2 Sand

When we hear the word 'sand', the visual image evoked is most likely of sand in aggregate—of a pleasant beach or a massive field of dunes. But the poet William Blake provides an apt perspective on the inspiration that can come from contemplating even a single, isolated particle:

> To see a world in a grain of sand,
> and heaven in a wild flower,
> hold infinity in the palm of your hand,
> and eternity in an hour.
> (from 'Auguries of Innocence', 1803; in The Pickering Manuscript, published 1863)

For an enchanting and accessible discussion of sand and its relationship to our planet and its inhabitants, we recommend Michael Welland's book, *Sand: The Never Ending Story* (2009). A good paragraph-length summary of the microcosm exposed in grains is this by Raymond Siever who expanded more scientifically upon Blake's poetic sentiment:

> A single sand grain, an irregularly shaped fragment of rock, is the mute record of former mountains, rivers, and deserts, and of millions of years of the Earth's upheavals and quiescence. To make a grain tell us its history, we tear it apart bit by bit to find out its crystal structure, its chemical composition, its radioactive age, its external shape, and its internal strain. Yet we cannot tell all we want to know of a sand grain's origin from its composition alone, any more than we can deduce political history from human physiology. The context of the state of the world's continents and oceans at a particular time is the background. That grain was produced by forces that made the rock it was eroded from, by the Earth's surface environment that eroded it from its parent and carried it to a resting place, and by the internal deformation of the Earth's crust that buried it. (Siever 1988, p. 1)

Here we attempt to expand upon Siever's terrestrial point of view, to consider sand and its associated landforms identified during spacecraft exploration that has been conducted in the other worlds of the solar system.

We can start by returning to the simple question: what is sand? A typical definition for sand is 'a hard, granular rock material finer than gravel and coarser than dust'. As this short statement points out, it is important to realize that 'sand' formally refers to sediment particle size (which we will quantify shortly), not to particle composition.

It is conventional too to think of sand as something—usually quartz (see later)—that is *broken down* from a larger mass of bedrock. However, from the viewpoint of sand being particles of a given size or, broader yet in the context of this book, dune-forming material in general, this perspective is somewhat parochial. Snow forms dunes, yet is crystallized in the air from water vapor; Titan's sand may start in a similar way, perhaps agglutinated somehow on the surface. Agglutination of dust is often responsible for the formation of granules that form the crest of ripples on Earth, and dustballs are suspected as particles in high-altitude martian bedforms (where the air density is so low that it would be hard to move solid particles). So material can grow into sand, not just be broken down into it.

Let's start with snow, as it defines an instructive end-member in the spectrum of dune-forming material. Because it often has a very low density (bulk snow can be 100 kg/m^3, about one-tenth that of water, although this is typically due to porosity between grains or flakes; the effective density of a fractal snow particle may be typically more like 300 kg/m^3, of course only a third as dense as a solid piece of ice), the drag at even low air speeds is comparable with its weight, and thus snow swirls in every eddy of wind, rather than leaping in little ballistic hops. In this sense, snow dynamics are sometimes more akin to sand underwater than to sand in air. A distinctive feature of snow, of course, is that it can be sticky, and so rather than clean slip faces on the lee side of dunes or drifts, it can form dramatic overhanging cornices, or accumulate into long streaks (Fig. 2.1).

Evaporite minerals can form dunes, most notably gypsum sand, famous at New Mexico's White Sands. This material, being both water-soluble and much softer than quartz, cannot migrate for long before it either becomes cemented or ground into dust (see also Synkiewicz et al. 2010). Gypsum appears to be a major component of some Martian dunes, too.

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Fig. 2.1 We deliberately challenge the reader's expectations by starting the illustrations in this sand section with a dune made from material that we do not typically call sand, but that meets our criterion of 'dune-forming'. Here, the lee of a stack of supply cases on a meteorite-hunting expedition in Antarctica has allowed blowing snow to form a somewhat linear dome dune overnight. A slight halo of saltating snow can be seen above the dune against the tent background. *Photo* Jani Radebaugh

Dunes can form on Earth in volcanic ash, a couple of celebrated examples being a dark ash barchan that has been marching away from the Ol Doinyo Lengai volcano in Tanzania at about 10 m per year, and the colorful painted dunes in Lassen Volcanic Field. Indeed, cross-bedding textures can often be seen in ash deposits; some may be caused not by conventional winds but by the strong out-flowing surge when an ash column collapses. Bedforms are not limited to forming from sand-sized particles: pumice gravel in the Puna of Argentina forms the largest wind-ripples known on Earth. These hard-to-move lumps define the other end of the dynamical spectrum of particulates—stuff that needs the strongest winds to be launched into the air, and is only modestly affected by the airflow once that happens. This is true, generally, for sands on Mars, many of which have a volcanic (basaltic) composition.

Some sands are quite literally grown. Shell fragments of mollusks are a common component of many beach sands, and limestones in particular (but carbonate rocks on Earth in general—e.g. Brooke 2001) may have a substantial amount of tiny shells, which if eroded out and transported by wind can be referred to as an eolianite. When these rocks break down, these tiny fossil shells are the natural result; oolitic limestone is defined by spheroids ('ooids', from the Greek word for 'egg') between 0.25 and 1.25 mm. The tiny but resistant silica corpses of smaller living things yet, hard-shelled algae known as diatoms, form sediments (diatomite, or diatomaceous earth) which can break back down into hollow particles typically 10–200 μ across. Their small size and very low density makes them easy to transport by wind, and makes them responsible for the dustiest places on Earth, like the Bodélé Depression in Chad (which also has some of the fastest-moving dunes made of these little shells, see Chap. 8).

At the densest end of the spectrum, sorting by fluvial or aeolian processes can concentrate minerals. Often, bands of dark magnetite can be found on sand dunes, and Gay (1999) describes a small dune in Peru where aeolian sorting led to it having a concentration of some 46 % magnetite. The density of magnetite is some 4900 kg/m^3, around double that of quartz. Of course, human activities are better yet at sorting: there are doubtless piles of metal ores at mines and foundries worldwide that beg for aeolian experimentation. And in a cruel imprint of human history on geology, the sands of certain beaches in Normandy have a high fraction of steel particles.

With such a wide range of 'sand' and formation processes on Earth, one might expect that an even wider range needs to be considered for other worlds. Yet in fact, by and large what we know of Mars at least suggests the processes that make sand, and the resultant compositions, are the same as, but just a subset of, what happens on Earth. Titan, at least, likely has sands of an exotic composition (probably containing such organic chemical compounds as phenanthrene, coronene and other exotica), although they may be processed into saltating sand in much the same way as evaporitic sands on Earth. However they are made, it is important to adopt a wide

Table 2.1 The modified Udden-Wentworth scale of particle sizes and names

Name	Size range (grain diameter)	ϕ-scale
Boulder	>256 mm	($\phi < -8$)
Cobble	64–256 mm	(ϕ −6 to −8)
Gravel	2−64 mm	(ϕ −1 to −6)
Granule	2–4 mm	(ϕ −1 to −2)
Sand	1/16–2 mm	(ϕ 4 to −1)
Very coarse	1–2 mm	(ϕ 0 to −1)
Coarse	1/2–1 mm	(ϕ 1 to 0)
Medium	1/4–1/2 mm	(ϕ 2 to 1)
Fine	1/8–1/4 mm	(ϕ 3 to 2)
Very fine	1/16–1/8 mm	(ϕ 4 to 3)
Silt	1/256–1/16 mm	(ϕ 8 to 4)
Clay	<1/256 mm	($\phi > 8$)

perspective, as Titan's discoverer Christiaan Huygens did in his book *Cosmotheoros* (1698)—it matters less what the stuff is made of, than how it behaves.

> Since 'tis certain that Earth *and Jupiter* have their Water and Clouds, there is no reason why the other Planets should be without them. I can't say that they are exactly of the same nature with our Water; but that they should be liquid their use requires, as their beauty does that they be clear. This Water of ours, in Jupiter *or Saturn*, would be frozen up instantly by reason of the vast distance of the Sun. Every Planet therefore must have its own Waters of such a temper not liable to Frost.

2.1 Sand Size and Shape

A challenge with something as mundane as dirt is to formally systematize something that everyone thinks they understand. Sand is small stuff, but not really small.[1] Jon Udden, a professor of geology at the small midwestern college of Augustana, was the first person to publish a statistical analysis of sand grain sizes that occur within windblown deposits (Udden 1898); he subsequently compared aeolian sands to the sands found in rivers and on beaches (Udden 1914). He chose to follow the lead of soil scientists, who used sieves to separate soils into mass fractions based on how the materials passed through a stacked array of progressively smaller meshes. Charles Wentworth (1922) codified the progressive size scale using divisions based on powers of 2, what is now termed the 'phi scale' (where $\phi = \log_2 d$, with the grain diameter measured in millimeters). The Modified Udden-Wentworth scale, still in wide use throughout sedimentary geology, lists several particle size divisions (Table 2.1). Many additional size descriptors and parameters have been applied to particle size measurements through the years (e.g., see Folk 1966; Blott and Pye 2001), but the subdivisions within the sand size fraction have remained constant since the introduction of the Udden-Wentworth scale.

It is common among geologists and geographers to document the size distribution recovered by sieving as a histogram, and it often looks somewhat like the bell-shaped Gaussian curve that elementary statistics is so full of. Such a plot in linear form is a useful guide, but a more broad-ranging and broadminded mathematical investigation can be more instructive yet.

Note that the factor-of-two binning is a logarithmic scale, which is what is needed to grapple with a wide range (much as stellar magnitudes, or earthquake magnitudes, or intensity of sound). The utility of logarithms is often forgotten, and in fact Bagnold himself found interest in the use of logarithmic axes in plotting not just the size (the x-axis) but also the the number of sand particles in each sieve (the y-axis). When Bagnold plotted the results, he got something like a bell-shaped curve. But it wasn't quite 'right'—at very small and very large sizes, there were more particles than a Gaussian or 'normal' distribution suggested there should be.

A more conventional scientist—better indoctrinated in the tyranny of the Gaussian distribution—would have shrugged his or her shoulders at the obvious and insignificant experimental error. But Bagnold, originally educated in Cambridge as an engineer, was too practical a man to ignore his own measurements.

> The difficulty was that the measured frequencies along the tails became so small that they were unplottable. Not being a statistican, I concluded that this difficulty could be overcome simply by plotting the frequencies indirectly as their logarithms, thus giving every frequency, however small, an equal prominence. The precise pattern of the complete size distribution of natural sand at once appeared. It consisted of two converging straight lines joined by a curved summit. The curve resembled a simple hyperbola.

A Gaussian, on logarithmic axes, falls away rapidly like a parabola. As the numbers involved tend towards zero, their logarithms tend towards minus infinity, and the tails of

[1] The number of grains of sand on Earth has long been a metaphor for a quantity beyond human comprehension. Scientists—at least since Archimedes' 'The Sand Recknoner'—however, have still attempted estimates of the number of sand grains after making certain assumptions. For example, one estimate for the number of sand grains on the beaches of the world is the staggering number of $\sim$5000 billion billion (5×10^{21}) grains of sand, assuming that the average sand grain is 0.25 mm in diameter, the 'average' beach includes 50 m of sandy beach that is 1 m deep, the sand grains are perfectly packed together, and that the world has 1.5 million km of shoreline (Greenberg 2008, p. 39). The vast sandy deserts present on several continents (e.g., the Sahara), along with the sand that is now stored within sandstone deposits exposed around the world, suggest that even this estimate of the number of beach sand grains is likely more than a factor of ten too small to encompass all of the sand grains on Earth.

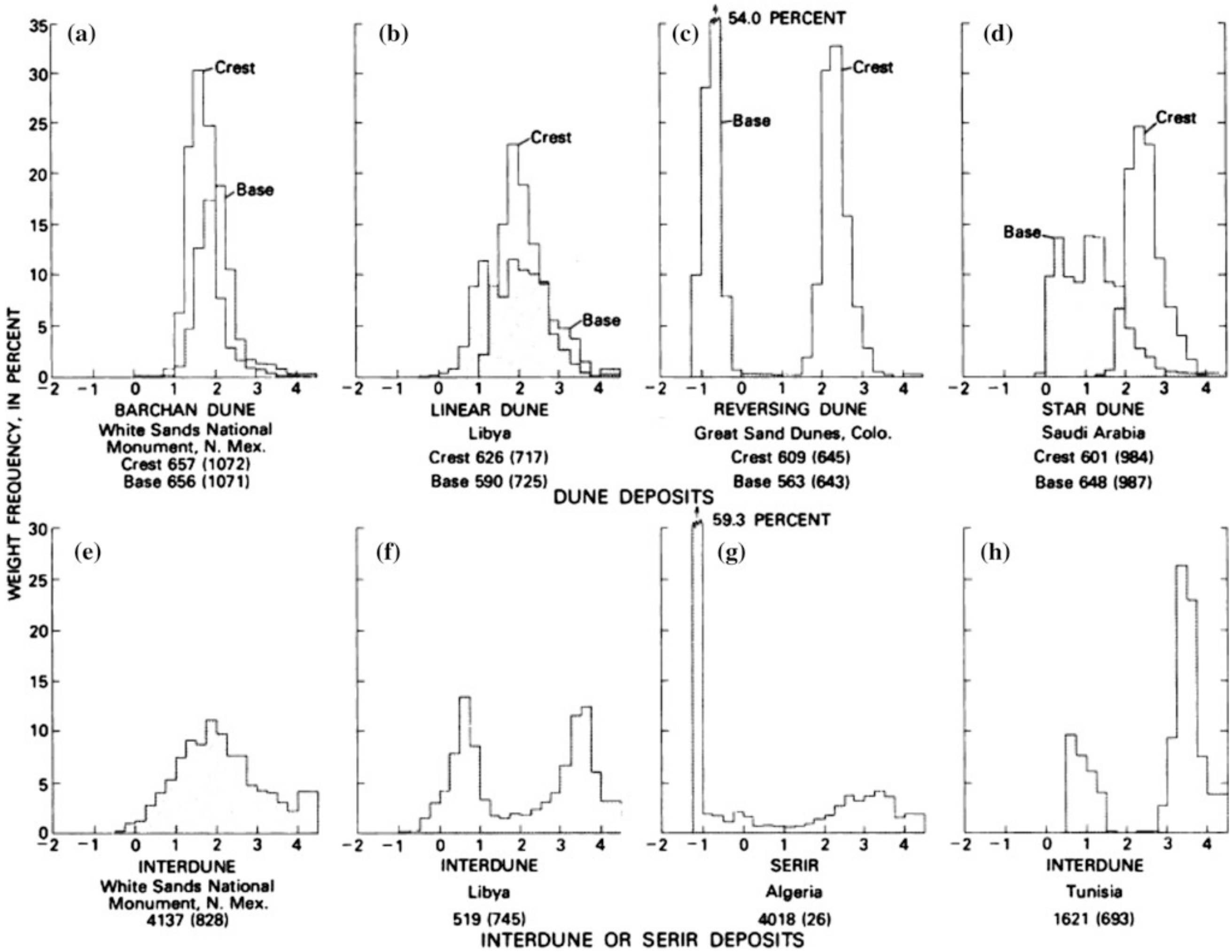


Fig. 2.2 Histograms of sand size: amount (in weight %) against the logarithm of particle size (expressed as the f number in Table 2.1). Note the differentiation between the base and crest of the dunes; the sharp peaks indicate strong sorting of the particles. Note also the generally broader sizes in the interdune areas. These data from Ahlbrandt (1979), USGS image

the distribution droop vertically. But Bagnold's sand numbers looked at this way were startlingly different: the points fell on two inclined straight lines, indicating two power laws. Such a functional form likely says something about the probabilities of moving a particle, or the process by which grains are broken down (Gaussian processes result from random additions, but successive fracturing, for example, leads to a power law). More generally, logarithmic plots avoid suppressing attention to the extremes of the distribution—we highlight the importance of this aspect in Chap. 3: Wind. In addition to logarithmic axes, sometimes data of this sort are plotted with 'probability' axes (essentially a way of stretching the plot under the assumption it is Gaussian); such approaches have been used in dune pattern analysis, although they seem less general and no better than logarithmic ones.

Note that much of the literature on sand sizes considers the statistical moments of the distribution—not only the mean size and the standard deviation, but also the skewness (how much one tail is fat relative to the other) and kurtosis (how spread the tails are). Sometimes these statistical measures are plotted for collections of sand samples in an effort to draw conclusions about the sand's provenance. Such conclusions may or may not be terribly robust (Figs. 2.2 and 2.3).

While the Udden-Wentworth scale is essentially configured by the measurement tool (sieves) it should be noted there are other ways to measure particle size. One is to observe the terminal velocity, to infer how long material takes to fall out of the air (or out of liquid suspension). Laboratory particle-sizers can use this technique, and the longevity of impact-raised dust clouds was used to constrain surface particle size at Venus and Titan. But electronic

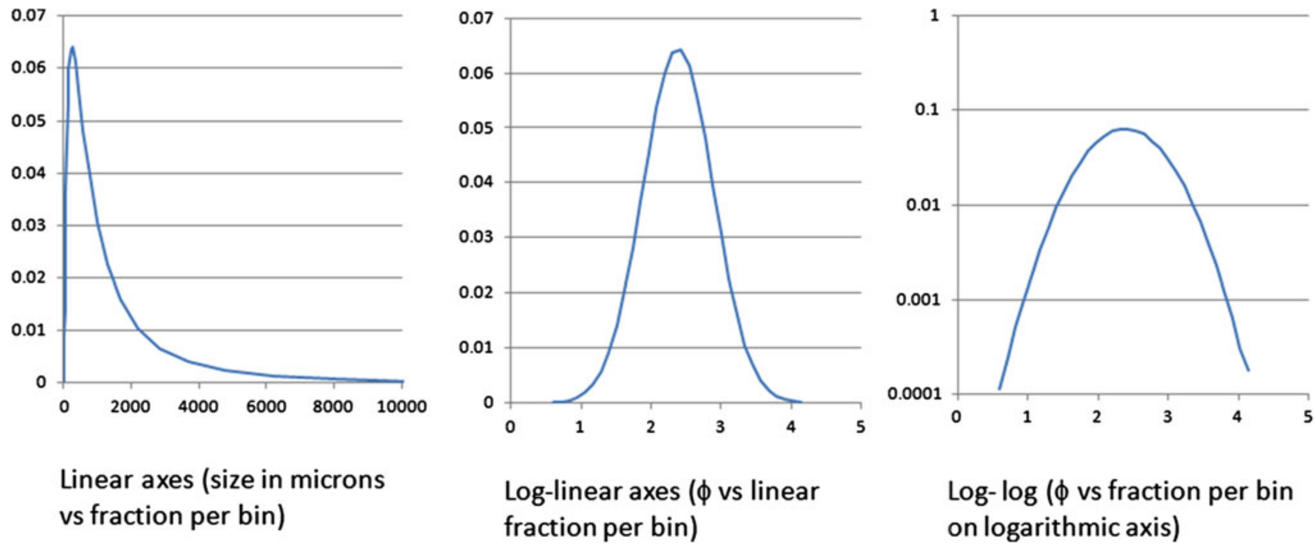
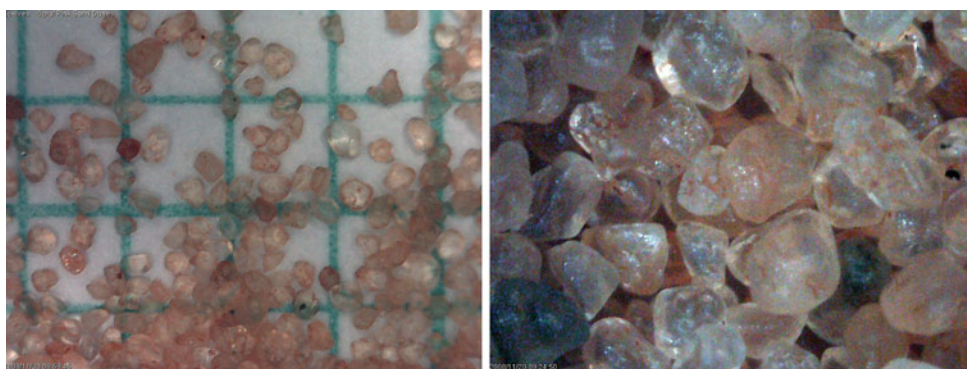


Fig. 2.3 Lies, damn lies, and statistics. These three graphs show exactly the same (synthetic) data, notionally a log-normal size distribution of sand. The extreme skewness of the distribution is evident in the leftmost (linear) plot, which loses detail at the small-particle end of the plot. That problem is restored by using a logarithmic size axis (one could simply use a logarithmic axis label, easy to do in a modern plotting program, or transform the size into a logarithmic measure such as f). This presentation makes it difficult to see quantitatively the abundance at the tails of the distribution, to which Bagnold noted some clarity could be brought by using a logarithmic ordinate. Some other aspects of chartmanship are highlighted in Chap. 10

Fig. 2.4 Microscopic images of sand. These are of sand from coral pink sand dunes in southern Utah, low res, high res; grid is 1 mm. *Photo* J. Zimbelman



imaging makes it now rather easy to measure the number, size and shape of sand grains optically (Fig. 2.4), and this has now become almost routine at Mars (Fig. 2.5).

There is more than one definition of particle size (e.g., the cube root of volume may be different from the largest or smallest dimension). But size is not the only aspect of a sand particle's dimensions that are of interest. For example, a rod-shaped grain can pass through a sieve opening that is smaller than its longest dimension if it happens to encounter the sieve in just the right orientation. Clearly, additional descriptive terms were needed to categorize sand grains derived from diverse source rocks and environments. Scientists struggled to determine the most utilitarian methods for categorizing sand beyond that of a sieve-derived measure of its size. The shape of the particle is an attribute that is related to the particle as a whole; it encompasses the three-dimensional aspects of the entire grain. Once sand was routinely observed through a microscope, various shape-related terms were used to describe the grains, among which descriptors such as spherical, cylindrical, tabular, blade-like, or sheet-like came into common usage. Early on, there was little consensus on how best to measure or quantify the shape of sand grains. At a finer scale, the microscope also revealed that the grains varied greatly in the smoothness or roughness of their surfaces, to which various modifiers could be added, such as well-rounded or poorly rounded (Fig. 2.6). By 1940, the basic definitions were in place for describing various attributes of grains, but a variety of methods were explored to quantify and measure these different properties (Siever 1998).

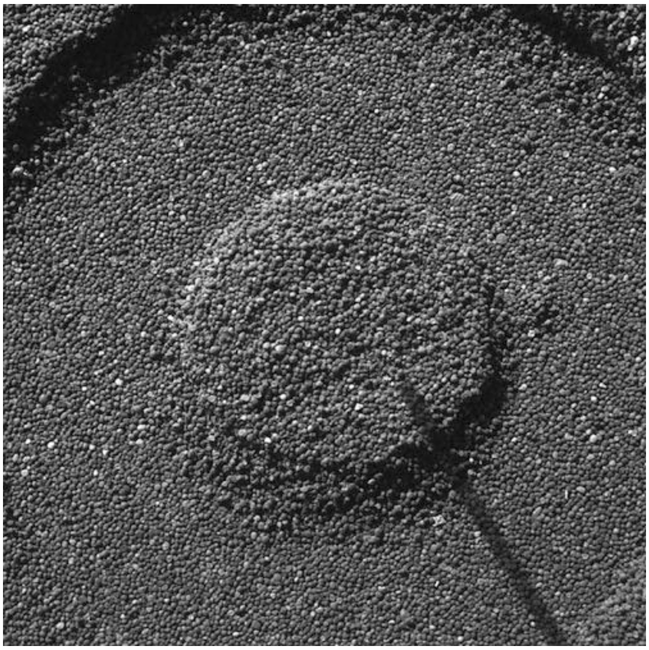


Fig. 2.5 MER microscopic imager view of basaltic sand (Spirit at El Dorado—see Chap. 12) showing individual grains; view is ~3 cm across. The annular depression is from the contact plate of an APXS instrument (see Chap. 17)

Haakon Wadell devised a simple method whereby the two-dimensional view of grains derived from photographs taken through microscopes could be systematically measured, which also provided a good way to distinguish between shape and roundness (Siever 1998, p. 52). Wadell defined shape as the ratio of the cross-sectional area of the grain to the smallest circumscribed circle, and roundness as the ratio of the average radius of curvature circles inscribed within corners on the grain to the radius of the maximum inscribed circle within the entire grain. These ratios led to both shape and roundness ranging from 0 to 1, where both a shape and a roundness of 1 would result from a perfect sphere. Rather than always having to carry out detailed measurements for each individual grain, calibrated silhouettes of measured grains allowed researchers to estimate the numerical value of both parameters quickly through visual inspection.

These shape parameters are important first in giving a quantitative, or at least consistent, basis for comparing different samples. Is one rounder than another? And what does this mean about how far it has been transported? For example, the sands of the Sahara, which have swirled around in North Africa for ages, are notably fine and round.

The shape influences how grains interact, defining the friction coefficient and thus the angle of repose. This is something that has been measured on Mars by making little piles of sand using the sampling arm of the Viking lander, for example. Grain shape is also important in generating sound by shearing (see Chap. 10). Grain shape also affects the fluid-dynamic properties, such that the drag and thus the saltation threshold depend on the shape. Generally, however, the shape effects on threshold are small compared with the influence of particle density, and the range of angles of repose encountered in nature is actually quite small.

2.2 Compositional Considerations

As discussed in the introduction to this section, sand grains consist of a wide variety of compositions. It is worth discussing, however, why we so often think of sand on Earth as referring to the mineral quartz. The abundance of quartz in sand on Earth is not a direct indicator of the quantity of silica in crustal rocks, and in particular the granitic rocks that dominate the continental crust (as opposed to the basaltic ocean crust). Rather, it is the result of the strong resistance of quartz to chemical weathering, at least compared with most other common rock-forming minerals. The combination of field observations of rock weathering processes and chemical experimentation on the stability of common minerals leads to a ranking of mineral in the order of their stability under terrestrial weathering conditions (Press and Siever 1974, p. 208; Table 2.2), with quartz by far the most stable common mineral, and olivine the least stable There are nonetheless two locations on Earth—Hawaii (e.g., Tirsch et al. 2012) and the Galapagos (both sites of basaltic volcanism)—where olivine-rich grains are present in such abundance as to form perceptibly green sand beaches. These two beaches (Iceland may also have some similar beaches) amount to perhaps a millionth of the surface area covered by predominantly quartz sands on Earth. Among other exotic sand compositions, there are reportedly a few garnet sand dunes in Namibia, and wave-ground steel particles are abundant on some beaches in Normandy.

It is the chemical instability of the silicate minerals which dominate igneous rocks on Earth that leads to the formation of clays, which are a major component of all of the different types of soils present around our planet. Extreme weathering conditions, such as the torrential rainfall that is common in equatorial jungles, can even leach away the quartz, which then leads to the formation of lateritic soils that are mined for their enhanced concentrations of aluminum and iron oxides. Thus, with increasing length or intensity of exposure to weathering (particularly by water), the mineral abundances within sand on Earth steadily evolves as the least stable materials progressively disappear, which also results in the steadily increasing relative abundance of the most stable mineral, quartz.

Measurements of composition, as well as of the size and shape of the sand, have been major tools in tracing the origins of sands in Earth's deserts. This approach

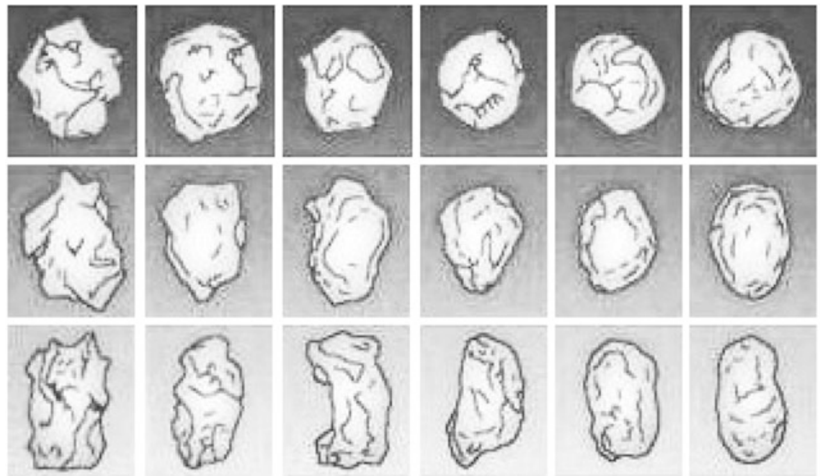


Fig. 2.6 A schematic of shape descriptors for sand grains

Table 2.2 Stability of some common minerals under weathering conditions at Earth's surface

	Mineral	Product of weathering
Most stable		Fe-oxides
		Al-oxides
	Quartz	
		Clay minerals
	Muscovite	
	K-feldspar (orthoclase)	
	Biotite	
	Na-feldspar (albite)	
	Amphibole	
	Pyroxene	
	Ca-feldspar (anorthite)	
Least stable	Olivine	

Table 2.3 Densities of bulk sand-forming materials. Porous materials (e.g., snowflakes, or ooids made of thin shells of calcite) can have much lower effective densities (see Chap. 4). The composition of Titan's sands is not exactly known, but simple alkanes and paraffins at Titan surface temperatures (94 K) have densities below 1000 kg/m^3. PAHs (polycyclic aromatic hydrocarbons) like Pyrene and Phenanthrene have densities rather higher than this, so Titan's sand density is somewhat uncertain at present

Material	Density (kg/m^3)
Ice	900
Gypsum	2300
Quartz	2600
Calcite	2700
Basalt	3000
Olivine	3300
Garnet	3100−4000
Magnetite	5180
Hydrocarbons	~800
PAHs	~1300

dominates, for example, the formidable study of the Rub' Al Khali by Helga Besler (Besler 2008), and the studies of the US and other deserts by Daniel Muhs (e.g., Muhs 2004, notes that, on the basis of the quartz vs feldspar abundance, the Algodones dunes were not derived from Whitewater river sands).

The terrestrial weathering sequence is not necessarily followed on the surface of other planets, where environmental conditions are very non-Earthlike, particularly with regard to the abundance and stability of liquid water. For example, spectroscopic data from Mars have revealed very little quartz on the Red Planet (Bandfield 2002; Bibring et al. 2005; Smith and Bandfield 2012), let alone in the abundant sand deposits present in many places on Mars, while at the same time the dark sand dunes in the Nili Patera region show an olivine signature (Mangold et al. 2007); both results are precisely the opposite of what would be expected from our terrestrial weathering experience. Rover investigations of dark sand in the Columbia Hills area show that the grains are predominantly comprised of fragments of basalt (Fig. A, Sullivan et al. 2008), but the Martian dunes in some areas have been shown to include olivine and pyroxene (Tirsch 2008) and even gypsum (Fishbaugh et al. 2007; Feldman et al. 2008; Calvin et al. 2009). Also, whereas terrestrial sand evolution may generally be

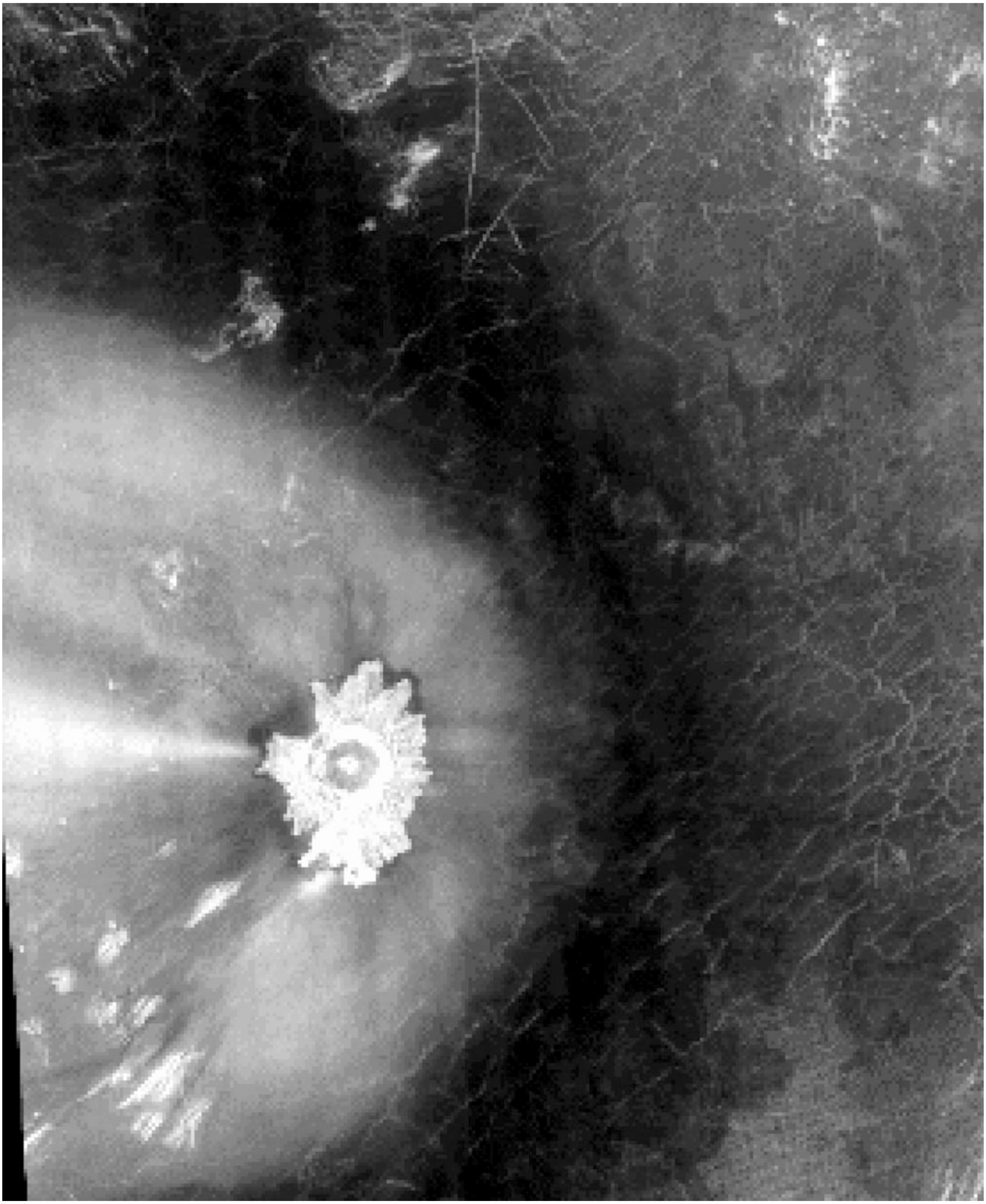


Fig. 2.7 Parabola on Venus formed by ejecta deposited above the atmosphere in an initially circularly symmetrical pattern, then winnowed eastwards by zonal winds. The inner region is bright due to blockier ejecta: the dark parabola is poorly radar-backscattering, requiring a thickness of several centimeters of fine ejecta. Source is the crater Adivar at the center (8.93 ± N, 76.22 ± E, 30 km across). *Image* Magellan Image F-MIDR-10N076, NASA

dominated by even rare exposures of water, Mars sands may be dry for millions of years and processes that are not usually noticed on Earth may become dominant. An interesting example is the experiment by Merrison et al. (2010) who found red coloration emerging in sand simply by rolling the sand around in a flask of simulated Mars atmosphere (CO_2 at 10 mbar pressure) for a few months, perhaps indicating a tribochemical process.

Different minerals have different densities, leading to different mobility in fluids such as water or air. Occasionally this effect is deliberately exploited to concentrate materials—panning for gold is one example—but more generally it contributes to an often striking uniformity of composition in a dune, or at least of layers within a dune (see Chap. 5). The range of densities encountered for sands known in our solar system at least is actually less (Table 2.3) than the range of densities of sand-forming material on Earth, although perhaps on some exotic world there are dense diamond sands!

Unfortunately, we have absolutely no observational constraints on the composition of sand on Venus. Although several Soviet landers provided clear evidence that basalt is the dominant rock type encountered at most of the landing sites, even then, the process by which sand-size particles are generated is not obvious. It may even be dominated by impact; large radar-dark (and thus likely fine-grained or smooth—see Chap. 18) parabolic deposits (Fig. 2.7) are seen around recent impact craters that may contain an abundance of sand-sized microtektite particles (launched above the atmosphere from the impact fireball and winnowed by the atmosphere). The compositional variations of sand throughout the solar system are the result of the unique chemical and atmospheric conditions present on each planetary body, where different groups of materials end up being either more or less stable within the corresponding surface environment. We have no idea, for example, how methane rain might progressively alter the composition of Titan's organic sands, if at all.

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