RESEARCH ARTICLE

VOLCANICA

Charles Darwin on Volcanoes

Dennis Geist *[α,β] and Sally Gibson[γ]

[α] Department of Earth and Environmental Geosciences, Colgate University, Hamilton, NY 13346, USA.
[β] Department of Earth and Spatial Sciences, University of Idaho, Moscow, ID 83844, USA.
[γ] Department of Earth Sciences, University of Cambridge, Cambridge, CB2 3EQ, UK.

Abstract

During the voyage of the H.M.S. *Beagle* (1831–1836), Charles Darwin had the opportunity to visit and observe volcanoes and volcanic deposits at several archipelagos in the Atlantic, Pacific, and Indian Oceans and also in the Andes. In the Galápagos Archipelago, he described hydrovolcanism and what we now know as pyroclastic surge deposits. Darwin also noted the relation between scoria and lava in Strombolian deposits and the role of effective viscosity on lava surface morphology. He observed volcanic eruptions in the Andes from a distance and speculated on the role of earthquakes in triggering eruptions. Darwin's field work on Ascension, the Cape Verde Islands, Mauritius, and the Azores included detailed work on volcanic bombs and the spatial relationship between basalt and evolved lavas. Much of his focus was on making detailed observations at the outcrop scale to deduce large-scale geologic processes, such as the relation between magmatism and mountain building and the distribution of magma in the deep Earth. While many of Darwin's theories involving volcanism did not stand the test of time, in contrast to his theories on coral reefs and the origin of species, they exemplify his genius at developing novel hypotheses and making observations to test those hypotheses.

Keywords: Galapagos; Cape Verde; Azores; History; Tuff cones; Crater.

Submitted: 2024-12-24 | Accepted: 2025-12-03 | Published: 2025-12-03

Editor: J. Farquharson | Typesetter: A. Ryan

1 Introduction

Charles Darwin is justifiably famous as the scientist who changed our understanding of life on Earth, owing to his revolutionary theory of evolution by natural selection [Darwin 1859]. While he is also celebrated for his contributions to the science of geology [Herbert 2005], including igneous petrology [Pearson 1996; Gibson 2009], Darwin's contributions to the science of volcanology are less widely known and the subject of this piece. Darwin was fascinated by volcanic processes and wrote extensively on volcanological topics throughout the earlier part of his career [Darwin 1844]. During the voyage of H.M.S. *Beagle* (1831–1836), he only witnessed volcanic eruptions from afar, but he was a brilliant observer and formulated novel theories on volcanic processes by applying skills of traditional field work, both at the outcrop and landscape scales.

As a preface, consider the following that Darwin wrote in a letter to his father from Bahia, Brazil on 1st March, 1832—after having visited volcanic islands of Cape Verde and Fernando do Noronha in the Atlantic—but before his travels in two of the most spectacular volcanic terrains in the world, the Andes and Galápagos:

> *"Geologising in a Volcanic country is most delightful, besides the interest attached to itself it leads you into most beautiful & retired spots."*

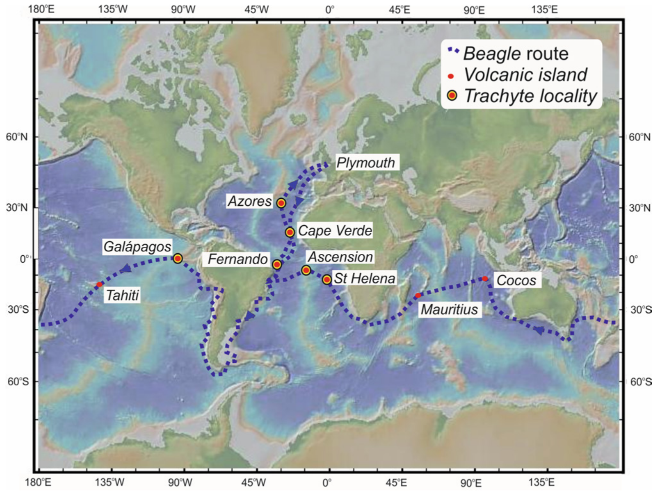

Figure 1: Volcanic islands visited during the voyage of the H.M.S. Beagle between 1831 and 1836 [from Gibson 2009].

2 Background

Charles Darwin's main contributions to the science of volcanology were derived from observations made during the voyage of the H.M.S. *Beagle* (1831–1836; Figure 1) and several volumes written on his return [Darwin 1839; 1844; 1845b], but before he tackled the origin of species [Darwin 1859] and the descent of man. An enormous biographical literature has been written on Darwin (the reader is referred to Browne [1996, 2003], and Herbert [2005]), but some points bear directly on his observations on volcanoes and volcanic deposits.

Darwin was employed as a natural scientist on the *Beagle* voyage, but natural science lacked the disciplinary focus in the early 19th century that it has today. Because he had served as a field assistant for one of the most eminent geologists of the day (Adam Sedgwick), Darwin considered himself a geologist during the voyage of the H.M.S. *Beagle*, and clearly geology dominated his thinking in those days [Herbert 2005]. His main function on the voyage in terms of botany and zoology was collecting; it is noteworthy that his rock collection (~2000 samples) exceeded both botanical and animal speci-

* dgeist58@proton.me

mens [Herbert 2005], and in many ways the rocks are better documented [Sulloway 1982].

For his scientific work in all disciplines, Darwin was the right person in the right place at the right time. His family's affluence connected him to the era's scientific giants and supported his travel to the most remote corners of the world for years. The family's wealth then enabled him to spend his adult life synthesizing his ideas on the natural world. There is little doubt that had he been required to work to earn a living, he would not have been so productive (Darwin did earn substantial income as an author [Browne 2003]). In addition to his financial independence, the time during and after the H.M.S. *Beagle* voyage and aftermath was in an era when geology had been revolutionized by the works of Hutton [1795], Lyell [1830] and Lyell [1858], not to mention seeds of thought on biological evolution [Secord 2003]. Moreover, Darwin was deeply influenced by Alexander von Humboldt, who wrote extensively on the volcanoes of the Canary Islands and Andes, and he admired him greatly [Barlow 1958]. Another aspect of the "right man-right time" designation is that Darwin's travels and later syntheses occurred when the foundations were in place for major discovery in the geological sciences, but most major scientific questions in the field remained open. That said, Darwin's long-term influence on the geological sciences, including volcanology, should not be exaggerated, despite the fact he pioneered important concepts such as crystal fractionation by gravity settling [Geikie 1909; Pearson 1996; Gibson 2009; Herbert et al. 2009] and the deposition of pyroclastic surge (see below).

Darwin's special talents were exactly those of any great field geologist. He had historically strong powers of observation but also had intellectual ambition: Darwin aspired to take on both very specific, detailed scientific challenges and larger syntheses. Darwin had the quality of understanding that tackling the grand challenges (e.g. evolution by natural selection) required a huge amount of systematic work on the details (e.g. barnacle taxonomy). This same mix of deductive and inductive reasoning is seen throughout Darwin's work on volcanoes [Darwin 1844]. He spent pages describing minute details of single outcrops or rocks, but much was a set up for a discussion of larger issues, like giant bodies of subterranean magma and the relation between volcanism and mountain building by uplift.

Despite his time in the field in North Wales with Adam Sedgwick in 1831, Darwin was not a dedicated geological mapper; instead, he worked largely from sketches of outcrops and landscapes and his interpretations of those. This approach was criticized at the time by some of Britain's leading geologists, who believed that the only route to characterizing geology is mapping [Herbert 2005]. In terms of volcanology, Darwin's most lasting contributions were case studies from the islands that he visited (many of which were discoveries), but he also took on grand challenges of the day, albeit few of which would be deemed correct in the modern context.

2.1 Volcanology and the Darwin bibliography

Darwin's work on volcanoes is available at Darwin Online*. This is a comprehensive compilation of Darwin's writing that also includes correspondence, the library aboard H.M.S. *Beagle* and works about Darwin [van Wyhe 2002]. The digital collection contains Darwin's diaries and field notes from the *Beagle* voyage that offer insight into what and how he was thinking at the time he was making observations. The collection includes images of the original notes and companion transcripts, which can be digitally searched.

Darwin's work on volcanoes is concentrated in the early part of his writing career, akin to the bulk of his geology writings. The book popularly known as *The Voyage of the Beagle* was published in 1839 [Darwin 1839] and includes dozens of pages on observations of volcanoes and volcanic deposits. This contribution makes use of the second edition, which was published in 1845. The *Voyage*, which is largely a travelogue and adventure narrative meant for the public, was followed by the trilogy of treatises *The Structure and Distribution of Coral Reefs* [Darwin 1842], *Geologic Observations on the Volcanic Islands Visited During the Voyage of the* H.M.S. *Beagle* [Darwin 1844], and *Geologic Observations on South America* [Darwin 1846]. *Geologic Observations on the Volcanic Islands Visited During the Voyage of the* H.M.S. *Beagle* [Darwin 1844], as the title suggests, includes the most details on volcanic geology within the Darwin oeuvre. Following his stint as Secretary of the Geological Society of London (1838–1841), Darwin's writing underwent a shift, and every subsequent book focused on life on Earth.

2.2 Historical context

The H.M.S. *Beagle* carried copies of Scrope's *Considerations on Volcanos* [Scrope 1825, *sic*] and Daubeny's *Description of Active and Extinct Volcanoes* [Daubeny 1826], along with the early volumes of Lyell's *Principles of Geology* (Lyell [1830]; some of the volumes were published during the H.M.S. *Beagle* voyage and acquired by Darwin underway), which includes important chapters on the actions of volcanoes [Herbert 2005]. Daubeny attributed magma to the exothermic reaction of air and water with subterranean metal, but his book (which emphasizes observations of the volcanoes of Auvergne and Eifel) is an excellent example of applying observation of ancient deposits to deduce geologic processes [Gibson 2009]. Scrope's work includes a map of the world's volcanoes, with an emphasis on the chains that we now attribute to plate tectonics. Darwin was especially fascinated by the occurrence of volcanic islands in the oceans, and Scrope's map shows the volcanoes that Darwin visited, including the Atlantic islands and the Galápagos.

One of the prevailing paradigms on the origin of volcanoes in the early 19th century was "craters of elevation" [Von Buch 1836], and Darwin devotes a great deal of discussion in his notes and books to the theory. Moreover, his field notes are rife with discussion and sketches of field evidence that he observed and which bears on the hypothesis. Adherents to the theory contended that volcanoes are structural domes, heaved

* https://darwin-online.org.uk

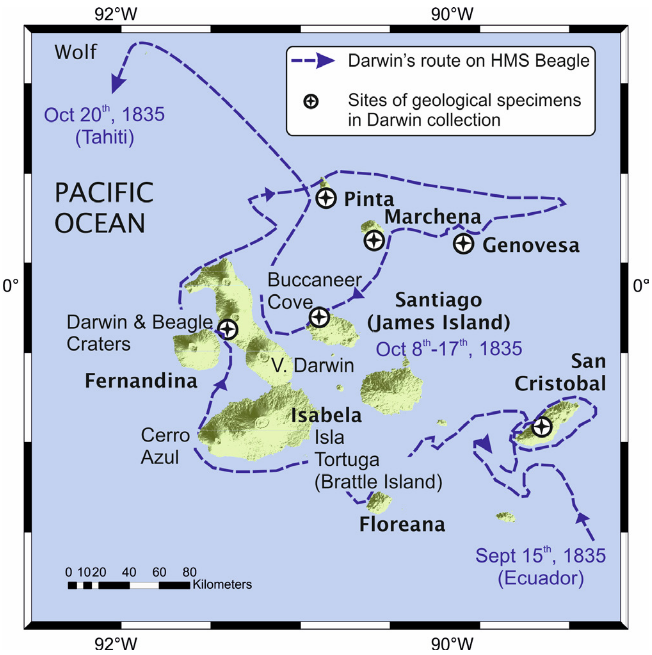

Figure 2: Route of H.M.S. Beagle in the Galápagos Archipelago in 1835. Most of the geological specimens collected from Galápagos by Darwin are housed in the Sedgwick Museum at the University of Cambridge.

up by the forceful intrusion of magma. Although we know that structural bulging and doming is a common volcanic process [e.g. van Wyk de Vries et al. 2014], the early adherents believed that it was responsible for the common morphology of volcanoes, and that lavas dipping more than a few degrees had to be tilted by deformation. The theory was also extrapolated by Darwin to the formation of mountain ranges, i.e. that they were pushed up by magma. As discussed below, Darwin was equivocal about the craters of elevation theory, alternating observations that seemed to support it with skepticism.

We now focus on the volcanic provinces where Darwin made some of his most important observations on the *Beagle* voyage, and discussed in order of what we consider to be the most insightful.

3 The Galápagos

> *"In a few days time the Beagle will sail for the Galapagos Isds. - I look forward with joy and interest to this, both as being somewhat nearer to England, & for the sake of having a good look at an active Volcano. - Although we have seen lava in abundance, I have never yet beheld the Crater."*
> —Letter to Henslow from Lima, July 12,1835

Darwin was one of the first scientists to visit the Galápagos archipelago, and he remains the best-known visitor for his descriptions and the legend of the impact of the endemic biota on his theory of evolution by natural selection. The Galápagos today is a center of scientific research. Dozens of scientists live and work in the Islands, and >50 papers annually are published in the natural and social sciences with "Galápagos" in the title. Hundreds of thousands of people visit the Galápagos Islands each year, and virtually all of them have an interest in natural science and the fundamental observations that gave rise to Darwin's theory of evolution.

The geology of the Galápagos is briefly described in the *Voyage of the Beagle*, but, after he saw the volcanic terrain of San Cristobal (Figure 2), Darwin's attitude about volcanoes had changed since his days in the Atlantic: "Nothing could be less inviting than the first appearance". In the *Voyage of* H.M.S. *Beagle*, the account on the geology of the Galápagos is abbreviated. Darwin [1845b] recounts his observations on a 9–15 ka lava field on San Cristobal [Geist et al. 1986; Mahr et al. 2016], which he compares to slag piles around foundries in Staffordshire (Wolverhampton in the *Beagle* diary [Keynes 1988]) and refers to it as the "craterised district" [Grant and Estes 2009]. Near one bivouac, he counts 60 craters, which he notes for their symmetry and being constituted of scoria and "slag" "cemented" together (what we would now phrase as partly welded spatter). He attributes the craters to great bubbles discharging still-molten lava. We concur with much of this interpretation: this part of San Cristobal has a field of dozens of rootless cones (a.k.a. pseudocraters), eruptive vents where the molten interior of a pāhoehoe lava explodes through its upper crust, driven by gas pressure. Most rootless cones are attributed to lava flowing over shallow water or waterlogged ground [e.g. Fagents and Thordarson 2009], but at San Cristobal this cannot be the case, because the pseudocraters are ~100 m above the coastline and on a sloped surface, and their origin remains a mystery. Darwin also notes in the *Voyage* the abundance of tuff cones in the Galápagos Archipelago and that they originate from the eruption of "volcanic mud" (see below).

By far the more important contribution for Galápagos volcanology is the volume *Geological observations on the volcanic islands visited during the voyage of* H.M.S. *Beagle* [Darwin 1844], and the following derives from that volume, the *Beagle* diary [Keynes 1988], and his field notebooks and geologic diary (transcribed by Thalia Grant and Greg Estes, in van Wyhe [2002]).

3.1 Lava morphology

In addition to the rootless spatter cones described in the *Voyage*, Darwin describes collapsed lava tubes and tumuli ("mammiform hillocks") in the young lava field on San Cristobal (the craterised district). He correctly attributes the tumuli to upheaving by pressurized lava from below [e.g. Walker 1991; Self et al. 1998]. He also notes that the lava here is young [Mahr et al. 2016], but there were different phases of activity, which could be evaluated by different extents of weathering and colonization by plants [Geist et al. 1986]. In addition to the pseudocraters observed at San Cristobal, Darwin makes note of a similar field on Cerro Azul volcano (Figure 2) on September 29, 1835, observed from sea, aboard the *Beagle* [Keynes 1988].

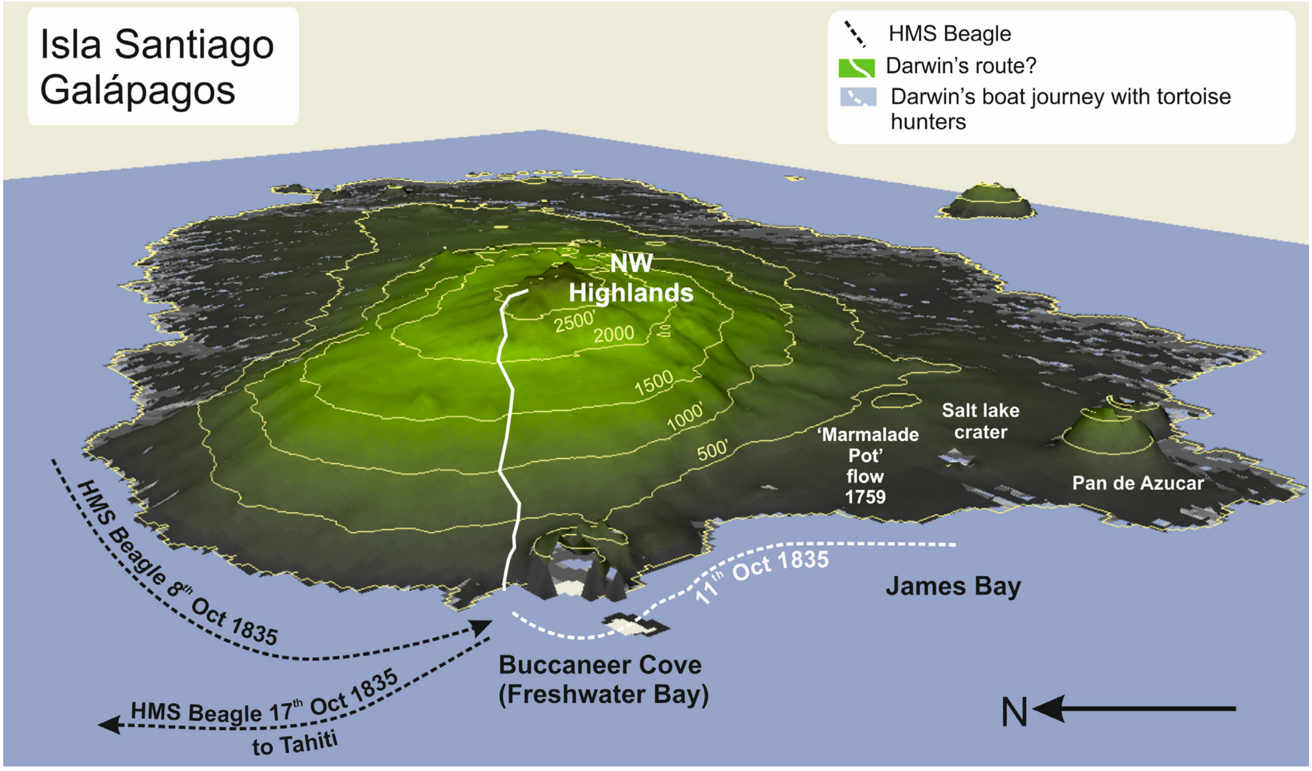

Figure 3: Route of H.M.S. Beagle around the west coast of Isla Santiago (James Island) and some of the volcanic landforms that Darwin visited. Also shown is Darwin's route to the trachyte dome at the summit of the volcano.

Darwin was particularly impressed by the textures and structures of a voluminous lava flow on Volcan Darwin, south of Tagus Cove on Isla Isabela (Figure 2). He observed the lava channels and levees, and that the lava bifurcated, one stream spilling into the breached crater of the tuff cone and the other to the sea. He notes a contradiction: this lava is loaded with plagioclase phenocrysts, which he suggests should have high effective viscosity, but the lava's morphology shows that it was clearly fluidal. He discusses the pāhoehoe-ʻaʻā dichotomy in basalts, comparing them to different states of the sea. He also observes that composition and phenocryst mode do not control the surface morphologic type of lava [e.g. Rowland and Walker 1990].

A diverse suite of satellite vents forms the landscape at Buccaneer Cove ("Freshwater Bay" to Darwin) on Isla Santiago (Figure 3) [Gibson 2009; Herbert et al. 2009; Gibson et al. 2012]. The peninsula forming the northeast boundary of the Cove is the erosional remanent of a scoria cone, including a fossil lava lake (thick lava filling a crater, recognized as such by Darwin; Figure 4). The geometry of the peninsula is quite complicated owing to the three-dimensional structure of the growing cone as it emerged above the sea. Moreover, loose scoria transitions to clastigenic lava both up- and down-dip, making tracing of individual layers extraordinarily difficult. The lava lake locality was crucial to Darwin's theory that minerals segregate by specific gravity, a form of crystal fractionation. Although this theory was well ahead of its time [Pearson 1996], it was flawed in several respects. First, Darwin observed that plagioclase, which is neutrally buoyant in basaltic melt, sank in the lava lake. He attributed this to the dedensification of the magma with bubbles, but this is erroneous thinking because the velocity of bubble ascent would greatly exceed that of plagioclase sinking in a froth, and froths with low capillary numbers (as would exist in a lava lake) have large effective viscosity and yield strength, preventing crystal settling. Also, we carefully inspected this outcrop and could not identify any zone of feldspar accumulation [Herbert et al. 2009]. Nevertheless, it is interesting that Darwin puzzled over multiphase fluid dynam-

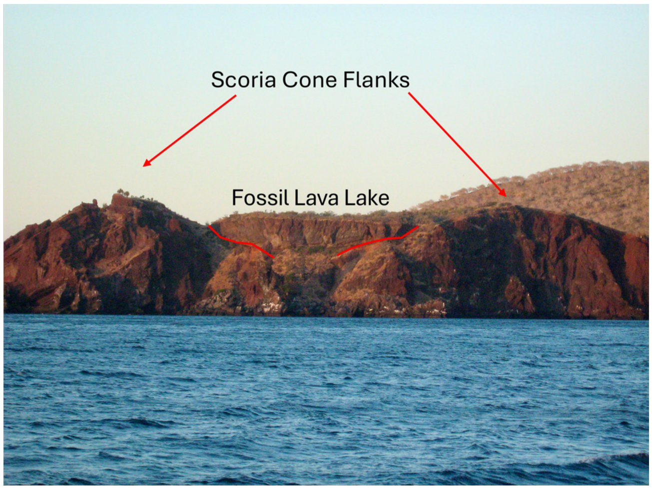

Figure 4: The peninsula forming the northeast border of Buccaneer Cove consists of scoria and lava dipping outward, and enclosed crater-filling deposits, capped by a fossil lava lake. Darwin worked extensively on this outcrop [Herbert et al. 2009].

Figure 5: Darwin's layer-cake sequence at Buccaneer Cove, a wave-eroded scoria cone.

ics in lava, a topic that also challenges modern volcanology [e.g. Kolzenburg et al. 2022].

A small promontory within Buccaneer Cove is the wave-eroded remnant of a scoria cone (Figure 5), described in detail by Darwin [1844] and locally known as "Darwin's layer cake". He notes a continuum in the extent of fragmentation and fusion: some pieces of scoria cooled as fragments, others are partly fused, and others are completely fused into clastigenic lava. We also observe that this continuum exists in individual layers up and down dip: individual layers grade from unfused scoria, to partly fused bombs, to lava with "ghost" clasts, to completely molten lava. We now know that the extent of fusion depends on both the thermal state of the clasts as they hurl through the atmosphere and the accumulation rate [e.g. Rader and Geist 2015].

3.2 Hydrovolcanism and surge deposits

Dozens of palagonite tuff rings and tuff cones form islets or decorate the coast of the larger Galápagos. Because Darwin spent most of his time in the Archipelago observing the islands from H.M.S. *Beagle*, he was particularly impressed by

Figure 6: View from the rim of Darwin Crater and Tagus Cove, Isla Isabela. A saline lake (which Darwin tried to drink from) fills the crater of the tuff cone.

these hydrovolcanic landforms and their deposits, which are concentrated along the coast and as islets offshore the major islands [Darwin 1845b]. From his detailed description of palagonite tuff and the large number of samples of tuff (e.g. 16 of 28 identified samples from San Cristobal), one surmises that this rock type was not widely accounted for in the literature that existed in 1835. Darwin observed that although palagonite tuff is resinous and yellow- brown and resembles sandstone, it fuses into dark (basaltic) glass when heated via a blow pipe [Darwin 1844].

Darwin also observed that fine glassy scoria was in progressive stages of conversion to palagonite and deduced that fresh basaltic particles were undergoing a chemical change. He also noted that palagonite tuffs are all near the coast and reasoned that they result from "trituration" of basaltic lava by interaction with seawater during eruption; we note that palagonite tuff also exists in the summit calderas of Cerro Azul, Sierra Negra, and Fernandina volcanoes, owing to magma interacting with intra-caldera lakes and perched groundwater [Howard et al. 2019], but Darwin did not climb to the summit of any of the caldera-topped western shields to witness hydrovolcanic deposits around the calderas. He also observed that basaltic lava fills the craters of several of the tuff cones, which we now know as a typical Surtseyan eruptive sequence, as the volcano builds from a shallow-water to a subaerial environment. Most remarkably, Darwin observed fossil land snails (*Bullimulus*) in the basal layers of the tuff at the peninsula of Buccaneer cove, proving that although the tuff is hydrovolcanic, it was deposited on land (n.b. we have scoured these outcrops for fossils but never found any. CD is clearly the superior field volcanologist).

On Isla San Cristobal, Darwin developed a facies model for a palagonite tuff ring that stands today [Wohletz and Sheridan 1983]. He notes a stratigraphic transition upward from massive palagonite to finely stratified basaltic tuff. Near the vent, the tuff is of an intermediate texture and massive.

Two of Earth's largest tuff cones surround Tagus Cove on Volcan Darwin, Isla Isabela (they are now known as Darwin and Beagle Craters; Figure 2 and Figure 6), and like tuff cones all over the world, they are constructed of interbedded surge and fall deposits. Darwin notes "pisolitic balls" in the palagonite tuff (Figure 7); these deposits contain layers that almost entirely comprise armored and accretionary lapilli (the former are round scoria fragments coated with fine ash; accretionary lapilli are formed entirely of concentric layers of fine ash; Darwin recognized both types). Longitudinal dunes ("longitudinal doons" in his geological notebook) form the upper surface of both cones (Figure 6), referred to as "convex ribs" by Darwin, and he compared the surface morphology of the cone to a scallop shell. Darwin realized that the dunes, and bedforms related to the formation of dunes, indicate deposition from a strong current. Such dunes are also notable features of the surge deposits formed during the hydrovolcanic eruption of Fernandina in 1968, which were mapped just a few years after the eruption [Howard et al. 2019]. Most importantly, Darwin noted that the furrowed surfaces are depositional, not erosional. He also notes that the stratification around the cone forms a pseudo-anticlinal structure, owing to

Figure 7: "Pisolitic" beds in surge deposits from Beagle Crater on Volcan Darwin. The large (5 to 10 mm) round particles are mostly armored lapilli: fragments of scoria coated with ash. Some of the finer spheres are accretionary lapilli, which are constituted of concentric fine layers of ash.

Figure 8: A large pāhoehoe flow of basalt (foreground) with the salt mine crater (low profile to the left) and Pan de Azucar in the distance, western Santiago.

the inward primary dips in the crater and outward dips on the flanks. Darwin observed that some dunes have hollows, which he interpreted as flowing of mud from below a hardened surface, shortly after deposition. Our interpretation is that this is simply a weathering phenomenon, because softer tuff underlies a hardened indurated surface. Darwin recognized that the tuff was wet upon deposition and refers to it as a "Mud Volcano", where "the boiling thick mass has poured over in narrow streams." It was not until the mid-20th century that volcanologists recognized transport and deposition of pyroclastic surge, and that many surge deposits form at temperatures well below the boiling point of water [Moore 1967; Waters and Fisher 1971].

Darwin visited a maar, Salt Mine Crater near James Bay on Santiago (Figure 3 and Figure 8). He noted that the crater floor is below the surrounding surface, and concluded that it formed by excavation into older lava. Darwin notes the startlingly different morphology between this maar (deposits ~5 m thick at the crater rim) and the adjacent tuff cone, Pan de Azucar (Figure 8), which stands ~300 m above the surroundings and whose crater floor is also above the surrounding landscape. He also recognizes the different morphology of Isla Tortuga ("Brattle" to Darwin; Figure 2), a tuff ring >1 km in diameter. Darwin [1844] may well have been the first to have recognized the 3 types of hydrovolcanoes by their morphology: what we now know as maars, tuff rings, and tuff cones [c.f. Wohletz and Sheridan 1983; White and Ross 2011].

Figure 9: GoogleEarth view of Ilhéu de Santa Maria offshore Sao Tiago, Cape Verde archipelago.

4 Atlantic Islands: Cape Verdes, Ascension Island, and the Azores

> *"The first examining of Volcanic rocks must to a Geologist be a memorable epoch"*
> —*Beagle* Diary, Jan. 17, 1832

By an unfortunate turn of events, H.M.S. *Beagle* anchored offshore Tenerife in the Canary Islands in early January, 1832, but none of the crew was permitted to disembark, owing to a quarantine imposed because of a cholera outbreak in England. This is a shame, because Tenerife is one of the most spectacular volcanoes in the Atlantic, with a prominent caldera, beautiful exposures, and young effusive and pyroclastic deposits. Moreover, the Canary Islands formed the basis of von Buch's theory of "craters of elevation", which attributed volcanoes to upheaval rather than accumulation from the surface [Von Buch 1836]. Also, Alexander von Humboldt climbed to the summit of Tenerife (1799), and his writings were influential to Darwin.

Darwin's first steps ashore after departing England were on the volcanic island Santiago (also known as Sao Tiago; "St. Jago" to CD), in the Cape Verde archipelago, where he "took a deliberate step into the world of investigative science" [Browne 1996]. One of the most interesting aspects of his geologic work in the Cape Verdes is that most of it was on a single outcrop, and from the observations Darwin deduced both volcanic and tectonic (uplift) processes.

The islet Ilhéu de Santa Maria, in a bay on the southern end of Sao Tiago, was referred to as Quail Island by Darwin (Figure 9). Because this locality was used as a calibration site for the Beagle's chronometer collection, Darwin returned 5 years later, equipped with a vast experience at observing both modern and ancient volcanic rocks and deposits (Johnson and Baarli [2015], which also contains detailed descriptions of the outcrops). At this locality, Darwin witnesses a limestone bed formed from coralline algae that had been baked by the overlying lava. From this observation he deduced that the lava had flowed on the seabed, and the entire sequence then uplifted. This obvious evidence of recent uplift was clearly formative for Darwin, as uplift and subsidence became his primary research interest in the geological sciences, especially their relationship to mountain belts [Darwin 1846] and coral reefs [Darwin 1842].

4.1 Structure and morphology of the lava flows

Darwin noted that the lava overlying the limestone on Quail Island was split by vertical fissures into 5-sided "plates" that were then piled into columns, a description of columnar basalt with a horizontal platy cleavage. At the base of the lava flow, he noted a zone of mixing, where a basal breccia formed with clasts of limestone intermixed with glassy scoria, a pepperite. He also noted the vesicle zonation of the lava, a subject of modern research [Self et al. 1998].

In addition to Quail Island, Darwin inspected outcrops exposed on the sea cliffs, and young lavas and scoria cones along the southeast coast of Santiago, at localities called Red Hill and Signal Post Hill [Johnson and Baarli 2015]. He also hiked to several older satellite cones higher on the mountain. At Signal Post Hill, Darwin traced lava to its source, noting textural changes from dense lava to scoria over short distances, features typical of near-vent facies of scoria cones and similar to the structures he would observe later at Buccaneer Cove on Santiago, Galápagos (see above). He also noted lava at the base of a steep-sided gorge at the foot of the cone, which is likely a lava channel from a breakout.

After departing the Galápagos, the *Beagle* set sail for Tahiti and then returned home to England via the volcanic islands of Mauritius, St. Helena, Ascension, and finally the Azores (Figure 1). One senses that on Ascension Island Darwin longed to return to verdant England: "The day was clear and hot, and I saw the island not smiling with beauty, but staring with naked hideousness" [Darwin 1845a]. One also senses that Darwin looks back on the day more positively much later in his life, when, in his autobiography, he recounts the field work after receiving a letter from Henslow reporting that his work had been reported to the Geological Society of London: "After reading this letter I clambered over the mountains of Ascension with a bounding step and made the volcanic rocks resound under my geological hammer!" [Barlow 1958], reflecting the joy a scientist experiences when a manuscript is accepted for publication.

At Ascension, Darwin focused on the morphology of the young rugged ʻaʻā lava and intervening pyroclastic rocks. He devotes much of the discussion to volcanic bombs [Darwin 1844; 1845b], which he correctly attributed to being ejected molten fragments. He recognized the aerodynamic shapes of the bombs and was particularly taken by the core-to-rim textural differences, grading from coarsely vesicular in the core

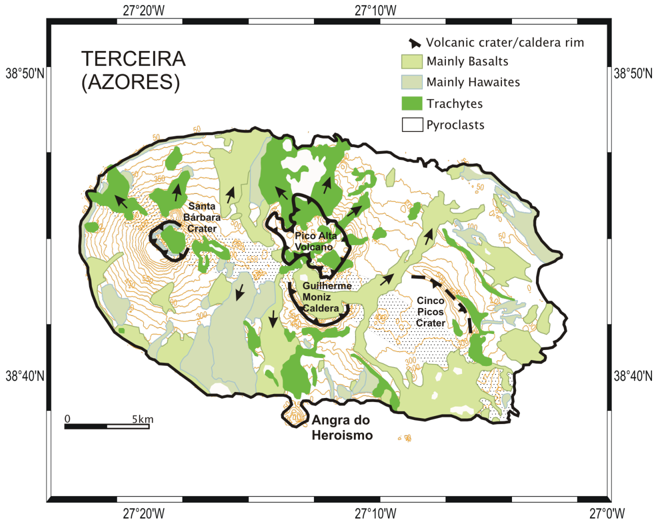

Figure 10: Simplified geological map of Terceira in the Azores [modified from Self 1976]. Darwin visited the island at the end of the voyage of H.M.S. Beagle (September 1836) when the ship anchored off the town of Angra do Herosimo.

to more finely vesicular at the rim, with a nonvesicular rim coated with scoria. He attributes the variation in vesicularity not to cooling rate and expansion of the bombs but to depressurization from the centrifugal forces in a spinning bomb.

Darwin [1844] investigated the near-vent deposits of a scoria cone (Green Hill) and describes what we would now call Strombolian deposits. He noted that the deposits fine and thin away from the vent and recognized that the pyroclasts were shot out of the vent as if out of a "great air-gun". He also describes a depression on the flanks, which is filled with lava. This is probably a boca, a lava vent on the lower flank of a scoria cone.

4.2 Textural banding in silicic lavas

Ascension Island is well-known for the abundance of silicic rocks [e.g. Kar et al. 1998], and Darwin [1844] was particularly interested in the small-scale textural variations in the silicic lavas. He notes 5 different textural varieties of lava, including obsidian. He suggests that cooling rate is probably not the only control on texture, because the different types are juxtaposed over very short length scales in the interior of the flows. He attributes spherulites to slow cooling of the volcanic glass, on the basis of observations reported on cooling of artificial glass. Unfortunately, Darwin was not aware of the important role of water on the nucleation and growth of crystals from an undercooled melt [e.g. Castro et al. 2005; Tuffen et al. 2020].

One of Darwin's more obscure papers equates banded textures in obsidian to "veined structure" in glacial ice [Darwin 1845a]. Darwin examined obsidian from Mexico and noted that the banding is due to concentration of flattened vesicles, and he generalized that this was the cause of lamination in trachytes. He also noted that the vesicles are likely to form in small-scale zones of tension, in turn caused by simple shear in a flowing viscous fluid. The deformation and distribution of vesicles in obsidian remains the subject of modern research, particularly as they relate to lava rheology [e.g. Castro et al. 2005].

The last volcanic islands that Darwin visited on the voyage of H.M.S. *Beagle* were Terceira and São Miguel in the Azores. Here he wrote in his geologic notes that "in their general form, number of craters, few scattered mounds, Lithological nature of the rocks ... degree of activity, general dimensions appear very closely to agree with the Galapagos Archipelago'. On his first day on Terceira, Darwin visited Furnas do Enxofre and observed some fissures with steam vents and suggested that "it is probable that this same water, trickling down to the neighbourhood of some heated subterranean lava, causes this phenomenon". On Terceira, Darwin also observed the relationship between magma type and proximity to the central vent of a volcano (Figure 10), as he had done on Isla Santiago in Galápagos.

Darwin's field notes from Terceira describe how he visited the summit of the active volcano (Pico Alta) and observed evolved magmas (trachytes) in the caldera and basalt on the lower slopes. He noted that there were "lavas of a smooth texture, of a blackish colour with crystals of glassy felspar [sic] similar to some on James Isd." (Santiago, Galápagos was called "James" by the British into the 20th century). More generally on Terceira, flows of trachyte are associated with large central vents and calderas whereas basalts and hawaiites have been erupted from fissures along the so-called Terceira rift zone (stippled ornament on Figure 10). Despite the comparable age and size of Terceira (Azores) and Isla Santiago (Galápagos), a far greater proportion of the lavas erupted on Terceira have evolved compositions. More recent studies have confirmed that if a silicic magma reservoir forms under the central part of the volcano, mafic magmas are restricted to the margins of the system [Bacon 1985].

5 Mauritius

Darwin observed that the Indian Ocean island of Mauritius is a strongly eroded basaltic volcano, surrounded by uplifted corals: this obvious evidence for uplift had been attributed to magma injection, the craters of elevation hypothesis. He noted that the central core of the islands is formed of lavas that dip away from the middle and emphasized that the lavas are subaerial. He noted the similarity of the island's structure to that of Santiago in the Cape Verde Archipelago [Darwin 1844]. Darwin also observed the interlayering of lava and scoria and the existence of uneroded cones that sit upon the eroded lavas of the shield-building phase of volcanism, what is now recognized as the rejuvenated stage of ocean-island volcanism. In the *Voyage* [Darwin 1845b], Darwin has an internal debate as to whether the quaquaversal dips of the central core of Mauritius is in fact due to upheaval or merely the eroded remanent of an ancient volcano. We now know that Mauritius formed at the Mascarene hotspot during the Miocene, and the currently active volcano is on Reunion Island. Post-shield lavas erupted on Mauritius in the Pleistocene [Baxter et al. 1985].

6 The Andes

While most of Darwin's notes of volcanic phenomena are from ocean islands, he was also fascinated by the Andes, where he observed the mountains and eruptions from a distance. He traveled across the Andes, between Santiago and Mendoza (at Portillo and Uspallata passes), but was 70 km from the nearest volcano, Tupungatito. Nevertheless, these were the first eruptions that he observed on the *Beagle* voyage.

Figure 11: Volcan Osorno was in eruption while Darwin was sailing along the coast of Chile and was one of the few eruptions he witnessed over the course of his life. The eruptive episode he witnessed lasted about 88 days (± 4). Osorno has had three eruptive episodes since, the most recent in 1869 [Global Volcanism Program 2024].

Even though viewed from the sea >100 km away, Darwin was impressed by the volcanic activity he witnessed in the Southern Volcanic Zone of the Andes: on November 26, 1834 (Chacao, N tip of Isla Chiloe), he wrote in his field notes, "The Volcano of Osorno was spouting out volumes of smokes; this most beautiful mountain, formed like a perfect cone & white with snow, stands out in front of the Cordilleras Cordillera. Another great Volcano, with a saddle shaped summit, also emitted from its immense crater little jets of steam or white smoke."

On Jan. 19, 1835, Darwin watched Osorno (Figure 11) erupt at night from Isla Chiloe, observing incandescent bombs flying out of the summit, but "By the morning the Volcano seemed to have regained its composure." When describing the eruption, he notes reports that Aconcagua was simultaneously erupting [Darwin 1845b], although this is impossible (see below). He also notes that Coseguina volcano in Nicaragua erupted simultaneously and implies a common cause and source.

6.1 Earthquake triggering hypothesis

Darwin initiated a centuries-long body of science that addresses the triggering of eruptions by tectonic earthquakes [e.g. Manga and Brodsky 2006]. On February 20, 1835, Darwin was lying down resting when an M8.1 earthquake struck the region around Concepcion, Chile and uplifted the coastline as much as 3 m. He was impressed by observations made by Fitzroy and a local resident, Mr. Caldcleugh, that the earthquake triggered eruptions in the Juan Fernandez archipelago (Robinson Crusoe Island; an explosive submarine eruption), although persistently active Villarica was unaffected (CD field notes of Feb. 20, 1835 [Darwin 1844]). According to the account, Osorno and Michinmahuida were already in eruption, but they increased activity during and after the earthquake. Darwin contended that the earthquake triggered eruptions throughout the Southern Volcanic Zone and Juan Fernandez, an area of 1200 × 650 km and speculated that the entire region (twice the area of the Black Sea) was underlain by a lake of lava [Darwin 1845b].

There is a fundamental problem with Darwin's hypothesis on earthquake triggering of eruptions: it is based on second-hand reports of eruption rather than direct observation, and many of the reported eruptions are fictive. In his field notes of July 31, 1834, Darwin refers to "The volcano of Aconcagua", and several other eruptions from the mountain are described in the *Voyage*. The problem is that although Aconcagua is partly constituted of Miocene volcanic rocks, it is not a volcanic mountain [e.g. Ramos 2009]. The eruption at Robinson Crusoe Island (Juan Fernandez Archipelago) is now discredited [Lara et al. 2020]. The Smithsonian Institution's eruption database also lists 3 of 5 eruptions in the Andes in 1835 as being "uncertain". In other words, Darwin based his consideration of earthquake-triggering of eruptions on falsities.

6.2 Volcanism and uplift

Darwin's main interest while exploring the Andes was not so much eruptive phenomena as it was the cause of volcanism and its relation to elevation [Darwin 1846]. In his field notes of March 5, 1835, Darwin presents the idea that solid crust of the Earth floats on a mass of molten rock, and volcanoes are "apertures" through the crust. Forces cause an undulation in the fluid which then trigger earthquakes and eruptions. This idea was then presented in a paper to the Geological Society of London in 1835, read by Professor Sedgwick [Darwin 1836].

When he visited the Andes, Darwin was generally sympathetic to the craters of elevation hypothesis [Herbert 2005]. Volcanoes were viewed as being upheaved structural domes rather than being built from the surface with steep primary dips. Darwin agreed with Von Buch [1836] that lava could not solidify on a 30° slope, so there had to be upheaval to explain the observed dips. Lyell later disproved the craters-of-elevation hypothesis by his work in Val de Bove on Etna, where he described modern lavas that had solidified lava on steep slopes with little change in thickness [Lyell 1858]. Darwin addresses the craters-of-elevation hypothesis throughout his geologic writing and seems to fall on both sides of the debate.

7 Conclusions

With little prior knowledge of the field geology of volcanic terrains, Charles Darwin interpreted modern and ancient volcanic features in terms of active process, one of the guiding principles of field volcanology. Because he was one of the first natural scientists to visit many of Earth's most iconic volcanic terrains, and he did his field work at a time when uniformitarianism was winning the intellectual competition with catastrophism, Darwin was able to observe and hypothesize on dozens of novel volcanological topics, ones that had rarely if ever been discussed by other scientists.

Among Darwin's most notable contributions to the science of volcanology are:

- The transport and deposition of wet ash from hydrovolcanic eruptions, the formation of palagonite, and hydrovolcanic landforms and bedforms.
- The structure and morphology of lava flows and scoria cones and a facies model for them.
- The origin of textural banding in silicic lavas.
- The triggering of eruptions by earthquakes.
- The relationship between volcanism and the uplift of mountain belts.

An attribute of all of these areas of study is that they remain rich topics of research in modern volcanology.

All of that noted, we also want to emphasize that Darwin's status in history as a pioneer in volcanology should not be exaggerated. Had he not figured out the origin of the diversity of life on the planet, he likely would have been best known as a productive natural scientist who had the opportunity to participate in one of history's great scientific voyages and write a compelling narrative of it. Even in geology, his work on the origin of coral reefs surpasses that on volcanoes [Herbert 2005].

As our final note, we will point out that on September 25, 1836, as the Beagle was approaching England, Darwin listed "an active volcano" as among the most remarkable spectacles he had observed over the past five years.

Author Contributions

Both authors performed field work that forms the basis of this paper, and both contributed to the writing of the paper and figures.

Acknowledgements

DG's field work in Galápagos has been funded by the U.S. National Science Foundation (most recently grant 1145271) and the National Geographic Society. SG's work was supported by the British Council and NERC (RG57434). The authors would like to thank Sandra Herbert, David Norman, Thalia Grant and Greg Estes for their decades-long collaboration in exploring Darwin's contributions to our understanding of the natural history of the Galápagos. The authors deeply appreciate the support of the Charles Darwin Foundation and the permission of the Galápagos National Park for field work in the Galápagos. We thank Markes Johnson for his thoughtful review.

Data Availability

This contribution contains no new data; the sources of data are all included in the References section.

References

Bacon, C. R. (1985). "Implications of silicic vent patterns for the presence of large crustal magma chambers". *Journal of Geophysical Research: Solid Earth* 90(B13), pages 11243–11252. DOI: 10.1029/jb090ib13p11243.

Barlow, N. (1958). *The Autobiography of Charles Darwin 1809-1882*. Collins. ISBN: 978-0393310696.

Baxter, A. N., B. G. J. Upton, and W. M. White (1985). "Petrology and geochemistry of Rodrigues Island, Indian Ocean". *Contributions to Mineralogy and Petrology* 89(1), pages 90–101. DOI: 10.1007/bf01177594.

Browne, E. (1996). *Charles Darwin: Voyaging*. Princeton University Press. ISBN: 978-0691026060.

– (2003). *Charles Darwin: The Power of Place*. Princeton University Press. ISBN: 978-0679429326.

Castro, J., D. Dingwell, A. Nicols, and J. Gardner (2005). "New insights on the origin of flow bands in obsidian". *Kinematics and Dynamics of Lava Flows*. Edited by M. Manga and G. Ventura. Geological Society of America, pages 55–65. ISBN: 978-0813723969. DOI: 10.1130/0-8137-2396-5.55.

Darwin, C. (1836). "Geological notes made during a survey of the east and west coasts of S. America, in the years 1832, 1833, 1834 and 1835, with an account of a transverse section of the Cordilleras of the Andes between Valparaiso and Mendoza". *Proceedings of the Geological Society of London* 2, pages 210–212.

– (1839). "Journal and remarks 1832-1836". *Narrative of the Surveying Voyages of His Majesty's Ships Adventure and Beagle Between the Years 1826 and 1836,* volume 3. Henry Colburn.

– (1842). *The Structure and Distribution of Coral Reefs: Being the Third Part of the Geology of the Voyage of the Beagle, Under the Command of Capt. Fitzroy, R.N. During the Years 1832 to 1836*. Smith Elder and Company.

– (1844). *Geological Observations on the Volcanic Islands Visited During the Voyage of H.M.S. Beagle, Together with Some Brief Notices of the Geology of Australia and the Cape of Good Hope: Being the Third Part of the Geology of the Voyage of the Beagle, Under the Command of Capt. Fitzroy, R.N. During the Years 1832 to 1836*. Smith Elder and Company.

– (1845a). "Extracts from letters to the General Secretary, on the analogy of the structure of some volcanic rocks with that of glaciers". *Proceedings of the Royal Socitety of Edinburgh* 2, pages 17–18. DOI: 10.1017/s037016460003532x.

– (1845b). *Journal of Researches Into the Natural History and Geology of the Countries Visited During the Voyage of H.M.S. Beagle Round the World, Under the Command of Capt. Fitz Roy, R.N.* John Murray.

– (1846). *Geological Observations on South America: Being the Third Part of the Geology of the Voyage of the Beagle, Under the Command of Capt. Fitzroy, R.N. During the Years 1832 to 1836*. Smith Elder and Company.

– (1859). *The Origin of Species by Means of Natural Selection, or Preservation of Favoured Races in the Struggle For Life*. John Murray.

Daubeny, C. (1826). *A Description of Active and Extinct Volcanos*. Cambridge University Press. DOI: 10.1017/CBO9780511978159.

Fagents, S. and T. Thordarson (2009). "Rootless volcanic cones in Iceland and on Mars". *The Geology of Mars: Evidence from Earth-Based Analogs*. Edited by M. Chapman. Cambridge University Press, pages 151–177. ISBN: 978-0511536014. DOI: 10.1017/cbo9780511536014.007.

Geikie, A. (1909). *Charles Darwin as Geologist: The Rede Lecture given at the Darwin Centennial Commemoration on 24 June 1909*. Cambridge University Press. DOI: 10.1017/CBO9780511702228.001.

Geist, D. J., A. R. McBirney, and R. A. Duncan (1986). "Geology and petrogenesis of lavas from San Cristobal Island, Galápagos Archipelago". *Geological Society of America Bulletin* 97(5), pages 555–566. DOI: 10.1130/0016-7606(1986)97<555:gapolf>2.0.co;2.

Gibson, S. A., D. G. Geist, J. A. Day, and C. W. Dale (2012). "Short wavelength heterogeneity in the Galápagos plume: Evidence from compositionally diverse basalts on Isla Santiago". *Geochemistry, Geophysics, Geosystems* 13(9), Q09007. DOI: 10.1029/2012gc004244.

Gibson, S. (2009). "Darwin the Geologist in Galapagos: An Early Insight into Sub-volcanic Magmatic Processes". *Proceedings of the California Academy of Sciences*. Volume 61. California Academy of Sciences, S69–S88.

Global Volcanism Program (2024). *Volcanoes of the World, v.5.2.4*. Edited by E. Venzke. DOI: 10.5479/si.GVP.VOTW5-2024.5.2.

Grant, K. and G. Estes (2009). *Darwin in Galápagos: Footsteps to a New World*. Princeton University Press. ISBN: 978-0691142104.

Herbert, S. (2005). *Charles Darwin, Geologist*. Cornell University Press. ISBN: 978-0801443480.

Herbert, S., S. Gibson, D. Norman, D. Geist, G. Estes, T. Grant, and A. Miles (2009). "Into the Field Again: Re-Examining Charles Darwin's 1835 Geological Work on Isla Santiago (James Island) in the Galápagos Archipelago". *Earth Sciences History* 28(1), pages 1–31. DOI: 10.17704/eshi.28.1.mjt982717p162323.

Howard, K., T. Simkin, D. Geist, G. Merlen, and B. Nolf (2019). "Large hydromagmatic eruption related to Fernandina Volcano's 1968 caldera collapse—Deposits, landforms, and ecosystem recovery". *Field Volcanology: A Tribute to the Distinguished Career of Don Swanson*. Edited by M. Poland, M. Garcia, V. Camp, and A. Grunder. Geological Society of America, pages 385–408. ISBN: 978-0813725383. DOI: 10.1130/2018.2538(18).

Hutton, J. (1795). *Theory of the Earth, with Proofs and Illustrations (in Four Parts)*. Royal Society of Edinburgh.

Johnson, M. E. and B. G. Baarli (2015). "Charles Darwin in the Cape Verde and Galápagos archipelagos: The role of serendipity in development of theories on the ups and downs of oceanic islands". *Earth Sciences History* 34(2), pages 220–242. DOI: 10.17704/1944-6187-34.2.220.

Kar, A., B. Weaver, J. Davidson, and M. Colucci (1998). "Origin of differentiated volcanic and plutonic rocks from Ascension Island, South Atlantic Ocean". *Journal of Petrology* 39(5), pages 1009–1024. DOI: 10.1093/petroj/39.5.1009.

Keynes, R., editor (1988). *Charles Darwin's* Beagle *Diary*. Cambridge University Press. ISBN: 978-0521003179. DOI: 10.1017/S0007087400044058.

Kolzenburg, S., M. O. Chevrel, and D. B. Dingwell (2022). "Magma / Suspension Rheology". *Reviews in Mineralogy and Geochemistry* 87(1), pages 639–720. DOI: 10.2138/rmg.2022.87.14.

Lara, L. E., R. Moreno, V. Valdivia, R. Aránguiz, and M. Lagos (2020). "The AD1835 eruption at Robinson Crusoe Island discredited: Geological and historical evidence". *Progress in Physical Geography: Earth and Environment* 45(2), pages 187–206. DOI: 10.1177/0309133320937998.

Lyell, C. (1830). *Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation*. John Murray.

– (1858). "On the structure of lavas which have consolidated on steep slopes; with remarks on the mode of origin of Mount Etna, and on the theory of "craters of elevation"". *Philosophical Transactions of the Royal Society of London* 148, pages 730–786. DOI: 10.1098/rstl.1858.0032.

Mahr, J., K. S. Harpp, M. D. Kurz, D. Geist, H. Bercovici, R. Pimentel, Z. Cleary, and M. D. Córdova Aguilar (2016). "Rejuvenescent Volcanism on San Cristóbal Island, Galápagos: A Late "Plumer"". *AGU 2016 Fall Meeting Abstracts*. V53C-3119.

Manga, M. and E. Brodsky (2006). "Seismic triggering of eruptions in the far field: Volcanoes and geysers". *Annual Review of Earth and Planetary Sciences* 34(1), pages 263–291. DOI: 10.1146/annurev.earth.34.031405.125125.

Moore, J. G. (1967). "Base surge in recent volcanic eruptions". *Bulletin Volcanologique* 30(1), pages 337–363. DOI: 10.1007/bf02597678.

Pearson, P. (1996). "Charles Darwin on the Origin and Diversity of Igneous Rocks". *Earth Sciences History* 15(1), pages 49–67. DOI: 10.17704/eshi.15.1.t06x771068434276.

Rader, E. and D. Geist (2015). "Eruption conditions of spatter deposits". *Journal of Volcanology and Geothermal Research* 304, pages 287–293. DOI: 10.1016/j.jvolgeores.2015.09.011.

Ramos, V. (2009). "Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle". *Backbone of the Americas: Shallow subduction, Plateau Uplift, and Ridge and Terrane Collision*. Edited by S. Kay, V. Ramos, and W. Dickinson. Geological Society of America, pages 31–65. ISBN: 978-0813712048. DOI: 10.1130/2009.1204(02).

Rowland, S. K. and G. P. Walker (1990). "Pahoehoe and a'a' in Hawaii: volumetric flow rate controls the lava structure". *Bulletin of Volcanology* 52(8), pages 615–628. DOI: 10.1007/bf00301212.

Scrope, G. (1825). *Considerations on Volcanos: the Probable Causes of Their Phenomena, the Laws Which Determine Their March, the Disposition of Their Products, and Their Connexion with the Present State and Past History of the Globe. Leading to the Establishment of a New Theory of the Earth*. W. Phillips.

Secord, J. (2003). *Victorian Sensation: The Extraordinary Publication, Reception, and Secret Authorship of Vestiges of the Natural History of Creation*. The University of Chicago Press. ISBN: 978-0226158259.

Self, S. (1976). "The Recent volcanology of Terceira, Azores". *Journal of the Geological Society* 132(6), pages 645–666. DOI: 10.1144/gsjgs.132.6.0645.

Self, S., L. Keszthelyi, and T. Thordarson (1998). "The importance of pāhoehoe". *Annual Review of Earth and Planetary Sciences* 26(1), pages 81–110. DOI: 10.1146/annurev.earth.26.1.81.

Sulloway, F. J. (1982). "Darwin and his finches: The evolution of a legend". *Journal of the History of Biology* 15(1), pages 1–53. DOI: 10.1007/bf00132004.

Tuffen, H., S. Flude, K. Berlo, F. Wadsworth, and J. Castro (2020). "Obsidian". *Encyclopedia of Geology*. Edited by D. Alderton and S. Elias. Second Edition. Academic Press, pages 196–208. ISBN: 978-0-08-102909-1. DOI: 10.1016/B978-0-12-409548-9.12527-8.

Van Wyhe, J., editor (2002). *The Complete Works of Charles Darwin Online*. URL: http://darwin-online.org.uk.

Van Wyk de Vries, B., A. Márquez, R. Herrera, J. L. G. Bruña, P. Llanes, and A. Delcamp (2014). "Craters of elevation revisited: forced-folds, bulging and uplift of volcanoes". *Bulletin of Volcanology* 76(11). DOI: 10.1007/s00445-014-0875-x.

Von Buch, L. (1836). "On volcanoes and craters of elevation". *Edinburgh New Philosophical Journal* 21, pages 189–206.

Walker, G. P. L. (1991). "Structure, and origin by injection of lava under surface crust, of tumuli, "lava rises", "lava-rise pits", and "lava-inflation clefts" in Hawaii". *Bulletin of Volcanology* 53(7), pages 546–558. DOI: 10.1007/bf00298155.

Waters, A. C. and R. V. Fisher (1971). "Base surges and their deposits: Capelinhos and Taal Volcanoes". *Journal of Geophysical Research* 76(23), pages 5596–5614. DOI: 10.1029/jb076i023p05596.

White, J. and P.-S. Ross (2011). "Maar-diatreme volcanoes: A review". *Journal of Volcanology and Geothermal Research* 201(1–4), pages 1–29. DOI: 10.1016/j.jvolgeores.2011.01.010.

Wohletz, K. H. and M. F. Sheridan (1983). "Hydrovolcanic explosions; II, Evolution of basaltic tuff rings and tuff cones". *American Journal of Science* 283(5), pages 385–413. DOI: 10.2475/ajs.283.5.385.