AIP

PHYSICS
TODAY

Hidden fluid dynamics of dry salt lakes FREE

A new theory reveals how polygons that decorate the surface of dry lakes are linked to phenomena at play below the ground.

Cédric Beaume; Lucas Goehring; Jana Lasser

Physics Today **77** (4), 62–63 (2024);
https://doi.org/10.1063/pt.xgqy.ushr

QUICK STUDY

Cédric Beaume is an associate professor in applied mathematics at the University of Leeds in the UK. **Lucas Goehring** is a professor of physics at Nottingham Trent University in the UK. **Jana Lasser** is a Marie Curie fellow at Graz University of Technology in Austria.

Hidden fluid dynamics of dry salt lakes

Cédric Beaume, Lucas Goehring, and Jana Lasser

A new theory reveals how polygons that decorate the surface of dry lakes are linked to phenomena at play below the ground.

Dry salt lakes are an extraordinary part of desert landscapes. Their surfaces are often covered by strikingly regular polygonal shapes bounded by narrow ridges. Familiar to millions of tourists who have visited Death Valley, shown in figure 1, or Bolivia's Salar de Uyuni—Earth's largest known natural source of lithium—these otherworldly patterns inspired the *Star Wars* planet Crait, site of the climactic battle of *The Last Jedi*. Surprisingly, the mechanism by which the polygons form has remained elusive until this past year.

However, dry lakes are not always as dry as they first appear. Instead, water flows underground in porous soil. That groundwater collects in valleys, where it resides close to the surface. Even at Badwater Basin in Death Valley, which holds records for its hot and dry climate, if you dig a few tens of centimeters into the soil, you will find water, albeit unpalatably salty. At such places, the water evaporates, and any dissolved minerals are left behind to slowly accumulate. Rather than only producing a flat crust on the lake surface, the salt instead develops into a network of narrow ridges, defining polygons that are always just a few meters across. In this Quick Study, we explain why.

Wrinkling?

Ecologically, dry lakes are known as sources of mineral-rich dust. Although detrimental to air quality, visibility, and respiratory health, the dust is a source of nutrients for ocean ecosystems. The minerals concentrated in salt flats can also be harvested, as they are at Salar de Uyuni. Because historically most attention has been focused on the salt, researchers have tried to explain the surface patterns via mechanisms acting in the crust itself. That line of inquiry led to the idea that salt polygons are the result of a mechanical instability of the crust, akin to cracking or wrinkling (see the article by Michael Marder, Robert Deegan, and Eran Sharon, Physics Today February 2007, page 33).

Theories based on the mechanics of the crust are logical candidates for several reasons. Dry salt is hard and brittle. The ridges bordering the polygons are often broken up by cracks, as in figure 1. Some salts, like sodium sulfate, change state near room temperature, absorbing or releasing moisture while dramatically altering their size. Their swelling can generate enough stress to shatter rock. Finally, the polygonal shapes in salt crusts look somewhat like the crack patterns of columnar joints, such as those at the Giant's Causeway in Northern Ireland.

FIGURE 1. SALT POLYGONS at Middle Basin in California's Death Valley. (Courtesy of Sarah Marino.)

The first time any of us encountered salt polygons was in Namibia, along the Skeleton Coast. A salt seep had been built to extract salt from seawater via evaporation. Polygons were forming in a thin crust that surrounded the seep on all sides. When we were standing on the real thing, however, it was immediately clear that those polygons were not just a crack pattern.

As with other problems in elasticity, cracking and wrinkling are strongly influenced by geometry. In a flat layer such as a crust, the typical distance between features should be a few times the thickness of that layer. The scaling works well for cracks in dried mud, columnar joints, frozen soils, and crocodile snouts (see the article by one of us [Goehring] and Stephen W. Morris, Physics Today, November 2014, page 39).

That, however, is not what we saw. In Namibia, meter-wide polygons were forming where the salt crust was thin enough to crunch underfoot. At other dry lakes, polygons appear with a similar size, despite differences in crust thickness, soil type, and salt chemistry. For example, near the Dead Sea in the Middle East, we have seen polygons growing out of a salt mush, a soft slurry lying directly on top of soaking-wet mud. There was nothing solid enough there to break, but the same pattern was apparent with the same meter-wide polygons. The discrepancy between those observations and the predictions of a purely mechanical model was a fascinating puzzle.

Convection!

Curious for a better explanation of how salt polygons form, we sought answers in other areas of physics. Convection in a porous medium, such as wet soil, has many applications, including in sea-ice formation, metallurgy, carbon geosequestration, and the dynamics of Earth's core (see the article by Daniel Anderson, Peter Guba, and Andrew Wells, Physics Today, February 2022, page 34). In those diverse cases, fluid flow takes the form of convection cells that can resemble the salt-crust patterns along their boundaries. Inspired, we began to look at the fluid dynamics taking place below the crust, away from sight.

In a dry salt lake, water rises to balance evaporation from the desert surface. Salts remain behind, either trapped in the crust or dissolved in near-surface water. Within the soil, the lake then becomes stratified, with saltier, denser water sitting above the fresher, lighter groundwater seeping up from below. For the conditions measured in dry salt lakes, the density-stratified situation cannot be maintained and plumes of heavy, salt-rich water develop and sink downward. We speculated that those convective plumes could provide a template for the surface patterns.

We initially predicted the size of the convection cells expected beneath a dry lake using a simple physical argument. Groundwater evaporates from salt deserts at modest rates and with surprisingly little geographical variation worldwide—at approximately 0.1 mm/day (10^{-9} m/s). Salt is carried by water travelling upward at the same rate. But it also diffuses, which spreads out any salt-rich layer that develops near the surface. The diffusivity of salt in water is about 10^{-9} m^2/s. If convection strikes a balance between diffusion and fluid transport, the ratio of the two quantities gives the natural scale of the convection—about 1 m.

Digging deeper (metaphorically), we combined experiments, numerical simulations, and field studies. In the lab, we reproduced desertlike conditions in a vertical slice of wet sand. Watching from the side, we witnessed how our artificial dry lake became stratified and developed the anticipated salinity-driven convection cells. Numerical simulations then allowed us to explore convection in a wider range of environments, without having to repeatedly clean our lab of sand and salt.

The simulated pattern is illustrated in figure 2. The side faces show high-salinity plumes draining the salt that had accumulated at the surface, interspersed with areas of fresher fluid seeping upward. The size of the polygonal patterns that emerge becomes independent of most parameters after the simulation is run and confirms the simpler argument we made about evaporation rates and diffusion. In other words, detailed models of the fluid dynamics taking place inside the lake can explain why the same pattern appears with the same length scale in salt deserts around the globe—from the thin crusts on the Skeleton Coast to the massive crusts of Salar de Uyuni.

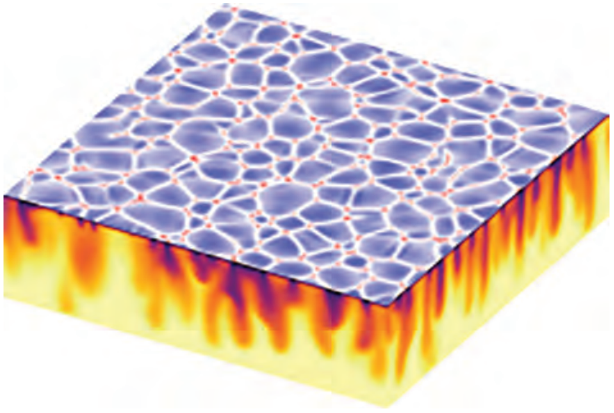

FIGURE 2. NUMERICAL SIMULATION OF CONVECTION in a dry salt lake. In this snapshot, groundwater salinity is shown on the sides (black: high salinity; yellow: low salinity) while the salinity flux into the surface is shown on the top face (red: positive salinity flux; blue: negative salinity flux).

Finally, a convective model can be relevant to salt polygons only if there is a direct link between the flow inside a real dry lake and its crust. So we spent weeks digging beneath the salty crust of Owens Lake, near Los Angeles, and subsequent months patiently separating the salt from thousands of soil samples. We found that the polygonal ridges consistently lay above soil with groundwater that was saltier than that collected from below the polygons' centers.

The observation compares well with our numerical simulations: Figure 2 shows that the high-salinity plumes are located under the lines of highest-salinity flux into the surface (red and white areas). Those regions, where more salt enters the simulated surface, correspond to the faster-growing salt crusts that form into the ridges found in nature. That correspondence represents the final link that connects the fluid dynamics of dry lakes to the formation of salt polygons.

The authors acknowledge long-standing and invaluable contributions from Marcel Ernst, Volker Karius, Joanna Nield, Matthew Threadgold, and Giles Wiggs.

Additional resources

▶J. Lasser et al., "Salt polygons and porous media convection," *Phys. Rev. X* **13**, 011025 (2023).

▶J. Lasser, J. M. Nield, L. Goehring, "Surface and subsurface characterisation of salt pans expressing polygonal patterns," *Earth Syst. Sci. Data* **12**, 2881 (2020).

▶J. Lasser, "Salt polygons and porous media convection," (2 April 2021), www.youtube.com/watch?v=vNJk6AdsOoI.