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EXOPALEONTOLOGY AND THE SEARCH FOR A FOSSIL RECORD ON MARS;
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Although present Martian surface conditions appear unfavorable for life as we know it (1), there is compelling geological evidence that the climate of early Mars was much more Earth-like, with a denser atmosphere and abundant surface water (2). The fact that life developed on the Earth within the first billion years of its history (3) makes it quite plausible that life may have also developed on Mars (4). If life did develop on Mars, it is likely to have left behind a fossil record. This has called for a new subdiscipline of paleontology, herein termed "exopaleontology" (5), which deals with the exploration for fossils on other planets. The most important factor enhancing microbial fossilization is the rapid entombment of microorganisms by fine-grained, stable mineral phases, such as silica, phosphate or carbonate. The oldest body fossils on Earth are preserved in this way, occurring as permineralized cells in fine-grained siliceous sediments (cherts) associated with ancient volcanic terranes in Australia and South Africa (6,7). Modern terrestrial environments where minerals may precipitate in the presence of microorganisms include subaerial thermal springs and shallow hydrothermal systems, sub-lacustrine springs and evaporitic alkaline lakes, zones of mineralization within soils where "hardpans" (e.g. calcretes, silcretes) form, and high latitude frozen soils or ground ice.

Subaerial thermal spring deposits are key targets for a fossil record on Mars (8) because high rates of mineral precipitation may occur together with microbial activity. Volcanic terranes are widespread on Mars and some possess outflow channels that may have formed by spring sapping (9). The association of such features with potential heat sources, such as volcanic cones or thermokarst features, is evidence for the past existence of hydrothermal systems on Mars. Siliceous sinters are very favorable for preserving fossils because they are generally fine-grained and relatively insoluble under a neutral to alkaline pH. Common subaerial spring minerals include silica and carbonate, in addition to a number of hydrothermal clay minerals, formed by the alteration of host rocks. These minerals have characteristic spectral signatures in the Near- to Mid-IR. In addition, epithermal ore deposits have been identified using airborne magnetometers (10). The identification of thermal spring deposits from would greatly facilitate site selection for Mars exopaleontology.

Although rates of organic matter degradation appear to be quite high in thermal environments, a great deal of biological information is preserved in thermal spring sinters as macroscopic biosedimentary structures (stromatolites) and biogenic microfabrics (8,11). Many of the primary biogenic features of sinters survive diagenesis and we have recognized them in rocks as old as 350 Ma. The fluid inclusions contained in thermal spring deposits sample primary liquid and vapor phases, and potentially, also microorganisms and biomolecules (12).

Sublacustrine spring carbonates (tufas) are deposited at ambient temperatures where fresh water emerges as springs from the bottom of an alkaline lake. Precipitation rates are often high enough to entomb associated microbial mat communities. In contrast to sinter deposits, tufas often contain abundant microbial fossils and organic matter (5). Sublacustrine springs are also common in volcanic settings, in association with crater and caldera lakes. Such volcani-lacustrine deposits are frequently heavily mineralized and include some of our best examples of well preserved terrestrial communities (13). In pluvial lake basins in western North America, sublacustrine springs are particularly common along the distal edges of alluvial fans where they enter alkaline lakes. Fresh water typically enters the upper portions of alluvial fans, moving downslope through unconfined aquifers, and emerging at shallow depths along the lake shore margin (14). If lake basin shales are deposited on coarser deltaic sediments, say during a previous lake high stand, they may form an aquaclude, favoring the development of an artesian spring system and high rates of spring mineralization. With a confined aquifer, springs may emerge at a greater depths in the lake, rising along faults of other natural fracture systems. Fresh water may also be forced to the surface by density differences, rising over wedges of saline water formed during periods of intense evaporation (15). Such models are being applied in a general way to lake basins on Mars, in order to identify potential targets for orbital imaging and to develop strategies for surface exploration (16).

When evaporites crystallize from solution, they commonly entrap salt-tolerant bacteria within inclusions of brine. Evaporites have been suggested as potential targets for extant life on Mars (17), although debate persists regarding the long term viability of microorganisms in salt. Still, brine inclusions offer an excellent environment for preserving fossil microbes and biomolecules. The disadvantage of evaporites is that they are easily dissolved and tend to have short crustal residence times, particularly where there is an active hydrological system. Thus, most

Precambrian evaporites are known from crystal pseudomorphs that were preserved by early replacement with silica or barite. The most likely places for evaporites on Mars are terminal lake basins, including impact craters and volcanic calderas, where standing bodies of water may have accumulated under arid climatic conditions. Evaporites possess characteristic spectral signatures in the Near-IR (18) and such data could be aquired from orbit.

Most terrestrial soils contain abundant microorganisms, and microfossils and biogenic fabrics are often preserved in hard pan deposits (19). This occurs as surface water percolates downward through soils, soluble compounds are dissolved from upper zones and re-deposited at depth forming mineralized soil horizons or "hard-pans" of carbonate, or under wetter climates, Fe- and Al-oxides. The Viking biology experiments suggest that surface soils on Mars are highly-oxidizing and destructive to organic compounds. However, mineralized soil horizons could protect fossil organic matter from oxidation and should not be overlooked as potential targets for exopaleontology. Interestingly, at the Viking Lander 2 site, soil exhibit surface crusts suggestive of cementation (20).

Although ice may also afford protection to organic matter against oxidation, the long term "cryopreservation" of organisms seems unlikely given the tendency of ground ice to be lost by sublimation under the present Martian climate. Climate models, supported by geomorphic evidence, suggest that ground ice on Mars is presently unstable at latitudes <40 degrees (21). This restricts potential target areas for fossiliferous ice to high latitudes. Given the potential for periodic global warming on Mars, it difficult to evaluate the time range over which ground ice and frozen soils may have been stable; thus, ice is given a lower priority for exopaleontology than the other mineral deposits mentioned.

In exploring Mars for molecular fossils, priority should be given to sedimentary deposits that are the most likely to have maintained a closed chemical system after deposition. Fine-grained marine and lacustrine sediments (e.g. shales, mudstones) tend to exhibit higher organic contents and low permeabilities. Certain classes of clay minerals selectively bind molecules (e.g. biogenic ammonia) as interlayer cations, thereby retaining a signature of the original biological environment long after organic matter has been thermally degraded (22). Compaction of fine-grained sediments, accompanied by early mineralization (cementation), may further reduce permeability, promoting the preservation of organic materials. Precambrian microorganisms and even macroalgae are often preserved as organic impressions in shales or fine-grained volcanic ash, attesting to the ability of such sediments to protect organic materials from oxidation. Potential targets on Mars for organic-rich shales include prodelta and deeper water facies of terminal lake basins (16) and possibly volcanic ash deposits within volcani-lacustrine sequences.

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