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Individuals

Birth and Character

Who could ever calculate the path of a molecule?
How do we know that the creations of worlds are not
determined by falling grains of sand?

Victor Hugo, *Les Misérables*

For Nature is the noblest engineer, yet uses a
grinding economy, working up all that is wasted
to-day into to-morrow's creation; not a superfluous
grain of sand for all the ostentation she
makes of expense and public works.

Ralph Waldo Emerson, "The Young American"

CONCEPTION

It was love at first sight. As the raven circled over the endless ocean, he saw a beautiful mermaid and was entranced. He flew close and asked her to marry him, and she agreed—but on one condition: "Make me some land where I can sit on a beach and dry my hair and I will marry you." The raven knew he would need help with this task and, in return for not insignificant favors but without revealing his intentions, enlisted the seal and the frog to procure some sand from the bottom of the sea. The raven then flew up into the strong winds above the ocean and scattered the grains to every corner of the world. At the place where each grain fell into the ocean, an island was formed: small islands from the tiny grains, large ones from the biggest grains. The mermaid was delighted, for the first time in her life drying her hair on a sandy beach. And then she and the raven were married.

This creation story, as told by the tribes of the Pacific Northwest whose ancestors were the raven and the mermaid, is only one example of myths from around the world in which grains of sand are the fundamental components of the Earth's creation. From the east coast of North America to the Carpathians, from West Africa to the Pacific Islands, sand is the parent for the birth of the land, a powerful symbol of origins. In *The Neverending Story,* the fantasy novel by Michael Ende, translated from the original German in 1983 and adapted into several films, the land of Fantasia is destroyed, with only a single grain of sand remaining. But that single grain enables the rebirth of the world.

The symbolism of sand as a foundation for our world continues in our collective subconscious, and the story of sand is indeed never-ending.

As we all know from the aftermath of a family visit to the beach, a single grain of sand can get anywhere. It physically penetrates, often to the detriment of health or a piece of machinery, and it can embed itself in our imagination. Pick up a single grain from the beach, look at it through a magnifying glass, and you have embarked on a journey taken by poets, artists, and philosophers—not to mention geologists. William Blake's "To see a world in a grain of sand / And a heaven in a wild flower," from his "Auguries of Innocence," has been put to use countless times to refer to flights of the imagination (the more gloomy direction that the poem subsequently takes is often ignored). Echoing Blake, but in perhaps a more approachable vein, Robert W. Service wrote, in "A Grain of Sand":

> For look! Within my hollow hand,
> While round the earth careens,
> I hold a single grain of sand
> And wonder what it means.
> Ah! If I had the eyes to see,
> And brain to understand,
> I think Life's mystery might be
> Solved in this grain of sand.

What is it about the idea that within its minuteness a grain of sand encapsulates greater things, that it is a metaphor for a grander scale, that it has a story to tell? There is a temptation to anthropomorphize, to gaze into the weather-beaten face of a sand grain and see ourselves reflected, our own life stories, our own journeys, our own worlds, to see the grain as an individual with a *character,* as well as a member of a family and larger clans, extended global tribes. Anthropomorphizing, yes, but it does provide a deep resonance and a framework within which to scrutinize a grain of sand. The birth of a sand grain is a microcosmic event, a flap of a butterfly's wings heralding greater change and a larger creation. Each grain carries the equivalent of the DNA of its parents and develops a character through its life that is molded partly by its parentage, partly by its environment. Compared to the scale of a human life, however, the sand grain's story is never-ending, and rebirth is a regular event.

BIRTH

In order to read the stories hidden in a grain of sand, we need to look at its exterior and interior, to take it apart. Like people, each sand grain is unique but belongs to a particular family with common genetics and origins. Just as stories are told in different languages and emerge from different cultures, sand can be created in different ways and can be composed of a wide variety of substances, although there is one dominant group in the population that shares a common history and a common chemistry.

Sand can be made by simply grinding up rocks into smaller and smaller pieces, but this is not easy and only glaciers do it effectively. Sand can be made biologically, from small shells and other products of the living world; whole beaches are formed this way. Warm seas can deposit their dissolved minerals, like limescale in a kettle, making minute pellets of sand. Sand grains can originate cataclysmically, as when molten rock spewed from a volcano chills and shatters in the air, or as the surface of the Earth melts under the impact of a meteorite, ejecting cascades of liquid droplets into the atmosphere; these solidify and shower back across oceans and land to be found as individual grains within sand or sandstone. But by far the majority of sand grains are made of one of the Earth's most common ingredients, the mineral quartz, and are formed by the process that works, day in, day out, on every exposed piece of land on the Earth's surface—weathering.

The most common element in the crust of the Earth and in the land around us is oxygen. Not as the gas that we need to survive, but chemically bound up with other elements to form solid—and not-so-solid—minerals, just as sodium and chlorine join forces to make salt. The second most common element is silicon, which teams up with oxygen and other common elements, such as aluminum, iron, magnesium, potassium, and sodium, to make the dazzling variety of minerals that are the ingredients of most of the Earth's crust—the silicates. One family of these minerals, the feldspars, are the most common constituents of the crust. But silicon and oxygen themselves make a fine couple, strong and enduring: together, they form the mineral quartz, the common form of silica. Close to 70 percent of all the sand grains on the Earth are made of quartz—tiny crystal balls, each with its own revelations.

Born in the cauldron of the molten depths of the Earth's crust, *igneous* rocks, cooled and solidified in a glittering matrix of crystals, are out of their element when they are ultimately jacked up by tectonic forces and exposed at the Earth's surface. However hard and durable they may seem, rocks such as granite are vulnerable to the weather, many of their constituents chemically unstable. The ravages of time and the elements are obvious on old gravestones and buildings—the corrosion of Cleopatra's granite needles is the classic example. In the midst of that corrosion, sand grains begin to sense freedom.

Chemistry and acidic rain are prime actors in the drama of weathering, but they are not the only members of the cast. Temperature changes, expansion and contraction, freezing, thawing, and the chemistry of water all work away at cracks, even in arid climates. And plants have leading roles, too. Not only does the merciless growth of roots physically tear open the fractures, as in the old tree-lined sidewalks of so many towns, but the roots are chemically active. They do, after all, feed the tree. In conspiracy with minute fungi, the roots extract ingredients essential to the plant's growth—removing them from the minerals among which the roots have worked their way, and removal weakens the rock. It doesn't take mighty trees to accomplish this—humble lichens and algae effectively rot, slowly but surely, the rock on which they live.

All rocks, even the tough ones, like granite and its relatives, rot. The weakest links in the chain are the first to go, and in a granite these are the feldspar crystals and their fellow silicates. Quartz is made of sterner stuff, thanks to its internal structure. In a quartz crystal, the average composition is one silicon atom for every two oxygen atoms, but there is no such thing as an SiO_2 molecule: the silicon and oxygen conspire together to construct incredibly strong chains of pyramids, and the chains interlink—like DNA—in long helix-shaped spirals. This structure is almost impregnable—quartz is a survivor, hard, resistant, and extremely difficult to dissolve. In granite, each crystal of quartz is surrounded by weaker neighbors; other minerals, originally formed under more extreme conditions, are more vulnerable and unstable at the Earth's surface: they corrode rapidly. Feldspars rot away to form clay (the granites of Dartmoor decay to provide the vast deposits of "china clay" historically vital to the ceramics industry). Support for the quartz grain vanishes and, like a loose tooth, it drops out of the rock. A sand grain has been born.

Rotted, corroded, fragmented, pulverized. *Comminuted.* The ultimate fate of the toughest rocks is to be broken into pieces, *clasts* (from the Greek *klastos,* "broken"). The feet of the towering cliffs of Yosemite are draped in the detritus of granite simply falling apart. "The mine which Time has slowly dug beneath familiar objects is sprung in an instant; and what was rock before, becomes but sand and dust" (Charles Dickens, *Martin Chuzzlewit*). The sand grain has become a symbol of impermanence and the fragility of our—and nature's—works.

The birth of a sand grain in this way signifies the death of a mountain. The rocky outcrop from which it fell is now infinitesimally smaller. But the effects accumulate. It has been estimated that on the order of a billion sand grains are born around the world *every second;* add up these seconds over the billions of years of the Earth's history and the scale of change that erosion can cause is clear. But we can also see it happening every day on our time scale. Dramatic changes can happen overnight, as when the Associated Press reported that "New Hampshire awoke Saturday to find its stern granite symbol of independence and stubbornness, the Old Man of the Mountain, had collapsed into indistinguishable rubble" (May 3, 2003). The average effects of these processes over the Earth's surface are difficult to measure, but typically the landscape of a mountain range will be lowered by a few millimeters, a tenth of an inch or so, every year, year in, year out. The processes of weathering and erosion are immensely complex and difficult to measure. The very term *weathering* is probably misleading, since the rate at which it happens does not correlate clearly with weather or climate. It is apparent that much of the corrosive chemistry happens *below* the surface, where rocks are saturated with water moving through fractures large and small, eating away between the mineral grains. But the effects are there for all to see.

Of course, weathering eats away at everything exposed to the elements, not just granite. Sand grains originally born from granite long ago may accumulate, be buried, and naturally glued together, *lithified* (from *lithos,* Greek for "stone" or "rock"), into a solid *clastic* sedimentary rock, a sandstone. When this, in its turn, is exposed at the surface, it is attacked by weathering and the sand grains are liberated again. The whole process is cyclic, over and over again, each time the grains carrying with them microscopic evidence of their parentage, their genetic origins. The majority of quartz sand grains are derived from the disintegration of older sandstones; perhaps half of all sand grains have been through *six* cycles in the mill, liberated, buried, exposed, and liberated again—as observed by Emerson in the opening of this chapter, reborn repeatedly.

THE IMPORTANCE OF SIZE

Our sand grain, newly born, finds itself, together with a motley collection of other detritus, organic and inorganic, as part of a soil, the *in situ* accumulation from the physical, chemical, and biological processes at work in a particular place. The sand grain is anonymous, waiting for rain and wind to sweep it away on an endless journey, to demonstrate its durability while its weaker companions fall by the wayside. But it is called *sand* not because of what it is made of or its origins, but because of how big it is.

Sand is somewhat like beauty—we know it when we see it, or touch it, but it seems difficult to describe. However, if we are to understand it, to use it, to live with it, then we have to tackle this problem. A U.S. geologist, Chester K. Wentworth, took on the task in the early twentieth century. The first sentence of his publication on describing sand reads: "In no other science does the problem of terminology present so many difficulties as in geology."

What Wentworth set in place was the concept that the only thing that matters is particle size: composition is irrelevant. This has proved an enduring and important approach. The behaviors of anything made up of relatively hard bits and pieces of a particular size, regardless of what the bits and pieces are made of, are unique and, in the case of sand, quite odd. The sugar in your teaspoon, poised over your cup of coffee, is, technically, sand. In the coffee it may not last long, but if you poured it over the kitchen floor and began blowing over it, you could begin to make sugar dunes. The salt in your salt grinder starts off as coarse sand and, when you grind it, becomes fine sand. It may dissolve in the saucepan, as does the sugar in the coffee, but until it does, it's sand. Indeed, there is a desert with massive glistening-white windblown dunes made of something very much like salt: the dunes of the White Sands National Monument, in New Mexico, are made of crystals of the calcium salt gypsum, formed from the evaporation of desert lakes—but the sand grains dissolve when it rains. And along the shores of the lowest point in Africa, Djibouti's Lake Assal, the water is so saline that the sand is made of salt crystals.

So, size is what matters. But how to define size? Sand grains come in a variety of shapes, which can make measuring size quite tricky. Think of tomatoes. How would you measure the size of a tomato, compared to another tomato? Certainly, many are roughly spherical, but they are also commonly rather wrinkled, some with deep and contorted folds; some are more pear-shaped, and some are obviously oval, with some of these being essentially long and thin. What they taste like—what they are made of—doesn't matter in this instance; it's simply a question of describing their *size,* and how is this done among objects with such varied forms?

The idea of measuring size works well only for regular objects, the obvious examples being spheres and cubes. The diameter of a sphere or the length of the side of a cube defines each one. But for an irregular object, its size depends on *how* we measure it. In turn, how we choose to measure it depends on *why* we want this information. Why should we want to describe the size of sand grains? From a scientific point of view, we want to understand, for example, how dunes form and what determines the shape of a dune in a particular place at a particular time. How do dunes move? How do sand grains get picked up and hurled around in a sandstorm or in a flash flood in the mountains? How do water and air compare in their ability to move materials of different sizes? We are interested in why rivers form the meandering shapes they do, and how the sandbars of ancient rivers from hundreds of millions of years ago are preserved and what they can tell us about conditions on our planet back then: all good geological science. But measuring the size of sand grains can also be important on a day-to-day, more "practical" level. The size of the sand in concrete or tarmac makes a difference to its strength and other properties; when sand is used as a filter, the size, and the range of size, of the grains is fundamental. Much of our water supply comes from underground sands whose grain size determines how much we can extract and how much will be replenished. How effectively we can maintain harbors, dams, rivers, and coasts depends on our understanding of sand movement, and movement depends on size. Measuring the size of a sand grain is critical to a surprising number of aspects of our daily lives.

SCALES

Wentworth established the scale of sand grain sizes that, essentially, is still in use today. But to do so, he refined and documented an earlier scheme proposed by Johan August Udden in 1914. Udden emigrated as a child from Sweden to the United States with his family and as an adult was fascinated by natural history. Like many natural historians of that era, he dabbled in different things, but his name lives on in the Udden-Wentworth grain size scale. Udden was obsessed with sand. He collected sand, as well as dust and pebbles, from a wide variety of locations, and measured the size of the grains. The data were published in an exhaustively long list that reveals the eclectic nature of his collecting. Samples of "sand blown on a snowdrift, Baltimore, Maryland" were carefully measured. Dust "collected in a running railroad coach in North Dakota after a storm," "from the top cloth on a flagpole, August 19, 1895, Rock Island, Illinois," and "washed from the leaves" of hickory, linden, and oak trees were all documented.

Most of Udden's measurements were made using the simplest tools: a series of sieves. The sand is put through the coarsest and then successively smaller and smaller mesh sizes, each fraction being weighed. The minimum size of the hole that allows a grain to pass through is then compared with the hole size that stops it, and the grain's size defined as the average of the two. It's a tedious and backbreaking business if automation is not available.

The Udden-Wentworth scale defines the terminology and size categories for different grain sizes, from microscopic particles of mud to boulders (the latter being measured directly, not sieved). It clearly averages out sizes for grains that are more or less oval—the shape of the grain has to be considered separately. Wentworth recognized that using a linear scale, like that on a ruler, would be impractical, given the huge range of sizes involved, and that it would distort the signifi-

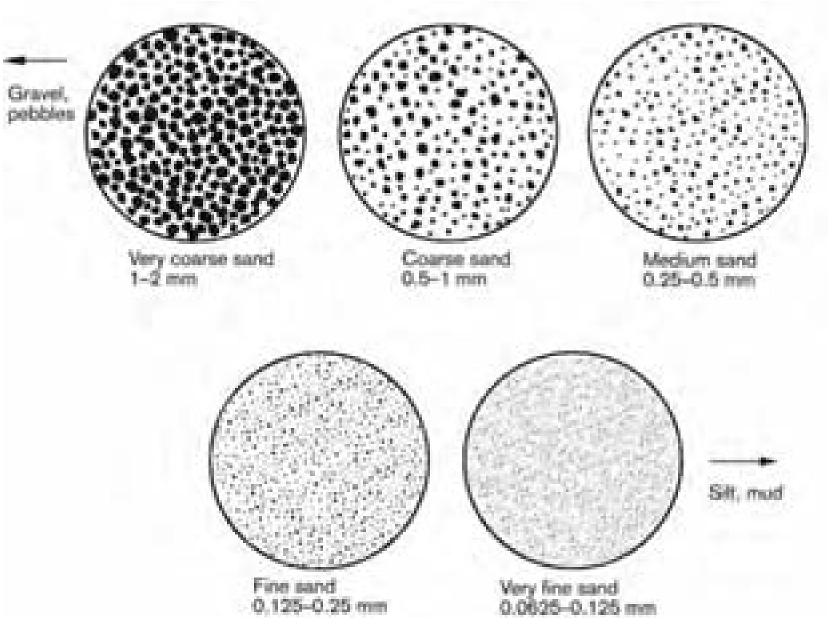

FIGURE 1. The classification of sand by size, after Chester K. Wentworth's original illustration, 1922. The scale shown here is accurate. The finest sand grains ("very fine") are .06 millimeters (1⁄400 in) in diameter, the largest ("very coarse") are 2 millimeters (1⁄12 in).

cance of size *increments:* an increase in size equivalent to the thickness of a human hair makes little difference to a pebble but could double the size of a sand grain. The sensible and practical way to address this would be to use a *geometrical* scale, one where each division boundary is a multiple of the previous one. As Wentworth wrote: "The use of a geometrical scale makes the successive grades fall into equal units on the graph—an arrangement much easier to read and interpret than any other known to the writer." This was, in fact, an early recognition of an important way in which nature works—on vast ranges of scales that are fundamentally geometrical, not linear, based on ratios rather than size for the sake of size.

The basic ratio in the sand size scale is two: each division is twice the previous and half the following as sizes increase. So, after all this, what does the scale of grain sizes look like?

[Figure 1 about here]

Figure 1 is redrawn from Wentworth's original publication and the scale is accurate: the grains appear as they would scattered on the sheet of paper. The smallest grain that can be called sand is essentially invisible to the naked eye as an individual grain; a magnifying glass becomes more and more necessary the further below "medium" one goes. The largest sand grain is 2 millimeters ($\frac{1}{12}$ in) across, but the majority of the world's population of sand grains measure around 1 millimeter ($\frac{1}{24}$ in).

A single layer of grains of very coarse sand covering an area the size of your fingernail would contain around thirty grains. A layer of very fine sand would contain twenty-five thousand grains—sand covers quite a spectrum of sizes. This range reflects the genetic inheritance of the grains—each is the size of the crystal that naturally constituted its parental rock. But the behavior of the sand family of grain sizes is very distinctive and different from that of its larger and smaller relatives, gravel and silt. Sand grains, when gathered *en masse,* form a very strange material, as we shall see in the next chapter.

FALLING SAND

There are other, more esoteric ways of describing grain size. The principle that the definition used depends on the purpose is illustrated by that particular group of scientists and engineers who are interested in how sand grains move, through air or water. Drop a spoonful of sand into a jug of water, and the grains will drift downward at a constant speed: the pull of gravity is balanced by the resistance put up by the water. If your sand contains grains of different sizes, the bigger, heavier ones (assuming they are all made of the same material) will settle faster since the resistance of the water affects them less. The result will be a layer of grains on the bottom of the jug that contains the coarsest ones at the base and the finest at the top. This effect can be seen in ancient sands now thoroughly solidified into rock. A sweeping current will flush along a range of grain sizes, and when it stops, the biggest grains settle first. The sand is graded; nature has carefully sorted out the sizes and dumped them in sequence on top of one another (Figure 2, left). This illustrates another of the important characters of families of individual sand grains: the *range* in size within that family. Pick up a handful of sand at the beach and look

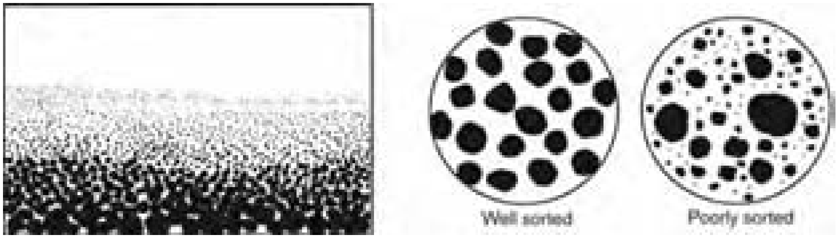

FIGURE 2. Graded sand (left); examples of well sorted and poorly sorted sand grains (right).

at it closely. Even to the naked eye, it's clear that while most grains may be roughly the same size, there are also smaller ones and bigger ones. Udden referred to the "law of the chief ingredient": in most sediments, the average size of grain is present in greater quantity than any other size. But the *range* of grain sizes is an important clue to the story of a sand family. By carefully sieving a sand through successively smaller sieve sizes, the proportion of grains of each size range can be measured. Families of grains that are all roughly the same size are called well sorted; those that comprise a wide range of sizes are poorly sorted (Figure 2, right). [Figure 2 about here]

If you were to drop your sand through the air, the grains would obviously fall faster than they did in water—the resistance of air is much less. But the ability of fluids, which, in our world, are generally air, water, or ice, to pick up and carry off sand grains of different sizes is key to fundamental geological processes. As will be discussed in later chapters, sand grains as individuals, families, and tribes love to move and to congregate—as sediment. The way in which they move is determined by the size of the grains, their shape, and the medium through which they are moving. It's therefore logical that those people interested in these processes of sand movement, on all scales, should define grain size in terms of how fast a grain falls through a fluid.

For some researchers, like Ralph Bagnold, their whole definition of sand is based on this. An extraordinary man, Bagnold had two remarkable careers, one in the military, the other in science: both brigadier and fellow of the Royal Society, he was a professional soldier and an "amateur" scientist driven by curiosity and armed with enthusiasm and a huge intellectual capacity for both practical and theoretical analysis. In his careful and quantitative approach to how sand moves, Bagnold made groundbreaking contributions from the 1930s to the 1980s. In the desert, he defined the lower limit of what could be called sand as grains that are too big to be picked up "by the average surface wind," suspended, and swept away as dust. In other words, the speed at which the grain falls is too slow for it to compete with the wind and settle on the ground; it stays in the air. The upper limit is anything that is too big to be even nudged along the ground by the wind or the impact of flying grains. The implication of this is that windblown sand in the desert should only be of a limited range of size, purely because of the physics of moving it around, and Bagnold showed, through his own and Udden's measurements, that this is indeed the case. Much of the sand in the deserts of the world is "very fine" (Figure 1). Bagnold recorded the minimum wind speed needed to start sand grains moving, a critical factor in explaining how deserts operate (more on this in chapter 6).

WATER

Obviously, water is a different matter from air—it's much more dense and viscous and is more effective than air at moving bigger grains (for example, boulders) around. But the principle remains the same. The movement of sand by water is an incredibly complicated process; Albert Einstein is reputed to have warned his son against becoming a river engineer because the physics of sediment transport is too complex. As with many natural processes, we can analyze some aspects and make complicated real and mathematical models of simplified situations, but we still do not understand it completely. Having tired of wind-blown sand (only because of the absence of accurate long-term wind data), Bagnold turned his attention to water and set the science firmly on its path. But it still has a long way to go. We will return to this thorny topic, but for now, a taste of the strange behavior of sand and why size is important:

Imagine that you have put on your scuba gear and have anchored yourself to the bed of a river. Beneath you is the riverbed, made of nothing but mud. The current of the river flows clearly over the bed, disturbing nothing. Suddenly, you feel the current speeding up—a storm upstream in the hills has poured volumes of water into the river and its flow has increased. But the mud remains undisturbed. Buffeted by the flow, you are suddenly surprised to see myriad grains of sand, a lot of them quite coarse, sliding, skipping, rolling, and jumping along the bed beneath you. You look more closely, and bouncing grains hit your face mask, but the mud remains undisturbed. Further upstream, the increased current has torn the side out of a sandbank on a bend in the river and is moving the debris downstream. But the mud remains undisturbed. Why? This seems to fly in the face of logic: larger material being mobilized while finer material stays where it is. You decide to retreat to the riverbank before the cobbles and boulders arrive.

Secure beside the surging river, you think this problem through. There are some simple rules in nature, but often there is a point at which simple rules stop working. It would seem obvious that if it takes a certain speed of current to move a particular size of sand grain, that current will also move anything and everything smaller. But your subaqueous observations conflict with this. The microscopic particles of mud and clay glue themselves together and resist being picked up by the current, which instead simply flows over them. Of course, if you had dug your hand into the mud and disturbed it, it would have been flushed away in an instant, but once mud has settled and consolidated itself, it's extremely difficult to budge—so difficult that doing so can take water flowing at the same speed that is required to shift a boulder a meter (3 ft) across. But in between, easily shifted at far slower speeds, is sand. Of the entire range of grain sizes in the Udden-Wentworth scale, sand grains are the most easily moved, which explains why there is so much of it in so many different places and why so many landscapes are constantly on the move.

The endless journeys that sand grains take age them. Sharp edges and angular corners are knocked off even durable quartz grains by the constant battering as grains collide with one another. However, once a grain has become smooth and round, it stays that way, with little further change, for enormous lengths of time. Wind is immensely more brutal than water in rounding off grains, the violence of the impacts being hundreds of times more effective than those cushioned by water. The world's deserts are the source of virtually all neatly rounded sand grains; it would take journeys down thousands of Mississippis to achieve the same effect.

Quartz grains may be the ultimate survivors of these journeys, but quartz is far from the only ingredient in the sands of the world. In fact, the dazzling variety of sands makes them collector's items.

ARENOPHILIA

Anything can be collected, and people collect anything. Stamps, beer cans, beetles, postcards, garden gnomes, chocolate bar wrappers—and sand. There are countless sand collectors around the world, and there have been for a long time. Today, they have websites (often with stunning photographs), chat rooms, and a market for the constant exchange of samples. Sand is, after all, a relatively simple thing to collect—it's free (excluding the cost of travel), found almost everywhere, compact and easily storable in small glass jars, and endlessly diverse.

Some sand collectors gather their samples for emotional reasons. It has become a tradition for survivors of Iwo Jima to revisit the island and take some of its sand home. Other collectors enjoy the unique character of sands from different places, the colors, shapes, and textures. An array of sand samples almost looks like a box of colored crayons, muted perhaps, more of a landscape painter's palette, but a dazzling range of hues. Even an apparently nondescript brown sand, if looked at closely, reveals its own glittering, granular character. A simple hand lens or, even better, a cheap microscope will open the door to worlds of extraordinary beauty and variety. Sand collectors call themselves *arenophiles,* or "sand lovers," from a mixture of Latin and Greek. The word *arena* derives from the ancient Roman habit of covering the ground in amphitheaters with sand (*harena* or *arena* in Latin)—to soak up blood. The pure Greek would be *psammophile,* and some sand collectors use this, but it is commonly used also to describe plants and creatures that are sand-loving, forging a livelihood among the grains.

An old friend of mine in California is a professional geologist and an arenophile; when he learned that I was working on this book, he sent me samples of his collection, set out in a pill-organizing container, a sand for each day of the week (Plate 1). These sands are samples from his travels in Florida, Sumatra, Algeria, Mexico, Tahiti, Bali, and the Galapagos. To this palette could be added sparkling green, deep red, true yellow, purple—a spectrum to gladden William Blake's eye. They are all sand, regardless of color, shape, composition, or origin, simply because the grains fall within the size range that defines sand.

The visually stunning spectrum of sand materials and colors is one of the factors that make sand collecting attractive. Displays of sands can seem like works of art, and works of art can exploit the character of sand—see, for example, some of the creations of Nikolaus Lang. Loes Modderman is a Dutch arenophile and an enthusiast for all things microscopic; her website contains images that are beautiful in their own right (Plate 2).

In the creation myth of the Shilluk people of Sudan, the diversity of the Earth's sands explains the diversity of its people: their creator, Juok, wandered the Earth, and as he did so, he shaped white people from white sand, red and brown people from the mud of the Nile, and the Shilluks from the black Earth around the White Nile.

INGREDIENTS

Quartz—otherwise known as silica, SiO_2—is the potato, the staple ingredient, of sand cuisine. Some sands are made of essentially 100 percent quartz——the top three in Plate 1, for example, which were taken from beaches and a desert. Other sands contain no quartz at all. We know that sand is simply a matter of size; therefore *anything* reasonably hard that presents itself as a sand-sized grain is entitled to form a sand. And a remarkable variety of things do.

A traveler expects to sample a local cuisine that has its origins in local ingredients, and it's no different with sand. Relaxing on a beach in North Carolina or the south coast of England, looking at the sand between your toes, you would hardly expect it to be made of bits and pieces thrown out of a volcano. Trekking along the coast of Greenland, you would be surprised if the sand were composed of the debris from a coral reef. What you *do* find are sand grains of predominantly local parentage. On the Normandy beaches where D-day landings took place, you will find sand-sized fragments of steel.

More often than not, each grain of sand is a member of a microcosmic family of local minerals, with local rocks providing the supply. Look closely at an everyday beach sand from the Isle of Wight, off the south coast of England (Plate 3, left): a nondescript brown sand becomes varied and sparkling under the microscope. Apart from clear grains of quartz, you see a variety of other, more colorful grains—different minerals, fragments of rock. On some beaches, the local ingredients can create dazzling collections of jewel-like grains—for example, the garnets from the coast of Provence in France in Plate 3 (right). These tiny grains are not the kind used to make jewelry, but they are certainly good for sandpaper.

Any kind of rock can provide the material for sand. Some of Hawaii's famous beaches are made up entirely of grains of, unsurprisingly, lava. Where the molten flows enter the sea, they are shattered by the thermal shock of hitting the seawater and then further pounded by the waves. The quenching of the molten lava often takes place so quickly that natural black glass is formed. The results are the famous black sand beaches, bizarre and stark places where jagged fragments of lava protrude from somber sands. Look at the sand grains closely, and the remains of the minute gas bubbles that were solidified into the lava can be seen. In places, the lava sand becomes so coated in iron oxide, rusted by the elements, that it takes on a deep red hue. But arenophiles beware: the volcanic goddess, Pele, is reputed to resent the removal of any of her landscape and is said to curse those who do so. Folklore or a taxi driver's tale this may be, but the U.S. mail has delivered envelopes of returned sand to Hawaii, together with apologetic notes.

Quartz may be the most durable of the Earth's common minerals, but many of its brethren are no wimps. A host of different individual minerals form individual sand grains. Many of them are quite valuable—the diamonds of the Skeleton Coast of Namibia, for example. Along other parts of Hawaii's shores, the apple-colored mineral olivine, another product of the volcanoes, survives well enough to construct startling beaches of green sand.

It has long been known that magnetic iron minerals can make up a sufficient proportion of a sand to affect a compass. In 1733, Petrus Van Muschenbroek, professor of "Mathematicks and Astronomy" at the University of Utrecht in Holland, wrote to the Royal Society in London of his experiments with "Magnetick-sand," describing samples from Virginia, Persia, and Italy in terms of how "attractive" they were.

One of Van Muschenbroek's forebears among Dutch scientists was Antony van Leeuwenhoek, an early and meticulous arenophile. Born in Delft in 1632, van Leeuwenhoek had endless curiosity but no wealth and no higher education. He did, however, have wide interests, learning the art of grinding glass and eventually making his own microscopes, more than five hundred of them. As we shall see in chapter 9, the technology of turning sand into glass underpinned the Renaissance.

The effect of the new high-quality glass, which allowed the examination of the very distant and the very small through telescopes and microscopes, was felt most dramatically in the sciences. Many of the great scientists of the Renaissance—René Descartes, Robert Hooke, Christiaan Huygens, Isaac Newton, and, of course, van Leeuwenhoek— were skilled glass grinders.

Van Leeuwenhoek's microscopes were far simpler devices than others already in existence, but his were capable of a significantly higher magnification. Through his lenses, he could examine clear, bright images, magnifying two hundred times whatever he put beneath them—which was anything and everything. His list of carefully documented discoveries is a long one; in his own words, "whenever I found out anything remarkable, I have thought it my duty to put down my discovery on paper, so that all ingenious people might be informed thereof." He was the first person to describe bacteria, extracted from between his own teeth. He documented algae and other microscopic creatures, bee stings, blood cells, living spermatozoa, minerals, fossils—and sand.

Van Leeuwenhoek was the first scientist to document the wide range of character displayed by individual sand grains. Perhaps originally interested in the sand he used to grind his lenses, he went on to obtain samples of different sands and subject them to his microscopic scrutiny. He wrote copiously over the years to the Royal Society of London, his letters translated into English or Latin and published in the society's *Philosophical Transactions.* In 1703, by then a fellow of the society, he published a letter "concerning the figures of sand." In this delightful illustrated piece (Figure 3), he begins: "I remember I have formerly affirmed of Sand, that you cannot find in any quantity whatsoever two Particles thereof, that are entirely like each other, and tho perhaps in their first Configuration they might be alike, yet at present they are exceedingly different." He described how sand grains might be abraded and rounded over time and how he had tested their durability with alchemical treatments of fire and acid. But he also had an overactive imagination, creating miniature scenes from the features within individual grains (Figure 3, right): "you might see not only, as it were, a ruined Temple, but in the corner of it GHI appear two images of humane shape, kneeling and extending their arms to an Altar that seems to stand at a little distance from them."

[Figure 3 about here]

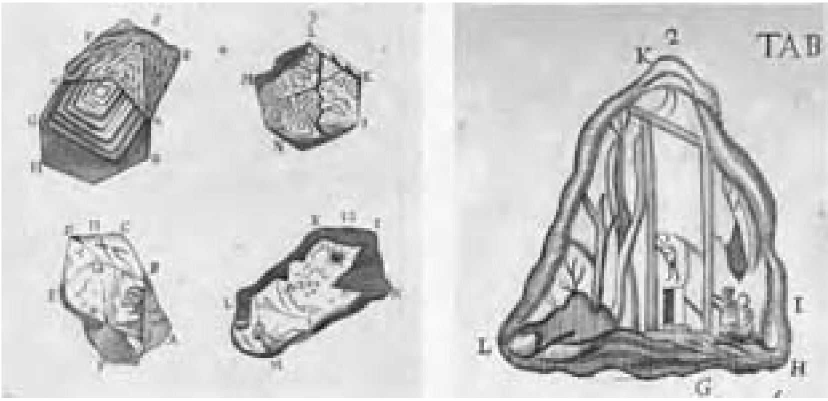

FIGURE 3. Drawings of sand grains from Antony van Leeuwenhoek, 1703. (Image © The Royal Society)

Among the myriad microscopic creatures first described by van Leeuwenhoek were members of the teeming population of the oceans—which themselves contribute spectacularly to the world's sands.

CREATURES GREAT AND SMALL

The living world contributes huge amounts of *biogenic* sand to coasts, beaches, barrier islands, and shoals. Particularly in regions rich in marine life at every scale, from coral reefs to minute floating organisms, much of the sand is the debris of this activity. Many of the world's prized tropical beaches, which are often far from major landmasses, are made up almost entirely of broken pieces of shell, coral, and the other hard parts of marine creatures. The inhabitants are the only source of the sand.

The cast of characters is huge, but among them are some extraordinary and beautiful creatures. The *foraminifera,* or, more colloquially, forams, are a widespread and remarkably diverse group of single-celled organisms. Over four thousand species are currently found all around the world, from the poles to the tropics and from the deep oceans to shallow lagoons; some are found in freshwater or salt lakes. The artistic diversity of the shells they build makes it difficult to believe that they are

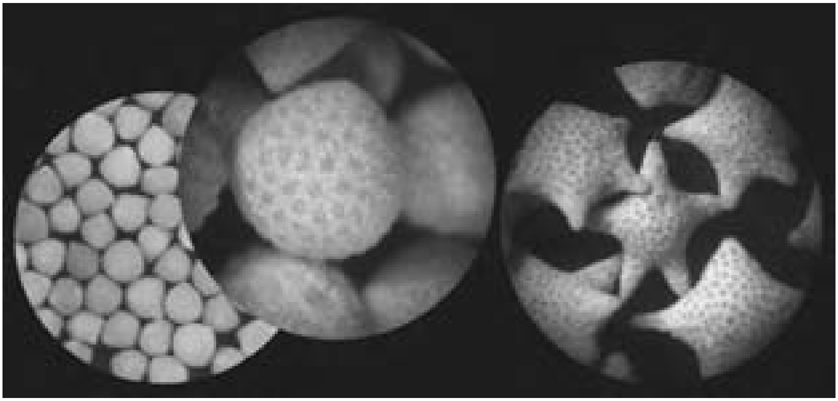

FIGURE 4. Sand grains made of foraminifera shells. (Photos by author)

all, in fact, related, as does their range in size, from fine grains to large coins. But however variable and diverse they may be, they are clever and well adapted—they have been around for at least 550 million years.

[Figure 4 about here]

Forams that inhabit the oceans are very particular about where they live. Some species float, some live on the seabed, and all are fussy about temperature. Their shells can be simple or complex, all of them of exquisite and delicate design (Figure 4). These shells survive after the foram dies; they sink to the seabed or are carried along by waves and currents as sand. Some beaches are made up almost entirely of foram shells. On the left in Figure 4 are foram shells from a beach in Bali (see also Plate 1) that, akin to ball bearings, make walking there in bare feet quite painful. One of the most exquisite and hauntingly beautiful forms of foram sands are the "star sands" of islands off the south coast of Japan, shown on the right in Figure 4. An old Japanese folktale describes how the Polar Star and the Southern Cross decided to bring life to Earth and were sent to one of the islands, where the sea was calm and warm, to give birth. Southern Cross duly produced thousands of children, but the Seven Dragon god of the sea was angry at not having been asked permission. He swallowed the babies and spat out the dead bodies, which floated ashore and formed the beaches of the island. A kindly local goddess gathered them up and put them in her incense burner so that they could join the smoke and be reunited with their mother in the sky. This is why there are so many stars around the Southern Cross and why local villagers still put sand in their incense burners.

In a strange twist, some forams actually *make* their shells out of sand grains, gluing them around themselves to provide protection. They are remarkably particular, selecting only certain kinds and sizes of grains.

Another strange group of grains—those producing gigantic banks and shoals in the tropics and elsewhere—are the ooliths (Plate 4). The two "o"s are pronounced separately, like "uh-oh" backward. The word means "egg stone," from the Greek, and that's what they look like, tiny white eggs. Wherever the water is warm, shallow, and charged with dissolved minerals, currents will gently roll small grains around. As they roll, minerals will precipitate on the surface of the grains, coating them and increasing their size until they are too big to roll anymore. The results are sand-sized grains (almost by definition, since they owe their origins to gently moving water), most commonly made of calcium carbonate, or limestone. The enormous Grand Bahama Banks have been built up over time by the accumulation of shoals and banks of ooliths and other carbonate material of biological origin. From the air, the banks seem to be swept by a delicate floating fabric of silk, festoons of ooliths.

On an island off the coast of Turkey, there is a stunning stretch of white sand known as Cleopatra's Beach. The story is that Mark Antony shipped barge loads of sand to the island to create this stretch of beach for his lover. There are no other beaches like this on the island, made, as it is, of exotic creamy white ooliths. Modern analysis has shown that the sand of Cleopatra's Beach is identical to that forming beaches west of Alexandria on the Egyptian coast; it probably took Mark Antony around sixteen Roman barges to deliver his exotic gift.

Before we move on from this brief sampling of the astonishing spectrum of materials that can make up sand, let us stop for a moment to consider the humble, but often gaudy, parrot fish. The parrot fish gains sustenance by chewing on coral reefs, ingesting the algae and small pieces of coral, and defecating the leftovers as pellets. Large fish can generate over a ton of sand-sized pellets every year. There are many beaches, for example on Hawaii, where you might be interested to know that you are walking through piles of, well, fish excrement.

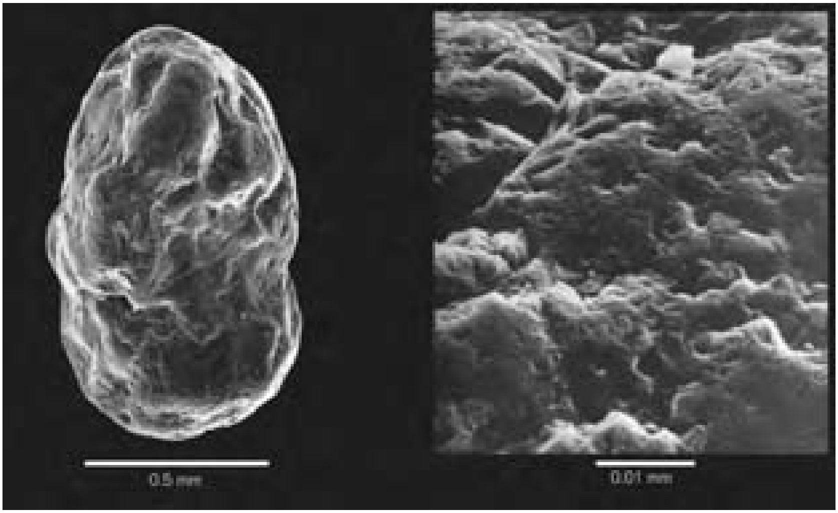

FIGURE 5. The face of a sand grain, 0.5 millimeters ($^1\!/_{50}$ in) across (left); part of the same grain, magnified 1,500 times its original size (right). (Photos courtesy of David Krinsley)

UP CLOSE AND PERSONAL: FACIAL EXPRESSIONS

Close examination reveals many of the details—and the beauty—of sand. This can be taken several steps further with the power of modern technology. Enormously powerful scanning electron microscopes allow the individual, personal features of each grain to be scrutinized, its facial features interrogated for what stories they can tell us about its history. This can, of course, rapidly become a very esoteric subject, but it is one to which many geologists devote their lives.

The face of a typical sand grain is weather-beaten. Pitted and wrinkled, its features show the ravages of time—lots of it. Most sand grains have been through the mill, the geological grinding and battering by wind, water, and ice over eons of time and endless itineraries. [Figure 5 about here]

The tiny sand grain on the left in Figure 5 has a distinct physiognomy. It has an oval, rounded profile, with no sharp edges or corners; it has been battered and scarred by countless collisions with its fellow travelers. Look at it even closer (on the right in the figure), and it begins to take on the appearance of an alien landscape, with valleys and ridges sculpted by violent forces; here, the magnification is equivalent to enlarging your thumbnail to the size of a tennis court.

The physiognomy of every sand grain tells a story of its origins and travels. As sand is carried along by rivers, waves, wind, ice, each process imprints a different record, a texture, on the surface of the grains. The ways in which a grain is battered and broken by impacts during a sandstorm are different from those caused by a flooding river. During each period of rest, whether in a dune, a riverbank, or in the soil of a garden, different processes operate on the grain and leave their record, sometimes overprinting, sometimes deleting previous textures. Grains can be naturally painted, coated with a thin mineral layer—the black sands of Hawaii turned rust red, for example. A grain may have spent a large part of its life entombed in a sandstone deep below the surface of the Earth, squeezed, heated, and gently, or not so gently, cooked. Chemically etched, perhaps partly dissolved, the hallmarks of this phase of its life often remain recorded on its surface even after its reliberation into the hectic world of rivers and waves. Sand grain detectives can reconstruct stories of each grain's life history.

Every sand grain in the world is unique, an individual. Looking closely at any one of them, diagnosing its condition, reconstructing its life story, and determining its origins is not only scientifically interesting, but also useful. Families and tribes of sand grains from the same place tend to show the same features, a kind of common genetic history. This enables another kind of detective work, the *forensics* of sand, tracking down places and environments of origin.

In late 1944, balloons 9 meters (30 ft) in diameter appeared in the skies above the United States. Landing from the West Coast to Michigan, they carried a deadly cargo: incendiary bombs. Although the only casualties over the following months were, tragically, members of a Sunday school group attempting to retrieve one that had landed, the potential danger to life, towns, and forests was considerable. It was apparent that the weapons had blown in from the Pacific, but where had they been launched? The devices had an automatic altitude-regulation system, releasing hydrogen or ballast to maintain height. The ballast bags were filled with sand. The U.S. Geological Survey's Military Geology Unit, established in 1942, was tasked with identifying the sand. The family of grains was consistent from one retrieved ballast sample to the next, and unique. Distinctive forams and other microscopic shells, together with small amounts of unusual mineral grains in among the granite debris, correlated precisely with beach sands described in prewar geological reports from two locations on the east coast of Japan. Air photographs identified hydrogen production plants at these locations, which were then targeted and destroyed.

The forensics of sand has proved widely useful in archaeology, establishing not only locations and environmental conditions of ancient sites, but also the origins of materials used in tools, carvings, pottery, and paintings. Sand forensics has also been successfully applied to modern criminal detective work.

THE SCENE OF THE CRIME

With the sophisticated microscopic diagnostics now possible, the character of soil and sand as evidence in a wide variety of criminal cases has taken on increasing significance. There are crimes that rarely make the headlines, such as cactus smuggling, that can be routinely solved by being able to point to the origin of sand clinging to the roots of the contraband. Investment scams where evidence for a new gold prospect is "salted" with grains of gold from elsewhere can be uncovered by a microscopic look at those grains.

A significant amount of the world's gold supplies comes from the sands of ancient and modern rivers. In 1997 a shipment of these grains of gold worth $3 million was made from mines in the interior of Ghana to the coast and then on to London for processing. After a dispute over the arrangements and cost, the shipment was moved on to Canada via Amsterdam. Canada was the first place where the crates were tagged and given new seals. When they were eventually opened, they contained ordinary sand and iron bars. Where on the shipment's circuitous route had the substitution taken place? The sand was examined by Richard Munroe, a Canadian forensic geologist and policeman. If the substitution had been made in London or Amsterdam, the sand would likely bear the imprint of its northern European origins—particularly the action of ice from the glaciers that had so recently sculpted the continent. But none of those signs were there. Instead, the grains bore the distinctive features of being subjected to a tropical climate, and their composition was typical of the geology of the interior of Ghana. While local security difficulties prohibited making an exact match of the sand grains, any Canadian involvement was ruled out and the insurance claim filed by the mining company was dropped. Sand is a popular material in crimes of "substitution"; in the lively commerce between North and South America, sand has been substituted for, among other goods, cigarettes going south and perfume going north. The genetic fingerprint of the sand involved has pinpointed the location of the crime and helped prove innocence and guilt.

Sand and soil found in the soles of shoes, on clothing, or on tires can place people or vehicles in a particular place—however much they may deny it. Geology has become a standard tool in the kit of government forensic laboratories the world over, but it has been around for some time. The fictional Sherlock Holmes claimed to be able to describe an itinerary from mud splashes on trousers. In real life, evidence from sand has been used for over a hundred years. In 1908, in Bavaria, a poacher was suspected of murdering a young woman. His wife had cleaned his shoes the day before the murder, but they now had three layers of sand and soil stuck on their soles. As part of the investigation, one Georg Popp, a local chemist, applied his geological expertise to these layers. He reasoned that the layer next to the sole of the shoe was the oldest; it was made of the same materials as those outside the suspect's house. The second layer contained red sand and other materials identical to those from where the body had been found. The last and most recent layer contained brick fragments, cement, and coal dust that matched samples from where the suspect's gun had been found. What this layer did not match was the soil from the fields where the suspect claimed to have been walking at the time of the murder. The prosecution case was complete.

On a dark, rainy night in September 2002, a black truck parked beside the Shenandoah River in Virginia. Another truck pulled up, and the window rolled down to reveal the barrel of a shotgun. The driver of the first truck was killed at point-blank range. The murderer left in a hurry, the wheels of his truck spinning in the sand and gravel. After a preliminary investigation, the police had a suspect but insufficient evidence to prove guilt. When the suspect was seen starting to wash his red pickup truck, the police swooped. The truck was spattered with fresh mud: time to bring in the forensic geologists. The mud contained some very distinctive sand grains, a variety of minerals that could only have come from a local quarry. While the quarry was not where the murder had taken place, water washed debris from the quarry into the river, which carried it downstream, mixing and diluting it with the other sand and mud in the river. At low water levels, these were dumped in sandbanks along the river's edge. Geological sleuthing demonstrated that each successive sandbar downstream from the quarry contained less and less quarry debris, and the only one that precisely matched the material from the suspect's pickup was the scene of the murder. The suspect pled guilty in the face of this incontrovertible evidence.

Forensic geology has played a part in a wide range of criminal cases worldwide, but perhaps the most high-profile, yet disappointing, example was the murder of the Italian prime minister Aldo Moro. In May 1978, the body of the kidnapped prime minister was found in a car in Rome. Sand from his clothes and shoes, and from the car, was shown to have come from a particular stretch of beach near the city, yet searches of the area provided no evidence. Other forensic work confirmed the association with this beach, yet the connection with the suspects could not be proved. Years later, the kidnappers declared that they had planted the beach sand as a decoy—whether this is true or not remains unclear.

The world's first database of sand grains has been assembled from soils in the United Kingdom, specifically for police forensics. This database contributed key evidence for one of the country's particularly appalling recent criminal cases, the murder of two young Cambridgeshire schoolgirls in 2002. Once again, distinctive soil under the murderer's car tied him to the location where the victims had been buried.

DEEP TIME FORENSICS

Rain had fallen on the sand, and the small person left clear footprints. Later, the wind rose and filled the prints with sand, covering and burying them. So they remained for 200,000 years until the covering layers were worn away and the prints were discovered by construction workers in South Africa. They are the oldest known footprints made by *Homo sapiens.* Originally thought to be much more recent, they were dated by analysis of individual sand grains through a remarkable technique known as *luminescence,* or *exposure dating.*

Cosmic rays constantly bombard the Earth, at a roughly constant rate. Individual atoms in material close to the Earth's surface are targets for this radiation, which, in the case of a silica sand grain, converts the nuclei of some silicon and oxygen atoms to new, unstable forms, or isotopes, by causing the ejection of electrons that are then trapped in the crystal structure. The longer the grain stays close to the Earth's surface, in soil, sand, or rock, the more isotopes and electrons it accumulates. Measuring the amount of these products in individual grains by stimulating them to release the electrons through luminescence tells us how long the grains have been exposed, or how long it's been since they were buried and shielded from cosmic radiation. There are several variations to this technique, but it has opened up the ability to discover the the age of materials for which no means of dating was available before. Essentially any sand grain can be dated this way. It takes microscopically detailed measurements of thousands of grains to come up with a date, but this method has revolutionized archaeology and our understanding of the history of the Earth's surface.

Prehistoric cave paintings are extraordinarily difficult to date, but occasionally, and with the help of luminescence dating, the archaeologist gets lucky. The Kimberley region of northwestern Australia is rich in art, often painted using ochre pigments that contain no datable materials. But wasps built nests over a couple of paintings in that region, using sand grains as part of the nest structure. The nests were preserved by minerals precipitated from water running through them, and the sand grains could be extracted and dated. The wasps were busy seventeen thousand years ago; the paintings themselves, therefore, must be older than that, making them potentially the oldest pictures of the human figure in the world.

Determining the age of ancient pottery, tools, and carvings is among the many revolutionary uses of this technique. Applied geologically, it tells us the ages of meteorite impacts, fault movements, cave systems—and the landscape itself. Because we can measure how long a sand grain has been exposed at the Earth's surface, we can understand rates of erosion and the durability of landforms. The Atacama Desert in Chile is one of the driest places on Earth and has been that way for a long time. What was not known, until luminescence dating techniques were developed, was quite *how* long the desert's aridity has lasted. Areas of the surface of the Atacama have been virtually unchanged for over twenty *million* years, far longer than previously thought. The desert has witnessed the building of the Andes.

Luminescence dating cannot take us back into the farthest reaches of "deep time," close to the Earth's beginnings, but sand grains do reveal clues from that far back. We know from the ages of meteorites left over from the birth of the solar system that the Earth was formed close to 4.6 billion years ago. For a long time, it was a fiery coagulating mass of molten material, constantly bombarded by incoming debris. This first eon in the planet's history is referred to evocatively as the Hadean, a hellish time. Any material that solidified early on was recycled; the oldest rocks we have found are from northwestern Canada and are "only" a little over four billion years old. But large areas of terrain almost that old are found in Greenland, Michigan, Swaziland, and Australia, and within these rocks are imprints of older events. Water was critical to the early Earth, helping form the atmosphere, rain, rivers, oceans—and life. It had long been assumed that water in any significant quantities, condensing from the steam erupted from volcanoes and arriving extraterrestrially via comets, had taken a long time to accumulate; it was thought a "hospitable" climate only developed after around 700 million years of turmoil. But some very special sand grains now tell a different story.

Western Australia has been the stage on which an immense drama of the Earth's history has been played and recorded. Not far, by Western Australian standards, from where the wasps built their nest and early humans painted self-portraits, lie the Jack Hills. The rocks of the Jack Hills have been around for three billion years and are too worn to form imposing topography. But in the hills are ridges of upturned slabs of red and orange rocks, stacked against one another like old tombstones along a churchyard wall. They are sandstone and conglomerate (a poorly sorted sediment with pebbles as well as sand) that bear the hallmarks of being deposited by rivers three billion years ago. The majority of the sand grains are quartz. However, other durable minerals are present as well, including zircon, the December birthstone, a silicate of the element zirconium. Zircon crystals are typically small (fine or very fine sand size) but ubiquitous in minute quantities in igneous rocks. They too are survivors, and because they contain atoms of radioactive elements such as uranium, they are excellent timekeepers as the uranium decays. The rocks of the Jack Hills contain zircons (which themselves contain minute diamonds) brought long distances from their place of birth by the rivers that deposited the sands and conglomerates.

The Jack Hills zircon grains, collected patiently by crushing and sorting kilograms of rock to extract a thimbleful, include ones that are 4.4 billion years old, the oldest bits and pieces on Earth. This is important enough, but when they began to tell stories of their parentage, things became really extraordinary. A typically international collaboration of Australian, North American, Chinese, and European geologists has probed the atomic character of the grains, first looking at the details of the oxygen atoms. The most abundant form of oxygen on the Earth is oxygen-16, so named because each atom contains eight protons and eight neutrons; however, this form has a very rare sibling, oxygen-18, with ten neutrons, an isotope that is also stable and behaves like oxygen. The proportions of the two forms of oxygen in a mineral vary depending on the conditions under which the mineral formed. Igneous rocks that originate deep within the Earth have a distinctive and uniform value of this ratio. Rocks that originate at cooler temperatures, interacting with surface waters of rain and the oceans, have a very different ratio. Even if these cool rocks are remelted, a common fate in the early Earth, they retain that distinctive characteristic. And the Jack Hills zircon grains showed exactly that ratio—they testified to an origin inescapably associated with water. This contradicted all conventional wisdom, which assumed that no significant quantities of water would have existed for another several hundred million years—that is to say, this evidence, gathered from a thimbleful of sand grains, turned our understanding of the early Earth on its head. And there is more. As the atomic scrutiny continued, results showed that granites were the parents of the zircons, and granites only form the crust of continents. The diamonds within the zircons must have formed deep within a solid continental crust. The very early Earth not only had plenty of water, but, rather than being a churning molten hell, it also had *continents.*

Continents created by the raven in his marriage quest? The stories that individual sand grains can tell are endless, and we shall hear more tales later. William Blake and Robert Service had a point.

THE SCALE AND IMAGERY OF VERY SMALL THINGS

Sand grains are small, and they have come to symbolize the microscopic, to register the size of very small things in our imagination. Van Leeuwenhoek not only examined sand with his microscope, but he used a sand grain as a standard measure of his other discoveries. He described foraminifera as "little cockles . . . no bigger than a coarse sand-grain" and estimated the number of bacteria (which he called *animalcules*) that would fit in a grain of sand—more than a million of them. We have continued to use a grain of sand as a marker to help us grasp the scale of the small and the extremely large. The molecules that today's nanotechnology manipulates are a million times smaller than a grain of sand; one could fit as many nanoparticles into a grain of sand as one could fit grains of sand into a 1 kilometer (3⁄5 mi) cube. The *absolute* number doesn't matter; it's the *relative* scale, the imagery, that works. Each image captured by the Hubble telescope is of an area of space equivalent to that covered by a grain of sand held at arm's length. If the Earth were a grain of fine sand, the Sun would be 11 centimeters (4.3 in) in diameter and 11.5 meters (38 ft) distant; the closest star to the Sun would be 3,000 kilometers (1,900 mi) away.

Playwrights, poets, songwriters, and philosophers have all exploited the potential of a single grain of sand to resonate in the human imagination. As we have seen, we are able to extract extraordinary information from a sand grain, but not as much as Gottfried Leibnitz thought possible: aspiring to greater horizons than Blake, he felt that the entire universe was there within a grain for our understanding. For Leibnitz, a philosophical alchemist as well as a mathematician, scale was fundamental, and comprehending how small things accumulate to create the vast and, by the same token, themselves contain the infinite, is an ultimate goal. He proposed that the noise made by a single grain of sand moving with the waves is one of a series of tiny perceptions that we accumulate to hear the roar of the ocean. This image of the sound made by a single grain of sand is echoed by Samuel Beckett in *Waiting for Godot,* where Estragon and Vladimir discuss "all the dead voices": "They make a noise like wings." "Like leaves." "Like sand." The imagery of sand was used extensively by Beckett—it forms the contents of Lucky's suitcase in *Waiting for Godot,* and Winnie is buried in sand in *Happy Days.* Interviewed in his late seventies, Beckett reflected: "With diminished concentration, loss of memory, obscured intelligence . . . the more chance there is for saying something closest to what one really is. Even though everything seems inexpressible, there remains the need to express. A child needs to make a sand castle even though it makes no sense. In old age, with only a few grains of sand one has the greatest possibility" (Lawrence Shainberg, *The Paris Review,* Fall 1987).

A grain of sand has a significance and effect far beyond its size: "It isn't the mountain ahead that wears you out—it's the grain of sand in your shoe" (attributed to Robert Service). In his journals, John Cheever wrote of a grain of sand in the heart as the origin of self-destruction; Eddy Arnold sang of the life-changing capability of "One Grain of Sand." A single sand grain can have an influence far out of proportion to its size, but when it gathers together with vast numbers of its colleagues, very strange things indeed can happen.