Reports

Origin of Española Island and the Age of Terrestrial Life on the Galápagos Islands

Abstract. *Geological studies of Española (Hood) Island, Galápagos, Ecuador, indicate that the island had a subaerial rather than a submarine origin. Because the younger lava flows are dated at 3 million years, Española has apparently existed as an island for at least that long. Thus terrestrial life may have existed or arrived on the Galápagos Islands at least 3 million years ago, more than twice as long as had been assumed.*

Ecuador's Galápagos Islands are best known for their unusual fauna and flora and for their role in the development of our understanding of biological evolution (*1*). Although descriptive studies of plant and animal life are well advanced (*2, 3*), relatively little is known about rates of evolutionary change. This is due in part to the lack of knowledge about the age and origin of the islands. Early radiometric dating indicated that the oldest lavas (submarine lavas) were no more than 1.5 million years old (*4*), an age implying an accelerated rate of biological evolution (*5*). More recent dating of lavas from Española Island yielded ages of about 3.2 million years by the potassium-argon method (*6*) and greater than 3 million years by paleomagnetic methods (*7*). If, however, Española Island represents a block of submarine lavas uplifted from below the sea (*8*), it could not have served as an island refuge for the earliest terrestrial plant and animal arrivals. New geological evidence indicates that the island's lavas formed above sea level (*9, 10*).

The archipelago consists of 14 principal islands and many smaller rocky islets. The youngest islands are found toward the archipelago's western limit, and the oldest toward the east and southeast. The geology and petrography of the islands has been described by McBirney and Williams (*8*). Española Island, located in the extreme southeast corner of the archipelago, measures about 14 km in length (east to west) and up to 7 km in width. In general the island has a subdued topography that slopes to the north, with its highest point (200 m) near its southern edge. The southern coastline is marked by a vertical cliff 100 m high; the northern coast dips gently under the sea. The island, with a dry and arid climate, is covered by palo santo trees, *Opuntia* cactus, and brush.

The island's geology has been described as a sequence of basaltic flows that generally dip to the north (*8, 9*). However, more detailed work has shown that the flows dip gently away from the highlands, suggesting the morphology of an old shield volcano, now greatly eroded (Fig. 1) (*10*). More than 30 individual lava flows, averaging 3 to 5 m in thickness, are exposed in the southern cliff. Petrographically the lavas show little variation and consist of microphenocrysts of olivine and calcic plagioclase in a very fine-grained groundmass of anhedral augite (at times titaniferous), plagioclase, iron oxides, and occasionally analcite. These lavas belong to the alkaline olivine basalt series (*8, 9*). Potassium-argon dating of three lava flows from the north coast of Española gave ages of 2.12 ± 0.38 million years, 3.04 ± 0.11 million years, and 3.31 ± 0.36 million years (*6*). This range in age is supported by paleomagnetic results (*7*). These values are the consistently oldest dates so far determined in the Galápagos Islands.

The evidence presented below implies that the lavas of Española Island formed under subaerial conditions.

Neither marine sedimentary rocks, pillow lavas, nor glassy crusted flows were observed, in spite of a detailed search of the excellent exposures along the southern cliff (*10*). On Baltra and Santa Cruz islands fossiliferous marine limestones are found interbedded with lavas, showing that conditions favorable to limestone formation existed in the past as well as today.

An ancient cinder cone was discovered (Fig. 2) that is preserved in the oldest lava flows of the island (south cone in Fig. 1). It is well known that a variety of pyroclastic cones may form upon, or adjacent to, basaltic islands. The degree to which seawater or ground water interacts with rising magma will largely determine the morphologic and stratigraphic characteristics of the resultant cone and the nature of its tephra. Where seawater gains access to the ascending magma (for example, in shallow submarine conditions or along the perimeter of basaltic islands), phreatomagmatic cones, such as maars, ash cones, and ash rings, often develop (*11–13*). In contrast, on the flanks of shield volcanoes well above the shoreline, where magma rising to the surface cannot react with seawater, the tendency is to form cinder cones and spatter cones with their distinctive characteristics (*14*).

Certain morphologic parameters of pyroclastic cones have specific ranges of values that serve to distinguish between various types of cones (*15*). The south

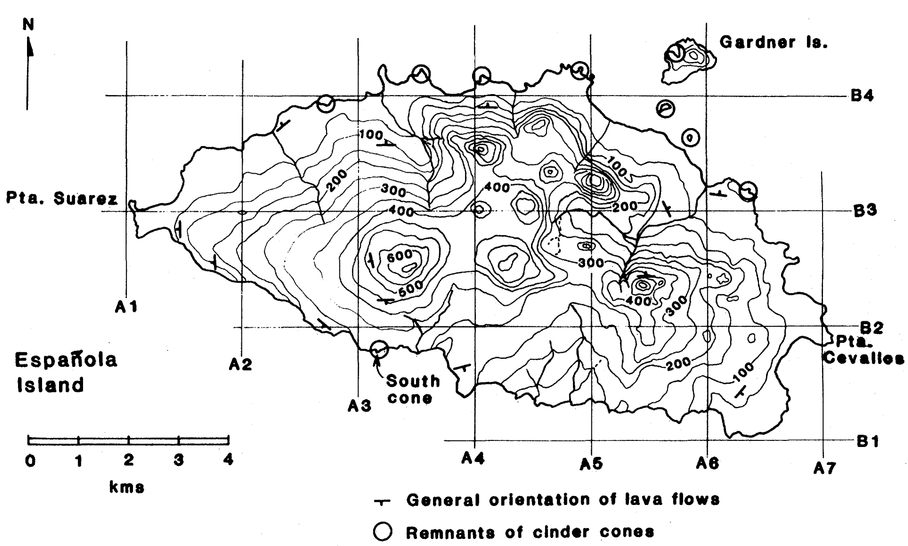

Fig. 1. Map of Española Island (contours in feet).

Table 1. Comparison of morphologic parameters of pyroclastic cones. W_{co}, basal diameter of cone (km); W_{cr}, diameter of crater (km); and H_{co}, height of cone (km).

Cone type	Cone parameters				Reference
	Average W_{co}	W_{cr}/W_{co}	H_{co}/W_{co}	Average outer slope inclination	
Maars and ash rings	1.38	0.60	0.02	5°	(*11, 15*)
Ash	2.37	0.43	0.074	35°	(*24*)
Cinder	0.80	0.40	0.18	30°	(*15, 19*)
Spatter	0.08	0.36	0.22	30° to 90°	(*15*)
South cone	0.28	0.40	0.15	26°	(*10*)

cone's apparent dimensions are: basal diameter, 280 m; height, 42 m; crater diameter, 113 m; and outer slope inclination, 26°. A comparison of its morphology with that of other cone types (Table 1) suggests that its parameters best conform to those of cinder cones and are distinct from those of phreatic cones. Furthermore, the crater floor lies well above the cone's base, a morphologic feature not characteristic of maars and ash rings (*11*).

The nature of the stratification is also useful in distinguishing vents of phreatomagmatic origin from those of magmatic origin. For example, the outer slopes of maars, tuff rings, and tuff cones are generally made up of well-stratified, extremely thin-bedded, poorly sorted, fine-grained (≤ 2 mm) tephra (*16–18*). In contrast, stratification in cinder cones is poorly developed, consisting of thick units and often demonstrating a crude graded bedding (*19, 20*). The size of individual fragments is considerably larger than those from phreatomagmatic cones, generally measuring 1 to 30 cm in diameter (*18, 21*). Good sorting is often reported (*18*).

The tephra of the south cone is only crudely stratified, relatively well sorted, and principally made up of reddish oxidized cinders that may attain diameters of up to 30 cm but generally measure only 5 to 10 cm. They are vesicular fragments, denser than scoria, and usually not welded together. Locally the cinders have an agglutinate-like appearance, suggesting that occasional spattering occurred. A few unipolar fusiform bombs, up to 5 cm in length, were found in the cindery material. Common sedimentary structures of phreatomagmatic cones—dunes, cross-bedding, graded bedding, bedding-plane sags, and accretionary lapilli (*12, 16*)—were not observed. Nor was evidence of slumping or erosion of the outer slope found.

The tephra's glassy fragments provide additional evidence of subaerial origin. Tachylyte is more likely to form in subaerial environments, while sideromelane is more typical of subaqueous conditions (*16, 18*). The coarse cinders of the cone are composed of black vesiculated glass (tachylyte) with plagioclase and olivine microlites. Achneliths—ash particles with shapes unique to nonphreatic eruptions (*17*)—were recognized in many samples. Most significantly, fine glassy threads (Pele's hair) were identified in the interstices of cinders from the younger beds. The presence of achneliths, fusiform bombs, and Pele's hair all imply a subaerial origin. Sideromelane and palagonite are important components only in the fine-grained material at the base and top of the cone, and these may represent posteruptive alteration.

Thus, the south cone is best described as a partially eroded cinder cone that formed well above the ancient shoreline. Other pyroclastic cones found on islets as well as along the north shore of Española (Fig. 1) have similar characteristics and are also considered to be subaerial cinder cones (*10*). The fact that several of the cones around Gardner Bay (locality A5–B4 in Fig. 1) are now partially submerged while the tops of others have been completely beveled by wave erosion, testifies to sea-level changes during the Pleistocene.

Furthermore, the island has had prolonged exposure to subaerial weathering. For example, solutional weathering of basalt flows, not reported elsewhere in Galápagos, has produced vertical fluting with up to 30 cm of relief. A soil 3 m thick, composed of unconsolidated basalt grus and spheroidally weathered fragments of basalt, was discovered interbedded in the upper lava sequence of the island (locality A28–B19 in Fig. 1). A caliche horizon 2 to 4 cm thick occurs in its upper part. The presence of this soil as well as the caliche horizon implies stable semiarid to arid conditions over an extended period. The absence of erosion of the loose soil suggests that its surface was never covered by the sea.

The strongest evidence previously cited in favor of a submarine origin for Española Island was the "pebbles and cobbles of limestone . . . found . . . near the summit peak" (*8*). These 1- to 10-cm calcareous nodules occur scattered over the dry, fine-grained tan-colored soil of the island's higher elevations (> 60 m). They are composed of microcrystalline calcite (micrite), similar in structure and texture to caliche (*22, 23*). Neither the remains of marine life, such as microfossils or algal reefs, nor marine sedimentary features, such as good stratification and sorting or oolites, were observed in hand specimens or thin sections. Consequently, these calcareous

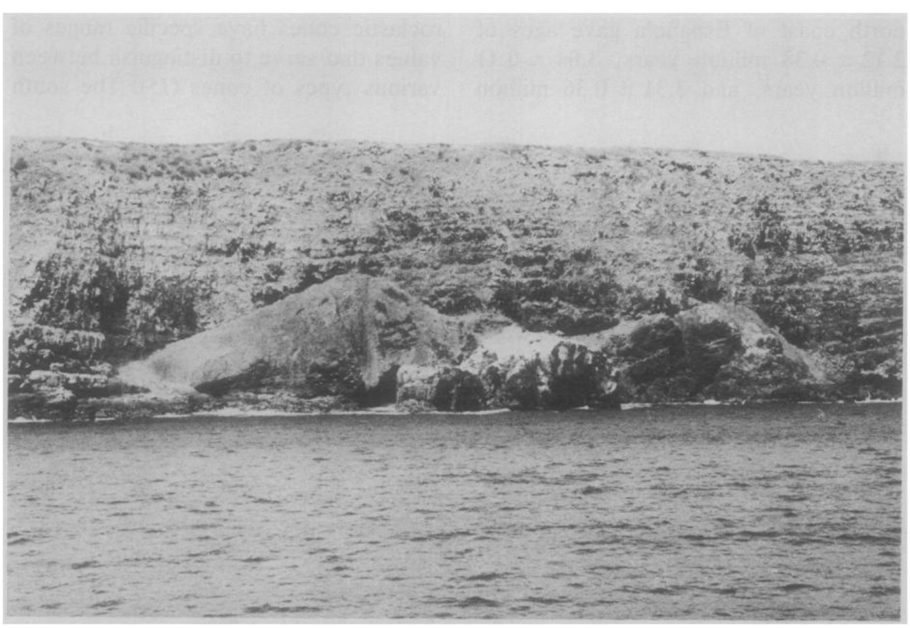

Fig. 2. South cone, interbedded in the basalt flows of the southern cliff, Española Island, is 280 m in diameter and 42 m in height. It has the morphologic, stratigraphic, and tephra characteristics of a cinder cone that formed above sea level.

nodules appear to be the remnants of an old caliche horizon, not of a marine limestone. Erosion of the island's upper slopes has exposed and widely dispersed the caliche.

Altogether the evidence points to the formation of the lavas of Española Island in a subaerial environment. Furthermore, the presence of both ancient and contemporary caliche-bearing soils implies that the greater part of the island has always been emergent. Because the lavas of the north coast are dated at more than 3 million years and because these are stratigraphically younger than the buried cinder cone, it follows that the island is older than 3 million years. Consequently, it is possible that terrestrial life arrived or existed in the Galápagos Islands at least 3 million years ago, which is more than twice as long as had been assumed.

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Boron in Sillimanite

Abstract. *Sillimanite in six granulite-facies, kornerupine-bearing rocks contains 0.035 to 0.43 percent B_2O_3 and 0.02 to 0.23 percent MgO (by weight). Substitution of boron for silicon and magnesium for aluminum is coupled such that the ratio of magnesium to boron is about 0.5. Sillimanite incorporates more than 0.1 percent B_2O_3 only at high temperatures in a boron-rich environment at very low partial pressures of water. In the amphibolite facies, the sillimanite boron contents are too low to appreciably affect the stability relations of sillimanite with kyanite and andalusite.*

Sillimanite usually occurs naturally as stoichiometric Al_2SiO_5. Analytical work has shown that Fe^{3+}, Cr^{3+}, or V^{3+} (mostly less than 2 percent oxide or 0.04 atom per three cations) and traces of titanium substitute for aluminum (*1–3*). This substitution has minimal effect on the thermodynamic properties of sillimanite and on its stability relations with the other Al_2SiO_5 minerals (*4*). Elements that have been reported present in sillimanite include boron, 0.006 to 0.05 percent B_2O_3 by weight [20 to 170 parts per million (ppm) boron by emission spectrographic analyses (*5*)] and magnesium, up to 0.3 percent MgO by weight [electron microprobe analysis (*6*)]. In contrast, the boron content in kyanite is reported not to exceed 10 ppm and that in andalusite, 25 ppm (*5*). On the basis of these boron contents, D. R. Wones (*4*, p. 208) suggested that boron's "effect on phase equilibria could be important."

Newly analyzed sillimanites from six kornerupine-bearing, granulite-facies rocks (*7*) contain 0.035 to 0.43 percent B_2O_3 (*8*), nine times the previously reported amount, and 0.02 to 0.23 percent MgO (Table 1). The atomic (Al + Fe + Cr)/Si ratio exceeds 2, the value for stoichiometric sillimanite. In contrast, sillimanite from two granulite-facies rocks lacking borosilicates (*7*), samples that were analyzed concurrently with the other six, contains only 0.02 percent MgO and is stoichiometric. We suggest that sillimanite found to contain magnesium should be suspected of containing boron as well, for example, the sillimanite containing 0.3 percent MgO in a borosilicate rock from Zambia (*6*).

The boron contents that we have found confirm that sillimanite is one of the very few anhydrous silicate minerals normally free of boron to incorporate boron in amounts greater than 0.1 percent B_2O_3. Another example is sapphirine; the sapphirine in our samples 1 and 2 contains 0.72 and 0.56 percent B_2O_3 (ion microprobe analyses). In contrast to sapphirine, sillimanite has a relatively simple crystal structure and chemical substitutions are very restricted.

The sillimanite structure consists of single chains of aluminum octahedra supported by double chains of ordered aluminum and silicon tetrahedra parallel to the *c* axis (*9*). In our sillimanite compositions recast to three cations (Table 1), the boron content varies inversely

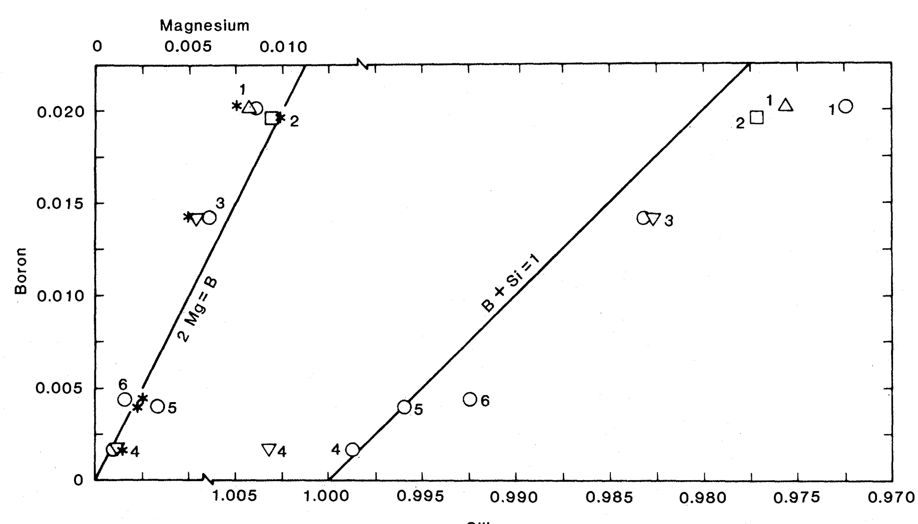

Fig. 1. The boron, magnesium, and silicon contents of sillimanite (in analyses recast to three cations). Asterisks indicate averages obtained during several sessions with the ion microprobe. Circles and squares designate electron microprobe data from Table 1. Triangles represent data from other sessions with the electron microprobe. Lines relating boron, magnesium, and silicon contents are for reference.