The Sedimentary Record of Mars

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INTRODUCTION

Mars presents a remarkable opportunity for geologists interested in early evolution of terrestrial planets. Although similar to the Earth in several respects, there are a number of differences that make comparative analysis of the two planets a rewarding study in divergence and evolution of surface environments on terrestrial planets. Perhaps the most intriguing is the geologic evidence for a wet ancient climate despite the unlikelihood that Mars' current climate could support extensive liquid water. Incision of bedrock by fluvial channels provides the cannonical line of evidence used to support this nonuniformitarian interpretation of climate history. However, carved channels provide evidence only for the integrated effects of the event and not so much a sense for how conditions may have evolved between Mars' early wet phase and its current dry phase. It is significant therefore, that the growing evidence for a sedimentary record on Mars creates the possibility to observe a time series of environmental evolution – a record that can be compared to that of Earth across the same time interval.

Sedimentary rocks on Mars have been known for only the past decade (Malin and Edgett, 2000). Data collected over the past five years by the Mars Express and Mars Reconnaissance Orbiter (MRO) spacecraft have shown the widespread distribution of these sedimentary rocks. It is remarkable how similar some of these of these rocks are to those formed on Earth, including evidence of transport, deposition, and diagenesis in water. Phyllosilicate-rich strata form terminal deposits of source-to-sink systems with well-developed fluvial networks (Metz et al. 2009; Ehlmann et al., 2008) whereas in other cases sulfate-rich deposits form thick successions analogous to terrestrial evaporites (Grotzinger et al., 2005). On the other hand, there are deposits whose origin may differ significantly from terrestrial processes, including thick veneers of strata that may have formed entirely from settling of wind-transported dust (Bridges et al., 2010). Mars science is in its golden era of exploration and the past decade of orbiter and landed missions has produced an extraordinary amount of new data relevant to the analysis of sediments and sedimentary rocks. These new data provide an excellent opportunity for the terrestrial Sedimentary Geology community to become involved in frontier research on Mars.

In April of 2010, the First International Conference on Mars Sedimentology and Stratigraphy was convened in El Paso, Texas for the purpose of reviewing the status of the field and what its major discoveries have been. Following two days of talks a field trip was led to the Guadalupe Mts., with emphasis on rocks that might be suitable analogs, particularly sulfate evaporites. This report summarizes some of the key conference conclusions, and the general state of understanding of Mars sedimentary geology (see also Grotzinger et al. 2011).

HISTORY AND THE STRATIGRAPHIC RECORD OF MARS

The formation of sedimentary minerals on Mars shows evidence of time-dependent transitions in the history of sedimentary mineral formation. These transitions may define global environmental breakpoints (Figure 1), just as the Earth's sedimentary rock record (e.g. banded iron formation) has been used as a proxy for understanding its evolution. Global mineralogical mapping of Mars shows an evolution from a Noachian (4.5 - ~3.7 Ga) era that generated clay minerals (wet, neutral pH Mars), to a Hesperian (~3.7 - ~3.2Ga) era marked by sulfate generation (wet, acidic pH Mars), to an Amazonian (~3.2 – 0.0 Ga) era dominated by formation of anhydrous ferric oxides (dry Mars; Bibring et al., 2006; McLennan and Grotzinger, 2008; Murchie et al., 2009; Milliken and Bish, 2010). These inferences based on global mapping are now being tested by mapping vertical stratigraphic sections that show upward changes in mineral composition.

The succession of sedimentary rocks at key reference sections (e.g. Gale crater; Milliken et al., 2010) appears to support the hypothesis that sulfate-rich strata succeeded clay-rich strata in time. In detail, there is evidence that this transition may also be gradational due to interbedding of the two mineralogically-defined facies (see Figure 2). In contrast, there are some places where the stratigraphic order of minerals may be reversed (e.g. Wray et al., 2010). It is clear that more work is required to establish the global nature and timing of sedimentary mineral deposition.

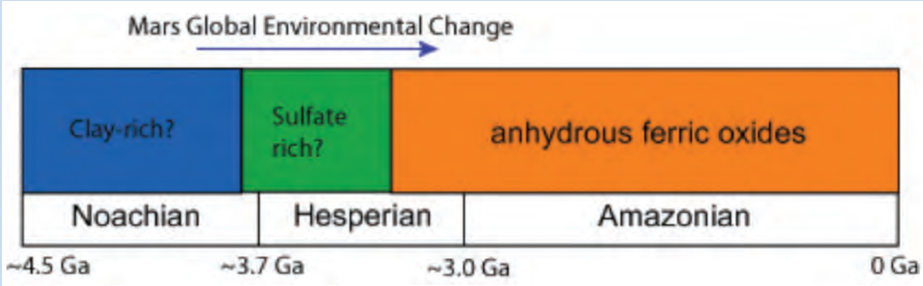

Figure 1. Model for the mineralogic evolution of Mars surface environments through time (after Bibring et al., 2006).

MECHANISMS FOR SEDIMENT PRODUCTION ON MARS

Sediment production on Mars occurs through physical and chemical weathering, but physical weathering likely dominates over chemical weathering, as compared to Earth. Significant volumes of sediment have been generated on Mars as inferred by the presence of sedimentary strata, eolian bedforms, fluvial networks, glacial ice caps, and blankets of impact ejecta. Physical weathering is known to be promoted by eolian abrasion, thermal stress, permafrost processes, and gravity-driven mass-wasting (Bell et al., 2004; Squyres et al., 2004). Bedrock erosion by eolian saltation-induced impact abrasion appears to have been an important ongoing process at the Martian surface. In the geologic past, fluvial incision of bedrock would have likely been driven by saltation abrasion and rock plucking.

Chemical weathering appears to have substantially differed from the behavior of Earth's carbon cycle for significant portions of Martian geologic history. Instead, chemical weathering likely occurred within a sulfur cycle dominated by low pH, water limitation, and cold environments (Hurowitz & McLennan, 2007; McLennan & Grotzinger, 2008), where chemical reactions did not proceed to completion (Madden et al., 2004; Tosca & Knoll, 2009) and were instead terminated by freezing and evaporation (Zolotov & Mironenko, 2007).

Lastly, a very insignificant earth process, albeit with great Martian significance would have been impact shattering of bedrock. This was also a key process for regolith generation on the moon (Haskin et al., 2003; Petro and Pieters, 2008), and would likely have been the case for Mars, particularly early on in its history when the flux of impacts was highest. However, in contrast to the Moon, the presence of a significant atmosphere and high *g* (~0.4 Earth) led to lateral transport of impact regolith by wind, water, and gravity. This may have created a rock record consisting of impact-derived debris, reworked by surface processes, to form significant sedimentary deposits ultimately derived from impact generated regolith (Figure 3).

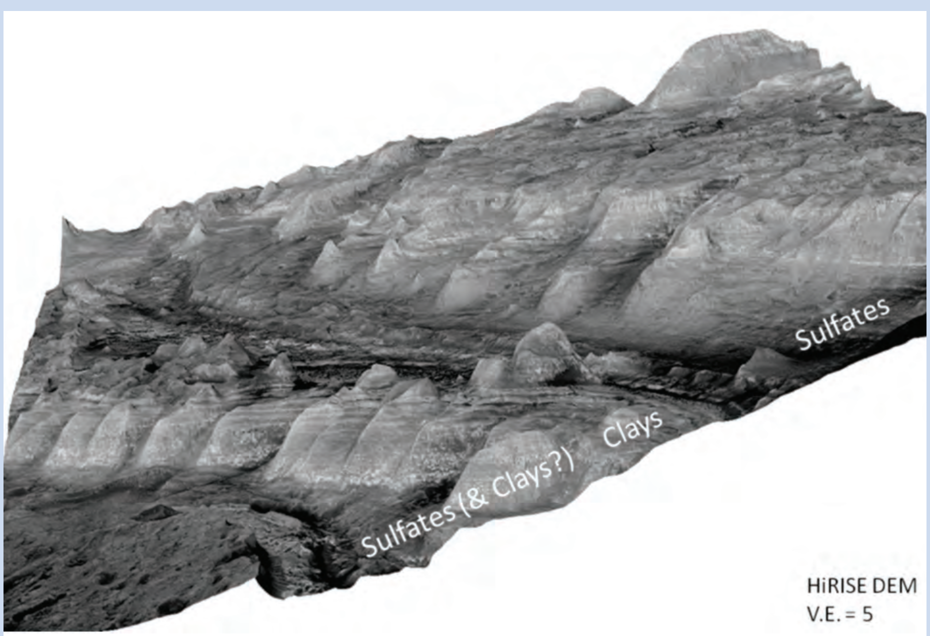

Figure 2. Perspective view of lower Gale mound deposits showing stratigraphic change from clay-rich strata to overlying sulfate-rich strata (Milliken et al., 2010). The mineralogy of beds correlates with changes in stacking patterns such that clay-rich strata tend to be thin-bedded whereas sulfate-rich units show thicker, possibly amalgamated, bedding. This image shows exposures through a section about 300 m high, as viewed to the south; the complete stratigraphic section at Gale exceeds 5000 m.

CHANNELS AND DISTRIBUTARY NETWORKS

Fluvial valley networks, exhumed meandering and branched distributary channels, deltaic sediment bodies formed in ancient crater lakes, and channel-linked crater-lake chains are all characteristic of the Noachian to early Hesperian surface of Mars (Figure 1) (Grant and Parker, 2002; Fassett and Head, 2008; Pondrelli et al., 2008). The end of Noachian time records a dramatic change in martian fluvial systems; huge equatorial outflow channels from pressurized groundwater sources episodically debouched into the Northern Lowlands (Warner et al., 2009), perhaps forming transient seas. The regions from which these outflows emerge locally contain layered sedimentary strata that host sulfate minerals. Sometimes they are brecciated at a scale of tens to hundreds of km, forming "chaos" terrain. Other strata within depressions of the great Vallis Marineris system have been interpreted as sub-lacustrine fan deposits (Metz et al., 2009), representing terminal sediment sinks (e.g. Figure 4).

In addition, there appear to be vast deposits (km-scale thick, hundred-to-thousand km-scale lateral extent) of wind-blown dust, analogous perhaps to terrestrial loess deposits, but deposited on a scale unlike anything that ever occurred on Earth (see Figure 5; Bridges et al., 2010; Lewis et al., 2008). In the absence of rainfall over hundreds of millions to billions of years it is conceivable that dust could have accumulated to form enormous deposits.

DISTRIBUTION AND ACCUMULATION OF SEDIMENTS

Sedimentary deposits have been identified across the southern hemisphere and near the equator of Mars, and in a fewer number of locations in the northern hemisphere (Figure 5). A variety of eolian facies tracts (Grotzinger et al., 2005), alluvial geomorphological

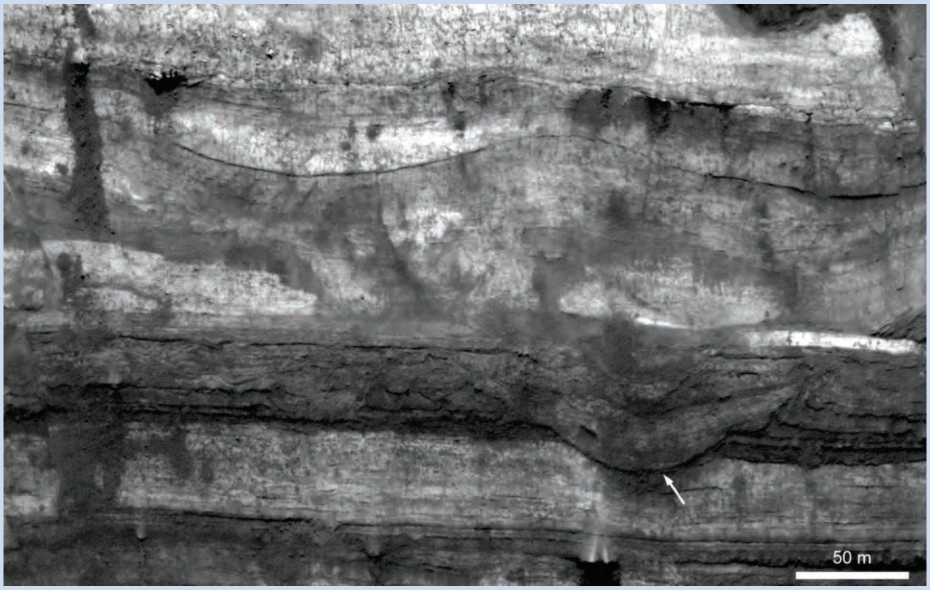

Figure 3. Strata exposed on the gently-sloping wall of a crater in the Mawrth Vallis region. An important feature of the strata is an inferred buried impact crater (arrow). Note dark stratigraphic unit pierced by impact depression that is also marked by overturned strata along right margin. Younger strata onlap margins of paleo-crater and bounding strata may represent reworking of impact-derived detritus.

elements (Pondrelli et al., 2008), and sub-lacustrine sediment fan deposits (Metz et al., 2009) have been documented. Most of these occurrences are preserved as erosional remnants and so it is suspected that the sedimentary record was previously much more continuous than it is today.

Lithospheric subsidence is not the primary mechanism for creating accommodation space on Mars. The Valles Marineris rift valley system is a spectacular but unique case of anomalous sediment accumulation up to several km-thick. It is a site of a significant (almost continuous from end to end) sedimentary accumulation (Figure 5). Generally, regional topographic lows evidently resulted from the removal of uppermost crust during impacts that created multi-ring crater basins. At a much smaller scale, single impact craters represent sites (Figure 5) very prone to sediment accumulation and preservation (i.e. the cores of remnant buttes are often preserved in crate interiors; Loizeau et al., 2008).

Subsurface ice and liquid water of capillary fringes above underground water tables were certainly essential to the cementation of unconsolidated sedimentary deposits (McLennan et al., 2005). Oscillations in the water level of lakes formed in Early Mars topographic enclosures may have organized sedimentary accumulations into distinct depositional units that define patterns of baselevel change. Typical stratal geometries associated with prograding clinoforms (i.e. truncations, onlap and downlap features) have been observed (Dromart et al., 2007).

DIAGENESIS

Alteration minerals such as clays and chemical precipitates (sulfates, chlorides, sedimentary silica, etc.) contain information useful in deciphering the evolution of Mars' surficial environment. Existing image data provides clear evidence for a range of diagenetic textures, that should be familiar to Earth scientists (e.g. Figure 6). On the downside it can be difficult to reconstruct primary processes given the overprint of diagenetic textures in ancient rocks (e.g., McLennan et al. 2003), and Mars is no exception.

Sulfate-rich sandstone outcrops examined by the *Opportunity* rover (Figure 6) show evidence of spatially variable recrystallization (McLennan et al., 2005; Tosca et al., 2005). This is expressed through disruption of primary rock textures in addition to mineral phase changes. The apparent persistence of amorphous silica in ancient sedimentary deposits helps constrain the thermal and fluid/rock regime of at least some specific Martian diagenetic environments (Tosca and Knoll, 2009). This observation suggests that silica-bearing deposits did not experience sustained interaction with fluids after their initial formation and thereafter remained stable for billions of years. In a similar way, the composition of martian clays (e.g., mixed-layered or illitic) indicates the extent to which they have experienced post-depositional heating or interaction with fluids. Understanding the effects of burial diagenesis and impact processes on martian sediments remains an important area of study because of its implications for preservation of organic carbon. In general, cementation and lithification processes on Mars remain poorly understood due to the absence of all but a handful of well-studied *in situ* surface locations.

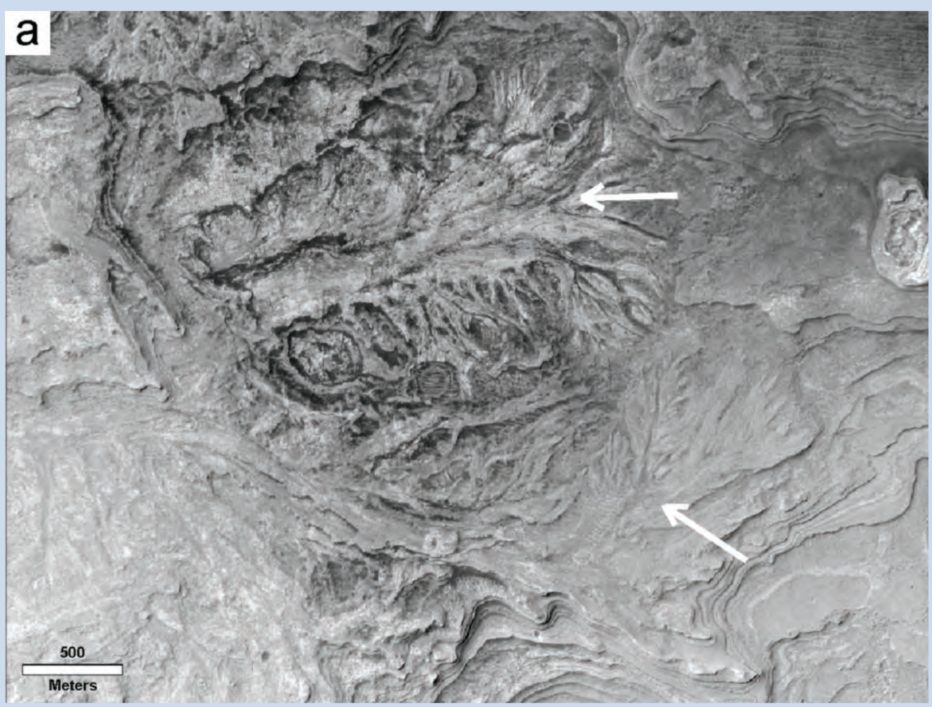

Figure 4. Interpreted sub-lacustrine fan systems in Southern Melas Basin, Valles Marineris (Metz et al., 2009).

CONCLUSIONS

The dynamics and evolution of Martian surface environments is preserved within a well-defined record of sedimentary rocks. The preserved record overlaps in age with the earliest record on Earth, even predating the oldest terrestrial rocks; the oldest Martian sedimentary rocks likely exceed 4 billion years. Younger Martian strata are comparable in age to Archean rocks on Earth but these Martian strata bear evidence for a dramatic divergence in the evolution of Mars' surface environments relative to Earth. As a result of the absence of plate tectonics and crustal recycling on Mars, the stratigraphic record on Mars is not just older but sedimentary textures may be better preserved, given the absence of overprinting thermal/metamorphic effects or penetrative deformation. Lower thermal overprints and water/rock ratios during diagenesis are suggested by the presence of unexpected minerals such as amorphous silica and smectites in rocks that are billions of years old. Consequently, the record of Martian strata may permit analysis of a dramatically different environmental course featuring global change from a wet, pH-neutral planet to a drier, more acidic environment. Comparative analysis with Earth's stratigraphic record yields the extraordinary opportunity to evaluate two terrestrial planets whose surface processes were subject to different initial and boundary conditions, including gravitational constant, degree of crustal differentiation, atmospheric properties, and liquid water composition.

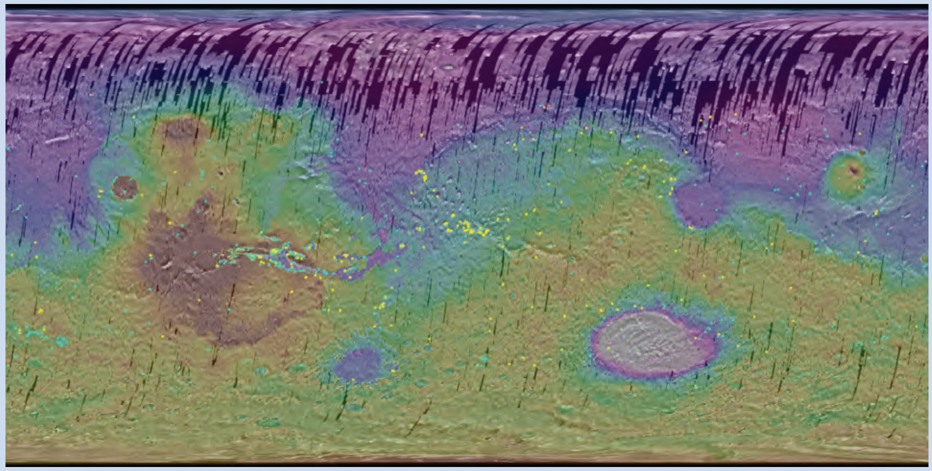

Figure 5. Distribution of sedimentary rocks on Mars plotted on map showing topography of Mars. Blue dots correspond to strata exposed inside of craters or wallrock of major canyon systems such as Vallis Marineris (high concentration of blue dots in center left part of image). Yellow dots correspond to strata preserved on plains away from obvious topographic depressions.

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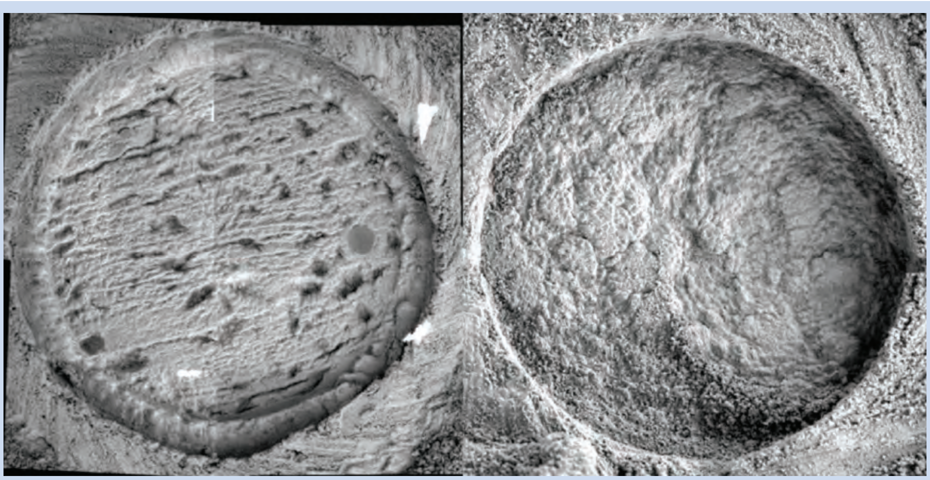

Figure 6. Textures consistent with recrystallization of sulfate-rich sediments. Left; well-stratified sulfate-rich sandstone showing crystal molds after unknown (possibly sulfate) mineral, and hematitic concretions, some of which are rimmed by later cement. Right; recrystallization results in homogenization and more coarsely crystalline texture. See McLennan et al. (2005). Each grind hole is ~4.5 cm in diameter.

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