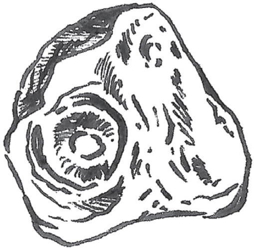

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vented by volcanoes, back to the mantle. In contrast, other planets, like Mars with its fossil river valleys, have simply lost their volatiles to space over time, with nothing held in reserve.

On Earth, water carried down with a subducting slab locally reduces the melting temperature of the adjacent mantle rock, yielding granitic magmas that build continental crust over time. Water also lowers the viscosity of the solid mantle as a whole, allowing it to flow convectively and thereby keep the plates in motion. Current estimates are that the volume of water in the mantle is greater than that in the world's oceans—a comforting planetary nest egg that eclogite has set aside for us.

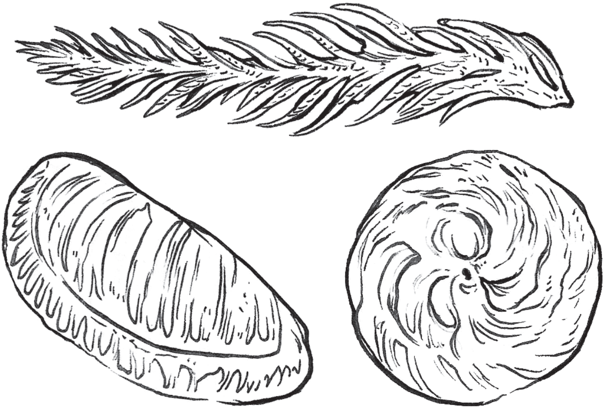
So let us sing the praises of eclogite. Although it generally stays out of the limelight, doing its work deep in the subsurface, very occasionally—by tectonic mechanisms not fully understood—some eclogite does find its way back to Earth's surface, where it can be rightfully admired and acknowledged for its indefatigable service to the planet.

See also Benioff-Wadati Zone; Granitization; Kimberlite.

Ediacara [ee-dee-ACK-ah-rah]

Peaceable kingdom

In the beginning, the earth was without forbs . . . or any other plants or animals. But soon after the primordial period of meteorite bombardment subsided around 3.8 billion years ago, microbial life emerged and gained a global foothold (even though feet were still far in the future). For at least 3 billion years after that, Earth's biosphere was a tranquil unicellular utopia.



Things might have continued like this indefinitely if the planet hadn't slipped into a long, deep ice age known as the Snowball Earth interval or, more formally, the Cryogenian period. Surviving this winter of winters would have required extraordinary toughness and versatility, and luckily some living beings were up to the task.

Remarkably, rocks that immediately overlie the last Snowball Earth glacial deposits preserve fossils not only of microbial communities but of macroscopic life-forms that were part of complex ecosystems. These mysterious organisms are known collectively as the ***Ediacara***, for the area in South Australia where they were first discovered in 1946. Ediacaran fossils have subsequently been found at forty other sites around the world, ranging from Norway to Namibia.

For a number of reasons, the Ediacara are paleontological enigmas. First, they seem to appear out of nowhere 635 million years ago, diverse and fully formed, with no clear antecedents. Although this can be attributed in part to the imperfection of the fossil record, the scant time between the end of the Cryogenian glaciation and the global appearance of this entirely new group of organisms is astonishing.

Their anatomical variety is also impressive. Some Ediacara, the so-called *rangeomorphs*, look like bloated ferns—frond-like and branching but inflated rather than flat. They towered over the seabed at more than three feet tall with holdfasts to anchor them in place. Other Ediacara were disc-shaped, including the radially grooved *Kimberella*, which appears to have been able to stretch to twice its size and shrink again, like an elastic Frisbee. The bizarre *Tribrachidium*, resembling a mini muffin-top, had a pattern on its crest with a threefold symmetry, seen in virtually no living group of organisms (but weirdly similar to the triskelion symbol on the flag of the Isle of Man).

And it's unclear what the Ediacara were made of. At several fossil sites, they occur as high-fidelity impressions in sand, which is not normally a good medium for preserving anatomical detail. This has led to the speculation that their exteriors were made of somewhat resistant yet still pliable material, perhaps an unknown biomolecule or finely crystalline, opaline silica.

The lifestyles of the Ediacara are equally mysterious. At the famous Ediacaran fossil site at Mistaken Point, Newfoundland, the organisms are preserved in life position, in a deep-sea turbidite deposit, indicating that they were living in darkness on the abyssal ocean floor, where photosynthesis would not have been possible. The fossils also lack any evidence of digestive systems—

and this, together with the large surface areas created by their ridged and branching forms, suggests that they somehow absorbed nutrients directly from seawater through a process called "osmotrophy." In other words, this was a world without predators, or even herbivores, a peaceable kingdom of strange, stretchy, puffy creatures that lived out their lives swaying placidly on the seafloor—the Garden of Ediacara.

But in later Ediacaran fossil strata, there are signs of unrest. Crawling tracks in the sediment indicate that organisms were on the prowl, some Kimberella specimens bear scratches that look like scars, and a growing proportion of the population has mineralized exoskeletons, suggesting that body armor was becoming a necessity. By early Cambrian time, 40 million years after they first appeared, the Ediacara vanished entirely—either driven to extinction by a new lineage of organisms with no qualms about eating fellow Earthlings or, perhaps in some cases, having themselves evolved into such organisms.

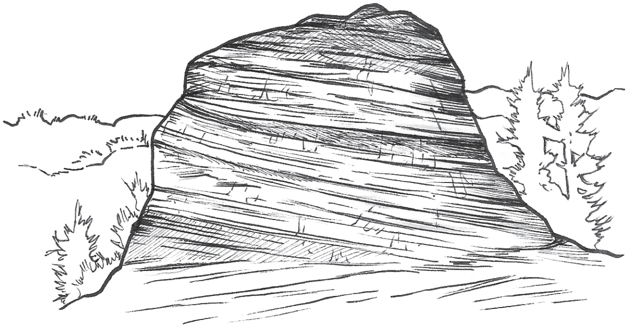
From that time onward, animal evolution has been an arms race between predators and prey. The first bite was the original sin.

See also Bioturbation; Cryogenian; Taphonomy; Turbidite; Simplified Geologic Timescale (Appendix 1).

Erg

The sands of time

To physicists, an erg is a tiny unit of energy, whose name comes from the Greek *ergon*, work; it's about the amount of effort needed to move a paper clip one-hundredth of an inch. To geologists, an ***erg*** is a large sea of sand, from the Arabic word meaning a "region of shifting dunes."



Measuring tens of square miles, ergs must have an extensive upwind source of sand—for example, an arid floodplain or a beach—and a downwind barrier that keeps the collected sand confined. Like an actual sea whose surface is wrinkled by waves, ergs are rucked by dunes of various sizes that march slowly across the landscape at the dictate of the prevailing winds.

In an inversion of the geologic mantra of uniformitarianism, “the present is the key to the past,” ancient ergs preserved as sandstone can shed light on how modern dunes migrate over the landscape, something that is difficult to observe in three dimensions in real time. In the steep canyon walls of Zion National Park, for example, where the lower Jurassic Navajo Sandstone is spectacularly exposed, one is able to see the internal structure of massive sand dunes formed 180 million years ago. The sweeping “cross beds”—strata inclined to the horizontal, so characteristic of the rocks in Zion—represent the downwind slip faces of ancient dunes that were continuously on the move, climbing up the backs of other dunes as they themselves were overridden. The sandstones at Zion are in effect an immense Jurassic weather almanac from which it is possible to reconstruct wind patterns and rainfall cycles at the time of the first dinosaurs.

It's dizzying to contemplate the immense energy embodied by such an erg complex: the weathering and erosion to grind rocks into so much sand, the wind power to gather it in one place and then propel the great dunes across the desert. The ergs of physics simply aren't the measure of their giant geological counterparts.

See also Dreikanter; Katabatic Winds; Uniformitarianism; Yardang.

Firn [fern]

Snows of yesteryear

A Swiss German word meaning "from last year," ***firn*** is sugary snow that has survived for several seasons and is on its way to becoming glacial ice. As it is buried beneath the snows of successive winters, firn gradually compacts, and open spaces between the grains of icy snow slowly close. Once firn reaches depths of 200 feet or so, the old snow is fully recrystallized, and any remaining air that was intermingled with the snowflakes when they fell becomes trapped as bubbles in solid ice.

These tiny bubbles—natural vials of ancient air—provide a continuous archive of atmospheric composition for the past few hundreds of thousands of years. Air bubbles in ice cores from northern Greenland, where yearly snowfall is abundant, represent a very high-fidelity record of atmospheric gases going back to the previous interglacial period 120,000 years ago. Cores from Dome C station in Antarctica, where the snow accumulates more slowly, document atmospheric changes at lower resolution but extend backward through seven glacial full cycles to 800,000 years. Though literally poles apart, the pockets of old air from the far north and far south tell the same sobering story: that global temperature variations closely track the concentration of greenhouse gases, especially carbon dioxide and methane, and concentrations of those gases are higher today than at any time the ice remembers.

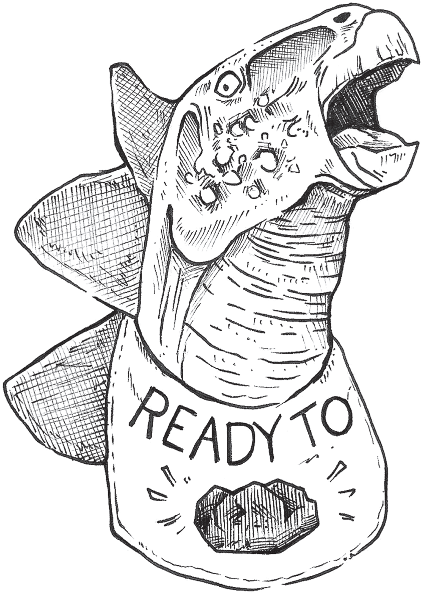
The snowflakes of yesteryear are now crystal balls foretelling our future.

See also Sverdrup; Varves.

Gastrolith

From the gizzards of lizards

A geologic neologism from the Greek words for "stomach" and "stone," a ***gastrolith*** is a fossil gizzard stone from a sauropod dinosaur or swimming reptile like a plesiosaur. Like modern poultry and some other plant-eating animals that lack grinding teeth, these voracious Mesozoic herbivores were actually also rock-eaters (petrovores?) who ingested stones to help grind up tough vegetation in their gut. But in contrast to chickens and turkeys, who swallow sand-sized particles, these dinosaurs and their marine cousins gobbled up cobbles as large as four inches in diameter. Leafy flowering plants (angiosperms), which today dominate the forests and grasslands, had not yet evolved in Jurassic time, and even the absurdly gigantic titanosaurs had to sustain themselves on the spiky, waxy needles and other prickly parts of conifers. Who could blame them for occasionally chowing down on chert or bolting some basalt?



Gastroliths can be easily identified as such if they occur together with dinosaur bones, but even if their former hosts didn't make it into the fossil record, gastroliths can be recognized on the basis of several criteria. First, they must be out of place geologically—for example, an anomalous pebble, or a cluster of them, embedded in an otherwise fine-grained rock like shale or limestone. Second, gastroliths tend to be remarkably smooth and polished, as if processed in a rock tumbler—which in a sense they were, though for the squeamish it may be best not to contemplate this image in too much detail.

See also Geophagy; Taphonomy.

Geodynamo [gee-oh-DIE-na-moh]

Electromagnetic blanket

Invisible but essential, the Earth's magnetic field is perhaps the least celebrated of the many environmental amenities provided by this hospitable planet. It is also one of the strangest. It has existed for more than 3.5 billion years but fluctuates daily. It emanates from Earth's deep interior but extends far out into space. It is intangible and mostly unseen—except when it lights up in ostentatious greens and reds during the auroras—but crucial to life. The magnetic field is our protective shield; it deflects not only the relentless solar wind, which could otherwise strip away Earth's atmosphere over time, but also cosmic rays, which zing in from interstellar space with enough energy to damage living cells.

Although sailors have navigated by the magnetic field for a millennium, and scientists have monitored it since the 1830s, much about it remains an enigma. Einstein himself said that understanding its origin and longevity was one of the great unsolved problems in physics. Although aspects of the magnetic field remain mysterious, the scientific consensus today is that it arises in Earth's outer core, where the movement of liquid iron creates a giant, self-perpetuating electromagnet, the ***geodynamo***.

The fact that the geometry of the field is approximately dipolar—like a bar magnet—and that the magnetic poles coincide, on average, with the geographic North and South Poles, indicates that Earth's rotation largely governs the motion of molten iron in the core. Until the mid-1930s, it was believed that Earth's core

was entirely molten. This was based on the observation that following a major earthquake, seismic S- (shear) waves, which cannot travel through liquids, are not detected on the opposite side of the globe. The paths of P- (pressure) waves, which are slowed but not stopped by liquids, are also altered in a manner that suggested the core, with a radius of about 2,100 miles, was molten top to bottom.

But in 1936, the Danish geophysicist Inge Lehman—one of the few women in a field that is still overwhelmingly male—analyzed seismic records from a great earthquake in New Zealand and noticed a few distinct P-wave arrivals that were not consistent with the all-molten core hypothesis. She correctly interpreted these seismic signals as waves that had ricocheted against a crystalline mass deep in the earth—a solid inner core 750 miles in radius. Modern geophysicists now recognize that a significant component of the dipolar magnetic field is generated by differential rotation between the fast-spinning inner core and comparatively sluggish outer core.

However, Earth's pirouetting on its rotation axis can't explain the full complexity of Earth's magnetic field, which in addition to the dipole also has "quadrupole" and "octopole" components, making its actual geometry something like a playground jack with extra spikes. These components are thought to reflect more complex choreographic movements caused by thermal convection in the outer core.

For reasons still not well understood, the superimposed spinning and roiling motions of liquid iron in the outer core intermittently cause the polarity of the magnetic field to flip—with magnetic north and south poles changing places over the course of a few millennia, during which the overall field strength is significantly lower. Seafloor basalts provide a high-fidelity chronicle of these reversals for the past 170 million years (at which point the record is lost to subduction).

Reassuringly, there is no clear paleontological evidence that magnetic reversals are linked with mass extinctions (though one wonders how migrating animals manage during the thousands of years it takes for a new magnetic regime to become established). The most recent flip, known as the Matuyama-Brunhes reversal, occurred about 770,000 years ago, deep in the Ice Age. Our Pleistocene ancestors likely never noticed, but we Anthropocene humans surely would: such an event would cause debilitating disruptions to the electrical grid and satellite communications.

So is the behavior of the magnetic field yet another planetary matter that should keep us awake at night? Since 1990, the Magnetic North Pole has migrated almost 900 miles, from Axel Heiberg Island in the high Canadian Arctic to a site close to the true Geographic North Pole, and the intensity of the field has been falling at a rate of about 6 percent per century. It's frankly hard to know whether this is cause for alarm. In my view, we're better off worrying about the much greater likelihood of catastrophic climate change—which we can do something about—than about the elusive, magnificent magnetic field, which is completely beyond our control, but to which we should raise a nightly prayer of thanks.

See also Areology; Chondrite; Mohorovičić; Simplified Geologic Timescale (Appendix 1).

Geophagy [gee-OFF-ah-gee]

Raw terroir

In some cultures around the world, humans eat soil or pulverized rock, especially clay and chalk, in a practice called ***geophagy***. Although this is sometimes associated with times of famine, anthropologists disagree about the reason for the habit. The nutritive "minerals" (actually elements) that we require—for example, calcium, sodium, iron, and zinc—generally come to us via plants, but plants in turn assimilate them from the soil. Sommeliers claim to be able to taste the distinctive mineral composition of soils in which wine grapes are grown. Geophagy is a more efficient (if less epicurean) way of sampling the goût de terroir.

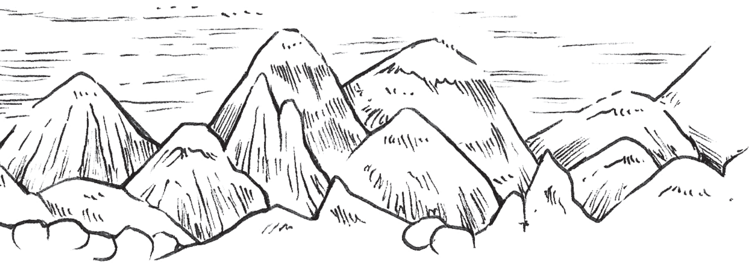
See also Gastrolith; Pedogenesis.

Geosyncline [gee-oh-SIN-kline]

*Magic mountains**

Mountains have long posed physical challenges to humans; their rugged terrain and capricious weather can be perilous for the unprepared. Mountains have also presented steep intellectual challenges for generations of geologists who did not have the theoretical "equipment" to scale them. Before the plate-tectonics revolution in the early 1960s, there was no good scientific explanation for the formation of mountains—and yet, in the words of George Mallory, they were there. For more than a century, an elaborate academic fantasy, the theory of ***geosynclines***, was the reigning paradigm for mountain growth. Now an embarrassing footnote in the history of geology, geosynclinal theory is perhaps best explained as the tectonic analog of spontaneous generation: like mice materializing in a sack of grain, mountains would spring up miraculously given the right ingredients.

* Adapted from https://aeon.co/essays/when-geology-left-solid-ground-how-mountains-came-to-be.



As irrational as the theory may now seem, it was grounded in an accurate observation about North American geology: that as one follows rock strata eastward from midcontinent into the Appalachians, their thicknesses grow by an order of magnitude. In the Midwest, where the strata are flat-lying, they are thin; while in the mountains, where they are folded and contorted, they are at least ten times thicker. It was hard to imagine that this was mere coincidence.

In 1857 James Hall (1811–98), the state paleontologist of New York and founding president of the Geological Society of America, first articulated the idea that there could be a causal relationship between thick piles of sediment and the formation of mountain belts. Hall declined to explain in any detail why sedimentary basins would necessarily fold themselves, but he alluded to gravitational instabilities within a shivering mass of watery clay, silt, and sand. Hall's idea was adopted and expanded by James Dwight Dana of Yale (1813–95), a towering figure in 19th-century geology and author of the definitive encyclopedia on minerals, *Dana's System of Mineralogy*, a version of which is still in print today.

Dana coined the term "geosyncline" for a deep trough of sediment that (somehow) became the crumpled strata in mountain belts. The term "syncline" was already in use for U-shaped folds in rocks, and its antonym "anticline," for arch-shaped folds. Dana's neologism suggested down-warping on a grand scale that could encompass the smaller buckles and crinkles within a mountain belt. Such internal features were being described in increasing detail by practitioners of a new subdiscipline called "structural geology," which focused on modes of rock deformation. In the Appalachians, Alps, Scottish Highlands, and Canadian Rockies, hardy structural geologists who were mapping folds and faults began to converge on the same conclusion: that the rocks in all of these mountain belts had experienced significant amounts of horizontal contraction—squeezed to about 50 percent of their original lateral extent.

Horizontal telescoping of this magnitude was an uncomfortable fit with geosynclinal theory, which suggested that gravity was the primary driving force for mountain building. Perhaps to avoid painful cognitive dissonance (and denouncement by powerful figures like Dana), most field geologists of the time seem to have excused themselves from theorizing about causes, preferring simply to document what the rocks had to say.

A late 19th-century European school of structural geologists, however, proposed an explanation that seemed to reconcile the geosynclinal concept of gravitationally foundering basins with field-based evidence for horizontal shortening: that Earth's crust was shrinking as a result of cooling. In this view, mountain ranges were like the wrinkles on a raisin, and ocean basins were the downward involutions. The idea of a cooling, shriveling Earth was compelling in part because it brought geology into alignment with the cutting-edge science of the day: Lord Kelvin's thermodynamics.

For decades, Kelvin had been the bane of geologists, including Darwin, with his decrees that Earth was no older than 40 million years, based on arguments involving its present-day heat flow and intimidating calculations that few geologists could understand or refute. But by the 1890s, most geologists had resigned themselves to a foreshortened timescale and had internalized the idea that Earth was growing inexorably colder. (Kelvin did not know that Earth actually generates heat through radioactive decay—the same phenomenon that provides a means for dating rocks, and that eventually showed his pronouncements of Earth's age to be too young by a factor of 100.)

In 1922, the "Shrinking Earth hypothesis" acquired renewed credibility for another generation of geologists when the German geologist Hans Stille (1876–1966) published his opus, *Die Schrumpfung der Erde*, a grand synthesis of thermal contractionism with geosynclinal theory. In *Schrumpfung* and subsequent work, Stille introduced a scholarly taxonomy of geosynclines that seemed to elevate their study through Linnaean-like classification but in fact created chimeras that geologists would chase unproductively for decades. There were "orthogeosynclines," the proper ones, made of rocks that could be folded and that usually consisted of two subparts: a "eugeosyncline" with volcanic rocks and a "miogeosyncline" without them (today recognized as deep and shallow ocean sequences, respectively; eugeosynclines included *ophiolites* and *turbidites*).

As late as 1958, the lexicon of geosynclines was still expanding. Marshall Kay, an eminent stratigrapher from Columbia University, published the third edition of his masterwork, *North American Geosynclines*. Kay's coinages reflect a particularly impressive command of Greek: "taphrogeosynclines" were fault-bounded; "zeugogeosynclines" formed on formerly stable continental crust; and "paraliageosynclines" were shallow and coastal, marginal to the real thing.

Some contemporary geologists grumbled about the absurd proliferation of prefixes, and many had privately lost their faith in geosynclinist doctrine, but few, particularly in the United States, were ready to cry publicly that the esteemed professors had no clothes. And then, less than a decade after Kay's treatise was reissued, geosynclinal theory was abruptly dethroned. Plate tectonics at last provided the motive force for building mountains: as the seafloor spreads, continents move and occasionally collide, crumpling the rocks on their margins.

The seminal observation that sedimentary sequences in mountains tend to be thicker than in continental interiors was accurate, but this is simply because sediments accumulate on continental shelves, which are the leading edge when continents collide. As Peter Coney, an American structural geologist, commented wryly in 1970: "Saying geosynclines lead to orogeny [mountain building] is like saying fenders lead to automobile accidents."

It is easy in retrospect to lampoon ideas that now seem so clearly misguided, but the geologists who advanced geosynclinal theory were motivated by the Newtonian scientific instinct to find patterns in nature and from these extrapolate universal laws. They correctly identified an attribute common to many mountain belts, but then, too eager to reach the summit, mounted the intellectual equivalent of a Himalayan expedition without any of the proper scientific gear.

See also Allochthon; Klippe; Ophiolite; Turbidite.

Granitization

Igneous agnostics

Earth is the granite planet. Although its bulk composition is comparable to that of the other rocky planets (and chondrite meteorites), only Earth has distilled significant amounts of granite—the foundation for the continents—from its mantle. So the question of the origin of granite is fundamental to understanding how the planet works, and the story of how geologic thinking about granite has evolved is a fascinating glimpse of science at its best—and worst.

The concept of ***granitization***—the misbegotten idea that granites are not from melts but instead created through the transformation of sedimentary rocks by infiltrating elements—was embraced between about 1930 and 1960 by geologists who felt they were at the fore of an intellectual revolution, overthrowing the stodgy old magmatic paradigm. Like the theory of geosynclines, granitization began with some reasonable speculations about a fundamental geological question but then mutated into a mass hallucination that clouded geologic thinking for decades. Granitization theory is rarely mentioned in geologic textbooks today, perhaps because it doesn't follow the favored narrative of continuous progress in science, and many modern geologists aren't even aware of it.

To early geologists, long before the granitization delirium, the origin of granite was a puzzle. In the late 18th century, different rock types were thought to have formed during distinct periods in the geologic past. Granites, which often occur as the "basement" beneath stratified rock sequences, were called "primary" rocks and believed to record Earth's earliest eons. A school of thought known as "Neptunism"—led by the redoubtable German mining geologist Abraham Gottlieb Werner (1747–1817)—held that all rocks (other than those that clearly emanated from volcanoes) had formed by deposition in water. The Neptunists considered volcanism to be a minor, shallow phenomenon caused by burning coal seams, wholly unrelated to granites, which they interpreted as deposits from primordial oceans of alien composition.

At this same time, there were others, notably James Hutton (1726–97), the Scottish polymath credited with discovering Deep Time (see *Unconformity*), who recognized evidence that granitic rocks were not marine sediments but instead solidified melts. Hutton was, of course, right, though he was not exactly a paragon for objective, dispassionate science on this matter. He had previously formulated a grand theory—a prescient glimmer of plate tectonics—about how the earth's crust was endlessly churned and reforged by an internal heat source, and he was looking for corroboration of his scheme. (This is another embarrassing little fact rarely shared with students of geology, who are trained to make observations first, *then* draw inferences.)

Hutton's ideas have come down to us mainly as transcribed by his friend John Playfair (1748–1819), in his 1802 volume *Illustrations of the Huttonian Theory of the Earth*, a heartfelt tribute published five years after Hutton's death. In one of the book's most vivid excerpts, Playfair describes an outing in the Cairngorm Mountains, where a giddy Hutton found confirmation of his heat engine hypothesis. In the bed of the River Tilt, he came across fingers of pink granite that had made inroads into dark metasedimentary rocks in a manner that could not be explained unless the granitic material had been molten at the time. This crosscutting relationship also showed that granites were not invariably primordial but rather in some cases younger than other rocks. Playfair describes the eureka moment:

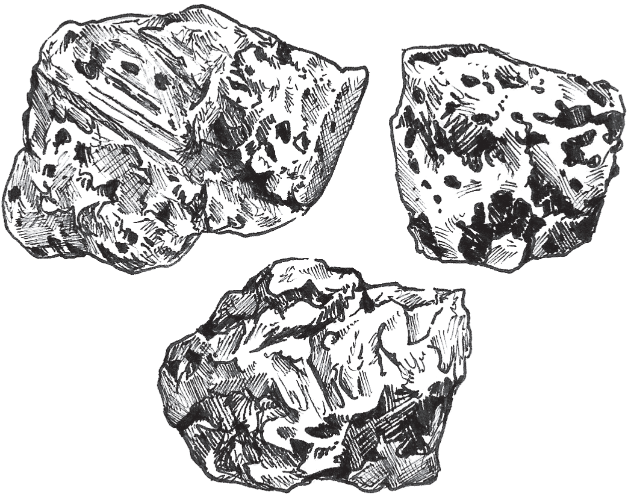
> In the bed of the river, many veins of red granite . . . were seen traversing the black micaceous schistus. . . . The sight of objects which verified at once so many important conclusions in [Hutton's] system, filled him with delight; and as his feelings, on such occasions, were always strongly expressed, the guides who accompanied him were convinced that it must be nothing less than the discovery of a vein of silver or gold, that could call forth such strong marks of joy and exultation.

We get a glimpse here of Hutton as a single-minded zealot, but the fact remains that he got very close to the truth in a way that many geological ideologues before and after him did not.

Over the course of the 19th century, geology matured from a pastime practiced by self-taught amateurs like Hutton into a profession with academic hierarchies and a growing range of analytical methods at hand. A special type of optical microscope, in which light was transmitted through thin slices of rock, allowed the mineral composition of granite and other igneous rocks to be determined in detail. Chemist Robert Bunsen, of the eponymous burner, demonstrated that the texture of granite —the nature of boundaries between crystals of different minerals—was consistent with cooling from a melt. By 1900, Hutton's intuitive concept of granite as a solidified magma seemed well established as empirical fact.

But then, beginning in the 1930s, there were rumblings of dissent. As laboratory methods improved, a burgeoning number of igneous rock types were identified, raising the question of how there could be so many distinct magma sources in Earth's interior: Was the mantle a "plum pudding" with pockets of different composition? Meanwhile, field geologists began to point out a geometric puzzle that became known as the "room problem": If large granite bodies like those in the Sierra Nevada had been intruded into other rocks, how had room been made for them—and what had become of the rocks they intruded? To some geologists, the obvious answer to both conundrums was that granites were not in fact magmatic but formed in situ by transformation of sedimentary rocks in a process they called "granitization."

This radical new view began with Helge Backlund, a Swedish professor from Uppsala, who had studied the odd *rapakivi* granites of the Baltic region. He argued



that the strangely rounded grains of the rapakivi granites, and what he perceived as layering within them, were consistent with their having formed from stratified sedimentary rocks that were later altered via chemical "metasomatism"—something akin to the atom-by-atom replacement by which buried tree trunks might become petrified wood. Soon geologists in Britain and the United States were arguing that they, too, had found outcrops where sedimentary rocks graded imperceptibly into granites. Like a religion splintering into sects, these "granitizers" or "transformists" then began to break into subgroups that held different views on the precise nature of metasomatism: Was it "dry," driven by heat and chemical gradients, or "wet," a consequence of deep crustal fluid flow? It's painful now to read the hairsplitting sniping in the academic literature among geologists who were all studying the mane of a unicorn.

Even before granitization began to gain followers, a geochemist at the Geophysical Laboratory of the Carnegie Institution in Washington, DC, Norman Bowen, had in fact largely solved the granite problem. Beginning in the 1910s, Bowen created batches of magma in the lab from rocks of different compositions, then let them cool and crystallize. He showed that different minerals crystallize at different temperatures, and that if early formed minerals are removed from the remaining magma (in nature, via gravitational settling), then the residual melt will evolve toward compositions far removed from the original.

More specifically, Bowen showed that this process of "fractional crystallization" could yield small amounts of granite from an original melt with the composition of Earth's mantle. (This is conceptually similar to the process of fractional distillation at oil refineries, in which various types of hydrocarbons are separated from crude oil through their different boiling points.) If the full spectrum of igneous rock types could be generated by such a process, there was no need to invoke a mottled mantle of heterogeneous composition.

Bowen's brilliant work was largely ignored by the granitization crowd, who tended to be field geologists with deep suspicions about laboratory research based in the methods of physics and chemistry (a lingering result of earlier skirmishes with outsiders like the physicist Lord Kelvin, who scornfully dismissed geologists' well-founded arguments that Earth was hundreds of millions to billions of years old). Also, Bowen's results did not address the "room problem," which loomed large in the minds of the granitizers (the resolution, by the way, is that the "host" rocks are domed up by, and, to a lesser degree, assimilated into, intruding granitic melts).

By the late 1950s, however, with no progress toward elucidating the shadowy phenomenon of metasomatism, granitization theory was in decline. It was quietly abandoned in the 1960s when the paradigm of plate tectonics at last provided a framework for where and why rocks melt. Since then, geologists have also attained a subtler view of how Bowen's results actually apply in nature: It's unlikely that granite could be extracted in a single step directly from the mantle. Instead, fractional melting of already "refined" rocks, rather than fractional crystallization of a "primitive" mantle magma, is the likely genesis of most granites. And to be fair, some granites are derived from sedimentary rocks—but through melting rather than the mysterious processes of transformation advocated by the granitizers.

The story of how geologists have come to understand granite does not follow a simple, triumphant arc. Hutton's remarkable intuition proved correct, even though he violated modern protocols for the scientific method. Geologists who understandably believed that the truth could only be found in the rocks at the outcrop ended up becoming hopelessly lost in a fiction of their own making. Bowen demonstrated the power of bringing experiment into the discipline but was not interested in the messy complexities of granite in its natural habitats.

The lesson for geologists-in-training is that it takes a combination of fieldwork, theory, experiment, and imagination, all tempered by intellectual honesty, to investigate Earth, this grand old planet of granite.

See also Chondrite; Geosyncline; Rapakivi; Unconformity.

Grus [groos]

Things fall apart

Although granite is considered a symbol of strength and durability, and can survive billions of years deep underground, it is ultimately no match for raindrops and microbes at Earth's surface. ***Grus***, from the Danish-Norwegian word for "gravel," is used in geology to describe thoroughly "rotten" granite—rock that has been so deeply weathered that it falls to pieces.

Grus is formed when water, often bearing organic acids, insinuates itself into granite along the boundaries of crystals and alters minerals through dissolution and hydration. Potassium feldspar, the mineral that gives granites their rosy pink blush, slowly changes to soft clays like kaolin. The black crystals of hornblende that pepper most granites turn into greenish flakes of chlorite. The interlocking mesh of crystals that formed as the granite solidified from a magma becomes weakened, the edges of grains no longer dovetailing. Rapakivi granites, with their unusual, rounded crystals, are particularly susceptible to this type of insidious disintegration.

Grus represents the natural first step in soil formation and can also be a valuable commercial commodity, sold for upscale driveways, landscaped paths, and some "clay" tennis courts. But grus is also a cautionary illustration of how quickly things that seem so solid—whether granites or the cultural bedrock of society—can crumble when components are compromised, connections are broken, and cohesion is lost.

See also Granitization; Pedogenesis; Rapakivi; Scree.

Haboob [huh-BOOB]

Dust in the wind

Like erg, ***haboob*** is an Arabic word for an impressive wind-related phenomenon—in this case, a looming wall of sand and dust propelled by a downdraft of dense air in a dry, sparsely vegetated region, often in advance of an approaching thunderstorm. Traveling at speeds up to 50 miles per hour, the leading edge of a haboob can be nearly a mile high—a menacing sight to witness, and a serious hazard for aircraft, drivers, and those with respiratory problems.

The term, which comes from the Arabic *habb*, "to blow," originated in the deserts of Sudan, where meteorological conditions conspire to produce dozens of haboob events each year. The adoption of the word into the geoscience lexicon can be traced to a 1972 paper in the *Bulletin of the American Meteorological Society*, which argued that the same processes that generate haboobs in Sudan also occur in Arizona.

Since the 1970s, the term has been applied to similar dust storms in a growing number of places around the globe—regions that never needed such a word, until unsustainable land-use practices and climate change accelerated desertification and began attracting haboobs to new territory.

See also Erg; Katabatic Wind; Yardang.

Hoodoo

Hats off

Like something from the sketchbook of Dr. Seuss, ***hoodoos*** are spindly, whimsical, gravity-defying towers of weathered rock that often occur in groups. Also called "goblins" or "fairy chimneys," many of them suggest either humanoid forms or unseen sculptors. The term "hoodoo" is probably a reference to their odd, otherworldly appearance.

Hoodoos form in horizontally layered rocks with vertical fractures that become enlarged over time by running water or by ice through the process of frost-wedging. The top of a hoodoo is always a relatively resistant rock that protects the softer underlying rock, temporarily, from erosion.

Depending on the particular rock type and the primary agents of weathering, these "caprocks" can have forms resembling headwear of diverse sorts: pointy wizard hats (Cappadocia, Turkey), tall fezzes (Bryce Canyon National Park, Utah), overhanging turbans (Drumheller, Alberta), or jauntily tilted fedoras (Putangirua, New Zealand). Once these caps are doffed by gravity or erosion—as if to say "Howdy Do"—the rest of the hoodoo will quickly succumb as well.

See also Grus; Pedogenesis; Yardang.

Jökulhlaup [YUH-kull-loip, very approximately, with aspirated Ls]

Breaking the ice

Hyperbole has no place in Iceland, where natural forces are intrinsically extreme. ***Jökulhlaup*** is an Icelandic word meaning "glacier run" (*hlaup* shares a root with the English words "lope" and "lap"). But don't be misled by the typically Icelandic understatement; a jökulhlaup is in fact a violent, high-volume flood caused either by the abrupt failure of an ice-dammed lake or by the sudden melting of glacial ice from volcanic heat. In other parts of the world, neither of these scenarios is likely to keep many people awake at night. In Iceland, both happen frequently enough that the government publishes detailed jökulhlaup preparedness plans.

The most recent major jökulhlaup in Iceland occurred in November 1996, when the volcanic vent called Grímsvötn erupted beneath the country's largest glacier, Vatnajökull. No one was particularly surprised, since there are records starting from the 12th century that Grímsvötn has been doing this regularly. Still, it was inconvenient. The floodwaters, carrying 1,000-ton icebergs, raged for a week and tore out 20 miles of the Ring Road, Iceland's main highway. Several major bridges, together with 100 million tons of ash and sediment, were washed out into the North Atlantic. The indomitable Icelanders rebuilt everything within a year—knowing full well that the same thing will inevitably happen again.

The torrents unleashed by Grímsvötn, however, are trickles compared with a series of gargantuan jökulhlaups that occurred between about 18,000 and 13,000 years ago in the northwestern United States, forming an area known as the Channeled Scablands in eastern Washington State. The evidence for these floods was recognized in the 1920s by an iconoclastic geologist on the faculty at the University of Chicago, J. Harlen Bretz. Bretz could see from the ground level what would not be evident to others until aerial photographs became available: that the peculiar, rough landscape of the Channeled Scablands was essentially like the bed of a river of unimaginable size, with ripples spaced hundreds of yards apart, "gravel" the size of trucks, and potholes that could swallow entire farmsteads.

But at the time Bretz was mapping the Scablands, the orthodoxy in geology was a strict form of uniformitarianism that refused to accept any catastrophic explanations for geologic phenomena. The aversion to giant floods in particular ran deep in geologists' veins, owing to ongoing battles with biblical literalists who attributed modern landscape features—including the Grand Canyon—to Noah's flood. Bretz's hypothesis about a massive ancient torrent, orders of magnitude larger than anything in recorded history, seemed likely to open the floodgates (so to speak) to a new generation of creationists eager to demolish the whole edifice of geology. (The Scopes Monkey Trial, in which a Tennessee science teacher was charged with the "crime" of teaching evolution, happened during the years that Bretz was trying to make his case for the Scablands megaflood.)

A more serious scientific weakness in Bretz's hypothesis was that he could not point to a source for the biblical volumes of water that allegedly scoured the

Scablands. Bretz was publicly renounced by fellow geologists (and they were all fellows at that time) when he dared present his "Spokane Flood" idea at professional meetings. One of the few contemporary geologists who dared to ally himself with Bretz was J. T. Pardee of the US Geological Survey. Early in his career, Pardee had documented the extent of a vast ice-age lake in Montana, Glacial Lake Missoula, and realized that this could have held enough water to account for the outsized flood features of the Scablands.

Over the following decades, using field observations, air photos, and fluid dynamic calculations, Bretz and Pardee pieced together the story of the Scablands floods. A lobe of the ice sheet that covered Western Canada formed an ice dam that blocked the Clark Fork River in what is now Missoula, Montana. Over time, a volume of water equivalent to that in Lake Michigan became impounded behind the ice until finally the pressure was too great—and in less than a week, the entire lake drained, in a flood that would surely have impressed Noah.

The geological community gradually, grudgingly admitted that Bretz and Pardee were right—and, in fact, subsequent workers have shown that there were as many as 30 megafloods over 5,000 years as the ice repeatedly advanced, dammed the river, and then failed again catastrophically. At its annual meetings, the Geological Society of America (GSA) now holds symposia named for Pardee, intended to be "safe spaces" where scientists with ideas that challenge prevailing paradigms can speak without fear of censure. And Bretz, who lived to see his work venerated by a new generation of geoscientists,