and conodonts and a variety of fragmentary fossils (Moore and Sylvester-Bradley, 1957), were not well received, as can be seen from the proposals and counter-proposals of Moore and Sylvester-Bradley (1957), Schindewolf (1957), Sarjeant and Kennedy (1973), Melville (1979, 1981a,b,c, 1995), Sarjeant (1979), Bengtson (1985) and Rasnitsyn (1987). Provision has been made under the ICZN to handle some of these fossils, but results are still not necessarily satisfactory from the point of view of the fossil taxonomist. The ICBN did not have any special provisions for dealing with problematic structures other than lichens, and the newer versions, the ICN (Melbourne Code and Shenzhen Code), have provisions for fungi, but abandon the concept of morphotaxa and treat all fossil parts as organs, requiring names to be assigned to the first named part (McNeill and Turland, 2011; McNeill et al., 2012; Turland et al., 2018).

It seems improbable that microbialites will find a slot within any of the four major codes, the International Code of Nomenclature for algae, fungi and plants (ICN), the International Code of Zoological Nomenclature (ICZN), the International Code of Bacterialogical Nomenclature (ICBactN) and the International Code of Nomenclature of Prokaryotes (ICNP), or even under an overarching biological code, the International Biocode (IBN), should it be adopted. Because most researchers acknowledge that microbialites are not species in the accepted biological sense, it will be difficult to convince the biological community to include microbialites within any of these codes. This does not alter the fact that binomial nomenclature provides a reasonable scheme of codification that enables rapid identification and a high degree of mutual understanding. More than two centuries of experience in biology and paleontology demonstrates the effectiveness of binomial nomenclature as an information storage and retrieval system for organisms. It must be remembered that all of the codes exist to regulate naming not taxonomic status. Exclusion from the major codes of nomenclature does not remove the necessity to have a naming scheme. An independent code that parallels existing code usage seems to be the most practical solution.

Unlike the large numbers of researchers who follow the existing codes of biological nomenclature, as well as the International (or national) Stratigraphic Codes of Nomenclature that regulate naming of stratigraphic units, microbialite specialists are low in numbers. Devising a microbialite code from scratch would be difficult and time consuming. The solution probably lies in adapting an existing code (the ICN seems the most appropriate) to accommodate the special requirements of microbialites. A further difficulty will be in forming some type of international commission capable of revising the code and making rulings on how to handle contentious names. In order to maintain the required expertise, it may be necessary to co-opt commission members familiar with nomenclature and systematics, but not necessarily with microbialites, because the issues are ones of naming rather than the nature of the objects named.

A great deal of discussion and deliberation will be required to set up a satisfactory solution. For the moment, our main objective is to draw attention to the problem and to explore a possible way forward. In this handbook, we offer suggestions about how such a code might look by basing a system on modifications of an existing code. Because most established microbialite names have been governed by the International Code of Botanical Nomenclature, we suggest that a microbialite code could be most easily established by modification of the ICBN and its successor, the ICN. In the interim, in order to maintain nomenclatural stability until a microbialite-specific code can be formally established, we strongly recommend that authors continue to follow the provisions of the ICN in establishing or modifying microbialite names.

The adoption of formal names for microbialites (stromatolites) will depend on each author's philosophy with regard to taxonomy, Linnean nomenclature, and its application to structures built by microbial communities. Meanwhile, the inclusion of a brief discussion of the naming methods adopted by the authors of publications would help clarify the approach for other researchers and make it easier for proposed names or name changes to be incorporated in any new system that is developed. Even where some form of Linnean nomenclature is adopted, researchers should bear in mind that any classification based on the morphology of organosedimentary structures will be an artificial one, and should be circumspect about drawing conclusions about relationships based on non-genetic connections.

Retaining Linnean nomenclature

If Linnean nomenclature is to be retained for microbialites for the purposes of those authors who require a naming system, it would be best to adopt one specific code, make appropriate modifications to suit any special requirements of microbialite naming, description and taxonomy, and require the adopted guidelines to be followed by all authors who apply names to microbialites. The introduction of specific terms applicable to microbialites would be best if they formed part of a Microbialite Code.

In other respects, formal microbialite names could comply with the accepted principles of naming taxa to ensure stability of the nomenclature. Nomenclatural rules should be observed in order to avoid erecting potentially invalid names, and the practice of erecting type specimens that are properly conserved and placed in a suitable, identified repository should continue.

Microbialite nomenclature

Nomenclature is a part of taxonomy that deals with the allocation of a distinctive name for a living or fossil entity. It was recognized early in the study of microbialites that they are constructs produced by more than one organism, rather than the direct preservation of a single organism, and that an artificial nomenclatural and classification scheme was used (Walcott, 1914, p. 10). Nevertheless, Johnson (1946) acknowledged that stromatolites comprised form genera and form species, and could be recognized and defined on their macroscopic characteristics. Accepting that stromatolite classification was artificial, Maslov (1953, p. 109) introduced the taxonomic categories Group and Form to replace genus and species respectively for stromatolite binomials. A notable exception to the application of nomenclature to a microbialite was Vologdin (1962) who described a large number of taxa based on the presumed cellular remains of microbes that were believed to produce a distinctive microstructure.

We do not recommend that every microbialite be named. Names should be avoided for stromatolites that:

- are morphologically highly variable from head (individual) to head (individual) with no apparent morphological theme
- possess very few morphologically distinctive characteristics
- are represented by one morphologically simple specimen
- are poorly preserved; for these, open nomenclature and an informal description should be substituted as discussed above.

Rationale for a Code of Nomenclature for Microbialites

Microbialites are useful to geologists and paleontologists for correlation (Krylov, 1975; Bertrand-Sarfati and Walter, 1981), paleoecology (Runnegar et al., 1979), reconstructing depositional environments (Serebryakov, 1975; Masson and Rust, 1983), documenting an Archean and Proterozoic fossil record (Walter et al., 1992), and understanding early microbial evolution (Awramik, 1992b). 'It is impossible to speak of the objects of any study, or to think lucidly about them, unless they are named' (Simpson, 1945, p. 1). Cloud and Semikhatov (1969, p. 1020–1022) presented cogent arguments for adopting a Linnean-style nomenclature for stromatolites. More importantly, they stressed that by naming stromatolites communication is expedited. In the case of bacteria, extant and fossil plants and animals, a stable and universally acceptable set of scientific names facilitates unambiguous scientific communication (Austin and Priest, 1986; McNeill and Greuter, 1986). These principles should also apply to microbialites.

We emphasize the following points with regard to the nomenclature of microbialites and urge that a formal code be followed for this nomenclature:

- microbialites are subject to standardizable methods of analysis that can yield comparable results to different investigators (Cloud and Semikhatov, 1969)
- a rigorously used nomenclature has the potential to produce unambiguous descriptions
- a stable nomenclature (whatever it is) facilitates discussion of microbialites and their significance
- Linnean-style nomenclature is universally used by biologists and paleontologists for extant and fossil material
- a formal name is the key to its literature (van Steenis, 1957)
- a code will lead to the stability of names
- type specimens will be established, properly curated, and available for study
- by emphasizing nomenclature and classification, many of the apparent problems of biostratigraphy can probably be resolved (Krylov, 1975, 1976; Bertrand-Sarfati and Walter, 1981; Grey, 1984; Raaben, 1986; Semikhatov and Komar, 1989).

Microbialite classification

Classification organizes objects according to characteristics deemed significant into a system of categories that are usually hierarchal. Taxonomy is the formal arrangement of the different kinds of life (Simpson, 1945) and includes the identification, nomenclature, and classification of objects of biological origin (Lawrence, 1951; Winston, 1999). By virtue of the fact that several stromatolite Forms have been described as belonging to the same Group, taxonomy is therefore currently being practiced. Classification and taxonomy above the Group level have also been applied, and have been based on broad, obvious features of the morphology. Pia (1927) established the Family Spongiostromata with two 'subfamilies', Stromatolithi and Oncolithi, under Class Schizophyceae (cyanobacteria). Korolyuk (1960b) subdivided all stromatolites according to the general shape of the buildups into three types: layered, nodular and columnar. Among the latter two types, she further recognized two subtypes: walled and wall-less. Krylov (1975) added columnar-layered stromatolites and Raaben (1980) added ministromatolites to Korolyuk's classification. Komar (1966) and Raaben (1964, 1969b, 1986) made attempts for further classification and suggested a taxonomy of columnar buildups above the Group level. Komar (1966) treated columnar, nodular and layered stromatolites in the supertype rank. Among the columnar stromatolites, he established nonbranching and branching types and active and passive subtypes within the columnar supertype. Komar (1979, 1989) further delimited several Supergroups according to the general features of the microstructure and the types of margins on columns. Raaben (1964, 1969b) established and formally named four Supergroups of the columnar stromatolites (Gymnosolenida, Tungussida, Conophytonida, and Kussiellida), each having a specific branching style. Some new schemes or variations on previously suggested schemes have been proposed; for example, by Konyushkov (1978), Liang et al. (1984), Raaben (1986), Raaben and Sinha (1989), Liang (1992). Hofmann (1969a), Krylov (1975, 1976), and Semikhatov and Raaben (2000) provide summaries.

We have no objections in principle to the classification of microbialites into such categories that facilitate communication — for example, 'columnar stromatolites' in Korolyuk (1960b) — and this handbook presents useful categories to assist in the description of microbialites. However, we suggest that the naming practices of the ICN be followed, so that each hierarchy has a specific ending (for example, —*aceae* to indicate a category equivalent in level to Family) and that the categories be named after a component of the category as is also required by the ICN. This has not always been the case, and schemes such as that proposed by Raaben and Sinha (1989) require modification for the sake of consistency and compliance with accepted rules for names of higher rank.

Proposed International Code of Microbialite Nomenclature

As stated in the Preamble 1 to the ICNafp, Shenzhen Code (Turland et al., 2018):

> Biology requires a precise and simple system of nomenclature that is used in all countries, dealing on the one hand with the terms that denote the ranks of taxonomic groups or units, and on the other hand with the scientific names that are applied to the individual taxonomic groups. The purpose of giving a name to a taxonomic group is not to indicate its characters or history, but to supply a means of referring to it and to indicate its taxonomic rank. This *Code* aims at the provision of a stable method of naming taxonomic groups, avoiding and rejecting the use of names that may cause error or ambiguity or throw science into confusion. Next in importance is the avoidance of the useless creation of names. Other considerations, such as absolute grammatical correctness, regularity or euphony of names, more or less prevailing custom, regard for persons, etc., notwithstanding their undeniable importance, are relatively accessory.

This succinct description of the role played by an international code of nomenclature applies equally to the need for a system of naming microbialites. Below, we make suggestions as to how such a code, modelled after the International Code of Nomenclature for algae, fungi and plants (ICN) and the 'Proposal of a Code for the Nomenclature of Trace-Fossils' by Sarjeant and Kennedy (1973) and Sarjeant (1979), could operate. In several ways, the problems encountered with trace fossils are analogous to stromatolites because both represent the activities of organisms rather than the remains of the actual organisms.

A microbialite code would follow very closely the International Code for Naming algae, fungi and plants (ICN). Some principles, articles, notes, and recommendations would need to be modified to reflect the unique nature of stromatolites; others could be adopted verbatim.

It may not be appropriate at this time to introduce a formally established classification hierarchy above Group level. There have been numerous attempts to do this, and all have the obvious features of the stromatolite's morphology as their fundamental basis for taxa. For example: Family Pseudogymnosolenaceae for certain types of columnar branching stromatolites (Liang et al., 1984); Class Ramaficantha for columnar branching stromatolites (Raaben, 1986; Raaben and Sinha, 1989); Type Columnar (Korolyuk, 1960b). To most paleobiologists and biologists, such a formal taxonomy above the rank of Group implies an understanding of the evolutionary relationships among taxa. There is no evidence at this time to support the notion that we understand the evolutionary relationships among various stromatolite taxa. Non-taxonomically based groupings, like columnar (note lower case), are probably best left until the lower levels of nomenclature are firmly established. However, some authors use taxa of the rank above Group (Raaben et al., 2001; Semikhatov and Raaben, 2000) and many such terms are in use in the current literature (especially in the Russian and Chinese literature) because they appear useful: (1) in routine paleontological work if many taxa of Group rank are involved, (2) in basin analysis, and (3) in evaluating general trends in the distribution of microbialites in time and space. Names must be correctly formed.

We propose that a draft code for the nomenclature of microbialites be adopted as an interim solution until a more permanent solution can be arrived at. Although microbialites are nomenclatural orphans, some sort of continuity is needed until a more formal naming structure can be established. By following a draft code, the names will remain stable and should conform to recognized naming practices. Because microbialites are no longer included under the ICN or any other recognized international code, we propose that the International Palaeontological Union establish a subcommittee on microbialite nomenclature to monitor the situation and recommend a procedure to follow. At a minimum, responsible microbialite taxonomists should consider this draft code as a guide to the proper naming of stromatolites and, in the case of doubt about how to proceed, should follow the ICN <www.iapt-taxon.org/nomen/main.php> and become familiar with the latest edition.

Like many of our colleagues we remain convinced that rigorous standards of description and nomenclature facilitate productive research on microbialites. The naming of rigorously defined microbialites is a powerful convention that expedites scientific exchange. Below we present a discussion of how an 'International Code of Microbialite Nomenclature' could operate using a system that mainly parallels the ICN and we also provide a model protologue (Appendix 2) that we suggest be followed to maintain stability in microbialite nomenclature. For the discussion below, we assume that, except where otherwise stated, wording of the Code would be very similar to that of the ICN. Rather than reiterate the wording of the ICN with modifications that would allow it to apply to microbialites, for the discussion below we have selected those articles that are either critical or that will require modification.

Applying rules of nomenclature to microbialites

In the following discussions, provisions concerning a proposed International Code of Microbialite Nomenclature are referred to as relating to the Microbialite Code; those concerning the International Code of Nomenclature for algae, fungi and plants (Shenzhen Code; Turland et al., 2018) as ICN; and any concerning earlier versions of the Botanical Code as ICBN followed by the relevant date. We have mainly followed the order, article numbering and wording of the Shenzhen Code (Turland et al., 2018).

Principles

1. For the purposes of the application of the proposed International Code of Microbialite Nomenclature, a microbialite is here defined as an organosedimentary structure produced by the sediment trapping, binding, and/or precipitation activity of microorganisms at a sediment–fluid interface. Microbialites embrace stromatolites, thrombolites, dendrolites, leiolites, potentially MISS, and any other related structures.
2. The nomenclature of microbialites is based wholly on the characteristics of the structure that can be observed and documented in the specimen, and that are considered to be relics of microorganisms interacting with their environment. It is recognized that a particular structure may be produced by many different microorganisms, related or unrelated, that different microorganisms might produce similar structures, and that non-vital processes can influence accretion and shape. Therefore the application of a particular name does not necessarily imply formation by a particular organism or organisms.
3. The nomenclature of microbialites follows that of the ICN with special applications that are peculiar to microbialites. Rules that parallel those of the ICN apply to names of taxa whether or not these taxa were originally considered to be microbialites; for example, *Cryptozoon* was originally considered to be animal (Hall, 1883). The name remains valid, but may have to be orthographically modified following the suggestions for such cases given in the ICN.
4. Names chosen for microbialites should not correspond to existing names of animal, plant, bacterial or other biological taxa. However, where an existing name is the same as a name of a plant or animal, that name can be conserved and is not regarded as a homonym of a name governed by a separate code.
5. Although the nature of a microbialite is more akin to that of an ecosystem rather than an individual organism, the microbialite name is applied to the whole structure.
6. As required by the ICN and applied to microbialites, names are determined by means of nomenclatural types. The nomenclature (correct name) of a taxon is based upon valid publication, legitimacy and priority of publication. There is only one correct name for each taxon. The names of taxa are treated as Latin regardless of their derivation. In this, we endorse the principles as stated in the ICN.

Rules and recommendations

Taxonomic ranks

1. Chapter I of the ICN (Shenzhen Code; Turland et al., 2018) discusses the ranks of taxa, and the terms used to denote them. Following Article 1 of the Shenzhen Code, taxonomic units of any rank are here referred to as taxa (singular: taxon). For the purposes of the proposed Microbialite Code, an extant microbialite or a fossil microbialite is as defined in Principle 1 above and a taxon of either an extant or fossil microbialite is based on a type specimen. The name of a microbialite is independent of any names applied to component organisms, such as bacteria, cyanobacteria, algae or other organisms incorporated within the microbialite, or of microfossils in the case of a fossil microbialite. Naming of identifiable component organisms in any microbialite remains under the domain of the ICN, ICBactN, ICNP, ICZN or IBN as appropriate.
2. For nomenclatural purposes two principle taxonomic units of microbialites are recognized: the Group and the Form (Maslov, 1953).
3. Paralleling Article 2 of the Shenzhen Code, the rank of Form (equivalent in rank to species), is regarded as the basic rank. A Group may comprise one or more Forms.
4. In contrast to Articles 3 and 4 of the Shenzhen Code, and in view of the highly variable structure and origin of microbialites, it is not considered that a comprehensive scheme of classification into ranks higher than Group is either feasible or desirable at the present time. Although Supragroup classifications have been proposed (e.g. Raaben and Sinha, 1989), none is well established. However, if used, any names above the rank of Group should be formed in accordance with the current version of the ICN. Names must have correct endings and they must be formed as specified in the Code by using the name of a constituent Group. Informal categories higher than Group, such as coniform microbialites, can also be used.
5. Article 4 of the Shenzhen Code also discusses the use of subdivisions. For microbialites, the use of subdivisions below the rank of Form is not encouraged, but if used, the taxonomic rank (equivalent to subspecies or variety) should be referred to as a SubForm.
6. Article 4 of the Shenzhen Code lists the ranks of taxa, in descending sequence. For microbialites the main ranks recognized would be: Group, Form and SubForm. As in the Shenzhen Code Article 5, the relative order of these ranks should not be altered.

Note 1. The microbialite ranks of Form and SubForm are not direct equivalents of the lowest recognized ICN ranks of form and subform.

Taxonomic names

1. Chapter II of the Shenzhen Code deals with general provisions for the naming of taxa and includes status, definitions, typification, priority and its limitations.
2. Article 6 of the Shenzhen Code deals with definitions of status and defines the terms 'effective publication', 'valid publication', 'legitimate name' and 'illegitimate name'. Microbialite taxonomists should ensure that proposed names are published in accordance with the suggested provisions of the Microbialite Code as modified after Article 6 of the latest version of the ICN.
3. A name which, according to the provisions of the proposed Microbialite Code, would be illegitimate when published, cannot become legitimate, unless conserved or sanctioned under the Microbialite Code.
4. Since microbialites are nomenclatorial orphans (i.e. they are not formally acknowledged under the ICN), it is not certain how a request for a ruling on conservation or sanction of a name could be handled at present. It would be necessary to establish a General Committee similar to the one that operates under the provisions of the ICN. Until procedures can be established, the author should explain fully the nature of the problem in their description and indicate that the course followed is an interim one pending the establishment of a formal Microbialite Code.
5. The Shenzhen Code Article 6 also deals with determining the correct name of a taxon. Because of the rule of priority, the earliest published legitimate name is the one that should be adopted. In the rest of this discussion, as in the Shenzhen Code (unless otherwise indicated), the word 'name' means a name that has been validly published, whether it is legitimate or illegitimate. The correct name is the senior synonym, and other names are junior or subjective synonyms.
6. Provisions for the introduction of new names, new combinations and replacement names parallel those of Articles 6.9, 6.10 and 6.11 of the Shenzhen Code.

Typification

1. Articles 7 to 10 of the Shenzhen Code deal with status, typification and priority of names. It is proposed that similar articles apply to microbialites. Following the requirements of the Shenzhen Code, names of all microbialite taxa are determined by means of nomenclatural types. A nomenclatural type is that component of a taxon to which the name of the taxon is permanently attached, whether as a correct name or as a synonym.
2. Type material should be housed in a permanent, responsible institution where it will be scrupulously conserved, and the name of the institution and catalogue numbers, and a numbered illustration of the type specimen, must be provided in any taxonomic or similar publication. As provided for in Article 40.7 of the Shenzhen Code, the single institution in which the type is conserved must be specified (see also Rec. 40A.5 and 40A.6) for the name of a new taxon published on or after 1 January 1990. A name would be regarded as invalidly published if such information is not included with the description.
3. Under the Shenzhen Code Article 7.2, the nomenclatural type is not necessarily the most typical or representative element of a taxon. In the case of

microbialites, this requires careful consideration because types (e.g. holotypes) involving large specimens are often based on only part of that specimen. In this, microbialites resemble some type specimens of corals in which the type is only part of the entire structure. The various codes state that the holotype (even if it is only one component of the structure) is the specimen as designated by the author. Unless a holotype is lost, it automatically determines how the name is applied.

4. The remaining subclauses of the Shenzhen Code Article 7 and Articles 8 and 9, relating to the selection of types for new combinations, replacement names, illegitimate names, autonyms and previously published names, should be followed in relation to the selection of types for microbialites. Type material should be scrupulously conserved and be accessible to bona fide researchers.
5. As in the Melbourne Code Article 7.11, the type must be clearly designated as such.
6. Typification of microbialite names should, in general, follow the provisions of the Shenzhen Code Article 8.
7. Article 8 also deals with with the constitution of a type specimen. For the purposes of typification of a microbialite type, an illustration only is not acceptable (unlike the Shenzhen Code Article 8.1).
8. Article 8.2 of the Shenzhen Code allows a specimen used for the purposes of typication to consist of parts (although some of the other provisions specific to botanical specimens do not apply to microbialites). To avoid any ensuing confusion, the author of a microbialite Form should state the nature of the material used in the designation of the type (e.g. hand specimens, slabs, thin sections, peels, etc.) and indicate clearly which figure or figures depict the holotype or other types. For extremely large microbialites, the type should consist of representative samples taken from a single microbialite. It is strongly recommended that the type description include illustrations and, where possible, field images showing the overall morphology. When a type specimen is subsequently cut into pieces, including the preparation of thin sections and peels, all the parts originally used in establishing the diagnosis should be clearly marked and conserved (see Shenzhen Code Article 8.3).
9. As in the Shenzhen Code Article 8.4, the type of an extant microbialite cannot be a living specimen or culture, so specimens should be dried or mounted in resin, or conserved in some other manner so that organic components do not remain active. The type of a fossil microbialite is always a specimen (the Shenzhen Code Article 8.5). Because it is difficult to designate a whole specimen of a microbialite, the type is the collection of components designated as the type by the author or authors.
10. In designating microbialite types, follow the Shenzhen Code Article 8 recommendations where they apply to microbialite specimens.
11. Provisions in the Shenzhen Code Articles 9 and 10 should be followed in designating and naming microbialite types, and for reference to terminology relating to different types (e.g. lectotype, paratype, etc.) and the rules governing their use.

Priority

Articles 11 to 15 of the Shenzhen Code deal with priority in naming and should be followed in relation to establishing a name for a microbialite. There can only be one correct name. Numerous examples are cited in the Shenzhen Code that are useful guides for determining the correct name.

Of significance for naming microbialites is Shenzhen Code Article 13.3, which defines fossil material for the nomenclatural purposes.

Some provisions under Articles 11 to 15, especially those applying to dates from which valid publication of names of various botanical groups are treated as having begun, and dates related to the conservation of names, do not currently apply to microbialites. Such dates will need to be determined and instituted when a Microbialite Code is adopted.

For microbialites transferred to the International Code of Microbialite Nomenclature, we suggest that taxa originally published either under the rules of the International Code of Zoological Nomenclature or the International Code of Botanical Nomenclature are treated as beginning on 1 January, 1883, with the publication in Hall (1883) of *Cryptozoan proliferum*. We are not aware that any microbialite taxa were originally published under other codes, such as the ICBactN.

This group of Shenzhen Code Articles also explains the circumstances under which a name may be conserved, an action that requires a formal ruling. A mechanism for referral of requests for names to be conserved and for making such rulings has yet to be devised for a Microbialite Code.

Taxonomic rank

The Shenzhen Code Chapter III Articles 16 to 28 deals with the naming of taxa of different ranks. Articles 16 to 19 concern the naming of taxa above the rank of Group and generally do not apply to microbialites at present. Should an author particularly want to apply a Supergroup classification, they should study the Shenzhen Code provisions carefully and determine how they might apply to microbialites. Such authors should pay particular attention to those articles governing the formation of names of higher rank, both in terms of forming names from the name of the type of a constituent taxon (Shenzhen Code Article 16.2), and with regard to the consistent application and formation of name endings, which are an indication of rank (Shenzhen Code Article 16.3).

Shenzhen Code Articles 20 and 23 are highly relevant to microbialites because they deal with the formation of names of genera and species, so need to be consulted in naming microbialite Groups and Forms respectively. Shenzhen Code Articles 24 to 27 apply to the naming of infraspecific taxa, so have relevance to SubForms. Shenzhen Code Article 28, on names of organisms in cultivation, is not relevant to microbialites.

Nomenclature for Groups

Shenzhen Code Chapter III Articles 20 to 22 provide rules governing the naming of genera. For microbialites, similar rules apply to the naming of Groups.

1. The application of Shenzhen Code Article 20 to microbialite nomenclature requires that the name of a Group be a latinized noun in the nominative singular, or a word treated as such, and written with a capital initial letter (traditionally, the name is italicized). The name may be taken from any source whatever, and it may even be composed in an absolutely arbitrary manner, although the name must not end in *–virus* (Shenzhen Code Article 20.1). Technical terms currently used in zoology, botany, bacteriology or geology may not be used for a Group name unless the formulation of that term postdated formulation of the Group (Shenzhen Code Article 20.2). The name of a Group may not consist of two, separate, unhyphenated words (Shenzhen Code Article 20.3). Recommendation 20A of the Shenzhen Code should be consulted for advice in the formulation of Group names.
2. Shenzhen Code Articles 21 and 22 discuss subgenera, and the retention of types and their names. We are not aware of the use of SubGroups in microbialite nomenclature and suggest that they not be used. However, if they are, the names should be formed in accordance with the Shenzhen Code Articles 21 and 22.

Nomenclature for Forms

Shenzhen Code Chapter III Article 23 deals with the formation of species and infraspecific taxa names and provides the models for naming microbialite Forms (and SubForms should they be required).

1. Shenzhen Code Article 23 lists the rules governing the naming of species, which should be applied to the naming of microbialite Forms. For microbialites, the name of a Form, like that of a species, should be a binary combination consisting of the name of the Group followed by a single specific epithet (the Form). The rules specific to coining Form names should follow those detailed in the Shenzhen Code Article 23 and Recommendation 23A.
2. An example of correct expression of a Form name is *Conophyton garganicum* Korolyuk 1963.

Nomenclature for SubForms

Shenzhen Code Articles 24 to 27 deal with the naming of infraspecific taxa. Infraspecific taxa have rarely been used for microbialites. Examples are *Conophyton garganicum garganicum* Korolyuk 1963 and *Conophyton garganicum australe* Walter 1972. We recommend that infraspecific taxa not be used; naming of a new Form would be preferable. Although the above examples were designated as varieties, we recommend that any infraspecific microbialite taxa should be designated as SubForms, rather than introducing a complex hierarchy similar to that allowed under the ICN. Most of the infrataxa that have been introduced are in need of taxonomic revision and they will probably be raised to Form level as studies progress.

1. Names for SubForms should follow the rules for naming infraspecific taxa (Shenzhen Code Articles 24 to 27). For microbialtes, the name of a SubForm is a combination of the name of a Form with an additional epithet; its rank should be denoted by the interjected word ‘SubForm’.
2. A SubForm, like a subspecies, is a ternary combination. The use of binary combinations for SubForm is inadmissible. SubForm epithets are created in a similar manner to those of Form and, when adjectival (i.e. not used as nouns), should agree grammatically with the Group name. SubForms can have the same name provided they are present in different Form. It is recommended here that authors proposing new SubForm epithets should avoid those previously used for a Form in the same Group.
3. An example of correct expression of a SubForm name is *Conophyton garganicum* SubForm *australe* Walter 1972, not *Conophyton garganicum* SubForm *C. australe* Walter 1972.

Publication of names

Shenzhen Code Chapter IV deals with conditions and dates of effective publication.

1. Shenzhen Code Article 29.1 should be followed with regard to conditions for effective publication of microbialite names. Publication should be ‘by distribution of printed matter (through sale, exchange, or gift) to the general public or at least to scientific institutions with generally accessible libraries’ (for microbialites, this would include geoscience libraries). The Melbourne Code Article 29.1 included new provisions concerning electronic publication that would also apply to microbialites: ‘Publication is also effected by distribution on or after 1 January 2012 of electronic material in Portable Document Format (PDF; see also Art. 29.3 and Rec. 29A.1) in an online publication with an International Standard Serial Number (ISSN) or an International Standard Book Number (ISBN)’. A date for acceptance of electronic material would need to be determined at the time of the adoption of a Microbialite Code, although it would avoid confusion if the starting date for acceptance of electronic publication were the same for both the ICN and the Microbialite Code. Note that ICZN was also emended to allow electronic publication under certain conditions from the beginning of 2012 (International Commission on Zoological Nomenclature, 2012).
2. As in Shenzhen Code Article 29.1, Note 1, electronic material distributed before the acceptance date would not count as a valid publication.
3. Similar provisions to Article 29.2 and 29.3, with regard to the definition of ‘online’ and a contingency plan should PDF format be superseded, would be required in a Microbialite Code.

4. A Microbialite Code would also need to include provisions similar to the Shenzhen Code Recommendation 29A with regard to what constitutes archival standards and requirements and for the depostion of printed copies that meet archival and curational standards.

5. The constraints and recommendations in the Shenzhen Code Article 30, which outline unacceptable means of publication, should apply to microbialite names. Authors are advised to avoid publishing new names and descriptions or diagnoses of new taxa in ephemeral media of any kind (Shenzhen Code Recommendation 30A.4); in particular, note the restrictions applying to the naming of new taxa in theses (Shenzhen Code Article 30.9). Authors should choose periodicals that regularly publish taxonomic articles, and arrange for at least 10 copies of printed matter to be available in accessible libraries worldwide (Shenzhen Code Recommendation 30A.5). New taxa and taxonomic changes should be listed in the publication's abstract or in the summary, as well as in an index, if present (Shenzhen Code Recommendation 30A.6). If chosing an electronic means of publication, take note of the provisions in Article 30. Note also the preferences expressed in the Recommendations for publications that display pagination and indicate a final version by the use of such words as 'Version of Record'. It may prove difficult to arrange for new microbialite names to be listed by an 'indexing centre appropriate to the taxonomic group' (Shenzhen Code Recommendation 30A.5) until such a system can be identified or set up.

6. Shenzhen Code Article 31 deals with the dates of effective publication. It states that the '…date of effective publication is the date on which the printed matter or electronic material became available as defined in Articles 29 and 30. In the absence of proof establishing some other date, the one appearing in the printed matter or electronic material must be accepted as correct.' Authors of microbialite taxa should follow these recommendations.

Validity

Shenzhen Code Chapter V deals with general provisions with regard to the validity of publication. The name of a taxon has no status unless it is validly published, so authors of microbialite taxa should take every precaution to ensure valid publication (Shenzhen Code Articles 32 to 37). Microbialite researchers should follow these articles carefully and adhere to them to ensure valid publication:

1. The name should be composed only of letters of the Latin alphabet, although there are a few exceptions (Shenzhen Code Article 32.1).

2. 'Names or epithets published with an incorrect Latin termination but otherwise in accordance with this Code are regarded as validly published.' Such names should be 'changed to accord with Articles 16–19, 21 without change of authorship or date' (Shenzhen Code Article 32.7).

3. Terms such as novus, new, combinatio nova, new combination, or appropriate abbreviations should be used when publishing nomenclatural novelties to ensure that the status as a new name or combination is clear. For microbialites, appropriate terms would be: Group nova, new Group, Gp. nov.; Form nova, new Form, F. nov.; combinatio nova, new combination, comb. nov.; nomen novum, replacement name, nom. nov.; status novus, name at new rank, stat. nov. (Shenzhen Code Recommendation 32A).

4. The date of a name is that of its valid publication and changing an incorrect spelling of a name does not affect its date of publication (Shenzhen Code Articles 33.1, 33.2).

5. The name of a Form is not validly published unless the name of the Group has been published previously or is published at the same time as the Form (Shenzhen Code Article 35.1), and a combination is only valid if the author associates the Form name with the Group name to which it is transferred (Shenzhen Code Article 35.2).

6. Articles 36 and 37 discuss examples that do not constitute valid publication and the problem of the simultaneous publication of two names by the same author based on the same type.

7. Shenzhen Code Article 38 requires the publication of a new taxon to include a diagnosis, which is the opinion of the author on what distinguishes the new taxon from other taxa. In applying this article to microbialites, it is recommended that reference to previous diagnoses or descriptions be as full and direct as possible, including dates and synonymies.

8. Other conditions associated with the publication of a diagnosis and description of a taxon listed in Shenzhen Code Articles 38 and 39 should be followed for microbialite descriptions.

9. An important recommendation is that a new taxon should be accompanied by illustrations. (Shenzhen Code Recommendation 38D). In the case of microbialites, where taxa are commonly illustrated by parts of specimens, it is particularly important to ensure that one of the validating figures must be of or from the type specimen and should be clearly labelled as such and that the identity of other illustrated are indicated in the figure caption (Shenzhen Code Recommendation 38D.2). The scale of the figure should be indicated (Shenzhen Code Recommendation 38.D), preferably by a scale bar that will resize with the image.

10. Shenzhen Code Article 39 requires the name and diagnosis of new taxon to be published in Latin or for the name to be accompanied by citation of a previously and effectively published description or diagnosis in Latin. An exception is allowed for fossil taxa, for which the description or diagnosis can be in Latin or English, or be by a reference to a previously and effectively published description or diagnosis in Latin or English (Shenzhen Code Articles 39 and 43). Shenzhen Code Recommendation 39A suggests that a full description be given in Latin or English in addition to the diagnosis. However, numerous microbialite taxa have been published in a variety of other languages, notably Chinese, French and Russian. Pragmatically, these microbialite taxa will need to be accepted as valid, and this will probably require them to be treated as nomina conservanda.

Just how this is to be effected will need to be considered in establishing a Microbialite Code. It is anticipated that the diagnosis will be in English in most formal descriptions of microbialites, although many authors will continue to publish microbialite papers in non-English languages. Where this is the case, it is recommended that an English translation of the diagnosis be included so that that the validity of a name cannot be challenged on that criterion. It would also be helpful if an English translation of image captions associated with the diagnosis be provided. It is recommended that in future all new taxa conform to Microbialite Code requirements with regard to language.

11. Shenzhen Code Article 40 provides a list of conditions that must be met before a new name can be considered as valid. In particular, Articles 40.1 and 40.2 require the type of the name to be indicated for the new taxon to be valid, and for it to be flagged by the use of the words 'typus' or 'holotypus', or its abbreviation, or its equivalent in a modern language (Shenzhen Code Article 40.6).
12. Shenzhen Code Article 41 deals with combinations, new ranks and replacement names. Among other considerations, it states that a combination (autonyms excepted) is not validly published unless the author definitely associates the final epithet with the name of the genus or species, or with its abbreviation. In other words, a new combination requires that the name be published as a whole (this will be the Group and Form in the case of a microbialite), otherwise it is invalid. For microbialites, full and direct reference should be given to the name, author and date of the original publication of the name being replaced.
13. Microbialite researchers should pay close attention to those details of Shenzhen Code Articles 41 to 45 that are applicable, especially those relating to fossil taxa (Shenzhen Code Articles 43) when forming and using new names, new combinations or replacement names. In the past, failure to do this and the lack of adequate synonymies has led to confusion. Note also Article 43.2 requires that in order to be validly published, a new fossil-genus or lower-ranked fossil taxon published on or after 1 January 1912 must be accompanied by an illustration or figure showing the essential characters, or by a refernce to a previously published figure. Article 43.3 requires that at least one of the validating illustrations be identified as representing the type specimen.

Author attribution

Chapter VI deals with how to attribute the authorship of names of taxa.

Shenzhen Code Article 46 deals with author attributions and should be followed carefully when recording authorship of the name of a taxon. In particular, make sure that authorship is cited as ascribed in association with the name. This may not always be the same as authorship of the publication (Shenzhen Code Article 46.2). Note also Shenzhen Code Recommendation 46B, which states that the romanization of the author's name given in the publication should normally be accepted. This article also makes recommendations about how authors' names should be romanized, and how to attribute names of taxa to more than one author. Although it recommends using the first author and et al. in the case of multiple-authored names of taxa, it is probably more helpful to refer to the full authorship at least once. Detailed additional instructions and recommendations with numerous examples are given in Shenzhen Code Article 46 to ensure the valid publication of new scientific names. Not all of these apply to microbialites; however, the following recommendations apply to microbialites.

1. Indicate the name of a taxon as accurately and completely as possible, and give a complete attribution that comprises the full name of the taxon, the name of the author(s) and the date of publication so that this information may be readily verified.
2. The correct citation of an author's name from a non-romanized language is a problem in microbialite taxonomy. As indicated in the Shenzhen Code Article 46B, 'in citing the author of the scientific name of a taxon, the romanization of the author's name given in the original publication should normally be accepted' and if an author 'failed to give a romanization, or where an author has at different times used different romanizations, then the romanization known to be preferred by the author or that most frequently adopted by the author should be adopted'. If such information is not available, then the author's name should be romanized 'in accordance with an internationally available standard'. As suggested by Shenzhen Code Article 46B.2, authors '...whose personal names are not written in the Latin alphabet should romanize their names, preferably (but not necessarily) in accordance with an internationally recognized standard and as a matter of typographic convenience, without diacritical signs'. Authors should then use the selected the romanization of their personal names consistently thereafter. 'Whenever possible, authors should not permit editors or publishers to change the romanization of their personal names' (Shenzhen Code, Article 46B.2).
3. It is preferable that authors' surname or family name be given in full and not be abbreviated, even though abbreviations are allowed under the Shenzhen Code.
4. Where it is necessary to distinguish between two authors with the same surname (family name), the given name(s), or initial(s) of the given name(s), should be used.
5. Both authors, linked by an ampersand (&) or by the word 'et', should be cited after a name published jointly by two authors (Shenzhen Code Article 46C.1).
6. When a name has been published jointly by three or more authors, only the name of the first author, followed by 'et al.' need be referred to except in the first use of the name of a new taxon as the heading to the diagnosis or description (Shenzhen Code Article 46C.2). However, because it is often difficult to access some microbialite literature, it may be helpful to designate the full list of authorship.
7. Use the word 'in' to connect the names of authors when a name supplied by one or more authors is

published in a work authored or edited by another person or persons. The name of the author of the description or diagnosis is the most important and it should be retained when it is desirable to abbreviate the citation.

8. Use the word 'ex' before the name of the publishing author to connect names when a name has been proposed but not validly published by one author and is subsequently validly published and ascribed to that author by another author.

9. Do not use expressions like 'nobis' (nob.) to refer to oneself in an author attribution. Use the author's name as for any other attribution of authorship (Shenzhen Code Article 46D.1).

Shenzhen Code Article 47 explains how to deal with alterations to diagnostic characters or to the circumscription of a taxon and should be followed for microbialites. This should only be done after careful consideration. Unless the type is excluded, a change in author citation is not warranted. However, when an author makes a substantial alteration to the diagnostic characters of microbialites (thus altering the diagnosis) this should be indicated by adding the word 'emend.' (emendavit) and the name of the author or authors making the emendment. Authors of later works who accept this emendation may indicate that fact by citing the original author, followed by the connecting word 'emend.' and the name of the emending author and date of the emendation. Additional ways of indicting changes are listed in Shenzhen Code Recommendation 47A.

Under Shenzhen Code Article 48, if a taxon is circumscribed in a way that excludes the original type of the name, the new name is a later homonym that must be ascribed solely to author of the homonym. Under the provisions, a name can only be retained if it is conserved and if a ruling in favour of conservation is obtained. However, a mechanism for making rulings in relation to a Microbialite Code would need to be developed.

Shenzhen Code Article 49 explains how to cite an author's name when there is a change in rank. For microbialites, when a Form is raised to a Group, the name of the author of the Form must be cited in parentheses, followed by the name of the author who effected the alteration (the author of the new name). When a Group name is divided into two or more Groups, the Group name must be retained for one of the Groups (provided the Group name is correct). The Group name retained must include the type Form of the original Group. If no type has been designated, a type must be chosen. This practice should also be followed when subdividing Form and SubForm.

Shenzhen Code Article 50 refers to hybrids, so is not relevant to microbialites, except for some of the general recommendations on citation (Recommendations 50A–G).

Rejection of names

Chapter VII discusses the rejection of names.

Shenzhen Code Article 51 makes the important point that 'a legitimate name must not be rejected merely because it, or its epithet, is inappropriate or disagreeable, or because another is preferable or better known or because it has lost its original meaning'. For example, a name based on a morphological feature must be retained even if that name is not representative of the morphology. In past studies of microbialites, they were frequently misinterpreted and sometimes inappropriate names were given. However, to provide stability in nomenclature, it is necessary that these names should be accepted.

Circumstances under which a name can be rejected are given, with numerous examples, in Shenzhen Code Article 52 and how to deal with homonyms is explained in Shenzhen Code Article 53. Under Article 52, a name should be rejected if the taxon to which it applied already includes the type of a name that should have been adopted under the rules of priority (Shenzhen Code Article 52.1). Several examples are cited for how the choice of name should be made. Later homonyms must be rejected (Shenzhen Code Article 53). The examples cited in that article should be followed for the case of microbialites.

Shenzhen Code Article 54 states that considerations of homonymy do not apply to taxa not treated as algae, fungi or plants. Microbialite names probably fall into this category. It is not clear how this should be interpreted, but it could mean that common microbialite names like *Acaciella* (which is a junior homonym of a plant) and *Baicalia* (a junior homonym of a gastropod) would be legitimate under an independent Microbialite Code. In the meantime, authors publishing new microbialite taxa should take note of Shenzhen Code Recommendation 54A and, as far as is practicable, avoid using names that already exist for zoological and bacteriological taxa, as well as any names existing under the ICN. Numerous listings of named organisms are available through the internet, and authors should check that a proposed new name does not duplicate any existing generic name.

Shenzhen Code Articles 55 to 58 contain further provisions concerning the rejection of names. They deal with cases in which names or parts of names are illegitimate, and with the rejection of names. Similar stipulations should apply to microbialite names. Several specific examples are cited and should be consulted as appropriate. In particular, Shenzhen Code Article 57, which states that a name that has been 'widely and persistently used for a taxon or taxa not including its type is not to be used in a sense that conflicts with current usage' until a decision has been made about its status. Several microbialite Group names may need to be examined under this provision.

Shenzhen Code Chapter VII, Article 59 and Chapter F deal with fungi and their various morphotypes. Although not directly applicable to microbialites, they present some interesting parallels that might be useful when dealing with microbialites.

Orthography

Shenzhen Code Chapter VIII is an important chapter that deals with the orthography and gender of names (how names should be formed and spelled). Articles 60 to 62 and their recommendations should be followed to ensure correct spelling, latinization and use of gender in microbialite nomenclature. Article 60.1 states that the original spelling of a name or epithet should be retained, except for the correction of typographical or orthographical errors and the standardizations imposed by correcting letters and ligatures foreign to classical Latin. Whether or not the rules of Latin grammar that govern the naming of organisms need to be used in a Microbialite Code will require careful consideration. On the one hand, it would mean abandoning a system that has been used for more than two centuries, and provisions for how existing names are to be handled would be necessary. On the other hand, names would be easier to handle in the digital age if it was no longer necessary to keep track of changes to Group and Form endings, and the setting up of a new and independent code might be the appropriate time to introduce such a break with tradition.

These articles (and other parts of the Shenzhen Code) contain several recommendations dealing with the preparation of a synonymy, which is perhaps one of the most important, and often neglected, aspects of dealing with microbialite taxonomy and nomenclatural issues. Microbialite taxonomy has suffered considerably because of the failure to provide adequate synonymies in a number of cases. It is vital that the taxonomic history can be traced and that a reader can follow the reasoning of the author. This should be done by providing a list indicating the status of names and specimens deemed by the author to belong to the taxon in question, or that should be excluded from that taxon.

Remaining articles

The remainder of the Shenzhen Code includes provisions for its governance, and follows with appendices on the names of hybrids, and conserved and rejected names of taxa. If an International Code of Microbialite Nomenclature is adopted, similar mechanisms for its governance will be required.

Acknowledgements

Numerous colleagues have been consulted for their opinions on descriptive aspects of microbialites over the many years this handbook has been in production. While we may not always have agreed with the views expressed, we would like to acknowledge that they have influenced our thinking either consciously or unconsciously. There are too many to thank individually, but we would like to acknowledge, in particular, the following: Janine Bertrand-Sarfati, Hans Hofmann, Brian Pratt, and Misha Semikhatov, who contributed to an initial draft of a stromatolite handbook in the early 1990s.

Over the years, we have benefited especially from discussions, correspondence and field excursions with numerous colleagues, including Paul Buchheim, Bob Burne, Frank Corsetti, Daniel Cupertino, Pierre Freytet, Dennis Gee, Bob Ginsburg, Mike Hall, Arthur Hickman, Bob Horodyski, Jim Jackson, Igor Krylov, David Locke, Sarah Martin, Linda Moore, Marjorie Muir, Nora Noffke, Noah Planavsky, Wolfgang Preiss, Russell Shapiro (particularly for his valuable assistance with thrombolites), Pam Reid, Peter Southgate, Erica Suosaari, Alan Thorne, Malcolm Walter, Ian Williams, and Zhu Shixing, some of whom are no longer with us. Several colleagues allowed us to collect or photograph some of the specimens illustrated in this volume or made specimens available. We also thank the many field geologists from the Geological Survey of Western Australia, an organization which, for more than 100 years, has discovered localities, collected samples, and illustrated or photographed and made observations on the numerous stromatolite occurrences in Western Australia. In particular, we thank Heidi Allen and Peter Haines, who shared data collected in recent years on the Amadeus Basin.

Many colleagues provided images used in this volume, including: HJ Allen, M Ang, HP Buchheim, K Coulson, DF Cupertino, DTO Flannery, JW Hagadorn, PW Haines, AC Hill, RM Hocking, JA Hollis, PD Kruse, DMcB Martin, S Martin, AJ Mory, NJ Planavsky, CV Spaggiari, and MR Walter. We are particularly grateful to Sarah Martin for her tireless help with accessing the GSWA collection, and to Madeline Ang and Heidi Allen for help with photographing GSWA specimens. Photographers are acknowledged on individual images.

Werner Greuter provided valuable feedback vis-à-vis the International Code for Botanical Nomenclature (ICBN, Saint Louis and Vienna Codes) and J McNeil on the succeeding International Code of Nomenclature for algae, fungi, and plants (ICNafp, Melbourne Code) (McNeill et al., 2012).

We also thank Heidi Allen and Malcolm Walter, who undertook the task of peer reviewing the handbook.

Many people have assisted in numerous ways over the years, including field assistants, laboratory technicians, students, and drafting personnel, and we have had numerous discussions in the field, the office, and at meetings with colleagues who contributed in small, but valuable ways. We apologize if we have overlooked any specific contributions and thank everyone who has assisted us in making this handbook a reality.

Glossary

Clear and unambiguous definitions are an integral part of precise communication. This glossary attempts to provide them. Unfortunately, semantics has been a problem in microbialite research for over 100 years, as exemplified by the different opinions on what Kalkowsky (1908) meant by stromatolite.

The definitions of the terms cited here are not necessarily those given by the author who introduced or used the term for the first time. In many cases, terms were introduced without a proper definition or illustration. In some instances, authors have modified existing definitions. The definition cited here in each case provides the most widely accepted use of the term in the current literature. Where there are several definitions for the same term, we have cited them to give an indication of the variety of ways in which the term has been applied. When there is a significant problem with a particular term, it is assessed and the preferred term is indicated. We indicate where terms are obsolete or not preferred. We have also provided references, where appropriate, to assist usage. Not all words in the glossary are used in the text. We also recognize that not everyone will agree with the definitions we have used in this handbook.

a

aberrant stromatolite: Stromatolite of unusual morphology (e.g. not columnar, domical, or planar) (Pratt and James, 1982, p. 548)

abiogenic: Not of a biological origin. The term abiogenic stromatolite is an oxymoron (see text)

abiophoric: Refers to a microbialite lacking microfossils (Hofmann, 1973, p. 350; Walter, 1976d, p. 687)

abiotic: ‘A term pertaining to substances or objects that are of nonbiologic origin’ (Schopf, 1983b, p. 443)

accretion vector: (obsolete term) The growth vector that joins the mid-points (centres) of successive laminae; modified after Hofmann (1969a, p. 17), who defined it as ‘the upward maintenance or duration of the stacking process’. Note this is best applied to columnar and domical microbialites. The preferred term is **height-to-width ratio**

active (of branching): (obsolete term) The characteristic should be described using a combination of the terms for **branching mode**, such as **beta** and **gamma**, and **angle of divergence**, such as moderately **divergent** and **markedly divergent**

acute (of lamina profile): (obsolete term) Used by Hofmann (1969a, p. 15, fig. 8) and similar to **parabolic** and **prolate**. The preferred term is **parabolic**

agglutinated stromatolite (microbialite): A stromatolite or microbialite produced by microbial sediment trapping and binding (Riding, 1991, p. 30)

algal: (partially obsolete) This adjective is no longer appropriate for microbial communities that are dominated by cyanobacteria and other prokaryotic organisms. Algae are eukaryotes and, depending on the scheme preferred, belong to either Kingdom Protista or Kingdom Planta in rank-based nomenclature or in Domain Eukaryota based on phylogenetic systematics. The modifier ‘algal’ should only be used when algae are the dominant microorganisms responsible for the structure. An example would be the algal bioherms from the Ries crater, Miocene, Germany, that are built by *Cladophorites*, a presumed green alga (Riding, 1979). The preferred term is **microbial**

algal mat: (partially obsolete) A microbial mat ‘whose prime determinant is eukaryotic (e.g. diatoms)’ (Bauld, 1981, p. 88). Prior to the replacement of the term blue-green algae with cyanobacteria, algal mat was commonly used for a microbial mat regardless of whether it was dominated by algae or cyanobacteria (Kendall and Skipwith, 1968). Unless the main components are demonstrably algal, the preferred term is **microbial mat**

allomicrite: A term introduced by Wolf (1965, p. 35) for autochthanous micrite (transported micrite). See **automicrite** and **orthomicrite**

alpha (of branching): A branching mode in which the width of the parent remains constant before branching occurs (Walter, 1972, p. 13). Similar to passive or false branching (obsolete terms). The preferred term is **alpha branching**

alternating (of lamination): (obsolete term) An ‘alternation of two types of laminae texturally and/or mineralogically different’ (Monty, 1976, p. 195). This commonly refers to the alternation of light and dark lamina although other combinations are possible. The preferred term is **lamina alternation**

alveolar (of laminar architecture): Solid laminae separated by subparallel voids. Some may have been infilled by later mineralization

alveolar (of microstructure): (obsolete term) A structureless micritic microstructure containing relatively large, more or less equant, pits, voids or fenestrae. Originally described as microstructure, this is now regarded as a type of mesostructure (see **alveolar laminar architecture**)

amplitude (of lamina): (obsolete term) The preferred term is **synoptic relief**

anastomosed branching (of branching style): A term used where two or more adjacent branches are overgrown by a larger branch, so that columns exhibit both branching and fusion (Hofmann, 1969a, fig. 10, p. 16)

anastomosed column (of branching style): The convergence of branches or columns into a new, larger column

angle of divergence (of branched microbialites): The angle at which branches diverge from one another. Types of angle of divergence include: **parallel**, **moderately divergent**, **markedly divergent**, **horizontal** or **subhorizontal**

angulate (of lamina profile): A lamina that is angular in profile, but which forms a ridge, crest or cusp, (not a cone) in three dimensions (see Hofmann, 1969a, fig. 8). The preferred term is **angulate**

aphanitic (of microstructure): Featureless microstructure found in leiolites (Riding, 2000, p. 195; 2011a, p. 637)

aphanostromata: (obsolete; rarely used term) Clotted to coarsely laminated, tabular to columnar structures usually of an encrusting nature comparable to stromatolites (Nitzopoulos, 1974, p. 19–20, 124–127; Flügel and Steiger, 1981, p. 375)

arboreal stromatolite: A stromatolite or microbialite that encrusts a tree or its branches; see Whiteside (2004, p. 147)

arborescent (of stromatolite): Hoffman (1975, p. 262, fig. 30-12) used the term for 'tiny' centimetre-sized branching stromatolites that resemble tufa. The term has also been used to describe stromatolites from the Cretaceous pre-salt lacustrine carbonates off the coast of Brazil (Terra et al., 2010)

arborescent (of thrombolite): A dendritic thrombolite with shrubs at the decimetre scale (dendrolitic mesostructure is at the centimetre scale) (Riding, 2000, p. 193)

arborescent (of thrombolite clot shape): A clot having a bushy shape (Kennard, 1994, fig. 7a; Riding, 2011a, fig. 8) with a flat base and lobate or branched upper portion

architecture (of laminae): A mesostructural term for fossil microbialites defined as the relationship visible between a microbially constructed element and the surrounding matrix. For stromatolites, it is the product of the lamina shape, lamina boundaries, stacking of individual laminar elements, and the relationship of the lamina to underlying or overlying laminae. A roughly equivalent term for living microbialites is **mat topography**, which refers primarily to the surface features (Bauld et al., 1992, p. 262). Similar to **community architecture** (Winsborough et al., 1994, p. 76). The preferred term for stromatolites is **laminar architecture**

architecture of laminae: The preferred term for stromatolites is **laminar architecture**

assemblage: An association of one or more entities (microbialites, taxa) (Hill et al., 2000)

asymmetrical (of lamina profile): A lamina profile that is skewed, i.e. the maximum curvature of the lamina is not at the column centre or axis

attitude (of columnar and branched microbialites): The orientation of a microbialite (especially a column) in relation to bedding; modified after Hofmann (1969a, p. 17 and fig. 13). Types of attitude include: **erect**, **inclined**, **prostrate**, **pendant**, **sinuous**, **hyponastic**, **epinastic** and **encapsulated**

automicrite: A term introduced by Wolf (1965, p. 35) for autochthanous micrite, or as stated in Keim and Schlager (1999, p. 15), 'in situ formed fine grained micrite'. In living microbialites, the precipitation of micrite often takes place within biofilms (Reitner et al., 1995, p. 5). See **allomicrite** and **orthomicrite**

axial zone (of conical stromatolites): A narrow region of thickening and contortion in the centre of a conical stromatolite with laminae that have a distinct change in slope and are commonly lensoidal with one or more laminae laterally offset as they are stacked. Axial zones are a diagnostic characteristic of *Conophyton, Jacutophyton* and other specific taxa of conical stromatolites. The width of the axial zone is the width of the thickened and/or contorted portions of laminae. Three types of axial zone were distinguished in conical stromatolites by Komar et al. (1965a,b) and a more detailed description was given by Walter (1972). A possible method of formation was described by Walter et al. (1976). There are three types of axial zone: **Type I**, **Type II** and **Type III**. In ridged stromatolites, the equivalent feature is referred to as the **crestal zone**

axis: 'The centre-line of a column' (Preiss, 1972, p. 92; Walter, 1972, p. 12)

b

bacterioherm: Infrequently used for 'algal bioherms'; see Ford and Pedley (1996, p. 124); algal refers to what today would be called cyanobacterial or microbial

banded (of laminar architecture): Architecture in which laminae are very continuous and have abrupt, distinct, generally parallel (equidistant) boundaries (Walter, 1972, p. 12). Types include: **evenly banded**, **broadly banded** and **wavy banded**

benthic microbial community (BMC): A term used to describe 'all those microbial inhabitants (bacterial, fungal and microalgal) residing on the surface of, and within, the sediments of lacustrine and marine waterbodies' (Bauld, 1986, p. 95)

benthic microbial mats: 'Mats…are microbial communities which colonize benthic surfaces and form cohesive, prostrate, often laminated, structures of varying preservation potential' (Bauld, 1981, p. 87)

beta (of branching): Branching mode in which the width of the parent column widens gradually before branching. This term has sometimes been used to include parallel branching (angle of divergence), but these characteristics are best described independently

bifurcate (of branching): A branching style in which columns branch into two smaller (filial) columns without increase in total width of the structure

bilobate (of plan view): A type of **laxilobate** plan view with two divergent lobe margins

bimodal (of lamina profile): A lamina having two crests. Bimodality frequently occurs just prior to branching

binomial nomenclature: The scientific naming of species whereby each species is given a latinized name consisting of two parts: genus and species. For microbialites, we recommend using **Group** and **Form**

biocoenose: An assemblage of organisms living together, interacting as a community within an ecosystem. With regard to microbialites, the term has usually been used when communities include cyanobacteria, other bacteria and eukaryotes, such as algae (Caudwell et al., 1997) and animals (Hägele et al., 2006)

biodictyon: A 3D network of filamentous and coccoidal microbes in soil, sediment or rock (Krumbein et al., 2003, p. 8)

biofilm: An 'assemblage of surface-associated microbial cells that is enclosed in an extracellular polymeric substance matrix' (Donlan, 2002, p. 881). For discussion see Krumbein et al. (2003)

bioherm: Any 'dome-like, mound-like, lense-like or otherwise circumscribed mass, built exclusively or mainly by sedentary organisms such as corals, stromatoporoids, algae, brachiopods, mulluscs, crinoids, etc., and enclosed in normal rock of different lithologic character' (Cumings 1930, p. 207). Preiss (1972) and Walter (1972), applying the term to microbialites, suggested that the minimum width is less than or equal to one hundred times its maximum thickness. See discussion in text. Bioherm types include: **tabular**, **domical**, **subspherical**, **club shaped**, **egg shaped**, **ellipsoidal**, **intertonguing**, **nodular**, **pedestal** and **tabular**

bioherm series: (obsolete term) Originally defined by Krylov (1975, p. 73) and translated in Bertrand-Sarfati and Walter (1981, p. 362): 'For most bioherms it is possible to put all constructions from them into rather distinct series of variations. Such series (call them bioherm series) are all the main morphological variants from one bioherm, or uniform bioherms from one bed, with a uniform microstructure (or complex of microstructures)'. See text for discussion

bioherm shape (of buildups): The distinctive shape of a bioherm which is commonly determined by dimensions and orientation. Bioherms vary considerably in size, so can be regarded as either megastructures or macrostructures (see text). Types of bioherm shape include: **tabular**, **domical** and **subspherical**. A variety of subsidiary shapes can also be recognized

biolaminites: A term for 'irregularly laminated structures formed by the binding action of blue-green algae' (Imbrie and Buchanan, 1965, p. 168). Gerdes and Krumbein (1987, p. v) also used the term for microbially laminated sediments that include both microbial mats and stromatolites. Another variation has been described from siliciclastic deposits where microbial mat layers alternate with deposited sediments (Bouougri and Porada, 2007)

biomarker: The term is short for biological markers and first became widely used in clinical medicine in the 1980s (Aronson, 2005). It was later also applied to geology and astrobiology, where it is usually defined as an 'organic compound with a specific structure that can be related to a particular source organism' (Neuendorf et al., 2011, p. 68). Also referred to as 'the molecular fossils of lipids and other natural products' that may be diagnostic for a specific group of organisms (Brocks and Grice, 2011, p. 147). It is recommended that this term not include morphological evidence. Brocks and Grice (2011, p. 148) elaborated further, noting that paleobiological biomarkers are 'mineralogical, elemental, isotopic, and morphological indicators for the presence and activity of life in the geological record'

biomat: A microbial mat (Krumbein et al., 2003, p. 1)

biomimetic: Refers to artificial processes, substances, devices, or systems that imitate nature. A computer simulation of stromatolite growth would be biomimetic (Grotzinger and Knoll, 1999, p. 340–341)

biophoric: Refers to microbialites that contain microfossils (Hofmann, 1973, p. 350)

biosignature: The 'morphological, chemical (organic, elemental and, or mineral), and isotopic traces of organisms preserved in minerals, sediments, and rocks' (Westall and Cavalazzi, 2011, p. 189). Similar to paleontological **biomarker**

biostrome: A term for 'purely bedded structures, such as shell beds, crinoid beds, coral beds, etcetera, consisting of and built mainly by sedentary organisms, and not swelling into moundlike or lenslike forms' (Cumings, 1932, p. 334). Preiss (1972) and Walter (1972), applying the term to microbialites, suggested that the minimum width is more than one hundred times its maximum thickness. See text for discussion

biostrome shape (of buildups): The distinctive shape of a biostrome which is commonly determined by dimensions and orientation. Biostromes vary considerably in size, so can be regarded as either megastructures or macrostructures (see text). Types of biostrome shape include: **tabular** and **non-tabular**

BMC: See **benthic microbial community**

boundstone: A 'term used by Dunham (1962) for a sedimentary carbonate rock whose original components were bound together during deposition and remained substantially in the position of growth (as shown by such features as intergrown skeletal matter and lamination contrary to gravity); e.g. most reef rocks and some biohermal and biostromal rocks' (Neuendorf et al., 2011, p. 80). See **microbial boundstone**

branch: A structure resulting when a column or existing branch) divides

branched conical (of conical microbialites): A compound microbialite in which a central cone is surrounded by lateral branches. Also referred to as **branched coniform**. The preferred term is **branched conical**

branched coniform (of conical microbialites): (obsolete term) The preferred term is **branched conical**

branched microbialite (of microbialite shape): A term for a microbialite shape that exhibits branching. The terms **branching columnar** and **columnar branching** have been used for the same feature (see text for discussion and types). The preferred term is **branched**

branching: Refers to the pattern of subdivision of columns and branches

branching columnar (of branching): (obsolete term) A microbialite that divides into discrete branches. Also referred to as columnar branching. The preferred term is **branched columnar**

branching columnar (of branched microbialites): (obsolete term) The preferred term is **branched columnar**

branching conical (of conical microbialites): (obsolete term) The preferred term is **branched conical**

branching mode: The manner of column widening, or lack of it, just prior to branching. See **alpha**, **beta**, and **gamma** branching. Previously used terms **active**, **passive**, **true** and **false** are obsolete

branching pattern: The style, mode, frequency, location, spacing, and angle of divergence of branching, and its overall conformation

branching style: Refers to the position of filial branches in relation to the parent column and the nature and number of branches resulting from division from a parent column (Hofmann, 1969a, p. 17, fig. 16). This also includes any amalgamation of columns or branches. Types of branching style include: **furcate** (**bifurcate**, **trifurcate**), **multifurcate**, **dichotomous**, **lateral**, **coalesced** and **anastomosed**

brevilobate (of plan view): A type of lobate plan view of a column or branch, in which the lobes are very short and irregular (Hofmann, 1969a, fig. 13)

bridge (of ornament): A term for laminae that cross the interspaces and connect adjacent columns. Types include **massive** and **delicate**. Also referred to as **bridged laminae**

bridged laminae (of ornament): Laminae that cross the interspaces and connect adjacent columns. Types include **massive** and **delicate**. Also referred to as a **bridge**

broadly banded (of laminar architecture): A type of laminar architecture where the laminae are continuous and sharply bounded and of considerable thickness (Preiss, 1974, fig. 10c)

buildup: A general term for a circumscribed body that displays topographic relief above the substrate

bulbous (of domical microbialites): A type of domical microbialite that generally has its height greater than its width with the plane of maximum width above the midpoint of the height. The width of the base is less than the maximum width. Also referred to as **cumulate**, **nuclear** and **picnostromic**. The preferred term is **bulbous**

bumpy (of ornament): A term for low, rounded protrusions on the surface of a microbialite. (Protrusions that are smooth and extend downwards are referred to as **tuberous)**

bushy branching (of branched microbialites): A shrub-like shape found in certain forms of branched microbialites

C

calcimicrobe: Calcareous filamentous and coccoidal microbial fossils (James and Gravestock, 1990, p. 460). These can be found in microbialites and 'include calcified cyanobacteria such as *Angusticellularia*, *Botomaella*, and *Girvanella*, and also *Epiphyton* and *Renalcis*, whose affinities are less certain' (Riding, 2011a, p. 643)

calcimicrobialite: A microbialite composed primarily of calcimicrobes (Lehrmann, 1999; Turner et al., 2000; Wang et al., 2005)

calcrete: '[A] secondary accumulation of fine-grained carbonate (typically cryptocrystalline calcite) formed in soil profiles' (Read, 1976, p. 55). See **terrestrial stromatolite**

calyptra: (obsolete term) A term used by Luchinina (1973) and Zhuraleva and Miagkova (1977, p. 89) for small bioherms or individual microbialites. The term has never been widely adopted. Also referred to as a **coenoplase**, **stromatoid**, **head** or **individual**. The preferred term is **head**

catagraph: 'Microscopic carbonate problematica. Many are probably grapestones, botryoidal lumps, and other sedimentary structures' (Walter, 1972, p. 13). Some researchers interpret catagraphs as biogenic structures (Zhuravleva, 1964; Knoll, 1985). Also referred to as **microphytolites**

catagraph-bearing microstructure: A microstructure composed of **catagraphs**

cave stromatolites: Laminated microbialites that form in caves. The microbes involved are chemolithotrophic or chemoheterotrophic, except for photosynthetic mircrobes in twilight regions at cave entrances (Cox et al., 1989; Boston et al., 2001) and lampenflora (photosynthetic microbes growing in artificially illuminated caves; Aubrecht, 2011, p. 838). Also referred to as **microbial speleothems** (Thrailkill, 1976; Aubrecht, 2011, p. 837) and **subaerial stromatolites** (Cox et al., 1989, p. 245)

cavity encrusting (of layered microbialites): Laminae or, in some cases, small columnar microbialites lining the walls of cavities. Also referred to as an **endostromatolite**, which Monty (1982, p. 343) described as a **cavity** or **fissure-filling** stromatolite

centrifugal (of attitude): (obsolete term) Growth outward from a central point (Hofmann, 1969a, fig. 10, p. 17). The term is innappropriate because it is associated with a force rather than a geometric pattern (see text). The preferred term is **encapsulated**

centripetal (of attitude): (obsolete term) Growth outward from a central point. The term is innappropriate because it is associated with a force rather than a geometric pattern (see text). The preferred term is **encapsulated**

cerebroid: A microbialite that in surface view resembles the cerebrum of the brain. In plan view, such a microbialite would be referred to as **maceriate**

circular (of plan view): Columns or branches in which the cross-section shape is mostly **rounded** to **subcircular**

clavate (of microbialite shape): Club shaped; elongated, narrowing towards the base and gradually expanded towards the apex. The preferred term is **turbinate**

closely spaced (of spacing): The spacing between microbialites is less than the width of the structures

clot (of thrombolite mesostructure): A general term for a compact mass of variable texture found in thrombolites

clot orientation (of mesostructure): The arrangement of mesoclots in regular patterns, either locally or throughout the entire thrombolite. Types of mesoclot orientation include: **normal**, **prostrate**, **radial** and **random**

clot shape (of mesostructure): The 3D morphology of a clot. Types of clot shape include: **rounded**, **subrounded**, **oblong**, **lanceolate**, **crescentic**, **scutate**, **pendant**, **lobate**, **saccate, arborescent** and **diffuse**

clotted macrofabrics (of mesostructure): (obsolete term) A term used for mesoclots by Riding (1991). The preferred term is **mesoclot**

clotted mesostructure (of thrombolite mesostructure): A term used for mesoclots by Shapiro (2000, p. 169) in defining thrombolites (see text)

clotted microstructure (of microstructure): A microstructure composed of silt-size micrite miniclots or peloids (usually indistinct), separated by interparticle and fenestral pores (Pratt, 1982, p. 1216)

club shaped (of bioherm or head shape): The height-to-width ratio is 3:2, the base is less than one third the maximum width and forms a stalk. Maximum width is more than two-thirds the height of the bioherm; also referred to as **turbinate** or **clavate**

cluster: (obsolete term) A term used by Bertrand-Sarfati and Potin (1994, p. 352) for a concept similar to fascicle. The preferred term is **fascicle**

coalesced (of branching style): A term used for a branching style in which two adjacent branches increase in width until they converge and widen upwards as a single larger branch (Hofmann, 1969a, fig. 10, p. 16)

coalesced column (of branching style): A term used where two or more adjacent branches widen upwards and converge to into a single, larger column or branch (Hofmann, 1969a, fig. 10, p. 16)

coefficient of crestal zone thickening (of axial zones): The thickness of a lamina at the apex of a cone or crest divided by the thickness of that lamina on the flank (Komar and others, 1965a,b; Preiss, 1972, 1976c, p. 12; Walter, 1972), but see Hofmann (1978, p. 601) for a dissenting view

coenoplase: (rarely used term) A term coined by Twenhofel (1919, p. 342) for morphologically distinctive growth forms of what today would be called stromatolites or microbialites (Hofmann, 1969a, p. 3). Hofmann (1969a, p. 55) further suggested that the term coenoplase was suitable for an individual structure; however, Hofmann (1969a, p. 3, 5) seems to have preferred **stromatoid** for an individual stromatolite. A coenoplase is also referred to as a **head**, **individual**, **bioherm** and **calyptra**. The preferred term is **head**

collared conical (of conical microbialites): (new term) A compound microbialite in which a central cone is partially encircled by a series of structures resembling a Medici or Elizabethan collar (a fan-shaped collar that stood upright behind the head and sloped down to meet the neckline). Each structure consists of a curved sheet that is vertical or slightly angled away from the central axis and is attached to the cone some distance above its base. The sheets are commonly offset and rarely surround the cone completely

column (of microbialite shape): A non-branching, pillar-like microbialite with a width smaller than its height. Avoid using column if referring to an individual branch, although terms like **column margin** can be inferred to apply to both columns and branches where both are present

column attitude (of columnar microbialites): The orientation of a microbialite (especially a column) in relation to bedding and a function of growth directions and whether the microbialite is straight or curved. Attitude commonly refers to the orientation as seen in vertical profile. Types of attitude include: **erect**, **inclined**, **prostrate, pendant**, **sinuous**, h**yponastic**, **epinastic** and **encapsulated**

column margin (of mesostructure): The boundary of a column and its associated features, including the wall if present (see **microbialite margins**, **column-surface characteristics, wall)**

column-surface characteristics (of mesostructure): Features of the **column margin**, principally **ornament**

columnar branching (of branching): (obsolete term) See **branched** and **branching** columnar. The preferred term is **branched**

columnar layered (of layered microbialites): (obsolete term) A stromatolite with short columns alternating with layered stromatolites. Also referred to as **linked columnar** or **layered columnar** (obsolete term). The preferred term is **linked columnar**

columnar microbialite: A microbialite in which height is much greater than width and which does not branch or rarely branches. Types of columnar microbialites include: **cylindrical**, **terete** and **turbinate**

community architecture: The 'lamination and three-dimensional arrangement of the microbial contents' (Winsborough et al., 1994, p. 76). Used mainly for living **microbial communities**

complex microbialite: A general term for microbialites with a variety of shapes in the buildup. They can be **compound** or **composite microbialites**

complex wall (of column margins): A wall in which one or more laminae overlap the edges of several underlying laminae. The overlapping laminae tend to terminate abruptly where they turn in against the **head** and the laminae that have been overlapped tend to be truncated

composite (**of lamina alternation):** Adjacent laminae consist of different microstructural types; boundaries can be sharp, but more commonly grade upward; more than two laminae types may be present

composite fabric: A microbialite mesostructure that contains a mixture of mesofabric types, such as mesoclots and laminae. The mesostructures often intergrade (Harwood, 2009, p. 19). Use of fabric in this way is questionable as fabric is a microstructural feature and a component of **texture**

composite microbialite (of microbialite subtypes): A microbialite with a combination of microbialite subsets such as stromatolites, thrombolites, dendrolites and leiolites. A microbialite with a **rind** would be a composite microbialite. Harwood and Sumner (2011, p. 1649) used the term for intermingled clotted and laminated mesostructure microbialites. Riding (2011a, p. 651) illustrated microbialite domes composed of leiolites, thrombolites, and stromatolites. The term has also been applied to a microbialite composed of one type of microbialite with a non-microbialite constructor, such as composite oncoids composed of microbialites and encrusting foraminifers (Neuweiler, 1993, p. 231)

compound microbialite (of branched and conical microbialites): A microbialite with a combination of shapes of the same type of microbialite, such as a conical stromatolite with branched columnar stromatolites or a columnar thombolite with branched columnar thrombolites. Aitken (1967, p. 1166) mentioned small domes regularly superimposed on large ones, and Pratt and James (1982, p. 546–547, fig. 6C) provided an example of columnar and pseudocolumnar stromatolites. Bunting (1986, p. 86) described compound stromatolites formed by the coalescence of small domes

concave conical (of conical microbialites): A simple conical microbialite comprising a single head or column, where laminae terminate at a distinct apex, are steeply inclined between the base and apex, and show concave (inward) curvature in vertical profile. The cone is not associated with branches or other complex structures. An **axial zone** may or may not be present

concave lamina (of lamina profile): A lamina in which the curvature is downward

coniatolite: A hard, sheet-like crust of aragonite found in supratidal saline environments first described from the Persian Gulf area (Purser and Loreau, 1973, p. 375)

conical (of lamina profile): A lamina with a pointed profile. The term conical has been widely used in the literature, but should be restricted to a lamina that is three-dimensionally cone-shaped. The preferred term for a ridge-like pointed lamina is **angulate** or **crested**. The preferred term for a three dimensionally pointed lamina is **conical**

conical microbialite (of microbialite shape): A microbialite with a cone-shaped external morphology or with conical laminae (most conical microbialites are stromatolitic) that has an oval, ellipsoidal, teardrop, polygonal or other non-circular base in plan view, and tapers to a point or crest. The height is commonly much greater than the width. Some conical microbialites develop highly complex morphologies, in which the central cone is surrounded by other structures such as branches, ridges, walls and protrusions. Types of conical microbialite include **simple conical** and **compound conical**. Similar to **coniform microbialite**. The preferred terms are **conical microbialite** and **conical stromatolite**

conical stromatolite (of microbialite shape): (see **conical microbialite**)

coniform microbialite (of microbialite shape): Similar to conical microbialite. The preferred term is **conical**

constringed (of variability of growth): The upward change in the span of the laminae is variable, but the changes in peripheral variability occur gradually (Hofmann, 1969a, p. 17, fig. 10)

contiguous (of spacing): Microbialites that touch or nearly touch one another

contiguous columns (of spacing): Microbialites (bioherms, domes, columns or fascicles) with margins touching each other. The interspace region is zero (Hofmann, 1969a, fig. 9)

continuous (of lateral continuity): Lamination extends continuously, the lithology is consistent, and there are only slight changes in thickness. The upper and lower boundaries are more-or-less parallel

continuous (of wall): The wall covers the entire microbialite. It is the opposite of a **patchy wall**

converged branch (of branching style): The amalgamation of two or more branches into a single branch as a result of **coalecence** or **anastomosis**

convergence (of branching style): The amalgamation of two or more columns into a single column as a result of **coalecence** or **anastomosis**

convex conical (of conical microbialites): A **simple conical** microbialite comprising a single head or column, where laminae terminate at a distinct apex, are steeply inclined between the base and apex, and show convex (outward) curvature in vertical profile. The cone is not associated with branches or other complex structures. An **axial zone** may or may not be present

convex lamina (of lamina profile): A curved surface like a portion of a circle or sphere that curves away from the region of initiation. The majority of stromatolitic laminae have this profile

corniced (of ornament): A term for overhanging laminae or set(s) of laminae that are that are rhythmically constringed to produce concentric, sharp-edged corrugations found on the surface of a microbialite. For practical purposes this can be considered equivalent to the term **rugate** (obsolete term)

corrugate lamina (of lamina waviness): (seldom used or obsolete term) Stromatolite with crinkly or wrinkled laminae. The preferred term is **wrinkled**

couplet (of laminar architecture): The pairing of dark and light laminae that comprise the lamination of most stromatolites (Hofmann, 1969a, p. 4; Freytet, 2000, p. 22; Berelson et al., 2011, p. 411). Each couplet consists of two laminae (see text). Laminae that do not form a regular alternation of light and dark laminae are referred to as **non-couplets**. Similar to **doublet**. The preferred term is **couplet**

crenate (of lamina waviness): (seldom used or obsolete term) The preferred term is **wrinkled**

crenulate (of lamina waviness): (seldom used or obsolete term) Equivalent to **crenate** (Hofmann, 1969a, p. 14, fig. 8). The preferred term is **wrinkled**

crescentic (of plan view): A branch or column that in cross section is oblong and in which the longer width is curved

crescentic (of thrombolite clot shape): An elongate mesoclot that has a pronounced curvature of the major axis

crest: 'The summit of an upward-convex lamina' (Preiss, 1972, p. 92)

crestal line: A line joining the crests of successive laminae (Preiss, 1972, p. 92; Walter, 1972, p. 13)

crestal zone (of axial zone): 'The environs of the crestal line' (Preiss, 1972, p. 92; Walter, 1972, p. 13). In *Conophyton* and certain other taxa of conical stromatolites, the crestal zone is specifically the narrow zone of thickening and contortion of the laminae at the axis of the cone or ridge. The width of the crestal zone is the width of the thickened or contorted portions of laminae. Three types of crestal (axial) zones were distinguished in conical stromatolites by Komar et al. (1965a,b) and a more detailed description was given by Walter (1972). A possible method of formation was described by Walter et al. (1976). The term **axial zone** is specific to conical stromatolites, whereas crestal zone applies to ridged stromatolites

crested lamina (of lamina profile): An angulate lamina that is inflexed and angular in profile (Hofmann, 1969a, p. 15, fig. 8) and forms a ridge rather than a cone. The preferred term for a 3D pointed lamina is conical. The preferred term for a ridge-like pointed lamine is **angulate** or **crested**

crinkled lamina (of lamina waviness): (seldom used or obsolete term) The preferred term is **wrinkled**

crust (of microbial): A microbialite that encrusts a substrate. It can have stromatolitic (laminated), thrombolitic (clotted), or leiolitic (featureless) mesostructure, or a combination of any of these

crustose (of height-to-width ratio): A term used to describe the type of column variability which produces a short, encrusting column in which H << 2r (2r = W in text) (Hofmann, 1969a, p. 17)

crypt-: Prefix, from the Greek, meaning hidden. In microbialite literature, often used in conjunction with algal or microbial inferring origin, but without direct evidence

cryptalgal: (superseded term) The 'influence of algae in the rock forming process is more commonly inferred than observed' (Aitken, 1967, p. 1163). In modern usage, cryptalgal would refer to algae, which are photosynthetic eukaryotes, so the term cryptalgal has been superseded except where the presence of algae can be demonstrated. Some microbialites are produced by algae, such as diatoms, but most are dominated by cyanobacteria or other prokaryotic microorganisms. The preferred term is **cryptomicrobial**

cryptalgal boundstone: (superseded term) A boundstone produced by algae. See comment under **cryptalgal**. The preferred term is **microbial boundstone**

cryptalgalaminate, cryptalgal laminite: (superseded terms) A 'distinctive form of discontinuous, more-or-less planar lamination believed to have resulted from the activities upon and within the sediments of successive mats or films of blue-green and green algae' (Aitken, 1967, p. 1164). Sometimes (Rouchy and Monty, 1981) it is spelled cryptalgal laminate. See comment under **cryptalgal**. The preferred terms are **microbial mat**, **layered microbialite** and **layered stromatolite**

cryptalgal tufa: (superseded term) A term used in Monty (1976, p. 231) in reference to the microbialites in Green Lake, New York, which Bradley (1929, p. 205) described as 'exceedingly porous or spongy and consist of more or less closely intergrown arborescent masses that are richly nodose'. A tufa that is inferred to have formed through microbial activity. The term cryptalgal has been superseded except where the presence of algae can be demonstrated. The preferred term is **tufa microbialite**

cryptic microbial carbonate: A term for 'microbial carbonates which have micritic, clotted, peloidal or sparitic microfabrics, but which lack distinctive macrofabrics' (Riding, 1991, p. 29). The term leiolite was introduced by Braga et al. (1995) for the same thing without reference to Riding (1991). The preferred term is **leiolite**

cryptic structure: A microbialite having 'a vague, mottled, or patchy texture attributed to microbial activity' (Burne and Moore, 1987, p. 251). Also referred to as a **cryptomicrobialite**

cryptomicrobial: A modification of 'the term 'cryptalgal' (Aitken, 1967, p. 1163), substituting microbial for algal

cryptomicrobialite: Literally 'hidden' microbialite; a structure that is presumed to be a microbialite. Also referred to as a 'flat-laminated microbial mat' (Préat et al., p. 54) and 'laterally discontinuous biohermal domes composed of diffusely laminated dolomicrite' (Kennedy et al., 2001, p. 445). The preferred term is **cryptomicrobialite**

cryptomicrobial tufa: A tufa that is inferred to have formed through microbial activity

crystal stromatolite: A term for 'hemispherical, laminated cementstones identical to classic stromatolites…but mostly composed of crystals'. (James et al., 2001, p. 1242)

cumulate (of domical microbialites): A domical microbialite or bioherm in which the maximum width of the dome greatly exceeds the maximum width of the base giving the structure an inflated appearance (Walter, 1972, p. 6); considered here to be similar to domical and bulbous. The preferred term is **bulbous**

curved (of column): A general term used to describe the bent attitude of a column (Hofmann, 1969a)

cuspate (of lamina profile): A type of angulate lamina profile that in three dimensions is concave on both sides of the crest (Hofmann, 1969a, p. 14, fig. 8). Sumner (1997b, p. 306, fig. 9) described cuspate structures as filmy laminae draping closely spaced supports creating dish-shaped voids

cyanobacteria: Term probably first used by Stanier (Gibbons and Murray, 1978, p. 3) for what used to be called blue-green algae. Bacteria that obtain energy through photosynthesis and can produce oxygen

cyanobacterial mat: A benthic microbial mat constructed by cyanobacteria (Bauld, 1981, p. 88)

cyanolith: A term discussed by Riding (1983, p. 277) for an oncoid constructed by calcified cyanobacteria. The oncoid should have obvious calcimicrobes

cyclothemic lamination: A succession of 'at least three different laminae which always appear in the same order and which can be grouped into genetic sedimentary units' (Monty, 1976, p. 195)

cylindrical (of columnar microbialites): A columnar microbialite in which the width is uniform in plan view and remains constant throughout the length of the column (see computer-generated growth forms of Hofmann, 1969a, p. 12)

cylindrical conical (of conical microbialtes): A term for a simple conical microbialite where the column margins are more or less vertical but the laminae are conical. In some cases microbialites may be **domical cylindrical**, where the column begins as a domical stromatolite but transitions to a cone

d

daughter branches (of branched): (obsolete term) Formerly a general term for branches that are derived from a single column or single branch. Avoid gender-specific terms by using **parent** and **filial** rather than mother and daughter. The preferred term is **filial branches**

decumbent (of attitude): (obsolete term, see discussion in text) A column that initially lies parallel (prostrate) to the substrate but then bends upward producing an inclined to erect tip; the initial stage may even dip below the horizontal (Hofmann, 1969a, fig. 13). Replaced by **hyponastic**

degree of inheritance (of laminae): The extent to which a lamina conforms in shape to underlying laminae see Hofmann (1969a, p. 17 and fig. 13); similar to the term **serial development** (obsolete term). The following types are included: **low**, **moderate** and **high**. The preferred term is **degree of inheritance**

dendriform (of branching): The overall conformation of the branching is tree-like in form

dendritic: The shrub-like or bushy mesostructure of a microbialite

dendroid (of branching): A term used by Hofmann (1969a, p. 16, 38, fig. 10) for active branching in which the branches are sub-parallel. In this sense it is similar to **divergent branching**. It is also used in a less specific sense to indicate multiple complex branching (see comment on **dendroid** below). The preferred term is **divergent branching**

dendroid (of dendrolite): The individual branch or component of a dendrolite (Howell et al., 2011, p. 337). The term dendroid is not recommended (see discussion in text). The preferred term is **shrub**

dendroidal oncoid (of microbialite shape): A type of oncoid that has small, commonly branching, columns in its outer portions (Johnson, 1946, p. 1105). Wade and Garcia-Pichel (2003, p. 550) called them dendroidal oncolites

dendrolite (of microbialite subset): Riding (1988, p. 5; 1989, p. 11) introduced the term for 'biomineralized microbial deposits with a dominant dendritic macrofabric'. Later, Riding (1991, p. 34) added they were unlaminated. Calcimicrobes have been implicated in their formation (Riding, 1991, p. 34–35; 2000, p. 194–195). Shapiro and Rigby (2004, p. 645) defined dendrolite as 'a centimetre-scale fabric dominated by vertically erect or radially oriented branching clusters of calcimicrobes'. Dendrolite refers to the structure containing shrub-like microbialites, termed **shrubs**. Here we define **dendrolite** as: a non-laminated, non-mesoclot-bearing microbialite composed of smaller, non-laminated **dendritic microbialites**, termed **shrubs**

dense microbialite: A term for 'structureless to faintly clotted to poorly laminated masses of various sizes and shapes of grey to black micritic limestone or dolomudstone inferred to have been formed by the activity of microorganisms' (Kahle, 2001, p. 410). Similar to **leiolite**. The preferred term is **leiolite**

densilobate (of plan view): A lobed cross-section of a column or branch in which adjoining lobe margins are parallel and very closely spaced

dentate lamina (of lamina waviness): (seldom used or obsolete term) The preferred term is **wrinkled**

descriptive formula: The application of letters (Logan et al., 1964) or other designators, for example numbers (Cao and Bian, 1985), in a formula fashion that is used in classifying microbialites. This system is infrequently employed

dichotomous (of branching style): Branching into two new columns (Walter, 1972, p. 13) in which the point of division occurs more-or-less at the centre of the parent column to give rise to two almost mirror-image filial columns

diffuse (of thrombolite clot shape): A clot with indistinct borders (Harwood and Sumner, 2012, fig. 7C)

digitate (of branching style): A term for 'slender, vertically to obliquely oriented columns' (Howe, 1966, p. 65). Also referred to as **microdigitate**. One of the more specific terms available to describe **branching style** is preferred

discontinuous (of lateral continuity): The lamination extends from one side of the head or column to the other, but forms a series of discontinuous, aligned lenses; the lithology within the lenses is consistent

discordant laminae (of lateral continuity): (new term) Laminae in one column cannot be matched with corresponding laminae in neighbouring columns. The opposite of **harmonized laminae**

divergent (of branching): See **moderately** and **markedly** divergent branching

domical (of bioherm shape): An individual microbialite with clearly defined margins that arises directly from the substrate and has a rounded top and a height-to-width ratio about 1:3. It is more or less hemispherical in vertical section and the base is only a little narrower than the maximum width. Dome and domed are general terms applied to this type of structure. Types of domical microbialite include: **hemispherical**, **bulbous**, **nodular** and **nuclear**, the last of which is a specific bulbous type in which the central and peripheral laminae differ from one another in texture and microstructure (Raaben et al., 2001, p. 66)

domical cylindrical (of cylindrical-conical microbialites): A term for a column that begins as a domical stromatolite but transitions to a cone

doublet (of laminar architecture): Paired light and dark laminae (Trompette, 1969, p.136; Freytet, 2000, p. 22) that comprise the lamination of most stromatolites (Hofmann, 1969a, p. 4; Freytet, 2000, p. 22; Berelson et al., 2011, p. 411). Zhang (1986, p. 109) interpreted doublets as forming as a result of noctidiurnal microbial behaviour, although this probably represents only one variant that can cause cyclicity. Similar to **couplet**. The preferred term is **couplet**

dubiostromatolite, dubiomicrobialite: A structure of uncertain origin resembling a stromatolite or other microbialite that may be either of a biogenic or abiogenic origin

e

egg shaped (of bioherm shape): A buildup with a height to length ratio 3:2, the base is very narrow compared with maximum width. The maximum width is at about two-thirds the height of the bioherm

ellipsoidal (of bioherms): A buildup with a height-to-width ratio about 1:3, with a rounded top and bottom. Commonly the base is considerably narrower than the maximum width. The maximum width is at about half the height of the bioherm

elliptical (of plan view): in which one diameter is much greater than the other but the outline is not regularly **ovate**

elongate (of plan view): A property of lateral growth in which one lateral axis greatly exceeds the other lateral axis producing an ovoidal or highly elongate plan view. The resulting structures are best described as **linear**. This term should not be used in the vertical sense (use the **height-to-width ratio**). See also **seif** (Playford, 1980, 2013) and **longitudinal** microbialites. The preferred term is **linear**

encapsulated (of attitude): A spheroidal to ovoidal structure that resulted from growth outward from a central point. This describes the growth form of oncoids and related structures. It was called **centrifugal** by Hofmann (1969a, fig. 10, p. 16); however, terms like **centrifugal** and **centripetal** are terms associated with forces, whereas the feature referred to is a concentric geometric pattern. The preferred term is **encapsulated**

encapsulating (of lamina shape): A lamina that completely encloses previous laminae (Hofmann, 1969a, p. 12)

encrusting (of microbialite shape): A microbialite, sometimes thin, that forms on and typically follows the contours of a substrate, usually a hard substrate. This is a type of **layered microbialite** and can also be referred to as **planar**

endolite: Centimetre-sized 'oval multiple-layered organosedimentary cryptic structures' (de Wet et al., 2012, p. 422) that 'occur in clusters inside submarine cavities' (de Wet et al., 2012, p. 432–433)

endolith: An organism that lives or lived within the rock (Golubic et al., 1981, p. 476)

endostromatolite: A cavity- or fissure-filling stromatolite (Monty, 1982, p. 343). Bertrand-Sarfati and Moussine-Pouchkine (1983, p. 233) likened what they called a **cave stromatolite** to Monty's **endostromatolite** (but see **cave stromatolite**). The preferred term is **cave stromatolite**

enveloping laminae (of wall): A term for a type of lamina stacking in which one lamina overlaps several others along the column flanks to form a **complex wall**

epinastic (of attitude): (new term) A column that is initially erect or inclined, which develops a lateral to downwards curvature. Replaces **recumbent** (obsolete term, see discussion in text). The preferred term is **epinastic**

EPS: See **extracellular polymeric substances**

equally spaced branching: Branching in which the distance between branches is equal

erect (of attitude): A term used to describe the attitude of a column that is vertical or near vertical (Hofmann, 1969a, fig. 10, p. 17). The term **normal** can also be used

euendolith: Microorganisms that actively penetrate rock (Golubic et al., 1981, p. 478)

even (of lamina alternation): all adjacent laminae consist of similar microstructural types; boundaries between laminae are distinct and commonly have sharp contacts

even lamina (of lamina waviness): (obsolete term) A lamina with no second-order curvature or flexures. The preferred term is **smooth**

evenly banded (of laminar architecture): A type of banded laminar architecture where the laminae are continuous, sharply bounded and of similar thickness (Preiss, 1972, fig. 14c)

extracellular polymeric substances (EPS): A term for 'molecules having a range of sizes, compositions, and chemical properties that are produced and secreted by bacteria and other microorganisms, and contribute to the cell adaptability, resiliency, and functional roles in the environment' (Decho, 2011, p. 359). Composed primarily of polysaccharides and proteins, but includes other molecules. EPS binds the microorganisms in biofilms (Wingender et al., 1999; Krumbein et al., 2003)

f

fabric (of microstructure): The 'orientation (or lack of it) of discrete particles, crystals and cement...' (Neuendorf et al., 2011, p. 227). Planavsky and Ginsberg (2009, p. 8) used the term fabric to cover several observational scales and not at the microscopic or hand lens (loupe) scale traditionally used in sedimentology. Bertrand-Sarfati and Walter (1981, p. 355) referred to the combination of lamina shape and microstructure as 'fabric'. More recently, Harwood (2009) referred to composite fabric as a mixture of mesofabric types, such as mesoclots and laminae and their intergradation, although use of fabric in this way is questionable as fabric is a microstructural feature and a component of texture. It is difficult to reconcile these different viewpoints. It is better to restrict the use of the term to its sedimentological meaning of Neuendorf et al. (2011). Several authors used the terms **microfabric** (Leinfelder et al., 1993, p. 200), **mesofabric** (Ibarra et al., 2014, p. 1) and **macrofrabric** (e.g., Braga et al., 1995, p. 347). Macrofabric and mesofabric should be referred to as mesostructure. **Fabric** and **microfabric** are synonomous

false branching: (obsolete term) Previously used for a combination of alpha branching (branching mode) and parallel branching (angle of divergence), but these characteristics are best described independently

fascicle: A term for 'a group of columns which have a common point of origin, have developed by branching, and which have only minor variation in fabric throughout the structure' (Grey, 1984, p. 4)

fastigiate: A branched microbialite whose branches are parallel or near parallel to the main column and taper towards the top

fenestra: A small cavity or void, either open or filled with cement or secondarily introduced sediment. The use of **fenestrae** for mesoclots (Pratt and James, 1982) was rejected by Shapiro (2000)

fibrous (of microstructure): A microstructure composed of fibrous crystals, which in a stromatolite are oriented normal to the lamina surface, or may consist of radiating crystals (see Hofmann and Jackson, 1987)

filial branches (of branched): A generalized term for branches that are derived from a single column or single branch. Avoid gender specific terms by using **parent** and **filial** rather than mother and daughter

film bounded (of lamina alternation): One of the laminae in a couplet (usually the dark one) consists of a thin film and may have a finer texture than the other lamina. Typically, a film-bounded microstructure consists of a light lamina with a sharp lower boundary and coarse-grained texture, which grades upward into a much thinner, fine-grained, dark lamina with a sharp, and often irregular, undulose, or wispy upper boundary. This type of alternation gives rise to **filmy architecture**

filmy (of laminar architecture): Architecture characterized by regularly alternating laminae of very different thicknesses (Bertrand-Sarfati, 1976, p. 253). Thick, usually lensoidal, light laminae (sometimes consisting of clear spar or microspar) are bounded on the upper surface by a very thin (a few micrometres thick), dark, micritic film (see text for more detailed description). Also referred to as **film microstructure**. The preferred term is **filmy architecture**

fimbriate (of ornament): A term for fringes or lips that hang downward from the surface of a microbialite (Hofmann, 1969a, fig. 12, p. 18)

fine-scale microstructure: Microstructure at the electron microscope level of investigation (Planavsky and Ginsberg, 2009, p. 8)

flat (of lamina profile): A horizontal, continuous lamina, also referred to as **planar** (obsolete term); however, planar implies no irregularities (shale is planar laminated), so the term should be avoided. Similar to **flat laminated**, **planar laminated**. The preferred term is **planar**

flat laminated: (obsolete term) A 'non-columnar stromatolite with flat continuous laminae' (Preiss, 1972, p. 93). The preferred term is **stratiform**

form: see **Form**

Form: In microbialite taxonomy, an artificial taxonomic rank equivalent to species. Also referred to as **form**, **form species** and **morphospecies**. The preferred term, as discussed in the text, is **Form**

fragile (of bridges): (obsolete term) A structure formed by one or a few laminae that cross the interspace and connect with adjacent head or column. The preferred term is **delicate**

fragmentary ribboned (of laminar architecture): (obsolete term) The preferred term is **streaky**

framestone (microbial): Rock 'composed of a framework formed…either as a result of biologically influenced calcification or (rarely) from microbial skeletal material (Skeletal Microbial Framestones)' (Burne and Moore, 1987, p. 243)

framework: 'The rigid, wave-resistant, calcareous structure built by sedentary organisms' (Neuendorf et al., 2011, p. 253). A term for 'organically constructed, mineralized masses that build reefs' (Turner et al., 2000, p. 89). In terms of microbialites, masses include stromatolites, skeletal stromatolites and thrombolites (Turner et al., 2000, p. 89)

***Frutexites* microstructure:** A microstructure composed of an iron-rich, dendritic microfossil (*Frutexites* spp.) (Maslov, 1960; Rodríguez-Martínez et al., 2011). Walter and Awramik (1979) described *Frutexites* that were composed of organic material. The stromatolite *Frutexina* is composed of the microfossil *Frutexites*

furcate (of branching style): Branching 'in which columns branch into smaller ones without increase in total width of the structure' (Hofmann, 1969a, p. 17, fig. 10). Furcate is now used to refer to an equal subdivision, and can be further refined by the use of terms such as **bifurcate**, **trifurcate** and **multifurcate**. In part, this was previously referred to as **passive** or **false branching**. Most furcate branching is **alpha parallel**

g

gamma (of branching mode): Branching in which the parent column widens abruptly before branching

geniculate (of lamina shape): (obsolete term) An inflexed lamina with a pointed crest which is convex on either side of the crest (Hofmann, 1969a, fig. 8, p. 14). The preferred terms are **angulate**, **convex conical** or **convex crested lamina**

gently convex (of lamina profile): A lamina with a 'ratio of height to diameter less than or equal to 0.5' (Preiss, 1972, p. 93)

geyserite: An 'opaline silica deposited nonbiologically within and around hot springs and geysers' (Walter 1976c, p. 111). May be partly biogenic

gigamicrobialite (of microbialite size): Microbialite structures >100 m in size (Hofmann, 2000, fig. 4, p. 322). The size terminology has not been widely used

globoidal (of lamina shape): Lamina (or laminae) which partly (penecinct) or completely (plenicinct) encloses a body, as in an oncoid (Hofmann, 1969a, fig. 8, p. 14). The preferred terms are **penecinct** or **plenicinct**

gnarled column: A 'column with large bumps' (Preiss, 1972, p. 93; Walter, 1972, p. 13) (rarely used)

granular (of microstructure): A microstructure composed of silt-sized or larger allochthonous sediment incorporated into the microbialite

Group: In microbialite taxonomy, an artificial taxonomic rank equivalent to genus. Also referred to as **group**, **form-genus** and **morphogenus**. The preferred term is **Group**

growth direction: See attitude

grumeau (pl. grumeaux) (of microstructure): (obsolete term) A term for 'elongate to equant patches of micrite, typically 50–100 µm across, with diffuse boundaries that grade, over 10–20 um, into surrounding, inclusion-rich microcrystalline cement' (Turner et al., 2000, p. 90). Grumeau is equivalent to clot or clump (Bathurst, 1971, p. 512). See also **miniclot**. The preferred term is **grumous**

grumelous (of microstructure): (obsolete term) The preferred term is **grumous**

grumous (of microstructure): A microstructure composed of micritic peloids or clots (commonly between 0.1 and 0.5 mm diameter) that can be clumped together in an irregular manner, with interparticle and fenestral pores

h

harmonized (of lateral continuity): (new term) Laminae in one column can be matched with corresponding laminae in neighbouring columns but the laminae do not necessarily extend across the interspace area. Sometimes they can be traced, but are usually fainter than in the columns. Also referred to as **matched**, **coordinated** and **synchronized**. Laminae that are not matched across adjacent columns can be referred to as **discordant**. The preferred term is **harmonized**

head: A term applied to an individual microbialite. There is no unambiguous term for an individual component of a bioherm or biostrome, although Hofmann (1969a, p. 3) pointed out that Kalkowsky (1908) used stromatoid to mean 'the individual laminated structure making up the bioherm or biostrome', and this has been one of the more widely accepted usages. The structure has also been referred to as a **calyptra** (Luchinina, 1973; Zhuraleva and Miagkova, 1977), **coenoplase**, and an **individual**. The preferred term is **head**

height-to-width ratio (of column or branch): The relative height of the growth vector that joins the mid-points (centres) of successive laminae; modified after Hofmann (1969a, p. 17), who defined it as 'the upward maintenance or duration of the stacking process'. Note this is best applied to columnar and domical microbialites. Also referred to as **elongation** or the **accretion vector** (obsolete terms). Types of **height-to-width ratio** include **crustose**, **stubby** and **slender**

heliotropism: 'Tropism (qv.) in which the stimulus is sunlight' (Walter, 1976d, p. 690)

hemispherical (of domical microbialites): A microbialite or bioherm that is equal in height and width, with the plane of maximum width at the base

heterogeneous (of lateral continuity): The nature of the lamination is different at the margins and in the centre of the the microbialite (a characteristic that can also be considered a feature of the microstructure). The thickness can also be variable

high (of degree of inheritance): A term used where most laminae conform to the shape of the underlying laminae

high synoptic relief: A lamina in which W << H, where W is the width of the lamina shape and H is the relief of the lamina, modified from Hofmann (1969a, p. 17 and fig. 13)

horizontal (of angle of divergence of branches): Branches that diverge perpendicularly to the axis of growth, with or without increase in the width of the parent column

horizontal (of clot orientation): Parallel to subparallel horizontal patterns within a thrombolite (Armella, 1994). The major axes of the clots lie horizontal or at an oblique angle to the vertical

horizontal (of growth attitude): A term referring to the attitude of growth of a column in which the column grows parallel to the horizontal (bedding) (Hofmann, 1969a, fig. 13). The preferred term is **prostrate**

hybrid stromatolite (microbialite): Alternations of a uniformly thick abiogenic crust or layer of sparry or fibrous minerals with an uneven layer of fine-grained, lithified microbial mat (Riding, 2008, p. 73; 2011a, p. 638)

hypidiotopic (of texture): 'A texture intermediate between xenotopic and idiotopic' (Preiss, 1972, p. 93; Walter, 1972, p. 13)

hyponastic (of attitude): (new term) A column that initially lies parallel (prostrate) to the substrate but then bends upward producing an inclined to erect tip; the initial stage may even dip below the horizontal. Replaces **decumbent** (obsolete term, see discussion in text). The preferred term is **hyponastic**

i

idiotopic (of texture): 'A texture in which the mineral grains are bounded by crystal faces' (Preiss, 1972, p. 93; Walter, 1972, p. 13); i.e. mineral grains are euhedral

inclined (of attitude): In which columns are straight but at an acute angle to the vertical

inclined conical (of conical microbialites): Any conical microbialite where the axis of the cone is tilted at an angle to the substrate

individual: A general term for a single discrete microbialite that is either isolated or a discrete structure within a group of microbialites. Also referred to as a **stromatoid**, **head** or **calyptra**. If individual is used, it should be as an adjective (e.g. individual structure). The preferred term is **head**

inflated (of lamina shape): Sometimes used for a **plenicinct** lamina. The preferred term is **plenicinct**

inflexed (of lamina shape): A laminar profile that is reflexed to form a crest. It can be **angulate**, **geniculate** or **cuspate** (Hofmann, 1969a, fig. 8)

informal classification: A non-taxonomic approach to classifying microbialites. An example would be the descriptive formulae of Logan et al. (1964)

inheritance: See **degree of inheritance**

interlobate (of texture): (obsolete term) 'A texture in which the intergrain boundaries are wrinkled' (Walter, 1972, p. 13)

interspace: The area between buildups, bioherms, domes, columns, cones, branches, heads, and oncoids

interspace filling: The material that occupies the **interspace**

intertonguing (of bioherms): A bioherm whose 'margins intertongue with the surrounding rock' (Walter, 1972, p. 14, under tonguing bioherm). Also referred to as **tonguing**. The term **intertonguing** is preferred

irregular (of lamina thickness): A lamina in which the lamination extends continuously and the lithology is consistent, but the thickness varies irregularly across the microbialite

irregular (of lateral continuity): A lamina in which the lamination extends continuously and the lithology is consistent, but the thickness varies irregularly across the microbialite

irregular (of streaky laminar architecture): A subsidiary type of streaky architecture, in which laminae are discontinuous and have jagged margins (Walter 1972, p. 12). Also referred to as **fragmentary ribboned** (Hofmann, 1969b, fig. 9)

irregularly spaced (of branching): Branching with unequal distances between branches

isolated (of spacing): Microbialites that are spaced at distances much greater than the widths of the structures, or are the only microbial structures present

isopachous: all laminae are of equal thickness along their full length

isopachous stromatolite: Using a descriptive (non-genetic) definition of stromatolite, this refers to stromatolites with isopachous laminae produced 'by chemogenic precipitation in the absence of microbial mats' and which are, therefore, abiotic (Pope et al., 2000, p. 1139)

l

labyrinthine (of plan view): A type of plan view in which columns consist of convoluted ridges separated by maze-like interspaces; used for microbialites that are **maceriate** in plan view and that have a **cerebroid** surface. Maceriate is the preferred term

lamella (of couplet): A single component (layer) of a couplet or doublet (lamination) in a stromatolite (Hofmann 1969a, p. 4)

lamina: 'The smallest unit of layering' of a stromatolite (Preiss, 1972, p. 93; Walter, 1972; p. 13)

laminar alternation: A term for the variation in texture and microstructure between successive laminae. This commonly refers to the alternation of light and dark laminae (couplets) but other combinations are possible. Types of lamina alternation include **even**, **composite**, **film bounded** and **void intercalated.** Also referred to as **alternating lamination** (obsolete term). The preferred term is **laminar alternation**

laminar architecture: The 3D structure of a lamina and its relationship to underlying and overlying laminae. Most descriptions and measurements are based on examination of the 2D laminar profiles. The characteristics of laminar architecture depend on the shape, lateral continuity, nature of boundaries, and stacking of individual laminar elements. Types of laminar archtecture include: **banded**, **filmy**, **striated**, **streaky**, **tussocky**, **pillared**, **vermiform** and **alveolar**

laminar inheritance (of laminae): See **degree of inheritance**

laminar profile: The 2D expression of the 3D laminar shape (see text). Types of laminar shape include: **concave**, **flat**, **gently convex**, **steeply convex**, **parabolic**, **penecinct**, **plenicinct**, **rectangular**, **rhombic**, **conical** and **angulate**

laminar shape: The 3D configuration of a lamina, usually inferred from the **laminar profile**

laminar type: (obsolete term) A term used by Hofmann (1969a, p. 15) in discussing laminar profile; see **laminar waviness**

laminar waviness: The degree of evenness of the laminae and an indicator of secondary curvature. Types of waviness include: **smooth**, **wavy** and **wrinkled**. Other terms used to refer to waviness, especially where it is less regular, include seldom used or obsolete terms: **crinkled**, **corrugate**, **crenate**, **crenulate** and **dentate**

lanceolate (of thrombolite clot shape): A mesoclot with one axis significantly greater than the other and terminating in pointed tips

lanceolate (of plan view): Shaped like a lance

lateral (of branching style): Branching in which a filial column develops on the side of the main column and commonly has a smaller width than the parent column

lateral continuity (of stromatolite laminae): A term referring to the degree of connection of the laminae across a microbialite and their variability in thickness and the uniformity of the lithology. Types of lateral continuity include: **continuous**, **discontinuous**, **lenticular**, **microcross-laminated**, **irregular**, **heterogeneous, harmonized** and **discordant**

laterally linked (of microbialites): '[W]ith wavy laminae continuous between crests' (Walter, 1972, p. 13). Refers to microbialites that are linked (connected) laterally with one another. Linkage between adjacent bioherms or adjacent heads. Types of lateral linkage include: **linked**, **locally linked, sporadically linked** and **unlinked**. The preferred term is **linkage**

laxilobate (of plan view): A branch or column cross-section in which adjoining lobes are divergent. Types of laxilobate plan view include: **bilobate**, **trilobate** and **multilobate** (Hofmann, 1969a, p. 14, fig. 8)

layered (of microbialite of stromatolite): A microbialite, with little or no positive relief; generally planar and laterally continuous. This has also been referred to as **stratiform** in the case of stromatolites. Types of layered microbialite include: **stratiform** (**flat laminated**, **planar laminated**), **encrusting**, **undulatory**, **linked**, **pseudocolumnar**, **linked columnar**, **columnar layered**, **pseudocolumnar** and **linked conical**. The preferred term is **layered**

layered columnar (of layered microbialites): (obsolete term) A stromatolite with short columns alternating with layered stromatolites. Also referred to as **linked columnar** or **columnar layered**. The preferred term is **linked columnar**

leiolite (of microbialite subset): A 'microbial deposit with a structureless macrofabric' (Braga et al., 1995, p. 347). A slightly expanded version appeared in Riding (2000, p. 195) as 'a relatively structureless, aphanitic, macrofabric lacking clear lamination, clots, or dendritic fabrics'. In handbook terminology, **macrofabric** equates with **mesostructure**. A **mesostructureless microbial boundstone** would also be a **leiolite**

lenticular (of lateral continuity): The lamination extends continuously and the lithology is consistent, but the thickness varies considerably across the curvature

linear (in plan view): A buildup, column or branch in which one axis is narrow and the other axis extends for many times the width of the narrower one. Also referred to as **elongate**, **seif** and **longitudinal** microbialites. The preferred term is **linear**

linkage (of spatial relationships): The degree of lateral connection between microbialites. Types of linkage include: **linked**, **locally linked**, **sporadically linked** and **unlinked**

linked (of linkage): Lateral connections are present between all or most microbialites

linked (of microbialites): Microbialites with lateral connections between all or most of the structures

linked columnar (of layered microbialites): A stromatolite with short columns alternating with layered stromatolites. Also referred to as **columnar layered** or **layered columnar** (obsolete terms). The preferred term is **linked columnar**

linked conical (of layered microbialites): Linked-conical structures have circular, oblong, elongate, ovoid, or star-shaped plan views. The name *Conophyton* is reserved for **cylindrical-conical** or **coniform stromatolites** with an **axial zone**

linked cumulate: A type of linked microbialite involving domical microbialites, often with bulbous domes

lithoherm: See **microbial lithoherm**

lithostrome: See **microbial lithostrome**

lobate (of thrombolite mesoclot shape): A mesoclot with several protrusions of the margin (Kennard, 1994, fig. 7E)

lobate (of plan view): An irregular outline with varying types of lobes. Types of lobate plan view include **laxilobate** (**bilobate**, **multilobate**), **densilobate** or **brevilobate** (Hofmann, 1969a, p. 14, fig. 8)

lobate (of ornament): A protrusion hanging downward from the margin of a microbialite. Similar to fimbriate, but with a more rounded appearance

locally linked (of linkage): Some adjacent microbialites are linked laterally whereas others are unlinked. Sometimes referred to as **laterally linked**, but this term can apply to other forms of linkage. The preferred term is **locally linked**

loferite: Term coined by Fischer (1964, p. 128) for 'carbonate sediment riddled by shrinkage pores. Partly synonomous with "birdseye limestone"'. Commonly occurs with stromatolites and mudcracks (Shinn, 1983, p. 622)

longitudinal (of plan view): A microbialite elongated in the direction of wave translation (Playford et al., 2013, p. 211). See also **linear**, **elongate** and **seif stromatolite.** The preferred term is **linear**

low (of degree of inheritance): A term used where successive laminae rarely conform to the shape of the underlying laminae

low (of synoptic relief): A profile of a lamina in which W >> H, where W is the width and H is the height of the lamina, modified from Hofmann (1969a, p. 17 and fig. 13)

M

maceriate microbialite: A microbialite that forms maze-like, linear ridges (Shapiro and Awramik, 2006, p. 412) and has a **labyrinthine** plan view and **cerebroid** surface view

macroclot (of thrombolite mesostructure): (obsolete term) Macroscopic clots (Pickard, 1996, p. 68). Has been used for several diffent clot types. The preferred terms are **maxiclot** and **mesoclot**

macrofabric (of mesostructure): Riding (2011a, p. 636) used macrofabric in the same sense that mesostructure is used in this handbook to identify different types of microbialite (Fig. 1). Because we recommend that the term **fabric** only be used in the sedimentological (microstructural) sense, the term macrofabric should not be used. The preferred term is **mesostructure**

macrolamina (of lamina stacking patterns): Any higher order pattern of banding produced by a grouping of laminae (see text). 'A distinct set of laminae' (Preiss, 1972, p. 93; Walter, 1972, p. 13)

macromicrobialite (of microbialite size): A microbialite between 10 and 100 cm in size. This size terminology has not been widely used

macroscopic clotted fabric (of mesostructure): (obsolete term) A term used by Aitken (1967, p. 1164) for **mesoclot**. The preferred term is **mesoclot**

macrostructure: The features of the gross morphology of the individual microbialite. **Macrostructure** is intermediate between **megastructure** and **mesostructure**

mantle: (obsolete term) A term introduced by Raaben (1964, p. 93) for an unlaminated coating on the margin of a column. See also Komar et al. (1965a, p. 18). Similar to **selvage** (which can refer to a micritic coating) and **rind** (which includes any kind of microbialite coating). The preferred terms are **selvage** or **rind**

markedly divergent (of angle of divergence of branches): A form of branching in which filial branches diverge at broad angles (greater than 45°), with or without increase in the width of the parent column

massif (of branched microbialites): A term introduced by Bertrand-Sarfati (1972b, p. 47) to refer to closely spaced fascicles

massive (of bridging): A structure comprising numerous laminae that connect adjacent microbialites

massive cryptalgal fabrics: A structure where there is no internal lineation or spatial organization of the constituent elements (Monty, 1976, p. 235). Monty's description seems to be at both the microstructural and mesostructural level. The preferred term is **leiolite**

massive microstructure: A term where the microstructure 'consists of homogenous micrite or neomorphic microspar' (Kennard, 1989, p. 62) in a stromatolite or thrombolite. Seemingly equivalent terms have been suggested, including: '**massive cryptalgal fabrics**' (Monty, 1976, p. 235), '**undifferentiated microbial boundstone**' (Kennard and James, 1986, p. 492) and '**structureless microbialites**' (Siahi et al., 2016, p. 259)

mat-induced sedimentary structures: Sedimentary structures that reflect microbial mat deposits in siliciclastics (Schieber et al., 2007b, p. 1). See **MISS**

matched (of lateral continuity): (obsolete term) Laminae in one column can be matched with laminae in neighbouring columns, but laminae do not extend across the interspace area. The preferred term is **harmonized**

matground: The microbially stabilized upper few millimetres of sediment producing an erosion-resistant, leathery layer (Seilacher et al., 1998; Pflüger, 1999). The term was introduced by Seilacher and Pflüger (1994, p. 101) but not defined. The preferred term is **MISS**

mat topography: The mesostructure in extant microbial mats (Bauld et al., 1992, p. 262). The topography of the surface of a microbial mat (Jorgensen et al., 1983, p. 1083)

maxiclot (of thrombolite mesostructure): (new term) The amalgamation of several **mesosclots** into a larger structure at the centimetre scale

megamicrobialite (of microbialite size): A microbialite between 1 and 100 m in size. The size terminology has not been widely used

megastructure: Large-scale aspects of microbialites and the beds in which they occur; commonly at the metre to kilometre scale

mesoclot (of thrombolite mesostructure): '[T]he mesostructural component of thrombolites' (Shapiro, 2000, p. 169). Mesoclots are millimetre- to centimetre-size spheroidal to polylobate masses composed of one to a variety of components (peloids, cement, grumeaux, calcimicrobes) within the groundmass of the unlaminated microbialite

mesofabric (of mesostructure): Use mesostructure. Fabric is a microstructural feature

mesomicrobialite (of microbialite size): A microbialite between 1 and 10 cm in size. This size terminology has not been widely used

mesostructure: Intermediate-scale features (between macrostructure and microstructure) that comprises the internal structure visible to the unaided eye. It is at this level that thrombolites, dendrolites, and leiolites show their distinction from stromatolites

micrite (of microstructure): Fine gained carbonate crystals or particles, usually 4 µm or less in size. An abbreviation for microcrystalline calcite (Flügel, 2004, p. 74)

micritic (of microstructure): A microstructure consisting of structureless micrite, 4 µm or less in size (Folk, 1959), which may be the principal component of a lamina or comparable structure

microbe, microbial: Referring to microbes. A non-specific term useful for describing mixed assemblages of bacteria, algae, and other microscopic organisms. Should be used instead of **algal** unless referring specifically to algal eukaryotic assemblages

microbial boundstone: A rock 'formed principally by microbial trapping and binding of detritus' (Burne and Moore, 1987, p. 242)

microbial buildup: A term used by Heckel (1974) to avoid the implications of positive relief or genetic origin associated with the term 'reef'. See also Grey (1984) and Burne and Moore (1987). A good, general term for a structure of microbial origin with positive relief

microbial carbonate: A term used for 'precipitates formed in situ directly or indirectly by the physiological activity of benthic microorganisms' (Mancini et al., 2013, p. 1836)

microbial earth: A 'terrestrial ecosystem of microscopic organisms in well-drained soils' (Retallack, 2012, p. 139)

microbial framestone: A rock 'composed of a framework formed either as a result of biologically influenced calcification or (rarely) from microbial skeletal material (Skeletal Microbial Framestones)' (Burne and Moore, 1987, p. 243)

microbial lithoherm: Microbially influenced, nonskeletal cementation producing a buildup. Burne and Moore (1987, p. 247) distinguished between buildups produced by skeletal organisms and those microbially produced. The preferred term is **bioherm**

microbial mat: Bauld (1981, p. 88) used the term for 'discrete benthic structures constructed by microorganisms (eukaryotic and prokaryotic; photosynthetic and nonphotosynthetic), the term "algal mat" for those structures whose prime determinant is eukaryotic (e.g. diatoms), and the term "cyanobacterial mat" for those constructed by the prokaryotic cyanobacteria'. '[C]omplex microbial communities that are composed of many kinds of cells (from all three domains of life), sometimes in a layered association with cells surrounded and trapped with biologically produced extracellular polymeric substances (EPS)' (Spear and Corsetti, 2013, p. 557). A single to multilayered microbial system living at the sediment-fluid interface that forms a cohesive, carpet-like construction, often stabilizing sediment; see discussion in Krumbein et al. (2003, p. 11–16). The term should be limited to living mats

microbial speleothems: See **speleothem** and **cave stromatolite**

microbial tufa: A rock 'formed when microorganic material is incorporated during inorganic precipitation of carbonate' (Burne and Moore, 1987, p. 243). See also Das and Mohanti (1997). The preferred term is **tufa microbialite**

microbialite: 'Microbialites are organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation' (Burne and Moore, 1987, p. 241–242)

microbialite margin: The outer boundary of a columnar or domical microbialite and its associated features, including the wall if present (see text). Also referred to as the **column margin**. See also **column-surface characteristics**, **ornament** and **wall**. The preferred term is **microbialite margin**

microbialite shape (of spatial relationships and interconnections): The shape of a microbialite. The following types are recognized: **planar**, **domical**, **columnar**, **conical**, **branched** and **compound**, **maceriate**, **tubestone** and **oncoid**

microbially induced sedimentary structures (MISS): A term used for sedimentary 'structures and textures in siliciclastic sediments [that] can be related to microbial activity' (Noffke et al., 1996, p. 315) (see text)

microbioherm: (obsolete term) '[H]and-specimen sized bioherm formed by the coalescing of individuals' (Walter, 1972, p. 13). The preferred term is **fascicle**

microbiota: 'A localized group of microscopic organisms that comprise a biocoenose, used especially in reference to communities of fossil microorganisms that occur within a stromatolite or a particular stromatolitic horizon' (Schopf, 1983b, p. 451–452)

microbolite: A term proposed as being more semantically correct than microbialite (Riding, 1991, p. 27). The preferred term is **microbialite**

microclot: small, 50–500 µm individual clots in a thrombolite (Harwood and Sumner, 2012, p. 713). Preferred term is **miniclot**

microcross-laminated: (of lateral continuity): Lamination that does not extend from one side of the structure to the other, but forms a series of discontinuous and offset lenses that may be truncated by succeeding laminae; the lithology within the lenses is consistent. Also referred to as **offset lenticular** and **offset lensoid**. The preferred term is **microcross-laminated**

microdigitate (of branching style): Although visible with the unaided eye, a general term for any small (one to several millimetres diameter), columnar stromatolite (synonymous with **ministromatolite**) (Grotzinger and Reed, 1983, p. 712; Grotzinger, 1986a,b; Hofmann and Jackson, 1987, p. 963). Some microdigitate stromatolites have been called **microdigitate tufa** (Grotzinger, 1986a, p. 1215; Sami and James, 1996, p. 216). One of the more specific terms for branching style is preferred

microfabric (of microstructure): See **fabric**

microfossiliferous (of microstructure): Refers to a microstructure or portions of a microbialite composed of recognizable microbial elements, such as calcimicrobes or in the case of silicified microbialites, organically preserved microfossils (Schopf and Sovietov, 1976; Schopf et al., 1977; Awramik and Semikhatov, 1979; Cao and Yin, 2011)

micromicrobialite: A microscopic microbialite

microphytolite: A general term for **oncoids** and **catagraphs** (Walter, 1972, p. 13; Knoll, 1985, p. 398)

microspar (of microstructure): A calcite matrix composed of 'uniformly sized and generally loaf-shaped crystals ranging from 5 to more than 20 micrometers in diameter' (Neuendorf et al., 2011, p. 413). The term was introduced by Folk (1959, p. 1) for crystal sizes between 5 and 15 µm and later set an arbitrary upper boundary of 30 µm (Folk, 1965, p. 37). The size range of microspar varies with authors (Tucker and Wright, 1990, p. 15). Much or most microspar forms as a result of the recrystallization of micrite-sized calcite or aragonite crystals (Flügel, 2004, p. 76)

microsparite: 'A term used by Folk (1959, p. 32) for a limestone whose carbonate-mud matrix has recrystallized to microspar' (Neuendorf et al., 2011, p. 413) (Figs 162b, 164). Technically this is a rock term, but has been used interchangeably with microspar (Riding and Tomás, 2006, p. 23)

microsparry (of microstructure): A microstructure composed of microspar

microstromatolite: A columnar stromatolite with a column width from c. 20 to 200 µm (Hofmann and Jackson, 1987, p. 963; Raaben, 1998; Tewari, 2001). Any microscopic stromatolite

microstructure: A term restricted to those features best studied under the microscope and including texture, fabric and microfossils, and microorganisms if present. Preiss (1972, p. 93) defined microstructure in relation to stromatolites as 'The fine-scale structure of the stromatolite lamination, in particular the distinctness, continuity, thickness and composition of the laminae'. Because lamination and mesoclots are visible to the unaided eye, they are here included in mesostructure, although details may not be visible without magnification. Types of microstructure include: **micritic**, **microsparry**, **peloidal**, **granular**, **spherical**, **fibrous**, **tubular** and **microfossiliferous**. Microstructure at the electron microscope level of investigation has been called fine-scale microstructure (Planavsky and Ginsberg, 2009, p. 8)

micro-unconformity (of lateral continuity): Used for a 'surface of lamination discordance due to penecontemporaneous erosion within a stromatolite' (Preiss, 1972, p. 93). Also defined as a 'surface of lamination discontinuity within a stromatolite' (Walter, 1972, p. 13). Also referred to as **offset lenticular**, **offset lensoid** or **microcross-laminated**. The preferred term is **microcross-laminated**

miniclot (of thrombolite mesostructure): Millimetre or smaller clot that is a constituent of a **macroclot** or is an isolated clot

minimicrobialite: Microbialites that have widths between 1 and 10 mm. Visible at the mesostructural level, although details may only be visible microscopically. Similar to **microdigitate.** One of the more specific branching style terms is preferred

ministromatolite (of branching style): Although a term used by Hofmann and Jackson (1987, p. 963) for columnar stromatolites with columns between 0.2 and 20 mm in width, we prefer to restrict this term to widths from 1 to 10 cm. Visible at the mesostructural level, although details may only be visible microscopically. Similar to **microdigitate** and **microstromatolite** (Raaben, 1998). One of the more specific branching style terms is preferred

MISS (of microbialite subset): See **microbially induced sedimentary structure**

modality (of lamina profile): The number of crests in a lamina profile. Types of lamina profile include **unimodal**, **bimodal**, **multimodal**, **symmetrical** and **asymmetrical**

mode of branching: A term referring to the changes, if any, in the parent column just before branching. It can be alpha, beta, or gamma. The term **branching mode** is preferred

mode of occurrence: The gross manifestation of a microbialite and its spatial relationships. Features such as **reefs**, **mounds**, **buildups**, **bioherms** and **biostromes** are elements of **mode of occurrence**

moderate (of synoptic relief): A measure of lamina amplitude in which W ≈ H, where W is the width and H is the height of the lamina. Modified from Hofmann (1969a, p. 17 and fig. 13)

moderate (of degree of inheritance): A term used where some, but not all, laminae conform to the shape of the underlying laminae

moderately divergent (of angle of divergence of branches): Branching in which the filial columns diverge at acute angles (less than or equal to 45°), with or without increase in the width of the parent column

multifurcate branching (of branching style): Branching in which columns divide into more than three smaller (filial) columns without increase in the total width of the parent column. Also referred to as **umbellate** (obsolete term). The preferred term is **multifurcate**

multilaminate (general term): Refers to having many laminae

multilaminate wall: A wall in which several laminae overlap the microbialite margin and continue parallel to each other, coating the sides of the microbialite over most of its length

multilobate (of plan view): A form of laxilobate plan view with numerous lobes (Hofmann, 1969a, fig. 13)

multimodal (of lamina profile): A lamina having more than two crests

N

naked (of head): A term meaning ‘without walls’ (Walter, 1972, p. 13). The preferred term is **unwalled**

niched (of ornament): A term for vertical, or near vertical, elongate depressions at the column margin that extend into the column

nodular (of bioherm or head shape): A domical microbialite (bioherm) that is generally equal in height and width with the plane of maximum width generally at mid-height. The width of the base is much less than the maximum width and the structure may be almost, but not quite, detached from the substrate

non-binomial nomenclature: Any method of naming specimens which does not follow Linnean taxonomy, which assigns a specimen a latinized name consisting of two parts

non-couplet (of lamina patterns): A set of laminae where there is no simple alternation of dark and light laminae. Additional types of lamina are interspersed between the light and dark. Types of non-couplet include: **even**, **composite** and **void intercalated**

non-laminated (of stromatolites): Usually refers to a **thrombolite**, but can also be a **dendrolite**, **leiolite** or **microbial boundstone**

non-tabular (of biostrome shape): A biostrome with clearly defined margins, with an undulating or irregular upper surface

non-tabular biostrome: A biostrome with an undulating or irregular top

non-uniformly wavy-ribboned (of laminar architecture): (obsolete term) (Hofmann, 1969b, fig. 9). The preferred term is **striated**

normal (of attitude): A term used for a column that is perpendicular to the bedding, in which the columns are straight and vertical. The preferred term is **erect**

normal (of clot orientation): The major axes of the mesoclots lie parallel to the thrombolite growth axis and generally normal to the inferred bedding

nuclear stromatolite (of domical microbialites): A specific type of nodular or domical stromatolite in which the nucleus of the structure and the peripheral laminae differ from one another in texture and microstructure (Raaben et al., 2001, p. 66)

O

oblong (of plan view): A cross-section of a column or branch in which one diameter is much greater than the other, and is longer than in an **ovate** plan view

oblong (of thrombolite clot shape): A mesoclot with one diameter much greater than the other

obscure (of lamina): Where laminae are poorly preserved or have undergone secondary alteration so that they are nearly obliterated (Hofmann, 1969a, fig. 8)

offset lensoid (of lateral continuity): A term for lamination that does not extend from one side of the stromatolite to the other, but forms a series of discontinuous and offset lenses that may be truncated by succeeding laminae; the lithology within the lenses is consistent. Also referred to as **microcross-lamination** and **offset lenticular**. The preferred term is **microcross-lamination**

offset lenticular (of lateral continuity): (obsolete term) See offset lensoid. The preferred term is **microcross-lamination**

oncoid (of microbialite shape): Unattached, generally spherical to ovoidal, stromatolite with a cortex of encapsulating or nearly encapsulating laminae. The term was coined by Heim (1916). In principle, it could refer to a spherical to ovoidal, unattached structure of microbial origin that is not laminated

oncoidal microbialites (of microbialite shape): A term for spherical to ovoid microbialites that are completely detached from the substrate and are commonly laminated

oncolite: A rock composed of oncoids

open nomenclature: A method of dealing with microbialites whose identity cannot be precisely determined (Matthews, 1973, p. 713) that either makes reference to an existing taxon using ‘aff.’, ‘cf.’, ‘?’, or ‘Form 1, 2’ etc. (Bengtson, 1988, p. 224), or does not use the formal method of binomial nomenclature, but makes use of terms such as ‘microbialite Form 1’ and is accompanied by a full description. See section on ‘Open nomenclature’

openly spaced (of spacing): Spacing between microbialites is about the same as the width of the structures

orientation (spatial relationships and interconnections): (obsolete term) The preferred term is **attitude**

ornament: An irregularity of a column margin, found on column surfaces, which has a consistent shape, and which in stromatolites results from the terminal development of the laminae. Types of ornament include: **smooth**, **bumpy**, **tuberous**, **fimbriate**, **lobate**, **peaked**, **corniced**, **ribbed**, **niched**, **with projections** and **bridged**

orthomicrite: 'Primary micrite that did not undergo subsequent changes, and micrite that is not the product of secondary processes…' (Wolf, 1965, p. 35)

orthostromatolite: (obsolete term) A laminated autochthanous microbial growth (Wolf, 1965, p. 5). The preferred term is **stromatolite**

ovate (of plan view): A buildup, column or branch that is regularly elliptical or oblong in shape; one diameter is much greater than the other

overlapped (of lamina): A term used where a single lamina overlaps the terminations of other laminae; in some cases with the overlap predominantly by light laminae and in others predominantly by dark laminae

P

palimpsest microstructure: A term derived from a word meaning something reused or altered but still bearing visible traces of its earlier form and applied to traces of previous microbial structures (Schopf and Walter, 1982, p. 558). 'Microstructure in a stromatolitic [microbialitic] sediment in which the distribution of kerogen, iron oxide, pyrite, or some other pigmenting material indicates the former distribution of microbial remains' (Schopf, 1983b, p. 453)

parabolic (of lamina profile): 'A lamina whose axial longitudinal [usually the vertical] section approximates a parabola' (Preiss, 1972, p. 93). This includes curves designated as **acute** or **prolate** (obsolete terms) by Hofmann (1969a, p. 15, fig. 8). The preferred term is **parabolic**

parallel (of angle of divergence of branches): Branching where filial branches are parallel or subparallel to one another, with or without increase in the width of the parent column (Walter, 1972, p. 13)

parallel (of lamina stacking patterns): A term used where each lamina terminates against the column margin with no overlap

parataxonomy: The practice of sorting samples into recognizable taxonomic units, generally known as morphospecies (Krell, 2004, p. 795–796); an artificial classification that is suggested for certain common organisms of doubtful affinities, or as yet unknown origins (e.g. fossil spores, dinosaur footprints)

parent column (of branched): A generalized term for a single column that subsequently divides into filial columns. Avoid gender specific terms by using **parent** and **filial** rather than mother and daughter

partly linked (of linkage): (obsolete term) A term used for lateral linkage between microbialites that occurs intermittently throughout the vertical profile. The preferred term is **sporadically linked**

passive branching: (obsolete term) Branching 'in which columns branch into smaller ones without increase in total width of structure' (Hofmann, 1969a, p. 17–18, fig. 16). The term is abandoned in favour of alternative terminology dealing with the **branching mode** such as **alpha branching**; **branching style** such as **furcate**; and the **angle of divergence** ranging from **moderately** to **horizontally divergent**. Adapted from Walter (1972, p. 13)

patchy wall: A wall that covers short segments of a microbialite. It is the opposite of a **continuous wall**

peaked (of ornament): A term for protrusions with sharp points on the surface of a microbialite

pedestal (of bioherm shape): A bioherm with a tabular top and a narrow, stalked base

pelletal (of microstructure): (obsolete term) Pelletal is innapropriate because it is commonly used to imply the presence of faecal pellets. The grain should be called a peloid. The preferred term is **grumous**

peloid (of microstructure): A micritic grain commonly without internal structure, subrounded, spheroidal, or irregular in shape, usually between 20 µm and about 1 mm in diameter (Flügel, 2004, p. 100)

peloidal (of microstructure): Refers to a microstructure composed of peloids. Some examples are complex where peloids and clots are clumped together in an irregular manner with interparticle and fenestral pores between them. The preferred term is **grumous**

peloidal stromatolite: A 'stromatolite composed of peloidal, discontinuous lamination' (Pope et al., 2000, p. 1139). The preferred term is **grumous**

pendant (of column attitude): A column that has a downward accretionary growth habit (Rasmussen et al. 2009, figs 3, 4); particularly common in cavity fill stromatolites (Playford and Wallace, 2001, fig. 7D)

pendant (of thrombolite clot shape): The term has been used inconsistently; for example, the term as used by Kennard (1994, fig. 7B) describes a mesoclot with a flat surface that forms the upper margin and the lower margin is lobate. This seems to have little in common with the usage by Kahle (2001, p. 412) who regards pendant mesoclots as bushy and projecting 'downward from the ceiling of a buildup cavity'. We recommend following the usage of Kennard

penecinct (of lamina profile): A lamina that almost completely encloses a body. Such forms are also referred to as **nodular** with a narrow base, or as **pedestal** (Hofmann, 1969a, fig. 8). Hofmann (1969a) also referred to this as **globoidal** (obsolete term). The preferred term is **penecinct**

petaloid conical (of conical microbialites): A compound microbialite in which a central cone is surrounded by radiating outgrowths that are petal shaped in plan view and that widen outward from where the base of the petals are joined to the cone flank

petee structure: Undulating, wrinkled surfaces forming ridges produced by alternating wetting and drying of microbial mats as well as by wind and slope gravity (Gavish et al., 1985, p. 192). Superficially resembles tepee structures

picnostromic (of domical microbialites): Mound-like or cabbage-head-like stromatolites (Raaben et al., 2001, p. 5). The preferred term is **bulbous**

pillared (of stromatolite architecture): Small columnar structures normal to and usually within a single lamina. These commonly give rise to a distinctive wrinkle pattern that may just be visible as mesostructure (Allen et al., 2016, fig. 4C,E), but are more correctly classified as laminar architecture

pillared (of stromatolite microstructure): Pillar-like, sub-millimetre-size columns (some branching) observable at the microstructural level but giving rise to a distinctive wrinkle pattern at mesostructural level (Allen et al., 2016, fig. 4C,E). They can also be referred to as **micropillared**

pinnacle: A generally small, conical microbial structure; commonly used for microbial mats (pinnacle mat; Sumner et al., 2016). Synonymous with **conical stromatolite** (Walter et al., 1976; Petroff et al., 2010). See also **tuft**

pitted (of plan view): Circular to ovoidal shape in plan view of sediment filled, relatively deep, steep-sided depressions extending into the microbialite (see Bradley, 1929; Lamond and Tapanila, 2003)

pitted microbialite: A microbialite with numerous, relatively deep, steep-sided depressions extending into the microbialite and filled with sediment (see Bradley, 1929; Lamond and Tapanila, 2003). **Tubestone** is an extreme case, where pits are very deep, forming cylindrical, tube-like structures in the rock (Corsetti and Grotzinger, 2005; Bosak et al., 2013b)

plan outline (of microbialite macrostructure): The shape of the cross-section of the buildup, head, column, or branch when viewed in a plane at right angles to the growth direction. Sometimes referred to as **transverse section** or **cross-section**. Types of plan outline include: **circular** (**subcircular**, **round**), **ovate** (**elliptical**, **oblong**), **lanceolate**, **linear**, **pitted**, **labyrinthine**, **polygonal**, **scutate**, **crescentic**, **lobate**, **laxilobate (bilobate, multilobate)**, **densilobate** and **brevilobate**. The preferred term is **plan outline**

plan view (of microbialite macrostructure): The appearance or shape of a microbialite when viewed in a plane at right angles to the growth direction. This has also been called the **plan outline** (Hofmann, 1969a, fig. 8), but plan outline should be restricted to an outline because **plan view** refers to the whole structure. Sometimes referred to as **transverse section** or **cross-section**. Types of plan view include: **circular** (**subcircular**, **round**), **ovate** (**elliptical**, **oblong**), **lanceolate**, **linear**, **pitted**, **labyrinthine**, **polygonal**, **scutate**, **crescentic**, **lobate**, **laxilobate (bilobate, multilobate)**, **densilobate** and **brevilobate**. The preferred term is **plan view**

planar (of lamina profile): A 'non-columnar [stromatolite] with flat continuous laminae' (Preiss, 1972, p. 93); however, the laminae in some columns can be flat or nearly flat. Also referred to as **stratiform**, **flat laminated** or **planar laminated.** Laminae are continuous and almost flat and parallel. They are usually horizontal; although, when not horizontal, flat surfaces of **cavity-encrusting microbialites**, **endostromatolites** and **teicholites** can have planar lamina profiles

planar (of layered microbialite): Similar to **flat laminated**; a 'non-columnar [stromatolite] with flat continuous laminae' (Preiss, 1972, p. 93). The preferred term is **stratiform**

planar laminated (of layered microbialite): Similar to **flat laminated**; a 'non-columnar [stromatolite] with flat continuous laminae' (Preiss, 1972, p. 93). The preferred term is **stratiform**

platy (of columns): (rarely used term) 'A strongly transversely [plan view] elongated column' (Preiss, 1972, p. 93). 'A column in which one of the transverse [plan view] dimensions is much larger than the other' (Walter, 1972, p. 13). The preferred term is **linear**

platy (of laminar architecture): (obsolete term) An architecture consisting of laminae that are moderately distinct and continuous; the darker ones are usually the most distinct and are set in a pale matrix into which they frequently grade vertically (Walter, 1972, p. 11, 14). Similar to **streaky** and **fragmentary ribboned** (obsolete term). The preferred term is **streaky**

plenicinct (of lamina profile): A lamina that completely encloses a body, as in an oncoid (Hofmann, 1969a, fig. 8). Hofmann (1969a) also referred to this as **globoidal** (obsolete term). The preferred term is **plenicinct**

plumb (tubes): Invariably vertically oriented, cylindrical structures (tubes) filled with sediment. A stromatolite with the plumb tubes has been called a plumb stromatolite (Hoffman et al., 2007). Also referred to as **tubestone stromatolites** (Corsetti and Grotzinger, 2005, fig. 1c; Bosak et al., 2013b). The preferred term is **tubestone**

plumose microbialite: A microbialite with an apparent central stem (support) and many fine branches that bifurcate and coalesce, producing an overall feathery appearance (Sumner, 1997b, p. 308). Gürich (1906, p. 50–51, fig. 1, plate XVIII) was the first to describe a plumose microbialite, *Malacostroma plumosum*

polygonal (of plan view): A column or branch that in cross-section has straight rather than curved sides

polygonal conical (of conical microbialites): A term for a conical microbialite in which the base is not circular but is indented, polygonal, or star shaped (stellate) in plan view. The flanks may be planar or concave. In some cases, the plan view is teardrop shaped.

polymorphic (of thrombolite clot spatial relations and arrangement): Clots (generally mesoclots) with variable or inconsistent shape throughout the thrombolite

polynomial: a system of naming consisting of several terms. Polynomials were replaced by the Linnean System of naming

porostromata (of microstructure): Pia (1927, p. 37) used the name *Porostromata* for a group of tubular calcimicrobes such as *Girvanella*, *Sphaerocodium*, *Ortonella* (also see Riding, 1977, p. 57). Pia's (1927) classification was reorganized by Monty (1981, p. 2), who introduced the term **porostromate microstructure** (see also **skeletal stromatolites**). The preferred term is **tubular microstructure**

porostromate microstructure: 'Porostromate micro-structures are defined by the growth of loose or tangled, vertical, flabellate or flat-lying, straight or sinuous calcified filaments or threads, or even of calcified unicells' (Monty, 1981, p. 3). A microstructure dominated by calcimicrobes. The preferred term is **tubular microstructure**

porostromate stromatolite: Similar to **skeletal stromatolite** (Riding, 2000, p. 191). The preferred term is **skeletal stromatolite**

post-depositional microbialite: Riding (2000, p. 194) introduced the concept of **post-depositional thrombolites**, which can be extended to microbialites in general when a mesostructure is syndepostionally produced, diagenetically enhanced, or diagenetically created, altering the original mesostructure

post-depositional thrombolites: A clotted macrofabric 'syndepositionally produced, diagenetically enhanced or diagenetically created' (Riding, 2000, p. 194), resulting in what could be called a thrombolite

potential stromatolites: 'Unconsolidated laminated systems, clearly related to the activity of microbial communities, and often called "recent stromatolites" or "living stromatolites" are defined as "potential stromatolites"' (Krumbein, 1983, p. 493). The adjective could be used for other types of microbialites

profile (of lamina shape): The 2D expression (e.g. as seen in a section cut parallel to growth) of the 3D shape of the lamina

projection (of ornament): A term for small, upward protrusions from the column margin, commonly separated from the column by a niche (see text)

prolate (of lamina profile): (obsolete term) Used by Hofmann (1969a, p. 15, fig. 8) and similar to **parabolic** and **acute**. The preferred term is **parabolic**

prostrate (of attitude): Columns or branches that are horizontal or nearly horizontal

prostrate orientation (of mesoclot): The major axes of the mesoclots lie horizontal or at an oblique angle to the vertical

pseudocolumnar (of layered microbialites): A term for a 'laterally-linked stromatolite in which successive crests are superimposed forming column-like structures (pseudocolumns)' (Preiss, 1972, p. 93)

pseudostalactitic microbialite: Stalactitic columns, coalesced columns, coniform shapes, and downward-oriented protruberences of microbial origin that occur in roofs of inter-reef paleocaves (Olivier et al., 2003, p. 388–389)

pseudostromata: (rarely used term) An informal subdivision of **Spongiostromata** referring to non-laminated, fixed, irregularly shaped carbonate growths (Wolf, 1965, p. 5). These could be thrombolites, leiolites or dendrolites, depending on their mesostructure. We recommend against using this term

pseudostromatolite, pseudomicrobialite: An abiogenic structure that resembles a stromatolite or other microbialite. Modified from the concept of dubiofossils and pseudofossils of Hofmann (1972). See text for use of this and parallel terms such as **dubiomicrobialites** (**dubiostromatolites**) (Awramik and Grey, 2005). Note: Wolf (1965, p. 5) used the term 'pseudo-stromatolite' for non-laminated microbial growths. Also referred to as a **stromatoloid** (Oehler, 1972; Buick et al., 1981; Dahanayake et al., 1985; Wacey et al., 2009). The term **abiogenic stromatolite** has often been used but is an oxymoron. The preferred term is **pseudostromatolite** or **pseudomicrobialite**

r

radial (of thrombolite clot orientation): Radiating patterns of digitate mesoclots within a thrombolite (Armella, 1994, p. 425)

radial ribs (of ridged conical): Ornament typical of conical stromatolites forming ridges radiating from the apex of the cone, and often producing a star shaped (stellate) plan-view (Komar et al., 1965a,b; Hofmann 1969b, p. 72, plate 20). Not to be confused with ribbed ornament. The preferred term is **ridged**

ragged (of surface ornament): This term is sometimes used where a wall is lacking and the laminae terminate abruptly at the column or dome margin and may be of uneven length giving the margin a ragged appearance. The term also applies to variability of growth, which involves changes to the column diameter. It is best to clarify the sense in which the term ragged is being used and the feature can be referred to as **unwalled**

ragged (of variability of growth): Whereby the width of the column is highly variable and the changes are abrupt producing a ragged or jagged outer margin (Hofmann, 1969a, fig. 10)

ramifying (of branching): (rarely used term) Branching that is usually complex

random (of thrombolite clot orientation): There is no regular orientation to the clots

rectangular (of lamina profile): 'Lamina which in a longitudinal section [usually the vertical profile] of a column is flat topped with edges deflexed at about 90°' (Preiss, 1972, p. 93)

recumbent (of attitude): (obsolete term, see discussion in text). A column that is initially erect or inclined, which develops a lateral to downwards curvature (Hofmann, 1969a, fig. 13). Replaced by **epinastic**

reef: The 'product of the actively building and sediment-binding biotic constituents, which, because of their potential wave resistance, have the ability to erect rigid, wave-resistant topographic structures' (Lowenstam, 1950, p. 433). The term can be applied to some large microbialite buildups but use of the term 'reef' is best restricted to structures that have evidence they were wave-resistant structures as discussed by Lowenstam (1950) and Heckel (1974). The preferred term is **buildup**

relief (of lamina): (obsolete term) The preferred term is **synoptic relief**

repetitive lamination (of lamina alternation): (obsolete term) The 'superposition of laminae of similar nature and configuration, separated by physical discontinuities' (Monty, 1976, p. 195). The preferred term is **even lamination**

rhombic (of lamina profile): A '[l]amina which in a longitudinal [usually the vertical] section of a column is flat-topped but has subparallel edges not perpendicular to the top' (Preiss, 1972, p. 93)

ribbed (of ornament): A term for abrupt and regular increases and decreases in diameter that produces horizontal projections on the surface of a microbialite. To some extent ribs are a small-scale version of constringed, but their influence is mainly restricted to the column margin

ridged conical (of conical microbialites): A term used for a compound microbialite in which lateral ridges connect adjacent cones

rind: A layer that envelops the entire margin of a microbialite, mainly used for Phanerozoic microbialites. A mesostructurally distinct coating of one type of microbialite on another kind of microbialite. The term has been used for both unlaminated (Ahr, 1971, p. 215) and laminated (Shapiro and Awramik, 2000, p. 176) coatings. Also referred to as a **selvage**

rounded (of plan view): A plan view in which the shape is mostly circular

rounded (of thrombolite clot shape): A mesoclot with both diameters more or less equal and margins are more or less equidistant from the centre (Kahle, 2001, fig. 5a,b)

rugate (of ornament): (obsolete term) A term for overhanging laminae or sets of laminae that are rhythmically constringed to produce concentric cornices (Hofmann, 1969a, p. 18, fig. 12). The preferred term is **corniced**

S

saccate (of thrombolite clot shape): A mesoclot with a distinct rim. Although they are often lobate, they can be of varied shape (Kennard, 1994, fig. 7E)

scutate (of plan view): A column or branch in which the cross-section is shaped like a shield

scutate (of thrombolite clot shape): A mesoclot shaped like a shield in which the flat side forms the lower margin

secondary alteration: The post-depositional diagenetic alteration of primary fabrics. It includes recrystallization (e.g. neomorphism), silicification, phosphatization, and dolomitization

seif (of plan view): An elongate stromatolite or microbialite parallel to the shoreline (Playford, 1979, p. 16; 1980, p. 74) Also referred to as **elongate**, **longitudinal** and **linear** microbialites. The preferred term is **linear**

selvage: 'Unlaminated coating on column margins' (Preiss, 1972, p. 93; Walter, 1972, p. 14). Similar to **rind** (which includes any kind of microbialite coating). The preferred terms are **selvage** or **rind**

serial development (of laminae): (obsolete term) The degree with which a lamina conforms in shape to underlying laminae; similar to **degree of inheritance** of Hofmann (1969a, p. 17, fig. 13). The preferred term is **degree of inheritance**

series: See **bioherm series**

shape (of bioherm, biostrome, individual structure, columns, head, fascicle, and lamina): The overall morphology of a microbialite feature. Each category has its own descriptive terminology

shrub: A millimetre- to centimetre-size, unlaminated arborescent structure that is characteristically the mesostructural component of a dendrolite. The term was initially used to describe millimetre- to centimetre-size arborescent carbonate structures found in travertine (Chafetz and Folk, 1984). Similar, non-travertine related structures, also called shrubs, were described from Neoproterozoic successions (Frasier and Corsetti, 2003). The term was also used for dendrolitic structures found in lacustrine carbonates, in particular the Aptian pre-salt off the coasts of Brazil and Angola (Ceraldi and Green, 2017), along with terms such as shrub-like (Wright, 2012) and shrubby (Saller et al., 2016). However, biogenicity of the pre-salt shrubs has been questioned (Wright and Barnett, 2015). The preferred term for a microbialite composed of shrubs is **dendrolite.** If the individual dendrolitic structures are laminated (Das and Mohanti, 1997, figs 9, 35) they should be called ministromatolites. Shrubs and dendrolites are not well known, hence terminology and interpretations are subject to change

silhouette: The profile view, or section, of a microbialite used in morphometric analysis (Hofmann 1976a, p. 48)

simple columnar: (obsolete term) A non-branching head or column. The preferred term is **columnar microbialite**

simple conical (of conical microbialites): A conical microbialite comprising a single head or column where laminae terminate at a distinct apex, are steeply inclined between the base and apex, and do not show curvature in vertical profile. The cone is not associated with branches or other complex structures. An axial zone may or may not be present

simple wall: A wall formed by one or two laminae, each continuing parallel to the sides of the microbialite for some distance and then tapering out

sinuous (of attitude): A term for a column that is alternately concave and convex (Hofmann, 1969a, p. 16, fig. 10)

skeletal (of microstructure): (obsolete term) Microstructure with calcimicrobes. Also referred to as tubular and vermiform (Pratt, 1982, p. 88), but this term already exists for a type of laminar architecture. If the microfossils are calcified filaments, the preferred term is **tubular**

skeletal calcification (of microstructure): A 'strictly directed biological process in which metabolism produces an organized mineralized structure with a pre-determined form. Although calcification in some cyanobacteria has been described as resembling skeletal formation (Golubic and Campbell, 1981) it is not a strictly directed biological process' (Burne and Moore, 1987, p. 246)

skeletal stromatolite (of microstructure): Stromatolites 'in which the organisms responsible for their formation are commonly preserved as calcified fossils' (Riding, 1977, p. 57)

slender (of bridging): Bridge consisting of only one or a few laminae that cross the interspace and connect with an adjacent head or column. Also referred to as **delicate** or **fragile**. The preferred term is **delicate**

slender (of height-to-width ratio): A description of the height-to-width ratio of a column in which H >> W; modified from Hofmann (1969a, p. 16–17, fig. 10). Also referred to as **digitate** (Howe, 1966, p. 65) and **microdigitate.** The preferred term is **slender**

smooth (of lamina waviness): A lamina with no second-order curvature or flexures

smooth (of ornament): A surface of a microbialite lacking ornament or irregularity (Hofmann, 1969a, p. 18, fig. 12)

spacing: The relative distance between microbialites; mostly applied to bioherms but can be applied to branching. Types of spacing include: **contiguous**, **closely spaced**, **openly spaced** and **isolated**

speleothem: Any secondary mineral deposit that is formed in a cave (Moore, 1952, p. 2; Thrailkill, 1976). A speleothem can be a microbialite when microbial activity is involved (Jones, 2010). See **cave stromatolites**

spar: 'A term loosely applied to any transparent or translucent light-colored crystalline mineral' (Neuendorf et al., 2011, p. 617)

sparite (of microstructure): A 'crystalline transparent to translucent … relatively coarse-grained calcite that was precipitated in situ' that exceeds 20 µm (Neuendorf et al., 2011, p. 617). See also **microsparite**

sparry crust pseudostromatolite: an isopachous laminated structure resembling a stromatolite but of an abiogenic origin

sparry crust stromatolite: A stromatolite with isopachous lamination whose origin is 'essentially abiogenic precipitates' Riding (2011a, p. 640). Properly called **sparry crust pseudostromatolite**

spherical (of microstructure): Used in the sense of Taylor (1975) and adopted by Burne and Moore (1987, p. 251) to describe microbialites with an internal structure consisting of spherical aggregates. Refers to hollow spheres incorporated into the microbialite. Caution is urged in the use of spherulitic. Spherulites have a radial fabric (Chafetz and Butler, 1980, p. 504). The preferred term is **spherical microstructure**

spherulitic microstructure: (obsolete term) A microstructure composed of spheroids, botryoids, or radiating crystals. Caution is urged in the use of spherulitic. Spherulites have a radial fabric (Chafetz and Butler, 1980, p. 504). The preferred term is **spherical microstructure**

spongiform (of microstructure): (obsolete term) The preferred term is **grumous**

spongiostromata: (obsolete term) This was based on **Spongiostromidae**, a family of what would now be called microbialites introduced by Gürich (1906, p. 7, 53) and later called **Spongiostromata** by Pia (1927, p. 36) to encompass stromatolites and oncoids that lack identifiable filamentous microfossils (calcimicrobes) (q.v. **Porostromata**). The preferred term is **skeletal microbialite (stromatolite)**

spongiostromate microstructure: (obsolete term) A term coined by Monty (1981, p. 2), and not clearly defined, but which he indicated 'result[s] from the individualization of micritic, spongious, fenestral, sparitic, pelloidal, detrital, etc. laminae or films, variously grouped and organized'. There are no preserved organic remains. Avoid using the term; use specific microstructural terms instead

spongiostrome: The term originates from spongiostromides of Gürich (1906, p. 53) with 'genera' and 'species' of microbialites identified by microstructure. Pia (1927, p. 36) introduced the term **Spongiostromata** for stromatolites at the macrostructural scale; discussed by Hofmann (1978, p. 572). The preferred term is **stromatolite**

sporadically linked (of linkage): Lateral linkage occurs intermittently between microbialites and may vary through the vertical profile. Also referred to as **partly linked** (obsolete term). The preferred term is **sporadically linked**

stacking pattern (of stromatolite mesostructure): The manner in which underlying and overlying laminae relate to each other vertically and how they overlap at the column margins. Types of overlap for **stacking pattern** include: **parallel**, **overlapped** and **walled**. Other features to be considered include **lamina alternation**, **lamina profile**, **lateral continuity** and **thickness,** and **macrolaminae**

steeply convex (of lamina profile): 'A lamina whose ratio of height to diameter [width] is greater than 0.5' (Preiss, 1972, p. 93)

stiriolite: (rarely used term) Abiogenic, laminated, geyserite-like deposits formed in the splash zone of springs (Walter, 1976c, p. 111). The term is used if the environment is unknown. If the deposit resulted from terrestrial hydrothermal activity, it should be termed geyersite

stratiform (of layered microbialites): A microbialite which is laterally continuous and more-or-less flat. For a stromatolite, laminae are continuous and essentially flat or parallel

streaky (of laminar architecture): An architecture consisting of laminae that are moderately distinct and continuous; the darker laminae are usually the most distinct and are set in a pale matrix into which they frequently grade vertically (Walter, 1972, p. 11, 14). Also referred to as **fragmentary ribboned** and **platy** (obsolete terms). Types include **irregular streaky**

striated (of laminar architecture): An architecture consisting either of chains of light lenses within dark laminae or dark lenses within light laminae (Komar and others, 1965a,b; Hofmann, 1969b, fig. 9; Walter, 1972, p. 12, 14). Also referred to as **non-uniformly wavy-ribboned** (Hofmann, 1969b, fig. 9). The preferred term is **striated**

stromatoid: Kalkowsky (1908, p. 101–102, 104) introduced the term stromatoid. Various authors have proposed different translations and interpretations of Kalkowsky's term (Hofmann, 1969a, p. 3; Monty, 1977, p. 18; Kennard and James, 1986, p. 496; Burne and Moore, 1987, p. 251; Gerdes and Krumbein, 1994, p. 107; Paul et al., 2011, p. 21), which has led to some confusing usage of terminology (Álvaro, 2015). There is no unambiguous term for an individual component of a bioherm or biostrome, although Hofmann (1969a, p. 3) used stromatoid to mean the 'individual laminated structure making up the bioherm or biostrome', and this has been one of the more widely accepted usages. The structure has also been referred to as a **calyptra** (Luchinina, 1973; Zhuraleva and Miagkova, 1977), **coenoplase**, **head** and **individual**. The preferred term is **head**

stromatolite (of microbialite subset): A laminated microbialite 'produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes [cyanobacteria]' (Awramik and Margulis, in Walter, 1976b, p. 1). Originally called 'stromatolith' (Kalkowsky, 1908, p. 68–69), but anglicized to 'stromatolite'. Hofmann (1969a, p. 3) pointed out that the term 'stromatoid' (Kalkowsky, 1908, p. 101, 104) was actually the term used for the individual laminated structures making up the stromatolite bioherm or biostrome. The term 'stromatolite' is now firmly entrenched in the literature and used in a broad sense. Reviews and comments on the use of the term have been given by several authors (Hofmann, 1969a, appendix; Monty, 1982; Krumbein, 1983; Buick et al., 1981; Burne and Moore, 1987; Riding, 2011b) and are not repeated here; instead some other well known definitions are quoted:

> Layered organo-sedimentary structure built by microscopic algae and bacteria (Walter, 1972, p. 14).

> [A]n attached, laminated, lithified, sedimentary growth structure, accretionary away from a point or limited surface of initiation (Semikhatov et al., 1979, p. 993).

> Stromatolites are laminated rocks, the origin of which can clearly be related to the activity of microbial communities, which by their morphology, physiology, and arrangement in space and time interact with the physical and chemical environment to produce a laminated pattern which is retained in the final rock structure (Krumbein, 1983, p. 501).

The following revised definition (modified from Awramik and Margulis, 1974, p. 5, unpublished; Awramik and Margulis *in* Walter, 1976b, p. 1; Burne and Moore, 1987) is adopted here:

> A laminated organosedimentary structure produced by precipitation, or by sediment trapping and binding, as a result of the growth, behaviour, and metabolic activity of micro-organisms, principally cyanobacteria.

stromatolite buildup: A circumscribed body or reef constructed of stromatolites that displays topographic relief (see **microbial buildup**, **bioherm**, **reef**)

stromatolite-margin clot: a term used by Turner (2000, p. 90) for an intermediate-scale clot, larger than **grumeaux** and and smaller than **thromboids** as used by Turner (2000), with clot size about 80–1000 μm)

stromatolith: (obsolete term) The original term used by Kalkowsky (1908, p. 68–69) for beds with distinct calcareous masses with fine, essentially flat, laminated structures in the lacustrine Triassic Buntsandstein of central Germany, and replaced by the term stromatolite. The term was also used for a '"rock mass consisting of many alternating layers of igneous and sedimentary rocks in sill relationship" (Foye, 1916, p. 791)' (Hofmann, 1969a, p. 3), but is now disused in this sense. The preferred term is **stromatolite**

stromatolitic bioherms: A term used by Eggleston and Dean (1976, p. 479) among others for bioherms composed of stromatolites

stromatolitic structure: A term based on the usage of Kalkowsky (1908) and restricted by Burne and Moore (1987, p. 251) to microbialites having an internal structure of 'fine, more or less planar lamination'

stromatoloid: 'Structures of uncertain origin that resemble stromatolites...' (Buick et al., 1981, p. 161). The preferred terms are **dubiostromatolite** and **pseudostromatolite**

structure grumeleuse (of microstructure): (obsolete term) The preferred term is **grumous**

structureless microbialite: Non-laminated microbialite (Siahi et al., 2016, p. 259). Presumably the microbialite also lacks mesoclots and shrubs. Preferred term is **leiolite**

stubby (of height-to-width ratio): A term describing the variability of growth in columns in which H ≈ W; modified from Hofmann (1969a, p. 17 and fig. 13)

style of branching: See **branching style**

subaerial stromatolite: Stromatolites that form in caves (Cox et al., 1989) (see **cave stromatolite**, **speleothem**)

subcircular (of plan view): A head, branch or column that is not completely rounded in plan view

subcylindrical (of types of columnar microbialite): A columnar microbialite in which the diameter is variable in plan view and the diameter may vary irregularly throughout the length of the column

subhorizontal (of angle of divergence of branches): Branches that diverge perpendicularly to the axis of growth, with or without increase in the width of the parent column

subrounded (of thrombolite clot shape): A mesoclot with nearly equal diameters, but one axis is slightly longer than the other and the margins are of irregular distance from the centre (Kahle, 2001, fig. 5A,B)

subspherical (of bioherm shape): A bioherm or other structure in which the width is nearly equal to the height

surface ornamentation (of column margins): A second-order characteristic of the vertical profile of a microbialite (commonly of stromatolites) present on the outer margin of the structure

surface view (of microbialite macrostructure): The appearance or shape of the surface of a microbialite. **Plan view** refers to the appearance when viewed at right angles to the growth direction. **Cerebroid** is a surface view while **maceriate** is a plan view

symmetrical (of lamina profile): A lamina in which the axis of the profile is at the centre of the column

synoptic profile: The 2D characteristic of the morphology of a microbialite surface at any point in time (Hofmann, 1969a, p. 36, fig. 18; Walter, 1972, p. 61, text-fig. 22). It is commonly described and measured as a proxy for the 3D feature of **synoptic relief**

synoptic relief: The height of a microbialite above its substrate. This could be the full height of a head, but more commonly applies to the height of a lamina above the substrate, particularly in the interspace. If bridges are present, it is the height of the lamina in the column above its height in the corresponding bridge

synoptic relief of lamina: The 3D amplitude of the lamina profile above its substrate at any point in time. It is commonly observed and measured as the 2D **synoptic profile**

t

tabular (of bioherm shape): A bioherm with clearly defined margins, a tabular top that parallels the lower surface, and height-to-width ratio between 1:5 and 1:10. The base is only a little narrower than the maximum diameter

tabular (of biostrome shape): A biostrome with clearly defined margins, a tabular top that parallels the lower surface, and a flat upper or gently domed upper surface

taxon: In biological classification, pertaining to a unit of any rank (that is, a particular species, genus, family, class, order, or division or phylum) or the scientific name. For microbialites, the most widely used ranks are **Group** and **Form** (or similar terms)

teicholite: (rarely used term) Stromatolites (microbialites) that form encrustations on rock walls (Hadding, 1939, p. 4). See **encrusting microbialites**. Also referred to as **flat laminated** or **planar laminated**, **cavity-encrusting microbialites** and **endostromatolites**. A preferred term is **cave stromatolite**

tented microbialite: Planar, filmy laminae that drape over a single, nearly vertically oriented support creating a tent-like structure (Sumner, 1997a, p. 306, fig. 3)

terete (of columnar microbialites): A microbialite in which the diameter decreases upwards in a regular manner; for example, see the computer-generated growth forms of Hofmann (1969a, p. 12). The shape of the column is best determined by 3D reconstruction because a cut face that is slightly tangential can give a false impression that a column has a terete termination

terrestrial stromatolite: Laminated calcrete formed by microbial activity (Wright, 1989, p. 2; also see Read, 1976)

texture: The 'size, shape, and arrangement (packing and fabric) of the component elements of a sedimentary rock' (Pettijohn, 1957, p. 13)

thromboid (of thrombolite clot): (obsolete term) A term that has been used in a variety of ways. Kennard (1994, p. 451) defined thromboids as 'individual millimetre to centimetre-size clots within thrombolites'. This is equivalent to mesoclot. Turner et al. (2000, p. 90) defined them as 'frame-building micritic clots, generally >500 μm in size'. Shapiro (2000, p. 169) indicated that Armella (1994) used the term for larger, columnar structures. It is recommended that this term be abandoned (Shapiro, 2000, p. 169)

thrombolite (of microbialite subset): There have been several definitions of thrombolite. Aitken (1967, p. 1164) originally proposed the term thrombolite (from the Greek *thrombos,* bloodclot) for:

> cryptalgal structures related to stromatolites, but lacking lamination and characterized by a macroscopic clotted fabric. A thrombolitic limestone or dolomite is a rock largely composed of thrombolites, or one possessing a macroscopic clotted fabric of crystalgal origin.

Some years later, Pratt and James (1982, p. 545) revised the definition to:

> cryptalgal structure of variable shape, from prostrate to columnar, that may branch and anastomose, that lacks a distinctly laminated fabric, and that usually occurs in groups, imparting a macroscopically clotted appearance to the rock.

Shortly after, Kennard and James (1986, p. 500) stated that a thrombolite was characterized by:

> [A] clotted mesoscopic fabric constructed by the penecontemporaneous growth and calcification of discrete colonies or growth forms of coccoid-dominated, internally poorly differentiated, microbial communities.

They recommended abandoning the definition given by Pratt and James (1982) and returning to that of Aitken (1967). More recently, Shapiro (2000, p. 169) defined a thrombolite as a:

> microbialite composed of a clotted mesostructure (mesoclots).

The preferred definition for a **thrombolite** is that of Shapiro (2000)

thrombolite boundstone: A thrombolite in which **boundstone** co-occurs with mesoclots, see Mancini et al. (2004)

thrombolitic structure: A term based on the usage of Aitken (1967) and restricted by Burne and Moore (1987, p. 251) to describe microbialites that have an internal structure consisting of 'a clotted texture'

tonguing (of bioherm shape): A bioherm whose 'margins intertongue with the surrounding rock' (Walter, 1972, p. 14). The preferred term is **intertonguing**

transverse view: A view normal to the growth of the microbialite, i.e. the shape of the column or branch when viewed in a plane at right angles to the direction of the growth vector. This has also been called **plan view**. Transverse has also been used to refer to an oblique plane or to a perpendicular plane. Because of this ambiguity, the preferred term is **plan view**

travertine: Like tufa, travertine has been defined a number of ways, among them:

> …a form of "freshwater" carbonate deposited by inorganic and organic processes from spring waters. (Chafetz and Folk, 1984, p. 290)

> …[deposits from] springs where the elevated temperatures, together with the dissolved materials present in these warm waters, excluding most eukaryotic organisms. (Riding, 1991, p. 37)

> Biotically and, or, abiotically precipitated calcium carbonate (predominantly calcite and aragonite) from spring-fed, heated and, or, ambient temperature waters… (Neuendorf et al., 2011, p. 685)

> A chemically-precipitated continental limestone formed around seepages, springs, and along streams and rivers, occasionally in lakes and consisting of calcite or aragonite, of low to moderate intercrystalline porosity and often high mouldic or framework porosity within a vadose or occasionally shallow phreatic environment. Precipitation results primarily through the transfer (evasion or invasion) of carbon dioxide from or to a groundwater source leading to calcium carbonate supersaturation, with nucleation/crystal growth occurring upon a submerged surface. (Pentecost, 2005, p. 3)

Travertine is generally denser than tufa and is frequently laminated. There is mounting evidence that bacteria play important roles in travertine formation (Chafetz and Guidry, 1999; Pentecost, 2005; Fouke, 2011) and these would be considered microbialites

trichome: 'In filamentous prokaryotic microorganisms, the threadlike, usually many-celled strand that is encompassed commonly by a tubular sheath to form a filament' (Schopf, 1983b, p. 458)

trifurcate (of branching style): Branching in which columns branch into three smaller (filial) columns

trilobate (in plan view): Column or branch that is laxilobate in outline and has three divergent lobes

tropism: The 'directed movement or growth of an organism in response to a particular stimulus' (Morita and Tasaka, 2010, p. 1)

true (of branching): (obsolete term) Previously used for combinations of beta or gamma branching (branching mode) and divergent branching (angle of divergence), but these characteristics are best described independently. Also referred to as **active branching**, and **moderately** and **markedly** divergent branching

tuberculate (of ornament): (obsolete term) A type of ornament consisting of small bumps (Hofmann, 1969a, p. 18, fig. 12). The preferred term is **lobate**

tuberous (of ornament): A term for low, smooth, protrusions on the surface of a microbialite that extend downward

tubestone (of microbialite shape): An extreme case of a **pitted** stromatolite (microbialite) in which an interconnected network of stromatolite (microbialite) is interrupted by very deep (up to 2 m), vertically oriented, mostly cylindrical structures (tubes) filled with sediment (Corsetti and Grotzinger, 2005; Bosak et al., 2013b)

tubular (of microstructure): A microstructure composed of hollow tubules with micritic walls (Batten et al., 2004, p. 252). The hollow tubules with micritic walls are commonly calcimicrobes

tufa: Like travertine, the term has been used and defined in several ways, among them:

> A variety of travertine that is commonly spongy or porous due to precipitation around a variety of floral structures, such as reeds, plant roots, leaves, etc. (Neuendorf et al., 2011, p. 691)

> …cool water deposits of highly porous or "spongy" freshwater carbonate, rich in microphytic and macrophytic growths, leaves, and woody tissue… (Pedley 1990, p. 143)

> …all cool or near ambient temperature freshwater low-Mg carbonates regardless of degree of lithification (Ford and Pedley, 1996, p. 118)

> …porous freshwater carbonate that is deposited from spring water of meteoric origin in a limestone area (Kawai et al., 2009, p. 41) [note: Kawai et al. attributed this definition to Ford and Pedley (1996) who, as the previous citation indicates, had a different preferred definition]

> …continental carbonates, composed dominantly of calcite… characterized by relatively low depositional rates producing highly porous bodies with poor bedding and lenticular profiles... (Capezzuoli et al., 2013, p. 3)

> spring-associated carbonates generated from carbonate-rich, ambient temperature groundwater… (Ibarra et al., 2015, p. 36)

There is growing consensus that tufas often result from the influence of microbial activity (Capezzuoli et al., 2014; Shiraishi et al., 2017) and, as such, are microbialites

tufa microbialite: A tufa forming as a result of microbial activity. This could be laminated, clotted, or shrubby

tufa stromatolite: A tufa with stromatolite-like lamination. Riding (1991, p. 32) used the term for 'stromatolites dominated by precipitation of minerals on (as opposed to within) organic substrates' and restricted them to freshwater lakes and streams. However, some have been described from marine settings (Perissinotto et al., 2014)

tufa thrombolite: A term introduced by Riding (2000, p. 194) in which he described, but did not define, it as clotted fabrics produced by calcium carbonate precipitation on organic surfaces in lakes and streams

tuft: A small, usually conical structure. Living tufted microbial mats and fossilized examples can have tufts ranging in morphology from well-developed millimetre- to centimetre-scale cones through to reticulate ridges (Logan et al., 1974, p. 151; Flannery and Walter, 2012, p. 6). Tuft is most commonly used for smaller structures while **pinnacle** for larger structures; at least some pinnacles have an axial zone. See **pinnacle**

turbinate (of columnar microbialites): A microbialite in which the diameter increases upwards as shown in the computer-generated growth forms of Hofmann (1969a, p. 12). Also referred to as **clavate** or **club shaped**. The shape of the column is best determined by 3D reconstruction because a cut face that is slightly tangential can give a false impression that a column has a turbinate termination. The preferred term is **turbinate**

tussock: A millimetre or less, hemispherical body, with microscopic, radial, rod-shaped internal structures (Bertrand-Sarfati, 1972a, p. 103; Bertrand-Sarfati and Pentecost, 1992, p. 469). A component of **tussocky microstructure**

tussock microstructure: A microstructure whose 'irregular lamination is defined by the juxtaposition of separate tussocks of different size' (Bertrand-Sarfati, 1976, p. 253). The preferred term is **tussocky**

tussocky (of laminar architecture): Irregular lamination defined by the juxtaposition of separate hemispheric tussocks of different size usually composed of radiating elements (Bertrand-Sarfati, 1976, p. 253; Bertrand-Sarfati et al., 1994; Bertrand-Sarfati and Pentecost, 1992)

Type I axial zone: In which the laminae are not offset or contorted and are of uniform thickness

Type II axial zone: In which laminae are not offset, but are of variable thickness

Type III axial zone: In which the laminae are offset and of uneven thickness

U

umbellate (of branching style): (obsolete term) A term for structures that 'at a certain level, pass into several considerably smaller, diverging branches' (Hofmann, 1969a, p. 18, fig. 10). The preferred term is **multifurcate branching**

undifferentiated microbial boundstone: Term used by Kennard and James (1986, p. 497) for non-laminated and non-clotted microbial boundstone. The preferred term is **leiolite**

undulatory (of layered microbialites): 'Laterally-linked stromatolite in which successive crests are not superimposed' (Preiss, 1972, p. 93; Walter, 1972, p. 14)

unequal division (of branching style): A branching style in which one of the filial branches is considerably larger than the other. The preferred term is **lateral**

uniform (of variability of growth): There is little or no change in the width of the column (Hofmann, 1969a, p. 16, fig. 10)

uniform lateral continuity: (obsolete term) The lamination extends laterally in a continuous manner, the lithology is consistent, and there are only slight changes in thickness. The upper and lower boundaries are essentially parallel. The preferred term is **continuous**

unimodal (of lamina profile): A lamina having one crest

unlinked (of linkage): No lateral linkage occurs between microbialites

unwalled: (new term) A term to describe a microbialite that lacks a wall and in which the laminae terminate abruptly at the margin of the column, head or buildup. Descriptions commonly refer to there being 'no wall' or the microbialite 'lacking a wall'. Walter (1972) used the term **naked**. We here introduce **unwalled** as a specific category with its own term to help with comparative studies. The laminae terminations may be even or uneven. If laminae end unevenly, they are referred to as **ragged**

V

variability of growth (of columnar and branched microbialites): The variations in the width of a microbialite along a column or branch. Types of variability of growth include **uniform**, **constringed** and **ragged**

vermiform (of laminar architecture): An architecture that consists of narrow, sinuous, pale-coloured areas (usually of sparry carbonate) surrounded by darker, usually fine-grained areas (usually carbonate) (Walter, 1972, p. 14; Bertrand-Sarfati, 1976, p. 255). Also referred to as **lumpy** (Hofmann, 1969b, fig. 9). The preferred term is **vermiform**

vertical profile: The shape of a microbialite in vertical section, usually as viewed in 2D

vertical view: The appearance or shape of a microbialite when viewed normal to bedding

void intercalated (of lamina alternation): Laminae with cavities (voids) that are regularly or irregularly interleaved with other lamina types filled with sediment or cement

void-intercalated texture: Architecture in which any type of lamina is separated from another lamina with voids (cavities) filled with sediment or cement

W

wall: A laminated structure that forms at the margins of a microbialite by the downturning of a lamina or laminae and which envelopes or partially envelopes the previously formed part of the microbialite. Types of walls include: **simple wall**, **multilaminate wall**, **patchy wall**, **complex wall**, **selvage** and **rind**

wall structure: The nature of the laminae at the column margins

walled (of lamina stacking patterns): In which continuous overlapping by successive laminae gives rise to **walls** and produces various types of wall structure

wavy (of lamina waviness): A second-order curvature with wavelengths commonly greater than 2 mm (Preiss, 1972, p. 93, fig. 1)

wavy-banded laminae: A type of laminar architecture where the laminae are continuous, sharply bounded and show a consistent waviness (Preiss 1974, fig. 11d)

wrinkled (of lamina waviness): A second-order curvature of the lamina with wavelengths less than or equal to 2 mm (Preiss, 1972, p. 93, fig. 1; Walter, 1972, p. 14). Synonyms for wrinkled, especially where it is less regular, include seldom used or obsolete terms **crinkled**, **corrugate**, **crenate**, **crenulate** and **dentate**. The preferred term is **wrinkled**

X

xenotopic (of texture): '[M]osaic of anhedral crystals with irregular or curved intercrystalline boundaries and undulatory extinction' (Gregg and Sibley, 1984, p. 908). The term was proposed by Friedman (1965, p. 648)

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Appendices and Index

Appendix 1

Field checklist of main microbialite features

This chart is designed as a quick reference to the main observations necessary in the field. Features are not mutually exclusive. It may be necessary to tick more than one box, or indicate a range of features, and supplementary notes are advisable. Microstructural features are not included because these normally depend on laboratory analysis. However, salient features, such as lithology, preservation, interstitial fill and alteration, should be noted.

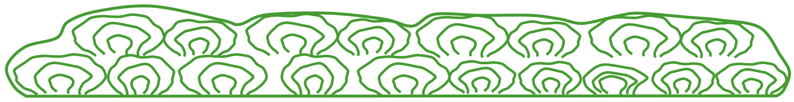
MEGASTRUCTURE 1/5

MICROBIALITE SUBSET

☐ Stromatolite ☐ Thrombolite ☐ Dendrolite ☐ Leiolite ☐ MISS ☐ Composite

Combination of:
☐ Stromatolite
☐ Thrombolite
☐ Dendrolite
☐ Leiolite
☐ MISS

MICROBIALITE BUILDUP (bed or reef)



DIMENSIONS

Length: ....

Height: ....

BUILDUP INTERFACE

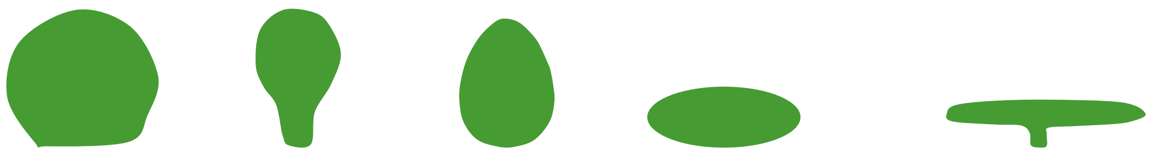
☐ Discrete ☐ Intertonguing

BIOHERM SHAPE / BIOSTROME SHAPE

Bioherm shape: ☐ Tabular ☐ Domical ☐ Subspherical

Biostrome shape: ☐ Tabular or domical ☐ Non-tabular or undulating

ADDITIONAL SHAPE



☐ Nodular ☐ Club shaped ☐ Egg shaped ☐ Ellipsoidal ☐ Pedestal shaped

SIZE

☐ Gigamicrobialites (>100 m)
☐ Megamicrobialites (1–100 m)
☐ Macromicrobialites (10–100 cm)
☐ Mesomicrobialites (1–10 cm)
☐ Minimicrobialites (1–10 mm)
☐ Micromicrobialites (<1 mm)

DIMENSIONS

Length: ....

....

Height: ....

....

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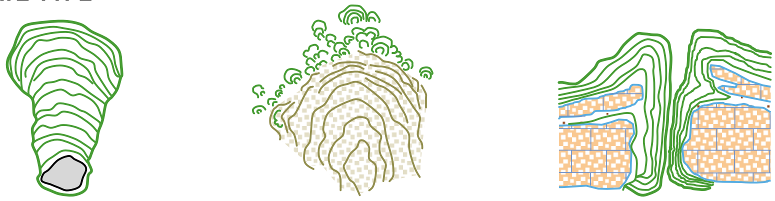
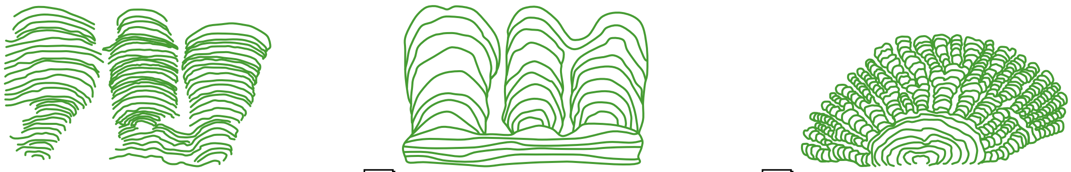
MACROSTRUCTURE 2/5

SUBSTRATE TYPE



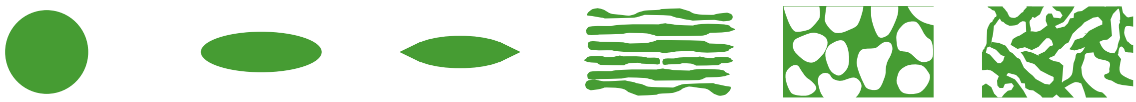
☐ Clast-supported ☐ Older microbialite ☐ Encrusting ☐ Other ....

INITIATION



☐ Directly on substrate ☐ On layered microbialite ☐ On domical microbialite

PLAN VIEW



☐ Circular ☐ Ovate ☐ Lanceolate ☐ Linear ☐ Pitted ☐ Labyrinthine

☐ Polygonal ☐ Scutate ☐ Crescentic ☐ Lobate

LINKAGE

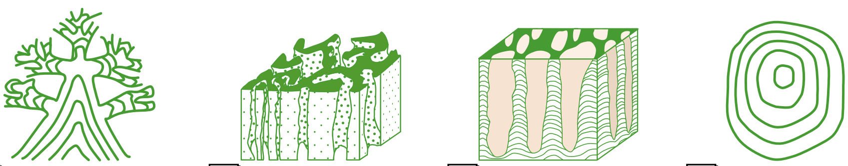
☐ Linked ☐ Locally linked ☐ Sporadically linked ☐ Unlinked

SPACING

☐ Contiguous ☐ Closely spaced ☐ Openly spaced ☐ Isolated

MICROBIALITE SHAPE

☐ Layered ☐ Domical ☐ Columnar ☐ Conical ☐ Branched



☐ Compound ☐ Maceriate ☐ Pitted ☐ Oncoid

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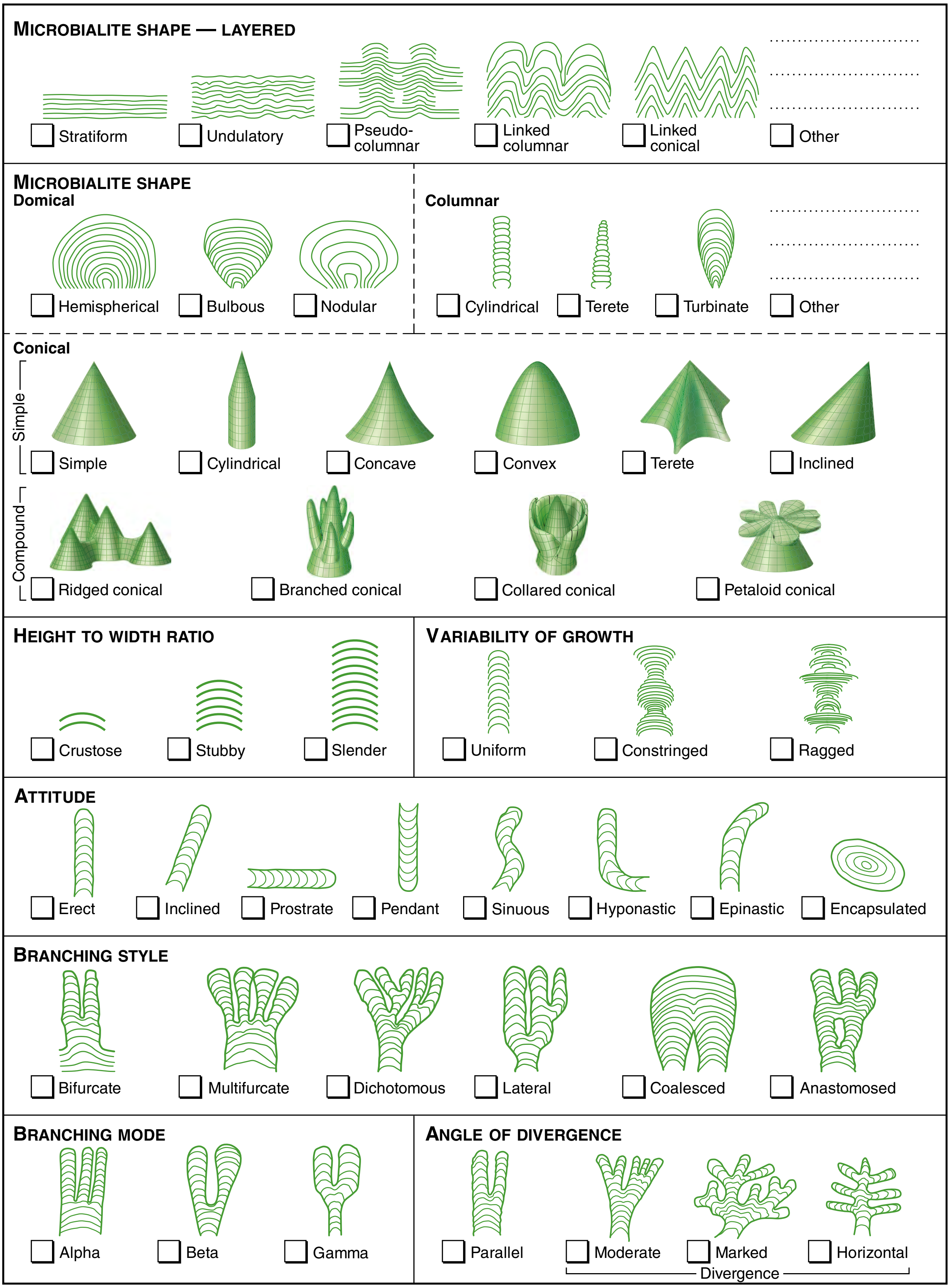
MACROSTRUCTURE 3/5



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MESOSTRUCTURE

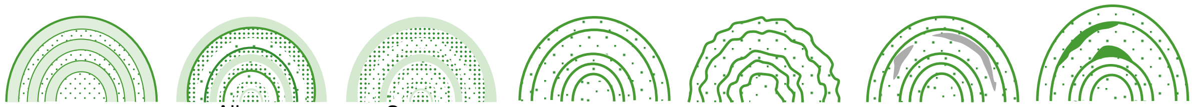
Laminar patterns

- ☐ Couplet
- ☐ Non-couplet

Stacking and overlap

- ☐ Parallel
- ☐ Dark overlap
- ☐ Light overlap

Alternation



- ☐ Even
- ☐ All gradational
- ☐ Some gradational

Composite

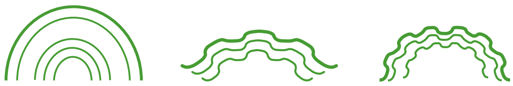
- ☐ Film bounded
- ☐ Intercalated

Lamina profile

- ☐ Concave
- ☐ Flat
- ☐ Gently convex
- ☐ Steeply convex
- ☐ Parabolic

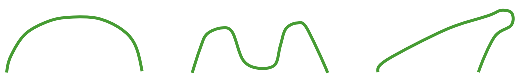
- ☐ Penecinct
- ☐ Plenicinct
- ☐ Rectangular
- ☐ Rhombic
- ☐ Conical
- ☐ Angulate

Waviness



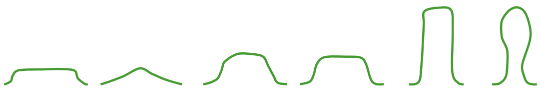
- ☐ Smooth
- ☐ Wavy
- ☐ Wrinkled

Modality and skewness



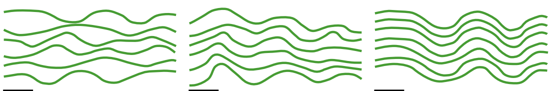
- ☐ Unimodal
- ☐ Bimodal
- ☐ Asymmetrical

Synoptic relief



- ☐ Low
- ☐ Moderate
- ☐ High

Degree of inheritance

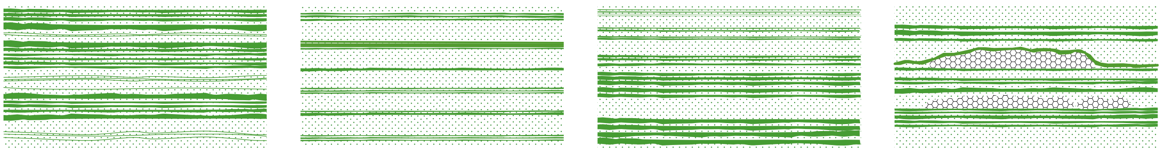


- ☐ Low
- ☐ Moderate
- ☐ High

Lateral continuity

- ☐ Continuous
- ☐ Discontinuous
- ☐ Lenticular
- ☐ Microcross-laminated
- ☐ Irregular
- ☐ Heterogeneous
- ☐ Harmonized

Macrolaminae



- ☐ Alternating light/dark
- ☐ Predominantly light
- ☐ Progressive thickness change
- ☐ Intercalated minerals

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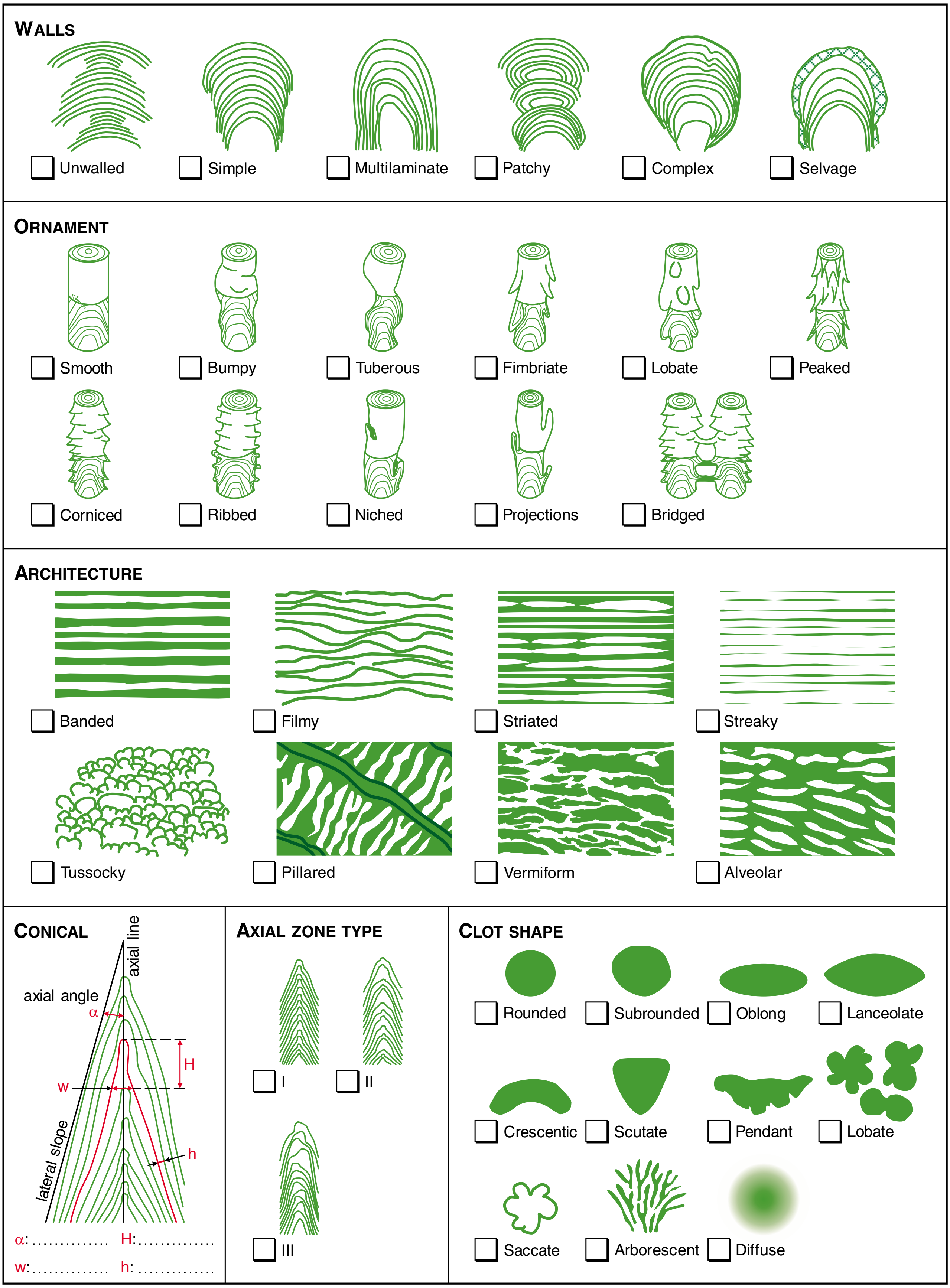
MESOSTRUCTURE 5/5



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Appendix 2

Guidelines for describing microbialites

Presented here are four options for the descriptions of microbialites (stromatolites). The options range from brief general to formal taxonomic descriptions (systematic paleontology).

Of the four options, only the fourth, 'formal taxonomic descriptions', is of sufficient rigour for use as a correlation tool. Miscorrelations have resulted from the unsubstantiated use of formal names. Use of names such as '*Collenia*', '*Cryptozoon*', and '*Conophyton*' (instead of domical, branching, and conical), or '*Conophyton*-like' in an informal manner, and names containing modifiers, such as cf. (*con forma*, having the form of), aff. (having affinities with), f. indet. (Form indeterminate), do not provide a basis for reliable correlation. The source of the identification should be cited and some indication of the degree of reliability given.

Option 1. Guidelines for brief, general descriptions

This option is most suitable for field geologists who wish to record the presence of microbialites and note a few of the key features. It is probably best to simply list appropriate descriptive terms and not attempt the use of formal names.

For example, 'The Duck Creek Dolomite contains several different stromatolites. One stromatolite has more-or-less parallel branches, niches, and wispy laminae. A second stromatolite comprises small, digitate columns with parallel branching, and well-banded laminae that can be traced across contiguous columns'.

Although these two stromatolites have actually been identified in the literature as *Pilbaria perplexa* and *Asperia ashburtonia* respectively, it is probably not a good idea to use these names for new occurrences unless detailed studies have been carried out to confirm the identifications. If you wish to comment on the fact that the stromatolites from new localities resemble some previously described examples, you could mention that 'These two stromatolites appear similar to *Pilbaria perplexa* Walter 1972 and *Asperia ashburtonia* Grey 1985, which were previously described from the formation by Grey (1985) and Grey and Thorne (1985).'

Option 2. Guidelines for more extensive, general descriptions

This option is more suitable for those geoscientists who wish to record a more detailed description without using open or formal nomenclature. This would probably be based primarily on field descriptions; however, follow-up laboratory analysis, in particular with regard to microstructure, is encouraged. As with the brief description, it is best to simply list a string of descriptive terms and not attempt to use formal names. Provide suitable illustrations of the microbialite. Provide relevant specimen numbers or locality details as appropriate. Use precise location information such as latitude and longitude, UTM map datum, or some other map grid reference that can be interpreted by someone in another country. It may be useful to give the topographic sheet name and number, and directions and distance from permanent topographic features. In some cases it may be necessary to include the height within a section and access details to the locality. Include the stratigraphic details and age.

Briefly describe the main characteristics that might be useful for identification of the microbialite, using as much of the terminology in the 'Handbook for the study and description of microbialites' as appropriate. Pay attention to features such as megastructure, macrostructure, mesostructure and microstructure. Provide size information where possible. Present general geographic, stratigraphic and sedimentological information.

Option 3. General format for open nomenclature

'Microbialite (Stromatolite) morphological form [number]'

We suggest using the term 'morphological form' (all lower case) for informal descriptions to distinguish the concept from the taxonomic term 'Form', which would indicate a formally designated name.

List all illustrations relating to this morphological form and list any relevant catalogue numbers.

Material: Give an indication of specific material used for your description. This could be specimens in a collection, in which case supply the relevant repository and numbers, or they could be field specimens, in which case supply locality details (unless the site needs to be protected; see the section on 'Preparation for fieldwork'). Use precise location information such as latitude and longitude, UTM map datum, or some other map grid reference that can be interpreted by someone in another country. It may be useful to give the topographic sheet name and number, and directions and distance from permanent topographic features. In some cases it may be necessary to include the height within a section and access details to the locality. Include the stratigraphic details and age.

Description: This is the main description of the microbialite. Present all the characteristics that might be useful for the recognition of the morphological form (megastructure, macrostructure, mesostructure and microstructure) and provide as much quantitative information as possible. Follow the order and terminology in the 'Handbook for the study and description of microbialites'.

Remarks or discussion: Include here comments on the morphological form, such as any previous relevant references to the microbialite being described, and possible associations with other morphological forms or named taxa. Comment on the preservation (for example, 'microstructure may be too recrystallized for diagnostic information'), mode of occurrence, presence or absence of microfossils, other significant features such as abundance, and spatial relationships with other microbialites in the same bed, bioherm, or biostrome.

Comparisons: This section provides vital information for researchers wishing to compare morphologies. Explain how the morphological form compares with, and differs from, other previously described microbialites. Comment on other microbialites that may have some characteristics in common. Remember that your identification may be used by field geologists without a taxonomic background as well as taxonomists, so emphasize the features that distinguish this microbialite.

Distribution and age: Present general geographic and stratigraphic distributions of the morphological form, together with relevant geochronometric information (radiometric dating; biostratigraphic determinations), and any stable isotope data.

Option 4. General format for formal taxonomic descriptions (Protologue)

Description of Group

[*name of existing Group* plus author and date] or [name of *new Group*] followed by 'new Group'

Synonymy: If required, list chronologically all synonyms (i.e. scientific names that have been used to denote the same taxon), and list chronologically any misidentifications preceded by a modifier such as ?, *non,* and *nomen nudum.*

Type Form: [*the name of the Type Form for the Group*] plus [author and date] or [*name of the new Type Form*], the museum or institute collection or acquisition number, the stratigraphic unit, the location where collected, and the age of the unit.

Diagnosis: For a previously described taxon, state 'For original diagnosis see' and give a reference to the previous author(s) and date. For a new Group, present a brief but rigorous paragraph on the distinguishing features. When describing a new Group that is monospecific, avoid using 'as for new Form' in the diagnosis; concentrate on the major diagnostic features of the Group rather than specifics of the Form.

Comparisons: Discuss how this new Group compares with and differs from other, previously described Group(s).

Remarks or discussion: Make any comments here concerning the circumspection of the Group.

Content: Present all contained Forms with authors and dates.

Distribution: Present stratigraphic and geographic occurrences of the Group.

Description of Form

[*name of existing Form*] plus [author and date] or [*name of new Form*] followed by 'new Form'

[**Figs XX–XX**]: List all illustrations in the publication that are relevant to the Form. A photograph of the holotype must be included and clearly identified, and its catalogue number indicated, otherwise the name is not validly published.

Synonymy: If required, chronologically list all synonyms (i.e. scientific names that have been used to denote the same taxon), chronologically list any doubtful, misnamed, or misidentified names preceded by a modifier such as ?, *nomen nudum*, or *non.*

Etymology: (Unnecessary for a previously described taxon) For a new taxon, explain briefly the origin of the name; for example, after a place or morphological attribute. Indicate the language of the root and give the gender of the name.

Material: Indicate the holotype and paratypes by their numbers and the locality (or localities if paratypes are from more than one locality) where they were collected.

> **Holotype –** For a previously described Form, cite the holotype using the basionym (the original name used when first described), authors and date (later revisions of the name may also be cited with attributions). List the catalogue number(s), the repository of the type, locality details, and age. Use precise location information such as latitude and longitude, UTM with map datum or some other map grid reference that can be interpreted by someone in another country. It may be useful to give the topographic sheet name and number, and directions and distance from permanent topographic features. In some cases it may be necessary to include the height within a section and access details to the locality. Include the stratigraphic details and age.
>
> For a new Form, record the catalogue number(s), the repository of the type, locality details, and age of the specimens used to define the Form and their locality details. In some cases, a specimen may be serially slabbed and thin sectioned; therefore, the type should be the specimen and all its parts (slabs, thin sections, peels), and any applicable numbers should be documented. Since the introduction of the Melbourne Code (McNeill et al., 2012) or any other international code that may apply, a taxon is not considered valid unless repository information is included.

Paratytpes and other material – Record similar information as for the type, presenting information on the repository, catalogue numbers, number of specimens, and locality details. Include the stratigraphic details and age. This information could be highly significant if a type is lost or destroyed and a new type has to be selected.

Diagnosis: For a previously described Form, state 'For original diagnosis see' and give the reference to the previous author. For a new Form, present a brief but rigorous paragraph on the distinguishing features. Present the main diagnostic features (i.e. those that distinguish it from other taxa). Refer to the diagnostic features of megastructure, macrostructure, mesostructure and microstructure. Include, if appropriate, as much size data as possible without necessarily using these to define the Form.

Description: This is the main description of the new Form. Present all the characteristics that might be useful for the identification of the Form (megastructure, macrostructure, mesostructure and microstructure) and provide as much quantitative information as possible. Follow the order and terminology in the 'Handbook for the study and description of microbialites'. Some characteristics that do not seem important at the time of description may assume a diagnostic significance later, so as many features as possible should be described.

Remarks or discussion: Include here comments on the Form, such as a taxonomic reassignment, previous references to the Form, and possible associations with other Forms and morphological forms. Comment on the preservation (for example, 'the microstructure may be too recrystallized for diagnostic information'), spatial relationships with other microbialites in the same bed, bioherm, or biostrome, mode of occurrence, abundance, presence or absence of microfossils, and any other significant features.

Comparisons: This section provides vital information for researchers wishing to compare taxa. Explain how the Form compares with, and differs from, other previously described Forms. Comment on other Forms that may have some characteristics in common. Remember that field geologists without a taxonomic background may use your identification, so emphasize the features that distinguish this Form from others in the same succession.

Distribution and age: Present general geographic and stratigraphic distributions of the Form, together with relevant geochronometric information (radiometric dating; biostratigraphic determinations), and any stable isotope data.

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Appendix 3

Systematics — author attribution

Acaciella Britton & Rose 1928 (vascular plant)

Acaciella Walter 1972

Acaciella angepena Preiss 1972

Acaciella augusta Preiss 1972

Acaciella australica (Howchin 1914) Walter 1972

Acaciella savoryensis Grey and Walter 1994 in Walter et al. (1994)

Acaciella villosa (Sw.) Britton & Rose 1928 (vascular plant)

Alcheringa narrina Walter 1972

Alternella hyperboreica Raaben 1972

Anabaria chisienensis Liang and Tsao 1974 in Tsao and Liang (1974)

Anabaria juvensis Cloud and Semikhatov 1969 (incorrectly assigned to *Kotuikania juvensis* by Walter et al. (1979) and a senior synonym of *Elleria minuta* Walter, Krylov and Preiss 1979 – revision in progress)

Angulocellularia Vologdin 1962 (calcimicrobe)

Angusticellularia Vologdin 1962 (calcimicrobe)

Archaeozoon Matthew 1890

Archaeozoon acadiense Matthew 1890

Asperia digitata (Grey 1984) Grey 1994a

Atilanya fennensis Allen, Grey and Haines 2017

Australoconus abnera Walter et al. 1988

Baicalia Krylov 1963

Baicalia burra Preiss 1972

Baicalia capricornia Walter 1972

Baicalia lacera Semikhatov 1962

Baicalia mauritanica Bertrand-Sarfati 1972b

'BALBIRINA PRIMA' see Walter et al. (1988). Invalid name that does not conform to the rules of naming ranks higher than Group (genus) under the rules of nomenclature. The authors were not named in the publication, but were presumably Walter and Krylov, the authors of the taxonomic section of the paper

Basisphaera irregularis Walter 1972

Botomaella Korde 1958 (cyanobacteria)

Boxonia divertata Sidorov 1960

Boxonia gracilis Korolyuk 1960

Boxonia pertaknurra Walter 1972

Calevia olenica (Ryabinin 1941) Makharikin 1983

Carelozoon Metzger 1924

Carnegia wongawolensis Grey 1984

Chihsienella chihsienensis Liang and Tsao 1974 in Tsao and Liang (1974)

Chlorellopsis coloniata Reis 1923 (?green alga)

Cladophorites Reis 1923 (?green alga)

Collenia Walcott 1914

Collenia compacta Walcott 1914

Collenia undosa Walcott 1914

Colonella Komar 1964

Conophyton Maslov 1937

Conophyton new Form (Balfour type) Grey unpublished data

Conophyton new Form (Beyondie type) Grey unpublished data

Conophyton new Form (Heartbreak Hotel type) Grey unpublished data

Conophyton new Form (Montgomery Reef type) Grey unpublished data

Conophyton new Form (Pingandy type) Grey unpublished data

Conophyton new Form (Throssell type) Grey unpublished data

Conophyton new Form (Swan Yard type) Grey unpublished data

Conophyton new Form (Trendall type) Grey unpublished data

Conophyton garganicum australe Walter 1972

Conophyton inclinatum Rezak 1957

Conophyton jacqueti Bertrand-Sarfati and Moussine-Pouchkine 1985

Conophyton ressoti Menchikoff 1946; Bertrand-Sarfati 1972b

Conophyton weedii Walter 1976 in Walter et al. 1976

Cryptozoon Hall 1883

Cryptozoan proliferum Hall 1883

Earaheedia kuleliensis Grey 1984

Entophysalis (Kützing 1843) Drouet and Daily 1948

Ephyaltes edingunnensis Grey 1994a

Epiphyton Bornemann 1886

Eucapsiphora leakensis Grey 1984

Externia yilgarnia (Preiss 1976) Grey 1984

Favosamaceria cooperi Shapiro and Awramik 2006

Frutexina rubia Raaben 1972 in Raaben and Zabrodin 1972

Frutexites Maslov 1960

Girvanella Nicholson and Etheridge 1878; emend Wood 1957

Gruneria biwabikia Cloud and Semikhatov 1969

Gymnosolen Steinmann 1911

Gymnosolen ramsayi Steinmann 1911

Inzeria conjuncta Preiss 1973

Inzeria djejimi Raaben 1964

Inzeria intia Walter 1972

Inzeria multiplex Preiss 1973

Jacutophyton Schapavolova 1965

Jacutophyton sahariensis Bertrand-Sarfati and Moussine-Pouchkine 1985

Jurusania burrensis Preiss 1973

Jurusania derbalensis Bertrand-Sarfati 1972b

Jurusania nisvensis Raaben 1964

Kotuikania juvensis (Cloud and Semikhatov 1969) Walter, Krylov and Preiss 1979. In part *Anabaria juvensis*, in part a new Form of *Kotuikania* (revision in progress)

Kulparia alicia (Cloud and Semikhatov 1969) Walter 1972

Kulparia kulparensis Preiss 1974

Kussiella kussiensis Krylov 1963

Kussoidella karalundensis Grey 1994b

Linella avis Krylov 1967

Linella munyallina Preiss 1974

Madiganites mawsoni Walter 1972

Minjaria pontifera Walter 1972

Minjaria procera Semikhatov 1962

Murgurra nabberuensis Grey 1984

Nabberubia toolooensis Grey 1984

Nouatila frutectosa Bertrand Sarfati 1972a

Omachtenia F. indet. (previously recorded as *Omachtenia utschurica* Nuzhnov 1967 by Preiss, 1974)

Omachtenia teagiana Grey 1984

Pilbaria deverella Grey 1984

Pilbaria perplexa Walter 1972

Rahaella Raaben and Tewari 1987

Renalcis Vologdin 1932

Rivularia (Roth) Agardh ex Bornet and Flahault 1886

Scopulimorpha regularis Liang 1962

Segosia finlaysoniensis Grey 1994b

Serizia radians Bertrand-Sarfati 1972a

Sphaerocodium Rothpletz 1890

Stratifera Korolyuk 1960

Tesca stewartii Walter and Krylov 1979 *in* Walter et al. (1979)

Tilemsina divergens Bertrand-Sarfati 1972a

Tungussia Semikhatov 1962

Tungussia confusa Semikhatov 1962

Tungussia erecta Walter 1972

Tungussia etina Preiss 1974

Tungussia globulosa Bertrand-Sarfati 1972a

Tungussia hemispherica Bertrand-Sarfati 1972a

Tungussia julia Walter and Krylov 1979 *in* Walter et al. (1979)

Tungussia nodosa Bertrand-Sarfati 1972a

Tungussia wilkatanna Preiss 1974

Tysseria voronovae Raaben 1998. There is doubt about whether Raaben (1998, *in* Russian), or Raaben (2003, *in* Russian with English translations) constitutes the first formal publication

Uricatella urica Sidorov 1960

Vacerrilla walcotti Walter 1976 *in* Walter et al. (1976)

Wilunella glengarrica Grey 1994b

Windidda granulosa (Preiss 1976) Grey 1984

Yandilla meekatharrensis Grey 1984

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About th

Kathleen Grey was born in Blackpool, England, and educated at Blackpool Collegiate School for Girls. She completed a BSc (Hons) in 1969 and MSc (Palynology) in 1971 at the University of Sheffield, England, and a PhD in 1998 at Macquarie University, Sydney. In 1971, she joined the Geological Survey of Western Australia (GSWA), initially as an editor, but soon moved to the Paleontology Section and eventually became Chief Paleontologist, a position held until she retired in 2013. Since then, she has continued her interest in Precambrian paleontology and biostratigraphy.

Kath's early career included biostratigraphic studies of Devonian and Carboniferous palynology and brachiopods. However, the prevalence of Precambrian successions in Western Australia meant an increasing focus on Archaean and Proterozoic paleobiology. While at GSWA, she wrote more than 100 publications and 200 other reports, mostly concerning the biostratigraphic role of stromatolites, microfossils and other putative fossils. Microbialites were collected from more than a thousand Australian localities, and micofossils from Australia-wide analysis of Neoproterozoic and Mesoproteozoic drillcores. Kath (with colleagues) produced an Ediacaran palynological zonation, and developed an Australia-wide late Tonian and Cryogenian correlation scheme by integrating palynology, stromatolite biostratigraphy and isotope chemostratigraphy. She interpreted several controversial structures, including *Horodyskia* (the contentious Mesoproterozoic 'string of beads') and >2.9 Ga complex microfossils from the Farrel Quartzite. In 1997, she (and colleagues) found some of the most convincing evidence of Earth's early life — conical stromatolites in the 3.45 Ga Strelley Pool Formation, which have potential as analogues for fossil life on Mars and have since been studied by several international teams. Kath's results have been incorporated in GSWA's maps and reports, and have applications for petroleum and mineral exploration throughout Australia.

Kath is a Fellow of the Geological Society of Australia (GSA) and she was awarded the 2003 Gibb Maitland Medal by the GSA (WA Branch) for contributions to understanding the state's geology. She co-authored 'The rise of animals: evolution and diversification in the Kingdom Animalia', which was awarded the 2009 Victorian Premier's Literary Award Prize for Science Writing. In 2018, the Australasian Palaeontologists awarded her the Robert Etheridge Jnr Lifetime Achievement Award.

e authors

Stanley M Awramik is Professor of Biogeology in the Department of Earth Science, University of California, Santa Barbara. He was born in Lynn, Massachusetts and his family moved to Niagara Falls, New York, when he was five. Growing up, the fossiliferous middle Paleozoic rocks of the Niagara Falls area piqued his interest in paleontology. Following this interest, he obtained his BA in Geology with Distinction from Boston University in 1968 writing a senior thesis on Ordovician calcareous algae. He earned his PhD in Geology from Harvard University in 1973 with a thesis on stromatolites. This was followed by a one-year postdoctoral position at Harvard studying the microbiota of the Paleoproterozoic Gunflint Formation. In 1974 he accepted a faculty position at the University of California, Santa Barbara, where he continues to teach.

Throughout his career, Stan's research interests have focused on microbialites and Precambrian microfossils. He has published over 100 papers, mainly on those topics. His research has taken him up and down the geologic column studying microbialites from many environments (lakes, springs, and oceans). Fieldwork, an integral part of his research, has taken him to Africa, Europe, China, Canada, Greenland, United States, and Australia, in particular Western Australia. Although weaned on ancient and modern marine microbialites, his attention has centred recently on lacustrine microbialites, both modern and fossil. Especially interesting are the lacustrine microbialites of the Neoarchean Tumbiana Formation in Western Australia and the Eocene Green River Formation in Wyoming, Colorado and Utah, US. Both these ancient lake systems were enormous and rich in microbialites. The Green River research is ongoing and includes determining the factors that control initiation and development of microbialites, their development into biostromes and bioherms, and their sedimentological context, stratigraphic distribution, and facies relationships. The Green River research has captured the interest of oil companies because of the role that microbialites play in lacustrine petroleum reservoirs.

Stan is a recipient of Boston University's College of Arts and Sciences' Distinguished Alumni Award. He is a Fellow of the American Association for the Advancement of Science and the Geological Society of America, and received the Outstanding Contributions to Geobiology Award from the Geological Society.

A lack of consistent, comprehensive descriptive terminology has hindered comparative studies of microbialites. This handbook addresses the problem by standardizing terminology, eliminating duplication, clarifying definitions and providing schematic and actual illustrations of the features described.

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An outcome of five decades of research on microbialites:

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- showcases microbialites in the field and in the extensive collections of GSWA, UCSB and other institutions
- examples represent a wide geographic and stratigraphic spectrum
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- proposes a Code of Microbialite Nomenclature to resolve a serious threat to existing and future microbialite systematics

This book will be of particular interest to:

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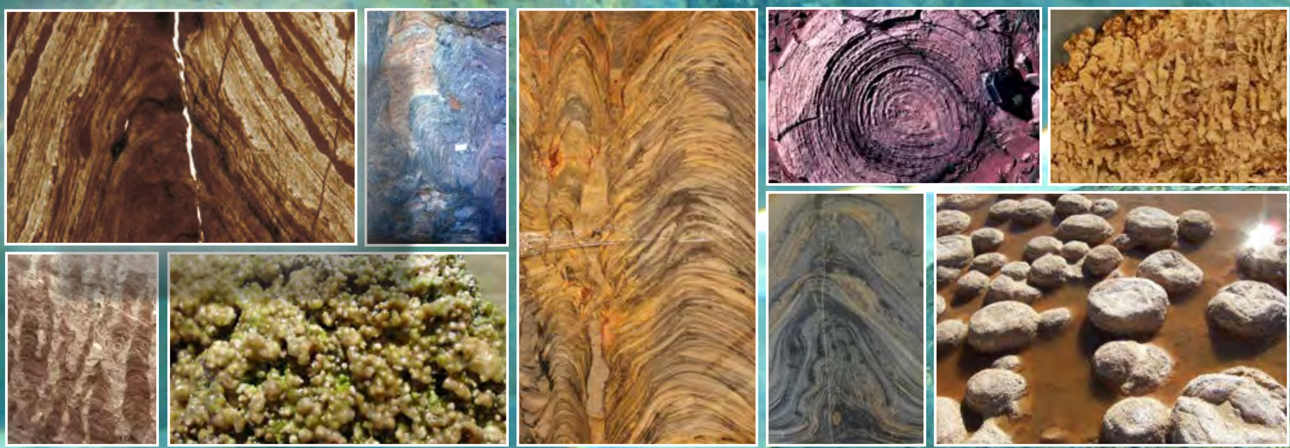
- members of the public interested in the origins and evolution of life



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