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THE MARTIAN SEDIMENTARY ROCK RECORD: RECENT ADVANCES IN OUR UNDERSTANDING OF DEPOSITIONAL PROCESSES AND ENVIRONMENTS. K. M. Stack¹, K. S. Edgett², S. Gupta³, S. G. Banham³, G. Caravaca⁴, B. T. Cardenas⁵, M. Day⁶, L. A. Edgar⁷, C. M. Fedo⁸, A. A. Fraeman¹, T. A. Goudge⁹, J. P. Grotzinger¹⁰, S. Gwizd¹, L. R. W. Ives¹, E. S. Kite¹¹, M. P. Lamb¹⁰, M. G. A. Lapôtre¹², N. Mangold¹³, M. J. Meyer¹⁴, R. E. Milliken¹⁴, K. L. Siebach¹⁵, M. Tebalt⁹, A. R. Vasavada¹, ¹Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109, kathryn.m.stack@jpl.nasa.gov, ²Retired from Malin Space Sci. Syst., San Diego, CA, ³Imperial College, London, ⁴IRAP, CNES, CNRS, Université Toulouse, Toulouse, France, ⁵Penn State, State College, PA, ⁶UCLA, Los Angeles, CA, ⁷USGS Astrogeology Science Center, Flagstaff, AZ, ⁸University of Tennessee Knoxville, Knoxville, TN, ⁹University of Texas Austin, Austin TX, ¹⁰California Institute of Technology, Pasadena, CA, 91109, ¹¹The University of Chicago, Chicago, IL, ¹²Stanford University, Stanford, CA, ¹³CNRS, Université Nantes, Nantes, France, ¹⁴Brown University, Providence, RI, ¹⁵Rice University, Houston, TX.

Introduction: Sedimentary rocks on Mars preserve a record of past depositional and diagenetic conditions that offers an opportunity to investigate the planet's geologic and climate history beyond the limits of the geomorphic and impact crater records. Since 2019, new rover and orbiter observations and analyses of the Martian sedimentary record, along with sediment transport modeling advances, have provided important insights into the environment, climate, and habitability of early Mars. This review presents: (1) key advances in Martian sedimentology and stratigraphy over the past 5 years, (2) current limitations, and (3) priority areas for future research.

Advances: Evolution of Mars surface environments through time. The high spatial resolution and ground-based viewing perspective of rovers with access to 100s of meters of stratigraphy has enabled the recognition of environmental and climatic oscillations at an unprecedented level of detail and complexity. In Gale crater, Curiosity data reveal transitions between lacustrine, fluvial, littoral, and aeolian depositional settings within Aeolis Mons (informally, Mount Sharp) strata [1-7], as well as high frequency wet-dry cycling [8] and evidence of seasonal atmospheric changes [9]. In Jezero crater, Perseverance has observed a time-ordered sequence of alluvial, lacustrine, deltaic, and fluvial sedimentary rocks [10] with fluctuations in lake level recorded in this stratigraphy [11].

Significance of mineral stacking patterns observed in orbiter data. Rover observations reveal that mineralogical transitions and associations observed in orbiter data often record diagenesis rather than primary depositional conditions. For example, the clay-sulfate transition in Gale crater results from an increase in the population of diagenetic sulfate-rich veins and concretions [12, 13] formed at depth [14]. The hematite in Vera Rubin ridge, once considered a candidate for deposition in a redox-stratified lake [15], records a concentration of diagenetic hematite [16]. Observations by Perseverance in Jezero crater reveal that clay minerals detected on the upper surface of the fan are not

detrital [17] and are either secondary cements or a signal of pre-deposition alteration of mafic clasts [18]. Caution is thus warranted when inferring depositional conditions from mineralogy observed in orbiter data.

Sediment cycling on early Mars. Recent observations show that Mars has a sedimentary rock cycle involving multiple cycles of deposition, lithification, and erosion [19]. Evidence in Gale crater includes sandstone clasts embedded within conglomeratic boulders [20] and numerous erosional surfaces within the Mount Sharp sequence [4, 20]. Unconformities and sequence boundaries also occur in the Jezero sequence [10]. These unconformities correspond to cycles requiring long intervals of geologic time and deep deflation by the wind [21]. Implications of an active sedimentary rock cycle include: (1) recognition that early Mars erosion rates must have been faster than previously acknowledged, and (2) major time gaps exist within the observed rock record.

Sedimentary systems as a proxy for temporal and climate diversity across the surface of Mars. Recent orbiter-based studies advance our appreciation of the diversity of sedimentary deposits on Mars through time [22] and have added complexity to the simplistic vision of early Mars as either “warm and wet” or “cold and dry.” There have been advances in the global characterization of rivers, alluvial fans, and deltas on Mars [23-29], which span variable elevations and inferred ages, some of which may be quite young [30]. There is now widespread evidence for discrete ancient lakes and possible seas across the surface of Mars [24, 25, 31], some of which were recorded in the sedimentary record by ancient ripples [7]. There is also new recognition of a robust record of ancient aeolian processes in Martian rocks [9, 32-34], including bedforms as indicators of atmospheric density [35]. The spatial and depositional diversity of sedimentary rocks hints at temporal heterogeneity [36], with the possibility of regionally variable climates and environmental conditions [37, 38], and/or globally coordinated shifts between arid and humid conditions [39].

Improved theory and models for fluvial sediment transport on Mars. Rivers on Earth and Mars appear to share morphological similarities, but recent studies highlight ways in which different conditions, such as gravity, fluid properties, and absence of vegetation, affected (or not) Martian rivers (e.g., [40]). Recent works include: (a) the potential for the development of meandering single-thread river systems in a variety of bank substrates, including unvegetated, muddy and gravel landscapes [41]; (b) the first facies models tailored to meandering rivers forming in unvegetated landscapes to aid in their recognition in future ground observations of fluvial stratigraphy on Mars [42]; (c) confirmation that—for a given discharge and channel morphology—Martian rivers should have been capable of mobilizing and transporting in suspension larger grains than rivers on Earth at larger transport rates due to reduced gravity [43].

Limitations: A key issue is the absence of absolute age constraints on Martian stratigraphy which not only prevents robust bracketing of sedimentary sequences in geologic time, but also correlation between different geographic regions across Mars. Also apparent is that the sedimentary rock record of Mars is vaster than previously realized [22], but distinction from igneous rock, particularly tuff, remains challenging even at sub-millimeter scales [22]. Coatings and dust cover can impede natural surface observations, and the abrasion and dust removal tools of Curiosity and Perseverance have limitations, particularly in very fine-grained rocks. Conclusively distinguishing between fluvial, deltaic, and aeolian deposition has often proven challenging with rover datasets given image resolution limits of and the non-uniqueness of some sedimentary structures at the outcrop scale.

Future Work and Priorities: *Outstanding questions.* Questions remain about sediment lithification processes including cementing agents, the amount and source of fluid, and the time involved, particularly for those sequences that may have experienced only shallow burial, e.g., Jezero fan and younger, unconformable units of Mount Sharp. Future research should consider clastic cementation at a range of burial depths and environmental conditions. This work would also inform interpretations of mineralogical observations from orbit as related to sedimentary rock deposition, diagenesis, and stratigraphic correlation.

Mars Sample Return and Future Missions. The past ~20 years have been a golden age of rover exploration on Mars, leading to the development of sedimentology and stratigraphy as a vital new field of Martian science. However, key questions can only be answered through laboratory analysis: for example, do Martian sedimentary rock samples record signs of ancient life?

When did water flow on the surface or in the subsurface and what is the absolute age of sedimentary rocks on Mars? How much time is missing from the sedimentary record as recorded by unconformities? What was the composition and extent of the ancient atmosphere, how did it change over time, and how did it interact with surface reservoirs of water and CO₂? Perseverance's onboard suite of sedimentary rock samples record diverse depositional environments and diagenetic conditions that are well-suited for addressing these questions if, and when, they are returned to Earth.

The spatial, temporal, and depositional diversity of the Mars sedimentary rock record suggests that the exploration and integration of many sites across the surface of Mars provide the best chance for advancing understanding of ancient Mars history. Build-to-print, multi-mission approaches, e.g., a fleet of helicopters or small rovers distributed to dozens of locations, may offer a relatively low-cost future exploration strategy.

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