# INTO THE FIELD AGAIN: RE-EXAMINING CHARLES DARWIN'S 1835 GEOLOGICAL WORK ON ISLA SANTIAGO (JAMES ISLAND) IN THE GALÁPAGOS ARCHIPELAGO[1]

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*Earth Sciences History*
v. 28, No. 1, 2009
pp. 1–31

**ABSTRACT**

In 1835 Charles Darwin's geological observations on Isla Santiago (James Island) in the Galápagos Islands led him to important insights as to the process by which different varieties of igneous rock might be produced from the same volcanic vent. His work figured in a tradition of interpretation that began with the work of George Poulett Scrope and would end in the twentieth century with the theory of magmatic differentiation of igneous rocks through the process of crystal fractionation. This article reports on the findings of an expedition to Isla Santiago in July 2007 during which we were able to locate samples of igneous rocks similar to those collected by Darwin. We have used these, together with Darwin's original specimens and transcriptions of his field notes, to examine how his understanding of the separation of the trachytic and basaltic series of magmas developed from his initial field observations through to publication of *Volcanic Islands* in 1844.

The mere fact that someone has expressed his thoughts in writing, and that we possess his works, does not enable us to understand his thoughts. In order that we may be able to do so, we must come to the reading of them prepared with an experience sufficiently like his own to make those thoughts organic to it (Collingwood 1962, p. 300).

## 1. INTRODUCTION

While his work on evolution made him famous, Charles Darwin (1809–1882) contributed to disciplines across a broad spectrum of the natural sciences, including geology (e.g. Herbert 2005). This was particularly true during his service as an unpaid naturalist aboard H. M. S.

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[1] The island that is now most commonly called Isla Santiago was known to Darwin as James Island. Another current name for the island is Isla San Salvador.

*Beagle* (1831–1836). Darwin's collection of fossil mammals from South America received immediate attention from Richard Owen (1804–1892), formed the basis of volume one of *Zoology* from the voyage (Darwin 1840), and contributed to his argument for *Origin of Species* (Herbert 2005, pp. 320–325; Herbert and Norman 2008). His theory of the origin and distribution of coral reefs, which was presented to the Geological Society of London soon after arriving back in England, became the foundation of the first (Darwin 1842) of three books on geology stemming from the *Beagle* voyage. The importance of the remaining two books is less widely appreciated, despite the efforts of Judd (Darwin 1890). The first (Darwin 1844) focused on volcanic islands, while the second (Darwin 1846) summarised the geology of South America. While writing these latter works Darwin had an increasing sense of working in isolation because his deteriorating health meant that he was no longer able to take such an active role in the Geological Society. While writing *Volcanic Islands* he wrote to Charles Lyell (1797–1875): "I hope you will read my volume for if you don't I cannot think of anyone else who will!—".[2] Later he complained to a friend, from his university days, as he was finishing up his geology of South America:

> As for your pretending that you will read anything so dull as my pure geological descriptions lay not such a flattering unction on my soul, for it is incredible—I have long discovered that geologists never read each others works, & that the only object in writing a Book is a proof of earnestness & that you do not form your opinions without undergoing labour of some kind. Geology is at present very oral, & what I say here is to a great extent quite true. But I am giving you a discussion as long as a Chap$^{r}$. in the odious Book itself.[3]

Darwin's assessment of the probable fate of his forthcoming books was exaggerated for effect, but he had a point. *Volcanic Islands* and *Geological Observations on South America* received nothing like the spirited reception of his earlier volumes. Geological ideas were promoted by active debate, and Darwin was no longer regularly present at the Society's meetings to press his case.[4] Since he was a private author, he did not have ready access to followers or students who might promote his ideas and relied instead on his friendship with senior figures in the geological community at large.[5] While admittedly of lesser influence than some of his other works these volumes do, however, deserve attention. Darwin's *Beagle* collections inform and play off each other, such that it is necessary to consider all of the parts in order to gather a sense of the overall enterprise of the voyage. Equally of interest is the insight this provides of Darwin's approach to scientific investigation: how he went about his work in the field, integrated his observations with his collections as he wrote up his field notes, and then moved towards formal publication.

This article focuses on one section of Chapter 6 of *Volcanic Islands* where, under the heading of 'Trachyte and Basalt', Darwin wrote what now seems to be a prescient discussion of aspects of twentieth-century theory regarding the origin of the diversity of igneous rocks. He described how the density difference between crystals and their surrounding melt might account for magmas of different compositions "within the body of the volcanic mountain".

> Lavas are chiefly composed of three varieties of feldspar, varying in specific gravity from 2.4 to 2.74; of hornblende and augite, varying from 3.0 to 3.4; of olivine, varying from 3.3 to 3.4; and lastly, of oxides of iron, with specific gravities from 4.8 to 5.2. Hence crystals of feldspar, enveloped in a mass of liquified, but not highly vesicular lava, would tend to rise to the upper

[2] CD to Charles Lyell, 15 or 22 September 1843, in Burkhardt *et al.* (1985, vol. 2, p. 389).

[3] CD to John Maurice Herbert, 3 September [?] 1846 in Burkhardt *et al.* (1985, vol. 3, p. 338.)

[4] On the spirited meetings of the Geological Society during this period see Thackray (2003).

[5] The geologist John W. Judd [1840–1916], who was Darwin's geological confidant in later life, might be an exception on this point.

> parts; and crystals or granules of the other minerals, thus enveloped, would tend to sink. We ought not, however, to expect any perfect degree of separation in such viscid materials (Darwin 1844, p. 120).

The concept of vesicularity was of importance to Darwin[6] as he believed that this would decrease the overall density of magma and permit the separation by gravity of different phases (*e.g.* feldspars would normally be less dense than the surrounding basaltic magma). He proposed that, from a single volcano, low-density trachytic magma would be erupted from the upper parts of the 'volcanic focus' (edifice). He further suggested that during later eruptions the lower flanks would be 'enveloped by basaltic streams' and that at some volcanoes fluid basaltic magma may be the only eruptive product. Darwin's theory proposed that basalt and trachyte might be erupted more or less contemporaneously from the same volcano. This was in strong contrast with those who associated the formation of trachyte with an earlier period in the Earth's history than the current one in which they believed basaltic magmas form, *e.g.* Alexander von Humboldt (1769–1859). Nevertheless, it was consistent with the views of scientists such as Lyell, George Poulett Scrope (1797–1876) and James Hutton (1726–1797) who believed that the diversity of volcanic rocks was caused by processes operating within and on the Earth, rather than as characteristic of successive parts of its geological history. Scrope (1825), however, believed that basalt and trachyte were both derived from an original granitic source, and that heat and pressure were important in generating the different magma types.

Graham Chinner (formerly Curator of Mineralogy and Petrology at the Sedgwick Museum) emphasized such points in an exhibit of Darwin's geological specimens on display in the Department of Earth Sciences at the University of Cambridge from 1991 until the present. Part of the text notes that "feldspar crystals in porphyritic glassy basalts were concentrated in the lower portions of lava flows. From the density and viscosity data available at the time he showed that the sinking of crystals in basaltic liquid was feasible and suggested it as a mechanism for differentiating trachyte from basalt." Paul Pearson (1996) likewise drew attention to Darwin's interest in the subject and his fieldwork on Isla Santiago in 1835:

> As Darwin rightly suspected, a molten rock is a complex mixture of chemicals in which, over an appreciable temperature range, particular components aggregate into crystals while the remainder stays fluid . . . . Although he did not explicitly make the point such incomplete crystallization amounts to chemical segregation. . . . This phenomenon was the first clue to the problem of the differentiation of the lava. . . . (Pearson 1996, p. 58).

Supplementing Pearson's account, Davis Young has provided the most extensive treatment to date of the context of Darwin's ideas on the differentiation of igneous rocks, which builds on the early and still valuable study of Joseph Paxson Iddings (1857–1920) (Young 2003, Chapter 8; Iddings 1892).

Chinner, Pearson, and Young did not have an opportunity to visit Isla Santiago to see for themselves where Darwin made his observations and collected samples. Two igneous petrologists who did were Alexander R. McBirney and Howel Williams, who travelled in the Galápagos Islands from 19 January to 28 February 1964 as part of the Galápagos International Science Project. Their published study focused on the geology of many of the islands in the archipelago and included maps, detailed petrological descriptions and major-element whole-rock analyses of numerous samples (McBirney and Williams 1969). Darwin's *Volcanic Islands* was a standard reference point in their treatment, although they did not have access to his specimen notebooks or his extensive field notes. But McBirney

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[6] In addition to the term 'vesicular', Darwin often used the word 'cellular' in his notes.

and Williams did have available a set of petrological descriptions of Darwin's specimens by Constance Richardson (Sister Constance S.S.P. 1907–1989: see Figure 1).[7] She had drawn particular attention to the presence of a sodium-rich trachyte from Isla Santiago, an unusual rock given the generally basaltic nature of other samples from the island; this rock bore Darwin's specimen number CD3268:

> The soda trachyte [3268] from James Island is compact, greenish-grey with a few small crystals of feldspar visible to the naked eye. A thin section shows abundant phenocrysts of feldspar, a few of augite, and also occasionally hornblende, olivine and magnetite set in a trachytic ground mass (Richardson 1933, p. 46).

*Figure 1.*
*Constance Richardson (Sister Constance S.S.P. 1907–1989) who published the first detailed descriptions of thin sections of Darwin's samples from Isla Santiago. While at the University of Cambridge, Richardson served as President of the Sedgwick Club, an organization composed of undergraduates and staff members, and which at that time required members to be elected. Richardson received a first class degree in geology. (Image by courtesy of D. Simons.)*

McBirney and Williams attempted to locate the outcrop of this distinctive rock during their fieldwork on Isla Santiago:

> Special effort was made to find the soda trachyte reportedly collected by Darwin from James Island and carefully described by Richardson (1933), but we found nothing remotely resembling this unusual rock. Dr S. O. Agrell furnished us with a thin section of Darwin's specimen, now in the Sedgwick Museum, Cambridge, and this is almost identical with the specimen meticulously described by Richardson. It is, however, quite unlike any rock we found in the entire archipelago; hence, until the presence of trachyte on James Island is confirmed, we cannot exclude the possibility that the specimen described by Richardson was erroneously included in Darwin's collection (McBirney and Williams 1969, p. 54).

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7 Richardson studied geology at the University of Cambridge at a time when Alfred C. Harker (1859–1939) held the readership in petrology and where Cecil E. Tilley (1894–1973), another distinguished petrologist, was a member of academic staff. From 1927 to 1932, Richardson was a student at Newnham College (Cambridge), which nourished the careers of several women in geology (see Burek 2007). After leaving the University, following a year at Bryn Mawr College in the USA, Richardson taught science in a series of schools; and in 1958 she entered a religious order. The analysis of Darwin's Galápagos rocks is her only publication known to us.

Since McBirney and Williams' observations did not dovetail with Richardson's descriptions of what were believed to be Darwin's specimens from Isla Santiago, there was an obvious anomaly to be addressed. This was significant since Darwin's field work and notes on Isla Santiago prompted him to speculate about the process whereby trachytes and basalts could be produced from the same 'orifice' [vent] (Darwin 1844, p. 120).

The processes by which basalt and trachyte are related are of much more than provincial interest. As detailed above, Darwin used 'trachyte' more generically than petrologists do today; his use included any feldspar-rich intermediate rock, including andesite.[8] The origin of andesite, and the basalt–andesite association, has been one of the most important problems faced by the science of petrology for the past 200 years.[9] Despite the fact that basalt is by far the most frequently erupted lava on Earth, the continental crust has an average composition of andesite, and andesitic magmatism has been the primary mode of continental growth for most of Earth's 4.6 billion year history. Darwin's interpretations were mostly correct: the two subsequent centuries of scientific study have generally concluded that crystal–liquid differentiation is the most important mechanism for the genesis of andesite and trachyte from a melt of basaltic composition. However, as Pearson (1996, p. 51) cautioned, it is "doubtful whether his ideas influenced the subsequent development of the science". Although this is probably too strong a statement, it is clear that Darwin's career bent in a different direction after the mid-1840s, and he was not sufficiently active in the field of petrology to control its direction. His ideas are cited in the nineteenth-century literature, but they are not the driving force.

One of the main questions that we have attempted to address is: are there true trachytes on Isla Santiago? It is clear from Darwin's field notes from *Isla Santiago* and his descriptions of the same rocks in *Volcanic Islands* that there are discrepancies with his use of the terms basalt and trachyte. If Darwin had been mistaken as to the identity of the rocks on the island the strength of his conclusions would be undermined.

## 2. DARWIN'S VISIT TO ISLA SANTIAGO

While in Lima on August 12th, 1835 Darwin wrote a letter to John Stevens Henslow (1796–1861), his mentor at Cambridge, in which he stated that:

> In a few days time the Beagle will sail for the Galapagos Islands. Is[ds].— I look forward with joy and & interest to this, both as being somewhat nearer to England and & 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.— (Burkhardt *et al.* 1985, vol. 1, p. 461.

Darwin's expectations of seeing an active volcano in the Galápagos archipelago (see Figure 2) were not realized: the only activity that he reported was a small jet of steam from a crater on Isla Isabela (Albemarle Island, Keynes 1988, p. 338). Nevertheless, during his time in the archipelago, Darwin made important observations on volcanic rocks. Of particular significance were the field observations that he made during the ten days (8–17 October) that he spent in the west of Isla Santiago.

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8 Andesites are the common type of magma erupted by volcanoes at subduction zones whereas trachytes are commonly found in intra-plate volcanic settings, such as ocean-islands and continental rifts.

9 Darwin first encountered the term 'andesite' on his return from the *Beagle* voyage (von Buch 1836, p. 464). He did not employ the term in *Volcanic Islands* but used it routinely in *Geological Observations on South America* (Darwin 1846). See also Wyatt (1986, p. 11), and Young (2003, p. 109).

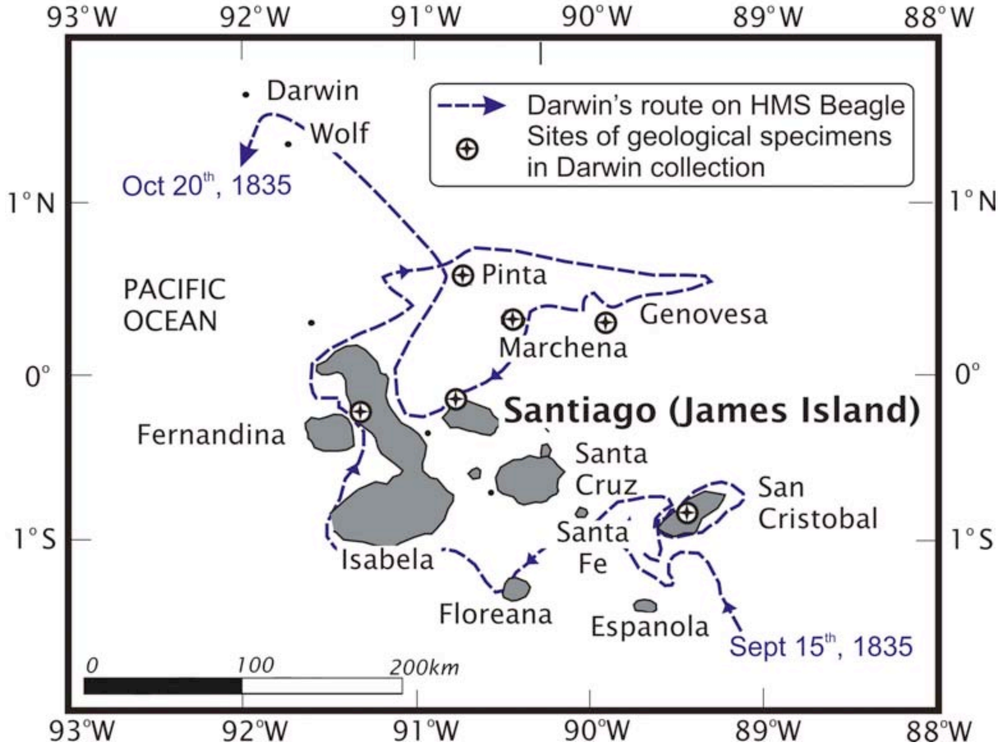


*Figure 2. Map of the Galápagos illustrating the location of Isla Santiago and the route of* HMS Beagle *(after Estes, Grant and Grant 2000). Sites of geological samples in the Darwin collection at the Sedgwick Museum are shown for reference. Darwin collected rock samples from: Chatham Island (San Cristobal) and Albemarle Island (Isabela). Additional samples were collected by Mr Edward Chaffers (dates unknown), Master of the* Beagle*, from Bindloe Island (Marchena), Abingdon Island (Pinta), and Tower Island (Genovesa) while Darwin was on Isla Santiago. (Figure prepared by S. A. Gibson.)*

Darwin's notes indicate that a party of four or five men landed at Buccaneer Cove on the west coast of Isla Santiago (see Figure 3) in the late morning of 8 October and left in the early afternoon on 17 October 1835. The party included Darwin, his servant Syms Covington (1816?–18661), the *Beagle*'s surgeon Benjamin Bynoe (1804–1865), the surgeon's assistant H. Fuller (dates unknown), and possibly one other man. Table 1 shows a summary of Darwin's activities on the island. His field equipment during the *Beagle* voyage included a two to three pound field hammer, lenses, a contact goniometer, acid bottles, and at least one blowpipe used for geochemical study.[10]

Some of Darwin's biological specimens were preserved in spirits in jars, with metal tags on which numbers were stamped. Dry specimens had paper labels on which a second series of numbers were printed (Keynes 2000, p. 317). Because his numbering related to type of storage, geological specimens were interspersed with other materials that were also stored dry. In his field notes, Darwin used broad terminology as well as physical qualities (hardness, colour and texture) to describe the rocks that he encountered (Harker 1907). From early in the voyage he noted the appearance of the volcanic rocks, such as whether they were 'cellular' or 'vesicular', and also the abundance and grain size of any feldspar that was

[10] On Darwin's recommended field equipment see Darwin (1849). Also see Judd (1909) and Herbert (2005, Chapter 3).

present (DAR 32.1:22v and 27v). He also recorded his on-the-spot observations in telegraphic style in field notebooks, and sometimes in loose notes, and wrote a more formal diary of his geological observations some time later. We assume that, as a general practice, the specimens were numbered sequentially in the same order that they were collected.

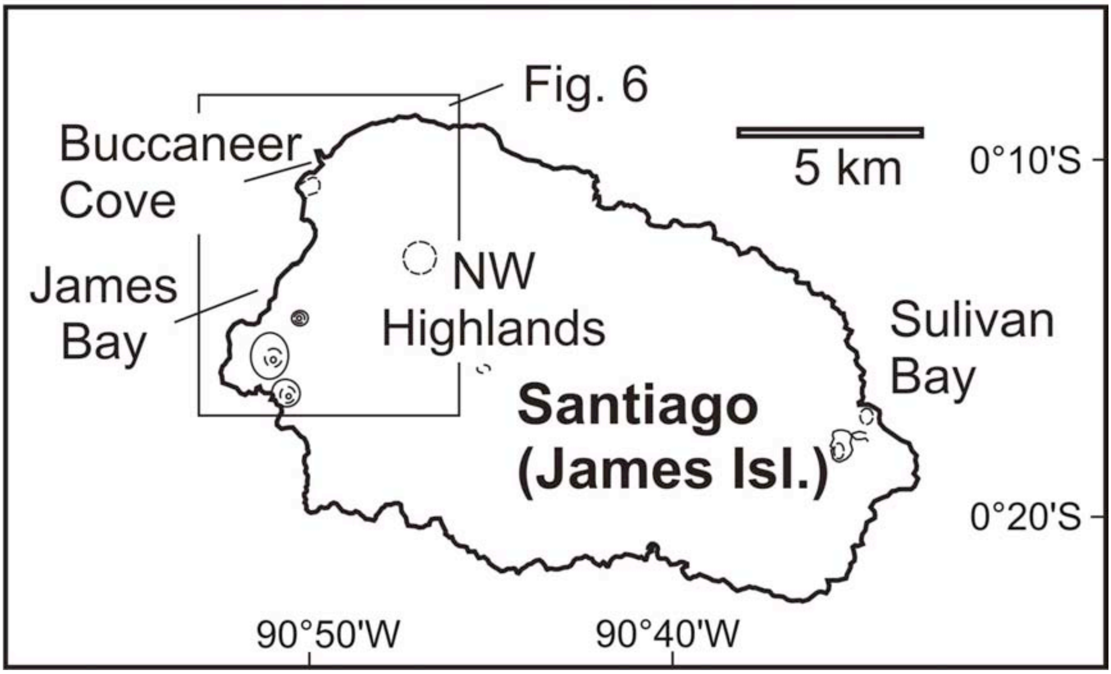


*Figure 3. Simplified map of Isla Santiago showing some of the locations mentioned in the text and sites of the largest craters. (Figure prepared by S. A. Gibson.)*

### *2.1. Darwin's geological specimens from Isla Santiago*

Darwin collected a total of nineteen geological specimens from Isla Santiago, which are labelled CD3265 to CD3283, consecutively. These are bracketed by Specimen 3264, described as 'Gorgonia', and specimen 3284 described as 'Cactus. Flower yellow' (Geological Specimen Notebook [DAR 236]; Keynes 2000, p. 423). The geological specimens listed for Isla Santiago formed a small portion of the nearly 2,000 geological specimens Darwin collected on the voyage, the majority of which are presently housed at the Sedgwick Museum of Earth Sciences in Cambridge.[11] Of the original nineteen geological specimens collected by Darwin on Isla Santiago, eighteen are currently stored at the Museum and one specimen (3274) is missing. It was catalogued by the Cambridge petrologist Alfred Harker but was not mentioned in his thin-section list or in the work of Richardson (1933).

[11] Harker (1907, p. 102) used the figure of 2,000. The most recent inventory at the Sedgwick Museum recorded 1371 (of 1930) specimens in the collection (Hide 2007). The number given in Herbert (2005, p. 99) is incorrect. The Harker Catalogue of geological specimens (Harker *ca* 1907) is available online at www.darwin-online.org.uk, as is *Volcanic Islands* (Darwin 1844) and DAR 37.2, which contains Darwin's geological field notes from the Galápagos Islands. The transcription of DAR 37.2 was done by Thalia Grant and read by other members of the team.

*Table 1. Summary of Darwin's visit to James Island between 8 and 17 October 1835. The quoted remarks are taken from Darwin's Diary (Keynes 1988, pp. 360–363).*

| Date (1835) | Location on James Island | Darwin's geological sample numbers |
|---|---|---|
| 8 October | Landed at Buccaneer Cove. "We pitched our tents in a small valley a little way from the Beach.— The little Bay was formed by two old Craters: in this island as in all the others the mouths from which the Lavas have flowed are thickly studded over the country." | CD3265–CD3279 |
| 9 October | "Taking with us a guide we proceeded into the interior & higher parts of the Island, where there was a small party employed in hunting the Tortoise.— Our walk was a long one.— At about six miles distance & an elevation of perhaps 2000 ft the country begins to show a green color.— Here there are a couple of hovels where the men reside.—. . . About 2 miles from the Hovels & probably at an additional 1000 ft elevation, the Springs are situated." | |
| 10 October | Darwin wrote the notes contained in DAR 37.2:716–723 on his samples CD 3265 to CD 3279. | |
| 11 October | "The Mayór-domo took us in his boat to the Salina which is situated about 6 miles down the coast.— We crossed a bare & apparently recent stream of Lava which had flowed round an ancient but very perfect Crater.— At the bottom of this Crater is a Lake, which is only 3 or 4 inches deep & lies on layers of pure & beautifully Crystallized Salt." Darwin recorded his findings on samples CD 3280 through CD 3283 in a note dated 11 October (DAR 37.2:723.) | CD3280, CD3281, D3282, CD3283 |
| 12 October to 13 October | "On the 12th I paid a second visit to the houses [the 'hovels' in the highlands], bringing with me a blanket bag to sleep in.— I thus enjoyed two days collecting in the fertile region.—" | |
| 14 October to 16 October | "During the last two days, the Thermometer within the Tents has stood for some hours at 93°.—" | |
| 17 October | "In the afternoon the Beagle sent in her boats to take us on board.—" | |

Darwin's geological specimens from Isla Santiago include four unconsolidated "volcanic sandstones" (now referred to as tuffs; CD3276, 3277, 3282, 3283) that are stored in specimen jars. The remaining fourteen specimens are rock samples collected from lava flows and dykes. The majority of Darwin's geological specimens were collected at Buccaneer Cove. These are numbered sequentially from CD3269 to CD3279 (Table 2). We believe that they are from the promontory and north end of the beach. The remaining samples were collected during Darwin's trek into the Highlands (CD3265 to 3268) and from a boat trip to James Bay (CD3280–3283). In Darwin's notes from Isla Santiago he refers to a specimen with red earthy spots as 3299 but this is almost certainly a mistake and should read 3279.

*Table 2. Summary of petrological descriptions of Darwin's geological samples from Isla Santiago.*

**1. SE traverse from Buccaneer Cove to Cerro Pelado**

| Darwin no. (Harker no. in brackets) | Equivalent sample (this work) | Darwin's description in his specimen notebook (abbreviated) | Richardson description (substantially abbreviated) | Description of sample location (Darwin [1835] in italics; and this work) | Description and classification (this work) |
|---|---|---|---|---|---|
| **CD3265** (32575) | **07DSG56** S0°10.737' W90°48.704' | Base. Blackish grey (few Felspar Cryst) with Olivine rare | Basalt with zoned feldspar phenocrysts of basic labradorite ($An_{79-60}$, p. 53). Few phenocrysts of pale-greenish augite & colourless olivine. | *Inland, beyond the influence of the sandstone craters.* Crater 1 (300m) | Vesicular, **basalt** flow containing large, rounded, strongly zoned and smaller lath-shaped plagioclase feldspars together with round olivines. |
| **CD3266** (32576) | **07DSG55** S0°11.294' W90°48.042' | Trachytic. cellular lava frequent large Cryst of glassy Feldspar; commonest kind | Differs from 3265 in containing no augite and larger proportion olivine (p. 53) | *Inland, beyond the influence of the sandstone craters.* Flows occur below 200m and also emanate from Crater 2 (500m) | Dark grey, vesicular **basalt** containing large rounded feldspar phenocrysts, olivine and clinopyroxene set in a fine-grained groundmass. |
| | **07DSG53** | | | NW Highlands near Crater 3 (Cerro Roja, >600m) | Dark and non vesicular. Exhibits a flow texture. A few phenocrysts (2mm in length) of plagioclase feldspar ($An_{66-35}$), olivine ($Fo_{75-66}$) and clinopyroxene (diopside). **Trachybasalt** |
| **CD3267** (4730, 6865, 32522) | **07DSG51** | Olivine do [ditto—i.e. as 3266] with few glassy Cryst | Blue-green **Oligoclase Andesite** (p. 48). Plagioclase feldspar (oligoclase, $An_{28}$), augite, brown hornblende, olivine (not obviously fayalitic) | NW Highlands near Crater 3 (Cerro Roja, >600m) | **Trachyandesite** |
| **CD3268** (6204, 6866) | **07DSG42** | Compact greenish grey Lava with many small Cry of glassy Fels | Soda trachyte, compact greenish-grey with small crystals of feldspar (zoned from potash-oligoclase to anorthoclase) visible to the naked eye (pp. 46–47). Phenocrysts of augite, blue-green and also brown hornblende (cossyrite) together with yellow fayalitic olivine. Aegirine-augite present in the groundmass. | NW Highlands (860m) Cerro Pelado | Grey-green colour. Mainly sodic plagioclase and alkali feldspar (Andesine–Anorthoclase, $An_{34-13}$), yellow fayalitic olivine ($Fo_{20}$), a blue-green (Ferro-edenite) and also a brown amphibole **Trachyte** |
| | **07DSG40**, **41**, **45** S0°12.408' W90°46.905' | | | NW Highlands near Crater 3 (Cerro Roja, >600m) NW Highlands (860m) Cerro Pelado | Green colouration and non-vesicular. Few feldspar phenocrysts (3 mm in length). Abundant alkali feldspar (Sanidine to Anorthoclase), some blue-green amphibole (Ferro-edenite) and minor olivine. **Trachyte.** |

**2. Buccaneer Cove**

| Darwin no. (Harker no. in brackets) | Equivalent sample (this work) | Darwin's description in his specimen notebook (abbreviated) | Richardson's description (substantially abbreviated) | Description of sample location (Darwin [1835] in italics; and this work) | Description and classification (this work) |
|---|---|---|---|---|---|
| | **07DSG26b**<br><br>S0°10.033' W90°49.567' | | | Buccaneer Cove | Fresh Olivine Gabbro xenolith in basalt. Xenolith contains abundant cumulus olivine, olivine (Fo83), intercumulus zoned plagioclase feldspar (Bytownite-Labradorite, An75–62) and clinopyroxene (diopside) |
| **CD3269** (6867 [loc?] 32583) | **07DSG01**<br><br>**S0°10.033' W90°49.567'** | Finely & much cellular Trachyte with much Cryst Gl. Fracture Feld. Outer surface. Red glossy Scoria | Porphyritic scoriaceous olivine-basalt [loc?]<br>Porphyritic vesicular olivine basalt with xenolith | Thin lava flow in red scoria. 'Layer cake' (Estes, Grant and Grant, 2000), Buccaneer Cove | Vesicular **Basalt** bearing xenoliths of gabbro together with large crystals of olivine, clinopyroxene, plagioclase feldspar and an opaque oxide |
| | **07DSG26d**<br><br>S0°10.033' W90°49.567' | | | Buccaneer Cove | **Leucogabbro** predominantly consisting of plagioclase feldspar (Bytownite–Labradorite, $An_{72–54}$) with clinopyroxene (augite) and olivine ($Fo_{77}$). |
| **CD3270** | **07DSG28**<br><br>S0°09.58' W90°49.27' | Ditto with fragment of altered Granite | Basalt with dominant feldspar phenocrysts, practically no yellow pyroxene (p. 54). Contains the most olivine | Buccaneer Cove | **Gabbro** mainly composed of plagioclase feldspar (Labradorite, $An_{61–52}$) and clinopyroxene (diopside). Olivine ($Fo_{75–66}$) is partially altered and less common |
| **CD3271** (32587) | | Imbedded fragments of ditto [Trachyte]. Varieties coarser & finer grained. Quartz generally visible. Mica changed into glassy minerals. Perhaps some Syenite | Gabbroic xenoliths—but 3271 is a **eucrite** rather than a gabbro, augite and less feldspar than in 3273, whereas 3271 and 3272 have more feldspar | Buccaneer Cove | |
| **CD3272** | S0°10.033' W90°49.56' | Ditto | Ditto | Buccaneer Cove | **Gabbro** xenolith with red-brown staining. Coarse grained (~ 5mm) with high modal abundance of plagioclase and pyroxene. Non interlocking framework no obvious olivine |
| **CD3273** (4731) | | Ditto | Contains zoned feldspar laths ($An_{72–61}$), pale-brownish green ophitic augite, colourless partially altered olivine ($Fo_{71}$) | Buccaneer Cove | |

### 2. Buccaneer Cove (cont.)

| Darwin no. (Harker no. in brackets) | Equivalent sample (this work) | Darwin's description in his specimen notebook (abbreviated) | Richardson's description (substantially abbreviated) | Description of sample location (Darwin [1835] in italics; and this work) | Description and classification (this work) |
|---|---|---|---|---|---|
| **CD3275** (32584) | **07DSG07** | Red, irregular fracture Claystone base. Very heavy with red earth & Cry. Of Glassy Feld. Generally more of the latter and more cellular | Altered porphyritic olivine-basalt | Buccaneer Cove | Red oxidized vesicular **olivine basalt** containing large crystals of plagioclase feldspar and altered olivine in a very fine-grained groundmass. Alteration of the olivine gives rise to the red specks in hand specimen |
| **CD3278** (32581) | **07DSG01?**<br>S0°10.033'<br>W90°49.567' | Brown, smally cellular Trachyte with blue iridescent patches of Olivine could not measure F. | Specimen has colourless augite with yellow rims; seen as an important mineral, p. 50. Resorbed plagioclase (labradorite, $An_{72–65}$) phenocrysts. Altered olivine | *'Pap' of lava in Buccaneer Cove*, beneath 'layer cake' | Red-brown colouration. Porphyritic and vesicular altered **basalt**. Phenocrysts of pyroxene and plagioclase feldspar (~3mm in length). High phenocryst content (~50 %). Small cognate xenoliths |
| **CD3279** (4732) | **07DSG21?** | Gray. Compact ditto. few Cryst of Gl. Feldspar [added: Olivine (B.P.) | Porphyritic olivine andesite contains feld spar laths, presence of a few large, slightly altered olivine phenocrysts, and having ophitic augite that is strongly zoned and passes locally into a yellow variety | *Dyke at Buccaneer Cove* | **Trachyandesite** |

### 3. James Bay

| Darwin no. (Harker no. in brackets) | Equivalent sample (this work) | Darwin's description in his specimen notebook (abbreviated) | Richardson description (substantially abbreviated) | Description of sample location (Darwin 1835, in italics; and this work) | Description and classification (this work) |
|---|---|---|---|---|---|
| **CD3280** (32524) (346) | **07DSG65**<br>S0°12.927'<br>W90°50.1' | Blackish grey Lava. abounding | Olivine basalt, pp. 48–49. Pale-green olivine phenocrysts enclosed in a groundmass of labradorite ($An_{65–61}$), ophitic purplish augite and olivine. | Older than historic (~1759) *flow at James Bay* | **Olivine basalt.** Small phenocrysts of olivine set in a fine-grained, grey, groundmass containing plagioclase feldspar and ophitic purple-brown clinopyroxene. |
| **CD3281** (4733) (323) | **07DSG61, 64**<br>S0°12.927'<br>W90°50.156' | Ditto. Blacker. more cellular | Glassy olivine basalt, p. 49. | Historic (~1759) pahoehoe *flow at James Bay* | **Vesicular olivine basalt.** Small phenocrysts of olivine ($Fo_{76–62}$) set in a fine-grained, black, glassy groundmass. Small laths of plagioclase (Bytownite, $An_{84–71}$) and clinopyroxene are also present. |

Age of James Bay flow is from Simkin and Siebert (1994). Latitudes and longitudes are GPS positions (WGS84 datum).

The fourteen surviving samples of crystalline igneous rocks collected by Darwin from Isla Santiago still bear his original specimen numbers, although his yellow labels are no longer visible. The specimens were donated to the Woodwardian[1] Museum in 1897 and curated by Harker, who had thin-sections made of the rocks (see Figure 4) and recorded brief petrographic descriptions of each one in his meticulous museum catalogues (*ca* 1907). Subsequently, Richardson (1933) provided more detailed descriptions of the hand specimens and thin-sections, as well as for several other samples collected from Isla Santiago by L. J. Chubb in 1924.[2] Richardson used an immersion method to estimate refractive indices and determine, for the first time, the composition of minerals (olivine, feldspar and amphibole) in Darwin's Isla Santiago samples. She also published a whole-rock analysis of one of these samples (the trachyte, CD3268); the analytical work was undertaken by W. H. Herdsman, a commercial analyst based in Glasgow, who used wet chemistry techniques and was one of the principal scientists engaged in this type of work at the time. The analysis of CD3268 required removal of part of the hand specimen and its subsequent reduction to a powder. Apart from the small slivers of rock that were removed for making Harker's thin-sections, all of the remainder of Darwin's samples from Isla Santiago remain intact. No other published information on the mineralogy and petrology of Darwin's samples exists or detailed study of Isla Santiago. There is, however, an unpublished PhD thesis on the petrology and geochemistry of volcanic rocks from Isla Santiago by Hartmut Baitis (1976). He identified trachytes close to the summit of Santiago but, since Darwin's samples were not available to him, no direct comparison was undertaken. We note that Baitis's samples of trachyte, which are currently housed at the University of Idaho, are much coarser-grained than Darwin's trachyte. Furthermore, Baitis made no mention of the presence of amphibole in these rocks.

In the early nineteenth century there were no guidelines in place for the systematic naming of volcanic rocks. An early attempt to classify igneous rocks based, on their mineralogy and textures, was proposed in 1823 by Karl Caesar von Leonhard (1779–1862), a German petrographer (Young 2003, p. 110). This information may not have been available to Darwin whose naming of igneous rocks would essentially have been learnt from lectures at Edinburgh under Robert Jameson (1774–1854), contact with his mentor Henslow at Cambridge, and fieldwork in North Wales with Adam Sedgwick (1785–1873) (Secord 1991). A record has been compiled of the books that Darwin had with him on the voyage, and from this, as well as from the surviving books, a number of which carry his annotations, we know which works he relied on.[3] As one might expect, the works of authors such as Humboldt, Charles Daubeny (1795–1867), Scrope, and Lyell, were useful to him. In addition, from the evidence of his extensive marginal annotations, it is clear that during the voyage he especially relied on a comprehensive two-volume work *Traité de géognosie* by J. F. d'Aubuisson de Voisins (1819)[4] for rock identification, and especially so in the

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[1] The Woodwardian Museum was re-named the Sedgwick Memorial Museum of Geology, following the construction and opening of a new purpose-built museum in 1904.

[2] These were housed in the British Museum of Natural History in London. The geologist Lawrence Chubb (1887–1971) studied and taught at University College London.

[3] See Burkhardt *et al*. 1985, vol. 1: 553–566, Appendix IV ('The books on board the *Beagle*'). Up to the point of his travel aboard H.M.S. *Beagle* Darwin's education in geology had progressed through four stages: (1) childhood collecting of interesting mineral specimens combined with experiences working in a home chemistry laboratory; (2) study under Robert Jameson at the University of Edinburgh; (3) study of natural history, broadly conceived, under John Stevens Henslow at the University of Cambridge; and (4) in the period immediately following completion of coursework at Cambridge, extensive reading of such authors as Alexander von Humboldt and John Herschel, combined with a short course of fieldwork in Wales under Adam Sedgwick. For further background see Secord (1991) and Herbert (2005).

[4] The French geologist and mining engineer Jean-François d'Aubuisson de Voisins (1769–1841) studied with Abraham Gottlob Werner at the *Bergakademie* in Freiberg in 1800–1801 but later adopted volcanism as an explanation for the origin of basalts. Adam Sedgwick recommended that Darwin bring d'Aubuisson's

Galápagos. Whilst there, Darwin used the most-widely accepted terms, which simply referred to coarse-grained plutonic rocks as granites or syenites and fine-grained volcanic rocks as basalt, greystone or trachyte. Nevertheless, he was clearly concerned about this terminology and how his use of it compared with that of other geologists. In 1836 he wrote to Henslow "I am anxious to know, whether Prof Sedgwick recommends any particular nomenclature for the rocks" (Burkhardt *et al*. 1985, vol. 1, p. 513). Usage was clearly a major issue, for Darwin needed to adopt a recognized vocabulary in order to make comparisons of his findings with those of other geologists.

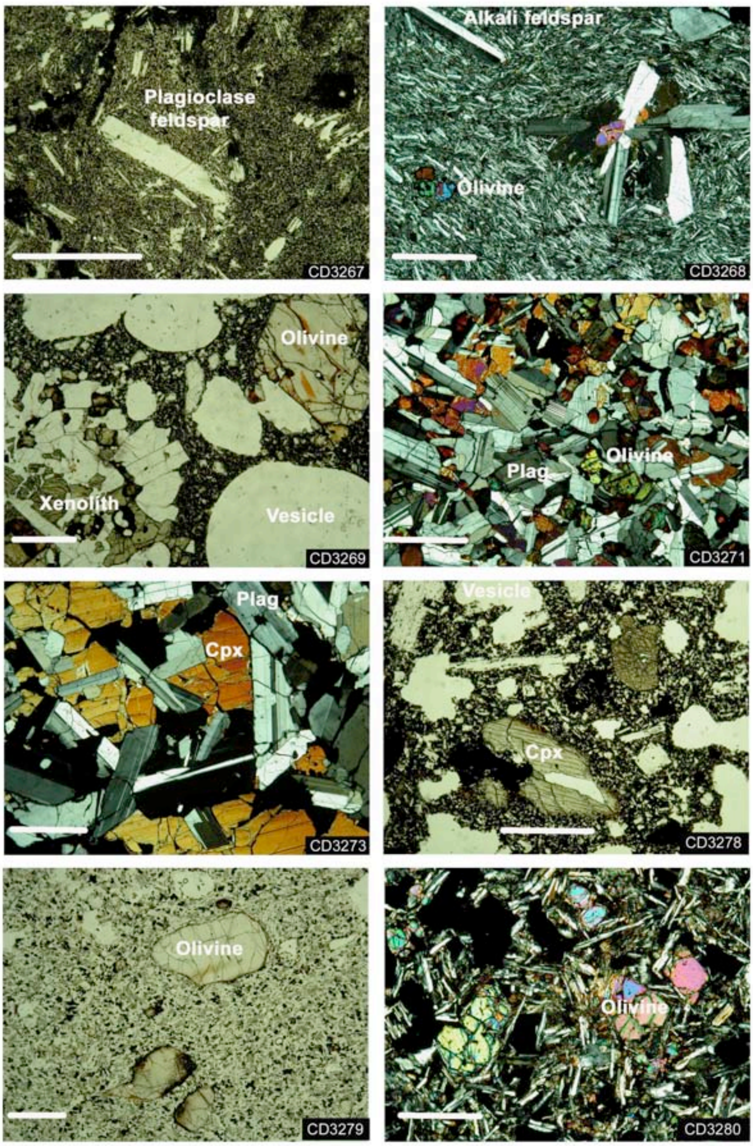


*Figure 4. Photomicrographs of thin sections of some of the geological specimens collected by Darwin from the west of Isla Santiago. CD3267 (trachyandesite) and 3268 (trachyte) were collected during Darwin's trek into the Highlands. CD3269 and 3278 are vesicular basalts from Buccaneer Cove. CD3279 is a large feldspar basalt from a dyke at Buccaneer Cove. Specimens CD3271 (troctolite) and 3273 (gabbro) are 'coarse-grained fragments' (xenoliths) from Buccaneer Cove; and CD3280 is an olivine basalt from James Bay. Images of CD3267, 3269, 3278 and 3279 were taken in plane-polarized light. Images of all other samples were taken using cross-polarized light. The scale bar in the bottom left-hand corner of each image is 1 mm. Brief descriptions of the samples are given in Table 2. (Images by courtesy of S.A Gibson.)*

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*Traité* on the voyage, which he did. Volume 1 of Darwin's copy of the book is inscribed "C. Darwin HMS Beagle". See also the article by Arthur Birembaut on d'Aubuisson de Voisins in the *Dictionary of Scientific Biography* (vol. 1, pp. 327–328, 1970).

*2.2. Darwin's nomenclature for igneous rocks on Isla Santiago*

In *Volcanic Islands* Darwin defined his use of the terms trachyte and basalt:

> Trachyte, which consists chiefly of feldspar, with some hornblende and oxide of iron, has a specific gravity of about 2.45; whilst basalt, composed chiefly of augite and feldspar, often with much iron and olivine, has a gravity of about 3.0. (Trachyte from Java was found by Von Buch to be 2.47; from Auvergne, by De la Beche, it was 2.42; from Ascension, by myself, it was 2.42. Jameson and other authors give to basalt a specific gravity of 3.0; but specimens from Auvergne were found, by De la Beche, to be only 2.78; and from the Giant's Causeway, to be 2.91) (Darwin 1844, p. 120).

However, these definitions were not used by Darwin during the *Beagle* voyage. A comparison between his Galápagos field notebook and *Volcanic Islands* reveals that there are several instances where he revised his field classification of rocks from Isla Santiago (Gibson 2009). In his published work Darwin also questioned whether or not there was actually any 'true' trachyte in the northern Galápagos.

> In the northern islands,[5] the basaltic lavas seem generally to contain more albite than they do in the southern half of the Archipelago; but almost all the streams contain some. The albite is not unfrequently associated with olivine. I did not observe in any specimen distinguishable crystals of hornblende or augite; I except the fused grains in the ejected fragments, and in the pinnacle of the little crater, above described**. I did not meet with a single specimen of true trachyte**; though some of the paler lavas, when abounding with large crystals of the harsh and glassy albite, resemble in some degree this rock; but in every case the basis fuses into a black enamel (Darwin 1844, p. 114, emphasis added in bold).

This contrasts with his full manuscript notes (DAR 32–DAR 38 in the Darwin Archive at Cambridge University Library) in which he stated that:

> Considering the Islands in the whole Archipelago, it may be remarked, that the Southern ones appear to be entirely composed of Basalt and Greystone whilst the Northern division is more essentially trachytic (DAR 37.2:786). (*In margin:* Chatham.)

In a description of a traverse from Buccaneer Cove to the NW Highlands (Jaboncillos) Darwin mentioned that:

> Travelling inwards in a SE line, where beyond the influence of the sandstone Craters All the rock is highly cellular blackish grey **Trachyte**, abounding with glassy Feldspar:(3265), parts are more compact (3266).— (Field Notes, DAR 37.2: 723, emphasis added).[6]

Thus we see Darwin using the term 'trachyte' in field notes where later he would alter his identification.

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5 Here, Darwin's writing is somewhat confusing, because it is unclear what he means by the 'northern islands'. In fact, lavas at Genovesa, Pinta, and Marchena (Figure 1) are notably rich in plagioclase (albite according to Darwin). Darwin did not visit these islands, but specimens from each, collected by Chaffers, are included in his collection. Darwin does, however, seem to have been including Santiago in this discussion, by referring to the 'ejected fragments' (xenoliths of Buccaneer Cove) and 'pinnacle'. We suspect that he originally thought some of his plagioclase-phyric rocks from Isla Santiago were trachytes, but he found them to be basalt using the blowpipe test. It is unclear whether he subjected the actual trachyte in his possession to a blowpipe test.

6 Darwin's deleted remarks are not included in the transcriptions from his manuscript notes reproduced in this article.

*2.3 Naming volcanic rocks in accordance with present-day international guidelines*

The present-day classification of igneous rocks encompasses their chemistry as well as their mineralogy and is based on a scheme proposed by Carl Bernhard von Cotta (1855), which divides 'eruptive' rocks on the basis of their silica content (Young 2003, pp. 116–117). Fine-grained and essentially anhydrous volcanic rocks are now conventionally classified on the basis of their whole-rock chemistry according to the recommendations established by a special sub-commission of the International Union of Geological Sciences (IUGS) on igneous rocks published by Roger W. Le Maitre (1989). One of these classification schemes involves the silica and total alkali content of volcanic rocks and relates these to recommended field boundaries on a bivariate plot.[7] Figure 5 shows how this type of plot can be used for all of the currently available analyses of samples from Isla Santiago (our unpublished data, Baitis 1976, Richardson 1933, Saal *et al.* 2007, White *et al.* 1993).

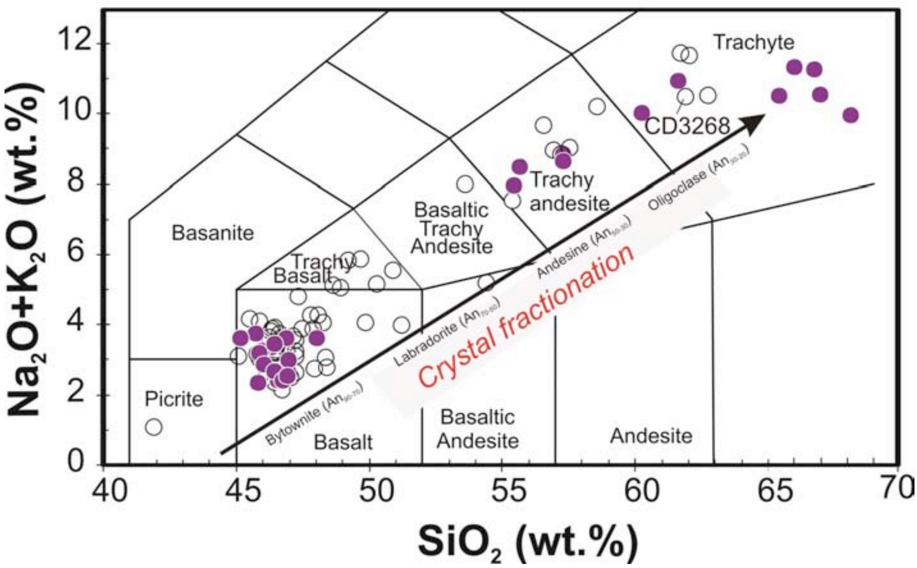


*Figure 5. Classification of fine-grained igneous rocks from the northwest of Isla Santiago according to the scheme proposed by an IUGS sub-commission (Le Maitre 1989). The Isla Santiago rocks range in composition from basalt to trachyte. The arrow shows the change in bulk-rock composition with crystal fractionation and how the approximate composition of the plagioclase feldspar changes as the magma composition evolves during this process. Note that the solitary picrite analysis designated E76 (McBirney and Williams 1969; White, McBirney and Duncan 1993) is from a sample collected in a small bay to the north of Buccaneer Cove. This rock is almost certainly a basalt that has accumulated a significant amount of olivine (McBirney pers. comm.; SAG/DG unpublished interpretation). Closed circles are our unpublished analyses and open circles represent samples from previous studies (Baitis 1976; McBirney and Williams 1969; Richardson 1933; White, McBirney and Duncan 1993). (Figure prepared by S. A. Gibson.)*

Richardson (1933) determined the chemical composition of CD3268 and noted that it had twice as much sodium as potassium; hence the reference to it as a 'soda' trachyte. In the 1960s, Herdsman's analyses were shown to have poor precision with respect to alkalis (especially Na) and also silica/aluminium ratios (C. H. Emeleus, pers. comm.). Despite this, CD3268 falls well within the 'field of' trachytes. Richardson (1933) also determined the chemistry of minerals (olivine, feldspar and amphibole) in most of Darwin's Isla Santiago

[7] Igneous rock classification is not always rigorously followed by all modern petrologists. Because there is completely continuous variation in rock composition and mineral assemblage, practitioners generally apply rock names that best suit their particular study.

samples on the basis of their refractive indices. We have combined her findings with state-of-the-art electron microprobe analyses of mineral phases present in our own samples (Table 2). The latter were chosen to be representative of the different types of volcanic rocks that we encountered in the west of Isla Santiago. These analyses were undertaken in the Department of Earth Sciences at the University of Cambridge and the results are summarized in Table 2. Details of analytical techniques are presented in Gibson *et al.* (2008).

## 3. RECONSTRUCTING DARWIN'S FINDINGS

In July 2007 we spent eight days on Isla Santiago, examining rock outcrops and collecting samples with the intent of verifying Darwin's findings (see Appendix for further expedition details). Prior to the fieldwork we re-examined all of Darwin's samples from Isla Santiago. Our goal was to find similar outcrops to those observed by Darwin, and to collect samples that resembled his specimens (Table 2). While it was not the expedition's goal to replicate his full experience on the island (after all he collected in all areas of natural history and his geological collecting came in the first half of his stay [Table 1]), it was necessary to identify his route in order to locate the sites he visited as accurately as possible (see Figure 6). In identifying his route we relied heavily on previous work by Greg Estes and Thalia Grant (Estes, Grant, and Grant 2000).

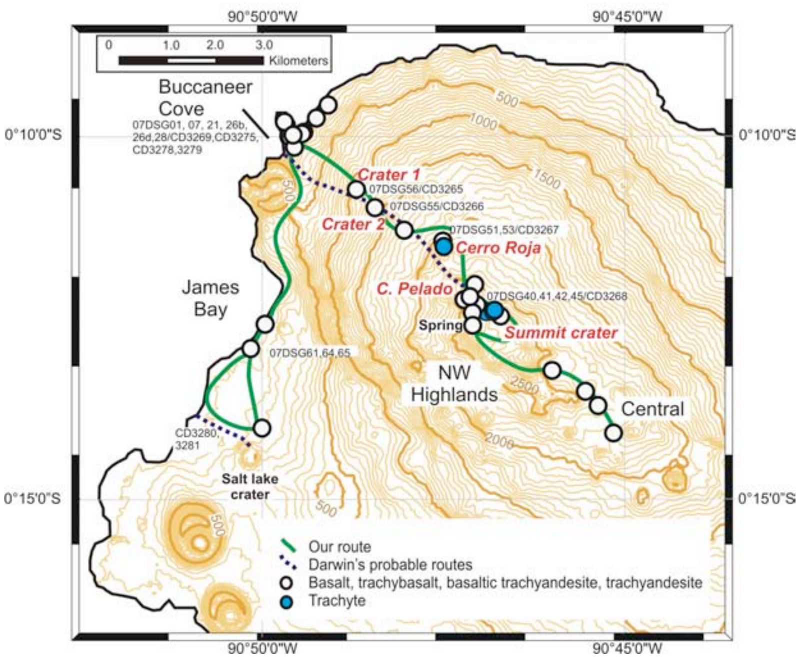


*Figure 6. Topographic map of northwest Isla Santiago showing the locations of samples collected during the 7 July expedition (serial code 07DSG–???) and possible correlations with sites of volcanic rock samples collected by Darwin in 1835 (serial code CD32–???). Contours are shown at fifty-foot intervals. (Figure prepared by S. A. Gibson.)*

Retracing the localities from which Darwin had collected his geological samples was by no means straight-forward because:

(i) He did not accurately describe his routes in his field notebooks. Transcriptions of his notes reveal that his descriptions of sample locations were quite general and only occasionally mentioned specific landmarks.

(ii) Darwin's samples were small (< 10 cm, with most being < 5 cm; and many have surfaces that are either covered with lichen or are weathered.

(iii) Darwin did not refer to his samples by number in his published work.

(iv) It has been proposed that one of the samples in the Harker Collection at the Sedgwick Museum (CD3268) at the University of Cambridge was not actually collected in the Galápagos (McBirney and Williams 1969) and therefore may not resemble any of the volcanic rocks on the island.

*3.1 Association of rock types and volcanic craters in west of Isla Santiago (James Island)*

The west of Isla Santiago consists of a major shield volcano with parasitic cones on its flanks (Gibson 2009). Eruptions of basaltic lava have occurred since Darwin’s visit but these are confined to the eastern side of the island, such as the 1906 lava flow at Sulivan Bay (Simkin and Siebert 1994). Although Darwin did not provide detailed descriptions of where he collected his samples on Isla Santiago, he stated that:

> James Island. The only part of this Island which I examined is the West side.— The country here gradually slopes upwards to an elevation of about 3000 ft (DAR 37.2: 769).

After describing and collecting samples from Buccaneer Cove, Darwin subsequently referred to two separate excursions that he made inland with resident tortoise hunters. He described how they took a south-east traverse and came across a perfectly-shaped volcanic crater near the summit of the island.

> Travelling inwards in a SE line, when beyond the influence of the Sandstone Craters, All the rock is highly cellular blackish grey Trachyte, abounding with glassy Feldspar: (3265), parts are more compact (3266).— More in the interior compact varieties are common, containing more or less numerous Cryst: of glassy Feldspar.— Here I found a very perfect Crater: well wooded, but entire and large.— Generally it may be remarked that the more cellular Trachyte. contains the largest and perhaps more numerous Cryst of Feldspar.— This is the reason, I do not believe, they preexisted.— Circumstances determine their size & numbers. Specimens of more compact kinds 3267:3268 (DAR 37.2:723).

And in notes made after his descent from the highlands to Buccaneer Cove, Darwin mentions that the walls of the crater are composed of bright red glassy scoria:

> In several parts there are old broken down Craters & In the central highest part of Is[d] —about 8 miles inland— (& between 2–3000 ft high. Estimation) there is a large & perfect Crater. Circular. sides very precipitous & bottom well wooded. In the vicinity. nothing but Trachytic Lava is found: the channels by which the Lava has flowed over the rim are yet visible.— The walls of the Crater are chiefly composed of bright red & very glassy ~~red~~ scoria united together.— (DAR 37.2:770).

Cerro Pelado is a prominent circular, steep-sided crater near the summit of Santiago Island (00°12′21″S, 90°47′3.1″W), at an elevation of about 840 metres (2,750 feet) and has a diameter of 200 metres. (see Figures 6 and 7; Estes, Grant and Grant 2000). It is located six kilometres inland of Buccaneer Cove. These distances are shorter than those reported by Darwin for his “large & perfect Crater”, but his estimates (eight miles for the journey inland and one third of a mile for the diameter of the crater) appear to have been recorded in his notebook several days after his return to Buccaneer Cove. Moreover, distances covered in the interior of the islands can be exceedingly difficult to estimate, especially in the heavily vegetated regions.

*Figure 7. Cerro Pelado: a perfectly shaped crater located close to the summit of Santiago. It contains bright red scoria and has a prominent lava flow that appears to have flown over the rim of the crater (left of image) and closely matches one described by Darwin in his field notes. (Image by courtesy of A. Thurman.)*

Vegetation and wildlife on Santiago has been altered since Darwin's visit, following the introduction of pigs and goats. Pigs dug up tortoise and turtle eggs and also ate the Galápagos petrels that nest in the highlands. Goats damaged the native vegetation, especially in the highlands. But both introductions had been eradicated by 2004, and saplings were already present in the crater floor in 2007. The lavas that emanate from Cerro Pelado contain large laths of plagioclase; in contrast to Darwin's field description, our thin-section investigation confirms that these are basalts rather than trachytes. Red scoria, some of which is glassy, is present in the northern and western walls of crater. We did not encounter this distinctive rock in abundance in any of the other craters and believe that Cerro Pelado is the crater that Darwin described. This is consistent with the description of Darwin's route proposed by Estes, Grant, and Grant (2000). A larger (one km in diameter) bowl-shaped depression lies to the southeast of the summit of the island, and to the southeast of the "perfect crater" at Cerro Pelado (see Figure 6). The geological origin of the bowl is not clear, but it seems to have formed by a ring of separate vents. It is not "very precipitous" and, although Darwin may have visited it (one of the ring vents is the highest point on the island), it is not in his description. A spring (00° 12.611′ S, 90° 47.097′ W) emerges less than 1 km from the southwest rim of the bowl at 865 m elevation. The horizontal position accuracy is ± 8 m. (Measurement made July 2007, WGS 84 datum.) This spring and its environs is likely where Darwin observed tortoises wallowing (Estes, Grant, and Grant 2000).

*3.2 Trachytes and trachyandesites in the northwest highlands*

On the higher northwest slopes of the main volcano on Isla Santiago (see Figure 6) a wide variety of rock types outcrop, including trachytes, trachyandesites and trachybasalts (Table 3). The most differentiated rocks (trachytes) occur nowhere else in the vicinity of the Isla Santiago highlands (Gibson 2009) and are readily distinguished in the field, on the basis of colour and texture, from the basaltic rocks that form lavas lower down the slopes. Trachytes occur to the east of Cerro Pelado and also at the crater known as Cerro Roja (Crater 3, see Figure 6).

*Table 3. Petrographic terms used to define fine-grained volcanic rocks in the west of James Island*[8]

| Rock type | Criteria for differentiating volcanic rocks in the field and also in thin section |
|---|---|
| Trachyte | Light coloured, generally porphyritic, fine-grained rock, composed primarily of alkali feldspar, plagioclase, quartz, biotite with minor hornblende and feldspathoids. In general, any mineral grains large enough to be seen will be alkali feldspar but not quartz. These rocks are commonly flow-banded. |
| Trachyandesite | Little or no free quartz but dominated by equal amounts of alkali feldspar and sodic plagioclase along with one or more of the following mafic minerals: amphibole, biotite or pyroxene. Small amounts of nepheline may be present and apatite is a common accessory mineral. |
| Basaltic trachyandesite | Intermediate between trachyandesite and trachybasalt. Plagioclase feldspar ranges in composition from labradorite to oligoclase. Ferromagnesian minerals are those more commonly found in basalts (olivine, augite). |
| Trachybasalt | An extrusive rock intermediate in composition between trachyte and basalt. Characterized by calcic plagioclase (labradorite) and sanidine, with augite and olivine. |
| Basalt | Dark-coloured, fine-grained may have visible phenocrysts of olivine, plagioclase feldspar and/or clinopyroxene. |

The trachyte that we observed near Cerro Pelado (e.g. 07DSG40) forms a prominent north-facing 300m long bluff (see Figure 8), which we interpret as a volcanic dome. The rock that constitutes the lower and middle parts of the bluff has a 'chalky' bright-green appearance but is quite different from Darwin's greenish-grey 'trachyte' (CD3268) which has less alkali feldspar and browner amphibole. CD3268 is slightly less evolved and resembles a slightly more mafic trachyte (07DSG42, Figures 4 and 9) that we collected from the top of the bluff, immediately below the summit ridge. 07DSG42 contains phenocrysts of alkali and plagioclase, yellow fayalitic olivine ($Fo_{20}$), clinopyroxene together with both a brown and also blue-green amphibole. The petrography and mineral chemistry of 07DSG42 are very nearly identical to CD3268 (Table 2).

8 Note that in both his field notes and *Volcanic Islands* Darwin referred to the 'Mineralogical composition of the rocks'. He is more precise about the compositions of mineral phases, such that plagioclase feldspar is referred to as albite, and alkali feldspar as orthite or potash feldspar and pyroxene as augite.

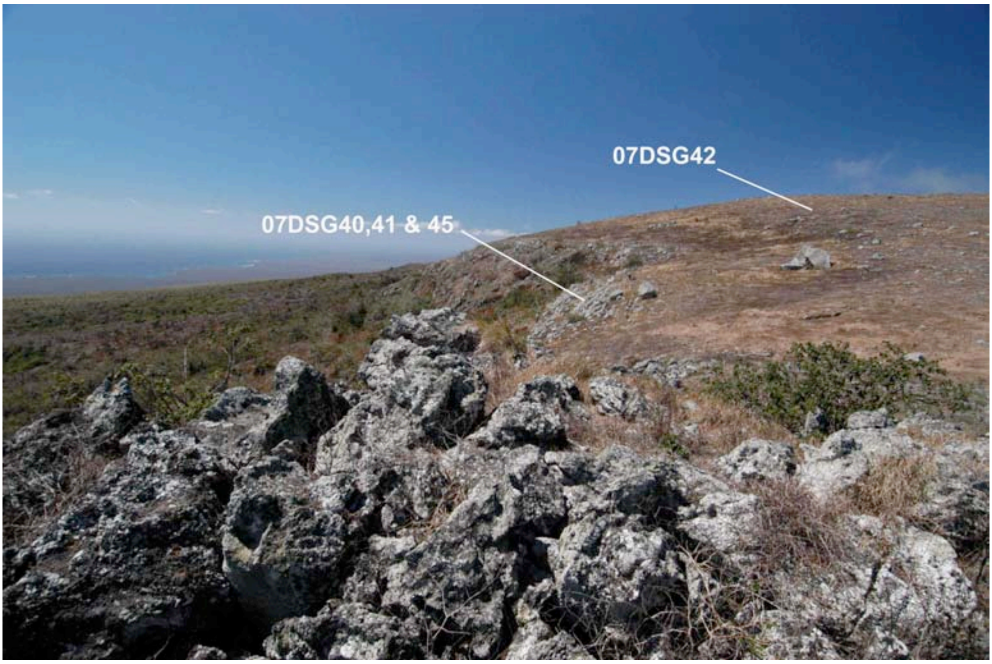


*Figure 8. Location of trachytes at an elevation of 860 metres (2,830 feet) and approximately one hundred metres due east of Cerro Pelado, near the summit of Isla Santiago. (Image by courtesy of A. Thurman.)*

The trachyandesites (see Figure 9) that we collected from the crater rim of Cerro Roja (07DSG50 and 07DSG51) on the north-west facing slope of Isla Santiago (Figure 6) were from large volcanic bombs, measuring up to 1 metre in length, and differ from CD3268 in that they are finer grained and vesicular. In many respects, 07DSG51 is similar to CD3267; both contain brown amphibole, clinopyroxene and olivine that is not especially fayalitic (Table 2, see Figure 4). We therefore suggest that Darwin may have collected CD3267 in the vicinity of Cerro Roja, as he ascended towards the summit of Isla Santiago.

### *3.3 Trachybasalts at Buccaneer Cove*

Several dykes outcrop on the promontory at Buccaneer Cove, some forming spectacular pinnacles, while others that form a small island off the cove (see Figure 10) are composed of trachybasalts. Darwin reported that:

> The piles of scoriae are traversed in several places by great broad dykes many yards thick, which vertically run for considerable distances.— They consist of a compact Trachyte with only few Crystals of [Fel] the sides and certain spots are cellular.— [*In margin:* 3279] (DAR 37.2:772).

Specimen CD3279, referred to in the above quotation, contains large phenocrysts of olivine set in a groundmass rich in plagioclase and clinopyroxene (see Figure 4). Richardson noted in her thin-section description of CD3279 that the feldspar was more sodic (labradorite) than in the basalts and that it contains a yellow clinopyroxene. She suggested that the rock is an olivine andesite. The high amount of plagioclase in this rock almost certainly prompted Darwin to classify it as trachyte rather than basalt, but using the present-day IUGS classification scheme it would probably fall in the field of trachybasalts or basaltic andesites, *i.e.* intermediate between basalt and trachyte (see Figure 5).

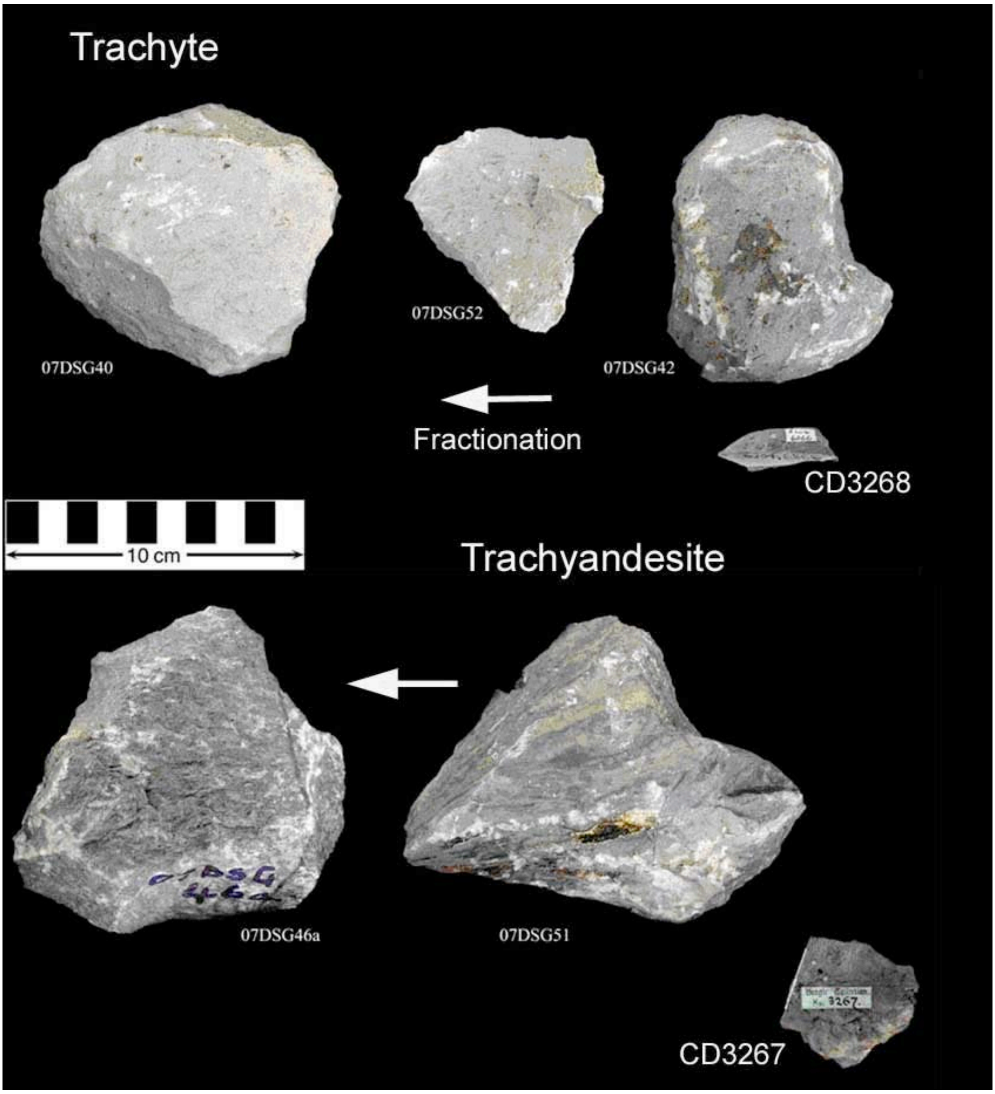


*Figure 9. Hand specimens of trachytes (07DSG40, 52, 42, 46a) and trachyandesite (07DSG51) collected from the northwest of Isla Santiago. Darwin's samples (CD3267 and 3268) are placed next to their closest equivalents in our sample collection. Arrows illustrate how the compositions of fine-grained volcanic rocks change with crystal fractionation; fractionation of mafic (iron and magnesium rich) minerals, such as olivine and pyroxene, causes an increase in the silica content of the magma. This increase in silica is often shown by the colour of fine-grained rocks, which changes from black (basalt) to blue/grey (trachybasalt or trachyandesite) to pale-green (trachyte). (Images courtesy of D. Simons.)*

*Figure 10. Promontory at the north end of Buccaneer Cove. Darwin interpreted this as the wreck of a large crater. (Image courtesy of A. Thurman.)*

### *3.4 Large-feldspar basalts in and around Buccaneer Cove*

Darwin was particularly unsure of the terminology (trachyte or basalt) that he should use for the volcanic rocks on Isla Santiago which are rich in large crystals of plagioclase. These are the dominant rock type over much of the northwest of the island, including Buccaneer Cove, Cerro Pelado, and the summit bowl. Concerning the promontory at Buccaneer Cove (Figure 10), Darwin wrote:

> In central & rather lower part of the promontory. which I believe to have been bosom of Crater. There is a mass about 200 ft thick of a quite compact, greenish or blackish grey **Trachyte** with few Cryst of glassy Feldspar: (DAR 37.2: 720–721, emphasis added).

But when referring to the same 200-foot outcrop in *Volcanic Islands* Darwin changed the name of this rock from trachyte to basalt.

> One side of Fresh-water Bay, in James Island, is formed by the wreck of a large crater, mentioned in the last chapter, of which the interior has been filled up by a pool of **basalt**, about two hundred feet in thickness. This basalt is of a grey colour, and contains many crystals of glassy albite, which become much more numerous in the lower, scoriaceous part (Darwin 1844, p. 117; emphasis added).

The reason for the discrepant descriptions is unclear. The origin of the prominent outcrop is straightforward: it was a lava lake that filled the crater of the scoria cone near the end of its eruption. It is closer to fifty feet than 200 feet thick, but massive blocks of it have tumbled to the sea, giving the impression that it could be 200 feet thick. Also, the base is not particularly vesicular (although the top is), and it is not very rich in feldspar phenocrysts (typically 2% by our observation). We note, however, that crystal sorting of feldspar typifies many other Galápagos lava flows and fossil lava lakes.

Darwin's other samples of volcanic rocks from Buccaneer Cove are mostly plagioclase-phyric types (i.e. with phenocrysts of plagioclase). Presumably, CD3275 was collected by Darwin because it contains 'bright red specks' and forms an abundant rock type at Buccaneer Cove. He wrote of this location:

> There were very many large pieces of a harsh red Claystone base, more or less vesicular & containing more or less Cryst[s] of glassy Feldspar and small bright red earthy specks.— Specimen Shows the two cases in lesser extreme (3275).— I did not reach any stream of this rock, but it must be very abundant.— (DAR 37.2:720).

Thin-section examination reveals that the red specks in CD3275 are formed of altered olivine and that the rock is a basalt that has undergone hydrothermal alteration. This process frequently affects rocks that are located near volcanic vents and olivine is particularly susceptible to this type of alteration.

The lowest crater (Crater 1, see Figure 6) above Buccaneer Cove occurs at an elevation of 300 metres (~1,000 feet). It contains highly vesicular basalt flows that resemble Darwin's sample CD3266. The rocks contain phenocrysts of rounded olivine and two generations of plagioclase that are set in a fine-grained groundmass. The largest feldspars are rounded, full of glass inclusions, and the sparser smaller crystals are more homogeneous and lath-shaped (Table 2).

Lava flows emanating from Crater 2, and also those that occupy much of the lower slopes below 200 metres (650 feet) around the northwest of Isla Santiago, are exceedingly rich in large (~5 mm) plagioclase phenocrysts and resemble CD3265 (Table 2). In thin-section, the plagioclase crystals show strong compositional zonation and are full of inclusions. Additionally, some of these samples (e.g. 07DSG55) contain phenocrysts of pale green clinopyroxene and olivine.

*3.5 Olivine basalt from James Bay*

In notes made on 11 October Darwin described how his party took a boat trip from Buccaneer Cove 6 miles south to James Bay (which he referred to as Puerto Grande) with resident tortoise hunters to visit the salina that had formed in a tuff crater. Darwin mentioned that at James Bay:

> Stream.— Have burst from several small Craters at foot of central Trachytic mass of highest hills & Craters.— Consists of <u>Greys</u>tones such as (3280) which abounds in a very remarkable degree, with quantities of olivine. is generally very Vesicular & sometimes rather a Darker color (3281).— The Basin is much the same as in Central Trachytes, the Olivine here replacing glassy Feldspar.— Its surface is smoother than the Basalt of Chatham Isd.— Yet many great fissures.— Surface ringed, (like Cow-dung), which often takes form of <u>cables</u>; folds in a [*illegible*] & branches with rough bark. In this Island we have this Olivine Lava as the latest, whilst in Albemarle, that of Trachyte.— Near to the Sea, it has burst through an ancient crater, (composed of igneo-cemented red glassy Scoriae & greystone Lavas) filled up Crater & left only 2 pieces, which stand in front of each other.— (DAR 37.2:722).

James Bay is a broad (~9.5 kilometres wide) bay located to the south of Buccaneer Cove (see Figure 6). The James Bay flows are olivine-phyric basalt and are distinguished from others in the northwest of the island by the fact that olivine is the only phenocryst phase. A prominent recent (~1759 AD) lava flow fringes the back of the middle part of the bay over a distance of more than three kilometres and erupted from a crater on the flank of the main volcano. The flow is covered by sparse vegetation (mainly cacti: *Brachycereus nesioticus*) and displays spectacular pahoehoe textures, including those resembling ropes, and, as noticed by Darwin, cow dung (Figure 11). This lava resembles specimen CD3281. The olivine grains in this flow are small (~1mm) and range in composition from $Fo_{76–62}$ (see Table 2). Small laths of plagioclase ($An_{84–71}$) and clinopyroxene (diopside) are also present. Below the recent pahoehoe flow at James Bay there is a grey-weathering lava flow that is coarser grained. The sample that we collected from this flow (07DSG65) has a similar appearance in both hand specimen and thin section to CD3280 (see Table 2 and Figure 4).

*Figure 11. Recent lava flow at James Bay, being examined by G. Estes, D. Geist, and S. A. Gibson. (By courtesy of A. Thurman.)*

### *3.6 Coarse-grained 'fragments' in lavas at Buccaneer Cove*

Darwin's fieldwork on Isla Santiago also influenced his ideas on the origin of coarse-grained igneous rocks contained in eruptive rocks. The lava flows at the north end of Buccaneer Cove, especially those that make up 'Darwin's Layer Cake' succession contain xenoliths (Estes, Grant, and Grant, 2000). (See Figures 12 and 13.)

As previously noted by both Richardson (1933) and Pearson (1996), Darwin referred to these inclusions as 'granites' in his field notes. 'Granite' was then defined as beng "composed of three simple minerals, feldspar, quartz and mica" (Lyell 1830–1833, Vol. 3 glossary). While on the voyage, Darwin subscribed to the largely Lyellian view that granite was still in the process of formation within the Earth (Oldroyd 1996, Chapter 9). Darwin wrote of specimens 3270 through 3273:

> This Trachytic Lava is remarkable by containing <u>very many</u> fragments of altered rocks, which clearly have been **Granites** and Syenites (3270:71:72:73) (DAR 37.2: 719, emphasis added).

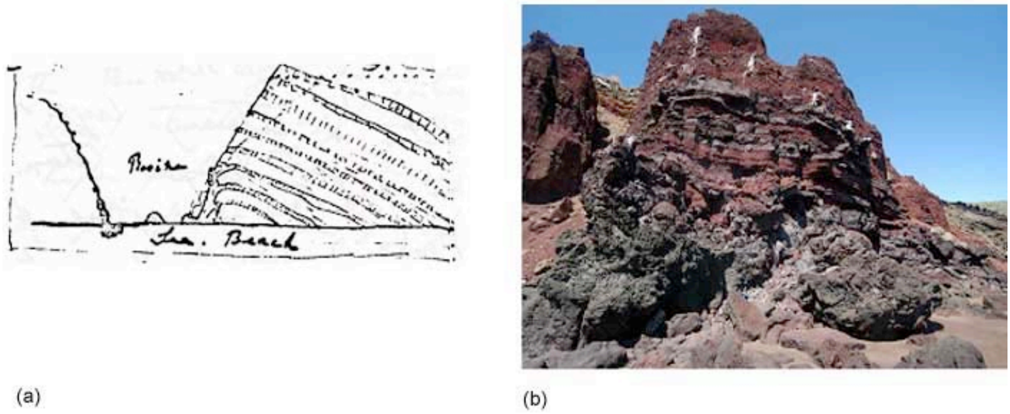


*Figure 12. (a) Darwin's field sketch (from DAR 37.2:773) of the thin streams of lava at Buccaneer Cove in which he has labelled the 'sea', 'beach' and 'ravine'. A similar but revised version of this sketch also appears in* Volcanic Islands *but is drawn from a different perspective. (b) Present-day outcrop at Buccaneer Cove. Individual 'streams' of lava ~ 40 cm thick are interbedded with bright red scoria. These flows are especially rich in coarse-grained fragments. (Image [b] courtesy of A. Thurman.)*


*Figure 13.*
*Hand specimen of one of Darwin's 'fragments' (CD3272) found at Buccaneer Cove. (We observed similar xenoliths in the thin lava flows at this locality. Some of the large crystals of feldspar that Darwin observed may have been derived from disaggregation of these xenoliths.) (Image by courtesy of D. Simons.)*

Darwin's initial description of these xenoliths as granites was influential in his initial interpretation as to how the trachytes formed. In notes made after his departure from Isla Santiago, he proposed that the lavas at Buccaneer Cove had been formed by the melting of material of composition similar to the fragments. Note that he again calls the plagioclase-phyric basalt 'trachyte':

> The Trachyte here is interesting from containing very many small generally angular fragments of altered rocks, which clearly have been Granites & Syenite. — Hand specimens do not impress the idea of their extraneous origin, with the force with which inspection of the bed itself does [*in margin:* 3270:71:72:73]. —The glassy substance into which the Mica has been changed is remarkable.— One piece seems to have been part of a Quartz vein (3274.).— [*in margin:* 3274] The Feldspar is in nearly the same glassy fractured state as is the Trachyte. (Is the form & size similar?). It will be observed that the fragments have not become vesicular. — In a like manner the Crystals of the most vesicular varieties of lava are not thus affected.—

> One is led to suspect that all such Crystals proceed from the Granite & that they are not produced in the liquid Lava.— Inspection of a specimen of a cindery, regularly & highly vesicular Trachyte, brought from Abingdon Is[d] by M[r]. Chaffers [*in margin:* 3288], where the Crystals are very large & perfect, will tell more on this side of the argument than any description.— Yet I am unwilling to take up this opinion: If the Trachyte is melted Granite the quartz & mica has formed the more fusible part.— [*in margin:* which composes the matrix for the glassy Feldspar:—] In the fused mass, when at an <u>intense</u> heat, does not the quartz & a small portion of the other ingredients form the Crystals of <u>glassy</u> Feldspar.— May not these Crystallize at a temperature when the rest of the matter is fluid? This will explain the imbedded & extraneous appearance of the Crystals.—I do not however understand in any [*alternative reading:* every] point of view the observation, which I believe to be exact, viz that the Crystals abound more in the more Vesicular varieties **(**DAR 37.2: 775–776).

It is clear, however, that by the time Darwin wrote *Volcanic Islands* he realized that there was no quartz in these rocks, and that they could therefore not be granites. Therefore, as is common practice among researchers, he revised his opinion of their proper classification:

> In the lava and in the scoriae of this little crater, I found several fragments, which, from their angular form, their granular structure, their freedom from air-cells, their brittle and burnt condition, closely resembled those fragments of primary rocks which are occasionally ejected, as at Ascension, from volcanoes. These fragments consist of glassy albite, much mackled, and with very imperfect cleavages, mingled with semi-rounded grains, having tarnished, glossy surfaces, of a steel-blue mineral. The crystals of albite are coated by a red oxide of iron, appearing like a residual substance; and their cleavage-planes also are sometimes separated by excessively fine layers of this oxide, giving to the crystals the appearance of being ruled like a glass micrometer. There was **no quartz** (Darwin 1844, pp. 110–111, emphasis added).

Although he initially considered that the xenoliths might have been the source of the trachytes, Darwin arrived at the currently held conclusion that these coarse-grained rocks consist of olivine, feldspar and pyroxene (*i.e.* they are gabbros) and formed from magma that solidified at depth:

> It is interesting thus to trace the steps by which a compact granular rock becomes converted into a vesicular, pseudo-porphyritic lava, and finally into red scoriae. The structure and composition of the embedded fragments show that they are parts either of a mass of primary rock which has undergone considerable change from volcanic action, or more probably of the crust of a body of cooled and crystallised lava, which has afterwards been broken up and re-liquified; the crust being less acted on by the renewed heat and movement (Darwin 1844, p. 112).

The coarse-grained xenoliths at Buccaneer Cove exhibit large variations in abundances of olivine, plagioclase and clinopyroxene. This diversity of rock types is also apparent in Darwin's collection. By far the most abundant are gabbros, which are composed of calcic plagioclase and clinopyroxene with minor olivine and resemble CD3270, 3272 and 3273 (Figure 4). CD3271 is distinctive because of its content of olivine and plagioclase (it is best described as a troctolite, see Figure 4). We also collected rare xenoliths with high proportions of plagioclase (07DSG26d) and of olivine (07DSG26b) from Buccaneer Cove. Their compositions are, however, subtly different to those of CD3271 (Table 2).

Richardson (1933) estimated the compositions of the plagioclases and olivines in the gabbroic xenoliths and the host lavas and established that they were different. She thus concluded that the large feldspars and olivines in the 'basaltic matrix' were not derived from the assimilated xenolithic material. Like McBirney and Williams (1969), we interpret these 'fragments' as the products of partial crystallization that have accumulated in a shallow magma chamber before being erupted in lava flows from a vent in the vicinity of Buccaneer Cove.

## 4. CONCLUSIONS AND OBSERVATIONS

The volcanic landforms and rock types that Darwin encountered during his ten day visit to Isla Santiago in 1835 are traceable and provide insight into Darwin's thinking while he was in the field. We were able to locate volcanic and plutonic rocks that resemble, if not match, all of Darwin's Isla Santiago specimens now curated in the Sedgwick Museum collection. With the aid of modern petrological and geochemical equipment we have been able to fully characterize rocks identical to those that Darwin collected and confirm the presence of trachytes in the NW Highlands. The trachyte that outcrops close to the summit resembles CD3268, the sample that McBirney and Williams (1969) doubted had been collected by Darwin on this island.

Darwin's characterization of igneous rocks and interpretations of their formation were revised following his return to England, prior to publication of *Volcanic Islands* in 1844. His initial field-based subdivision of fine-grained rocks into basalts and trachytes reflected what he would have been taught during his studies at the Universities of Edinburgh and Cambridge. On his return to England, Darwin re-classified the vesicular volcanic rocks rich in large feldspar phenocrysts as basalts rather than trachytes. Darwin's revised classification is in line with modern-day terminology and presumably a response to his discussions with other authorities, particularly William Hallowes Miller (1801–1880), Professor of Mineralogy at the University of Cambridge.[9] This explains the apparent discrepancy that exists between Darwin's use of the term trachyte in his field notes and in *Volcanic Islands*. This is important when trying to understand, for example, how Darwin used his field evidence from places such as Isla Santiago to make the connection between the spatial and temporal distribution of basalts and trachytes and how he linked these to the depth of magma extraction from beneath individual volcanoes. On the basis of his observations, Darwin proposed that the diversity of igneous rocks was caused by dynamic processes operating underneath volcanoes, rather than being a characteristic of the Earth's changing composition over the course of geological time, which was one of the principal hypotheses of the time.

Given Darwin's fame, it would be easy enough to over-credit his contribution to modern petrology (Merton 1968). Our combined field and laboratory-based study has examined the extent to which Darwin's initial observations align both with his own published conclusions and with present-day understanding of igneous processes. We note that Alfred Harker, who is recognized as one of the founders of modern igneous petrology, devoted much effort to preserve Darwin's specimens. Harker attributed to Darwin the leading role in establishing a new notion of magmatic differentiation, noting that the only practical alternative to the idea was the "doctrine of countless special creations" (Harker 1909, p. 310. For a more nuanced account published in the same year see Judd 1909). Pearson (1996), however, has emphasized the limited impact of Darwin's work on the subsequent development of igneous geology after 1844 (Pearson 1996, Young 2003, Chapter 8). Even with the caveat of the danger of over-crediting Darwin, it is impressive that he drew so boldly from his observations on Isla Santiago.

The final observation we wish to make pertains to the relationship between Darwin's petrological work on Isla Santiago and his zoology and botany. There are several points of

[9] William Hallowes Miller succeeded to the professorship of mineralogy at the University of Cambridge in 1832, after it was vacated by William Whewell. Miller continued Whewell's focus on crystallography. After returning from the *Beagle* voyage, Darwin consulted Miller on a number of the geological specimens that he had collected during his travels.

commonality coming as they did during the later stages of the *Beagle* voyage. Darwin's researches in Galápagos geology, as in zoology and botany, represented a culmination of his South American work and an opportunity for him to test some of his skills of both observation and reasoning. Furthermore, common ideas, drawn particularly from Scrope and Lyell, emphasized the on-going nature of processes operating within the Earth and upon its fauna and flora. For Darwin, as well as for Scrope and Lyell, such processes were seen to affect species as well as rocks (Lyell 1830–1833, vol. 2, chapters 8–11; Scrope 1825, pp. 238–239). Darwin took time to develop his ideas in each of these areas; in all his work on natural history there was an interval of several years between initial observation and formal publication. During that interval he developed his views and reworked them in the light of the then-current science, without losing the originality of his field-based insights. This was as true for his geological work on Isla Santiago as it was for his work with plants and animals at the same location.

## APPENDIX: NOTES ON THE JULY 2007 EXPEDITION

The existence of the 'trachyte problem', and some idea of where the outcrop of this rock type might be, was discussed by members of our group in 1999 (Estes, Grant and Grant 2000; Herbert 2005, pp. 120–126). An opportunity to undertake geological fieldwork on James Island arose in July 2007. The timing of this expedition stemmed from the inherent interest relating to the existence of trachyte on James Island and from the circumstance that the Sedgwick Museum of Earth Sciences is in the process of preparing a full-scale exhibit of Darwin's geological specimens to open in 2009, the bicentenary of Darwin's birth. David Norman and Sandra Herbert submitted a successful application to the Charles Darwin Research Station for a study entitled "Reconstructing Charles Darwin's 1835 Geological Expedition on Isla Santiago in the Light of Twenty-First Century Science".

The team that went on James Island included the geologists David Norman, Sally Gibson and Dennis Geist and, as guide and natural historian Greg Estes. Andrew Thurman served as photographer. Melina Neira from Ecuador and Andrew Miles from the UK were student members of the team. José Luis Villa Fuerte from Ecuador served as field assistant. Sandra Herbert, Thalia Grant, and James Herbert remained on Isla Santa Cruz where they facilitated arrangements with the Charles Darwin Research Station and the *Parque Nacional Galápagos*. Interestingly Darwin's own party included about the same numbers on site and was also in effect a multi-national effort. While on James Island, Darwin's group was materially assisted by local, and visiting Spanish-speaking residents and by 'Yankee' whalers who gave them a supply of fresh water, the fresh water of Buccaneer Cove having been contaminated by a surge of salt water. Darwin's group stayed on James Island 8–17 October 1835; the present team stayed on James Island 7–14 July 2007.

Unlike in Darwin's time, Isla Santiago is uninhabited and access is restricted by the *Parque Nacional Galápagos*. The only sources of fresh water used by visitors are rainwater-fed tanks in the highlands. We therefore took all of our own provisions and fresh water. The majority of our time was spent in the west of the island, around James Bay, Buccaneer Cove and in the northwest Highlands (see Figure 6). We set up a base camp behind the beach at Buccaneer Cove in a valley where the promontory intersects the coastline. Darwin is believed to have camped in this same area (Estes, Grant and Grant 2000). In his 'Diary' Darwin referred to this area as 'Freshwater Cove of the Buccaniers' (*sic*), which has now been shortened to Buccaneer Cove (Keynes 1988, p. 361). We camped for a further two nights inland from Buccaneer Cove at an elevation of approximately 650 metres (2,100 feet) just below the altitude at which the dense woodland changes to grassland. The ascent to our second camp took approximately half a day, and we spent two days exploring volcanic craters and lava flows in the NW Highlands (Figure 6). A further day was spent walking to and collecting samples from James Bay. The remainder of our time was spent at Buccaneer Cove. These locations and our route into the NW Highlands are similar to those described in Darwin's field notebook (Estes, Grant and Grant 2000). Almost all of the geological features described by Darwin are still visible on Isla Santiago. An exception may be the northeast-facing cliffs on the promontory at the north end of Buccaneer Cove, where there is evidence of steady on-going erosion and of a considerable recent fall of large blocks. Darwin believed that this outcrop represented the core of an eroded crater.

## ACKNOWLEDGEMENTS

We are grateful to Susana Cardenas and Sonia Cisneros at the Charles Darwin Research Station (CDRS), and to Alan Tye, formerly Director of Research at CDRS, for advice and for their assistance with logistical support for our research on Isla Santiago. We also wish to thank Graham Watkins, Executive Director of the Charles Darwin Foundation, for his support. We are deeply indebted to the *Parque Nacional Galápagos* for granting us permission to undertake research on Isla Santiago.

At the Department of Earth Sciences of the University of Cambridge we wish to thank Stephen Laurie for arranging access to Darwin's geological specimens, Dudley Simons for photography of the specimens, Chris Hayward for his assistance with the electron microprobe, and Jason Day for sample preparation. For information on Constance Richardson we thank Anne Thomson, Archivist of Newnham College of the University of Cambridge and also Bob Myhill, who looked through the archives of the Sedgwick Club for information about Richardson. We also wish to thank Mark Schneider, formerly Director of the Peace Corps (USA), for providing us with scientific maps of the Galápagos Islands. Funding for the expedition and analytical work was provided by the National Science Foundation in the USA and by the University of Cambridge, Trinity College, and Christ's College in the UK.

## ARCHIVES

The Darwin manuscripts cited in the text are held by Cambridge University Library and are cited with permission from its Syndics. The manuscripts bear the class mark 'DAR'. Darwin's specimens along with the Harker Catalogue are kept at the Sedgwick Museum of Earth Sciences, Cambridge University.

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