

John K. Warren

Evaporites : Sediments, Resources and Hydrocarbons

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With 654 Figures

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Preface

My aim in writing this book is to offer a comprehensive synthesis of the low temperature (sedimentary) realm of evaporite evolution. It's now more fifteen years since the last comprehensive book on evaporite sedimentology was published; an excellent piece, edited by Judy Melvin (1991). There are also the earlier efforts of yours truly in 1989 and the volume edited by Charlotte Schreiber back in 1988. The present volume follows on from my previous book on evaporites (Warren, 1999). That book attempted to address the diversity of evaporites from deposition into the igneous and metamorphic realms. To achieve this in a single volume without destroying large areas of rainforest meant I had to brush over substantial parts of our wealth of knowledge in evaporite sedimentology, especially in terms of modern depositional studies. In this volume I have attempted to redress this, while also attempting to publish for the first time a comprehensive discussion of the role of evaporites in hydrocarbon generation and trapping. The pulling together of diverse sources of knowledge on exploitable salts, along with a summary of evaporite karst hazards as well as a summary of exploitation methods and pitfalls in dealing with evaporites in conventional and solution mining has not, to my knowledge, been done before.

After an introduction to evaporite textures and depositional brine chemistries (Chapters 1 and 2) this book goes on to present detailed discussions of; Quaternary environments (Chapters 3, 4), ancient salts (Chapter 5), salt tectonics (Chapter 6), evaporite karst and its indicators (Chapter 7), burial hydrology (Chapter 8), life in evaporitic settings and their potential for sourcing hydrocarbons (Chapter 9), the role of evaporites and seals as instigators of hydrocarbon reservoirs and traps in many sedimentary settings (Chapter 10). The last two chapters deal with the characteristics of exploitable salts (Chapter 11) and the methods for their exploitation and utilisation as waste storage receptacles via solution mining (Chapter 12). Chapter 12 also discusses some of the environmental problems that overzealous exploitation or ignorance has created. Parts of this book are updated and expanded versions of some of the chapters in my 1999 book (Chapters 1, 2, 5, 6, 7 and 11), the other chapters are completely new.

I would like to thank the following individuals and companies who allow me to work at the things I enjoy most; geological research and training. First and foremost my thanks to his Majesty, Sultan Haji Hassanal Bolkiah Mu'izzadin Waddaulah Sultan Yang Di-Pertuan of Brunei Darussalam for allowing me to live and work in Brunei. Thanks to the Universiti Brunei Darussalam, which has generously allowed me the time to write this book and also through the UBD research facility funded some of the trips to various libraries to facilitate the gathering of the reference material so necessary in compiling a comprehensive text. Thanks to Brunei Shell (BSP) and to Total Brunei for their foresight in funding the Department of Petroleum Geoscience at UBD and so allow a centre of excellence to grow in this part of the world. My thanks to my fellow faculty and staff in Petroleum Geosciences at Universiti Brunei - Chris, Joe, Angus, Martin, Iqbal, Farrah and Lim. Thanks also to Schlumberger, Earth Sciences at Flinders University, King Fahd University of Petroleum and Minerals, to Ian Cartwright's Group at Monash University in Melbourne and to the former National Centre of Petroleum Geology at Adelaide University for allowing the use of their library facilities in compiling this book. Thanks to Chess at the DMR in Thailand and to Mahbub at King Fahd University, Saudi Arabia, and to all the other groups and individuals who over the years have challenged and changed my ideas on evaporites.

Most importantly and most completely, my thanks to my wife Jennifer, who even after more than 30 years of marriage still manages to live with her at times abstracted other half.

Lastly, I would like to acknowledge NASA. The numerous Landsat images used throughout this book to illustrate modern depositional patterns were cut from larger scenes downloaded from the GeoCover Orthorectified Landsat Thematic Mapper Mosaics site (<https://zulu.ssc.nasa.gov/mrsid/>). The data set was produced by the Earth Satellite Corporation for NASA and came from satellite imagery acquired by Landsat 5 & 7, circa 1990 & 2000. It is an excellent scientific resource published on the internet for free use by the world community but now perhaps superseded by Google Earth.

John K. Warren, November, 2005
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TO MY WIFE, JENNIFER
AND MY SONS,
MATTHEW AND TRISTAN

Eppur si muove

(And yet, it does move)

Galileo Galilei after recanting Copernican beliefs

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Chapter 1: Interpreting evaporite texture

Salts such as halite, gypsum and trona, have long been significant in the affairs of man, both as a preservative and as an industrial feedstock. Gypsum and halite are listed, along with several other salts, in the Sumero-Assyrian dictionaries written during the rule of the Assyrian king Assurbanipal (668-626 BC). By then the ancient Egyptians had been using *natrum*, an impure mixture of trona and other sodium salts, for several thousand years, both as an important part of the mummification process and for salting food. Today halite is a major feedstock to the chemical manufacturing industries, as are several other varieties of salt. Salts are also important in the trapping, sealing and perhaps generation of hydrocarbons and various metal deposits. Manufactured salt cavities are used as long term waste repositories, as receptacles for the safe storage and cycling of liquids and gases and even for the manufacture of peak load electricity. This book is all about where, how and why this is so in the sedimentary realm.

What are the basic requirements to form and preserve a bed of salt? We need; 1) a surface and nearsurface brine body that is saline enough to precipitate and preserve salt, this typically means an arid to semi-arid climatic setting with a drawdown hydrology capable of maintaining substantial volumes of brine at or near the landsurface, 2) accommodation space in a sedimentary depression that is not filled by other sediment, and 3) a burial environment that does not allow sufficient undersaturated throughflow to completely dissolve the buried salts (Figure 1.1).

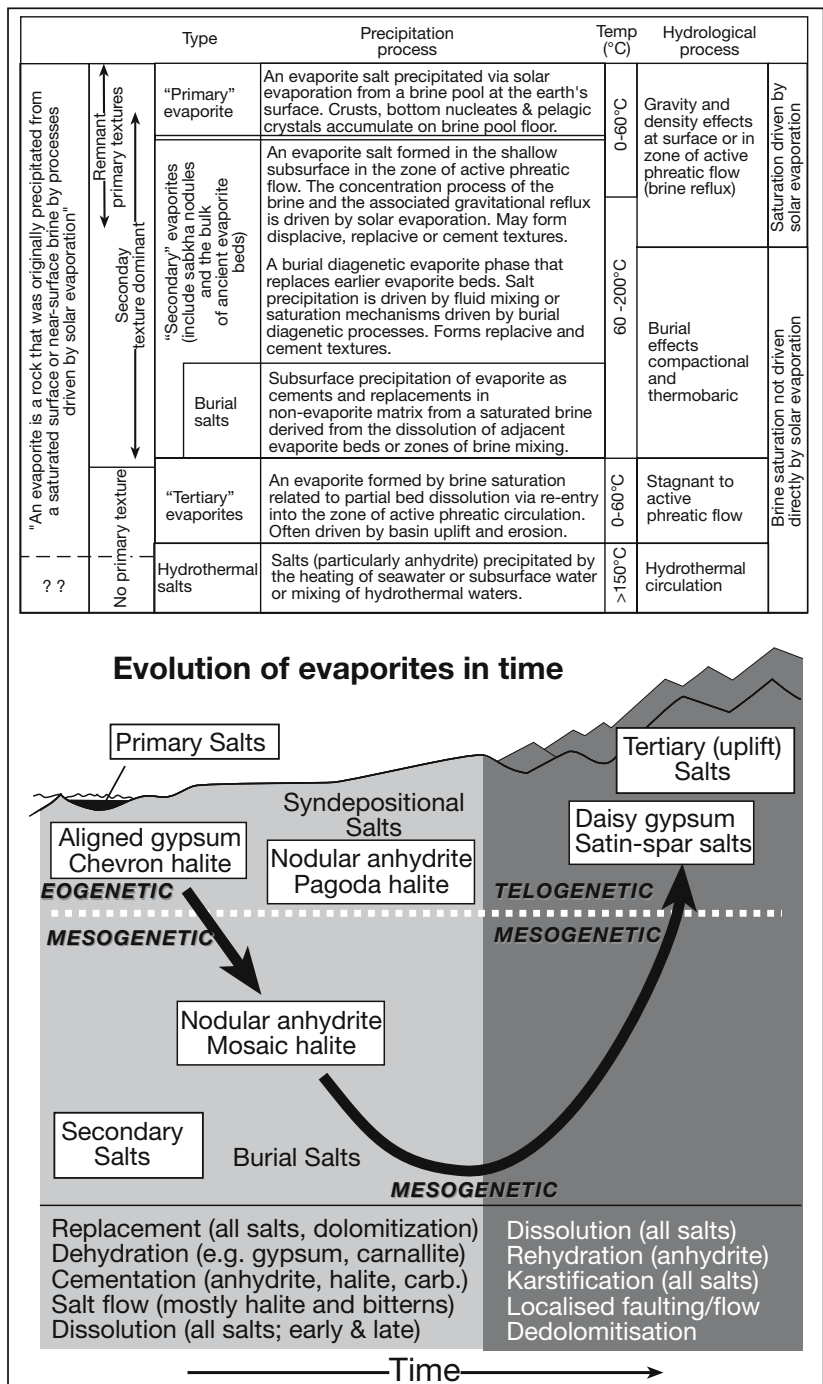


Figure 1.1. Classification of evaporite formation in the depositional-diagenetic realms emphasizing ongoing postdepositional evolution of mineralogy and texture.

Evaporites defined?

I define an evaporite as a salt rock that was originally precipitated from a saturated surface or nearsurface brine by hydrologies driven by solar evaporation (Figure 1.1). This simple definition encompasses a wide range of chemically precipitated salts and includes alkali earth carbonates (Table 1.1). Some workers restrict the term evaporite to those salts formed directly via solar evaporation of hypersaline waters at the earth's surface. In order to emphasise the highly reactive nature of evaporites in the sedimentary realm I think of such evaporites as primary, that is, precipitated from a standing body of surface brine and retaining crystallographic evidence of the depositional process (e.g. bottom-nucleated or current-derived textures). Outside of a few Neogene examples, there are few ancient evaporite beds with textures that are wholly and completely “primary” (Figure 1.1).

Almost every subsurface evaporite texture is secondary; it is diagenetically altered, frequently with fabrics indicating pervasive early recrystallisation and perhaps some later crossflow of basinal waters. Under this definition of a primary versus secondary salt, even the nodules in Holocene mudflats, including those in the type area for sabkhas the Arabian (Persian) Gulf, are secondary textures. They are a porewater overprint superimposed on a primary matrix of mud and sand. Ancient bedded evaporites are typically dominated by secondary textures, although beds may still retain “ghosts” or partial relicts of primary textures such as laminae, aligned anhydrite nodules after growth-aligned gypsum, or patches of aligned halite chevrons floating in a matrix of mosaic halite spar. Even when evaporite beds are extensively recrystallised, most retain laminae made up of impurities that define primary depositional laminae.

In the subsurface it is the ability of evaporites to flow easily, even as they backreact or dissolve, that distinguishes them from other types of sediment. Earliest secondary evaporites are syndepositional precipitates, forming cements and replacements even as the primary matrix accumulates around them. Early replacement sometimes preserves remnants of the original depositional texture, such as gypsum ghosts in nodular anhydrite or aligned halite chevrons. Nodular anhydrite ghosting lenticular gypsum was recognised in Permian mudflats in the early 1960s by Kerr and Thomson (1963), they interpreted it as a subaqueous saline pan indicator. Unfortunately, for the next two decades their results were overlooked by workers in the Permian Basin who incorrectly applied supratidal capillary models based on the Arabian Gulf sabkha anhydrite (Warren and Kendall, 1985).

Early diagenetic overprints and effects of later compaction-driven flow and pressure solution destroy much of the depositional evidence in any ancient evaporite bed. This means retention of primary crystal textures is at best patchy in both halite and anhydrite beds. Many ancient bedded halites are dominated by coarsely crystalline halite spar. Much of it was deposited in multiple episodes of early diagenetic (syndepositional) cementation, leaving less than 10-15% of the bed as primary growth-aligned chevrons. This syndepositional coarse sparry halite formed in multiple dissolution-precipitation events in microkarst pits and was precipitated between successive depositional episodes of chevron halite crust formation (Chapter 3). Other coarsely crystalline halite spar, especially in halokinetic beds, shows pervasive and multiple flow-aligned textures created by pressure-solution. Textures are driven by numerous salt creep and recrystallisation episodes, which occur millennia to millions of years postdeposition, and after hundred to thousands of metres of burial (Chapter 6).

Secondary evaporites form in subsurface settings equivalent to the eogenetic and mesogenetic porosity realms as defined for carbonates by Choquette and Pray (1970). Tertiary evaporite textures tend to form in the telogenetic realm (Figure 1.1) And, as in carbonate diagenesis, the most pervasive alteration of evaporites is either early in the burial history (eodiagenesis) or it occurs much later during uplift (telodiagenesis). Both the eogenetic and telogenetic settings are characterised by relatively permeable evaporites and hydrologies capable of high volumes of pore fluid crossflow. Alteration of a salt mass in the mesogenetic realm consists largely of recrystallisation overprints within a flowing salt mass, but with substantial alteration and dissolution possible about the edge of a bed or a flowing salt mass. In carbonates the mesogenetic overprint tends to be pervasive throughout the bed (Choquette and Pray, 1970). In evaporites the pervasive early loss of porosity and permeability in the shallow diagenetic/eogenetic realm means that deep burial (mesogenetic) alteration tends to be concentrated about the edges of a buried salt body (see discussion of dissolving salt “block of ice” model in Chapters 7 and 8). Unlike carbonates and siliciclastics, the core of the subsurface salt unit is largely unaffected by processes of burial alteration, although they are ongoing in the encasing nonevaporitic sediments and will only cease when the adjacent nonevaporite beds lose their effective porosity. Preservation of the unaltered core of the salt unit is why viable Permian halobacteria can be cultured from brine inclusions in remnant chevrons in Permian salt from west Texas (Vreeland et al., 2000).

Mineral	Formula	Mineral	Formula
Anhydrite	CaSO ₄	Leonhardtite	MgSO ₄ ·4H ₂ O
Antarcticite	CaCl ₂ ·6H ₂ O	Leonite	MgSO ₄ ·K ₂ SO ₄ ·4H ₂ O
Aphthitalite (glaserite)	K ₂ SO ₄ ·(Na,K)SO ₄	Loewite	2MgSO ₄ ·2Na ₂ SO ₄ ·5H ₂ O
Aragonite **	CaCO ₃	Mg-calcite **	(Mg _x Ca _{1-x})CO ₃
Bassanite	CaSO ₄ ·1/2H ₂ O	Magnesite**	MgCO ₃
Bischofite	MgCl ₂ ·6H ₂ O	Meyerhoffite	Ca ₂ B ₅ O ₁₁ ·7H ₂ O
Bloedite (astrakanite)	Na ₂ SO ₄ ·MgSO ₄ ·4H ₂ O	Mirabilite	Na ₂ SO ₄ ·10H ₂ O
Borax (tincal)	Na ₂ B ₄ O ₇ ·10H ₂ O	Nahcolite	NaHCO ₃
Boracite	Mg ₃ B ₇ O ₁₃ ·Cl	Natron	Na ₂ CO ₃ ·10H ₂ O
Burkeite	Na ₂ CO ₃ ·2Na ₂ SO ₄	Nitratite (soda nitre)	NaNO ₃
Calcite**	CaCO ₃	Nitre (salt petre)	KNO ₃
Carmallite	MgCl ₂ ·KCl·6H ₂ O	Pentahydrate	MgSO ₄ ·5H ₂ O
Colemanite	Ca ₂ B ₅ O ₁₁ ·5H ₂ O	Pirssonite	CaCO ₃ ·Na ₂ CO ₃ ·2H ₂ O
Darapskite	NaSO ₄ ·NaNO ₃ ·H ₂ O	Polyhalite	2CaSO ₄ ·MgSO ₄ ·K ₂ SO ₄ ·H ₂ O
Dolomite**	Ca _(1+x) Mg _(1-x) (CO ₃) ₂	Proberite	NaCaB ₅ O ₉ ·5H ₂ O
Epsomite	MgSO ₄ ·7H ₂ O	Priceite (pandermite)	CaB ₄ O ₁₀ ·7H ₂ O
Ferronatronite	3NaSO ₄ ·Fe ₂ (SO ₄) ₃ ·6H ₂ O	Rinneite	FeCl ₂ ·NaCl·3KCl
Gaylussite	CaCO ₃ ·Na ₂ CO ₃ ·5H ₂ O	Sanderite	MgSO ₄ ·2H ₂ O
Glauberite	CaSO ₄ ·Na ₂ SO ₄	Schoenite (picromerite)	MgSO ₄ ·K ₂ SO ₄ ·6H ₂ O
Gypsum	CaSO ₄ ·2H ₂ O	Shortite	2CaCO ₃ ·Na ₂ CO ₃
Halite	NaCl	Sylvite	KCl
Hanksite	9Na ₂ SO ₄ ·2Na ₂ CO ₃ ·KCl	Syngenite	CaSO ₄ ·K ₂ SO ₄ ·H ₂ O
Hexahydrate	MgSO ₄ ·6H ₂ O	Tachyhydrate	CaCl ₂ ·2MgCl ₂ ·12H ₂ O
Howlite	H ₅ Ca ₂ SiB ₅ O ₁₄	Thernadite	Na ₂ SO ₄
Ikaite**	CaCO ₃ ·6H ₂ O	Thermonatrite	NaCO ₃ ·H ₂ O
Inyoite	Ca ₂ B ₆ O ₁₁ ·13H ₂ O	Tincalconite	Na ₂ B ₄ O ₇ ·5H ₂ O
Kainite	4MgSO ₄ ·4KCl·11H ₂ O	Trona	NaHCO ₃ ·Na ₂ CO ₃
Kernite	Na ₂ B ₄ O ₇ ·4H ₂ O	Tychite	2MgCO ₃ ·2NaCO ₃ ·Na ₂ SO ₄
Kieserite	MgSO ₄ ·H ₂ O	Ulexite	NaCaB ₅ O ₉ ·5H ₂ O
Langbeinite	2MgSO ₄ ·K ₂ SO ₄	Van'thoffite	MgSO ₄ ·3Na ₂ SO ₄

Table 1.1. Major evaporite minerals: less saline alkaline earth carbonates or evaporitic carbonates are indicated by **, the remainder are the more saline evaporite salts. Documented dolomite composition ranges from Ca_{1.16}Mg_{0.84}(CO₃)₂ to Ca_{0.96}Mg_{1.04}(CO₃)₂. Less common evaporite minerals, such as borates, iodates, nitrates and zeolites are not listed here, but are discussed in detail in Chapter 11.

Unlike quartzose and aluminosilicate sediments, buried evaporite beds can flow as ductile masses from the surface down to 8-10 km of burial and even into the metamorphic realm. At the same time their dissolving edges supply ions to adjacent nonevaporitic sediments. Salt flow can be: a) early diagenetic, coinciding with syndepositional fractionation, reflux or dissolution; b) later diagenetic, associated with complex

burial-stage bed dissolution or reprecipitation and driven by subsurface fluid flow in the zone of free convection below the zone of overpressure; c) widespread and pervasive, as occurs during halokinesis (salt tectonics); and d) postdiagenetic and extending well into the metamorphic realm where daughter minerals, such as scapolite and tourmaline, can act as a source of volatiles and lubricants long after the precursor salts have gone (Warren 1999; Chapter 6).

	Siliciclastic: (continental, fluvio-deltaic, shelf, submarine)	Carbonate: Humid-Oceanic/marine Tropical/subtropical	Carbonate-evaporite: Arid, land-locked Subtropical/Temperate
Early marine cementation	Rare	Local occurrence	Pervasive (especially in mesohaline platform)
Dolomitisation	Rare	Locally in mixing zones (?)	Pervasive (brine reflux and burial)
Leaching	Uncommon, mostly related to freshwater leaching, rare in burial diagenesis	Common, related to subaerial exposure and karstification	Intensive, related to hypersaline brines
Calcite cementation	Uncommon, locally common (mostly related to burial)	Common	Rare to local occurrence (mostly burial)
Anhydrite-halite	Uncommon	Rare to absent	Common to pervasive
Porosity types	Intergranular	1) Mouldic, vuggy and chalky microporosity (common) 2) Fracture and intercrystalline porosity (local occurrence)	1) Intergranular, mouldic, vuggy, and intercrystalline (dolomitic) porosity (very common) 2) Fracture and chalky microporosity (locally common)
Controls on reservoir quality	1) Stratigraphic position 2) Depositional facies	1) Stratigraphic position 2) Depositional facies 3) Karst in zones on meteoric influx	1) Depositional facies 2) Accessibility of sulphate- and chloride-bearing and later corrosive fluids (karstic or deep)
Geometry	Layered	Layered	1) Carbonate-basinwide evaporite: Massive irregular 2) Carbonate-salttern-mudflat evaporite: layered

Table 1.2. Characteristics of siliciclastic and carbonate depositional systems (in part after Sun and Esteban, 1994).

Exhumed or uplifted evaporite beds also undergo pervasive alteration, dissolution and replacement as they re-enter the zone of active phreatic flow (telogenesis) and regain permeability. Once again, alteration tends to occur from the edges inward. Soluble components from the altering and dissolving bed can be reprecipitated in adjacent shales as alabastrine and satinspar gypsum or fibrous halite. Exhumed evaporite textures are termed tertiary (Figure 1.1) and are varying combinations of competitive crystal alignment and geopetal void fills. The resulting fabrics can duplicate “primary” crystal alignments, especially when parts of a cavern fill can only be studied at a limited scale, as in core or a mine face. Not recognising a telogenetic overprint typically misidentifies tertiary evaporite textures as primary and so creates interpretive confusion (Chapter 7).

Adjacent nonevaporitic sandstones, shales and limestones also undergo diagenetic reactions when flushed by evolving pore fluids, but the diagenetic rock/fluid framework is slower to respond and requires years to millennia to overprint an original depositional texture. But, given enough time the textures of many other sediments, like evaporites, evolve during burial (Table 1.2).

Evaporite mineralogy and texture will change with time, but all ancient secondary and tertiary evaporites occur within the volume of rock that was originally precipitated as the primary or syndepositional salts. Outside of these evaporite sediments

there are two other classes of salts that are not “true evaporites” in that they did not form via hydrologies first driven by solar evaporation and are precipitates that do not necessarily occupy the same position in earth space as the precursor evaporites. I term the two classes, burial salts and hydrothermal salts (Figure 1.1). Burial salts are made up of minerals, such as anhydrite or halite, which do not necessarily occupy the same rock volume as the original sediment. Their occurrence is related to subsurface fluid flow, hydrofracturing, brine mixing and brine cooling. Burial salts typify the commonplace authigenic cements and replacement salts that precipitate in a nonevaporite matrix from subsurface brines derived by dissolution of an adjacent evaporitic salt bed. Because of the proximity to a “true” evaporite bed, most authors would consider burial salts a form of “true” secondary evaporite.

In contrast, hydrothermal salts do not require a nearby dissolving evaporite to form. Hydrothermal anhydrite forms by heating of seawater or by the subsurface mixing of CaSO_4 -saturated hydrothermal waters, either during ejection of hot hydrothermal water into a standing body of seawater, or during convective magmatic circulation. Hydrothermal salts are poorly studied, but often intimately intermixed with sulphides in areas of base-metal accumulations, such as the Kuroko ores in Japan or the exhalative brine deeps in the Red Sea. Hydrothermal anhydrite is a commonplace salt in many such active volcanogenic-hosted massive sulphide deposits (see Warren, 1999; Chapter 9).

Primary evaporites

The simplest subdivision of evaporite minerals is into evaporitic alkaline earth carbonates – aragonite, dolomite, low-Mg calcite and high-Mg calcite – and evaporite salts – gypsum, anhydrite, halite, trona, carnallite, etc. (Table 1.1). Primary evaporitic carbonates tend to form in the initial stages of brine concentration, whereas the other primary evaporite salts are precipitated in the more saline stages of concentration (Chapter 2). Evaporitic carbonates can contain and preserve elevated levels of organic matter that subsequently generate hydrocarbons or act as reductants for base metal sulphides (Chapter 9).

Evaporitic carbonates

Evaporitic alkaline earth carbonates are the first evaporite minerals to precipitate from a concentrating hypersaline surface water and are usually composed of aragonite, high- and low-Mg-calcite, magnesite or even primary dolomite. The essential hydrology of any evaporite depositional setting is that evaporative outflow exceeds inflow. This results in two characteristics of the carbonate depositional system, which hold also for the more saline evaporite salts. First, rapid changes in water level are possible, especially in the more marginward facies, leading to interlayering of strandzone and subaqueous units. Under such a regime any subaqueously precipitated carbonate is liable to subaerial exposure and syndepositional subaerial diagenesis. Second, the solute content, especially the Mg/Ca ratio, of shallow hypersaline water fluctuates as the salinity fluctuates. For example, the Ca content of any brine is depleted by the early precipitation of calcite or low-Mg calcite. Subsequent carbonate precipitates drop out of an increasingly saline water and so will have a higher Mg/Ca ratio and tend to be dominated by high-Mg calcite, aragonite, magnesite, or even dolomite.

Carbonate laminites (subaqueous sediment?)
Mm-scale lamination is volumetrically the dominant

sedimentary structure in modern and ancient evaporitic carbonates as well as in higher salinity salts, but its origins are varied and complex (Figure 1.2). Sometimes it is an inorganic cumulate, other times it is biologically structured (biolaminite - see next section). Beds dominated by finely laminated, regular alterations of two or more sediment types are called laminites or rhythmites. Many evaporitic carbonate laminites form couplets or even triplets by the regular superposition of micrite with siliciclastic clay, organic matter or evaporite salts. Such couplets and triplets are frequently referred to as varves, yet are not necessarily “true” varves in that the layers do not define annual couplets.

As an example of a contemporary carbonate laminite, consider deep bottom sediments deposited prior to 1979 in the Northern Basin in the Dead Sea, Israel (Figure 4.48). They are made up of alternating light and dark mm laminae that accumulated beneath a density-stratified brine column more than 350 m deep. The whitish laminae are composed of stellate clusters of aragonite needles (5-10 μm diameter), which precipitated each summer at the air-brine interface and then sank. The darker laminae consist of clay minerals, quartz grains, detrital calcite and dolomite that washed in as suspended sediment from the surrounding highlands during occasional storm floods (Garber

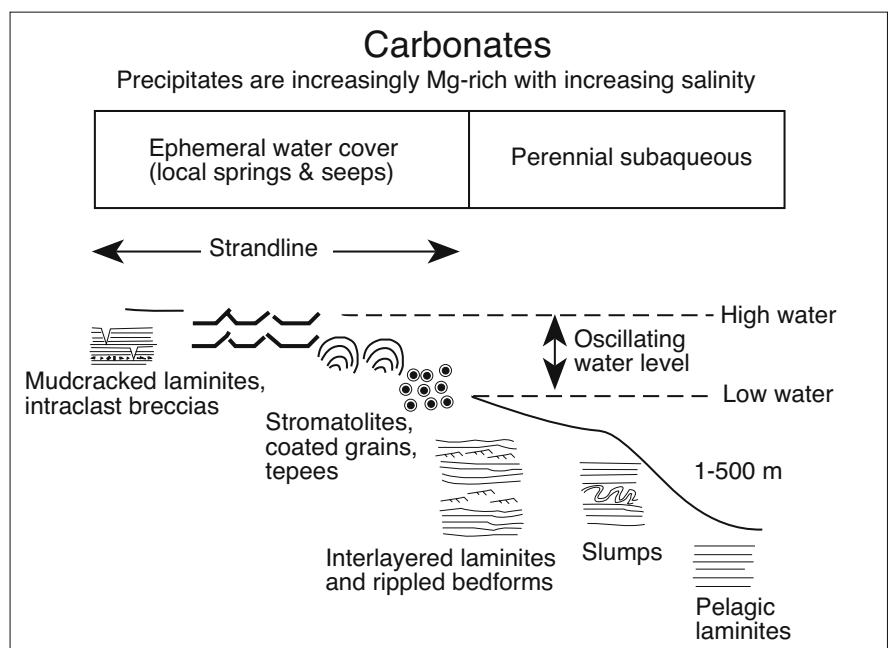


Figure 1.2. Depositional significance of evaporitic carbonate textures. Note the distinction between subaqueous and strandline (ephemeral water) indicators.

et al., 1987). Thus laminites in the Dead Sea are not annual layers, but indicate flood events that occur every 3-5 years.

Permanent water column stratification, with periodic algal blooms at the surface, characterises the waters of Lake Tanganyika. Deep bottom laminites (seasonal varves) containing between 7% and 11% total organic carbon (TOC) accumulate as modern lake bottom sediments where waters are anoxic and more than 250m deep (Cohen, 1989). Or consider the shallow lacustrine laminites of the more saline Holocene Coorong Lakes, Australia (Warren, 1988, 1990). Coorong laminites make up more than 80% of the Holocene sediment volume in the Coorong Lakes and are composed of alternating dark-grey organic-rich and light-grey organic-poor laminae. Matrix mineralogies range from hydromagnesite to aragonite to Mg-calcite to dolomite and organic levels can be as high as 16% TOC. As in the Dead Sea, the Coorong laminites formed subaqueously on the floor of a chemically stratified lake. Unlike the 250+ metres depths of the Dead Sea and Lake Tanganyika, Coorong laminites accumulated as microbially entrained pelletal wackestone/mudstones beneath seasonally stratified perennial lake waters, less than 1-5 metres deep (Figure 4.4b). Once on the bottom these pellets are easily eroded and redeposited as wave-driven bedload, the resulting laminite layering is not a varve.

Laminites can also be preserved under conditions of ephemeral subaerial exposure. Algal-bound laminites (algal mats or biolaminites) crosscut by mudcracks characterise the algal channel and strandzone facies in many modern and ancient evaporitic carbonates such as the sabkhas of the Arabian Gulf (Figure 3.4e). Modern and ancient laterally extensive carbonate laminites, without evidence of subaerial exposure, indicate subaqueous deposition under fluctuating surface water chemistries. They indicate water depths that may have ranged from a few decimetres to hundreds of metres and are not necessarily associated with deepwater conditions (Warren, 1985; Kendall, 1992). They do indicate a lack of burrowing metazoans in saline carbonate sediments deposited across this wide range of water depths.

Strandzone associations: Microbialites, pisolites and tepees

The strandzone in many evaporitic carbonate systems is characterised by an association of stromatolites, mud-cracked cryptalgalaminites (biolaminites), pisolites, ooids, intraclasts, cemented crusts and tepees (Figure 1.2). Strandzones typify deposition associated with fluctuating shorelines about the

edge of a more permanent brine lake or seaway and form in areas of groundwater springs, mudflats and ponds. Rapid fluctuations of strandlines (wet and dry cycles) and associated high rates of capillary crossflow mean this facies association is syndepositionally cemented as it aggrades into stacked layers of intraclast breccia, biolaminites, pisolites and tepees, typically separated by salt beds or their dissolution breccias. Biofilms and mats, in otherwise muddy and granular matrices of any uncemented strandzone sediment, gives a leathery depositional strength to this sediment that encourages the preservation of rip-ups, tears and overfolds due to storm-induced erosion. Biostabilization also tends to encourage the preservation of fenestrae and gas-filled cyanobacterial domes in the surface crusts of many modern strandzones of saltflats and playas.

Stromatolites and microbialites

Microbialites are biogenic structures, the mineralised result of the metabolic activities of microphytic algae, cyanobacteria or archaeobacteria (Figure 1.3; Riding, 2000). Microbialitic structures are commonplace sediments in evaporitic strandzones, textures range from biolaminites (\approx cryptalgalaminites) and stromatolites (matrix-supported agglutinated microbial reefs) through tufa/travertine (cement-supported) reefs to thrombolites (agglutinated reef). Stromatolites and cyptalgalaminates are the most easily recognised microbialites in ancient evaporitic settings (Figure 1.3). Quaternary tufas and travertines tend to characterise the humid hydrological stages of saline lakes when water levels tend to be high and surface water less saline. Internally, microbial textures can be stromatolitic (fine planar-undulating to wavy-crenulated lamination), oncologic (concentrically laminated), thrombolitic (with mesoscale clotted textures, not to be confused with clotted or grumous microfabrics, which occur in both thrombolites or stromatolites) or cryptic (no obvious internal structure).

Biology of stromatolites and microbial layers

Stromatolites to some researchers are a specific layered type of microbialite, often defined as laminated organosedimentary structures with positive relief away from a point or limited surface of attachment (e.g. Burne and Moore, 1987). In this sense stromatolites are equivalent to agglutinated microbial reefs in the terminology of Riding, 2002. To others, stromatolites are not necessarily a biological construct. Microbes and biofilms may be present at the time chemical sediments accumulate, but they play a passive role in textural style during the deposition of this type of stromatolite. Researchers with this view of stromatolites like to add the phrase "it may or may not be of

biological origin” to any definition of an ancient stromatolite. This distinction becomes important as we shall see in a later discussion of pre-Mesozoic evaporitic stromatolites, but reliably defining the contribution of a biofilm to rock texture in ancient evaporitic carbonates is at times near impossible.

Stromatolite shapes range from columnar to domal to subspherical. Internal layers of most modern stromatolites define the successive positions of an agglutinating bioplexi (algal/bacterial community), with each accreting layer produced by trapping and binding of sand to mud-sized sediment. In some settings agglutination occurs in conjunction with direct carbonate precipitation onto or within cyanobacterial trichomes, a process driven by changes in ambient $p\text{CO}_2$ (Figure 1.4a). Modern lacustrine stromatolites tend to be precipitative biochemical structures, while modern marine-margin stromatolites tend to be largely agglutinated structures; both possess surface microbial communities that evolve as the stromatolites prograde (Duane and Al-Zamel, 1999). Many coarser-grained stromatolites in the modern marine and marine margin realms, as in Lee stocking Island and Shark Bay, are poorly layered agglutinated forms and are transitional into thrombolitic structures. Fine-grained mm-laminated stromatolites tend to form best in or near seepage zones in modern hypersaline lakes, such as Marion Lake in South Australia, Gotomeer in the Netherlands Antilles and the Dead Sea in the Middle East, rather than in the open marine realm (Warren, 1982a; Kobluk and Crawford, 1990; Druckman, 1981).

Dominant members of modern microbial plexi range from archaea to eubacteria to cyanobacteria to algae with the proportions and species changing with depth in the sediment and salinity of the water column (Figures 9.16, 9.17). The most common biotal constituents of well-preserved stromatolitic bioherms in Phanerozoic evaporitic settings are filamentous and coccoid cyanobacteria, with lesser halobacteria (Figure 1.4b, c). Species components not only change with water depth and brine salinity but have changed over the course of geological evolution (Figure 1.4b). Modern cyanobacteria typically extrude a mucilaginous sheath that protects the contributing biota from UV radiation. The gooey mucilage also captures sediment particles creating further UV screening, but too thick a sediment layer can cut the necessary exposure to light and so slow photosynthesis. Large amounts of water are held in the mucous sheath and so it also serves as a buffer against osmotic stress.

Modern mesohaline stromatolites exhibit regular occurrences of the halotolerant cyanobacterial species

Microcoleus chthonoplastes, *Lyngbya* sp., *Entophysalis* sp. and *Synechococcus* sp. (Gerdes et al., 2000a). *Microcoleus* is one of a number of cosmopolitan cyanobacteria that form ensheathed filamentous cellular bundles in most growing biolaminites. It grows best in the salinity range 80-160‰ but is present as living filaments in salinities as high as 300‰.

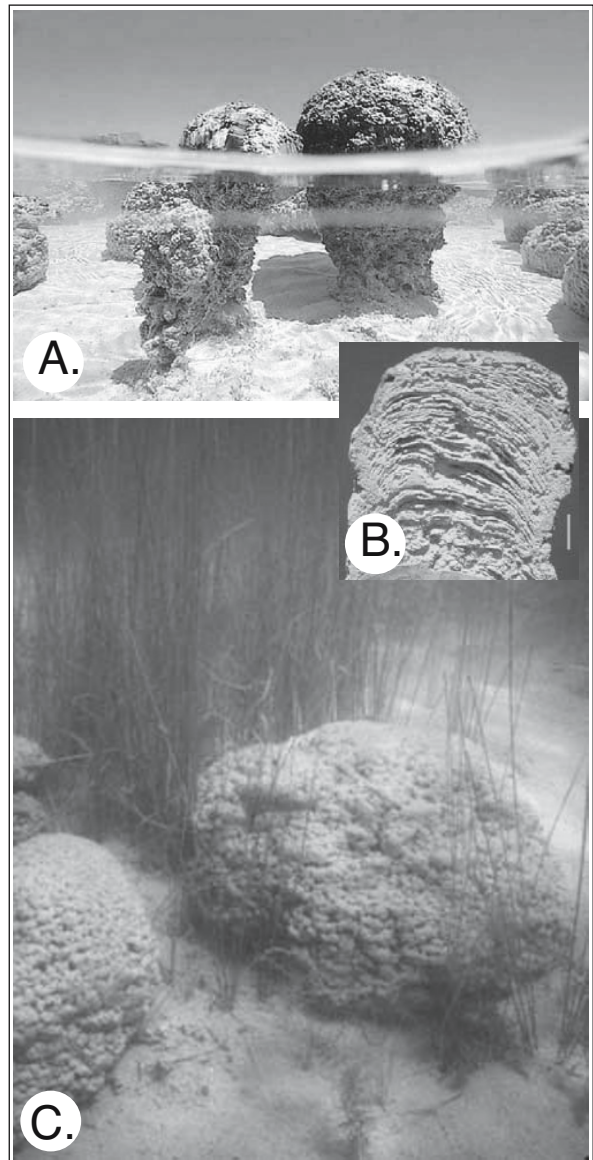


Figure 1.3. Modern agglutinated stromatolite reefs. A) Intertidal stromatolites in Hamelin Pool, Shark Bay Australia (image courtesy of DiscoverWest). B) Cross section of a Shark Bay intertidal stromatolite showing internal mm lamination with truncated edges. C) Lacustrine stromatolites from Cuatro Ciénegas Posas, Mexico. Most particles are captured by the mucilage are diatom frustules (Image courtesy of Alan Riggs).

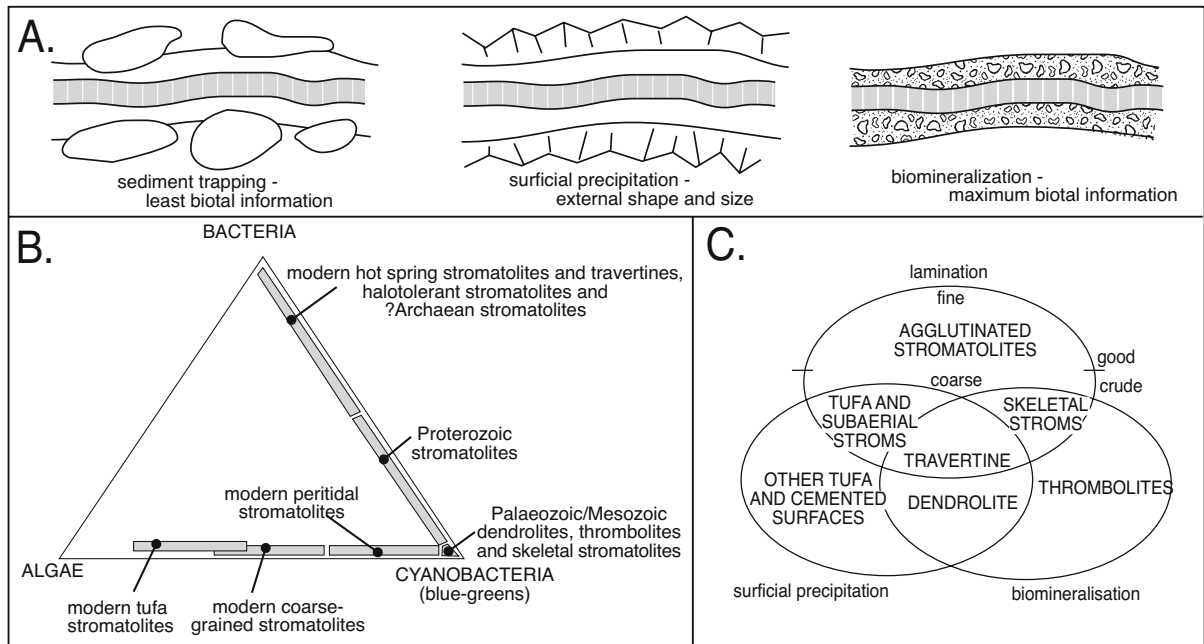


Figure 1.4. Microbialites. A) Styles of mineral accretion about a trichome. B) Biological components that construct various microbialites and the changes over geological setting and time. C) Classification of microbialites according to dominant constituents (after Riding, 1991; 2000).

Fibrillar cyanobacteria are able to glide up and down through nearsurface sediment in order to position themselves in optimal light conditions. This is done by hormogonia, a part of a filament of a photosynthetic cyanobacterium that detaches and grows by cell division into a new filament. Hormogonia are motile and respond phototactically so that, if too much sediment accretes to the mat or if a deepening brine cover reduces the light reaching the filaments, they move upwards to where they accumulate on or just below the sediment surface. It is this periodic repositioning that creates the internal laminated structure and phototropic thickening seen in modern stromatolites and algal mats. Left behind in the sediment matrix are the abandoned sheaths, immotile filaments, cells and mucilage that after passing through the decomposer community becomes buried organic matter (Chapter 9).

Coccolids in modern biolaminites tend to create slime-sheathed pustules and individual cells grow by binary fission (Gerdes et al., 2000a). *Gloeotheca* and *Synechococcus* are two of a number of such coccolid cyanobacteria that make up the other major component of a cyanobacterial plexi. These organisms increase their slime content in order to deal with phototoxicity and tend to dominate exposed surfaces of algal mats and stromatolites, as in the algal mats of the Abu Dhabi and Saudi sabkhas. Coccolids tend to occur in zones about edges of water-covered biolaminites flourishing on the floors of tidal channels (Chapter 3).

Pleurocapsalian cyanobacteria are a cosmopolitan type of coccoid bacterial that dominate modern pustular and pinnacle mats. The typical internal structure in a pustule is colonial, with individual nodules showing discontinuous but more or less concentric layers. Slime production is stimulated by an increase in light intensity, salinity or temperature. This creates sediment with a yoghurt-like consistency made up of polysaccharides interwoven with sediment matrix. The slime coat not only protects the coccoids, but also insulates the other species of the mat community from the lethal effects of increasing light, salinity and temperature. Microbial metabolism facilitates or even drives the precipitation of primary dolomite in many evaporitic carbonates (van Lith et al., 2002).

It is the alternation between mm-scale layers dominated by the filamentous forms and layers enriched in the coccoids that creates the biolamination of modern marine and marine margin stromatolites (Reid et al., 2001). Aggradation in a modern marine-edge stromatolite represents a dynamic balance between sedimentation and intermittent lithification within the cyanobacterial mat. Periods of rapid sediment accretion, during which stromatolite surfaces are dominated by pioneer communities of gliding filamentous cyanobacteria, alternate with hiatus intervals. Microscale discontinuities in sedimentation are characterized by development of surface films of exopolymer and subsequent heterotrophic bacterial decomposition, which

forms thin crusts of microcrystalline carbonate. During prolonged hiatus, climax communities develop, which include endolithic coccoid cyanobacteria. These coccoids modify the sediment micro-environment to create thicker lithified laminae. Subsequence preservation of lithified layers at depth creates the millimetre-scale biolamination that characterises modern and ancient stromatolites.

At the broader scale, successive layers in modern biolaminites can indicate seasonal changes. *Microcoleus*-dominated layers (often associated with diatoms) accumulate in the winter, while coccoid-dominated layers typify the more saline summer growth layers. Alternations of coccoid and filamentous layers in a mat can create lamination even in the absence of agglutinated sediment, although the preservation potential of such organic-only layers is low unless deposited on the anoxic floor of a perennial stratified brine lake (Chapter 9).

Non-stromatolitic lacustrine microbialites

Stromatolites are one part of a much wider group of layered microbialites growing in a wide range of saline marine and nonmarine settings (Figure 1.4c; Riding, 1991, 2000). According to Riding, sediment trapping by filamentous plexi in a modern biolaminite results in an agglutinated stromatolite reef, which is characterised by a particulate microstructure that preserves few, if any, details of the original size, shape or orientation of the biotal plexi responsible for capturing sediment (Figure 1.4a).

On the other hand, biomineralized deposits, such as tufa/travertine cement reefs described by Riding 2002, retain considerable palaeontological detail about the constituent organisms preserved as skeletal microfossils. Mineralisation is especially important in nonmarine microbialites, as in lacustrine tufa cement reefs that define the water-covered margins of the less saline high-water stages of many Quaternary salt lakes. These tufa cement reefs are porous, unbedded or only poorly bedded, and created by cyanobacteria, algae, grasses, and reeds thriving in brackish to fresh lake and river waters and groundwater seeps along the landward side of the saline pan or lake edge. Rapid CaCO_3 precipitation veneers living plants, which would otherwise be masses of soft vegetation, with cement crusts (Riding, 2000; Pedley et al., 2003). Relief on a tufa buildup can be high, with commonplace steep to overhanging, locally cavernous, cemented masses. Tufas tend to occur where inorganic CaCO_3 precipitation is enhanced by CO_2 degassing of venting spring waters.

Likewise travertines, which tend to form layered deposits of CaCO_3 near the outflow points of groundwater and thermal springs, can preserve details of the contributing microbes. Travertine cement reefs are layered microbialites with “shrub” and crystalline fabrics associated with non-skeletal organisms (Figure 4.3; Riding 2002). Deposits tend to form steep-sided mounds, with elevated rimmed pools, normally developed atop and about the mounds. Smoothly banded crystalline crusts construct horizontal, sloping, vertical or overhanging sheets with pisoids typically developing at the bottom of water-filled pools and polygonal saucers. Chafetz and Folk (1984) and Folk (1993, 1999), along with many others working in travertines, document microtextures such as spheroidal dolomite, dumbbell-shaped crystals, fine diurnal-layered dendrites and bushes, all of which indicate a strong bacterial contribution to travertine precipitation. Reeds and grasses can be preserved as moulds within bacterial travertines, but most macro-organisms are excluded by the elevated temperatures and high levels of dissolved minerals (salinity) that typify travertine carbonates. Most travertines are only a few kilometers in lateral extent and, as in tufa cement reefs, subaerial surfaces are common, as are gradations into adjacent marsh and fluvial environments.

CO_2 degassing, in combination with evaporation and rapid microbial growth, can drive extreme carbon isotope enrichment in the organic matter and co-precipitates in many CO_2 -limited organic-enriched sediments, including evaporitic marls, tufas and travertines (Schouten et al., 2001). Enriched $\delta^{13}\text{C}$ values of up to +13‰ in calcite and -10‰ in organic matter were measured in calcite tufas accumulating in well-oxygenated carbonate saturated waters in El Peinado and San Francisco lakes, both high altitude saline lakes in the southern Andean Altiplano, northwestern Argentina (Figure 1.5). Valero-Garces et al. (1999) argue that the large enrichments of the heavier carbon isotopes in the algally bound sediments indicate non-equilibrium gas-transfer fractionation of the carbon isotopes during CO_2 degassing. Parent waters were derived from thermal springs and subject to subsequent evaporative concentration. In general most ions in lacustrine tufas in volcanic settings ultimately come from geothermal and volcanic CO_2 sources. Physical fractionation, rather than biological enrichment in these settings, may have a greater significance than credited in the commonly accepted biological metabolism arguments typically used to explain carbon isotope records in evaporitic carbonates (see Schouten et al., 2001 for opposing argument). Likewise, the dilution of the isotopic signature by C-14-free CO_2 from volcanogenic sources may hinder accurate C-14 chronologies of lake sedimentation when based on samples of lacustrine organic matter and other aquatic plants.

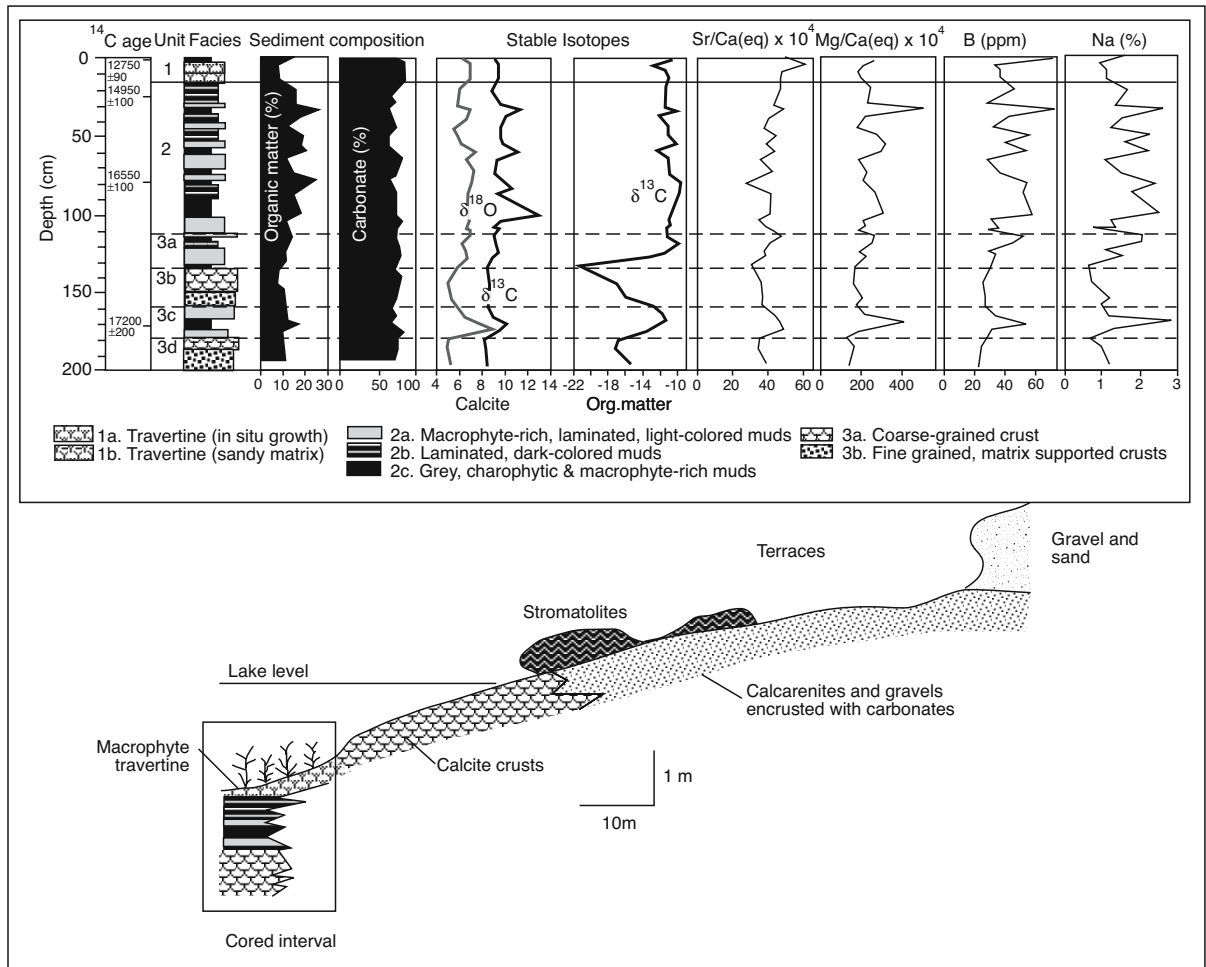


Figure 1.5. Sedimentary facies, sediment composition, stable isotopes and geochemistry of the Lake El Peinado core, Andean Altiplano. Core was collected in the perennially subaqueous carbonate margin of the lake (after Valero-Garcés et al., 1999, 2001). Macrophytes are the current active carbonate binders. Stromatolites today are not active, but grew at an earlier time of more saline water when conditions did not favour macrophytes. Dates are uncorrected AMS ^{14}C ages (years BP). All isotopic measurements are reported as δ values vs. the PDB standard.

Microbialite sedimentology in saline lakes

Mineralisation associated with biofilm metabolism is much more important than simple agglutination in many Holocene lacustrine stromatolites. Niches occupied by stromatolites and tufa/travertine cement reefs in saline lacustrine settings circumscribe a much wider range of salinities and water conditions than evidenced by modern marine thrombolites and stromatolites. Isopachous biomineralized subaqueous stromatolite reefs, texturally identical to their ancient mm-laminated counterparts, still grow in the mesohaline carbonate-saturated seepage waters of some modern marine-fed gypsum lakes (von der Borch et al., 1977; Warren 1982a). The coarse-layered sandy agglutinated forms of Shark Bay and the mud-cracked supratidal algal mudstones of the Abu Dhabi sabkha have fewer ancient evaporitic counterparts.

Similarly, healthy carbonate-precipitating microbialite communities in the upper parts of less-saline carbonate-rich littoral and slope breaks about many prograding lacustrine margins in modern temperate and tropical carbonate lakes, can be used as analogues for microbial growth in the high water stages of some ancient saline basins (Dean and Fouch, 1983). For example, modern thrombolites, tufas and stromatolites occur in littoral waters (10–60m deep) about the edges of Lake Tanganyika (Cohen and Thouin, 1987) and Salda Gölü in Turkey (Braithwaite and Zeder, 1996). Near identical fresh to brackish water stromatolites, along with oncoids, travertines and tufas, occur in Plio-Pleistocene sediments of the East African Rift Valley lakes (Casanova, 1986). Similar marginward microbial tufa cement reefs (bioherms) reached thicknesses of 7 metres, with diameters of 15 metres, in the Oligocene Ries Basin (Rid-

ing, 1979; Arp, 1995). Freshwater to mesohaline stromatolites characterise Oligocene lake margins in France (Casanova and Nury, 1989) and the 1-10m deep freshwater-filled evaporite karst pond fills (posas) in a modern gypsiferous playa, Cuatro Ciénegas in Coahuila, Mexico (Figure 1.3c; Minckley, 1969; Winsborough et al., 1994). Other examples of ancient lacustrine counterparts include the Tertiary of southern France (Truc, 1978) and the Eocene Green River Formation of the USA (Surdam and Wolfbauer, 1975).

Widespread mm-laminated evaporitic stromatolites also accumulate in more saline lacustrine settings, settings where surface brines are waters supersaturated with respect to a carbonate phase, typically aragonite. In these settings the role of biology is less obvious in the laminates. Biofilms of archaea, eubacteria and algae may be passive rather than active participants during the formation of domal to massive laminar stromatolites. It is in this group of structures that the phrase “may or may not be of biological origin” comes into play. Modern examples of such enigmas include manganiferous aragonitic stromatolites that define the northwestern strandplain margin of the Northern Basin of the Dead Sea (see Druckman, 1981 vs. Garber and Friedman, 1983). Texturally identical evaporite-associated biomineralized stromatolites and biolaminites have characterised the mudflat and strandzone margins of saline and alkaline playa lakes and marine evaporite basins throughout much of the Phanerozoic, especially at times or in regions of transition into or out of episodes of basinwide evaporite precipitation (Figure 1.8a).

Mineralogy of most modern lacustrine stromatolites is dependent on what carbonate phase is precipitating in the ambient lake water. This is true even when biotal metabolism plays a significant role in driving carbonate precipitation. Stromatolites and microbial bioherms are aragonitic in many modern saline lakes (e.g. Great Salt Lake, Eardley, 1938; Marion lake, South Australia, von der Borch et al., 1977) and the precipitation process is often facilitated by the metabolic activities of bacteria (Pedone and Folk, 1996). Hydromagnesite-aragonite mm-laminated stromatolite domes and mats dominate in the schizohaline ephemeral waters of North and South Stromatolite Lakes in the Coorong region of South Australia (Figure 4.5a), while poorly preserved hydromagnesite-magnesite stromatolites characterise much of the present-day playa surfaces of the Caribou Plateau in Canada (Renaut, 1993a). Similar stromatolite domes characterise the highly alkaline

(pH>9) fresh to brackish waters of Salda Golu (Lake) in Turkey where lake margin subaqueous stromatolites are composed mostly of hydromagnesite, along with entrapped diatom tests (Figures 1.6, 4.29; Braithwaite and Zedef, 1994, 1996).

At the basin scale, Quaternary calcitic and aragonitic algal tufa and travertine reefs form atop spring vents in groundwater outflow zone where they can construct substantial spring mounds (Habermehl, 1988). Tufa growth rates can be impressive; Rosen et al. (2004) documented aggradation rates of 30 cm/year in the modern subaqueous tufas of Big Soda Lake in Nevada. Some impressive thinolitic tufa reef mounds in temperate and high-altitude saline lakes were originally constructed of an unusual but interesting variety of low temperature calcite called ikaite (Chapter 4). This hexahydrate form of calcite is found today forming ephemeral precipitates in near freezing brines around spring vents of CO₂-rich waters in Mono Lake and in Quaternary sediments of the Lohanton Basin (Pyramid Lake), Nevada. Similar spectacular tufa mounds occur in groundwater outflow zones on the subaqueous floor of Lake Van, Turkey. Once the water temperature about a spring mound rises above 3-4°C the ikaite dehydrates to calcite, but the calcite can preserve the characteristic lenticular and twinned outline of its precursor. But a lenticular to lozenge shape in a calcite pseudomorph is easily confused with other evaporite minerals, such as gypsum and gaylussite, which also are readily pseudomorphed by calcite (Chapter 7). Ikaite pseudomorphs can have little to do with an evaporite precursor, and occur in modern marine shelf sediments of the Antarctic and in modern and ancient glacial outwash fans from around the world (Shearman and Smith, 1985; Larsen, 1994; Riccioni et al., 1996).

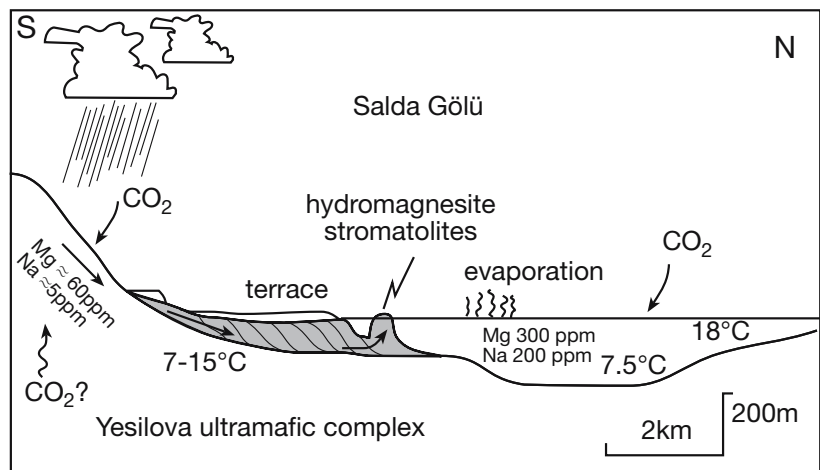


Figure 1.6. Schematic cross section of Salda Gölü showing hydromagnesite stromatolite growing subaqueously in front of the carbonate tufa terrace (after Russell et al., 1999).

Microbialite sedimentology in marine settings

Unlike modern stromatolites and microbialites, which tend to construct significant rock masses in salinity or temperature stressed environments, Precambrian stromatolites were environmentally diverse and abundant across hypersaline, normal marine and nonmarine settings. They first appeared around 3.45 Ga and dominated biogenic sedimentation from 2800 to 1000 Ma (Riding, 2000). The beginning of their Proterozoic decline and environmental restriction, variously identified at 2000, 1000 and 675 Ma, has been attributed to reduced marine cementation or to eukaryote competition. The former was perhaps tied to higher calcium concentrations in Precambrian oceans compared to oceans of today (Laval et al., 2000), while the latter related to the evolution of the gastropod radula (Garrett, 1970). The previously enigmatic lack of calcified cyanobacteria filaments in stromatolite-bearing Precambrian sequences is now explained as a likely result of high concentrations of dissolved inorganic carbon in the Precambrian ocean (Arp et al., 2001) or by the postulate that many Archaean stromatolites were inorganic precipitates (Pope et al., 2000).

Precambrian stromatolites were not confined to the more arid peritidal marine or marginward lacustrine seep situations that characterise most Phanerozoic stromatolites. Such high stress environments (hypersalinity/exposure) tend to exclude many metazoan marine grazers that otherwise browse and destroy algal mats. Modern areas of thick extensive marine-margin stromatolites/cryptalgal laminites are located at the edge of the cropping range of marine grazers, examples of gastropod restriction include the seaward side of the algal facies of the Arabian Gulf (Figure 3.4d; Kendall and Skipwith, 1969) and the hypersaline intertidal flats of Shark Bay, Western Australia (Figure 1.3a; Logan, 1987).

Various thrombolites and dendrolites, mainly formed by calcified cyanobacteria, became important marine microbialites early in the Palaeozoic and reappeared in the Late Devonian, as marine stromatolite populations declined. Microbial marine carbonates retained their importance through much of the Mesozoic, they became scarcer in marine environments in the Cenozoic, but locally re-emerged as large agglutinated domes, possibly reflecting increased algal involvement in sediment binding and cementation.

There are still a few modern normal-marine settings where metre-scale stromatolites flourish. Holocene columnar stromatolites grow as part of a thrombolite-stromatolite association on the floor of modern tidal channels off Lee Stocking Island, Exuma Cays. These bio-columns show three

associations of internal sedimentary structures: (1) prokaryotic stromatolites comprised of alternating layers of coarse-grained ooids and peloids, and fine micrite that are formed exclusively by microbial activity; (2) eukaryotic stromatolites comprised of microbially-induced micritic layers alternating with detrital layers bound and cemented by eukaryotic algae; and (3) thrombolites displaying irregular, clotted fabrics and formed by communities of microbes, algae, and metazoans (Figure 1.7a; Feldmann and McKenzie, 1998).

Onshore in San Salvador in shallow turbid water, beneath the modern mesohaline waters of Storr's Lake, marine-influenced thrombolite layers alternate with stromatolite layers to create mushroom shaped mounds. This alternating layering perhaps reflects changes in salinity and light penetration (Figure 1.7b; Mann and Nelson, 1989). Formation of many modern marine thrombolites has been attributed to carbonate precipitation driven in large part by sciaphile (dark-loving) bacteria, which flourish under low sedimentation rates, low water energies and higher turbidity, hence the preservation of a clotted fabric and lack of lamination (Dupraz and Strasser, 1999; Riding, 1991). Phanerozoic marine thrombolites, in contrast, are mostly interpreted as non-laminated microbialites (not a stromatolites) constructed by cyanobacteria and are not usually interpreted as sciaphiles.

According to Feldmann and Mckenzie (op cit.) the contemporaneous formation of prokaryotic stromatolites, eukaryotic stromatolites, and thrombolites under identical conditions within the present marine environment is unlikely. They suggest that the prokaryotic stromatolites in the Lee Stocking bioherms represent microbial forms that began to develop in an environmentally-stressed intertidal setting during the early Holocene flooding of the Great Bahama Bank. In contrast, thrombolites began to form under the present, normal-marine subtidal conditions (Figure 1.7a). The eukaryotic stromatolites represent intermediate forms between prokaryotic stromatolites and thrombolites, with a gradual change from stromatolite to thrombolite reefs tied to rising sealevel. With the deepening, there would have been a decrease in salinity, an increase in energy, and possibly an increase in nutrient supply; all factors that favour thrombolite growth.

Unfortunately, most environmental and depositional models for Phanerozoic stromatolites tend to draw heavily on Holocene peritidal marine-margin analogues, such as Shark Bay, a hypersaline setting where sand grain trapping (agglutination), rather than micrite precipitation, is the dominant mode of sediment accretion. Accordingly, using modern analogues, many

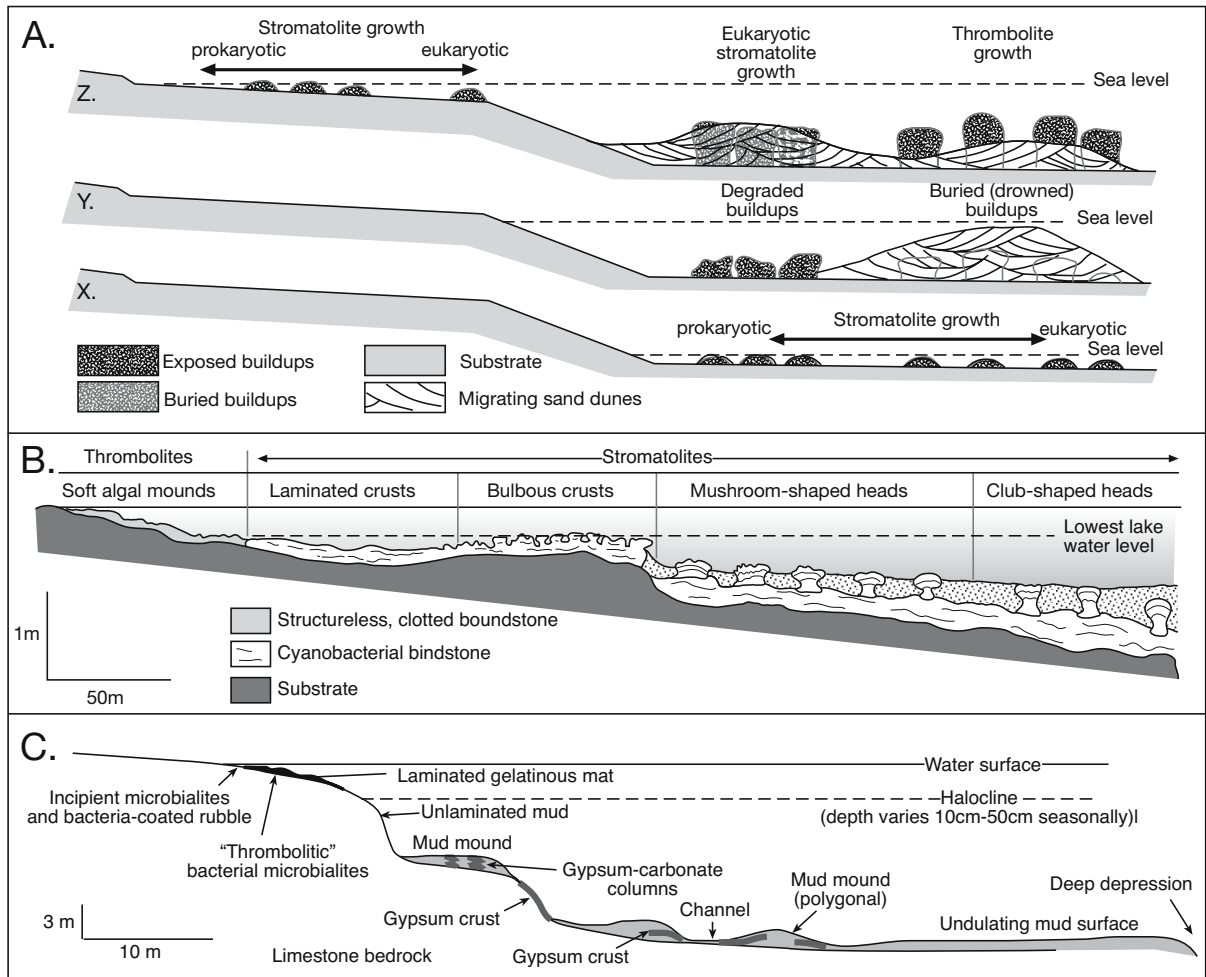


Figure 1.7. Thombolites in mesohaline to marine settings. A) Evolution of microbialites during a rise in sea level from time X to time Z in the formation of marine subtidal stromatolites in Lee Stocking Island in the Bahamas (after Feldmann and Mckenzie, 1998). B) Distribution of algal/thombolitic structures in mesohaline aragonite muds of Storr's Lake, San Salvador (after Neumann et al., 1988; Mann and Nelson, 1989). C) Thombolites (aragonitic) passing into gypsiferous mud mounds below the halocline at the southern end of the channel in Gotomeer, Bonaire (after Kobluk and Crawford, 1990).

sedimentologists assume that well-preserved Phanerozoic stromatolites must have formed in intertidal to supratidal marine settings. As we shall see in Chapter 5, a marine-connected basin is not the best way to model evaporitic carbonates associated with thick evaporites. Microbes living in ancient saline systems constructed a far more diverse and wide ranging biotal association in evaporitic settings than simplistic Shark Bay analogs imply (Chapter 9).

Microbialites typify marine to evaporite and evaporite to marine transitions

Throughout the rock record, Pope et al. (2000) noted that a transition between a carbonate platform or an isolated carbonate

buildup and the overlying evaporites is commonly defined by assemblages of stromatolites or interlaminated carbonates and evaporites. The stromatolites display lamination textures that vary from peloidal and discontinuous on a scale of a millimetre to a few centimetres, to isopachous and continuously laminated on a scale of a centimetre to a few metres. The isopachous lamination may be composed of either: (1) micrite or radial-fibrous calcite, or (2) dolomite. The isopachous laminae are remarkably uniform, varying little in thickness over a given lateral distance, whereas stromatolites formed of peloidal laminae, also show marked variations in thickness over an equivalent lateral distance (phototactic thickening). They observed that isopachous textures are uncommon on most open-marine carbonate platforms and apparently developed in transitional

Location	Units	Carbonate Fabrics	Composition
Great Slave Lake, Canada, Palaeoproterozoic (1.8-1.9 Ga)	Perthei Grp. (c) Stark Fm. *e)	Tufa, isopachously laminated stromatolite at contact in shallow water; Fibrous marine cements throughout platform	Basinwide evaporite Halite >> gypsum (no anhydrite)
Oman, Vendian (570-543 Ma)	Buah Fm. (c) Ara Fm. (e)	Fibrous marine cements throughout platform and isolated thrombolitic bioherms; Isopachously laminated stromatolites at contact; tufa-like crusts in carbonates within evaporites	Basinwide evaporite Halite >> gypsum
Michigan Basin, Silurian (≈ 400 Ma)	Guelph Fm. (c) Salina Fm. (e)	Fibrous marine cements within pinnacle reefs; Isopachously laminated stromatolites (travertine-like coatings) cap marine reefs; Calcite laminites in interpinnacle reef areas	Basinwide evaporite Halite >> anhydrite, potash salts
Western North America; Middle Devonian (≈385 Ma)	Winnepegosis (c)	Stromatolites cap marine reefs, fibrous marine cements in reefs and carbonate-evaporite laminites between reefs in deeper-water settings	Basinwide evaporite Halite >> anhydrite
Sverdrup Basin, Carboniferous, Arctic Canada	Nansen (c) Otto Fiord (e)	Carbonate-evaporite laminites in basinal setting, fibrous marine cements throughout shelf-margin reefs and buildups	Halite ≈ anhydrite
Zechstein Basin, England, Late Permian (≈ 260 Ma)	Middle Magnesian Limestone (c) Hartlepool Anhydrite (e)	Fibrous marine cements throughout reef complex; Isopachously laminated stromatolites (Crinkly Beds) in bioherm capping marine reef complex; Laminar coatings within bioherm, neptunian dikes and cavities; Laminites in basinal setting between buildups	Basinwide evaporite Halite >> anhydrite Locally on platform: Anhydrite >> halite
Mediterranean Messinian (Middle Miocene)	Terminal Carbonate Complex (c)	Thinly laminated stromatolites at transition from marine carbonate to evaporite; fibrous marine cements within reefs underlying stromatolites	Basinwide evaporite Halite >> gypsum
Abu Shaar Complex, Egypt; Messinian (Middle Miocene)	Ruidais Fm. (c) Kareem Fm. (e)	Fibrous marine cements throughout marine reef complex; Thinly laminated stromatolites with fibrous cements on toe of slope; Unique pisoids with distinctive fibrous fabric	Basinwide evaporite Anhydrite > gypsum > halite

Table 1.3. Selected examples of unique evaporitic carbonate fabrics in basinwide transition facies passing from carbonate through mesohaline to hypersaline deposition. Carbonate = (c), Evaporite = (e). (after Pope et al., 2000 and contained references).

carbonate-to-evaporite settings because of basin isolation and drawdown leading to increasing temperature, salinity, and anoxia related to water stratification (Table 1.3; Figure 1.8a). The resulting ecologic restriction created an opportunity for isopachous stromatolite growth.

Stromatolites with isopachous lamination are interpreted to form via in situ precipitation of sea-floor-encrusting calcite and possibly dolomite, whereas the stromatolites composed of peloidal, discontinuous lamination are inferred to have formed by trapping and binding of loose carbonate sediment in microbial mats and can be unrelated to the onset of basinwide evaporite restriction and drawdown. According to Pope et al. (2000), isopachous stromatolites may have accumulated by chemogenic precipitation in the absence of microbial mats, while peloidal stromatolites grew by agglutination in the presence of microbial mats and since the onset of the Phanerozoic have been largely restricted to environmentally stressed biogenic sediment. I would not exclude biofilms from isopachous stromatolites, it is just that high inorganic precipitation rates can swamp the phototactic effects used to interpret biofilms.

Pope et al. (2000) went on to note that when compared to pre-Mesozoic occurrences, stromatolites with thin, isopachous lamination and radial-fibrous textures, though present, are rare to absent in transition facies in Jurassic and younger evaporite basins, such as the Messinian of the Mediterranean region. Instead, the isopachous precipitative facies have been replaced by stromatolites with peloidal, clastic phototropic textures and by mesohaline mudstones with a low-diversity diatomaceous and coccolith biota. These stromatolites are sometimes interlayered with thrombolites (as in Storrs Lake, Caribbean). They interpret the shift away from chemogenic stromatolites to agglutinated stromatolites as a change in seawater chemistry tied to the evolution of the nannoplankton. Accumulation of the biogenic planktonic mudstones in deeper ocean waters since the Mesozoic has had two important effects: (1) Production of coccolith tests in the world's oceans (chalks) helped extract calcium carbonate from seawater, thus lowering the growth potential for inorganic precipitation of sea-floor-encrusting stromatolites. (2) Settling of both coccoliths and diatoms would have created a sediment flux to the sea floor, which would have served to impede growth of chemically precipitated stromatolites because of ongoing smothering of any growing seafloor crystals.

Post-Mesozoic peloidal stromatolites (bio-agglutinates) and thrombolites tend to characterise transitions into and out of episodes of basinwide evaporite deposition. One of the best-preserved transitions of this style of stromatolite/thrombolite occurrence comes from the Late Miocene of SE Spain in cyclic stromatolitic carbonates deposited during and at the termination of the Messinian salinity crisis (Figure 1.8b; Chapter 5). For example, large microbial carbonate domes (both stromatolites and thrombolites) defined the margins of the Sorbas and Alboran Basin during the uppermost Messinian. They occur in a unit overlying the Messinian evaporite succession and were deposited in a variety of environments, including fan deltas (Martín et al., 1993; Braga et al., 1995), beaches, and oolitic shoals (Riding et al., 1991).

Their abundance and continuity in the transitional marine setting is comparable in many respects to their omnipresence as transitional forms in the Precambrian. There is, however, an important difference in some parts of the Messinian sequences. Although major unconformities separate normal marine reefs

from the carbonates of the “terminal complex complex (TCC),” an impoverished and depauperate, normal-marine biota of Late Miocene corals (*Porites*), coralline algae, serpulids, bivalves, and encrusting foraminifers at times lived alongside the stromatolitic microbes as the TCC was accumulating (Martín et al., 1993; Braga et al., 1995). The intimate association of stromatolites with a stressed, but stenohaline, marine biota rules out the possibility of continually elevated salinities at the onset of TCC deposition, as suggested by several earlier authors to account for the occurrence and proliferation of widespread microbial structures in the Messinian strata (Esteban, 1980; Rouchy and Saint-Martin, 1992). The most plausible explanation for this transition into and out of hypersaline into normal marine waters is that microbes acted as opportunistic biota and, for a time, outcompeted other organisms, settling and growing successfully in most of the available and rapidly expanding marine niches (Pope et al., 2000; Feldmann and McKenzie, 1997). This happened during the initial stages of marine recolonization of the Mediterranean Sea, after drawdown and deposition of either the lower or upper evaporite sequences.

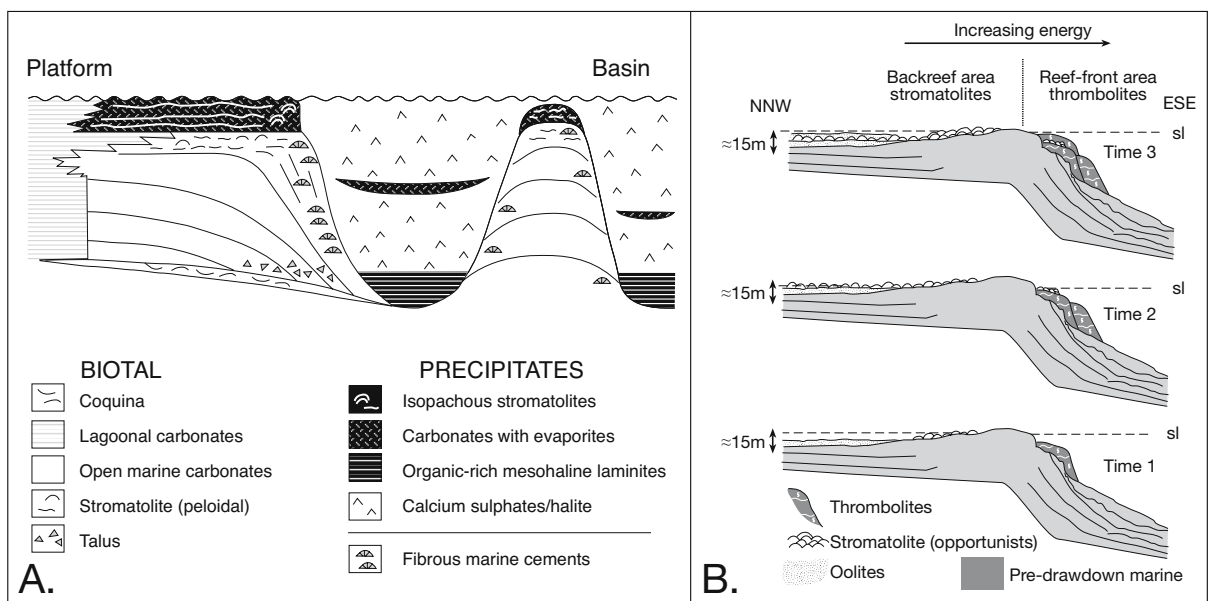


Figure 1.8. Schematics of marine carbonate to evaporite transitions. A) Typical transitions, showing relative positions in the basin stratigraphy of precipitated isopachous stromatolites and the precipitated carbonate fabrics that typify sediments accumulating mesohaline carbonates immediately prior to complete basin isolation and drawdown that defines the onset of basinwide calcium sulphate and/or halite evaporite deposition (after Pope et al., 2000). B) Platform edge distribution of stromatolites and thrombolites relative to cyclic sea-level changes during the Intra-Messinian flooding event in a marginal Mediterranean sub-basin. Time 1) Relative high sea-level stand with thrombolite growth in the subtidal zone at the front reef, oolite deposition in the deeper parts of the back-reef area, and stromatolite growth in the intertidal zone of the back-reef area. Time 2) Relative low sea-level stand promoting thrombolite growth in the basinward migrated subtidal zone at the front reef and opportunist stromatolite growth in the intertidal zone on both the previously deposited ooid sands and thrombolites. Time 3) Relative high sea-level stand with thrombolites growing over the preceding stromatolites in the subtidal zone at the front reef, opportunist stromatolite growth in the intertidal zone of the back-reef area, and sand deposition in the deeper water of the back-reef area (after Feldmann and Mackenzie, 1997).