THE OTHER SEDIMENTARY ROCKS OF EARLY MARS.

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Introduction: Mars presents a sedimentary rock record—a record of past environments—that includes lithologic bodies older than the oldest on Earth. The occurrences which have been the focus of study for the past ~16 years are a sub-set of the full range found at or near of the surface of Mars. These occurrences do not all exhibit the tonal, stratal, nor erosional expression properties of those described in the seminal [1–3] and key summative [4] publications. Geologic forms observed in images from rovers and orbiters lead to recognition that sedimentary rock outcrop expressions include additional forms and that they are more widespread than previously discussed. In particular, the observations raise the possibility that the landscapes of the heavily cratered terrains of Mars are dominated by exposures of sedimentary rock.

Hypothesis: Under exploration, here, is the hypothesis that the ancient upper crust of Mars—its heavily cratered terrain—consists largely of bodies of sedimentary rock returned to the surface after periods of burial and lithification. Further, bodies of igneous rock might be rare except for where they have long been known (*i.e.*, since 1972) to occur. The underlying assumption is that the original surface of Mars was heavily cratered by impactors and weathered and eroded in the presence of gravity and gaseous (wind), liquid (*e.g.*, water), and, perhaps, solid (ices) agents. A fraction of the impact-fragmented rock, condensed rock vapor, and solidified melt produced by these events was further weathered, eroded, transported, sorted, and re-deposited. At the same time, volcanism produced tephra and lavas and these would also undergo weathering and erosion (including via impact events), again with some of the debris becoming weathered, eroded, transported, sorted, and deposited elsewhere. Some of these sediments—including those formed of primary, un-reworked tephra, landslide debris, and impact ejecta—would have become buried and lithified, forming clastic sedimentary rocks. Some sedimentary rocks would, in turn, be further weathered and eroded, shedding clasts that were incorporated into later generations of sedimentary rock. Salts precipitated from solution would also be preserved in the rock record.

General Statements Regarding Mars: Study of the geologic materials exposed at the Martian surface by remote means is, constantly, an exercise in asking the question, “What is missing?” The question is deepened by also asking, “Is it missing because it is buried or because it was removed?” Mars sedimentary rocks and landscape evolution go together—they are linked through the differential erosion of rock bodies composed of fragmental debris. Craters like Henry and Gale were sites of net sediment deposition and later became net sediment sources, with millions of cubic meters of clasts removed [*e.g.*, 5]. Many craters were filled, buried, and some were exhumed; others were completely or partially removed—by erosion—from the record. Valley networks and their channel systems, too, are discontinuous; some were filled, buried, exhumed, removed, and the channel sediments of some are now inverted or vanished and the valley host rock has also been removed (*e.g.*, **Figs 1, 2**). The configuration of the Martian surface is temporary, with landscape gradation dominated for a large fraction of the planet’s history by the results of differential wind erosion and lag development. Where rocks exposed at the surface are susceptible to dis-integration into small fragments, they do so, and the products are removed (largely by wind).

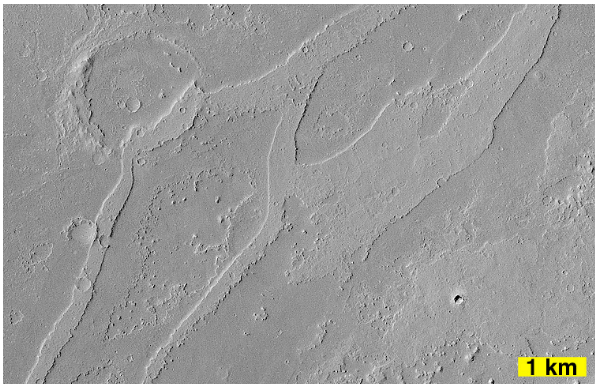

Fig 1. Deeply-eroded western Arabia Terra intercrater landscape composed of butte- and mesa-forming stratified rock. The remains of a body of fluvial channel sediment are evident; the host rock for the valley has been removed, as has most of the impact crater which had to have been buried before the fluvial system was superimposed. The terrain is thinly mantled by a covering of dust which provides the appearance of a uniform albedo. Located near 8.2°N, 11.1°W, this is a portion of MRO CTX image D16_033628_1871_XI_07N011W.

Mars Science Laboratory (MSL) Contributions: Images acquired by the MSL rover, Curiosity, examined together with the high resolution views from the Mars Reconnaissance Orbiter (MRO) and Mars Global Surveyor (MGS), provide new insights: **(1)** Some bodies of sedimentary rock, particularly sandstones, are sufficiently well-cemented so as to be as heavily peppered with, and preserve, small (< 1 km diameter) impact craters, as do erosion-resistant lava surfaces. **(2)** Yet, even these erosion-resistant sandstones do not last forever, as lateral eolian undermining, collapse, and further break-down of the debris eventually removes the sandstones. **(3)** A body of rock exhibiting a light tone, as observed in images acquired from afar (*e.g.*, orbiter), is not necessarily a property of the rock; at the Opportunity site, the Burns formation rocks were indeed light-toned; at the Curiosity site, tone is sometimes a function of mm- to cm-scale roughness and the presence of dust coatings—rocks that appear light-toned from a distance can be dark gray when examined in a dust-free state. **(4)** The geomorphic expression of a body of sedimentary rock exposed on Mars does not necessarily provide clues—or readily obvious clues—regarding depositional setting; the fossil form of a river delta in Eberswalde crater [2] is an excellent example of one that does; the "orbital striated outcrop" at the Kimberley field site in Gale [6] is an example of one that does not. **(5)** At the Curiosity site, bedrock is almost always at or very near the surface; this is also the case at the Opportunity and Spirit sites. **(6)** Wind erosion of a conglomerate produces a lag of its own debris, composed of the coarser, resistant clasts shed from that rock; this can also trap dust; the landscape as viewed from afar (*e.g.*, orbiter images) is thus of a fairly uniform albedo, hummocky terrain. Breccias would likewise produce an erosional expression and lag development similar to that of conglomerates.

Identification in Orbiter Images: The MRO Context Camera (CTX) has covered > 95% of Mars at 6 m/pixel, and both the MRO High Resolution Imaging Science Experiment (HiRISE) and MGS Mars Orbiter Camera (MOC) provide views of several percent of surface at higher resolution. Mars Odyssey THEMIS infrared images reveal candidate Cl-salt-bearing (evaporitic?) strata [7] and provide thermophysical observations that aid in rock body identification [*e.g.*, 8]. Some vital observations include: **(1)** Depositional setting mimicry—some bodies of sedimentary rock exposed at the Martian surface exhibit a geomorphic expression that provides clues to depositional setting; these include lithified eolian dunes, fluvial deltas, alluvial fans, stream channels, stream channels convergent on a larger body of lake or pond sediment, landslide deposits, and, perhaps most importantly, impact ejecta deposits. **(2)** Groundwater and diagenesis—Rovers [*e.g.*, 3, 6] and orbiters have both shown ample evidence for past movement of fluid through porous and fractured sedimentary rock and changes that occurred in those rocks. Orbiter views include examples of diagenetic halos adjacent to fractures [9] and meter-scale boxworks where erosion-resistant fracture fills stand above surrounding terrain [10]; observations such as these aid in remote identification of bodies of sedimentary rock. **(3)** Ubiquitous sedimentary rock occurrences—CTX coverage and supporting higher resolution MOC and HiRISE views support the notion that sedimentary rock bodies occur nearly everywhere, exposed or thinly mantled with debris or dust, throughout the heavily cratered terrains of Mars. Some bodies are readily recognized because of their mimicry of depositional setting, others because of their geomorphic resemblance to more familiar occurrences such as those at the Curiosity and Opportunity sites or the canonical identification criteria used for the past ~16 years [1, 4].

References: [1] Malin, Edgett (2000) *Science 290*, doi:10.1126/science.290.5498.1927. [2] Malin, Edgett (2003) *Science 302*, doi:10.1126/science.1090544. [3] Squyres *et al.* (2004) *Science 306*, doi:10.1126/-science.1104559. [4] Grotzinger, Milliken, eds. (2012) *Sedimentary Geology of Mars, SEPM Spec. Publ. 102*. [5] Bennett, Bell (2016) *Icarus 264*, doi:10.1016/-j.icarus.2015.09.041. [6] Grotzinger *et al.* (2015) *Science 350*, doi:10.1126/science.aac7575. [7] Osterloo *et al.* (2008) *Science 319*, doi:10.1126/science.1150690. [8] Fergason *et al.* (2012) *Space Sci Rev 170*, doi: 10.1007/s11214-012-9891-3. [9] Okubo, McEwen (2007) *Science 315*, doi: 10.1126/science.1136855. [10] Siebach, Grotzinger (2014) *J. Geophys. Res. 119*(1), doi:10.1002/2013JE004508

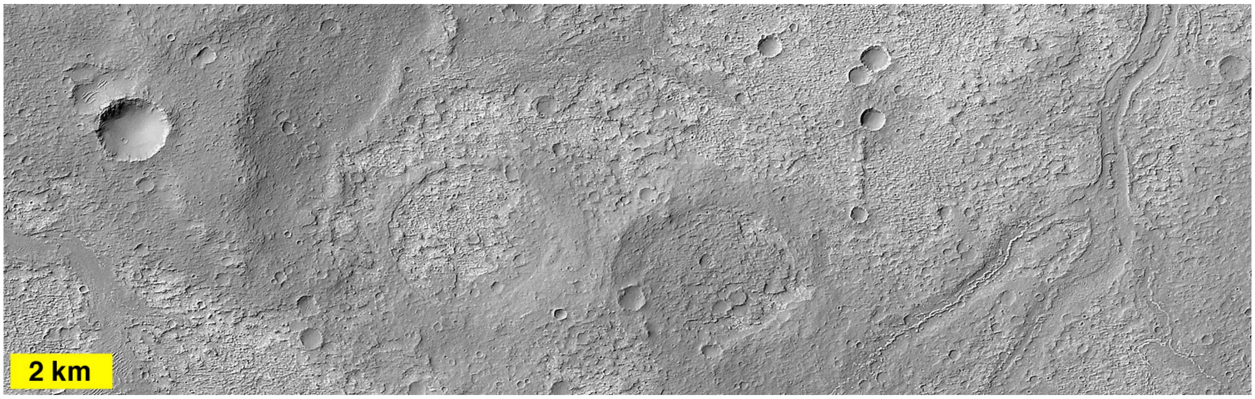

Fig 2. Sedimentary rock exposures in Terra Cimmeria near 31.9°S, 184.6°W. This is a mosaic of portions of MRO CTX images P14_006590_1474_XN_32S184W and P16_007447_1470_XI_33S184W.