MARTIAN EOLIAN SCIENCE: RECENT ADVANCES, REMAINING QUESTIONS, AND ROADMAP FOR FUTURE IN SITU INVESTIGATIONS. M.G.A. Lapôtre[1], M.M. Baker[2], S. Carpy[3], M. Chojnacki[4], M. Day[5], S. Diniega[6], O. Durán-Vinent[7]. R.C. Ewing[7], L. Fenton[8], M. Golombek[6], A. Gunn[9], L. Kerber[6], C. Newman[10], J. Radebaugh[11], L. Rubanenko[1], S. Silvestro[12], C. Swann[13], D. Tirsch[14], D.A. Vaz[15], C. Weitz[4], H. Yizhaq[16], J. Zimbelman[2].

[1]Stanford U., Stanford, CA (mlapotre@stanford.edu), [2]CEPS/NASM, Smithsonian Institution, Washington D.C., [3]CNRS–Nantes U., Nantes, France, [4]PSI, Tucson, AZ, [5]UCLA, Los Angeles, CA, [6]JPL, Caltech, Pasadena, CA, [7]Texas A&M University, College Station, TX, [8]SETI Institute, Mountain View, CA, [9]Monash U., Clayton, VIC, Australia, [10]Aeolis Research, Pasadena, CA, [11]Brigham Young U., Provo, UT, [12]INAF, Naples, Italy, [13]Ocean Science Division, US Naval Research Laboratory, Stennis Space Center, MS, [14]DLR, Berlin, Germany, [15]CITEUC, University of Coimbra, Coimbra, Portugal, [16]Ben-Gurion University of the Negev, Beersheba, Israel.

This abstract is an update to a conference presentation [1] given at the 9th International Conference on Mars in July 2019, expanded with a roadmap for future *in situ* investigations.

Introduction & Relevance to the Mars Program: Wind-driven processes that modify planetary surfaces include the production and transport of windblown sediments, their deposition, and their erosive impact on the landscape. Eolian processes are widespread in the Solar System [2], and the landforms they create contain direct clues about the atmospheric conditions under which they form, offering a powerful record of both paleo- and modern environments. Along with periglacial processes, eolian processes largely dominate the surface of Mars today [3], and likely have for more than 3 Ga [4]. Thus, the transport of windblown sand on Mars has exerted a major control on landscape evolution. Quantifying the rates of wind-driven landscape modification would provide direct constraints on the rates of exhumation of putative buried organics – a prerequisite to evaluating candidate astrobiological targets [5]. Even early in Mars' history when liquid water was present at the surface, eolian processes would have acted in concert with fluvial systems to route sediments across the landscape, from sources to sinks [6–7]. Learning to decipher clues from sedimentological data can provide critical insights into Mars' geologic and climatic history [8–9], as well as its habitability through time. Finally, eolian processes, including the production and suspension of fine airborne dust during planet-encircling events, may, e.g., create challenges for surface operations, so understanding the modern eolian environment in a predictive way is critical for both robotic and human exploration.

State of Knowledge and Recent Advances: Since Mariner 9 first detected dunes on the martian surface almost 5 decades ago [10], 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). Dune fields mapped across the entire martian surface [11] 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 on par with some terrestrial dunes [12]. The Mars Exploration Rovers made ground-based observations of windblown bedforms [13–14], including decimeter and meter-scale ripples [14–15], as well as ventifacted float rocks [16] (complementing orbiter observations of yardangs across the planet [17]), and ancient windblown sandstones [18]. Physical models for the thresholds of saltation under the thin modern martian atmosphere were developed [19]. 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 [20]. Planet-encircling dust storms have been observed near perihelion by multiple spacecraft and Earth-based telescopes [21]. The composition of martian dust was assessed by both orbiting and ground assets [22].

In the past decade, orbiter- and lander-based analyses have enabled a refined characterization of eolian processes. *Curiosity* performed the first *in situ* investigation of an extraterrestrial dune field (the Bagnold Dunes) [23], witnessed a global dust storm in 2018, and encountered a small TAR at Dingo Gap [24]. China's *Zhurong* rover conducted the first *in situ* investigation of a TAR field [25]. *Perseverance* encountered enigmatic flat-topped, likely indurated coarse-grained ripples [26]. Select advances in martian eolian science will be summarized in the presentation.

Physical Properties of Eolian Sands: Observations 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 [27]. 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 [28]. Ground-based measurements of the thermophysical properties of active sand revealed that previous grain-size overestimates from orbiter data at Gale crater resulted from subpixel sand-bedrock mixing, not grain-size variability, armoring, or induration [29].

Morphodynamics: Three scales of bedforms were documented in the Bagnold Dune Field – decimeter-scale impact ripples, meter-scale ripples, and larger (>80-m) dunes [8,30–31]. Large martian ripples display a rich morphologic diversity, and can form transversely to longitudinally relative to the net sand-flux direction [31–33], thus recording a complex wind signal [32–33]. The origin of the meter-scale ripples in fine sand is debated [8,34–36]; it has been proposed that they are large impact ripples [35] or form from a hydrodynamic anomaly that arises on Mars due to the low atmospheric density [34]. This anomaly would produce two distinct scales of "dunes" on Mars, the initial wavelengths of which would decrease with increasing atmospheric density – a prediction that is consistent with global measurements of large-ripple [8] and dune sizes [37–38]. Meter-scale ripples forming between dunes and with slightly brighter albedos are largely thought to be coarse-crested *megaripples*. Puzzling coarse-grained ripples with flat tops were observed by *Perseverance* at Jezero crater and appear to be ancient [26]. Analog field studies of coarse-grained ripples in Iran and Libya [39–40] further helped improve our understanding of martian megaripples and, possibly, TARs. TARs have been observed *in situ* in Gale crater by *Curiosity* [24] and Utopia Planitia by the *Zhurong* rover [25]; their investigation in Utopia Planitia is ongoing.

Winds, Active Transport & Fluxes: Orbiter-based observations of the seasonal nature of sand motion on Mars suggested an overall low impact threshold [41] – a result supported by recent low-pressure wind-tunnel experiments that revealed a lower than previously estimated fluid threshold for entrainment [42–43]. A new physical model was developed to explain the initiation of sand motion below the fluid threshold [44]. The effect of topography and sand supply on sand fluxes [45] and dune migration [46] were investigated globally. The REMS wind sensor onboard *Curiosity* characterized the diurnal to seasonal wind environment at Gale crater [47]. Consistent with orbiter-based observations, no significant sand motion was detected in southern autumn/winter in the Bagnold Dune Field [48], but motion of coarse grains on bedrock [49] as well as migration of small ripples were observed in southern summer [50–51]. Episodic dust-removal events and moderate transport of granules driven by turbulent vortices were documented by *InSight* [52–53]. The motion of megaripples was detected for the first time from orbit in polar and mid-latitude areas [54].

Composition: Dune-sand composition was estimated globally [20,55]. Most eolian sands are basaltic and, in the Bagnold Dunes, coarser grains are typically enriched in mafic phases. Subtle spatial variations in mineralogy and chemistry reflect eolian sorting by grain size and the contribution of local bedrock sources to eolian sands. Active sands show a general depletion in S, Cl, and H relative to inactive dusty bedforms [56–57]. Conversely, dust shows an enrichment in those elements [58–59].

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 [60]. Wind-driven exhumation rates were calculated from estimated sand fluxes at candidate *Mars 2020* landing sites [5]. Surface mapping demonstrated that recent wind-driven deposition and erosion shaped the landscapes of Oxia Planum, the landing site of ESA's planned *ExoMars* mission [61]. Analog field studies focusing on yardangs also provided insights into the role of substrate properties [62] and wind-flow patterns around them [63].

Ancient Eolian Record: Detailed sedimentological data from the *Curiosity* rover revealed that Gale crater's Stimson formation sandstone was deposited in a dry eolian environment dominated by crescentic dunes and including compound oblique dunes [64–65]. Decimeter-scale trough cross-stratification was identified in several ancient eolian sandstones, including the 3.7 Ga Burns formation in Meridiani Planum [8]. These strata were recognized as the signature of meter-scale ripples, suggesting Mars had a modern-like atmospheric density at the time [8]. Lithified meter-scale ripples overlying lacustrine strata at Gale crater suggest alternations between dry and wet atmospheric regimes [9]. 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 [66] – and more examples of largely preserved paleo-dune fields [67–68].

Remaining Questions & Roadmap for Future *In Situ* Investigations: A series of critical questions remains and will require *in situ* observations to be answered. *In situ* investigations on Mars will (1) further the usefulness of the eolian record as a quantitative paleoenvironmental archive, (2) develop predictive capabilities with respect to the modern eolian environment, and (3) understand the erosional history of the martian surface as it pertains to astrobiological endeavors. We will review a selection of these important questions, such as:

(i) What wind shear velocities mobilize sediments on Mars? Although wind sensors have been fitted to spacecraft in the past, all but one provided single-height measurements and all were affected by the spacecraft's body. Local thermal convection on Mars modifies the boundary layer, putting into question the application of convection-free boundary layer models. Solving this long-standing mystery will require a dedicated mission, involving a minimally invasive apparatus (e.g., vertical arrays of anemometers [69] or alternatively, doppler lidar or PIV if power requirements and data rate permit), the capability of measuring full grain-size distributions (e.g., with nested sieves) instead of surface counts [27], and a refined understanding of aerodynamic roughness [70].

(ii) What length-scale dominates aerodynamic roughness over martian sand sheets? Aerodynamic roughness on flat surfaces on Earth is determined by grain size in the absence of a well-developed saltation layer or the thickness of the latter under saturated transport conditions [71]. However, the low-density of the martian atmosphere implies the formation of thicker viscous sublayers for a given shear velocity, and large martian ripples may contribute significant roughness as their heights may exceed the thickness of the saltation layer. Answering (i) and (ii) would require a similar setup [70].

(iii) How do large martian ripples form, what is their characteristic formation timescale, and how can they be used as proxies for modern and paleo- environments? This question could be tackled from answers to (i–ii) and long-term monitoring of large ripples and winds (complemented with low-pressure wind-tunnel experiments on Earth). Night-time imaging of active saltation using a laser sheet would help visualize saltation trajectories and wind flow over large ripples, providing critical insights into large-ripple formation.

Additional questions and measurements pertaining to, e.g., dust lifting and wind-driven bedrock erosion rates will be included in the presentation.

References: [1] Lapôtre et al. (2019), *9th Int. Conf. Mars.* [2] Hayes (2018) *Science.* [3] Diniega et al. (2021) *Geomorph.* [4] Carr & Head (2010) *EPSL*. [5] Chojnacki et al. (2018) *JGR*. [6] McLennan et al. (2019) *Annu. Rev. Earth. Planet. Sci.* [7] Gunn et al. (2022) *Geology*. [8] Lapôtre et al. (2016) *Science*. [9] Rubin et al. (in press) *JGR.* [10] Masursky (1973) *JGR*. [11] Hayward et al. (2007) *USGS Map*. [12] Bridges et al. (2012) *Nature*. [13] Greeley et al. (2004) *Science*. [14] Sullivan et al. (2008) *JGR*. [15] Jerolmack et al. (2006) *JGR*. [16] Golombek et al. (2010) *JGR*. [17] Ward (1979) *JGR*. [18] Grotzinger et al. (2005) *EPSL*. [19] Kok (2010) *Phys. Rev. Lett*. [20] Tirsch et al. (2011) *JGR*. [21] Kahn et al. (1992) *U of A Press*. [22] Hamilton et al. (2005) *JGR*. [23] Lapôtre & Rampe (2018) *GRL*. [24] Zimbelman & Foroutan (2020) *JGR*. [25] Ding et al. (2022) *Nat. Geosci.* [26] Sullivan et al. (2022) *53rd LPSC*. [27] Weitz et al. (2018) *GRL*. [28] Golombek et al. (2018) *50th LPSC*. [29] Edwards et al. (2018) *JGR*. [30] Ewing et al. (2017) *JGR*. [31] Lapôtre et al. (2018) *GRL*. [32] Vaz et al. (2017) *Aeol. Res.* [33] Silvestro et al. (2016) *GRL*. [34] Durán-Vinent et al. (2019) *Nat. Geo.* [35] Sullivan et al. (2020) *JGR*. [36] Lapôtre et al. (2021) *JGR*. [37] Rubanenko et al. (2021) *IEEE-JSTARS*. [38] Lapôtre et al. (2022) *7th Int. Planet. Dunes Work*. [39] Foroutan & Zimbelman (2016) *Icarus*. [40] Foroutan et al. (2019) *Icarus*. [41] Ayoub et al. (2014) *Nat. Comm.* [42] Swann et al. (2020) *GRL*. [43] Andreotti et al. (2021) *PNAS*. [44] Sullivan & Kok (2017) *JGR*. [45] Chojnacki et al. (2019) *Geology*. [46] Rubanenko et al. (2022) *7th Int. Planet. Dunes Work*. [47] Newman et al. (2017) *Icarus*. [48] Bridges et al. (2017) *JGR*. [49] Baker et al. (2018) *JGR*. [50] Baker et al. (2018) *GRL*. [51] Baker et al. (2022) *JGR*. [52] Charalambous et al. (2021) *JGR*. [53] Baker et al. (2021) *JGR*. [54] Silvestro et al. (2020) *JGR*. [55] Fenton et al. (2019) *Icarus*. [56] Ehlmann et al. (2017) *JGR*. [57] Rampe et al. (2018) *GRL*. [58] Berger et al. (2016) *GRL*. [59] Lasue et al. (2018) *GRL*. [60] Farley et al. (2014) *Science*. [61] Silvestro et al. (2021) *GRL*. [62] McDougall et al. (2020) *6th Int. Planet. Dunes Work*. [63] Rabinovitch et al. (2019) *50th LPSC*. [64] Banham et al. (2018) *Sedimentology*. [65] Banham et al. (2021) *JGR*. [66] Day & Catling (2018) *JGR*. [67] Chojnacki et al. (2020) *JGR*. [68] Hunt et al. (2022) *Icarus*. [69] Swann et al. (2021) *Aeolian Res.* [70] Zimbelman (2022) *this conf*. [71] Kok et al. (2012) *Rep. Prog. Phys.*