Science Societies

The Galápagos Islands: the ultimate outdoor soil science laboratory

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Galapagos Islands Ultimate Outdoor Soil Laboratory

The Galápagos Archipelago is home to an astonishing amount of biodiversity, but scientists know much less about the soil below the flora and fauna's feet.

An international team of researchers studied soil formation using the unique properties of these volcanic islands, creating a timeline of pedogenesis in this "outdoor laboratory."

Their *Soil Science Society of America Journal* study spurred further research into the impacts of soil formation on modern-day problems like heavy metal contamination in agricultural soils.

The research team stares into the caldera of volcano Sierra Negra on Isabela Island. Photo by Sebastian Postl.

When you picture the Galápagos Islands, you likely think of rocky outcroppings surrounded by an ocean of surreal cerulean blue, brimming with monumental tortoises, Darwin's finches, and the odd flock of blue-footed boobies.

But that's not the whole picture. There are 30,000 human beings who call the islands home, too. These residents produce much of the food they need to survive—and feed many of the islands' **hundreds of thousands** of tourists each year—right there on the islands. Residents are allowed just 3% of the archipelago's land for human activity, including agriculture and urban areas. The Ecuadorian government protects the remaining 97% of the islands through the Galápagos National Park Service.

"Three percent seems like a small portion of land," Maria Rechberger says. "But what you don't realize is that this 3% is mostly in the humid zones, and those are the areas on the islands with the greatest biodiversity, the highest number of endemic species."

A Galápagos giant tortoise makes its way through an agricultural field on Santa Cruz Island while members of the project team confer near the greenhouse. Photo by Maria Rechberger.

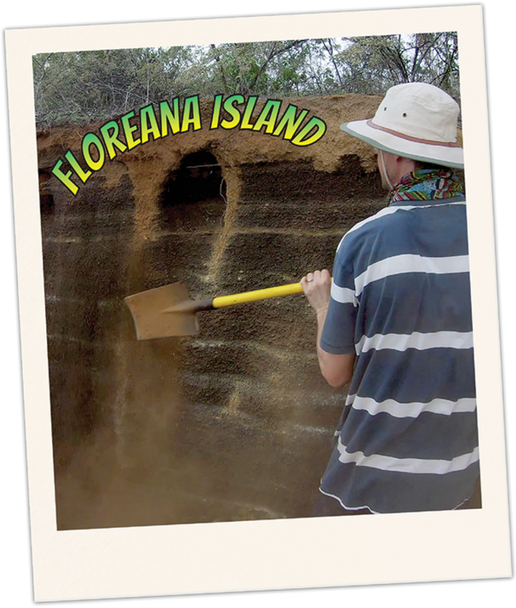
Rechberger, while completing her Ph.D. at the University of Natural Resources and Life Sciences, Vienna, was part of a multinational team of researchers tasked with studying the soils of the archipelago. Under the direction of her adviser, Franz Zehetner (an associate professor of soil science at the university), Rechberger helped discover that there are unusual levels of heavy metals—particularly cadmium—in Galápagos soils used for agriculture in these humid zones.

But the team only discovered the heavy metals while completing a totally different kind of study: one that you can only do with a chain of volcanic islands.

"The Galápagos are like an outdoor laboratory when it comes to understanding soil development," Zehetner says. And his team made fantastic use of it. They established a chronosequence, which is a glimpse into the stage-by-stage formation of soils from the same parent material over time. Their study in the *Soil Science Society of America Journal* (**https://doi.org/10.1002/saj2.20317**) is the first of its kind, documenting in detail the weathering and transformation of volcanic soils on the one-of-a-kind Galápagos Archipelago.

A Soil Scientist Abroad

The Galápagos Archipelago sits atop the **Nazca tectonic plate** in the Pacific Ocean, 1,000 km off the coast of Ecuador. This clump of islands is the product of repeated eruptions from a single volcanic hotspot below the plate. As the Nazca plate has moved eastward toward the South American coastline at the clip of 51 mm per year, the volcanic islands moved along with it. Just as bubbles blown by underwater swimmers pop up on the surface and outline their path, the hotspot below the moving plate created islands along its trajectory.



Franz Zehetner "cleaning" a soil profile wall in the dry lowlands of Floreana Island. Photo by Sebastian Postl.

Though the Galápagos' unique flora and fauna has attracted countless researchers from across the globe in the 186 years since Darwin's first voyage, the research community has paid little attention to the soil. In fact, the late Georges Stoops (a SSSA Fellow and author of **Guidelines for Analysis and Description of Soil and Regolith Thin Sections**) wrote in a 2014 review of Galápagos soil research that the first systematic investigation of any of the islands' soil was only conducted in 1962 by a

Belgian geopedological mission—even so, they only investigated soils from Santa Cruz island (**https://doi.org/10.2984/68.1.1**).

This “outdoor laboratory” was ripe for investigation when Franz Zehetner first visited the islands in the early 2000s. He’d been studying volcanic soils in Ecuador during his Ph.D. research at the University of Georgia, and he spent some time in the Galápagos on a break.

“I was fascinated already when I visited 20 years ago,” Zehetner says. When Ecuador’s Ministry of Higher Education, Science, Technology, and Innovation (SENESCYT) started the **Prometeo Project** in the early 2010s, Zehetner saw his chance. The project sought to elevate Ecuador’s research output by creating partnerships with experts worldwide. Zehetner applied for the program and was accepted in 2016, and his work in the Galápagos began in earnest.

Along with several researchers from Zehetner’s home university and other institutions, Zehetner spent many months on the islands. The team scouted for soil-sampling locations, dug soil pits, and examined agricultural sites. They worked with the Ecuadorian government, the National Parks Service that maintains and protects the uninhabited areas of the islands, and the **Charles Darwin Foundation**, which provided the research team with lodging and logistic support.

The team took samples on site and then schlepped them back to Austria for testing.

“Remember, you always thought the ice wasn’t going to stay frozen,” Rechberger said on our shared Zoom call.

“Oh, that was so stressful,” Zehetner laughed. Along with a cooler filled with ice for temperature-sensitive samples, Zehetner packed soil and rock samples among his own clothing and possessions to cut back on the weight of his suitcases. “It was crazy, going through security in Ecuador with seven suitcases coming from the Galápagos. We did so much paperwork to get those samples.”

The Chronosequence

Back in Austria, the crew set about testing their soil samples to establish a chronosequence. Without time machines, our best bet for understanding soil formation over thousands of years is to find locations where the same parent material has been exposed to similar weathering for different lengths of time. This approach is called “space-for-time” substitution.

The Galápagos represent one of a handful of locations where volcanic parent material was expelled from the same hotspot at different intervals in distinct geographic locations. Another is the Hawaiian Islands, which were also formed as shield volcanoes springing from a single hotspot under a moving tectonic plate.

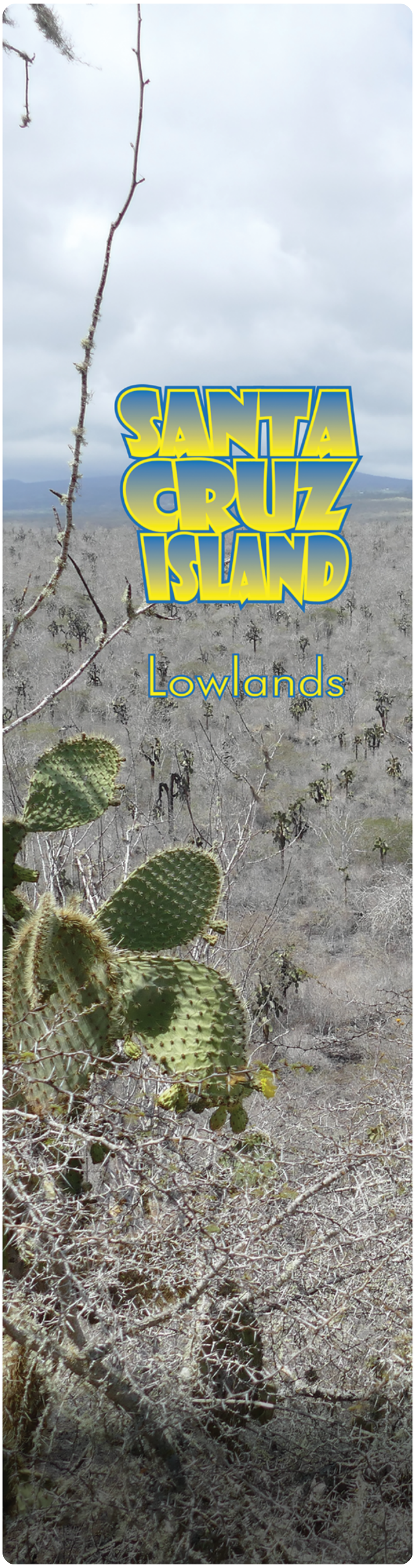
Before the team could dive into the specifics of soil pedogenesis, they first verified the age sequence of four islands in the Galápagos Archipelago, publishing their findings in a 2020 study in the *Journal of South American Earth Sciences* (

https://doi.org/10.1016/j.jsames.2020.102500). Using radioactive carbon (^{14}C) and argon ($^{40}Ar/^{39}Ar$) isotopes, Zehetner and the team dated soils from the easternmost island, San Cristóbal, at about 1.07 million years old while soils from the more westerly Isabela Island charted at 1,450 years old.

With island ages verified, there was just one other factor the team needed to take into account: climate.

“The islands are exposed to the Humboldt current and trade winds from the southeast,” Zehetner says. “The trade winds bring moisture to the highlands and trap stratus clouds there. You end up with much more moisture than in the lowlands, which are almost desert-like.”

So Zehetner and the team found soils along both age and climate gradients, seeking out sampling sites in both the wettest and driest locations formed from similar parent materials on multiple different islands. But finding suitable sampling sites wasn’t always easy. These islands, formed from shield volcanoes, have been sporadically active over the many thousands of years soils have formed. There are lava flows serving as parent materials in various states of weathering and soil formation, and Zehetner’s team had to be sure they were sampling from the same flow. If they sampled from a different flow, the age constraint would not be accurate.


SANTA
CRUZ
ISLAND
Lowlands

The dry lowlands of Santa Cruz Island. Photo by Franz Zehetner.

From oldest to youngest soil profile, here's what they found. Soil formation progressed from Histosol to Andisol to vermiculitic Alfisol. From there, the Alfisol became parasesquic, and then formed Ultisols at the second oldest site. The oldest soils of all were very nearly classified as Oxisols—but more on that in a minute.

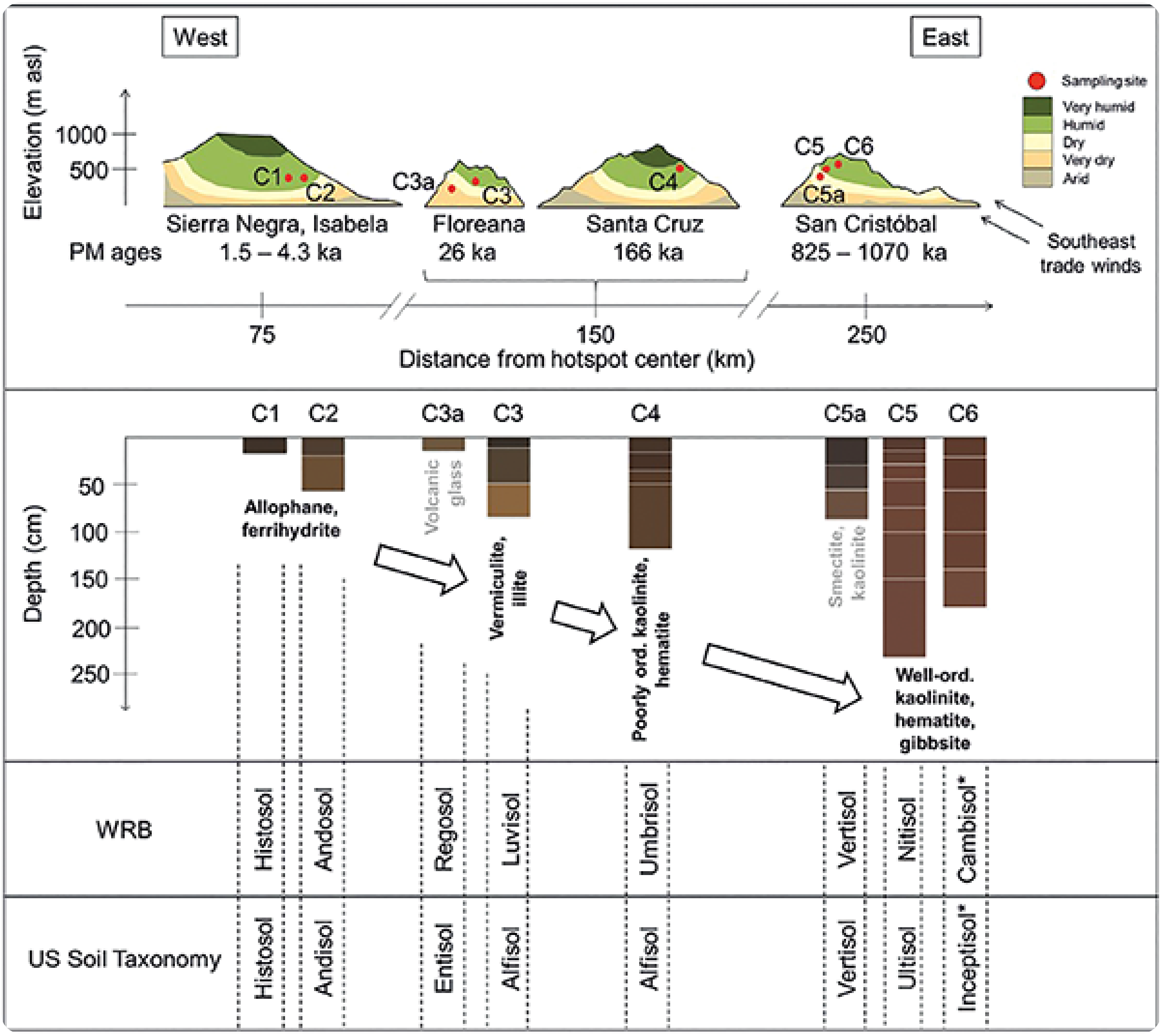
The youngest sampling site—1,450 years old—was a Histosol dominated by organic matter. These soils on Isabela Island were "almost pure organic matter intermingled with cinder deposits," Zehetner says. Some of them were already starting to show andic properties, which are special features related to volcanic soils. Soils with andic properties have very low bulk density—they're incredibly light. They contain reactive aluminum and iron compounds, which contributes to their high reactivity with phosphorus.

Just a bit further along in soil formation were the Andisols. This soil type sometimes contains peculiar soccer ball-like nanostructures with hollow centers called allophanes. Allophanes are incredibly interesting—the researchers posit that these structures might be the reason that organic matter measurements from these young soils came back so high.

"We really couldn't believe it—we kept remeasuring, actually," Rechberger says. "The soil samples were reddish brown, but they had a whole lot of organic carbon."

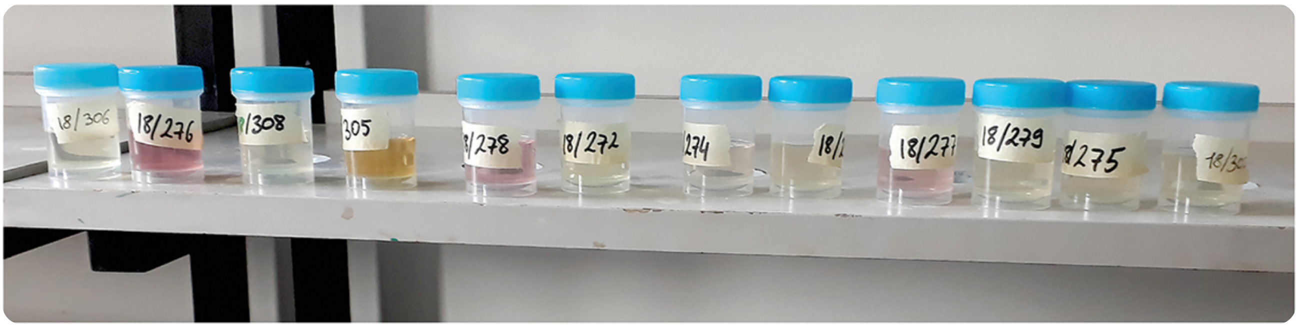
Allophanic Andisols tend to form in soils with higher pH levels. Zehetner's team thinks they were present in such high amounts in the generally rather dry climate of the Galápagos because less rainfall means less leaching, maintaining the elevated pH that favors allophane formation. Notably, Hawaii—another volcanic island chain—has a much moister climate that favors the formation of non-allophanic Andisols.

“Andisols cover less than 1% of the Earth’s land surface,” Zehetner says, “yet contain the highest amounts of organic carbon among all mineral soil types.”



*Conceptual summary of soil development, mineral transformation, and soil classification along the studied chronosequence covering four islands in the Galápagos Archipelago. Color of the soil profiles is based on diffuse reflectance spectroscopy. PM, parent material; *soil has the morphological appearance and meets all requirements of an Oxisol or Ferralsol except for the required low potential cation exchange capacity. Source:* ***https://doi.org/10.1002/saj2.20317***.

Though it hasn't been verified, scientists think that the hollow centers of the allophanes trap and hold soil organic carbon very tightly—which could explain why the soils looked reddish brown yet had the carbon content of a pitch-black topsoil. In the future, nifty applications for engineered allophane-type materials, or nanoparticles, could be used as soil amendments that help capture carbon. It's a long way off, but imagine if we had a means of boosting carbon capture in soil types incapable of retaining high levels of soil organic carbon. Just a little food for thought.



Mehlich-3 extracts of soils from different Galápagos islands; the heterogeneity of the soils is reflected in the different colors of their extracts. Photo by Maria Rechberger.

Moving further along the chronosequence to the third youngest site, the team found that allophanic Andisols had disappeared in soils after 26,000 years of weathering, making way for the 2:1 clay, vermiculite. Vermiculitic Alfisols are much less reactive than Andisols even though they still have high surface areas.

The next stage in weathering induced soil with a 1:1 clay structure called kaolinite, which is even less reactive.

Finally, on the oldest island, the team analyzed samples aged 800,000 years and one million years old. These sites were highly weathered with incredibly deep profiles and mineralogy dominated by kaolinite as well as aluminum and iron oxides.

The humid highlands of Santa Cruz Island. Photo by Franz Zehetner.

"The oldest soils looked very much like an Oxisol, but they weren't—the cation exchange capacity was still too high," Zehetner explains. "The soil was still an Inceptisol, making its way to being an Oxisol, but it just wasn't there yet. And the volcanic origin is still noticeable in these soils—it hasn't been weathered away completely, yet."

After such pains to find sites, take samples, cart them across the globe, and analyze them, the team paints an incredible picture of the pedogenic process. But there's more to the story. Remember those 30,000 folks living on the islands? Well, soils in different stages of weathering—even with the same parent materials—interact incredibly differently with agricultural inputs. And these different reactions to the same management could mean something that works on one island might negatively impact the magnificent biodiversity of another.

Soil Properties and Cadmium

Of all the Galápagos Islands, Santa Cruz has the most farming.

"Most of the green parts of the island are being used for agriculture," Zehetner says. "There's a tiny fringe outside of the agricultural area that's still green, but then it all turns brown."

Though agriculture takes up just a fraction of the 3% of populated land on the islands, it can bleed over into the protected areas, as well. Blackberries, for example, have spread onto uninhabited islands as birds munched the sweet berries and flew to nearby islands, launching seeds along the way.

“Birds don’t care what they’re allowed to carry,” Zehetner says.

When there’s competition, the protected species that inhabit the island get the right-of-way. At one point, the team was sampling carrots, maize, and beans from a farm on the island when a giant tortoise ambled through, munching on plants in its path.

And there’s one small mystery that Zehetner and the team still haven’t solved. In a study published in *Chemosphere*, Zehetner was among the authors who detected heavy metal contamination in agricultural topsoil of the Galápagos Islands (**https://doi.org/10.1016/j.chemosphere.2021.129821**).

“We found incredibly high levels of cadmium in the soils in some areas,” Zehetner says. Cadmium is most often found in areas contaminated by mining waste—and it’s only present in some of the agricultural soils on the islands. The team also discovered elevated levels of cobalt, chromium, copper, nickel, and zinc. But cadmium is incredibly toxic if ingested.

“We think there’s a connection between phosphate fertilizer use and these elevated levels of cadmium,” Zehetner explains. But even when they sampled fertilizers that the farmers were currently using, they didn’t note elevated cadmium levels. “But we don’t know what they used in the past. It could be the legacy of these older fertilizers.”

And here’s where it all ties in with the chronosequence. Soil properties deeply influence the mobility of contaminants like heavy metals. In a study in the *Journal of Environmental Quality*, Rechberger served as first author, examining how the different soils along the chronosequence retained cadmium (**https://doi.org/10.1002/jeq2.20275**). The group discovered that cadmium sorption decreased with increasing soil age and higher levels of rainfall. As soil sorption decreases, cadmium is more likely to move into waterways, which increases its likelihood of ending up in the sensitive food chain of the islands.

The study offers insights for guiding fertilizer recommendations on the islands. The older the soil (or the higher the elevation and rainfall), the more likely any heavy metals in fertilizer will end up in the environment. And with the impacts of climate change on the island, over a long time, the younger soils will weather as temperature and rainfall increase.

“We’ve already started writing a proposal about how the biogeochemistry of phosphorus changes along the chronosequence, as well,” Rechberger says. Agriculture on an island is never too far away from the water, and the team is worried that any fertilizer runoff could negatively impact fresh and saltwater ecosystems alike.

Though the team has already discovered so much about soil formation from the “outdoor laboratory” of the Galápagos, there’s much they still would like to do. With their amassed soil samples, Zehetner estimates they have enough for another 10 dissertations. And their work is laying the foundation for a better understanding of how human interactions with the natural world—and with the factors we can’t control or observe in real time, like soil formation—impact delicate ecosystems.

Dig deeper

Read the *Soil Science Society of America Journal* study “Soil Development and Mineral Transformations Along a One-Million-Year Chronosequence on the Galápagos Islands” here: **https://doi.org/10.1002/saj2.20317**.

Read the *Journal of Environmental Quality* study “Cadmium Retention and Microbial Response in Volcanic Soils Along Gradients of Soil Age and Climate on the Galápagos Islands” here: **https://doi.org/10.1002/jeq2.20275**.

Watch the documentary showing the team’s work in the Galápagos, “Galápagos Beneath the Surface” here: **https://www.youtube.com/watch?v=55H8UANUEQw**
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