Reports

Gravitational Evidence for a Low-Density Mass beneath the Galápagos Islands

Abstract. *A residual negative free-air and Bouguer anomaly of at least 80 milligals, superimposed on a broader high, occurs over the Galápagos Islands. The axis of the anomaly trends roughly east and plunges eastward. Thus, a low-density mass in the crust or upper mantle must underlie the archipelago. This anomaly may be caused by thermal expansion over a crust-mantle "hot spot."*

The Galápagos Islands are geologically youthful [late Miocene (?) and younger] volcanoes in the eastern equatorial Pacific, which have erupted lavas that include tholeiitic basalts, magnesium-poor alkali basalts, magnesium-rich alkali basalts, and their pyroclastic equivalents. Differentiated, more silicic and alkaline lava flows are of minor volumetric importance. McBirney and Williams (*1*) have presented a comprehensive summary of the geology and petrology of the islands, and Simkin and Howard (*2*) have described the eruption and caldera collapse that occurred on Fernandina volcano in 1968. Active shield volcanoes, similar to Hawaiian volcanoes, dominate the western part of the archipelago.

A reconnaissance gravity survey of the Galápagos Islands was conducted during expeditions in 1970, 1971, and 1973 (*3*). Traverses were made across the islands of Marchena, Fernandina, and Floreana, and isolated nearshore stations were established on most of the larger islands (Fig. 1).

Although all gravity anomaly values are positive, a free-air anomaly map, based on 32 points of shoreline or nearshore control, indicates that a major residual negative anomaly extends across the archipelago (Fig. 1). The same pattern is shown by simple and complete Bouguer anomaly maps computed for a variety of reduction densities. The axis of the anomaly trends nearly east from Fernandina through Santa Cruz and Baltra to the north of San Cristobal, and the anomaly apparently closes at its western end. Because control for the offshore gravity field is not available to us, the total amplitude and areal extent of the anomaly is unknown. Bouguer anomalies at shoreline stations range from +22 mgal on Isla Baltra to +107 mgal at the northern end of Isla Isabela. The minimum amplitude of the anomaly is therefore about 80 mgal, and the minimum north-south breadth is about 200 km. The anomalies over the Galápagos are extraordinary because mean free-air anomalies at sea have normal values of 0 ± 25 mgal; in view of the fact that all anomalies in the Galápagos exceed +20 mgal, it is clear that the residual negative anomaly is superimposed on a broader positive anomaly of unknown amplitude and extent.

Fernandina, perhaps the most active of the volcanoes, is near the axis of the residual negative anomaly. A gravity traverse of the volcano, including a few stations in the northwest part of the caldera, indicates that the caldera itself is expressed by a local residual positive gravity anomaly of about +30 mgal (Fig. 2). This anomaly probably reflects relatively dense congealed basalt in the lava lakes that have built the interior portion of the volcano and

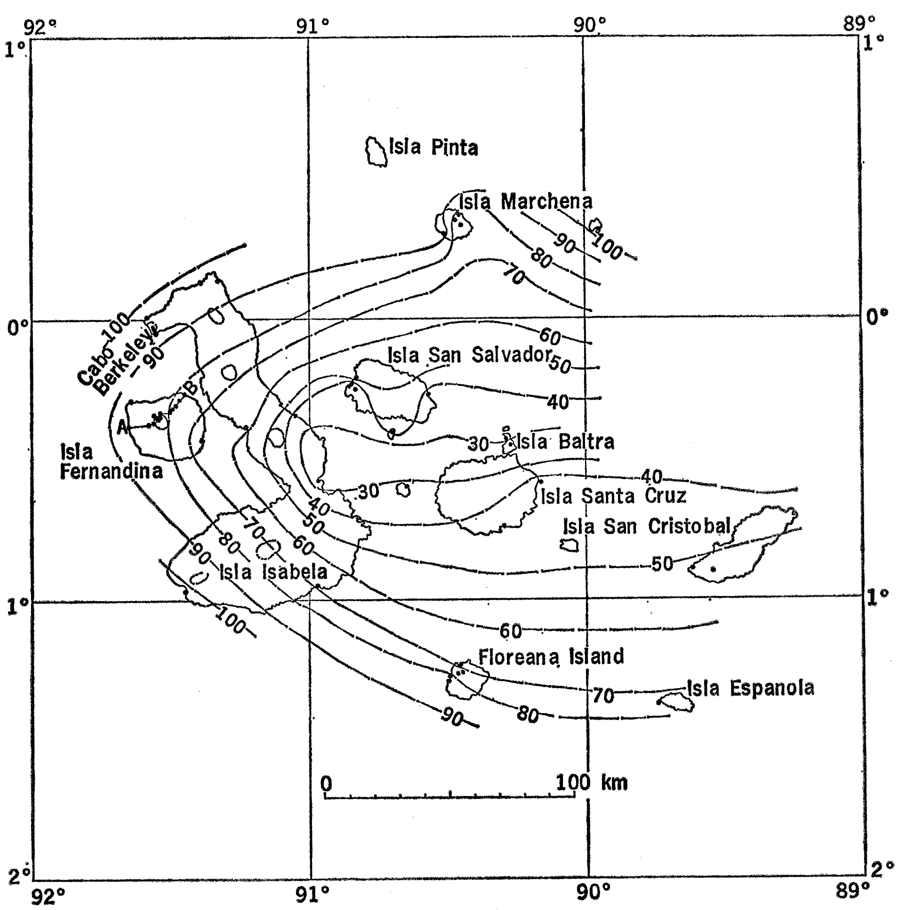

Fig. 1. Free-air anomaly map of part of the Galápagos archipelago based on shoreline or nearshore control points; contour interval, 10 mgal. Black dots indicate the positions of gravity stations. All contours are conjectural except in the immediate vicinity of control points. Bouguer anomaly maps, prepared from all stations, show the same broad residual negative anomaly, except that the Bouguer anomaly values are slightly more positive because of terrain effects. For example, the Bouguer anomaly at the northern end of Isla Isabela is about +107 mgal. Calderas on Islas Isabela and Fernandina are indicated by short dashed lines. Residual positive gravity anomalies are predicted over the Isabela calderas.

concentrations of basalt feeders. Faulting has led to exposure of a natural cross section of a caldera at Cabo Berkeley (Fig. 1), and it is clear that the caldera interior is composed of successive thin pahoehoe flows with virtually no fragmental tops to lower the density. Filson *et al.* (*4*), for example, assumed a bulk density of 2.8 g/cm^3 for the caldera block of Isla Fernandina. The external volcanic edifice probably has a much lower density because it is composed of vesiculated and fragmental flows, interlayered with minor pyroclastic material.

Simple Bouguer anomalies (uncorrected for terrain effects) were plotted along profile A–B (Fig. 2) across Isla Fernandina for a series of reduction densities ranging from 2.0 to 2.8 g/cm^3. The profiles for 2.3 and 2.4 g/cm^3 show the least correlation with topography and the minimum range in amplitudes of anomalies across the shield and caldera. Thus, it may be presumed that a density of about 2.35 g/cm^3 represents a good approximation to the mean density of the volcanic pile above sea level. This is strongly confirmed by plots of the complete Bouguer anomalies (Fig. 2) where terrain corrections were made through Hayford-Bowie zone J (*5*). This result is very similar to Woollard's (*6*) findings across Oahu, where a density of 2.3 g/cm^3 was derived for the island platform above the sea floor. Kinoshita *et al.* (*7*) used a reduction density of 2.3 g/cm^3 in their study of the island of Hawaii, based partly on density determinations of basalt flows made by R. R. Doell. Although the densities of 63 specimens ranged from 1.8 to 3.0 g/cm^3, the mean density was 2.3 g/cm^3.

Strange *et al.* (*8*) showed that residual gravity highs range from + 10 to + 110 mgal over various shields of the southern Hawaiian ridge; similar anomalies occur over many other marine volcanic groups (*9*). These highs are commonly interpreted as caused by dense "plugs" near the centers of the volcanoes.

If we assume that the residual positive anomaly over Fernandina caldera is caused by a vertical cylinder of length 4 km, radius 2 km (about the present caldera radius), and density contrast 0.6 g/cm^3, which is buried 200 m beneath the level of observation, the

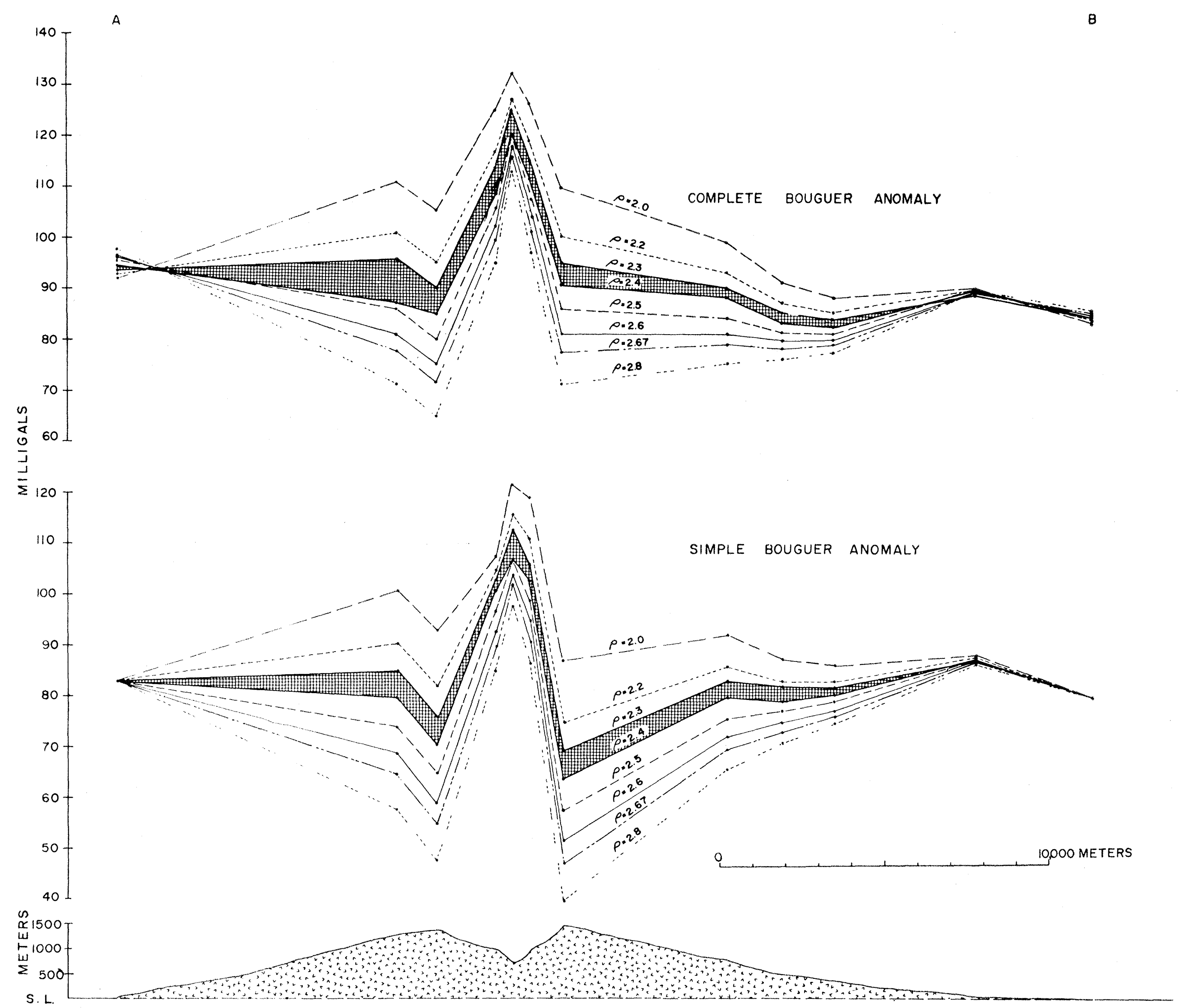

Fig. 2. Bouguer anomalies and simplified topographic profile along line A–B (Fig. 1) across Isla Fernandina. The shaded area between anomalies computed for reduction densities (ρ) of 2.3 and 2.4 g/cm^3 shows the least correlation with topography. Note that a residual positive anomaly of about 30 mgal occurs in the vicinity of the caldera on the complete Bouguer anomaly profile. The main caldera floor is south of the line of profile. Abbreviation: *S.L.* denotes sea level.

anomaly at the center is about +34 mgal. If the cylinder is infinite and its top is buried 1 km beneath the level of observation, the anomaly over the center is about +31 mgal. Thus, if the mean density of the exterior volcanic pile is 2.3 g/cm^3, a reasonable density contrast would result if the plug has a mean density of 2.9 g/cm^3. Similar density contrasts were obtained by Robertson (*10*) [cited by Malahoff (*9*)], who derived a density of 2.32 g/cm^3 for the Cook Island platforms, which contain plugs of density 2.88 g/cm^3. It should be emphasized that a narrower plug of greater density would also generate a 30-mgal anomaly. The residual anomaly over the Fernandina caldera might well be greater than 30 mgal: we obtained gravity observations only on the northwest margin and not at the center of the caldera, so that the maximum anomaly was not determined.

The residual negative 80-mgal gravity anomaly across the archipelago must be caused by a large mass of low density in the crust or upper mantle. An infinite slab, 10 km thick, having a density contrast of −0.2 g/cm^3, produces an anomaly of about −84 mgal. So the Galápagos anomaly can readily be accounted for by a small density deficiency in the crust and upper mantle: a density contrast of only 0.1 g/cm^3 in the upper 30 km, for example, would cause the observed anomaly. The curvature of the anomaly contours through Islas Isabela and Fernandina suggests that the western margin of the low-density region is close to these islands. Three possible causes of this mass deficiency may be geologically plausible. (i) The Galápagos platform (and possibly the Carnegie Ridge, which extends eastward from the Galápagos Islands) may be underlain by a block of continental crust (*11*). (ii) The anomaly could be caused by a rising plume or hot spot as suggested by many investigators (*12, 13*). Thermal expansion of the mantle and crust at the hot spot would lead to decreased density across the site of elevated isotherms. (iii) Weight of the volcanic pile may have caused some crustal downwarping, an effective thickening of oceanic crust by additions of basalt and associated fragmental material.

Because of the "oceanic" composition of most of the Galápagos volcanic rocks and the absence of inclusions of typical "continental" rocks, we believe that the hypothesis of continental crust can be largely discounted. Most of the more silicic plutonic rocks from the islands can be accounted for by differentiation from tholeiitic basalt (*1*).

In the absence of crustal seismic refraction data across the site of the gravity anomaly, it is impossible to evaluate fully the effects of crustal downwarping, and it cannot be entirely discounted. If a porous volcanic pile 5 km thick were built up on the sea floor, and if the density contrast were −0.3 g/cm^3, a local negative anomaly of about 63 mgal would be produced without the necessity of a plume or hot spot. The residual negative free-air anomaly indicates an isostatic imbalance that should tend in the long run to raise the crust rather than bend it down.

We believe, however, that the gravity data can be most readily interpreted in terms of a low-density region related to a hot spot or plume. This preference is based on the direct evidence of the widespread active Holocene volcanism of the islands themselves and the topographic expression of past volcanism leading away from the islands along the Cocos and Carnegie ridges.

Compared with anomalies computed for many other postulated plume hot spots, the residual negative free-air anomaly is uncharacteristic (*12, 13*). The Hawaiian Islands, for instance, have high positive free-air and Bouguer anomalies, although they may be in a broader negative Bouguer anomaly field (*6, 14*). Isostatic anomaly maps from satellite data (*15*) indicate that most other hot-spot regions are sites of long-wavelength positive anomalies, but the Galápagos appears to be an exception. Over a rising convective plume, a negative Bouguer anomaly might be more expectable than a positive one (*16*), although Morgan (*12*) and Deffeyes (*17*) have offered theoretical explanations for positive free-air anomalies at plume sites. The problem is succinctly stated by McKenzie (*18*): "There are . . . two competing effects. The higher temperature causes a deficit of mass in the rising current, giving a negative anomaly. This effect is opposed by the upward surface deformation. It is easy to show that both are of the same magnitude, and therefore it is not clear which will win." The broader positive and somewhat localized negative anomaly over the Galápagos suggests that "which will win" may be in delicate balance. Refraction surveys will ultimately provide the regional velocity structure of the crust and mantle beneath the Galápagos; it will then be possible to estimate density distributions that best fit the gravity and seismic data. Such distributions, in combination with heat-flow measurements, will provide a basis for estimating the configuration of isothermal surfaces beneath the islands.

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