THE SEDIMENTARY HISTORY OF MARS AS OBSERVED BY ROVERS. E. B. Rampe[1], R. E. Arvidson[2], L. A. Edgar[3], K. S. Edgett[4], C. M. Fedo[5], A. A. Fraeman[6], J. P. Grotzinger[7], S. M. McLennan[8], D. W. Ming[1], R. V. Morris[1], K. L. Siebach[9], R. J. Sullivan[10]. [1]NASA Johnson Space Center, Houston, TX, elizabeth.b.rampe@nsaa.gov, [2]Washington University, St. Louis, MO, [3]USGS Flagstaff, [4]Malin Space Science Systems, [5]University of Tennessee, Knoxville, [6]JPL-Caltech, [7]Caltech, [8]SUNY Stony Brook, [9]Rice University, [10]Cornell University.

Introduction: Mars has a sedimentary history that spans billions of years [e.g., 1,2]. Orbital images have allowed for the identification of vast regional sedimentary deposits that can be traced over 100s of km and are 100s of m thick [e.g., 3-5] including localized alluvial, deltaic, and lacustrine deposits [e.g., 6,7]. Detections of secondary minerals in these deposits from orbital spectroscopy suggest the aqueous history of early Mars varied as a function of space and time [e.g., 1,2,5,8]. Orbital observations, however, provide a simplified and incomplete picture of Mars' sedimentary history because measurements for inferring sediment transport and deposition, such as lithology, grain size, and internal structures [9], and measurements for inferring sediment source and aqueous alteration, such as outcrop-scale mineralogic and geochemical composition and diagenetic features [2], cannot be identified from orbit. Rover observations have significantly enhanced our view of ancient and modern sedimentary environments on Mars, resulting in detailed reconstructions of paleoenvironments and habitability.

Sedimentary Cycles on Mars vs. Earth: To better understand the sedimentary history of Mars, it is important to discuss the differences in the sedimentary cycles of Earth and Mars [e.g., 1,2]. On Earth, the sedimentary cycle is primarily driven by plate tectonics, where mountain-building events provide a source for sediments that are transported by fluvial processes to sinks, such as ocean basins. Plate tectonics allows for the recycling of these sediments and for the evolution of igneous rocks such that the average crust has a granodiorite composition [10]. Mars never had robust tectonism, so, on early Mars, sediments were primarily produced by impacts and volcanism. Impacts also provided basins in which sediments were deposited by fluvial and eolian activity. Furthermore, Mars is primarily a basaltic planet [e.g., 11], which results in distinct differences in the common aqueous alteration products found on Mars vs. Earth [e.g., 12]. Minimal large-scale sediment recycling on Mars has allowed for the preservation of ancient depositional environments so that we can investigate much of Mars' history.

Sediment Transport and Deposition on Early Mars: Evidence for sediment transport and deposition in aqueous environments has guided landing site selections for rovers on Mars. The Mars Pathfinder *Sojourner* rover landed in the outflow channel Ares Vallis and identified boulders that were deposited by one or more flood events [13]. The Mars Exploration Rover *Opportunity* landed on the intercrater plains of Meridiani Planum to study outcrops enriched in hematite, which commonly forms in aqueous environments. Here, the rover investigated an extensive sedimentary deposit called the Burns formation, beautifully exposed in crater walls. The Burns formation is late Noachian/early Hesperian in age [14]. At the base of one exposure, the unit is comprised of primarily sulfate-rich basaltic sandstone that show large-scale cross-bedding, which is overlain by fine-scale planar laminated and low-angle stratified sandstone, both of which are capped by wavy bedded, irregularly laminated, and festoon cross-laminated sandstone [15]. These sedimentary structures are consistent with an evolution to a progressively wetter environment that changed from an eolian dune, to an eolian sand sheet, to a mixed eolian sand sheet and interdune environment [15], although alternative depositional hypotheses have been proposed [16-18].

The Mars Science Laboratory *Curiosity* landed in Gale crater to study sedimentary units that show variation in mineralogy suggesting a change in aqueous environments over time [19]. *Curiosity* has investigated ~400 m of vertical stratigraphy and has discovered an incredible diversity of sedimentary environments. The oldest sedimentary units (the Bradbury group and Murray formation) are early Hesperian in age and are comprised of conglomerate, sandstone, and laminated mudstone [e.g., 20-23]. These sediments were primarily deposited in shallow streams and lakes that likely existed for upwards of 10 million years [20]. Outcrop-scale images taken by the Mastcam instrument and hand lens-like images taken by the MAHLI instrument have allowed for detailed reconstructions of paleoenvironmental conditions. For example, images of a fluvial sandbody called Shaler in the Bradbury group indicate it formed from accretion of a barform that migrated to the southeast during short periods of sustained flow [23]. The small grain size and mm-scale laminations of mudstone in the Pahrump Hills succession in the Murray fm is consistent with deposition in lacustrine environments, and low-angle cross-stratification in the mudstone is consistent with river-generated plumes plunging into a lake [24]. *Curiosity* has also investigated the Stimson formation, which is an eolian sandstone that unconformably overlies the Murray formation. The amount of time

between the end of the Murray formation and the deposition of the Stimson formation is unknown, but was likely significant because the Murray formation must have been deposited, lithified, and partially eroded before deposition of the Stimson formation [24].

Aqueous Alteration and Diagenesis: Mineralogical and geochemical measurements and the detection of diagenetic features by rovers have demonstrated a diversity of aqueous environments were present on the surface and near surface, at least intermittently, for over a billion years. Although the Burns formation in Meridiani and the Murray formation in Gale crater may have been deposited nearly contemporaneously, their compositions suggest very different aqueous histories. Abundant sulfate salts, hematitic concretions, and secondary porosity caused by dissolution in the Burns formation suggest multiple aqueous episodes, including evaporation of acidic fluids and diagenesis in high-ionic strength groundwater [25]. The Murray formation, however, has much less sulfate, and shows variations in mineralogy within the stratigraphy that suggest changes in aqueous conditions over time [e.g., 26-28]. Differences in relative abundances of hematite and magnetite indicate changes in oxidation potential of aqueous fluids [26,27], and a greater abundance of dioctahedral smectite going up section suggests more intense alteration over time [28]. These mineralogical changes in the stratigraphy observed by *Curiosity* may be tied to changes in climate and/or diagenetic processes [26-28]. The observation of a variety of diagenetic features and a K-Ar age of 2.1±0.4 Ga for jarosite in a sample from the Pahrump Hills demonstrate a long history of groundwater in Gale crater [e.g., 29-30]. In-situ sedimentological and geochemical measurements of ancient sedimentary rocks on Mars suggest many of these depositional environments would have been habitable to microbial life because of the evidence for liquid water, the availability of key elements for life, and sources of energy for chemolithotrophs [31,32].

Mineralogical and geochemical data of sedimentary rocks measured by rovers also provide information on igneous sources for the sediments and sediment sorting. Geochemical variations in the Bradbury group are primarily tied to hydrodynamic sorting and segregation of larger plagioclase grains from smaller mafic mineral grains in a plagioclase-phyric basalt source [33]. Mineralogical and geochemical data from *Curiosity* also suggest more evolved igneous sources for some sediments [e.g., 33-35], demonstrating greater igneous variability than can be appreciated from orbit.

Modern Sedimentary Processes: Sediment mobilization and deposition in the current surface environment is dominated by wind [e.g., 36,37]. Despite the thin atmosphere, ultrafine particles are routinely lofted into suspension around the planet to be deposited as mantles, and saltation of sand-sized grains is enabled by a large difference between fluid and impact thresholds compared with Earth [38-40]. Rovers have observed dust storm effects [41], encountered active ripples and dunes [42-44], and documented some bedform types lacking clear terrestrial analogs [e.g., 42, 44].

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