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Introduction

This book is about dunes and planets, the interactions of earth and air.

Sand provides a paradox. It is a solid, and yet it moves. This paradox applies to rocks in general—moving rocks are, after all, what geology is ultimately about—but granular materials on the Earth's surface can move much faster, at rates that are important to, and observable by, humans. This is due to the peculiar conditions and processes on our planet, and results in some spectacular landscapes (e.g. Fig. 1.1) in specific regions where the sand (and sometimes snow) has apparently organized itself into magically regular structures—dunes.

The ancients knew of four planets, wandering points of light in the night sky, plus Earth and its moon. The invention of the telescope led to the discovery of a few more planets and a few moons, some of which are bigger than the smallest planet. We know of hundreds of planets (many of which will have moons too) around other stars. But more importantly than the astronomical cataloguing of celestial objects has been the Space Age and, by means of robotic exploration, the transformation of some of these planetary bodies from mere dots in the sky to worlds in their own right.

This unmanned space exploration perspective has shown us that first Mars (Fig. 1.2), then Venus, and recently and remarkably, Saturn's moon Titan have dunes similar to those on Earth, despite very different conditions and materials. Thus the formation of dunes and ripples is a general phenomenon, unified by the same physical processes, even though the conditions under which these processes operate can be quite different (Fig. 1.3). This universality is perhaps nowhere highlighted better than by the vast sand seas of Titan where, despite sands made of organic muck, in frigid air four times denser than ours, on a world with gravity only one-seventh our own, the landscape is covered in dunes of exactly the same shape, height and width of the Earth's largest sand seas. Thus Titan is almost as exotic a world as one can imagine, and yet standing on its surface are landforms (Fig. 1.4) almost indistinguishable from those on Earth.

Our aim in this book is to survey dunes on these worlds with this physical perspective, highlighting the morphological similarities and differences that are exposed by dramatically improved remote sensing instrumentation at Earth and elsewhere. Over the 40 or so years of Mars exploration since dunes were discovered, the quality of orbital images (in terms of number of pixels per square kilometer) has improved ten-thousandfold (Fig. 1.5), and after the first pioneering wanderings of the Sojourner rover in 1997 (Fig. 1.6), what is now decade of continuous roving across the surface by its successors has brought a 'field geology' perspective (Fig. 1.7) with millimeter-scale imaging and advanced scientific instruments brought to bear on individual ripples, showing us the sands of Mars at the grain level.

Dunes on Earth were first explored by field geologists and geographers. While many of their traditional techniques are still applied, new methods, such as GPS and photogrammetry using digital images from the ground or the air, allow us to rapidly and quantitatively measure the shape of dunes in the field (Fig. 1.8). We can now even probe the internal structure of dunes, revealing the layers that record the history of deposition and migration, using ground-penetrating radar (Fig. 1.9).

There have also been spectacular advances in physical and computational modeling of the processes by which sand and wind interact: it is now possible to follow the formation of dunes, and indeed the interactions between dunes, in silico. A wide range of dune morphologies can be replicated via the successive application of very simple rules, taming the bewildering diversity of the landscape under a unifying algorithmic whip (Fig. 1.10). Furthermore, while observation of real dune formation and motion can take months, years, or even millennia, their virtual counterparts can be brought to animated life in seconds on the computer screen.

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Fig. 1.1 A striking picture, setting the stage for planets and dunes, with *vibrant red sand* and *blue skies* is familiar to millions as a 'desktop' background image for the Windows operating system. The image shows the moon atop a dune. But not just a dune; after reading this book, we hope you will recognize avalanche lobes and two generations of ripples in the foreground. What millions in the northern hemisphere have probably not noticed is that the moon is 'upside down'; there the moon is seen as in the inset on the *right*, with the pattern of mare (dark impact basins). The reason that the moon above the dune looks 'wrong' is that this dune picture is from the southern hemisphere (perhaps Australia, but more likely Namibia.) Montage by J. Zimbelman

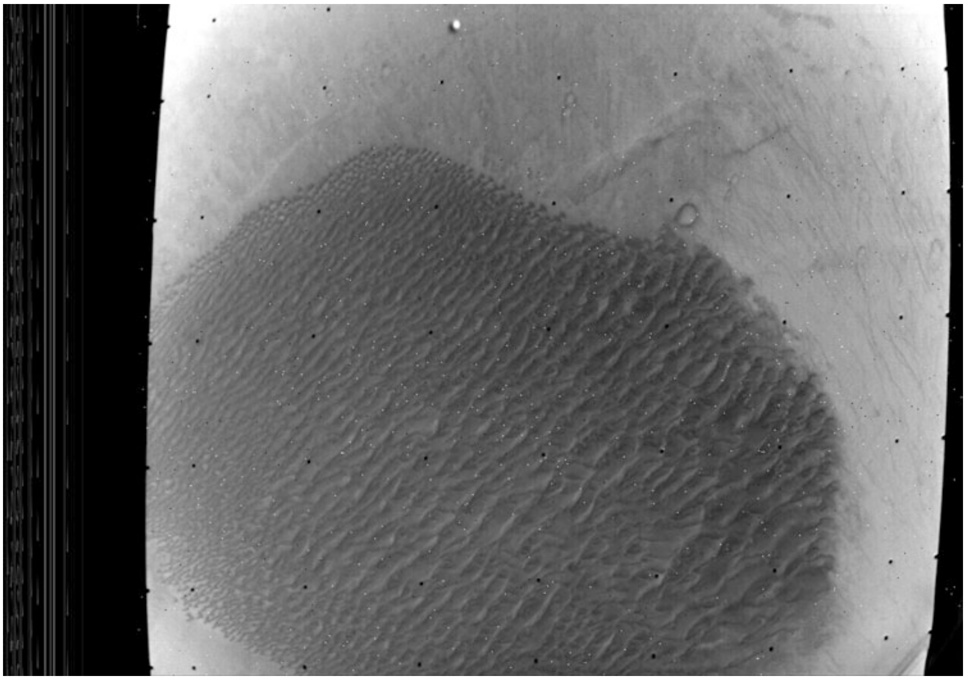

Fig. 1.2 The first dunes recognized on another world. After the 1972 dust storm cleared, Mariner 9 snapped this image showing what at the time was called a 'suspected dune mass' in the floor of the Hellespontus crater. Note the curved edge of the image: the vidicon TV cameras of the time could cause geometric distortion of the image, which would be corrected by lining up the regular pattern of *black dots* ('reseau marks'). Note the gradient in dune size across the dunefield. Also visible towards the *upper right* is a small impact crater, and (just barely visible here, and not recognized at the time) some faint dust devil tracks. Tick marks at the left are for synchronization in data handling; the *white dots* across the dunefield are transmission errors. Mariner 9 image DAS 09807429, processed by R. Lorenz

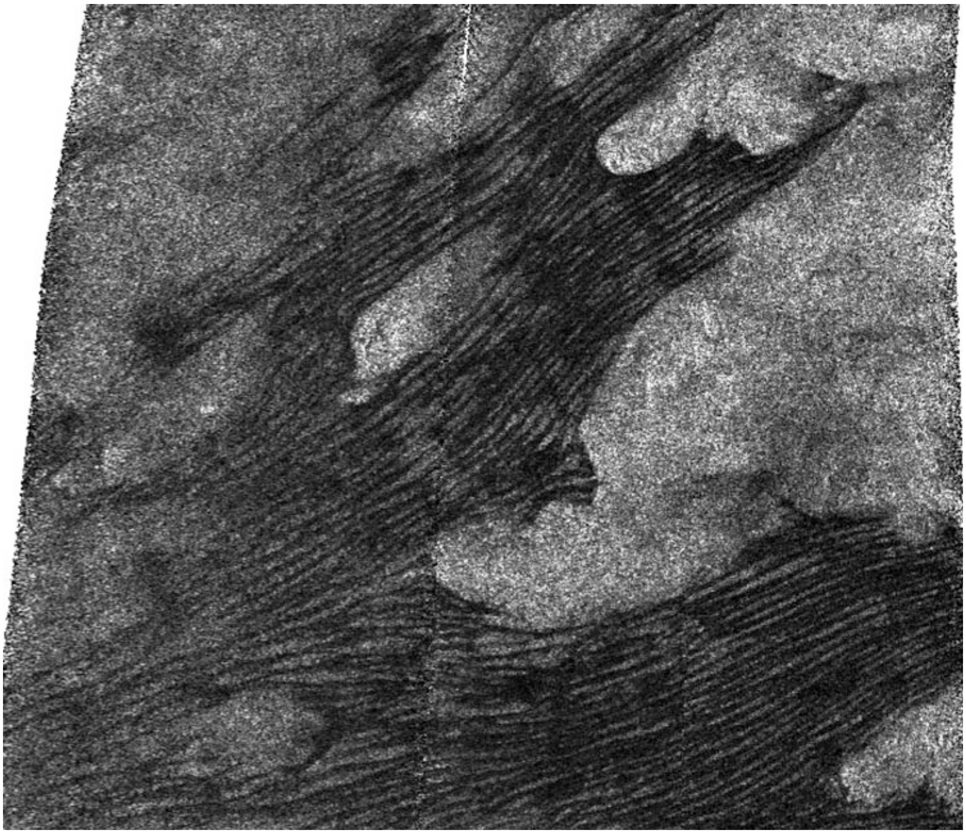

Fig. 1.3 A radar image of a region of Titan's surface, about 150 km across, from the Cassini spacecraft. The *dark stripes* are linear sand dunes, about 1 km wide, snaking around a bright highland (shaped a little like a snout) at the *right*. Similar deviation of dunes by topographic obstacles is seen on Earth (Fig. 12.10). Image by R. Lorenz and the Cassini RADAR Team

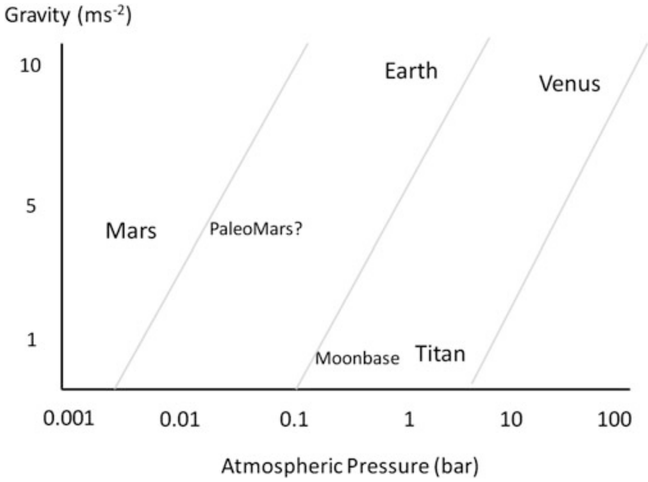

Fig. 1.4 A schematic of the fundamental environmental features of planets with dunes. While Mars' atmosphere is thin today, it may have been substantially thicker in the past, perhaps making it easier to transport sand. A pressurized lander or base on the moon would see a gravity the same as Saturn's moon Titan, but with thinner air. The faint diagonal lines are a crude indication of equal transportability; Venus and Titan can move sediments with the gentlest winds, whereas today very violent winds are needed to launch sand into the air on Mars. These parameters are explored in more detail in Chap. 4

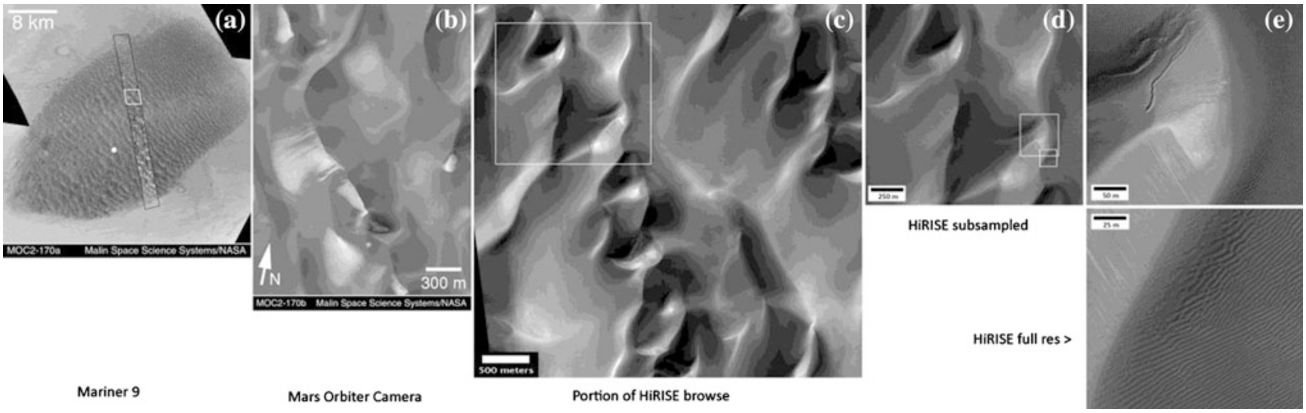

Fig. 1.5 A mosaic of images of dunes in the Proctor crater on Mars, assembled by J. Zimbelman. **a** A Mariner 9 image from 1972 (at ~60 m/pixel); **b** a Mars Global Surveyor image at several m/pixel in 1999; **c**–**e** progressive zooms into a massive image (PSP_006780_1320), from the HiRISE camera on Mars Reconnaissance Orbiter in 2008, with a resolution of about 50 cm/pixel. From the dunefield perspective we can now zero in on individual dunes and even see (and observe the migration of—see Chap. 8) the small superposed ripples. (Several of these images are shown individually at a larger scale in Chap. 12)

Fig. 1.6 First 'field trip' on Mars. The shallow bedforms in the foreground are 10 cm or so high, but were hidden from the camera on the Mars Pathfinder lander by the 'Rocknest' formation. This image was only possible because the Sojourner rover trekked away from the lander, revealing new territory. The familiar 'twin peaks' hills (also visible from the lander) can be seen on the horizon. NASA/JPL image PIA00965

These computer models also allow us to bridge the real world and laboratory experiments (which themselves have reached an impressive level of fidelity (Fig. 1.11)).

This tremendous arsenal of data and tools has brought a new level of understanding to planetary dune studies and lets us offer answers to some basic questions.

1. **How do sand dunes develop, move, and change shape?** In order to understand how sand moves, we first need to establish what sand is, which can be very different in other planetary environments. But once the different fluid and gravitational forces that act on a sand grain are identified, some simple math can tell us the basics about what winds are required to set grains in motion, although a prominent theme in modern aeolian studies is how to tackle the complex and highly fluctuating character of transport in turbulent winds.
2. **Are sand dunes the same everywhere?** Like the canonical snowflake, no two dunes are exactly alike. And yet there is clearly order in the bewitching infinity of duneforms. The first job in science is usually to classify objects into groups of more-or-less the same. While that always entails some subjectivity, it is an essential simplification. But once that is embraced, the same sets of forms can be recognized on different planets, and in the computer, and in water tank experiments, paving the way for a quantitative link between what we see on dune worlds, and what wind and time was needed to make what we see.
3. **So what do the dunes tell us?** There is a 'Goldilocks' element to the formation of dunes. The particles involved must in general not be moving, otherwise they do not really define a landscape. And yet they must move often enough to assemble into a dune. 'Often enough' is

Fig. 1.7 Image from the Mars Exploration Rover Opportunity. The rover's solar cells and the Planetary Society's sundial are visible at bottom. The tracks show wheel slippage as it negotiates wind-blown ripples; some coarse granules can be seen on the flanks of the ripples, and cracked white bedrock is exposed in some places. JPL/NASA

Fig. 1.8 Small digital cameras make the recording of field conditions exceptionally easy. New computational tools (Chap. 17) make it possible to build quantitative shape models of dunes and ripples with only minutes of effort. Digital cameras are small and light enough to take to the air; this example, showing barchanoid ridges with interdune lagoons in the Lencois Maranhenses in Brazil, was lofted by a parafoil kite that could scrunch up into a coat pocket. *Photo* R. Lorenz

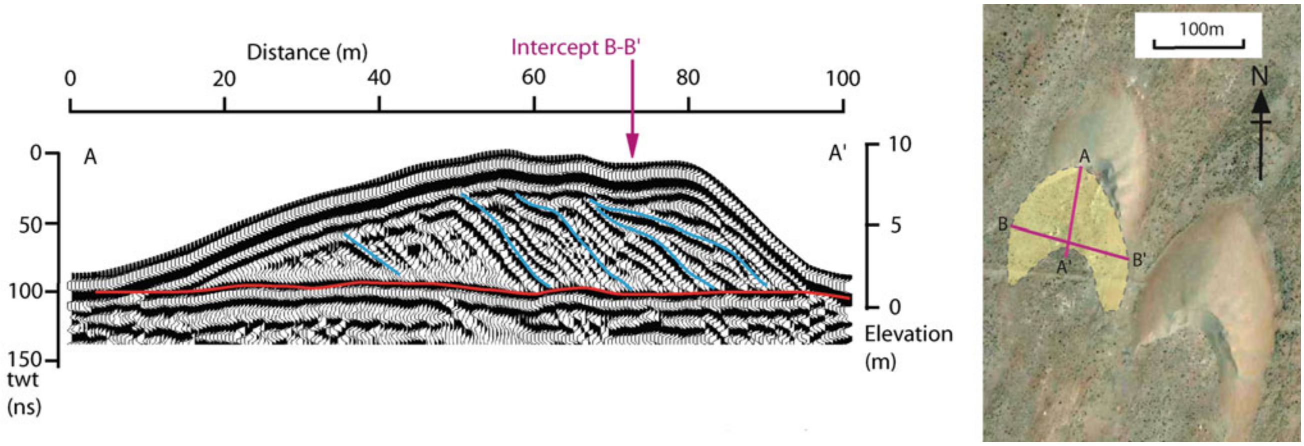

Fig. 1.9 The internal structure of a crescentic barchan dune in Morocco is revealed in this Ground-Penetrating Radar (GPR) survey. The transect (A-A') moves left to right in the downwind direction (top to bottom in the orbital view) and shows the steeply-dipping former slip faces that marked the previous position of the dune. Enough time has elapsed between this survey (where the dune outline and transects were measured by GPS) and the orbital image at right that the dune has moved southwards. Image courtesy Charlie Bristow

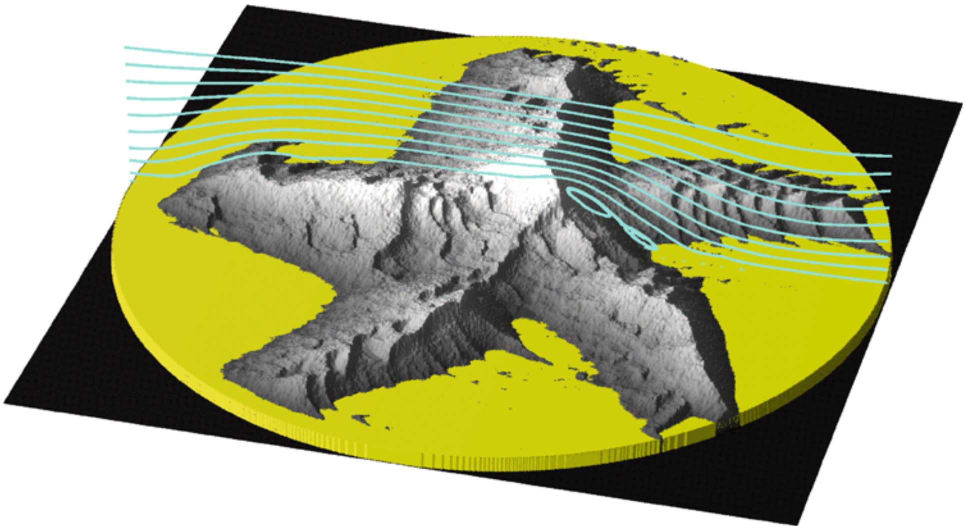

Fig. 1.10 Modern coupled simulation of the airflow and sand transport, using a cellular automaton sand model (showing here a 5-pointed star dune). Streamlines in a lattice gas flow model are shown, influenced by the evolving topography underneath; the streamlines compress at the dune crest, and separate, leaving a vortex in the lee of the dune. Image courtesy Clement Narteau

a relative term—it depends on what else is going on. For a dune to exist, it must form or move or repair itself faster than other processes destroy it. Various geological processes prevail to different degrees on different planets: on Earth, for example, there are relatively few impact craters because fluvial or glacial erosion or other processes have removed them. There are just a couple where craters recognizable from orbit are in deserts with prominent dunes (Fig. 1.12), yet this sort of interaction is common on Titan where erosive activity, while present, is less vigorous than on Earth. On Mars, in contrast, rain has not been widespread for billions of years (if ever) and thousands of craters are visible, acting as traps for the sand.

On Earth, at least, there are dunes present where dunes do not presently form or move—they are fossils of a past climate. This brings another paradox, resurrected into the wider planetary arena from eighteenth and nineteenth century Earth science more generally: to what extent does the landscape we see today represent processes happening today, versus what processes may have happened in a catastrophically-different past? This question has come to the fore in studies of Martian dunes, a few of which have only recently been observed to move, but others of which may be very old and cemented by ice or evaporite minerals, and even on Titan where some dune-like features stand distinct in location and orientation from the majority.

Fig. 1.11 Morphologically identical to dunes a thousand times larger, these cm-scale bedforms are generated in a water tank in which a sediment-covered platform (see Chap. 17) is moved back and forth, rotated between cycles to impose a desired ‘wind regime’ to quantitatively explore the dependence of morphology on the angular diversity of winds. Picture courtesy of Sylvain Courrech du Pont

Fig. 1.12 The sand streaks and falling dunes show a clear corridor of sand transport across the Arounga impact structure in Chad in this image from the International Space Station. The crater is 12.6 km in diameter. On Earth’s young surface with relatively few impact craters there are few similar examples; on Mars, craters tend to be traps for sand. On Titan, many craters appear to be partly overrun by dunes. NASA Image

Fig. 1.13 Erwin Rommel (with binoculars) in his Sd.Kfz 250/3 half-track ‘Greif’ during the African campaigns. Half-tracks are a useful compromise vehicle for difficult terrain, balancing traction and manoeuvrability. Bundesarchiv—Wikimedia Commons

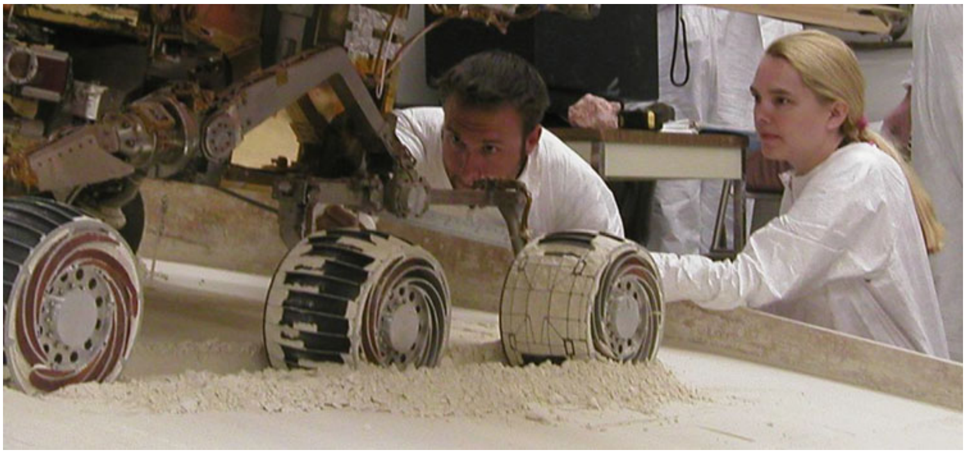

Fig. 1.14 Mike Seibert and Sharon Laubach, engineers on the Mars Exploration Rover team at NASA’s Jet Propulsion Laboratory, Pasadena, check the exact position of a test rover in preparation for the next test of a possible maneuver for Spirit to use on Mars. The test setup at JPL simulates the situation where Spirit is embedded in a patch of soft soil dubbed ‘Troy’, in Mars’ Gusev Crater. The preparation shown here on July 7, 2009, preceded an assessment of straight-backward driving the next day, one of several possible maneuvers assessed in the test sandbox. *Image Credit* NASA/JPL-Caltech

Fig. 1.15 Living in the Antarctic is perhaps a close analogy to how people might one day live on other planets. Quartz is not the only material on Earth to be blown by wind and form dunes—snow can do so as well, especially when very cold and dry. As the old dome at the South Pole became buried by blowing snow, the new Amundsen-Scott South Pole Station was built 1999–2008 on stilts to allow snow to blow under it, and the building was somewhat aerodynamically-shaped, with the wedge-shaped underside oriented into the prevailing wind specifically to inhibit snow accumulation. *Photo* National Science Foundation

Whether active today, or fossils of the past, dunes tell us certain things about the conditions of their formation. There must be sand—whatever it happens to be made of, it means particles of a size with the right mobility. In some cases, this means particles that have been ground down from massive rock, sometimes evaporite crystals formed as a lake dries up, sometimes it means sand re-liberated from sandstone rock that was once in the form of dunes. Yet in other cases (as at Titan) it may mean grains built up from smaller particles somehow, or falling from the sky as with snow on Earth. Like the dunes it can form, sand itself evolves—often initially jagged or sharp-cornered from its origin in fracture or precipitation, the innumerable collisions with its fellows as it bounces along the ground may grind it smaller or make it round. New analytical methods, and even remote sensing, can let us match the minerals from which a grain or dune is made to a locale where the grain must have come from. Other laboratory techniques can even tell us how long a sand grain has been buried inside a dune, letting us gauge the dune's age. Yet the microscopic properties of sand grains can influence such experiential phenomena as how the sand sounds when jump on a dune and make the sand slide.

In addition to telling us about past climates, sand and dunes are a major factor in how humans live and work in some desert environments. Large deserts have been barriers to commerce and military operations and many different machines and/or techniques have been developed to enable vehicular travel across sand dunes. Some of the first traverses of the Sahara were made with half-track vehicles, also a favourite[1] of World War II's 'Desert Fox', Erwin Rommel (Fig. 1.13).

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[1] During the preparation of this book, we searched for images in the Bundesarchiv but sadly failed to find any of this vehicle on an actual dune. Most operations were (prudently) on the flat coastal plains and in the mountains.

Fig. 1.16 The 'Star Wars' film set near Tozeur, Tunisia. A set of buildings (used to portray the city of Mos Espa on the planet Tatooine in 'Star Wars, Episode 1') makes convenient reference marks to track the migration of nearby dunes. The slip face of a barchan dune, about 20 m away from the set when this picture was taken in 2009, can be seen behind the first author who is standing next to a 'moisture vaporator' (sic). The dunes have been measured (Fig. 9.8) to move at about 15 m/year, threatening the site with erosion and burial. *Photo* R. Lorenz/J. Barnes

In fact, it was one of Rommel's most daring adversaries, Brigadier Ralph Bagnold, who first made a systematic study of sand transport and dunes as a physical process. Bagnold explored the deserts prior to WWII, and his initial curiosity about desert landforms motivated him to investigate the physics underlying wind-induced particle motion, both in a laboratory of his own design and through fieldwork in deserts around the world. Bagnold's seminal book, *The Physics of Wind Blown Sand and Desert Dunes* (1941), is the starting point for all modern investigations of the geomorphology of sand dunes and sand deposits. Bagnold instigated the famous 'Long Range Desert Group' employing special vehicles and tactics and using his desert knowledge to prevent Rommel invading British Egypt by making deep strikes behind enemy lines across desert thought to be impassable.

Similar challenges in locomotion are encountered in snow, and now in traversing the loose, dry terrain on Mars. The difficulties of negotiating noncohesive ground have even claimed their first victim on another world. The Spirit rover (Fig. 1.14) at the Gusev crater on Mars got stuck in soft ground in an orientation that did not let it generate enough solar power to survive the winter.

Sand giving way under one's wheel s or feet is one set of problems; sand moving under the action of wind presents others. Wind-blown snow presents a similar challenge, prompting architecture that is aerodynamically designed to prevent accumulation (Fig. 1.15) which can completely bury

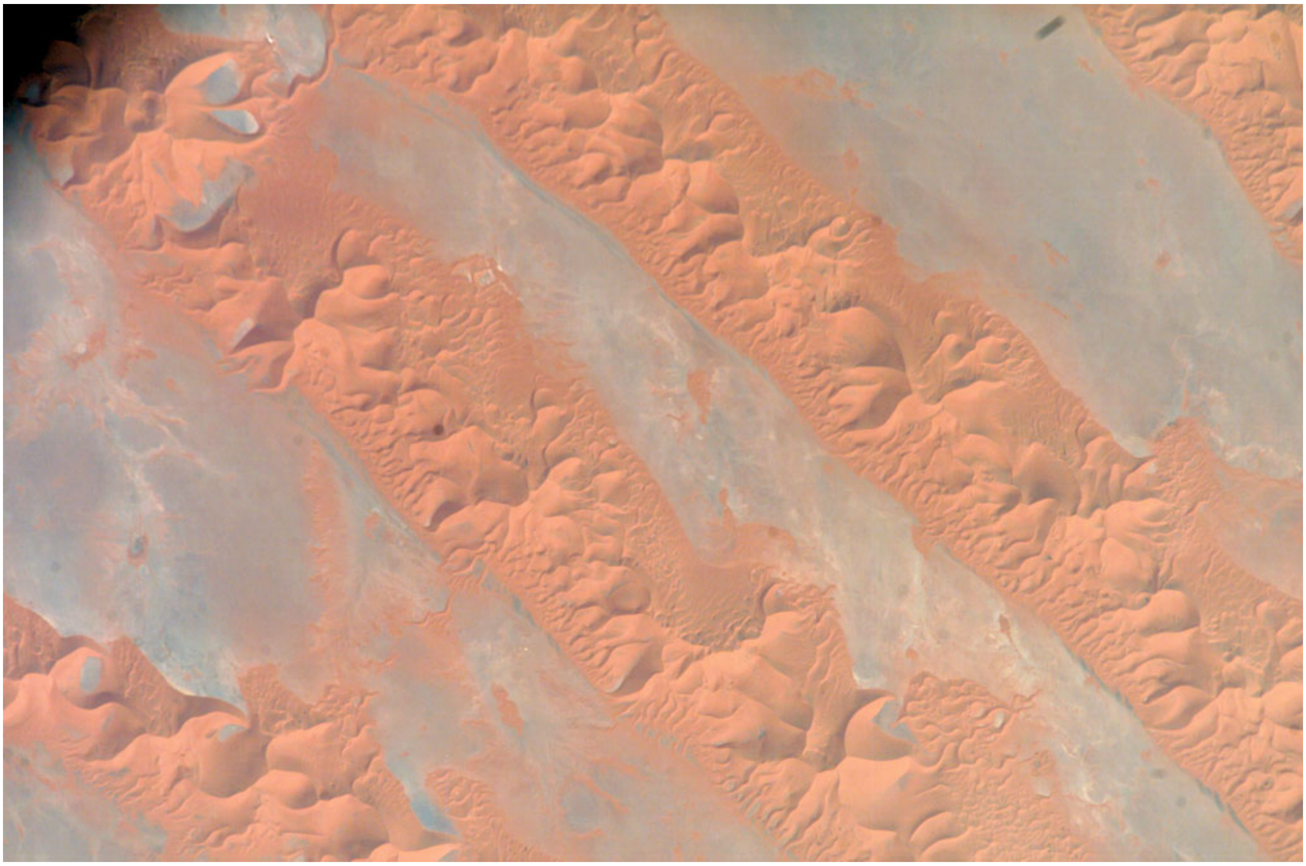

Fig. 1.17 An image of the Grand Erg Orientale (part of the Sahara) in Algeria, taken through the window of the International Space Station. The overall arrangement is clearly linear, but the crestlines are star-shaped. Are these linear dunes that have been morphed into star shapes, or are they star dunes that just happen to have formed in lines? The linear dunes are about 2 km wide. Image Science and Analysis Laboratory, NASA-Johnson Space Center. "The Gateway to Astronaut Photography of Earth"

buildings over some decades. Migrating dunes can block roads, railways or canals, requiring expensive mitigation; on the larger scale, the burial of fields or oases by dunes can simply force us to migrate ourselves, admitting defeat against the onslaught of sand. In fact, the battle of arid lands ecologists against dunes in Oregon inspired the science fiction author James Herbert to write his iconic *Dune* novel, and dunes feature on a number of fictional worlds (Fig. 1.16).

Our aim in this book is to survey the physical principles behind dunes, review observations and measurement techniques, emphasizing the newest developments, and to draw together what has become known about dunes on other planetary bodies with what has been learned about the Earth. Just as dunes are a feature of the interface between the ground and the air, so studies of dunes have fallen across the domains of geography, physics, geomorphology, geochemistry, planetary science and other fields. We hope the reader enjoys the adventure, as we have, of straying beyond the traditional bounds of whatever discipline they consider themselves in. This is not a textbook, merely a travel guide. Our goal is to provide breadth, and to identify pathways in data, techniques and the literature for the reader to wade in as deeply as they wish.

We have organized the book in five main sections. First is the introduction you are now reading. In the second section, we describe the principal physics behind dunes, what they are made of, and what controls their size, shape and movement. Next, we discuss the aeolian features seen on various dune worlds, namely Earth, Mars, Titan and Venus, as well as the possibility for bedforms on a few other planetary bodies. The fourth section discusses the various ways in which dunes are studied: in the laboratory or wind tunnel, in the field, and by computer simulation. The various remote sensing techniques applied to aeolian studies are also reviewed. Lastly, we survey why dunes and related landforms and processes are important—as physical systems, as environmental

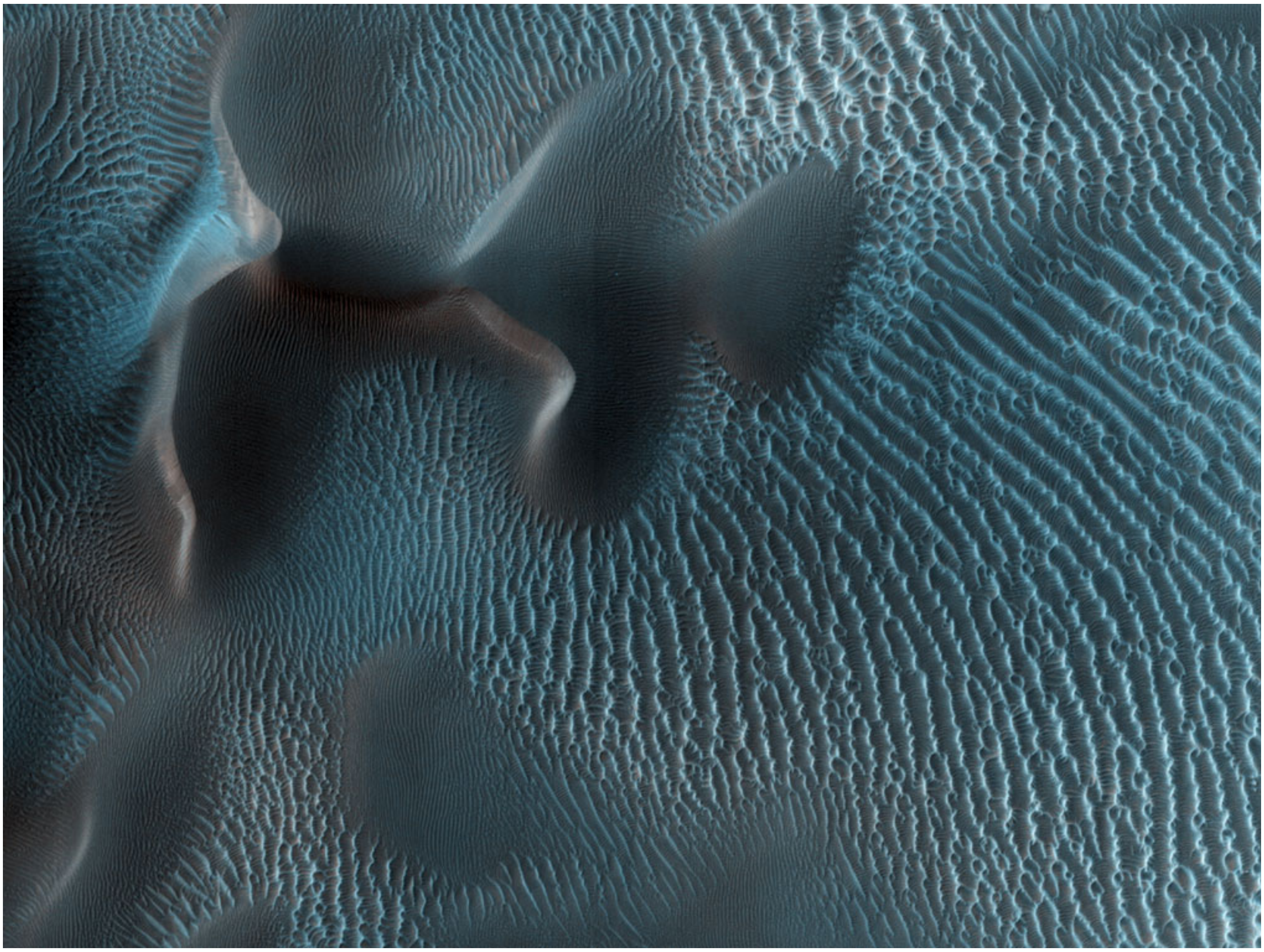

Fig. 1.18 An image from the HiRISE camera of the Martian surface (this image forms the *dark blue background* on the cover of this book) with aeolian features on three scales. The image shows a set of barchan and dome-like dunes (see Chap. 6). Dominant at the *right* of the image are sharp-crested ripples or TARs (see Chap. 5). Close examination will also reveal small ripples on the surface of the dunes. *Image* U. Arizona/JPL/NASA

indicators, and how they affect infrastructure and mobility, on Earth and other planets (including fictional ones). Along the way, we provide images to illustrate particular points, although as researchers entranced by the beauty of our subject, we have unashamedly included some images (like Figs. 1.17 and 1.18), just because they are pretty.