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Microbial carbonates: processes and products in time and space

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Microbial carbonates reflect the influences of microbial metabolism, cell surface properties, and extracellular polymeric substances (EPS) on mineral precipitation, in combination with grain stabilization at the sediment-water interface by mat-forming communities. The early lithification essential for the accretion and preservation of benthic microbial carbonates is biologically mediated but also environmentally dependent.

Significance of column-dome morphology Microbial carbonate morphotypes reflect synoptic relief during formation determined by accretion rate relative to adjacent sediment. Low relative accretion rate results in low relief and complex shape; high relative accretion rate results in high relief and simple shape. It follows that increase in morphotypic diversity, e.g., in Proterozoic branching stromatolites, reflects low synoptic relief due to low relative accretion rate and is not a measure of abundance.

Microfabrics 'Porostromate' (calcified filament) and 'spongiostromate' (clotted) microfabrics mainly appear to respectively reflect aerobic surface (e.g., photosynthetic) and anaerobic subsurface (e.g., sulphate reduction) calcification processes in benthic microbial mat communities. Photosynthetically induced calcification of cyanobacterial sheaths is enhanced by carbon-concentrating mechanisms (CCMs) and elevated saturation state of overlying waters. At or immediately below this level, bacterial degradation of residual cell material and EPS creates clotted and peloidal 'spongiostrome' microfabrics. Dolomite precipitation can also result from sulphate reduction. Coarse agglutinated fabrics may reflect enhanced trapping due to incorporation of algae into microbial mats.

Macrofabrics Macrofabrics reflect the degree of uniformity of components and their patterns of accretion or disturbance. The processes of calcification and agglutination that determine microfabrics also result in distinctive macrofabrics. Typically, stromatolites (laminated) have spongiostrome microfabrics, whereas thrombolites (clotted) and dendrolites (dendritic) have porostromate and related microfabrics. In coarse agglutinated stromatolites (e.g., Lee Stocking, Shark Bay) crude lamination results from coarse sediment supply, but also suggests irregular and

uneven accretion.

Development in time and space Processes of mat accretion and calcification change through time in response to changes in (i) atmosphere-hydrosphere composition and their effects on microbial metabolism (e.g., sulphate reduction, photosynthetic calcification), and (ii) in microbial evolution. These changes are reflected by micro- and macrofabrics. Scarcity of micrite in Archaean stromatolites may reflect limitation of mat sulphate reduction by low seawater SO_4^{2-} levels, and inhibition of planktic whiting precipitation by elevated CO_2. Clotted and other micritic fabrics could reflect changes in these conditions during the Proterozoic, as SO_4^{2-} levels rose and CO_2 declined. Falling CO_2 and rising O_2, stimulating whiting production and inducing carbon-concentrating mechanisms (CCM) in cyanobacteria, would account for Mesoproterozoic increase in micrite and Neoproterozoic cyanobacterial sheath-calcification. Global cooling ~700-570 Myr ago would have favoured diffusive entry of CO_2 into cells, slowing CCM development, and lower levels of temperature and p_{CO2} would have reduced seawater saturation state, hindering cyanobacterial calcification. As Earth emerged from 'Snowball' glaciations in the late Neoproterozoic, global warming and O_2 rise could have reactivated CCM development. At the same time, rising levels of temperature, calcium and p_{CO2} are likely to have increased seawater saturation state. These changes would have stimulated widespread cyanobacterial sheath calcification in the Early Cambrian. This biocalcification event promoted rapid widespread development of calcified cyanobacterial reefs and transformed benthic microbial carbonate fabrics. Rise of algal and metazoan reef builders during the Phanerozoic inhibited microbial dome-column formation in favour of reefal crusts and irregular masses, except during Mass Extinction aftermaths and in ecological refuges such as Shark Bay. Long-term decline in overall abundance mainly reflects decline in seawater saturation state that slows lithification and therefore growth. Grazing may not have been a significant factor so long as microbial mats were well-lithified, but is likely to have increased as saturation state declined. Fluctuations in seawater saturation state are reflected in Phanerozoic changes in microbial carbonate abundance and episodic development of dendrolites and thrombolites in the Cambrian-Early Ordovician, Late Devonian, and Permo-Trias. Present-day coincidence of high metazoan diversity and low saturation state results in reefal microbial carbonates being scarcer than at almost any other time during the Phanerozoic. Diversification of diatoms has transformed some mat communities during the Cenozoic. Present-day examples of marine columnar microbial carbonates at Shark Bay and Lee Stocking Island have been depicted as ancient survivors in ecological refuges protected from metazoan competition. However, the coarsely agglutinated and crudely layered fabrics prominent in these columns are not closely comparable with the fabrics in most pre-Neogene microbial carbonates. These examples appear to be a relatively recent development of algal-cyanobacterial mats adapted to trapping coarse grains in current- and wave-swept environments.

Microbial carbonates are therefore sensitive archives of geobiological change over much of Earth history.