MARTIAN EOLIAN SCIENCE SINCE THE EIGHTH INTERNATIONAL CONFERENCE ON MARS: SUMMARY OF ADVANCES AND REMAINING QUESTIONS. M.G.A. Lapotre[1], N.T. Bridges[2†], B.L. Ehlmann[3,4], E.B. Rampe[5], R.C. Ewing[6], J.R. Johnson[2], F. Ayoub[4], M.M. Baker[7], S.G. Banham[8], M. Chojnacki[9], A. Cousin[10], M.D. Day[11], S. Diniega[4], O. Duran Vinent[6], C.S. Edwards[12], L.K. Fenton[13], T.S.J. Gabriel[14], M.P. Golombek[4], L. Kerber[4], J.F. Kok[11], M.P. Lamb[3], J. Lasue[10], C.E. Newman[16], C.D. O'Connell-Cooper[17], D.M. Rubin[18], S. Silvestro[19,13], J.C. Stern[20], R.J. Sullivan[21], A.R. Vasavada[4], D.A. Vaz[22], C.M. Weitz[23], H. Yizhaq[24], J.R. Zimbelman[25].

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Introduction & Relevance to the Mars Program: Eolian science focuses on the set of wind-driven processes that modify planetary surfaces, including the production and transport of windblown sediments, their deposition, and their effects on the landscape and local environment. Eolian processes are widespread in the Solar System [1], and the landforms they create contain direct clues about the atmospheric conditions under which they form, and as such, offer a powerful record to decipher both paleo- and modern environments.

Along with periglacial processes, eolian processes largely dominate the surface of Mars today, and likely have for more than 3 Ga [2]. Thus, the transport of windblown sand on Mars has exerted a major control on landscape evolution, and understanding the rates of wind-driven landscape modification directly feeds into, for example, quantifying the rates of exhumation of putative buried organics, and thus, evaluating the prospect of candidate astrobiological targets. Even under an active hydrologic cycle, eolian processes would have acted in concert with fluvial systems on Mars to route sediments across the landscape, from sources to sinks [3]. Learning to decipher clues from sedimentological data can provide critical insights into Mars' geologic and climate history, as well as its habitability through time. Finally, active eolian processes, including the production and suspension of fine airborne dust during planet-encircling events, may constitute severe challenges for surface operations by humans, and understanding the modern eolian environment in a predictive way is critical for the eventual human exploration of Mars.

Brief Summary of the Pre-2014 State of Knowledge: Since Mariner 9 first detected dunes on the martian surface almost five decades ago [4], the eolian environment of Mars has been largely characterized using orbiter-based assets. Three main types of eolian bedforms were detected from orbit – large dunes, meter-scale ripples forming in dark sand, and meter-to-decameter high-albedo ripple-like bedforms called *transverse aeolian ridges* (TARs). The latter two bedform types were not widely recognized on Earth. Dune fields were mapped across the entire martian surface [5], and display dynamic and complex behaviors, much like terrestrial dune fields. Time series of HiRISE images revealed that martian dune fields are globally active, with some modern martian dunes migrating at rates that are on par with some terrestrial dunes [6]. The Mars Exploration Rovers made ground-based observations of windblown bedforms [7-8], including decimeter- to meter-scale ripples [8-9], as well as ventifacted float rocks [10] (complementing orbiter observations of yardangs across the planet [11]), and ancient windblown sandstones [12]. Physical models for the thresholds of saltation under the thin modern martian atmosphere were developed [13]. In addition, the composition of windblown sediments was investigated with orbiter-based spectrometers, and were shown to be largely made of basaltic grains, with a few dune fields containing variable amounts of other minerals including gypsum [14]. Prior to 2014, planet-encircling dust storms had been observed, by multiple spacecrafts and Earth-based telescopes, when the planet was near perihelion [15]. The composition of martian dust was constrained by both orbiting spectrometers and ground assets [16].

Advances in Martian Eolian Science Since 2014: Since the 8th International Conference on Mars, additional orbiter-based analyses have enabled a refined characterization of sand fluxes, composition, and mineral sorting. In addition, Curiosity performed the first in situ investigation of an extraterrestrial dune field – the Bagnold Dunes of Gale crater – and witnessed a global dust storm in 2018. Selected advances in martian eolian science will be summarized. Results related to martian dust will only be presented here as they pertain to eolian processes at the surface; dust storms will not be covered.

Physical Properties of Eolian Sands: Observations of varied bedforms along Curiosity's traverse revealed that bedforms within the Bagnold Dune Field are made of fine sand and are dust-free, whereas coarse-grained ripples (either isolated or in ripple fields) display coarser crests (medium to very coarse sand) and variable amounts of dust [17]. Based on the distribution of clast sizes at various landing sites on Mars, fragmentation theory was shown to readily explain the formation of sand-sized particles that can then be entrained by martian winds [18]. Ground-based measurements of the thermophysical properties of active sand revealed that previous grain-size overestimates from orbiter data resulted from subpixel sand-bedrock mixing, not grain-size variability, armoring, or induration [19]. Dunes were shown to affect the microclimate within the Bagnold Dune Field by inducing brief temperature fluctuations in the interdune [20].

Morphodynamics: Three scales of bedforms were documented in the Bagnold Dune Field – decimeter-scale impact ripples, meter-scale ripples, and larger dunes [21-24]. The origin of the large meter-scale ripples forming in fine sand is debated [21,25-26]. Large martian ripples display a rich morphologic diversity, and can form transversely to longitudinally to the net wind direction [23,27-28]. A new mechanistic model for coarse-grained ripples was formulated [29]. Analog field studies of coarse-grained ripples in Iran and Libya [30-31] further helped improve our understanding of TARs. Relationships between dune orientation and sediment cover were used to infer the wind regime based on a dune-growth model that incorporates both the bed-instability and fingering modes [32].

Fluxes & Winds: Orbiter-based observations of the seasonal nature of sand motion on Mars confirmed an overall low impact threshold [33]. The REMS wind sensor onboard Curiosity characterized the diurnal to seasonal wind environment at Gale crater [34]. Consistent with orbiter-based observations, Curiosity did not detect significant sand motion in southern autumn/winter (aphelion) in the Bagnold Dune Field [35], but the motion of coarse grains on bedrock [36] as well as the migration of small ripples were observed in southern summer near perihelion [37]. Sand fluxes associated with small ripples, large ripples, and dunes were estimated for the Bagnold Dune Field [35,37]. The motion of TARs was detected for the first time in polar and mid-latitude areas [38]. A new physical model was developed to explain the initiation of sand motion below the fluid threshold [39]. An update on orbiter-based analyses of sand-motion will also be presented in [40] at this conference.

Chemical & Mineral Composition: A global dataset of dune-sand composition was compiled [41]. Eolian sands are basaltic, and in the Bagnold Dunes, coarser grains are typically enriched in mafic phases [42-49]. Subtle spatial variations in mineralogy and chemistry reflect eolian sorting by grain size and the contribution of local bedrock sources to eolian sands [42-50]. Active sands show a general depletion in S, Cl, and H relative to inactive dusty bedforms [42,47-49,51-52]. Conversely, dust shows an enrichment in those elements [53-54]. Evolved gas analysis of dust-free and dusty eolian materials showed distinct carbon contents, with a large fraction of evolved CO_2 attributed to carbonates and organics [52]. Finally, active sands of the Bagnold Dunes contain high abundances of oxychlorine and nitrates relative to all other soil samples from Gale crater, which are thought to reflect a long exposure to the atmosphere and the lack of aqueous alteration to dissolve and transport these compounds [52].

Wind Erosion: Cosmogenic-nuclide exposure dating of a mudstone in Gale crater revealed that the rock was only recently exposed to the surface, suggesting high modern rates of wind-driven exhumation [55]. Wind-driven exhumation rates were also calculated from estimated sand fluxes at candidate landing sites for NASA's next rover mission [56]. Analog field studies focusing on yardangs provided insights into, e.g., wind-flow patterns around them [57].

The Ancient Eolian Record: Detailed sedimentological data from the Curiosity rover revealed that the Stimson Formation sandstone was deposited in a dry eolian environment dominated by sinuous to crescentic dunes [58], though compositional differences, including enrichment in S and Cl relative to the Bagnold Dunes, suggest a role for water-formed cements in lithification [42]. Decimeter-scale trough cross-stratification was identified in several ancient windblown sandstones, including the 3.7 Ga Burns Formation. These strata were recognized as the signature of meter-scale ripples, suggesting Mars had a modern-like atmospheric density at the time [21]. Orbiter-based imagery enabled the discovery of two ghost dune fields – where ancient dunes were once engulfed by a flow of unknown nature, leaving dune casts behind as loose sediment was removed through time [59] – and more examples of largely preserved paleo-dune fields [60].

Remaining Questions: Despite the large number of advances made since 2014 in martian eolian science, a series of critical questions remains to be addressed and answered to (1) further the usefulness of the eolian record as a quantitative paleoenvironmental archive, (2) understand the erosional history of the martian surface as it pertains to astrobiological endeavors, and (3) develop predictive capabilities with respect to the modern eolian environment and pave the road for the human exploration of Mars. At the conference, we will review a selection of these important questions, such as: How do large martian ripples form, and how can they be used as a robust proxy for paleoenvironment? What wind speeds mobilize martian sediments? What is the relative importance of various transport modes in forming small and large ripples? How do TARs form, and what can they tell us about the past atmosphere? What does the composition of windblown materials tell us about sources, sorting, and exchanges with the atmosphere?

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