

Erosion pillars, from circuits to the cosmos

Matthew Vonk

The visually fascinating, elongated shapes that result from anisotropic erosion are the products of varied and sometimes surprising physics.

Matthew Vonk is an associate professor of physics at the University of Wisconsin–River Falls.

As a physics professor, I encourage my students to see their everyday world through the lens of science and to look for the elegance of physics even in the mundane. And it's hard to find anything more mundane than a snowbank in February. Don't get me wrong: I like snow as much as the next Minnesotan, but it's the most fun when it's fresh, white, and soft. Come February all that remains are dirty piles heaped around parking lots like crusty exhaust-flavored snow cones. Yet, as panel a of the figure shows, under the right conditions, the Sun's directional radiation can sculpt the piles into wondrous little sundial gnomons capped by twigs, dirt balls, or trash. It is a fleeting phenomenon best seen in Minnesota toward the end of February when the sunshine is strong but the air is still cold.

I was especially thrilled when I sighted the impressive erosion pillar seen in panel b of the figure. Weeks before, a snack-cake box somehow made its way onto the snowbank. In the weeks that followed, the rest of the snowbank eroded under the Sun's increasingly powerful rays, but the snow behind the box remained to form a meter-long pillar. The angle of the arm, about 57° below vertical, mirrors the difference between the latitude of Minneapolis (45°) and the declination of the Sun (-12° on 16 February).

Finding a well-formed, latitude-indicating snow pillar may seem to be a happy accident involving snack cakes, but it is not alone. Pillars are a typical and expected result when anisotropic erosion encounters a heterogeneous substrate. Admittedly, most erosion is somewhat isotropic. Like battery acid eating away at a surface, it tends to smooth out roughness and yield a certain worn and softened look. Yet examples of highly directional erosion can be found at nearly all length scales.

Mud delivers a lesson about rain

During a recent hike, I found a cluster of tiny mud pillars on the side of the path. They were about 5 cm high and 1 cm across, each one protected by a pebble from the percussive impact of the rain (see panel c of the figure).

In general, erosion is a complex, nonlinear process that doesn't lend itself well to simple models. It is often dominated by the results of capricious events: a crack, a tree root, a tiny asymmetry. At times it exhibits positive feedback such that already eroded material is more likely than neighboring substances to erode; the Grand Canyon is an excellent example. At times erosion exhibits negative feedback whereby the least eroded material sticks out and is therefore most

prone to erode; that effect has led to riverbeds lined with rounded rocks.

But the simple observation that raindrop impact was responsible for the clay fingers seen in the figure suggests some calculations. A typical raindrop with a diameter d of 3 mm has a terminal velocity v of about 8 m/s. Given the density of water, 1000 kg/m^3 , we can readily obtain the mass m and the momentum of the drop just before it hits the ground: $mv = 1 \times 10^{-4} \text{ kg m/s}$. To estimate the average force of the raindrop as it collides with the ground, we can take the preimpact momentum and divide by the time of impact, roughly d/v . The resulting force is 0.3 N; dividing by the drop's cross-sectional area gives a pressure of 40 kPa—about 40% of atmospheric pressure and more than a full 2-liter soda bottle would exert standing on its cap.

Figuring out that a single raindrop can exert such a large pressure gave me new respect for rain and its destructive power. It's no wonder the clay that lacked pebble hardhats was so decimated, especially given that a storm delivering 2 cm of rain pummels each square meter of ground with more than a million drops.

To estimate how much rain was needed to form the pillars, I assumed that every raindrop removed a single layer of clay particles—which by definition have radii less than a micron or so, about $1/1500$ the radius of a raindrop. That means that each raindrop would splatter an area that includes roughly 1500×1500 particles; if the density of clay is comparable to that of water, then the layer of clay particles hit by a single raindrop would have a mass of about 0.01 mg.

Curious to check my answer, I found that raindrops from intense storms eject 1 mg of unprotected clay per raindrop (see the first or the last of the additional resources). That means 100 layers are detached by each raindrop; I was off by two orders of magnitude! The total thickness of all those layers is still just a fraction of a millimeter, but my error reiterates the surprising power of the lowly drop. The mud pillars were 5 cm high, so forming them required the removal of 50 kg of clay for every square meter scoured. At 1 mg per drop, that comes out to 50 million drops per meter, about 0.7 m of precipitation.

A variety of fragile forms

To see anisotropic erosion writ large, one might turn to the buttes, mesas, and spires of the American West. But, as panel d of the figure shows, perhaps the most exquisite examples of geological pillars are in Cappadocia, Turkey. Three million



Erosion pillars can be found in nature and in the laboratory, on microscopic and on cosmic scales. **(a)** Tiny pillars on a Minnesota snowbank. **(b)** A meter-long snow pillar, protected by a snack-cake box. **(c)** Mud pillars with pebble caps. **(d)** Fantastic rock pillars topped by solidified lava, in Cappadocia, Turkey. (Photograph by Wolfgang Beyer.) **(e)** Microscopic posts etched in silicon. (Adapted from C.-M. Hsu et al., *Appl. Phys. Lett.* **93**, 133109, 2008.) **(f)** The famous finger in the Carina Nebula. (Courtesy of NASA.)

years ago, volcanic eruptions there deposited tens of meters of ash, which later hardened into a soft rock, ironically called tuff, capped by several meters of basalt lava. In the years since, the basalt has mostly eroded away, but in the places where it hasn't, it has protected the soft tuff below it and enabled the creation of huge rock pillars called fairy chimneys. Certainly, the pillars do have a fairytale look to them, whimsical and quixotic despite being made of solid rock.

Directional erosion on microscopic scales can result from the masking and etching techniques used to fabricate integrated circuits. Although etching is usually used to make shallow horizontal circuits, some applications—including sensors, lasers, and solar cells—need high-aspect-ratio nanopillars with lots of surface area. The nanopillars shown in panel e, for example, were formed with a technique that involves a clever mix of isotropic and anisotropic etching. First, a single layer of silicon dioxide spheres is deposited on silicon; their size determines the eventual spacing of the columns. Then the spheres are uniformly shrunk through isotropic etching to a final size that determines the columns' diameter. To form the pillars, highly reactive ionized chlorine gas accelerated toward the positively charged sample removes all areas not protected by the SiO_2 caps.

On the largest scales, stunning erosion pillars exist in space, where directional erosive forces and nonuniformity abound. Famous examples include the Eagle Nebula's Pillars of Creation and the Carina Nebula's finger, seen in panel f of the figure. The pillars found in photo-irradiated nebulae

share many commonalities with those mentioned earlier, but their dynamic character makes them more complex and interesting—and less well understood—than solid pillars.

By their very nature, erosion pillars are ephemeral. They are made up of soft erodible stuff, and it's only a matter of time before they dissolve away. I'm sure that not long after I photographed it, the snack-box pillar was undermined by the warm convective winds of the Minnesota spring. Even sadder, results from NASA's *Spitzer Space Telescope* indicate that the Pillars of Creation were destroyed millennia ago; only their distance allows us to see them as they used to be. But don't mourn the loss of those fragile beauties. Rather, keep an eye out for other examples and try to figure out what they can tell you.

Additional resources

- P. P. Sharma, S. C. Gupta, W. J. Rawls, "Soil Detachment by Single Raindrops of Varying Kinetic Energy," *Soil Sci. Soc. Am. J.* **55**, 301 (1991).
- N. Hudson, *Soil Conservation*, 3rd ed., Iowa State U. Press, Ames (1995).
- N. Smith, R. H. Barbá, N. R. Walborn, "Carina's Defiant Finger: *HST* Observations of a Photoevaporating Globule in NGC 3372," *Mon. Not. R. Astron. Soc.* **351**, 1457 (2004).
- M. N. Wuddivira, R. J. Stone, E. I. Ekwue, "Clay, Organic Matter, and Wetting Effects on Splash Detachment and Aggregate Breakdown Under Intense Rainfall," *Soil Sci. Soc. Am. J.* **73**, 226 (2009).