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The hidden fluid dynamics of dry salt lakes

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

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Dry salt lakes are a remarkable part of desert landscapes. Their surface is often covered by strikingly regular polygonal shapes, bounded by narrow ridges. Familiar to millions of tourists who have visited Death Valley in California (Figure 1) or Salar de Uyuni in Bolivia, these otherworldly patterns inspired the Star Wars planet Crait, site of the climactic battle of *The Last Jedi.* Surprisingly, the mechanism by which these polygons form has remained elusive until recently.

Appearing on Earth in arid regions, dry lakes are not always as dry as they first appear. Instead, a flow of water continues beneath the ground, in the porous soil. This groundwater collects in valleys, where it can come 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 (although unpalatably salty water) At these places, 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 polygonal ridges that always spans a few meters across.

FIG. 1. Salt Polygons at Middle Basin in Death Valley, CA. Courtesy of Sarah Marino.

CRACKING OR WRINKLING?

Ecologically, dry lakes are known as sources of mineral-rich dust. Although detrimental to air quality, visibility and respiratory health, this dust is also a source of key nutrients for ocean ecosystems. The minerals concentrated in salt flats can also be harvested, as at Salar de Uyuni, the largest known natural source of lithium. Since most attention has historically focused on the salt, researchers have tried to explain the surface patterns by mechanisms acting within the crust itself. This led to the idea that salt polygons are the result of a mechanical instability of the crust, akin to cracking or wrinkling.

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 changing in size. Their swelling can generate enough stress to shatter rock, a problem also of concern when these salts leach out of the walls of historical buildings. 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.

The first time any of us encountered salt polygons was in Namibia, along the Skeleton Coast. A salt seep had been built to concentrate seawater through evaporation in order to extract sea salt. Polygons were forming in a thin crust that surrounded the seep on all sides. Standing on the real thing, however, it was immediately clear to us that these 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 like a crust the typical distance between features should be a few times the thickness of that layer. This scaling works well for cracks in dried mud, columnar joints, frozen soils and crocodile snouts (see article by Goehring and Morris, Physics Today, November 2014, page 39). However, that 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 Israel, we have seen polygons growing out of a mush of salt, a soft slurry lying directly on top of soaking, wet mud. There was nothing solid enough there to break, but the same pattern was present, with the same meter-wide polygons. The discrepancy between these observations and the predictions of a purely mechanical model was a puzzle, but a fascinating one.

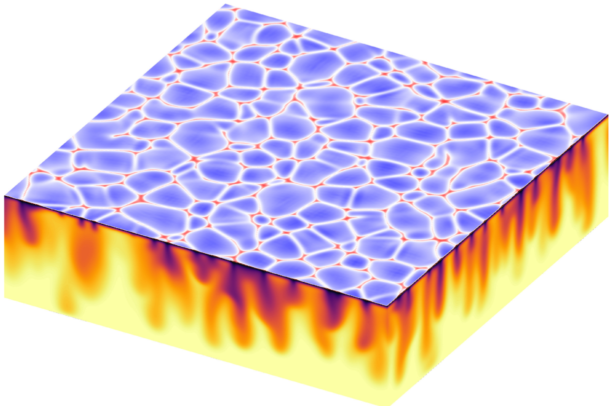

FIG. 2. Snapshot from a numerical simulation of convection in a dry salt lake. Groundwater salinity is shown on the sides (black: high salinity; yellow: low salinity) while the salinity flux into the surface is shown on the top face (red: positive salinity flux; blue: negative salinity flux).

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 applications including in sea-ice formation, metallurgy, carbon geosequestration and the dynamics of the Earth's core (see article by Anderson, Guba and Wells, Physics Today, February 2022, page 24). In these diverse cases, fluid flow takes the form of convection cells that, along their boundaries, can resemble the salt crust patterns. Inspired, we began to look at the fluid dynamics taking place below the crust, away from sight.

In a dry salt lake, water migrates upwards to balance evaporation from the desert surface. Salts remain behind, trapped not only in the crust but also dissolved in the 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, this density-stratified situation cannot be maintained and plumes of heavy, salt-rich water develop and sink downwards. We speculated that these 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 in salt deserts at modest rates and with surprisingly little geographical variation worldwide, at approximately 0.1 mm/day (10^{-9} m/s), as the crust limits evaporation. Salt is carried by the water, travelling upward at the same rate. However, 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. Assuming that convection strikes a balance between diffusion and fluid transport, the ratio of these two quantities gives the natural scale of the convection: about one meter.

Digging deeper, metaphorically, we combined experiments, numerical simulations and field studies. In the lab, we reproduced desert-like 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 from sand and salt. The simulated patterns are illustrated by Figure 2, where the side faces show high-salinity plumes draining the salt that has accumulated at the surface, interspersed with areas of fresher fluid seeping upwards. The size of the polygonal patterns that emerge becomes independent from most parameters after a while, confirming 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 we see the same pattern with the same length scale in salt deserts around the globe, from thin crusts on the Skeleton Coast to the much more massive crusts of Salar de Uyuni.

Finally, a convective model can only be relevant to salt polygons 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 out 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' centres. 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). These regions, where more salt is entering the simulated surface, correspond to the faster growing salt crust that forms into the ridges in the field. This analogy represents the final link that connects the fluid dynamics of dry lakes to the formation of salt polygons.

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Additional Resources

► J. Lasser, J. M. Nield, M. Ernst, V. Karius, G. F. S. Wiggs, M. Threadgold, C. Beaume, L. Goehring, "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**, 2881–2898 (2020).

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