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Key Points:

- Results from the 5th International Planetary Dunes Workshop are presented
- Future line of research for aeolian dune science are discussed

Abstract

Aeolian landforms are widespread in our solar system. Understanding the exact nature and process of formation of these features are challenging tasks implying a strong collaboration between scientists with different skills and scientific backgrounds. This paper describes the special issue for the 5th International Planetary Dunes Workshop which includes 16 research papers and one commentary. Among the 16 papers included in this collection, 14 cover Martian aeolian science and two Titan aeolian science. The papers presented focus on bedform morphology and dynamics via remote sensing data, modelling, analogues studies and laboratory experiments. Here we put the main results of the papers in their appropriate scientific context and discuss potential future lines of research.

Plain language summary

Wind-sculpted (aeolian) landforms are found on many bodies of our solar system. Their study is fundamental to understand the geology and climate of these bodies and to safely plan extraterrestrial missions. Here we introduce a collection of papers describing aeolian features on Mars and Titan. Collectively, the papers presented in this special issue show the importance of an interdisciplinary approach in comprehending what we are seeing on other planets but not only. The study of wind landforms on extraterrestrial planets is sparking a new interest on terrestrial aeolian geomorphology highlighting the significance of planetary studies in advancing the understanding of our Earth.

1 Introduction

The study of aeolian landforms is a key aspect for understanding surface atmospheric interactions on different bodies of the solar system [*Fenton et al.*, 2003; *Radebaugh et al.*, 2008; *Bourke et al.*, 2010; *Thomas et al.*, 2015; *Diniega et al.*, 2017; *Bishop*, 2018; *Michel et al.*, 2018; *Telfer et al.*, 2018]. Dunes, ripples and yardangs (wind-sculpted hills) [*Laity*, 2009; *Ding et al.*, 2020] can give clues on present and past atmospheric conditions and can serve as valuable "ground truth" for atmospheric models [*Fenton*, 2005; *Radebaugh et al.*, 2008; *Ayoub et al.*, 2014; *Michel et al.*, 2018]. The diversity of aeolian planetary environments provides new exciting challenges for scientists that have to deal with different types of surfaces and atmospheres [*Fenton et al.*, 2013; *Diniega et al.*, 2017, 2021]. Thus, a multidisciplinary approach is fundamental to the understanding of aeolian processes in the solar system. Promoting the collaboration of scientists with different backgrounds was one of the main objectives of the Fifth International Planetary Dunes Workshop: From the bottom of the Oceans to the Outer Limits of the Solar System, that was held May 16-19, 2017 in Saint George (UT), USA. Sixty-five researchers and students attended the workshop, which included a field trip to the Zion National Park and Coral Pink Sand Dunes State Park. The workshop focused on planetary aeolian processes with a particular emphasis on bedform morphology and dynamics on Mars, Earth, Titan, Venus, Pluto and the Comet 67P/Churyumov-Gerasimenko. Potential analogs from terrestrial oceans were also considered due to the morphologic similarities between ripples forming in water on Earth with some Venusian [*Kreslavsly and Bondarenko*, 2017; *Neakrase et al.*, 2017] and Martian examples [*Lapotre et al.*, 2016a; *Vaz et al.*, 2017]. The full program of the meeting can be found at the workshop website (https://www.hou.usra.edu/meetings/dunes2017/), as well as the workshop highlights in an EOS meeting report (Titus et al., 2018).

This paper introduces the Journal of Geophysical Research - Planets special issue including some of the works presented at the workshop and it follows a series of reports presenting paper collections from previous meetings [*Bourke et al.*, 2010; *Zimbelman et al.*, 2013; *Bishop*, 2014; *Zimbelman*, 2014; *Chojnacki and Telfer*, 2017]. Most of the papers from this collection focus on Martian aeolian landforms and their understanding through terrestrial analogues [*Wang et al.*, 2018], laboratory experiments [*Bristow and Moller*, 2018], imagery and numerical/atmospheric modelling [*Baker et al.*, 2018a; *Banks et al.*, 2018; *Chojnacki et al.*, 2018; *Day and Catling*, 2018; *Fenton et al.*, 2018; *Urso et al.*, 2018; *Siminovich et al.*, 2019; *Zimbelman and Foroutan*, 2020; *Silvestro et al.*, 2020; *Sullivan et al.*, 2020; *Yizhaq et al.*, 2021b]. A commentary describing the first conference of planetary aeolian research (The Planetary Geology Field Conference on Aeolian Processes) held at the College of the Desert in Palm Springs, California in January 1978, is also part of this collection to highlight the importance and history of a terrestrial analogue approach to tackle extraterrestrial studies [*Zimbelman and Tsoar*, 2018]. Two papers focus on Titan dunes, morphology and transport pathways [*Yu et al.*, 2018; *Telfer et al.*, 2019]. What is visibly lacking from this special issue are papers discussing aeolian bedforms on Venus. This is likely due to a lack of high-quality surface data acquired since the Magellan mission, which ended in 1994. With the selection of three new missions to Venus, NASA's VERITAS and DAVINCI and ESA's EnVision missions, this dearth of quality surface observations should be rectified, and Venusian dunes may finally be unmasked [*Titus et al.*, 2021].

2 Aeolian landforms on Mars

2.1 Dune activity and surface erosion

Mars is an aeolian planet where sand is mobilized at the surface on a daily/seasonal basis [*Ayoub et al.*, 2014; *Bridges et al.*, 2017; *Baker et al.*, 2018b] and where bedforms (ripples and dunes) are currently migrating at the surface [*Fenton*, 2006; *Bourke et al.*, 2008; *Sullivan et al.*, 2008; *Chojnacki et al.*, 2011; *Bridges et al.*, 2013]. Because the saltating sand has a major role in the production of dust [*Bristow and Moller*, 2018], monitoring bedform migration is a key aspect to understand Martian geology and climate. Bedform migration on Mars can be accurately monitored thanks to the High Resolution Imaging Science Experiment (HiRISE) having spatial resolution up to 25 cm/pixel and a low signal to noise ratio [*McEwen et al.*, 2007; *Geissler et al.*, 2012; *Bridges et al.*, 2013; *Chojnacki et al.*, 2016, 2019]. Importantly, HiRISE repeat image acquisitions of several dunes on Mars over a long base time, can be used to constrain the current aeolian activity at different spatial scales [*Banks et al.*, 2018; *Urso et al.*, 2018] and to perform detailed studies of aeolian landscape modification in key areas such as landing sites [*Chojnacki et al.*, 2018]. In addition, high resolution satellite images are used to analyze aeolian landforms such as yardangs [*Urso et al.*, 2018; *Wang et al.*, 2018] and to study intriguing features such as ghost dune pits [*Day and Catling*, 2018].

Deposition of aeolian bedforms depends on three independent components: sediment supply, sediment availability, and wind transport capacity, which define the sediment state of an aeolian system [*Kocurek and Lancaster*, 1999]. Because these components can all vary in space and time, a better understanding of the sediment state is key to comprehend the aeolian sedimentary record of Mars and to interpret spatial dune morphological variations [*Fenton et al.*, 2013]. For instance, previous workers have shown that in the present climatic state, sediment availability near the Martian south pole seems to be limited by the presence of near-surface ground ice [*Fenton and Hayward*, 2010]. This hypothesis is further confirmed by the analysis of bedform dynamics observed in overlapping HiRISE images southward of 60°S showing a decrease in sand mobility (dune and ripple migration rates) and an increase in non-aeolian erosive signs of modification (the dune field stability index) [*Banks et al.*, 2018]. In this case, the ground ice is an external factor (or boundary condition) [*Ewing and Kocurek*, 2010] that is governing dune morphology and mobility at the regional spatial scale. Another important boundary condition affecting the sediment state of Martian dunes is the topography, which affects the wind regime near the surface [*Cardinale et al.*, 2012; *Runyon et al.*, 2017; *Vaz et al.*, 2017; *Chojnacki et al.*, 2019]. The topographical influence on bedform mobility can be addressed thanks to the availability of accurate three-dimensional models of the surface (digital terrain models – DTMs) from HiRISE [*Kirk et al.*, 2008] and by the high temporal coverage of HiRISE images over the dunes (several Martian years). For instance, in Becquerel crater, the sheltering effect of a 700 m tall layered mound on dune migration and flux is evaluated [*Urso et al.*, 2018]. Results show that the dune crest flux decreases as the dunes approach the mound and increase again for the dunes downwind of the obstacle [*Urso et al.*, 2018]. The erosion rate derived from the Becquerel dune fluxes [*Bridges et al.*, 2012a] was used to give constraints on the timescale formation for the yardangs carving the mound (Fig.

1a), estimated to be just a few millions of years [*Urso et al.*, 2018]. Estimating the timescale of yardang formation is particularly important for Mars as these landforms are widespread on the surface of the planet [*Liu et al.*, 2020]. As it was clear since the first planetary aeolian meeting [*Zimbelman and Tsoar*, 2018], terrestrial analogue studies can be invaluable for understanding the Martian aeolian landscape, including yardangs, features that haven't received much attention in the past [*Laity*, 2009]. Yardangs in the northeastern Tibetan Plateau in China (Fig. 1b) are classified into 11 different types resulting in a multistage evolution triggered by sand blasting and other erosional processes [*Wang et al.*, 2018]. Their striking similarities with Martian yardangs (Fig. 1) indicate that a similar evolution can be hypothesized for these landforms on Mars, shedding light on landscape modification rates and on the ability of these features to record major climatic variations [*Wang et al.*, 2018; *Ding et al.*, 2020].

Correctly evaluating present-day erosion rates at the surface of Mars is particularly important for landing site characterization. The analysis of Martian dune fluxes, and thus erosion rate magnitudes [*Bridges et al.*, 2012a] shows large variability [*Chojnacki et al.*, 2018, 2019]. Of interest, the NASA Perseverance Jezero landing site has relatively high abrasion rates leading to young rock exposure ages and augmenting the possibilities to find astrobiologically relevant outcrops [*Chojnacki et al.*, 2018]. Ghost dune pits, dune-shaped depressions formed by the flooding of dunes by water or lava and the subsequent wind erosion of the dune strata (Fig. 2), are described for the first time on Mars [*Day and Catling*, 2018]. Besides giving important paleo-wind constraints (Hesperian in the presented case), dune pits might also represent interesting targets for Martian exploration. Remnants of the dune strata shielded from cosmic rays by pit walls can be astrobiologically relevant especially if water was the main flooding agent [*Day and Catling*, 2018].

2.2 Ripples on sand

2.2.1 The large Martian ripples

Anomalously large (by terrestrial standards) ~2 m spaced wind ripples have been observed on Mars over the slopes of dark dunes (Fig. 3a) [*Bridges et al.*, 2007; *Vaz and Silvestro*, 2014] or in isolated fields accumulated in local depressions [*Sullivan et al.*, 2008, 2020] (Fig. 3b, c). Images from rovers on the surface of Mars have shown that these large ripples are overprinted by smaller (~ 10 cm) impact ripples (Fig. 3) [*Sullivan et al.*, 2008; *Lapotre et al.*, 2016a, 2018; *Ewing et al.*, 2017]. The reason for the large size of these bedforms and the superposition of multiple scales of ripple sizes is matter of debate in the scientific community [*Kok et al.*, 2012; *Lapotre et al.*, 2016a, 2018; *Duran Vinent et al.*, 2019]. Data from the Mars Hand Lens Imager (MAHLI) [*Edgett et al.*, 2012] show that the large Martian ripples analyzed in situ in Gale crater consist of fine grains with unimodal grain size [*Lapotre et al.*, 2016a, 2018; *Weitz et al.*, 2018]. Therefore, they cannot be interpreted as megaripples, which are bedforms containing a bimodal grain size distribution [*Sharp*, 1963; *Yizhaq et al.*, 2021a]. Thus, large Martian ripples have been interpreted as fluid-drag ripples (or aerodynamic ripples; *Wilson* [1972]) that form due to the higher kinematic viscosity (v) of the Martian atmosphere [*Lapotre et al.*, 2016a]. A given flow regime is characterized by the Reynolds number ($\frac{\mathrm{uL}}{\nu}$) for velocity (u) and length-scale (L). The two orders of magnitude higher Martian value of v leads to smaller Reynold numbers, so the Martian wind close to the surface is assumed to be in a more laminar regime than on Earth for similar wind speeds [*Read et al.*, 2017]. Being shaped under such a thick viscous sublayer makes the Martian large ripples analogous to "current ripples" forming under subaqueous conditions on Earth [*Allen*, 1968; *Lapotre et al.*, 2016a; *Duran Vinent et al.*, 2019]. Interestingly, the ripple-like bedforms found on the neck of the comet 67P/Churyumov–Gerasimenko may be shaped in a similar way [*Jia et al.*, 2017]. The fluid drag interpretation is supported by peculiar characteristics that differentiate large ripples from impact ripples on Earth. Martian ripples are larger, locally sinuous and show avalanche and grainfall features, which are not observed on ordinary ripples on Earth [*Lapotre et al.*, 2016a, 2018; *Ewing et al.*, 2017; *Vaz et al.*, 2017]. In addition, Martian large ripples are dynamically different from terrestrial impact ripples as, like dunes, they have been observed to move obliquely and longitudinally [*Silvestro et al.*, 2016; *Vaz et al.*, 2017]. By using a combination of in situ rover images and Computational Fluid Dynamics (CFD) modelling, *Sullivan et al.* [2020] suggest that the fluid drag hypothesis is not consistent with the Martian atmospheric environment. The authors suggest that large ripples on Mars can form through the impact process (similar to Earth) and advocate that their larger dimension is due to the low wind dynamic pressure (the kinetic energy per unit volume of a fluid) characteristic of the Martian boundary layer [*Sullivan et al.*, 2020]. The low wind dynamic pressure of the Martian atmosphere allows the ripples to penetrate higher into the boundary layer so secondary ripples can form onto larger ripple slopes [*Sullivan et al.*, 2020]. Due to their larger size, ripples on Mars also have a longer developmental history than ripples on Earth (larger ripples need more time to develop into a mature stage). Therefore, the ripples can potentially integrate a more complex wind signal (i.e., shifting seasonal winds) [*Ewing et al.*, 2015] giving birth to oblique and longitudinal elements and explaining their "dune-like" dynamical behavior [*Silvestro et al.*, 2016; *Sullivan et al.*, 2020]. Together with the longitudinal ripples, the impact mechanism in a low wind dynamic pressure environment can also explain the presence of megaripples and transverse aeolian ridges (TARs), which are not explained by the fluid-drag hypothesis [*Lapotre et al.*, 2016b, 2016a; *Sullivan et al.*, 2020]. The Martian low density boundary layer also imposes lower (compared to Earth) shear velocities over the ripple slopes [*Siminovich et al.*, 2019; *Yizhaq et al.*, 2021b]. CFD simulations have been used to investigate if and where shear velocities reach the fluid threshold for sand motion over a synthetic and a more realistic ripple profile [*Siminovich et al.*, 2019; *Yizhaq et al.*, 2021b]. Results show that in the Martian atmospheric environment shear velocities at the ripple crest do not reach the fluid threshold, while the opposite is happening on Earth for similar wind speeds [*Siminovich et al.*, 2019; *Yizhaq et al.*, 2021b]. Thus, grains can continue to accumulate faster than they are leaving, leading to higher (and thus larger) ripple sizes.

2.2.2 Megaripples and coarse grain transport: Implications for climate

Megaripples (or granule ripples) are poorly sorted ripples that consist of grains with a bimodal size distribution [*Sharp*, 1963; *Greeley and Iversen*, 1985; *Yizhaq et al.*, 2009, 2012a]. Coarse grains (~1 mm in diameter) tend to accumulate over the crest of megaripples, enabling them to protrude higher into the boundary layer. Because they are taller (i.e. larger amplitudes) megaripples are also larger than normal ripples [*Sharp*, 1963], with wavelength ranging between ~ 30 cm to 43 meters (the latter are very extreme cases) [*Milana*, 2009; *Yizhaq et al.*, 2012b]. In addition, as the threshold for sand movement is higher for coarse grains, the coarse fraction makes megaripples more reluctant to movement [*de Silva et al.*, 2013; *Bridges et al.*, 2015].

Megaripples are found to be abundant on Mars [*Balme et al.*, 2008]. In the NASA Mars Exploration Rover-B (Opportunity) landing site in Meridiani Planum, the Opportunity rover traversed over megaripples (also called "plain ripples") that were armored with 1-2 mm in size hematite fragments [*Sullivan et al.*, 2005; *Weitz et al.*, 2006] (Fig. 4a). Megaripples in Meridiani form a vast field of N-S oriented bedforms reworked by NNE-SSW ripples [*Sullivan et al.*, 2005; *Weitz et al.*, 2006; *Arvidson et al.*, 2011; *Fenton et al.*, 2015; *Silvestro et al.*, 2015]. The last phase of migration for the Meridiani megaripples, constrained by looking at their stratigraphic relationships with impact crater ejecta and crater counting, occurred between ~50 ka and 200 ka, bracketing the most recent (~100 ka) obliquity variations and changes in insolation on Mars [*Golombek et al.*, 2010]. This study indicates a major climatic control on the migration of the megaripples in Meridiani Planum. Similarly to Earth, the climate of Mars varied cyclically during its geological history due to the variation of orbital parameters such as axial tilt, obliquity and orbit eccentricity [*Jakosky and Phillips*, 2001; *Laskar et al.*, 2004; *Mischna*, 2018]. However, for Mars such climatic variations are more extreme as not mitigated by standing bodies of water at the surface [*Zurek*, 2017]. In addition, Mars' orbit is not stabilized by the influence of a large moon and is perturbed by the gas giants nearby (Jupiter in particular) [*Zurek*, 2017]. Martian climatic and orbital variations, therefore, are more chaotic than Earth and cannot be precisely calculated beyond 20 million years in the past [*Laskar et al.*, 2004; *Zurek*, 2017]. Yet, such a time range is relevant for the age of the Meridiani megaripples [*Golombek et al.*, 2010], so constraints on their mobility can be validated through atmospheric models run at past orbital configurations [*Fenton et al.*, 2018]. Results from the NASA Ames Mars Global Climate Model [*Haberle et al.*, 2003] indicate that augmented sand drift potential correlates with increased axial obliquity and atmospheric pressure and a longitude of perihelion near southern summer solstice [*Fenton et al.*, 2018]. Modelling results suggest that the last pulse of westward migration for the N-S plain ripples in Meridiani Planum occurred during the most recent oblique maximum ~111-86 ka while the superposed NNE-SSW ripples formed as the axial obliquity decreased ~82-76 ka [*Fenton et al.*, 2018].

Megaripples were closely imaged and subsequently traversed by the Mars Science Laboratory (MSL) Curiosity in Gale crater [*Arvidson et al.*, 2017; *Zimbelman and Foroutan*, 2020; *Bretzfelder and Day*, 2021] (Fig. 4b). Crossing the megaripples (or TARs) at the Dingo Gap and Moonlight Valley locations enabled a detailed sedimentological analysis of these bedforms, which identified a dark sand interior and armoring by coarse grains (1-2 mm) [*Zimbelman and Foroutan*, 2020]. In addition, sand drift orientations of wind tails in the lee of small boulders indicate that the Dingo Gap bedform formed in a bimodal wind regime, thus explaining its symmetrical profile which is indicative of reversing winds [*Zimbelman and Foroutan*, 2020]. Of interest, other symmetric TARs on Mars have been proposed to form in a reversing flow regime, though this is the first time it has been proved in situ [*Zimbelman and Scheidt*, 2014; *Zimbelman and Foroutan*, 2020]. Despite observed differences from the two rover sites (for example, some megaripples at Meridiani Planum have brighter interiors compared to bedforms in Gale crater [*Squyres et al.*, 2006]), both sites were found to have grains coated by surficial dust, indicative of inactivity [*Zimbelman and Foroutan*, 2020]. Thus, there is a general consensus that movement of mm-sized grains by direct fluid drag should be unusual for present-day Mars and constrained to past epochs [*Bridges et al.*, 2012b, 2013]. For this reason, the finding of coarse grain movement in Gale crater and the migration of megaripples in two areas on Mars came as a surprise [*Baker et al.*, 2018a; *Silvestro et al.*, 2020]. Images from Curiosity show evidence for short-path movement of isolated coarse (1-3 mm) grains in Gale crater during the southern summer [*Baker et al.*, 2018a]. The detected movement confirms the seasonal trend in aeolian activity observed by other researchers [*Ayoub et al.*, 2014; *Bridges et al.*, 2017; *Baker et al.*, 2018b] and challenge atmospheric models that do not predict the direct lift of these grains by the present-day winds [*Baker et al.*, 2018a]. The finding for widespread movement of megaripples on Mars expanded this finding further [*Silvestro et al.*, 2020]. Bedforms of 5 meters in wavelength on average were found upwind and in between active dunes (normal location for megaripples on Earth), migrating across two equatorial areas of Mars during a time-span of 7-9 Earth years [*Silvestro et al.*, 2020]. The migrating megaripples, some of which are bright toned and ~20 meter spacing, like small TARs [*Zimbelman*, 2010, 2019; *Hugenholtz et al.*, 2017], are associated with high-sand flux dunes, suggesting the existence of a relationship between dune and megaripple migration [*Balme et al.*, 2008; *Silvestro et al.*, 2020]. Such a relationship may suggest an impact-related mechanism for coarse grain motion in the formation of megaripples [*Silvestro et al.*, 2020], helping to reconcile observation of coarse grain transport at the surface with atmospheric models [*Baker et al.*, 2018a]. Of interest, migrating megaripples found in continuity with dark dune sands coexist with static bedforms found stratigraphically below (see supporting information, movie S2 in Silvestro et al. [2020]). The finding of coarse grain movement at the surface can alter the way the Martian sedimentary record is interpreted, acknowledging that both water and wind can be responsible for the accumulation of coarse-grained sandstones [*Baker et al.*, 2018a].

3 Aeolian landforms on Titan

3.1 Sediment source – local versus polar

Perhaps the most intriguing mystery of Titan dunes is composition. Unlike dune fields found on Mars, Earth and Venus, where composition is typically mafic or felsic, the dunes on Titan likely comprise organics (tholins), water ice, or a combination of the two.

Several studies have suggested the particle size for Titan's sediment is in the hundreds of microns range [*Lorenz et al.*, 2006; *Burr et al.*, 2014; *Yu et al.*, 2017]. However, the original source of the organics thought to form the sediment particles, are from atmospheric aerosols [*Soderblom et al.*, 2007], which are smaller than 1 micron [*Tomasko et al.*, 2005]. Four mechanisms have been suggested to increase the size: 1) sintering, 2) lithification and erosion, 3) flocculation, and 4) evaporation [*Barnes et al.*, 2015]. The first two suggested mechanisms do not require liquid environments, but flocculation and evaporation do. The known liquid environments are all near the poles, and thus far from the equatorial dune fields. Yu et al. [2018] (this issue) examined whether organic sediment (or organic covered water ice) particles had sufficient hardness and were strong enough to survive transport from the polar regions to the equatorial belt. They found that the sediment composed of organics and/or ice were too soft and brittle for long transport. In addition, others have found no evidence of transport pathways [*Charnay et al.*, 2015; *Malaska et al.*, 2016]. Therefore, the source of the sediment is likely local, possibly formed through sintering or lithification and erosion [*Brossier et al.*, 2018; *Solomonidou et al.*, 2018].

3.2 Topographic effects on longitudinal dunes

Linear (or longitudinal) dunes are common on both the Earth and Saturn's moon Titan and are characterized by regularly spaced, long linear ridgelines that extend for great distances parallel to the wind direction. Deviations in direction often occur in the presence of obstacles that deflect air flow. However, there are cases when linear dunes were observed to be curvilinear, with no observable obstacle. These cases occur on both the Earth and on Titan, providing an opportunity for comparisons and ground-truth. In this issue, Telfer et al. [2019] suggested that the curvilinear features are a result of underlying topography. They examined two terrestrial analog dune fields, one in Australia and one in southern Africa. In both cases, changes in the linear dune directions were correlated to deflections downslope. While curvilinear structures in linear dunes on Earth is rare, these features are more common on Titan. Analysis of the Belet Sand Sea, a dune field on Titan that appears similar to the Great Sandy Desert, Australia, found linear dune defections to occur at the local level, and in many cases, absent any visible obstructions. Tefler et al. [2019] suggested these deflections were a result of the underlying topography inducing downslope defections, where steeper slopes cause greater deflections. However, the DTMs for the region did not have sufficient resolution to be sensitive to local topography. Local topography that cannot be resolved with current data could pose a threat to future landing missions. Tefler et al [2019], while not proposing a technique to fully recover local topography from curvilinear dunes, did suggest avoiding these regions as a landing site in order to reduce risk.

4 Conclusion and future directions

The papers presented in this special issue touch on many different topics in Martian and Titan aeolian science. Some works show that correctly evaluating the topographic effect on dune/ripple morphologies/migrations and fluxes at different spatial/temporal scales is now possible [*Banks et al.*, 2018; *Chojnacki et al.*, 2018; *Urso et al.*, 2018] and track a path for future studies [*Roback et al.*, 2020]. Many areas of Mars show dunes that are now covered by overlapping HiRISE images, some of which are more than ten Earth years spaced in time so the long-term topographic effect on dune/ripple fluxes can now be evaluated. A better comprehension of Martian geology and climate necessarily passes through the analysis of these data that are, at the time of writing, still largely unanalyzed. Compared to Mars, radar images from Titan have low resolution so dune changes and related fluxes cannot yet be constrained. This is similar to currently available data for Venus as well [*Kreslavsly and Bondarenko*, 2017]. However, dune morphology can give precious hints on the underlying topography [*Telfer et al.*, 2019]. This is key to correctly choosing the safest and scientifically compelling landing sites for future missions [*Chojnacki et al.*, 2018; *Telfer et al.*, 2019]. The analysis of terrestrial analogues from orbiters and direct field observation together with laboratory experiments are fundamental on this regard [*Bristow and Moller*, 2018; *Wang et al.*, 2018; *Yu et al.*, 2018; *Telfer et al.*, 2019]. Erosional features like yardangs and ghost dune pits need more detailed studies to better understand their evolutionary history and formation timescales both on Mars and Earth [*Day and Catling*, 2018; *Wang et al.*, 2018].

The nature of large Martian ripples and the mode of grain transport associated with their formation and evolution is tackled in this special issue by Sullivan et al. [2020]. The authors of this work concluded that an Earth-like impact mechanism is likely responsible for their formation without the necessity to invoke other explanations (e.g. fluid-drag) [*Sullivan et al.*, 2020]. This article is key to continuing discussions concerning ripple formation processes within the aeolian scientific community and highlights the need for future work [*Lorenz*, 2020; *Gough et al.*, 2021; *Lapôtre et al.*, 2021]. Terrestrial aeolian fluid-drag ripples are not well understood and most of the knowledge of these features relies on the Bagnold [1954] wind tunnel seminal work. More experimental work is needed to comprehend the fluid-drag mechanism, a process that might be relevant even for other planetary environments (e. g., Venus) [*Lorenz*, 2020]. As recently reported, more detailed grain size analysis from Martian bedforms must be performed in order to have statistically significant measurements to derive formation mechanisms [*Gough et al.*, 2021]. Nevertheless, the results reported in this collection show that even dedicated fluid-dynamic modelling can be used to understand the effects of a different atmospheric environments on ripple morphologies [*Siminovich et al.*, 2019; *Yizhaq et al.*, 2021b]. The same approach can be used for different planetary bodies in future.

The ability of ripple and dune systems to record past wind conditions is another exciting line of research, and atmospheric models run at different orbital configurations are a powerful tool to that end [*Fenton et al.*, 2018]. Are climatic fluctuations recorded by the aeolian bedforms in Meridiani regional/global in nature [*Silvestro et al.*, 2021]? More mapping efforts aimed at recognizing complex bedform patterns are needed to address this question. Additionally, more sedimentological analysis of megaripples and transverse aeolian ridges are necessary to better understand the exact nature of these bedforms, their formation mechanism(s) and formative winds [*Milana*, 2009; *de Silva et al.*, 2013; *Bridges et al.*, 2015; *Hugenholtz et al.*, 2015; *Hugenholtz and Barchyn*, 2017]. As suggested by close analysis, traversing these bedforms do not necessarily pose a serious risk for rovers or UAVs [*Zimbelman and Foroutan*, 2020].

Coarse grain displacement and megaripple migrations are reported for the first time by two papers in this collection [*Baker et al.*, 2018a; *Silvestro et al.*, 2020]. The hypothesized relationship between dune and megaripple fluxes seem to point towards an impact-driven creep process of movement for the coarse grain fraction, though this hypothesis needs to be properly tested elsewhere on Mars [*Chojnacki et al.*, 2021]. A better knowledge of where and when coarse sediment is displaced will be helpful to correctly understand atmospheric model output and interpret the sedimentary record of Mars (and of Titan in the future) [*Baker et al.*, 2018a; *Barnes et al.*, 2021]. In particular, as previously reported, the knowledge of bedform grain size distributions is key to correctly scale sediment transport models to the Martian and Titan environments [*Burr et al.*, 2014; *Gough et al.*, 2021]. The ~ 5 meter on average bedforms that were observed to migrate on Mars are located in between dunes, which are preferentially occupied by megaripples [*Silvestro et al.*, 2020]. Their exact grain size is unknown, a knowledge gap that must be filled by specific surface observational campaigns. Current (Perseverance, Zhurong) [*Maki et al.*, 2020; *Tian et al.*, 2021] and future (ExoMars, Dragonfly) [*Josset et al.*, 2017; *Vago et al.*, 2017; *Barnes et al.*, 2021] missions on Mars and Titan can give precious insights into bedform morphologies and grain sizes. Three new missions to Venus; NASA's VERITAS and DAVINCI and ESA's EnVision missions will reignite the unmasking of Venusian dunes [*Titus et al.*, 2021]. Terrestrial fieldwork aiming to constrain different bedform flux proportions will be helpful to correctly scale Martian observations to formative processes [*Silvestro et al.*, 2020; *Chojnacki et al.*, 2021]. The analysis of aeolian bedforms on Titan and Mars is a topic that has both geological and astrobiological implications. Minerals of great astrobiological interest were detected on aeolian deposit on Mars [*Sun and Milliken*, 2018]. In addition, organic molecules were recently discovered in dune sand on Mars, as well as Titan dune sand hypothesized to be rich in organics [*Lorenz et al.*, 2006; *Millan et al.*, 2021].

The discovery of aeolian landforms in the solar system, including the comet 67P/Churyumov-Gerasimenko and Pluto, have increased (and continues to increase) interest in similar wind-related landforms on Earth [*Zimbelman et al.*, 2009; *Milana*, 2009; *de Silva et al.*, 2013; *Bridges et al.*, 2015; *Hugenholtz et al.*, 2015; *Foroutan and Zimbelman*, 2016; *Jia et al.*, 2017; *Foroutan et al.*, 2018; *Telfer et al.*, 2018; *Favaro et al.*, 2020, 2021]. A better understanding of bedform formation in the presence of transient atmospheres could be an important research topic over the next decade.

Thus, it is correct to state that over the last few decades, the understanding of aeolian processes on other planets have greatly benefited through the study of the Earth analogs [*Zimbelman and Tsoar*, 2018]. The converse is also true; the study of planetary aeolian bedforms provides a new prospective of these same features on Earth.

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Data Availability Statement

In this paper, no new data are presented. Link to access to the images:

Figure1: https://www.uahirise.org/PSP_003656_2015,

Figure 2: https://www.uahirise.org/ESP_047965_1720,

Figure 3: https://www.nasa.gov/sites/default/files/thumbnails/image/pia20316-cr.jpg, https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx, https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx,

Figure 4: https://www.jpl.nasa.gov/images/cobbles-in-troughs-between-meridiani-ripples-false-color.

For Figures 5 see *Telfer et al.*, [2019] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JE006117.

Additional information on the data used in this paper can be found on the papers of the special issue, https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2169-9100.DUNEWKSHP1, or at the HiRISE Planetary Data System (PDS) website, https:// hirise.lpl.arizona.edu/PDS/, the Geosciences node, https://pds-ge- osciences.wustl.edu/missions/mep/index.htm, the Curiosity (MSL) Analyst's Notebook, https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx?AspxAutoDetectCookieSupport=1, and the Mars Exploration Rovers page, https://mars.nasa.gov/mer/gallery/all/opportunity.html.

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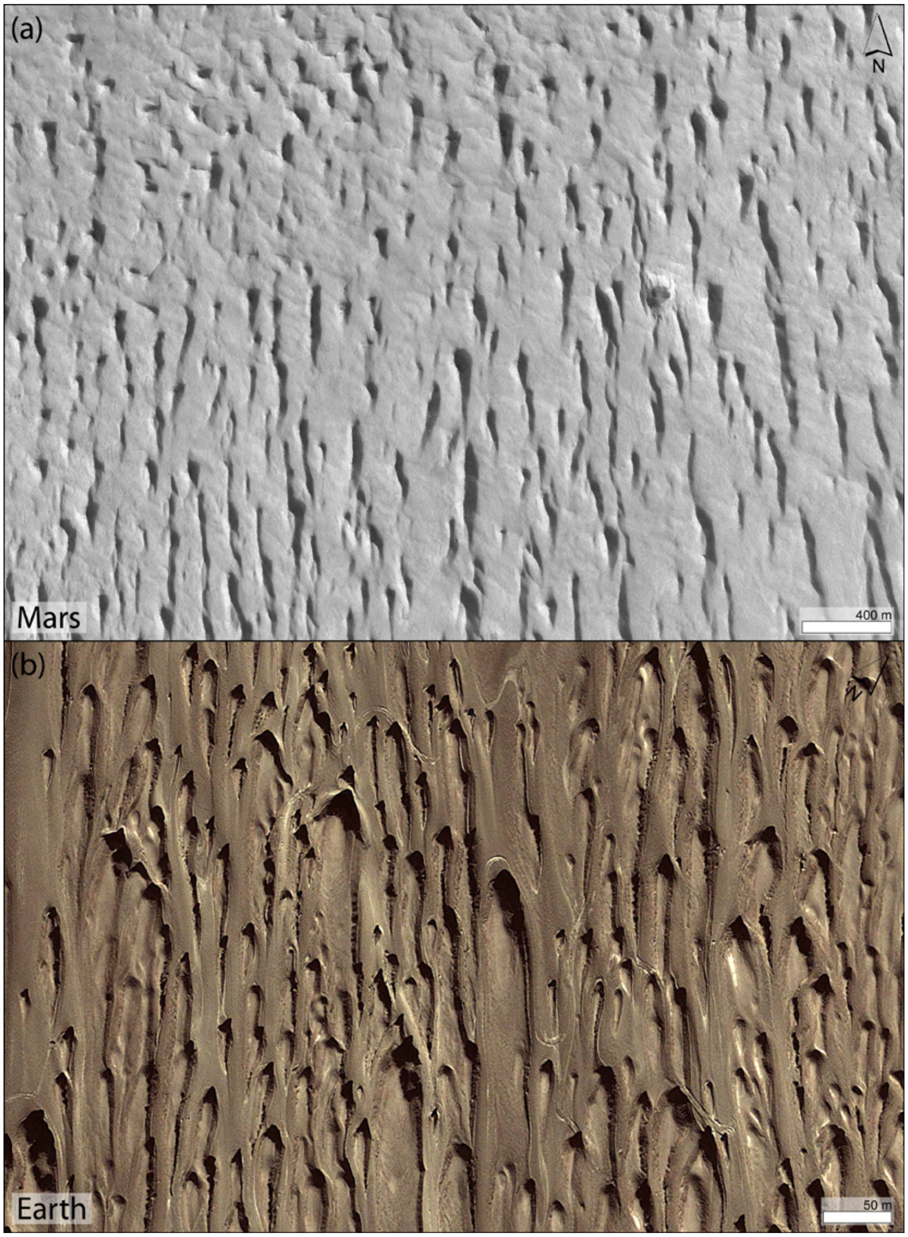

Figure 1. Yardangs on Mars and Earth. (a) Yardangs carved on the layered mound in Becquerel crater, Mars [*Urso et al.*, 2018], HiRISE PSP_003656_2015 (https://www.uahirise.org/PSP_003656_2015). (b) Yardangs in the Quaidam Basin, China, Google Earth see details on the area on *Wang et al.* [2018].

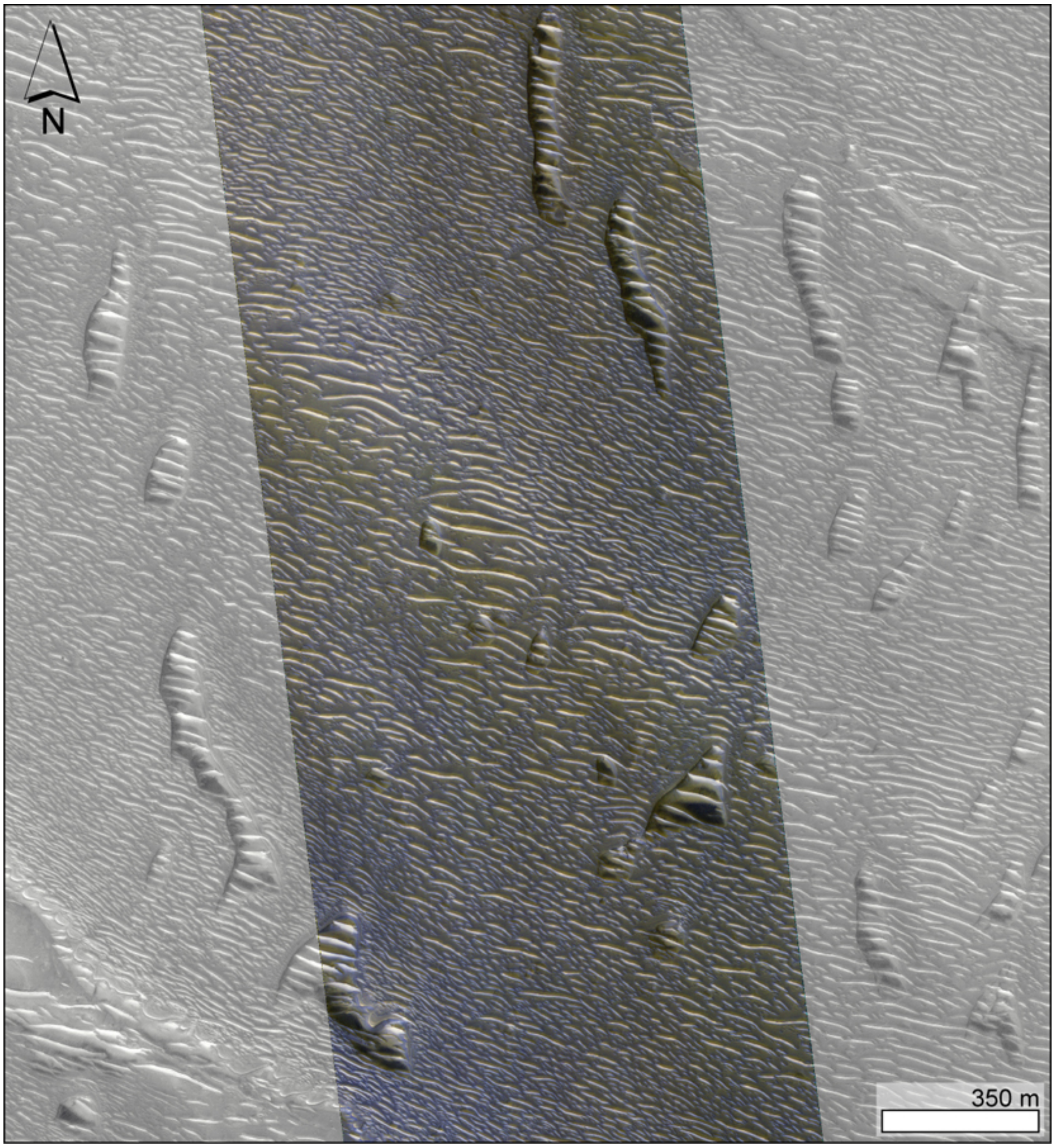

Figure 2. Ghost dune pits in Noctis Labyrinthus (Mars) [*Day and Catling*, 2018], HiRISE ESP_047965_1720 (https://www.uahirise.org/ESP_047965_1720).

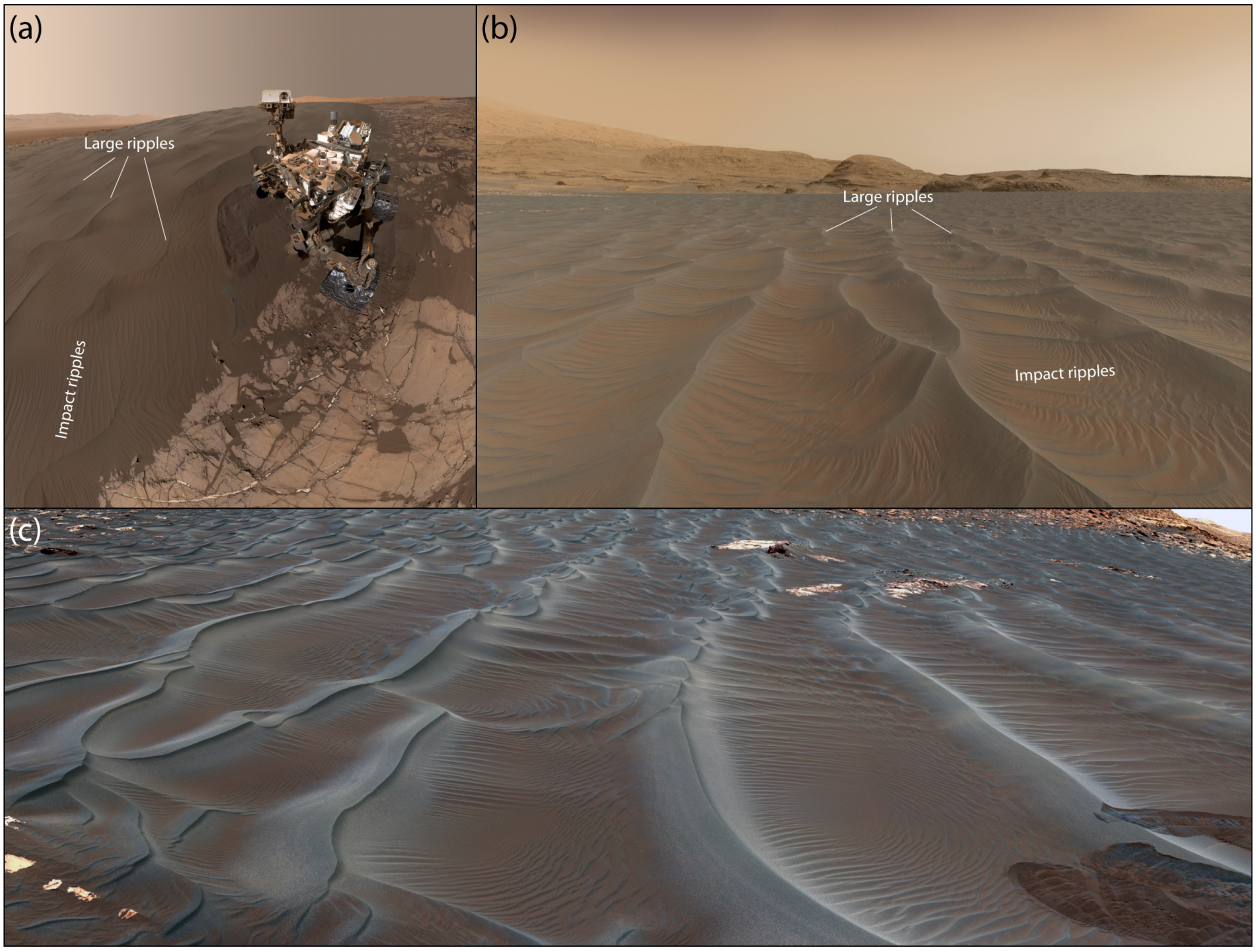

Figure 3. Two scales of ripples on Mars, as imaged by the NASA MSL Curiosity rover in Gale crater. (a) Ripples over the Namib dune slopes NASA/JPL-Caltech/MSSS (https://www.nasa.gov/sites/default/files/thumbnails/image/pia20316-cr.jpg). (b). The Sands of Forvie ripple field. MAHLI camera mosaics, sol 2991, NASA/JPL-Caltech/MSSS (https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx). (c) Ripple field at the Enchanted Island site. Color contrasts between ripple crests and troughs have been interpreted as grain sizes [*Sullivan et al.*, 2020] or compositional [*Lapôtre et al.*, 2021] differences (Sol 1752 color-enhanced mcam09157, https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx).

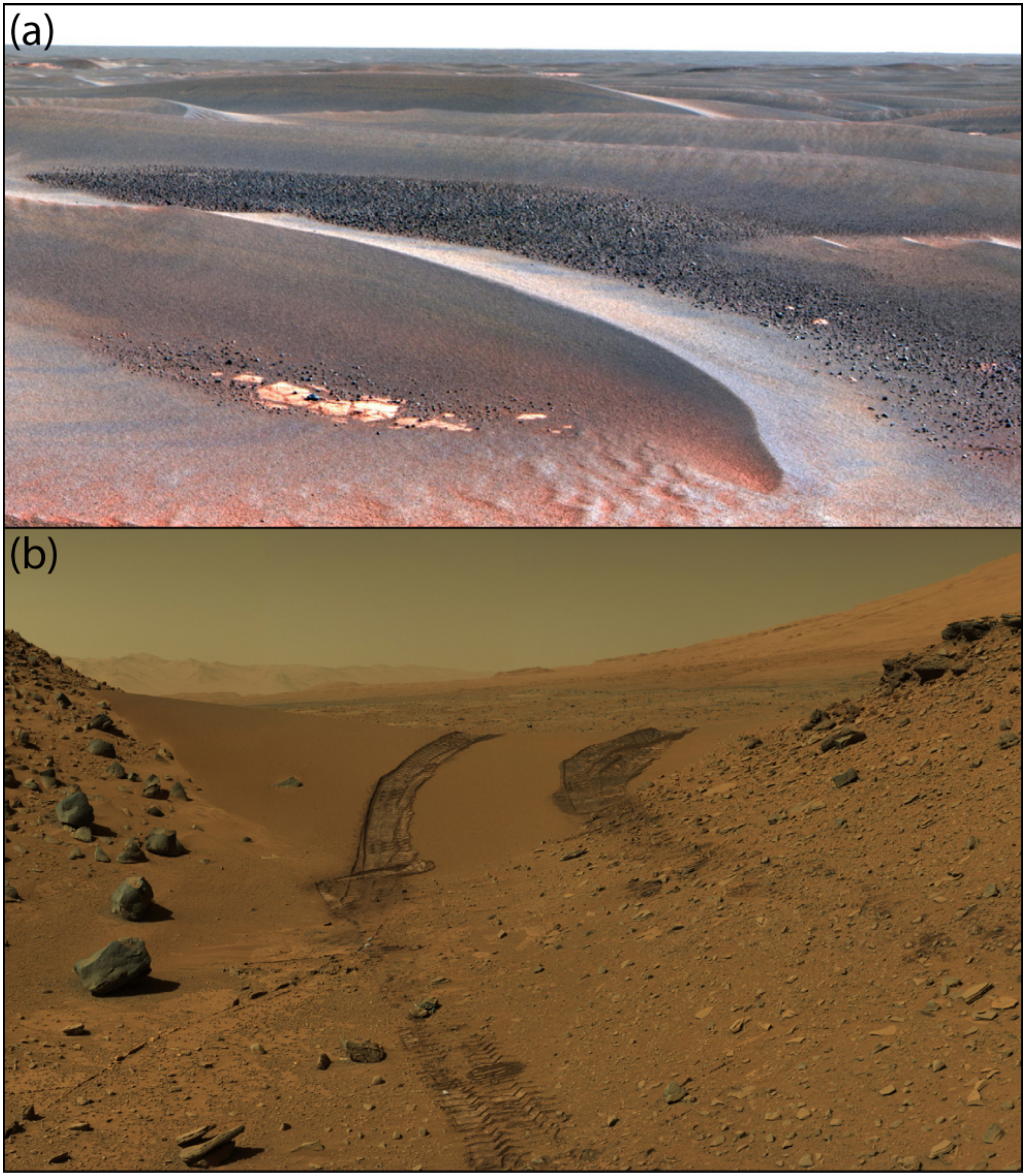
(a)
(b)

Figure 4. Megaripples on Mars. (a) Megaripples in Meridiani Planum as imaged by the NASA Opportunity rover's panchromatic camera (false color). Ripples are about 20 cm high. Opportunity panchromatic mosaic acquired on sol 802, NASA/JPL-Caltech/Cornell (https://www.jpl.nasa.gov/images/cobbles-in-troughs-between-meridiani-ripples-false-color). (b) The Dingo Gap megaripple in Gale crater imaged by the NASA MSL Curiosity rover's Mascam on sol 538, tracks are 40 cm wide [*Zimbelman and Foroutan*, 2020], NASA/JPL-Caltech/MSSS.

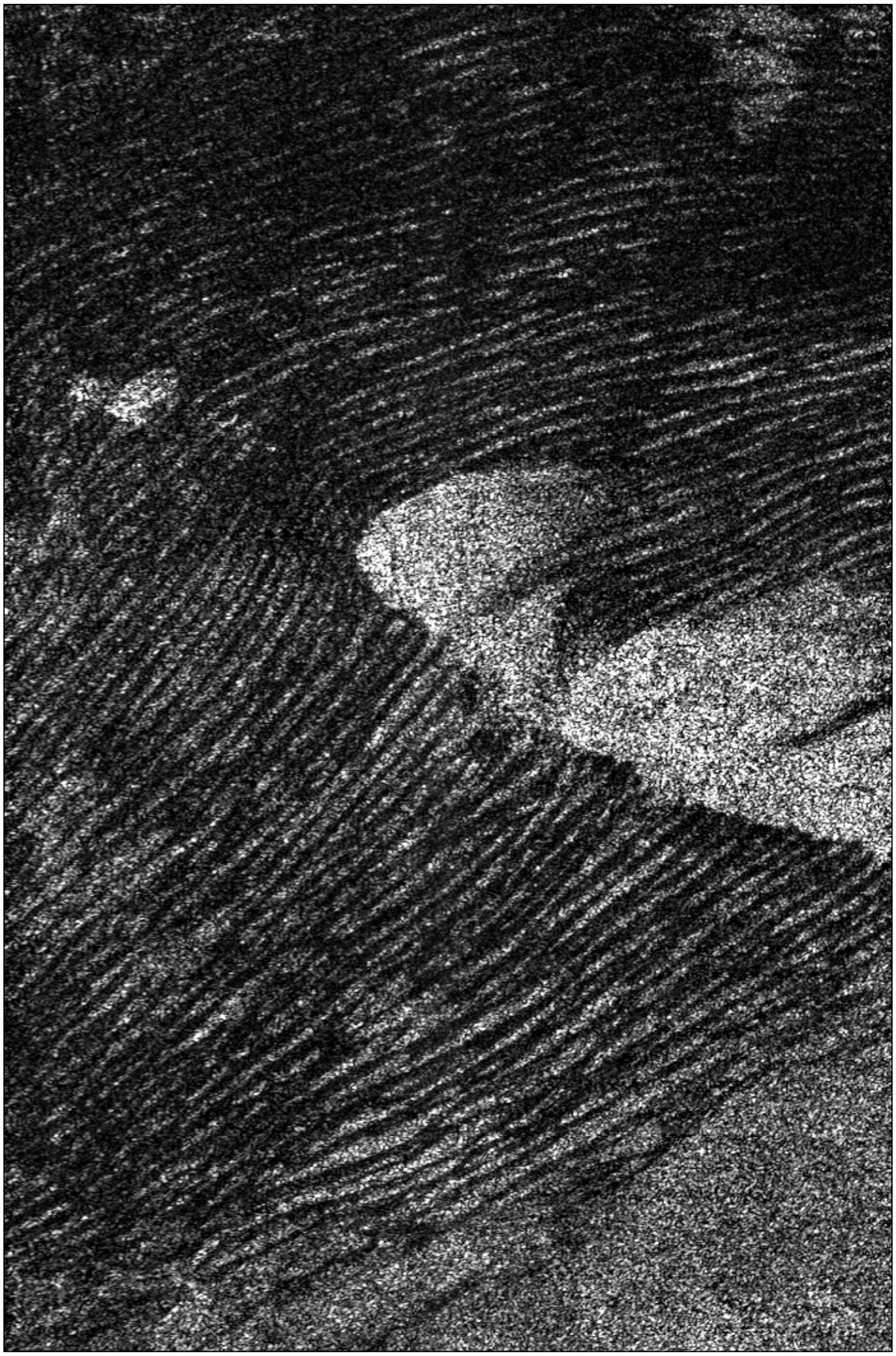

Figure 5. Linear dunes on Saturn's moon Titan. SAR image, NASA/JPL-

Caltech (detail on image sources can be found in *Telfer et al.* [2019]).