Figure 1. The iconic Galápagos vista, looking west from the summit of Bartolomé Island to Santiago Island. Both islands belong to the northeastern Kea trend, sourced from average lower Pacific mantle (Harpp and Weis, 2020; see text). Credit: Lon Abbott.

The Galápagos Islands: Scientific Insights from the Core-Mantle Boundary to the Atmosphere

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On a misty July morning I stood on the rim of the Galápagos Islands' Sierra Negra caldera watching a group of Darwin's finches flitting about, musing about the outsized influence these diminutive birds have had on the history of scientific thought. Few geoheritage sites can rival the significance of the Galápagos (Fig. 1), the chain of volcanoes in the Pacific Ocean 900 km west of Ecuador that inspired a scientific paradigm: Darwin's theory of evolution.

One sentence in Charles Darwin's 1845 second edition of Voyage of the Beagle neatly sums up the enormous influence of the variety of beak shapes displayed by the 17 closely related local finch species on his thinking about evolution: "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends" (Darwin, 1845).

THE FIRST WORLD HERITAGE SITE

The Galápagos are listed as the first UNESCO World Heritage and were inscribed in 1978. To make the World Heritage list, a site must possess "Outstanding Universal Value" (OUV) in at least one criterion. The Galápagos

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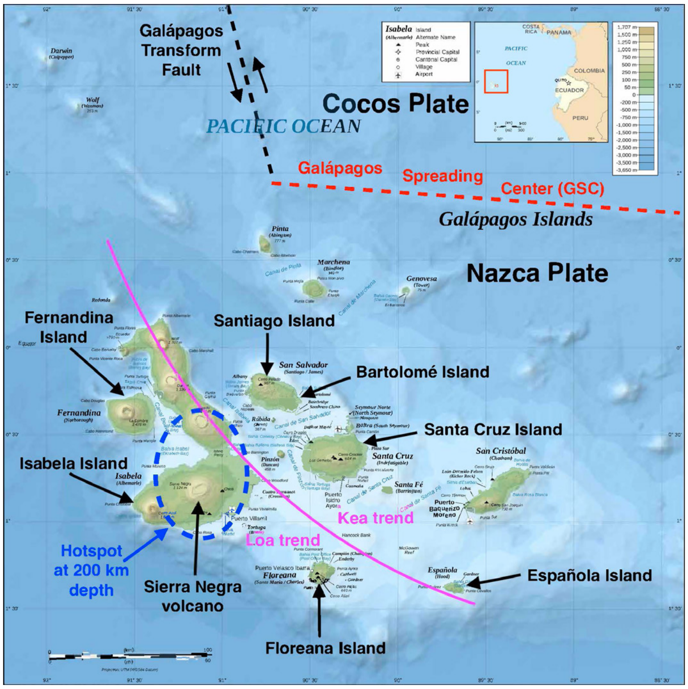

Figure 2. Map of the Galápagos Islands. The boundary between the more enriched Loa and less enriched Kea trends, marked in pink, is after Harpp and Weis (2020). The approximate hotspot footprint at 200 km depth is after Villagómez et al. (2014). Credit: Eric Gaba/Wikimedia Commons.

possess OUV in all four UNESCO criteria for natural sites. They were of course inscribed under Criterion IX, which focuses on ecological and biological processes. But their geology was also deemed of global significance under Criterion VIII—as an “outstanding example representing stages of earth’s history.” The citation notes that “almost no other site in the world offers protection of such a complete continuum of geological and geomorphological features” (UNESCO, 2025). I had arrived in the Galápagos days earlier with a group of undergraduate geology students and professors from the University of Colorado and Ecuador’s Escuela Superior Politécnica del Litoral (ESPOL) to explore those features, which are primarily young (3 Ma and younger) basaltic shield volcanoes and cinder cones built by magma from the Galápagos hotspot.

SIERRA NEGRA: NOT YOUR TYPICAL BASALTIC SHIELD VOLCANO

Like the Hawaiʻian Islands, the Galápagos (Fig. 2) were built by voluminous basaltic eruptions fed by a hotspot. In each case, massive shield volcanoes (with low, <10° slope angles) erupted atop a hotspot, forming an island that tectonic plate movement eventually shifted off the hotspot, making room for a new, younger island to grow. Consequently, the oldest islands in both groups stand farthest from the hotspot. The Galápagos formed on the Nazca Plate, which is moving east at 51 km/My, so the southeastern-most island, Española, is the oldest at ~2.8 Ma (Rojas-Agramonte et al., 2022). Isabela and Fernandina Islands, ~230 km NW of Española, straddle the modern hotspot. Fernandina has been built by eruptions from one shield volcano, whereas Isabela, the biggest Galápagos island, consists of six shields that grew together.

Given the many Hawaiʻi–Galápagos similarities, it’s tempting to assume that the geologic evolution of the Galápagos mirrors that of the more intensively studied Hawaiʻian Islands. But closer examination of the Galápagos also reveals significant differences, from the architecture and behavior of individual volcanoes to archipelago-wide evolution. These Galápagos distinctions offer insights into how hotspot-producing mantle plumes interact with tectonic plates.

Active Galápagos shield volcanoes possess an atypical architecture produced by their equally unusual eruptive styles. Isabela Island’s Sierra Negra, which erupted in 2005 and 2018, is the best-studied Galápagos shield and illustrates the type. Hawaiʻi’s Kilauea, the archetypical shield volcano, provides a useful comparison. Both volcanoes have a large summit depression—the central caldera (Figs. 3A and 3B). But Kilauea also has two prominent rift zones extending outward from the caldera (Fig. 3C), an architectural element Sierra Negra and other Galápagos shields lack. Instead, Galápagos shields possess networks of smaller fissures inside the caldera rim’s circumference (Figs. 3A and 3D) and radially oriented fissures (like spokes on a wheel) outside the caldera (Maerten et al., 2023; Ortiz et al., 2024). Kilauea’s 2018 eruption illustrates a typical shield eruptive sequence. Deeply sourced lava filled the caldera, then drained into the rift zones, triggering 500 m of caldera subsidence. By contrast, Sierra Negra erupted lava from some of the circumferential and radial fissures during both the 2005 and 2018 eruptions (Geist et al., 2008; Bell et al., 2021).

Between eruptions, Kilauea’s caldera experiences minimal uplift and few earthquakes, indicating that little magma is rising through its plumbing system. The situation at Sierra Negra is quite different. Its caldera rose 5 m in the years before the 2005 eruption and 6.5 m between 2005 and 2018, accompanied by frequent earthquakes. These inflation episodes document the filling, between eruptions, of a sill-like magma chamber 2 km beneath the caldera. The caldera subsided modestly during each eruption, but long-term uplift exceeded subsidence, making Sierra Negra a resurgent caldera. Resurgence is common in high-silica calderas but absent on typical basaltic shields (Geist et al., 2008; Bell et al., 2021). Clearly, Sierra Negra and the other Galápagos shields don’t behave like their Hawaiʻian archetypes.

WHEN PLUME MEETS RIDGE: LITHOSPHERIC THICKNESS INFLUENCES VOLCANIC STYLE

The distinction between Hawaiʻian and Galápagos volcanism doesn’t stop there. Hawaiʻian volcanoes exhibit a predictable geochemical evolution that Galápagos volcanoes lack. Over a span of ~1 My, as they migrate over the hotspot, Hawaiʻian volcanoes experience an alkalic (high potassium and sodium) “preshield” phase, evolve to a tholeiitic (less potassium and sodium) “shield” phase, experience another alkalic “postshield” phase, and then, after being dormant for up to 2.5 My, they commonly erupt again (the “rejuvenated” phase). Galápagos volcanoes, by contrast, experience just the tholeiitic shield phase (Harpp and Weis, 2020). Why the difference?

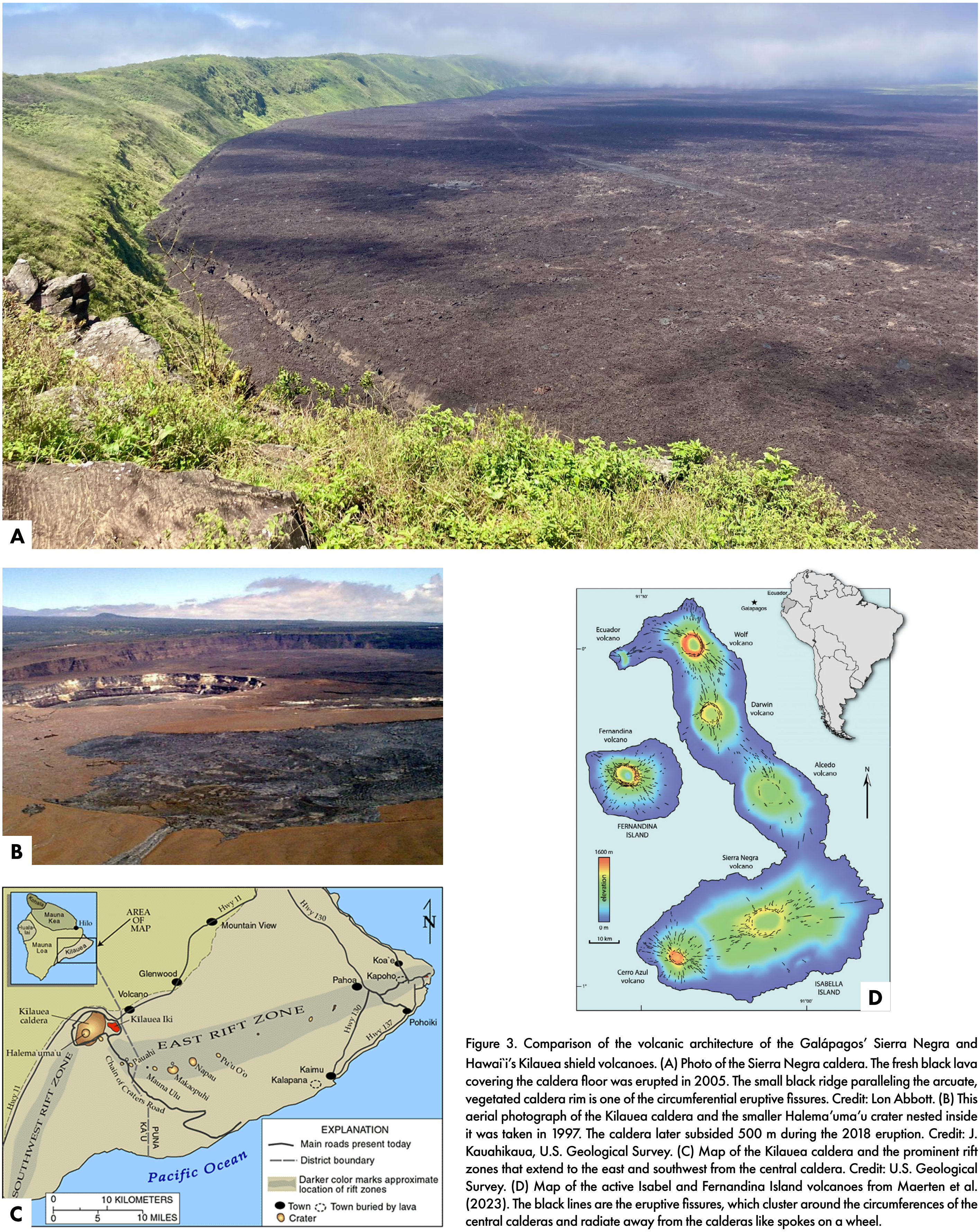

Figure 3. Comparison of the volcanic architecture of the Galápagos' Sierra Negra and Hawai'i's Kilauea shield volcanoes. (A) Photo of the Sierra Negra caldera. The fresh black lava covering the caldera floor was erupted in 2005. The small black ridge paralleling the arcuate, vegetated caldera rim is one of the circumferential eruptive fissures. Credit: Lon Abbott. (B) This aerial photograph of the Kilauea caldera and the smaller Halema'uma'u crater nested inside it was taken in 1997. The caldera later subsided 500 m during the 2018 eruption. Credit: J. Kauahikaua, U.S. Geological Survey. (C) Map of the Kilauea caldera and the prominent rift zones that extend to the east and southwest from the central caldera. Credit: U.S. Geological Survey. (D) Map of the active Isabel and Fernandina Island volcanoes from Maerten et al. (2023). The black lines are the eruptive fissures, which cluster around the circumferences of the central calderas and radiate away from the calderas like spokes on a wheel.

Even more puzzling, there isn't an evolutionary link between the western Galápagos' active, caldera-forming shields and the older, eastern Galápagos islands downstream from the hot spot. The eastern shields don't have calderas now and they never did (Wilson et al., 2022). Why didn't they host calderas when they were located atop the hotspot plume, as the active western Galápagos volcanoes do today (Figs. 3A and 3D)?

The explanation for these Hawai‘i–Galápagos and intra-Galápagos differences appears to be the relative proximity of the hotspot plume to a mid-ocean ridge during volcanism. The lithosphere is vanishingly thin at mid-ocean ridges and thickens away from them. That's because rigid lithosphere and convecting asthenosphere are compositionally identical; asthenosphere, by definition, becomes lithosphere when it cools below ~1350 °C. Hawai‘i's mid-plate location means its islands grow on thick oceanic lithosphere. But the Galápagos lie just 150–300 km south of the Galapagos Spreading Center (GSC), the divergent plate boundary between the Nazca and Cocos plates (Fig. 2), so their lithosphere is much thinner.

Hawai‘i's thick lithosphere can support the geochemical evolution seen at Hawai‘ian volcanoes, but the thin Galápagos lithosphere cannot (Harpp and Weis, 2020). Thin lithosphere also means the ambient regional stress is comparatively weak. By contrast, the high magma pressures in and around the active Galápagos calderas dominates the local stress field, resulting in their unusual pattern of circumferential and radial eruptive fissures (Maerten et al., 2023). The stress situation was different, though, >1 Ma when the eastern Galápagos islands began to grow. The GSC has repeatedly shifted southward, toward the Galápagos, including during construction of the eastern islands. Wilson et al. (2022) suggested that the ultra-thin, GSC-adjacent lithosphere on which the eastern Galápagos shields were built had such a weak stress field that it was incapable of focusing magma, precluding development of the long-lived plumbing systems necessary for caldera formation. Furthermore, the GSC currently siphons magma away from the Galápagos plume; such magma theft was likely more pronounced when the ridge was closer to the plume, meaning the eastern shields formed in a magma-starved environment, further inhibiting caldera development (Harpp and Geist, 2018).

THE HAWAIʻIAN AND GALÁPAGOS HOTSPOTS: FRATERNAL TWINS BORN FROM THE PACIFIC LLSVP

Both Hawai‘i and the Galápagos hug the edge of the Pacific Large Low Shear Velocity Province (LLSVP), a vast region of low seismic velocity above the core-mantle boundary. LLSVPs are enigmatic; geophysicists debate whether they possess higher- or lower-density material than the surrounding lower mantle. Understanding what they are and when they formed is a first-order challenge in geoscience (Duncombe, 2019). But the fact that most hotspots cluster around their edges suggests they play an essential role in plume dynamics.

Most scientists think the material in LLSVPs differs compositionally from the adjacent lower mantle. This supposition was validated by the discovery that Hawai‘i's two parallel volcanic trends, the Loa and Kea (named for the two biggest volcanos on Hawai‘i's Big Island), are geochemically distinct. The SW (Loa) trend is fed by a thin filament of material rising from the Pacific LLSVP, whereas the source for the NE (Kea) trend is average lower Pacific mantle, which is less "enriched" than the LLSVP-derived magma. In this context, "enriched" means that lavas from this source have high Rb/Sr, U/Pb, Th/Pb, and low Sm/Nd and Lu/Hf ratios (Weis et al., 2011). Such parallel, chemically distinct filaments were soon discovered feeding other plumes, but not the Galápagos. It appeared that the Galápagos and Hawai‘ian plumes differ fundamentally.

The Galápagos' proximity to the GSC produces a complex geochemical milieu. But a 2020 study cut through that complexity and detected the parallel Loa and Kea compositional trends in the Galápagos. The western and southern islands of Fernandina, Isabela, and Floreana carry the enriched Loa signature, and the Kea trend is found on the northern and eastern islands. Hawai‘i and the Galápagos share a common magma generation mechanism after all. But the geochemical signatures of the enriched, Loa magmas are different for Hawai‘i and the Galápagos, suggesting internal heterogeneity within the Pacific LLSVP (Harpp and Weis, 2020).

MORE GALÁPAGOS INSIGHTS: FROM SOIL FORMATION TO OCEANIC AND ATMOSPHERIC CIRCULATION

The study of Galápagos geology has also yielded important insights beyond the fields of volcanology and tectonics. Understanding soil formation processes is necessary to maximize food production. Paque et al. (2024) quantified the influence of climate and rock porosity on the rate of soil production for Santa Cruz Island (Fig. 2). The island's windward side provides an ideal natural laboratory thanks to its uniformly young (20–165 ka) basaltic rock coupled with a strong rainfall gradient from <200 mm/yr on the arid coast to 1600 mm/yr on the shield volcano's crest. The authors analyzed soil formation processes using ten pairs of low-porosity lava and high-porosity scoria samples collected along a transect through the precipitation gradient. Where mean annual precipitation is <600 mm/yr, in situ basalt weathering is a sluggish 0.5 tons/km^2/yr, and the soil contains 1.7 times more atmospheric dust than in situ rock weathering products. The degree of soil development increases with increasing precipitation, as revealed by soil depth, pH, and mass-loss coefficients. Above a precipitation threshold of 1000 mm/yr, in situ rock weathering dominates. Rock porosity is another important control; at high-precipitation sites, soil developed on high-porosity scoria is ten times thicker and exhibits a 10-fold greater mass loss (due to chemical weathering) than basalt soils.

The Galápagos Islands rise in the eastern equatorial Pacific, a key location for global climate regulation. This is primarily because of the presence there of the "cold tongue" (CT), a zonal band of minimum sea surface temperature. The CT is produced by trade wind–induced coastal upwelling along the west coast of South America combined with equatorial upwelling caused by Ekman divergence (Karnauskas et al., 2006). Those authors state: "It would be difficult to overemphasize the importance of the CT in global hydrological and geochemical cycles" because of the key role it plays in tropical cloud formation, precipitation patterns, oceanic nutrient delivery, and carbon cycling (p. 1266). The general circulation models (GCM) used for climate modeling prior to 2006 produced a "too cold" CT, resulting in unrealistic models of tropical cloud and precipitation patterns.

The Galápagos present a barrier to the equatorial current system, likely influencing CT behavior, but none of the contemporary GCMs in 2006 included the Galápagos. Karnauskas et al. (2006) tested whether the absence of the Galápagos in GCMs caused their too-cold CT. Sure enough, they discovered that the Galápagos obstruct the Equatorial Undercurrent, resulting in a warmer sea-surface temperature than would otherwise exist. Inclusion of the Galápagos in GCMs eliminated the CT cold bias.

As our group traveled through the Galápagos, we saw tortoises, iguanas, and more finches, reminding us repeatedly of the Galápagos fauna's legendary significance for Darwin's development of evolutionary theory. Our tour of the islands' unique geology educated us to other, less celebrated but tremendously important scientific insights of planetary scale, ranging from the core-mantle boundary's chemical composition to the fundamental controls on oceanic and atmospheric circulation. The Galápagos possess a truly extraordinary biological and geological heritage that amply justifies their status as the first-ever World Heritage Site.

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