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

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ABSTRACT

The 1831–1836 voyage of H.M.S. *Beagle* under Captain Robert FitzRoy launched Charles Darwin's entry into the world of geology with two pioneering publications on oceanic islands to his credit. Best known is Darwin's 1842 contribution on the theory of atoll development from the subsidence of volcanic islands and coeval upward growth of coral reefs. This work can be linked, in part, to the ten days during which the *Beagle* visited the Keeling (Cocos) Islands. The subsequent and lesser known of Darwin's parallel contributions is his 1844 summary on all the volcanic islands visited during the expedition, including Santiago (Cape Verde Islands), Terceira (Azores), St. Paul's Rocks, Fernando Noronha, Ascension, St. Helena, the Galápagos Islands, Tahiti, and Mauritius. Ostensibly, the centerpiece of the 1844 volume is Darwin's extensive coverage of Ascension based on the five days spent there in 1836. However, Darwin had many more days at his disposal in the Galápagos and 'St. Jago' (Santiago), where the *Beagle* stopped in the Cape Verde Islands at the outset and again near the end of the voyage. The volcanic islands where Darwin spent the most time were in the Galápagos (thirty-five days) and the Cape Verdes (twenty-nine days). In particular, those island groups make an interesting comparison with respect to the development of Darwin's ideas on tectonic uplift based on basalt flows with inter-bedded limestone formations. Chance played a huge role in what Darwin saw and did not see during his island travels. The initial visit to the Cape Verde islands was instrumental in shaping Darwin's earliest vision of a book on volcanic islands, but his time there was entirely fortuitous due to a forced change in FitzRoy's plan for a stay in the Canary Islands. Although Darwin was on the look out for limestone formations in the Galápagos islands comparable to those on Santiago in the Cape Verdes, he missed finding them due only to the vagaries of FitzRoy's charting schedule in the Galápagos. This overview looks at limestone distribution in the Cape Verde and Galápagos archipelagos as now understood and speculates on how a wider knowledge of both regions may have influenced Darwin's thinking on global patterns of island uplift and subsidence.

Keywords: Oceanic islands, coastal geomorphology, limestone markers, peperite deposits, tectonic uplift. doi: 10.17704/1944-6187-34.2.220

1. INTRODUCTION

One of the simplifications often perpetuated in the history of science relates to the experience of Charles Darwin (1809–1882) as a guest naturalist during the second voyage of the H.M.S. *Beagle* from December 1831 to October 1836 as though the maturation of a budding evolutionist was a clear outcome leading to the 1859 publication of *On the Origin of Species*. The extent to which geology quickly captured the imagination of the 22-year-old Cambridge graduate is better appreciated due to detailed research by Herbert (2005), although the extent to which Darwin's mindset was impacted by serendipitous choices executed during even the earliest stages of the ship's charting mission bears further inquiry. The twenty-two chronometers carried by the *Beagle* required calibration at a known geographic starting point early in the voyage in order to accurately calculate longitude during the following global circumnavigation. Captain Robert FitzRoy (1805–1865) planned to carry out this task at the first opportunity in the Canary Islands. The *Beagle* anchored off Santa Cruz on Tenerife on 6 January 1832 only eleven days out of Plymouth harbor, but local authorities denied permission for the crew to leave ship before going through a twelve day quarantine imposed on account of a cholera outbreak in England. Darwin was much disappointed at this turn of events, as he had looked forward to spending time on the island following the exploits of Alexander von Humboldt (1769–1859). FitzRoy decided to leave the Canary Islands immediately and set course for the Cape Verde Islands, where the *Beagle* arrived in Praia harbor on 'St. Jago' (Santiago) 16 January 1832. A small harbor island, Ilhéu de Santa Maria which was named 'Quail Island' by the crew, became the site dedicated to the all-important task of calibrating the ship's chronometers. As luck would have it, the islet holds the key to unraveling some of the most extraordinary geology exposed along the coast of Santiago. While the great volcano on Tenerife presents interesting aspects peculiar to it alone, the tenor of Darwin's explorations would have been much altered had the main part of his physical journey started and ended in Humbolt's shadow on that island.

The special status of 'Quail Island' in the Cape Verdes is reinforced by the fact that FitzRoy needed to return to the same place near the conclusion of the voyage in order to verify the accuracy of his longitudinal calculations. Thus, Darwin had the rare opportunity to re-evaluate his earliest geological observations after gaining five years of experience with stops at many other volcanic islands during the ensuing voyage. The limestone formations found on 'Quail Island' that are repeated on the adjacent shores of Santiago are visually striking and without parallel in thickness or lateral extent on Tennerife. Furthermore, the unique place that 'St. Jago' came to represent in Darwin's unfolding career is underscored by his own biographical recollections published posthumously and uncensored much later on. Therein, Darwin (1958, p. 81) described the effect on viewing a continuous line of white limestone baked hard by "a stream of lava" that "formerly flowed over the bed of the sea." He claimed instantly to have understood the implications of the relationship in terms of island uplift, although Pearson and Nicholas (2007) showed that the first part of *Principles of Geology* authored by Charles Lyell (1797–1875) and published in 1831 had yet to influence the young naturalist. Given his severe proclivity to seasickness, it is unfathomable that Darwin had much chance to read the Lyell volume given to him by FitzRoy in Plymouth (see Herbert 2005, p. 63) prior to reaching the Cape Verdes. In any case, it remained a "memorable hour" in the self-expressed consciousness of Charles Darwin when the thought "first dawned" that he "might perhaps write a book on the geology of the various countries visited" during the course of the voyage. Retrospective as it was, such a firm resolution seldom pinpoints the beginning of a life's intellectual arc in one so young.

Santiago's coastal geology and geomorphology set a high standard for comparisons with other oceanic islands visited by Darwin during the ensuing five-year voyage of the HMS *Beagle*. The degree to which this is the case is readily tracked by direct and indirect references to 'St. Jago' made by Darwin (1844) in the context of several other islands, most notably the Galápagos, Mauritius, and Ascension islands. Regional prevailing winds and the generation of surface marine currents also found a prominent place in his observations on the formative processes of erosion and deposition (Darwin 1844). Overall, the amount of time available to Darwin for exploration in the various island groups provides a scale by which the thoroughness of his results may be judged. The chief goal of this review is to focus on the Cape Verde and Galápagos archipelagos taking Darwin's observations into account, but also paying attention to what Darwin did not see in relation to what is presently known about the distribution of Neogene limestone formations in those island groups. As his geological career played out, Darwin's theory on the development of island atolls from his 1842 study attracted significantly more and longer-lasting attention than his notion on island uplift as loosely sketched in the 1844 volume. The reasons for this outcome are discussed and it is considered how Darwin's arguments for uplift are strengthened had he been allowed more time to explore additional islands in the Cape Verde and Galápagos archipelagos. Such questions are increasingly relevant as paleontologists, sedimentologists, coastal geomorphologists, and volcanologists continue to explore and think about the ups and downs of oceanic islands in relation to geographic patterns of island distribution (Ramalho *et al*. 2013; Woodroffe 2014).

2. GEOGRAPHIC AND GEOLOGIC SETTINGS

The Cape Verde archipelago includes fifteen volcanic islands spread across the seafloor of the Cape Verde Rise in the eastern Atlantic Ocean located from 500–1500 km off the northwest coast of Africa. Modern dating techniques in relation to plate tectonics provide a context for the archipelago's physical setting that came to be understood long after Darwin's visit. Due to a nearly stationary position with respect to sources of magma from the upper mantle (McNutt 1988; Pim *et al*. 2008), the archipelago takes on a cluster shape arrayed in a crude, west-facing semi-arc on the Nubian Plate. Generally, the islands range in age from eight million years in the west to as much as twenty million years in the east. Historically, only the southwestern island of Fogo has remained volcanically active with the most recent eruptions occurring in 2014, 1995, and previous to that in 1951. In relation to the dominant NE trade winds, the Cape Verdes are classified into windward and leeward islands that are evenly divided by a line of latitude crossing approximately 16° north of the equator (see Figure 1, upper-left inset). The only island visited by Darwin was Santiago (see Figure 1, upper-right inset), where he described inter-bedded limestone and basalt formations (Darwin 1839, 1844) that extend for several kilometers along the coast

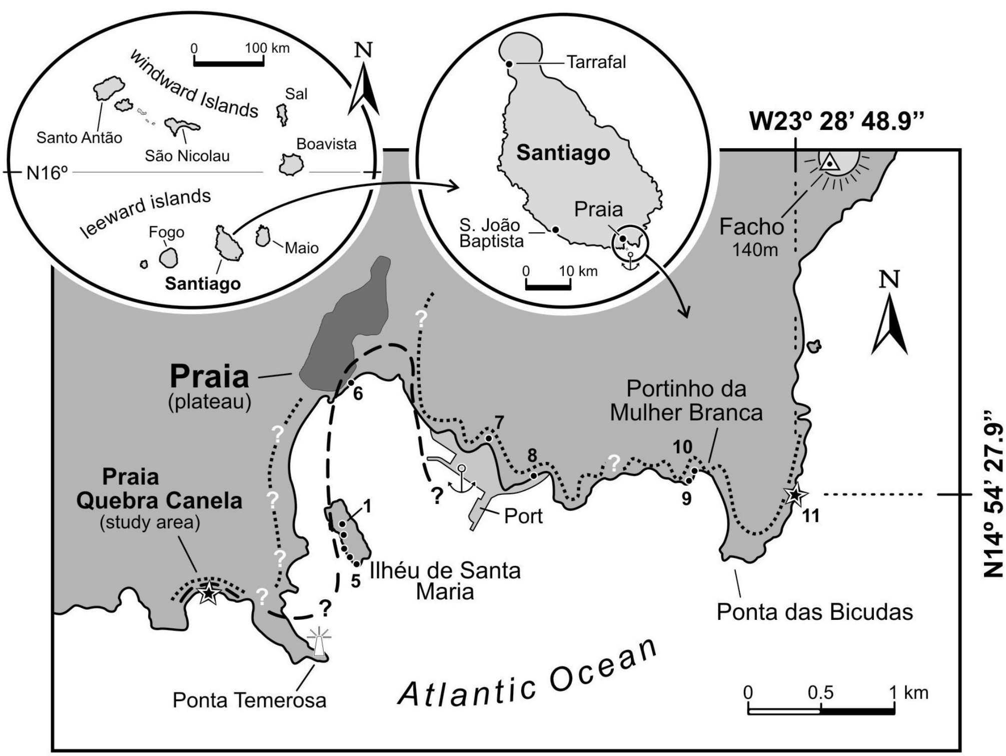

Figure 1. Maps for the major islands of the Cape Verde archipelago (North Atlantic Ocean) with closer details on the southeast coast of Santiago (figure prepared by C. M. da Silva).

nearby what was then the Portuguese provincial capital of Praia (see Figure 1, main map). Similar limestone and basalt formations occur on at least four other islands in the archipelago. Praia is now the capital city of the Republic of Cape Verde, an independent island nation since 1975. The city has grown in size but not so much that the original itinerary followed by Darwin is difficult to retrace in detail to see what Darwin first witnessed in 1832 (Johnson *et al*. 2012).

The Galápagos archipelago straddles the equator and consists of eighteen main volcanic islands distributed in a broad band in the eastern Pacific Ocean (see Figure 2) located from 995–1200 km off the coast of Ecuador in South America. Again, it is acknowledged that modern dating techniques in relation to plate tectonics provide a context to the archipelago's physical setting that came long after Darwin's visit. All the islands belonging to the archipelago now reside on the Nazca Plate south of the Galápagos Spreading Center, which marks the boundary between the Cocos and Nazca plates (Geist et al., 2014). The Carnegie Ridge that follows eastward to the South American continent shows the progress of the Nazca Plate over a mantle plume responsible for the magmas that fed the island volcanoes. Maximum age of emergence

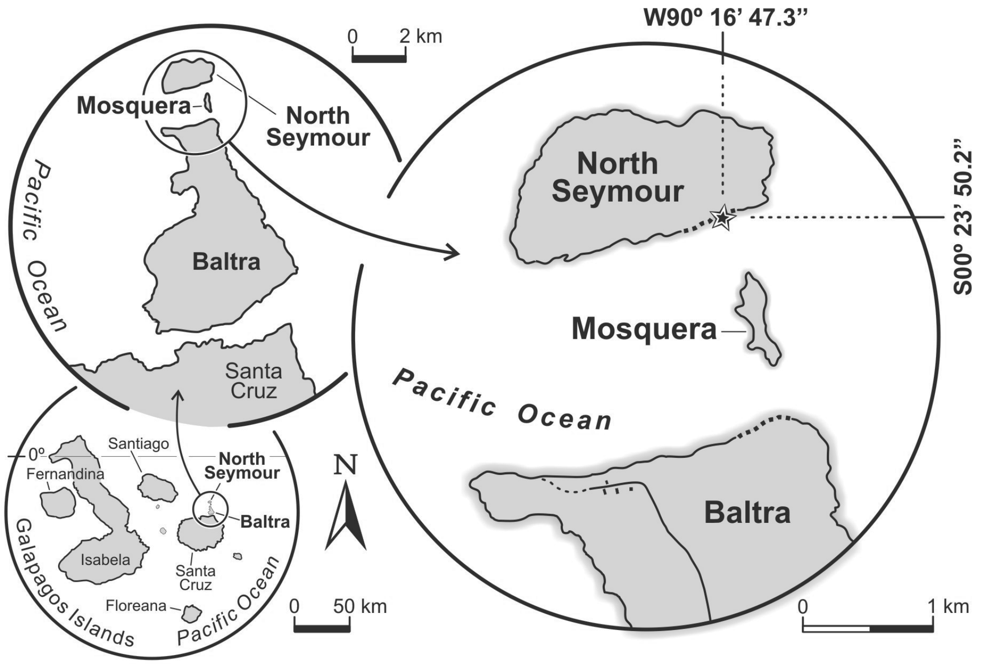

Figure 2. Maps for some islands in the Galápagos archipelago (East Pacific Ocean) with closer details on the opposing shores of Baltra and North Seymour (figure prepared by C. M. da Silva).

ranges from four million years for San Cristobal in the east to 60,000 years for Fernandina in the west (Geist et al., 2014, their Table 8.2). Historically, Fernandina and parts of Isabela have remained volcanically active with the most recent eruptions occurring on Fernandina in 2009. A major eruption on Fernandina took place in 1825, ten years before the arrival of HMS *Beagle* in that vicinity. Darwin never witnessed an active lava flow, but did report seeing a jet of steam issuing from a crater on Isabela (also known under its English name as Albermarle (Keynes 1988, p. 338)). The islands are impacted by seasonal patterns that bring cooler waters pushed by strong SE trade winds from May to December and Darwin was aware of this arrangement. Darwin visited four of the archipelago's islands, including San Cristobal (Chatham), Floreana (Charles), Santiago (James), and Isabela. Due to the status of the Galápagos National Park established under the protection of Ecuador in 1959, most of the land area in the islands is preserved from a geomorphological point of view much as Darwin experienced it in 1835. Accounts by Grant and Estes (2009) provide descriptions of where Darwin went and what he did during his entire stay in the islands. Herbert *et al*. (2009) give a more detailed account of where Darwin went and what he found during his extended stay on Santiago, or James Island. With respect to fossil deposits that Darwin knew about, in addition to several others discovered since his time in the islands, brief summaries are given by Hickman and Lipps (1985) and by García-Talavera (1993).

3. STUDY METHODS

The contents of Darwin's fifteen notebooks compiled during the voyage of the *Beagle* were reviewed from annotated sources (Chancellor and van Wyhe, 2009) with specific attention paid to entries on limestone and marble to see how his outlook on those rock types may have developed during the entire course of the expedition. In relationship to the number of days devoted by Darwin to each island group, the original published texts written by Darwin (1839, 1844) were analyzed in order to find changes in length and topic of focus for all those segments on the oceanic islands encountered during the global circumnavigation of the HMS *Beagle* in 1831–1836. Visits to the Cape Verde Islands with the intention of following Darwin's itinerary for close examination of the same geological outcrops described by him were conducted in June/July 2011, as well as March 2012. Visits to the Galápagos Islands with the object of viewing as much coastal landscape as possible in addition to key localities with fossil limestone deposits were made in March/April 2009, as well as February 2014.

4. RESULTS FROM NOTEBOOK AND TEXT ANALYSES

Darwin never sat for formal courses in geology while a student at Cambridge from 1828 to 1831. Professor Adam Sedgwick (1785–1873) agreed to take him on as an assistant for fieldwork in North Wales in August 1831 in order to provide some useful geological experience in anticipation of a trip to Tenerife in the Canary Islands Darwin planned with a group of his Cambridge classmates. The landscape around Darwin's boyhood home in Shrewsbury on the Welsh Borderland features extensive Silurian limestone, but there is no evidence he knew or cared much about limestone prior to his instruction during fieldwork with Sedgwick. That summer, the Cambridge professor was particularly interested in the Devonian Old Red Sandstone exposed in the Vale of Clwyd. Traversing the valley, the pair followed contacts between the older sandstone and younger Carboniferous limestone (Keynes, 2003, p. 20). Darwin clearly learned to recognize limestone and to appreciate its organic composition during fieldwork at that time as determined by shelly fossils and other kinds of fossils such as corals.

The extent to which Darwin subsequently commented on exposures of limestone or marble during the *Beagle*'s tour may be gauged by the number of pages from his extensive notebooks that record those rock types (see Table 1). Out of 1,945 pages of written notes in fifteen notebooks, only 116 pages include information on limestone or its metamorphic product as marble. This amounts to a mere six percent of the written notebook pages, and yet those particular rock types made a deep impression on Darwin as markers that show changes in relative sea level in connection with uplift over geologic time. It is striking that in the first notebook covering his observations in the Cape Verde Islands, there are no references to limestone at all and a single notation on marble. In the Galápagos notebook, there are only four notations on limestone and none on marble. This may appear odd considering those rocks played a key role in Darwin's later geological writings. With rare exceptions, however, the rock types appear to a greater or lesser degree in Darwin's notes collected throughout the voyage. The exception is the Port Desire notebook (Table 1), which omits any mention of limestone or marble. This notebook covers the period of Darwin's experiences in Patagonia, the Falklands, Tierra del Fuego, and the island of Chiloe off the coast of Chile from 2 January to at least 8 December 1834. Even in such boreal settings where deposits of Neogene limestone are uncommon, Darwin recorded observations that reveal his thinking about relative changes in sea level and uplift. For example, on 17 January 1834 at Barranca south of Port St. Julian on the shores of Patagonia, Darwin observed mudstone with many blue-colored mussel shells together with oyster fragments at the top of a cliff "60 or 70 feet high" (Chancellor and van Wyhe, 2009, p. 307). In this case, the concentration of shelly materials was insufficient to make a limestone out of a mudstone, but the meaning was clear. Likewise, notations from the Valparaiso notebook record Darwin's encounters with limestone near the Portillo Pass uplifted to elevations 14,000 feet or more above sea level (Chancellor and van Wyhe, 2009, p. 359; Keynes, 2003, p. 280). Both examples show that Darwin remembered lessons learned earlier with respect to the uplifted volcanic shores around Santiago Island in the Cape Verde archipelago.

Table 1. Pages devoted by Charles Darwin to descriptions of limestone and marble from his serial notebooks (1832–1836)

Notebook number and name	Total written pages	Pages on limestone	Pages on marble
1. Cape de Verds	80	0	1
2. Rio	81	3	0
3. Buenos Ayres	88	4	0
4. Falkland	142	17	2
5. Bahía Blanca	87	1	0
6. Santa Fé	238	35	6
7. Banda Oriental	242	8	0
8. Port Desire	182	0	0
9. Valparaiso	98	10	0
10. Santiago	125	9	0
11. Galapagos	100	4	0
12. Coquimbo	132	13	0
13. Copiapó	134	4	1
14. Despoblado	135	3	0
15. Sydney	81	5	0
Totals	1,945	116	10

Abstracted and reworked from his travel diary and notebooks, the initial contribution by Darwin (1839) was a natural history narrative with a wide-ranging mix of observations on plants, animals, and rocks, as well as social commentary. When it came time to produce the volume on volcanic islands that he had dreamed of writing almost from the start of the voyage, some chapters from the travelogue were expanded to incorporate additional geological information based on subsequent library work starting from the material already covered, whereas other segments were severely truncated (see Table 2). As an example of the latter, the 1839 text on Tahiti was reduced by 53.4% mainly through exclusion of all social commentary but also because Darwin had little to report on the island's actual geology. Darwin (1844) had much of substance to say about the geology of the Galápagos Islands, although a 17.5% reduction in size from the travelogue resulted partly from exclusion of all the biological material covered, therein (Darwin 1839). On the other hand, the geology of Ascension Island (Darwin 1844) resulted in a major 854% increase over what was covered in the earlier travelogue. Although Darwin had only five days at his disposal for explorations on Ascension, the resulting 1844 text devoted to this particular island far exceeded those individual segments on the other islands under study. Overall, the ratio of days spent on Ascension-related fieldwork compared to length of resulting text shows the highest yield for productivity with respect to any of the oceanic islands visited by Darwin (see Table 2).

Table 2. Text in words devoted by Charles Darwin to island descriptions in his voyage narrative (1839) and geological observations (1844).

Island	Island days	1839 Narrative (number of words)	1844 Geology (number of words)	Percent change
Cape Verde (St. Jago)	29	2,680	7,355	+174%
St. Paul's Rocks	1	1,072	676	-37%
Fernando Noronha	1	195	294	+50.8%
Galápagos	35	11,373	9,378	-17.5%
Tahiti	12	6,049	819	-53.4%
Keeling	10	11,361		
Mauritius	11	1,144	1,261	+10.2%
Ascension	5	1,364	13,008	+854%
St. Helena	7	1,867	8,580	+360%
Azores	4	11	612	+5,464%

The importance assigned by Darwin to the Ascension segment is underscored by the fact that a detailed foldout map for that island forms the frontispiece of the 1844 volume. Such a capacious outcome is accounted for by Darwin (1958, pp. 81), where he recalls his excitement on receiving mail from home on reaching Ascension on 19 July 1836 with news that geologist Adam Sedgwick had called on his father, Robert Waring Darwin (1766–1848) in Shrewsbury and confided that the aspiring young geologist "should take a place among the leading scientific men". Further, he recalled: "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!" (Darwin 1958, p. 82). There can be little doubt that Darwin's flagging spirits were lifted by this news on nearing the end of a long voyage and realizing that his labors had already found appreciation and some token of respect.

In fact, Darwin's time on several other islands exceeded that spent on Ascension with the greatest number of days being devoted to 'St. Jago' in the Cape Verde Islands (29 days) and to the islands of the Galápagos (35 days). In length measured by number of words, the amount of geological text ascribed to the Galápagos Islands places second after Ascension, whereas the 'St. Jago' text is the fourth longest among all the 1844 segments. Darwin's remarks on the geology of Ascension are unique among those for the other oceanic islands he visited, on account of the medium-grained granite (syenite) he discovered there embedded as xenoliths within fragments of scoria. The Ascension segment (Darwin 1844) also is notable for his observations on the effect of the SE trade winds with respect to sculpting the shape of the island's many secondary crater rims. In all other respects, the content of the 1844 'St. Jago' and Galápagos segments may be considered as superior for the holistic nature of their content demonstrating a mix of igneous and sedimentary geology together with aspects of geomorphology and the physical processes of sedimentation and erosion.

5. CAPE VERDE AND GALÀPAGOS ACCOUNTS RE-EVALUATED

The first chapter of Darwin's 1844 volume gave a geological description covering the southeast part of 'St. Jago' with a focus mainly on a 10-km stretch of rocky coastline running east of Praia to Ponta das Bicudas and around to the north beyond Facho (see map, Figure 1), a volcanic crater that he identified as 'Signal Post Hill'. Landscape geomorphology also was treated with regard to several other hills located a short distance inland. Chapter Five in the 1844 volume is devoted to the Galápagos archipelago with separate segments on San Cristobel (Chatham Island), Isabela (Albemarle Island), and Santiago (James Island), whereas commentary on the geology of Floreana (Charles Island) was very limited. Chapter Six was devoted to aspects of differential mineralogy in volcanic rocks specifically related to James Island, as Darwin knew it under its English name. Consequently, it is relevant to point out that Darwin's geological description of 'St. Jago' in the Cape Verde archipelago was generally more concentrated in terms of the actual amount of physical ground canvassed in comparison to those texts describing several of the Galapagos islands which cover a much larger composite area.

5.1 Inter-bedded limestone and basalt layers in the Cape Verde archipelago

Praia's harbor on the south shore of Santiago (see Figure 1) provided not only a safe anchorage for HMS *Beagle* from the region's brisk NE trade winds, but offered Ilhúe de Santa Maria (or 'Quail Island') as a secure base of operations for at least part of the crew's visit from 16 January to 7 February 1832. This harbor islet still exists as it was then, essentially untouched for more than 180 years since Darwin first landed to be confronted by a distinctive cliff line (see Figures 3A–C). While FitzRoy and others attended to the ship's chronometers, Darwin had ample time to investigate the stratified layers exposed around the margin of the table-like islet and to consider their significance.

Then, as today, the visitor is struck by the distinctive tri-part nature of strata with white limestone sandwiched between dark layers of basalt. Darwin (1844) identified the dominant fossil component of the limestone as an accumulation of concretions precipitated by 'Nulliporae' or coralline red algae. He observed that the algae often are nucleated around a basalt pebble (see Figure 4). The fossil material collected by Darwin from 'Quail Island' is held by the Sedgwick Museum at the University of Cambridge (Herbert 2005, see her figure 5.6). There can be no doubt that Darwin's 'Nulliporae' represent what now are referred to as rhodoliths, or spherical-shaped, unattached coralline red algae that grow in a concentric pattern as they roll around on the sea floor moved by wave action and shifting bottom currents.

On site at Ilhúe de Santa Maria, Johnson *et al*. (2012) logged and correlated a series of five stratigraphic columns. Spaced out along a line from north to south (see Figure 1), the profiles demonstrate lateral changes in the limestone from deposits of sand-size particles derived from crushed rhodoliths consistent with a beach setting to those with abundant whole rhodoliths consistent with a more offshore position. Overall, Darwin (1844, p. 2) understood that the limestone is unconformable in position above volcanic rocks drowned by the sea, and that subsequently "a wide sheet of basaltic lava" from a landward source capped the limestone. He also proposed that the lava stream reached the sea by flowing between a set of "square-topped hills" shown to be located inland about one and a half miles (two and a half kilometers) on his localized map. In this regard, Darwin's description pre-figures the Hawaiian expression for a 'kipuka' as a semi-formal geological term for an isolated piece of land surrounded by lava flows. Also, without quite applying the full name for columnar basalt, Darwin (1844, pp. 9–10) described a subaerial flow that caps the limestone on 'Quail Island' as lava "split by vertical fissures into five-sided plates, and these again, being piled on each other … forming fine

Figure 3. Views of Ilhúe de Santa Maria: (A) From the air, (B) From cliffs on the Praia City plateau, and (C) From the inner harbor facing the islet's east shore (images by B.G. Baarli).

symmetrical columns". Nearby on the same page, he referred to vesicular lava "divided into balls, frequently as much as three feet in diameter, made up of concentric layers". This appears to be as close as Darwin came to a description of weathered pillow basalt indicative of a former submarine flow.

Figure 4. Limestone layer from 'Quail Island' showing abundant rhodoliths against a 50-cm grid for scale (image by M. E. Johnson).

Both kinds of basalt are well represented at different places along the southeastern coast of Santiago Island, and often so by pillow basalt vertically succeeded by columnar basalt (see Figure 5). The juncture between layers of pillow basalt and columnar basalt is called a passage zone and the thickness of the pillow basalt on the underlying limestone is taken to represent the former water depth on the seafloor occupied by a submarine flow before the accommodated lava breaks the surface of the water (Ramalho *et al*. 2010). Typically, the thickness of pillow basalts exposed along the shore between localities 8 and 10 east of Praia harbor (see Figure 1) amounts to 12 m, which indicates that the seawater directly above the accumulated carbonate deposit was about 12 m deep when the first basalt flow arrived (Johnson *et al*. 2012). Darwin drew no such distinction in attempting to qualify changes in relative sea level shown by the occurrence of limestone layers between basalt flows. However, he clearly recognized that the successive layering of limestone beds represented the history of a marine onlap against a paleoshore. Describing the disposition of the limestone outcrop along the mainland coast, Darwin (1844, p. 8) wrote: "In some ravines at right angles to the coast, it [the limestone] is seen gently dipping towards the sea, probably with the same inclination as when deposited round the ancient shores of the island".

The attention to detail with which Darwin described relationships between limestone and succeeding basalt layers is of particular interest, because the coastal outcrops on Ilhéu de Santa Maria and the adjacent mainland of Santiago exhibit outstanding examples for understanding the physical dynamics between carbonate sediments subjected to molten lava. In this regard, he was among the earliest to represent features that later gave rise to specific terminology. For example, Darwin (1844, p. 6) offered the following observation regarding the transition between limestone and basalt on 'Quail Island':

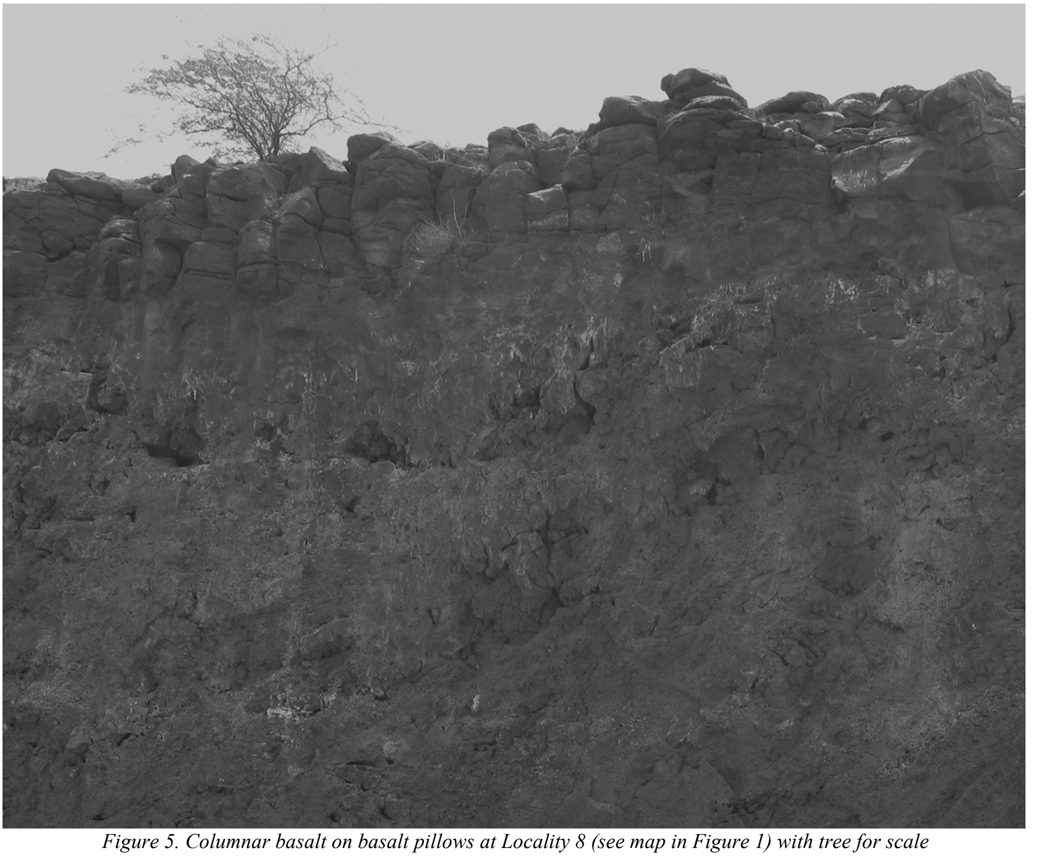

Figure 5. Columnar basalt on basalt pillows at Locality 8 (see map in Figure 1) with tree for scale (image by M. E. Johnson).

> The lowest and most scoriaceous part of the lava, in rolling over the sedimentary deposit at the bottom of the sea, has caught up large quantities of calcareous matter, which now forms a snow-white, highly crystalline, basis to a breccia, including small pieces of black, glossy scoriae. A little above this, where the lime is less abundant, and the lava more compact, numerous little balls, composed of spicula of calcareous spar, radiating from common centres, occupy the interstices.

This description relates to the term 'peperite' often applied today to the same composite rock, but also characterized by Darwin (1844, p. 99) as 'peperino' when considering potentially similar rocks in the Galápagos. As an extension of this discussion, Darwin invoked the formation of "carbonic acid gas" as having been generated by the direct application of lava to carbonate sediments, and he considered that the gas was pressurized under the weight of the overlying lava delta. Darwin struggled with this concept in attempting to explain variations in the fusion of lime with different volcanic products. In his examination of broken fragments collected from "scoriae embedded in the calcareous mass", Darwin (1844, p. 11) discovered "cells lined and partly filled with a white, delicate, excessively fragile, moss-like, or rather conferva-like, reticulation of carbonate of lime". Somewhat awkwardly further on, he argued (Darwin 1844, p. 12):

> It is obvious that the lava and lime have on a large scale been very imperfectly mingled; where small portions of the lime have been entangled within a piece of the viscid lava, the cause of their now occupying, in the form of a powder or a fibrous reticulation, the vesicular cavities, is, I think,

evidently due to the confined gases having most readily expanded at the points, where the incoherent lime rendered the lava less adhesive.

Examples of what Darwin tried to describe are evident at many places close to the juncture of the basalt and underlying limestone both on Ilhúe de Santa Maria and along the adjacent coastal cliffs of the mainland to the east. A good example may be observed in a road exposure across from the port terminal near locality 7 (see map in Figure 1). The remobilization of calcium-carbonate material is illustrated by a hyaloclastite and pillow basalt breccia that resulted from magma extruded in sea water over wet sediments dominated by carbonate sand (see Figure 6).

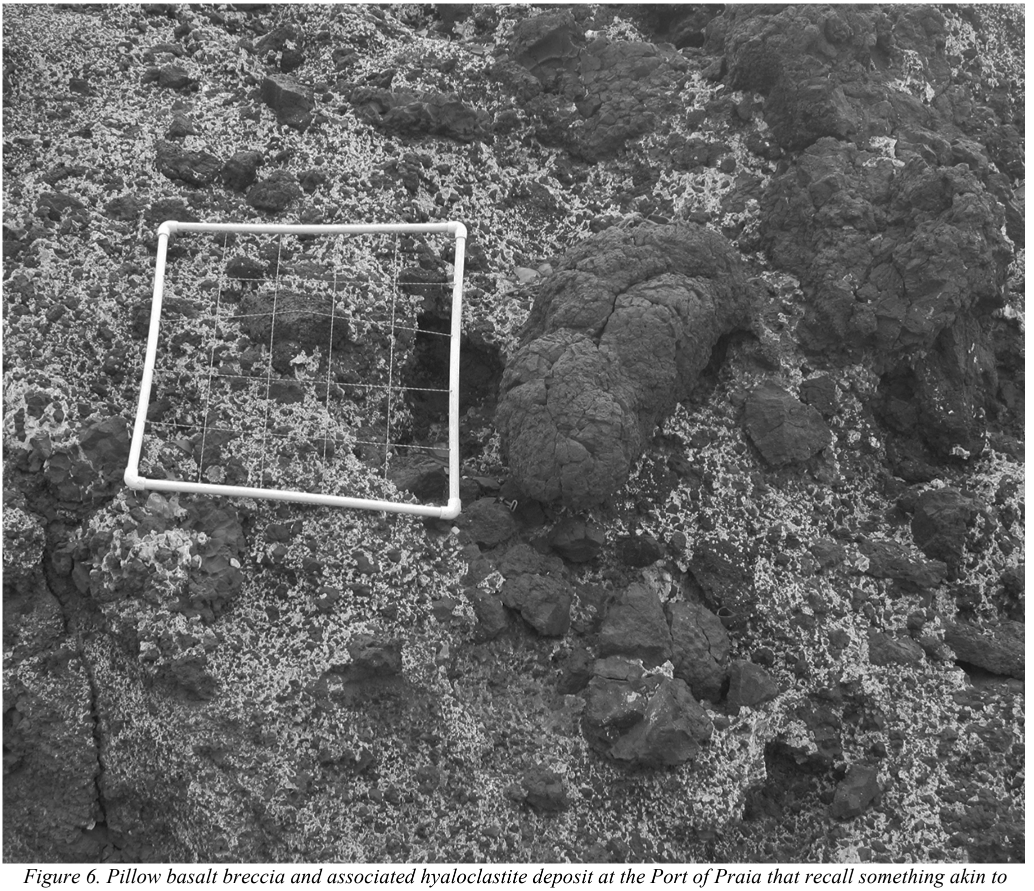

Figure 6. Pillow basalt breccia and associated hyaloclastite deposit at the Port of Praia that recall something akin to Darwin's peperino. Scale shown by grid 50 cm on each side (image by M. E. Johnson).

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In terms of thickness and lateral extent, Darwin interpreted a single seam of limestone that he estimated to be as much as twenty feet (six meters) thick directly traceable from the Praia harbor area to Signal Post Hill, and beyond. Based on fossils collected from 'Quail Island', he concluded that the limestone was Late Tertiary in age. He explored the landscape east and northeast of Praia on foot and devoted considerable space to the description of the geology and terrain around Signal Post Hill that included a cross section showing the tri-part basalt and limestone layers exposed in the coastal cliff face below the crater at Facho (Darwin 1844, p. 9, illustration No. 2). He also mentioned an attempt to look for coastal exposures of the limestone west of Praia as the *Beagle* cruised along the shore in that direction.

Johnson *et al*. (2012) found not one but two distinct limestone formations interbedded among basalt flows along the south coast of Santiago Island. On the basis of calcareous nanofossils collected from intervals within the limestone formations, it was determined that two distinct events of marine onlap occurred between approximately 1.1 and 0.7 million years ago. Visual proof for the second event was confirmed during a second field season in 2012 based on a new study site at Praia Quebra Canela (see map in Figure 1), where a combination of beach cliffs and road-cut exposures demonstrate the physical relationship between the two separate limestone formations. The shoreline east of Praia features a continuous exposure of limestone that is somewhat older than found in the harbor at Ilhéu de Santa Maria. At Quebra Canela, overlap of the two limestone layers shows that the younger event left a limestone rim in a position topographically lower on the shore than the earlier event. Traces of the younger event on the coast east of the city plateau largely have been removed by erosion. The relevance of this discovery is that the uplift history of Santiago Island is more complicated than Darwin envisioned, as it entails not one episode of island uplift but rather a sequence of discrete subsidence and uplift events more akin to a bobbing action.

Further exploration along the coast near Punta das Bicudas to the northeast (see map in Figure 1, locality 11) also resulted in discovery of a distinct variation in the older limestone formation shown by Pleistocene corals preserved in growth position attached directly to the basalt substrate (Baarli *et al*. 2013). Darwin, who was thrilled to see his first living corals in tide pools on 'Quail Island' and probably elsewhere along the coast, would have been much pleased had he made this discovery. The locality is significant, because it illustrates a unique set of local physical conditions with strong wave activity against the island's southeast corner that stimulated vigorous coral growth. It is likely that Darwin walked along this part of the coast, but was unable to see the corals because active quarrying to remove the overburden of limestone at this spot had not yet gone into operation. Darwin's notebook entry for "concentric crystalline white marble" (Chancellor and van Wyhe, 2009, p. 13) can be appreciated at a spot further north of Punta das Bicudas. Heat from pillow basalt in direct contact with the rhodolith deposit transformed the original limestone into a porcelain-like texture much like marble while retaining the structure of the rhodoliths (see Figure 7).

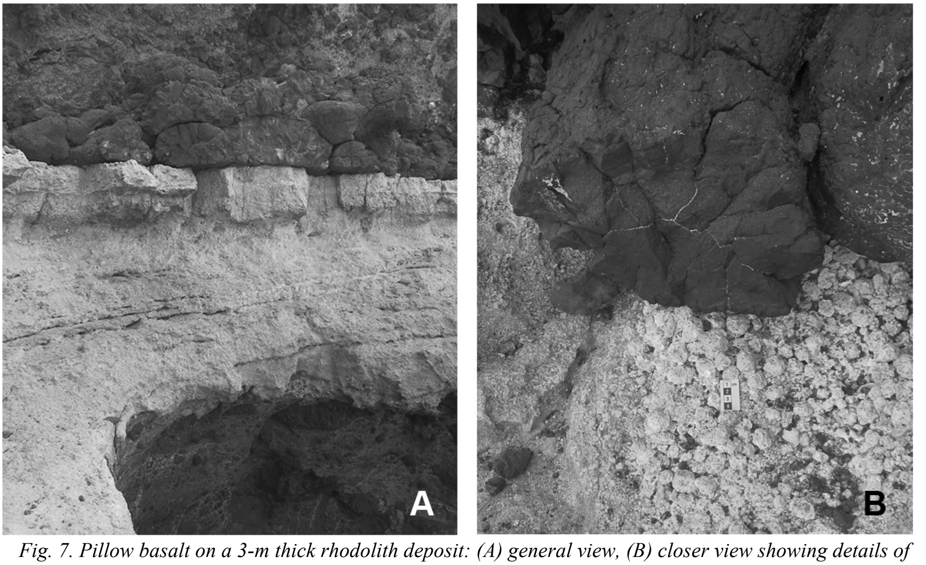

Fig. 7. Pillow basalt on a 3-m thick rhodolith deposit: (A) general view, (B) closer view showing details of individual rhodoliths (scale 3 cm) (images by M. E. Johnson).

Innovative as the first geological results of Darwin's explorations on 'St. Jago' happened to be, the essential charting mission of the HMS *Beagle* gave Captain FitzRoy no excuse to spend more time than absolutely necessary in the Cape Verde archipelago. The ship would not return to Praia until 31 August 1836, spending only five days in port. However, at least four other islands in the Cape Verdes are presently understood to exhibit extensive limestone formations that relate to variable patterns of uplift and subsidence throughout the island group (Ramalho *et al*. 2010). Close by Santiago in the leeward islands is Maio (see map, Figure 1), where carbonate dunes of Pleistocene age are reported to include a major component of rhodolith sand deflated from beaches on the east side of the island by the strong NE trade winds (Johnson *et al*. 2013). Although considered a leeward island, the strength of the prevailing NE trade winds that blow across 'St. Jago' clearly were appreciated by Darwin (1839, p. 3):

> On a small plain which we crossed, a few stunted acacias were growing; their tops, by the action of the steady trade-wind, were bent in a singular manner – some of them even at a right angle to the trunk. The direction of the branches was exactly N.E. by N., and S.W. by S., and these natural vanes must indicate the prevailing direction of the force of the trade wind.

The massive Pleistocene dunes preserved at Lomba Greija on Maio conform in shape and the orientation of cross bedding to the influence of the NE trade winds (Johnson *et al*. 2013), which also agrees with the present-day disfigurement of local trees just as Darwin described. His observations in this regard mirror the application of the term '*krummholtz*' widely used for wind indicators shown by 'bent wood'. Extensive Pleistocene limestone beds also are exposed on the south shores of Maio that are rich in rhodoliths and trace-fossil suites that compare well with those on Santiago (Mayoral *et al*. 2013). On São Nicolau (see map, Figure 1), even more extensive limestone beds with a high concentration of rhodolith material crop out in the sea cliffs along the southeast part of that island. These beds are sandwiched between basalt flows that give the same appearance of a tri-part formation as witnessed by Darwin on 'St. Jago'. In this case, however, dating of the limestone on the basis of calcareous nanofossils from correlative beds indicates a Late Miocene age (Johnson *et al*. 2014). This configuration may be traced uninterrupted along the shore for a distance of 2.5 km, and would have been readily spotted from the deck of the *Beagle*, had the ship been piloted past São Nicolau close by on that side of the island. Limestone deposits of Pleistocene age that sit on marine terraces at different levels on basaltic basement rocks may be followed practically around all sides of the windward islands of Boavista (Serralheiro 1974) and Sal (Zazo *et al*. 2007) in the northeast part of the Cape Verde archipelago. The stair-step geomorphology of raised terraces is emblematic of coastal uplift, patterns that are often observable from offshore by ship.

Shipboard observations on coastal geomorphology were not excluded from Darwin's practice on the HMS *Beagle*. Writing under the heading of 'coast denudation' in a general vein but also in connection with the island of St. Helena, he recorded (Darwin 1844, p. 92):

> When reflecting on the comparatively low coasts of many volcanic islands, which stand exposed in the open ocean, and are apparently of considerable antiquity, the mind recoils from an attempt to grasp the number of centuries of exposure, necessary to have ground into mud and to have dispersed the enormous cubic mass of hard rock which has been pared off the circumference of this island.

Given time and opportunity, Darwin clearly was capable of directing his energies to this topic, and island uplift in connection with coastal erosion proved to be a subject of particular interest as demonstrated from the beginning with his focused attention on 'St. Jago' in the Cape Verde archipelago.

5.2 Inter-bedded limestone and volcanic layers in the Galápagos archipelago

Stepping ashore in the Galápagos archipelago for the first time near Cerro Tijeretas (Frigatebird Hill) on the southeastern end of Isla San Cristobal (Chatham Island) on 16 September 1835, Darwin was eager at once to find evidence for island uplift following the same principles as illustrated in the Cape Verde archipelago. Writing under the heading 'Elevation of the Land', Darwin (1844, pp. 114–115), dutifully recorded: "At Chatham Island, I noticed some great blocks of lava, cemented by calcareous matter, containing recent shells; but they occurred at a height of only a few feet above high-water mark". This statement was prefaced by the remark that elsewhere in the islands: "Proofs of the rising of the land are scanty and imperfect". According to Grant and Estes (2009, p. 87), the conglomerate sampled by Darwin at the San Cristobel locality included "the plates of chitons and the broken shells of limpets and bivalves" characteristic of life in the littoral zone. During the remainder of Darwin's stay in the Galápagos, he failed to find anything remotely similar to the tri-part, inter-bedded basalt and limestone beds he had experienced on 'St. Jago' in the Cape Verdes. However, based on tuffaceous rocks also encountered on San Cristobel, he made extensive comments on the effect of volcanic rocks in contact with marine sediments having a high content of shelly material (Darwin 1844, p. 99):

> The position near the coast of all the craters composed of this kind of tuff or peperino, and their breached condition, renders it probable that they were all formed when standing immersed in the sea; considering this circumstance together with the remarkable absence of large beds of ashes in the whole archipelago, I think it highly probable that much the greater part of the tuff has originated from the trituration of fragments of the grey, basaltic lavas in the mouths of craters standing in the sea. It may be asked whether the heated water within these craters has produced this singular change in the small scoriaceous particles and given to them their translucent, resin-like fracture. Or has the associated lime played any part in this change? I ask these questions having found at St. Jago, in the Cape Verde Islands, that where a great stream of molten lava has flowed over a calcareous bottom into the sea, the outermost film, which in other parts resembles pitchstone, is changed, apparently by its contact with the carbonate of lime, into a resin-like substance, precisely like the best characterized specimens of the tuff from this archipelago.

Darwin's fascination with tuff cones was extended to his recording the number and orientation of breeched cones encountered by himself and others from among the *Beagle*'s crew during charting duties in the Galápagos, which he identified as "the most striking feature in the geology of this Archipelago" (Darwin 1844, p. 113). Based on sightings of twenty-eight tuff cones, most of which "form either separate islets, or promontories attached to the larger islands", Darwin concluded that their soft crater walls had been breeched by the steady erosion of waves driven by trade winds blowing preferentially from the southeast. He also argued that some tuff craters must have been already worn away judging by the extreme wear exhibited by some surviving craters. Furthermore, he noted that even among islets formed by hard basaltic rock, the southern windward exposure was "invariably steeper" than the northern, leeward slope.

Darwin failed to find any substantial examples of limestone deposits inter-bedded with volcanic flows exposed along the shores of islands in the Galápagos archipelago, but such examples do exist in the regional rock record and the potential for future development of such examples also persists. Grant and Estes (2009) acknowledged as much, citing the example of local seafloor uplift in Urvina Bay on Isla Isabela (Albemarle Island) associated with a 1954 earthquake when a half square-kilometer area including a coral reef was suddenly raised four meters above sea level (see Figure 8). All that is required for the extensive tract of coral reef to become fossilized is for a fresh eruption of volcanic ash to bury the area with a capping layer of tuff. It is an impressive spot that rivals anything a paleontologist might imagine as a significant ecological site in the process of likely preservation in the context of a major limestone deposit.

Despite the enormous volume of tourist traffic with which virtually all the islands in the Galápagos archipelago have been subjected since establishment of the National Park in 1959, places of scientific interest remain yet to be discovered by visitors and dedicated researchers. One such study on Quaternary deposits that features inter-bedded limestone and basalt comes from Isla Sombrero Chino adjacent to Santiago, or James Island (Johnson *et al*. 2010). Two separate limestone lenses occur inter-bedded within a sequence that includes basalt flows and a layer of tuff. The limestone lenses are beach deposits that include a prolific intertidal gastropod (*Nodilittorina galapagiensis*), as well as other mollusks, detached spines of echinoids, and rare fragments of bird bones. Sitting from three to four meters above present mean sea level, the stratigraphic package is capped by a protective layer of conglomerate consisting of basalt cobbles and rip-up clasts of platy limestone. The beach limestone and basalt-limestone conglomerate indicate moderate to strong wave activity consistent with a southern exposure on Isla Sombrero

China to the SE trade winds. The overall scenario indicates that a repetitive pattern of small-scale subsidence and uplift was recorded.

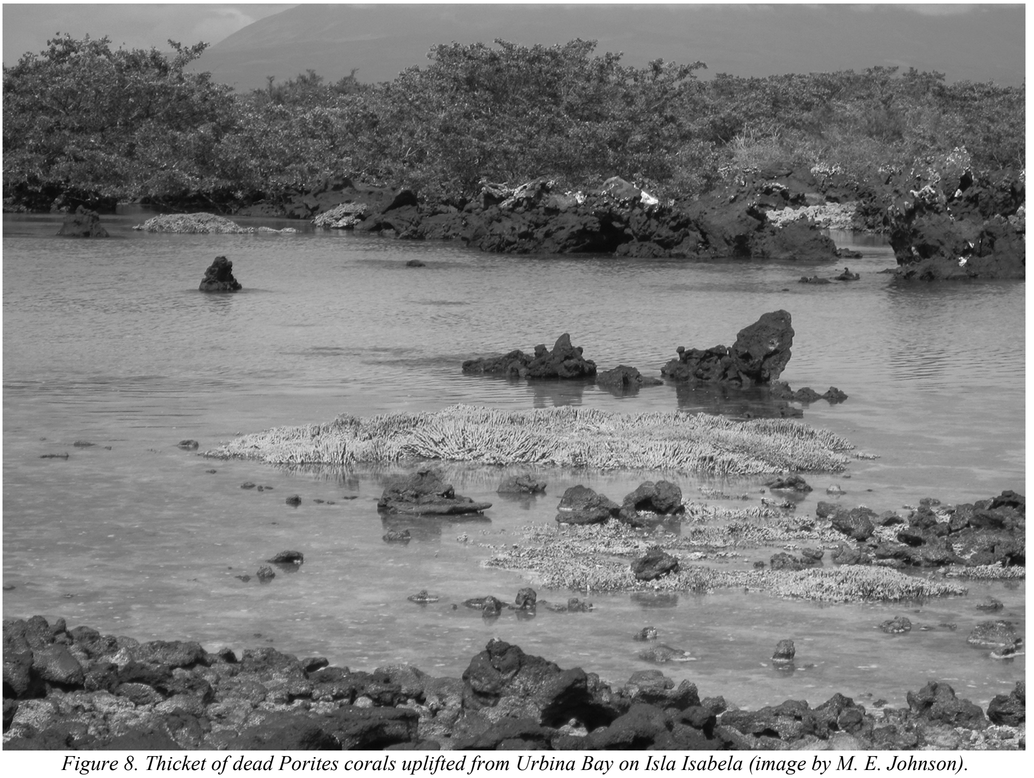

Figure 8. Thicket of dead Porites corals uplifted from Urbina Bay on Isla Isabela (image by M. E. Johnson).

The most striking comparisons with Neogene limestone formations from the Cape Verde archipelago to be found anywhere in the Galápagos are located on the adjacent coasts of Baltra and North Seymour islands (see main map, Figure 2). Only brief accounts for this area were supplied by Hickman and Lipps (1985) and by García-Talavera (1993), although Hertlein (1972) prepared a detailed report on the Pliocene marine fossils from the limestone. While Darwin was busy with geological prospecting on Santiago (James Island) to the west of Baltra, the crew of the *Beagle* was engaged with coastal survey work that took them around the outer coast of North Seymour Island and close to the eastern entrance of the strait between North Seymour and Baltra islands. The small Mosquera Island (three-quarters kilometer in length) broadly blocks the east entrance to the shallow strait, and vessels with a moderately deep draft generally avoid the area. Thus, it is not surprising that the *Beagle* kept clear of the passage between the two islands. Had smaller boats been sent into the strait, the crew would certainly have recognized the distinctive limestone layers exposed along the opposite cliffs of Baltra and North Seymour. Moreover, news of this locality would have been communicated to Darwin (as had other observations on breeched tuff cones so acknowledged by Darwin). Had he been given the opportunity to study this area, however briefly, Darwin's opinion regarding the scarcity of evidence for island uplift in the Galápagos may have changed.

Darwin's instincts as a field geologist were keenly formed (Herbert 2005) and it would have been possible for him to quickly make critical observations on the overall relationships among the rock layers exposed within the channel, as well as an evaluation on the present-day importance of abundant carbonate sand accumulating on Mosquera Island. Indeed, it is surprising that basic observations in terms of historical geology have not been put forward for this area by later investigators, given that Darwin's account of similar relationships on 'St. Jago' in the Cape

Verde archipelago left such a clear picture. Cliff faces clearly demonstrate the band of white limestone sandwiched between basalt flows on the north side of Baltra (see Figure 9A) and south side of North Seymour (see Figure 9B) from positions roughly perpendicular from the south and

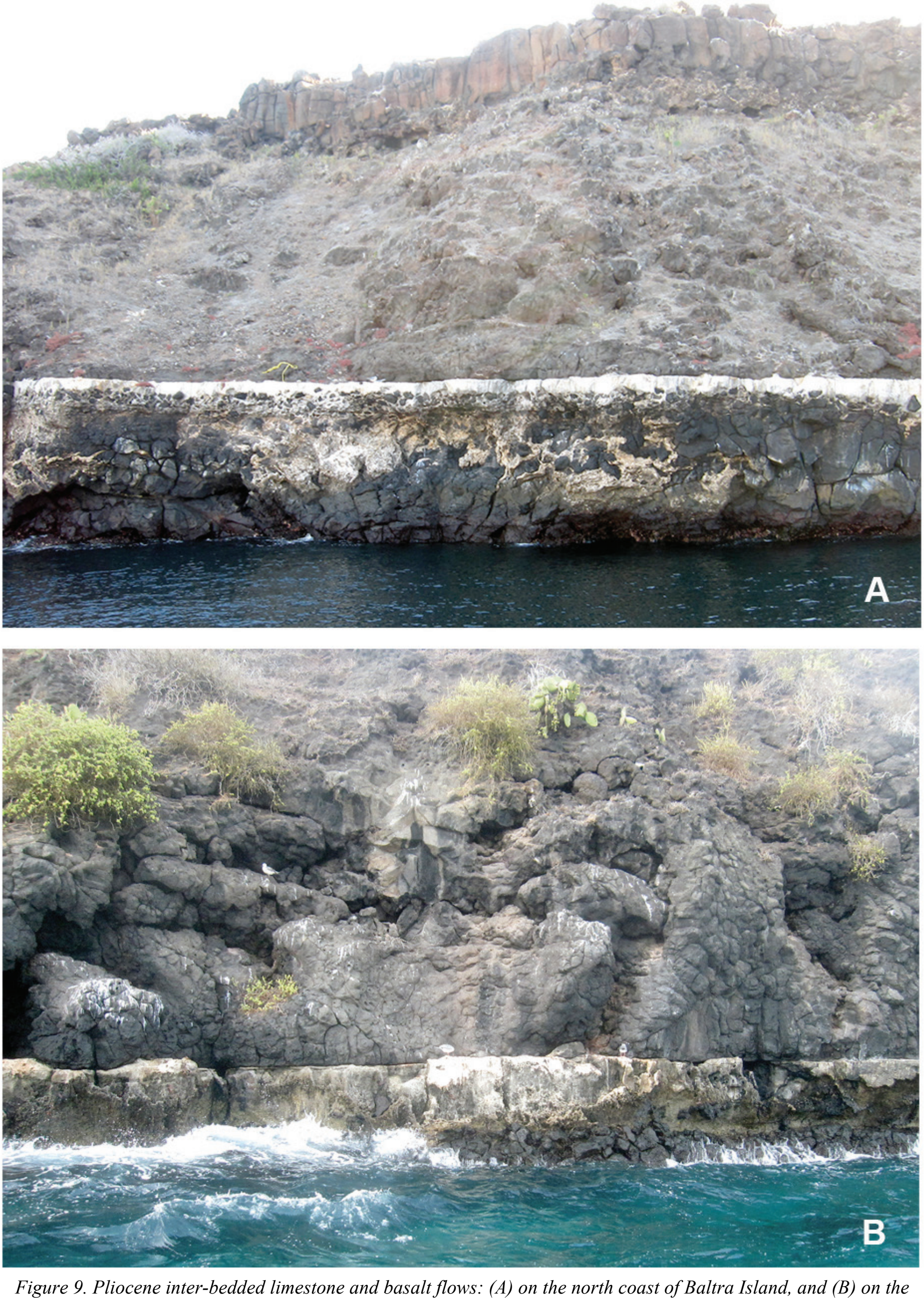

Figure 9. Pliocene inter-bedded limestone and basalt flows: (A) on the north coast of Baltra Island, and (B) on the opposite shore of North Seymour Island (images by M. E. Johnson).

north ends of Mosquera Island (see map, Figure 2). Darwin was accustomed to thinking about the lateral correlation of rock units along a cliff face over considerable distances, as he had done on the southeast coast of 'St. Jago'. The same operation is readily accomplished along the separate opposing shores of Baltra and North Seymour islands, but the next step is to correlate the limestone layers across the width of the intervening channel – a distance of only one and a half kilometers. The correlation is balanced on both sides of the strait by the same sequence of events that include a basal basalt formation, followed by limestone, succeeded mainly by basalt pillows, and capped by columnar basalt. The pillow basalt between the limestone and columnar basalt is approximately twelve meters thick on both sides of the channel, which further strengthens the cross-channel correlation. Much as the case back on 'St. Jago', a twelve-meter water depth is estimated at the time lava poured onto the former seafloor between Baltra and North Seymour islands.

There is no trace of limestone on Mosquera Island, which is formed by a low platform of basalt. However, a massive amount of carbonate sand is washed onto the island's west shoulder with dunes being blown across the basalt surface from west to east. Darwin would have understood this relationship intuitively and attributed the shifting carbonate sand to the influence of wave refraction forced through the channel under the seasonal influence of the SE trade winds. It is reasonable to suppose that Darwin also was capable of drawing a connection between the modern carbonate sand and the origin of the Pliocene limestone found on the opposite shores of the channel.

6. DISCUSSION

Widespread limestone deposits occur on five of the fifteen islands in the Cape Verde archipelago. The youngest islands, such as Fogo (see map, Figure 1) not only lack coastal limestone formations, but also lack the raw components that contribute to the build-up of limestone from rhodoliths and shelled invertebrates expected to thrive on adjacent marine shelves. Fogo is so young, for example, that the surrounding marine shelf is narrower and more steeply sloped than found around older islands like Sal to the northeast where a longer history of erosive shelf development has taken place. On average, islands in the Cape Verde group are older than those in the Galápagos group by several millions of years (Pim *et al*. 2008, Geist *et al*. 2014). The oldest eastern islands in the Cape Verde group also are closer to the continental shelf of Africa than the most eastern Galápagos islands are to the South American shelf. This factor has a bearing on the immigration of marine species. By comparison, major limestone formations occur on only three of the Galápagos islands, assuming that reports of a limestone band along the eastern shores of Santa Cruz are verified as coeval with those from Baltra and North Seymour. Hence, some disparity in the extent of limestone formations from the Galápagos in comparison to the Cape Verdes is to be expected.

The key to the equation is that similar limestone formations found in both island groups represent measurable episodes of subsidence and uplift during the prolonged lifetime of volcanic islands that form on thermal swellings in ocean crust with limited plate mobility. Flows from late-stage reactivation of subsidiary volcanic cones that erupt from the radial rift arms on older shield volcanoes also have the potential to interact with younger marine limestone. This clearly was the case with volcanic flows from the crater at 'Signal Post Hill' that Darwin associated with the burial of Late Tertiary limestone on 'St. Jago' in the Cape Verdes. On a much smaller scale, the same is true of the Quaternary limestone lenses found on Isla Sombrero Chino adjacent to Santiago, or James Island (Johnson *et al*. 2010) in the Galápagos. The youthful crater on Sombrero Chino is essentially a late-stage volcanic cone associated with a radial fracture on the adjacent James Island. Other volcanic archipelagos in the North Atlantic Ocean, including the Azores, Madeira, and Canary island groups, exhibit similar patterns whereby uplifted limestone beds of substantial thickness are restricted to the older islands. The Galápagos archipelago fits this particular model with its scattered islands of varying ages sitting on the Nazca Plate in the eastern Pacific Ocean. Darwin was fortunate to have spent a decent amount of time in both the

Cape Verde and Galápagos island groups, although he was unable to canvass enough islands in order to bolster his initial premise regarding the vertical movements of islands through uplift along a Lyellian model.

Entries on limestone and related topics from Darwin's notebooks show he was able to maintain different lines of inquiry throughout the voyage and to make comparisons with earlier experiences as new observations accrued. A good example comes from the Despoblado notebook, which was started in June 1835, but returned to during the last five months of the voyage. While on the island of St. Helena, Darwin was struck by something that reminded him of an earlier observation in the Galápagos Islands: "Galapagos – Structure of shell sand, sometimes no trace of shells" (Chancellor and van Wyhe, 2009, p. 546). Three pages later, Darwin makes the following comparative observation regarding clastic sand: "Granitic sand, coarse composed of rounded pebbles of quartz distinct horizontal strata *–[analog]* with Bahia *[Blanca]"* (Chancellor and van Wyhe, 2009, p. 547). The juxtaposition of these two entries reveals that Darwin was intellectually engaged in a new discipline concerned with comparative sedimentology. However, no detailed studies have been conducted on the microscopic-scale attributes of carbonate sand from Galápagos beaches and dunes such as amply found, for example, on Mosquera Island.

On 20 October 1835, the HMS *Beagle* hoisted sails and departed the Galápagos on a course set for Tahiti across a distance of 3200 miles through the South Pacific Ocean. The ship's company arrived twenty-six days later on 15 November 1835, and it was there offshore the northwest coast of Tahiti that Darwin first experienced a true coral reef from the immediacy of a native canoe he hired for that purpose (Darwin 1839). He had seen his first living corals in small tide pools on 'St. Jago' in the Cape Verdes, but the luxuriance of an actual coral reef made a more vivid impression. Only a day or so prior to reaching Tahiti, the *Beagle* was certain to have passed nearby Makatea in the Tuamuto archipelago, which represents an unusual example of massive limestone raised from the bottom of a former atoll (Menard 1986). The seventy-six meter thick limestone layers on Makatea are readily observable from the deck of a large ship, and had Darwin witnessed them it might have rekindled an interest in island uplift. As it happened, Darwin caught his first glimpse of the barrier reef that surrounds the neighboring peaks of Mo'orea (known to Darwin as Eimeo Island), when he climbed the hills above Matavai Bay on Tahiti to an elevation of about 900 meters. The close-up impressions of living reef corals and more distant sighting of the line of white water defining the barrier reef that skirts Mo'orea put Darwin on a line of inquiry more focused on island subsidence.

After interludes on the North Island of New Zealand, Australia's New South Wales, and Tasmania, the *Beagle*'s next destination was the Keeling (Cocos) Islands in the Indian Ocean. Departing southwestern Australia from Albany on 13 March 1836, the *Beagle* reached the greater ring that forms the South Keeling Islands on 1 April 1836. These islands represent the only two atolls ever visited by Darwin, and the ten days spent there by the *Beagle*'s crew gave him the foundational experience for his theory on the development of atolls already outlined in considerable detail by 1839 but subsequently developed in full (Darwin 1842). During the nearly three weeks it took to cross the Indian Ocean from Australia to the Keeling Islands, Darwin's diary is empty. As Darwin's diary entries during the stay in the Keeling Islands make it clear how deeply he was impressed by their formation, the general development of his thinking about atolls can be traced. However, it is unclear whether or not Darwin used time either before reaching the Keeling Islands or afterwards during the rest of the voyage through the Indian Ocean to study the existing charts of other atoll groups that the *Beagle* surely carried. The remarkable color-coded chart (Plate 3) that forms the frontispiece of the 1842 volume demonstrates the enormous amount of detail that went into Darwin's research on the distribution of the many fringing reefs, barrier reefs, and atolls scattered throughout the Pacific and Indian oceans. The only named atoll located in the Atlantic Ocean is Atol das Rocas located off the coast of Brazil, and it went missing in Darwin's account. Atol das Rocas stands in a line with the volcanic islands of Fernando de Noronha and is considered to share an origin with the same hotspot in the Earth's mantle (Courtillot *et al*. 2003). Ironically, Darwin visited Fernando de Noronha during a single day on 20 February 1832, but the *Beagle* passed well south of the related atoll on its way to Brazil.

The varied history of reception accorded to the theory of atoll development introduced by Darwin (1839, 1842) is covered more thoroughly, elsewhere. James Dwight Dana (1813–1895) was the first to endorse the theory based on his own extensive explorations in the Pacific Ocean with the United States Exploring Expedition (1838–1842) under the command of Lieutenant Charles Wilkes (1798–1877), which set out from Hampton Roads in Virginia nearly two years after the *Beagle* returned home to England in 1836. Darwin's theory subsequently was challenged by John Murray (1841–1914) and Alexander Agassiz (1835–1910), who devoted decades to travel and research on coral reefs around the world in search of alternative models (Dobbs 2005). Reviewed by Menard (1986), Darwin's elegant hypothesis was eventually substantiated by deep drilling through reef limestone on various atolls such as Enewetak in the Pacific Ocean during the 1960s. Coral thicknesses between 800 and 1400 meters were encountered, all found to have formed in shallow water residing on basement volcanic rocks. As noted most recently by Toomey *et al*. (2013), there remain certain aspects of the Darwin model that require adjustments for variability. However, the drawn-out controversy and its general resolution have magnified this particular aspect of Darwin's geological career and lent it value over his many other accomplishments in geology.

Both Darwin (1844) and Dana (1849) considered the size, shape, and collective orientation of oceanic islands grouped in various archipelagos with which they were familiar from personal experience. For Dana, a major theme was the linear arrangement of many islands and atolls in the Pacific Ocean. In particular, the Hawaiian chain of islands became the main example of this phenomenon and Dana (1849) cited patterns in coastal geomorphology to demonstrate that smaller islands at the NW end of many Pacific Ocean chains were subject to a longer history of erosion than the largest island at the SE extremity of a particular chain. Darwin (1844) attempted to sort out different lines of orientation in the Galapagos, Canary, and Cape Verde islands, but he had to admit that those belonging to the Cape Verde archipelago were the least symmetrical of any he had studied. In current thinking, the origin of true oceanic islands (i.e. excluding island arcs related to crustal subduction) is associated with mantle plumes rising through the Earth's upper mantle to drive further melting that penetrates oceanic crust to form island volcanoes above active hotspots. Courtillot *et al.* (2003, their Table 1) classified forty-nine of the Earth's hotspots and sorted them according to whether or not they may be related to a linear track of oceanic islands. The Hawaiian hotspot ranks as a linear pattern of associated islands as does Fernando de Noronha, whereas the Azores, Canary, and Cape Verde hotspots do not. However, they also gave a qualified "yes?" for a linear pattern connected with the Galápagos hotspot (Courtillot *et al*. 2003, p. 297). Another critical factor already well known by the late 1970s and early 1980s was the variable speed with which the Earth's tectonic plates pass over stationary hotspots. Menard (1986, p. 65) cited a speed of ten cm/year for the Pacific Oceanic Plate on which the Hawaiian chain resides, whereas the African Plate was assigned a speed of only one cm/year. Volcanoes that ride faster-moving plates such as the Pacific Plate are relatively short lived, because they are more rapidly disconnected from a given hotspot and they are more prone to form a straight line so long as the plate continues to move in the same direction. In contrast, slower plates with a speed of two cm/year or less, as for example the Nubian Plate off the west coast of Africa, are buoyed by hotspots that form huge swells with comparatively thick oceanic crust. This is considered to promote long-lived volcanoes that cluster together and experience more episodes of uplift relative to subsidence due to an extended history of volcanic reactivation (Ramalho *et al*. 2013). Hence, Darwin's difficulties fitting the Cape Verde archipelago into a more common pattern of development may be understood as a prime example of a disorganized island cluster connected with episodic volcanic growth on a tectonic plate that moves slowly in relation to a lithospheric swell (Ramalho *et al*. 2010). How well the Galápagos archipelago conforms to this model may be open to argument, but the islands also move at a speed intermediate between those of the Pacific and Nubian plates (Courtillo *et al*., 2003).

7. CONCLUSIONS

After charting rocky coasts in the nether regions of Terra del Fuego at the tip of South America during the first cruise of the HMS *Beagle* (1826–1830), Robert FitzRoy was eager to bring aboard someone with knowledge of geology as an unofficial guest for the ship's second voyage (Keynes, 2003, p. 25). It was FitzRoy, who on the eve of the *Beagle*'s departure from Portsmouth in December 1831, presented Darwin with a copy of Part I of Lyell's *Principles of Geology*. That Darwin became a devotee of Lyell's philosophy on processes in physical geology is well known, although his conversion is likely to have taken place a short time after his initial experiences exploring the landscape and coastal geology on the island of Santiago in the Cape Verde archipelago. It was a serendipitous choice that brought the *Beagle* to Praia harbor on the southeastern shores of Santiago in the first instance, but once arrived Darwin was introduced to a textbook setting that featured outstanding examples of physical interactions between coastal limestone deposits and over-riding volcanic flows of a subaerial and submarine nature shown both by columnar basalt and pillow basalt. Moreover, by choosing Praia harbor as the official starting point of the voyage, FitzRoy was impelled to return to the same place near the end of the voyage in order to test the accuracy of longitudinal calculations using the ship's many chronometers during the lengthy circumnavigation of the world's oceans. This gave Darwin the unusual opportunity to revisit and modify the results from his earliest introduction to island geology during that five-year voyage.

A close reading of Darwin (1844) on the various oceanic islands visited by the *Beagle* during the ship's second voyage demonstrates that he was continually on the lookout for additional examples of limestone inter-bedded with basalt that might fit a Lyellian model for patterns of island subsidence and prolonged uplift. Nowhere was this search more disappointing for Darwin than in the Galápagos archipelago. As a consequence of serendipitous choices in FitzRoy's charting schedule among those islands, Darwin missed the opportunity to visit the one area between Baltra and North Seymour islands where he would have discovered coastal outcrops most evocative of those he was so impressed with initially on 'St. Jago' in the Cape Verdes. After leaving the Galápagos archipelago and reaching Tahiti in the South Pacific Ocean, Darwin (1844) once again set out to find elevated limestone deposits on the slopes of the island, but failed to do so. During that island visit, he also was introduced to a living coral reef that outshined his previous encounter with small living corals in the tidal pools on 'St. Jago'. By the time Darwin reached the Keeling (Cocos) Islands in the Indian Ocean, he was less certain about widespread patterns for island uplift around the world and became more attracted to the notion of island subsidence in the development of atoll island systems from submerged volcanoes. The resulting theory of atoll development was already well formed by Darwin (1839), but subsequently much enlarged and strengthened by Darwin (1842). Island uplift survived as a concept introduced by Darwin (1844) only two years later, but the concept failed to attract as much attention from geologists over the following century as did his work on atolls and island subsidence.

Darwin's place in history as a leading pioneer in the study of geology on oceanic islands is secure, both on account of his work on subsidence (Darwin 1842) and his keen observations on uplift (Darwin 1844). Very much following in the tradition of his boyhood hero, Alexander von Humboldt, Darwin carried on in a tradition that encouraged a holistic approach to the accumulation of information in natural history and geology. His detailed observations included aspects of hard-rock and soft-rock geology, as well as observations on geomorphology including processes of erosion and sedimentation that today demand the devotion of dedicated specialists. Ongoing co-operation among these several specialists is required to reach a fuller understanding of global patterns in the development of oceanic islands. With the arrival of plate tectonics and a deeper understanding of the Earth's internal heat-flow dynamics during the 1970s and 1980s, it has become increasingly clear that Darwin's application of Lyellian principles leaves room for future studies that incorporate evidence both for subsidence and uplift around volcanic islands.

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