casing, and (c) inside the well casing. A nonlinear relation between discharge and drawdown could arise also in part from nonlinear boundary conditions at the water table in the vicinity of the pumping well.

For nearly all wells in which three or more drawdown measurements at different discharge rates were taken during a pumping test, the discharge and drawdown show a nonlinear relation. Examples of the relation are given on figure 359.1, which shows the results of pumping tests on 5 wells. The relation can be expressed mathematically in the equation

$$Q=as^b \qquad (1)$$

in which Q is the discharge rate, a and b are constants related to head losses, and s is the drawdown within the well. The logarithmic expression for this equation is

$$\log Q=b\log s+\log a \qquad (2)$$

in which $\log Q$ is expressed as a linear function of $\log s$. The constants a and b are determined by the method of least squares.

The observed drawdown at different discharge rates and the resulting specific capacity in well 256–2A (fig. 359.1) are as follows:

Discharge rate (Q) (gallons per minute)	Drawdown (s) (feet)	Specific capacity (Q/s) (gallons per minute per foot)
520	0.8	650
540	.8	675
700	1.4	500
800	1.7	471
950	2.5	380
1,130	3.6	314

From these data the computed value of log a is 2.77 and the value of b is 0.51. The curve for this equation for well 256–2A is shown on figure 359.1.

From the given relation, drawdown can be estimated graphically or mathematically for a discharge rate that is greater or less than, or that falls within the range of measurements taken during a step-drawdown test. The specific capacity also is seen to decrease with increase in discharge rate. The method described may apply to wells drilled in other types of aquifers.

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USGS PP-424D 1961

East Rift Zone

360. PRELIMINARY GRAVITY SURVEY OF KILAUEA VOLCANO, HAWAII

By H. L. Krivoy and J. P. Eaton, Hawaiian Volcano Observatory, Hawaii

Kilauea is the smaller of two active shield volcanoes that form the southern half of the Island of Hawaii. The summit of Kilauea is a slight protuberance on Mauna Loa's easterly flank, and the region between the two summits contains the intercalated products of each volcano.

Eruptions of Kilauea have taken place either in the region of the summit or else along one of Kilauea's two conspicuous flank rifts. The southwest rift was last active in 1920 and is marked by an extensive pattern of linear cracks. The eruption of 1959–1960 (Eaton and Murata, 1960; Richter and Eaton, 1960) began as a summit eruption in the pit crater Kilauea Iki and continued as a flank eruption at the Kapoho graben in Puna, some 30 miles from the summit. This active region is the coastal terminus of the east rift zone, which extends from Kilauea summit as a low topographic ridge.

In 1957 and 1958, elevation loops were run in the summit and east-rift sectors of Kilauea. Bench marks were spaced along these loops at intervals of one half and three tenths of a mile near the rifts, and at intervals of one mile in more stable regions. The elevations determined during these surveys and during re-leveling of the summit in 1960 served as the basis of the 1959–60 gravity survey here described.

Tilt studies and elevation surveys before and after the 1959–1960 eruption show that Kilauea summit was progressively inflated before the Kapoho flank eruption and then suddenly deflated contemporaneously with the eruption. Summit deformation decreased symmetrically from a maximum collapse of about 5 feet on the floor of the caldera to an undetectable amount about 5 miles from the summit. Wilson (1935) reports similar summit pulsations for other volcanic epochs.

A gravity survey was made in the summit region of Kilauea in December 1959 and January 1960. The survey was repeated in March and April 1960, after the major subsidence described above. Bouguer anomalies shown on figure 360.1 have been computed using the

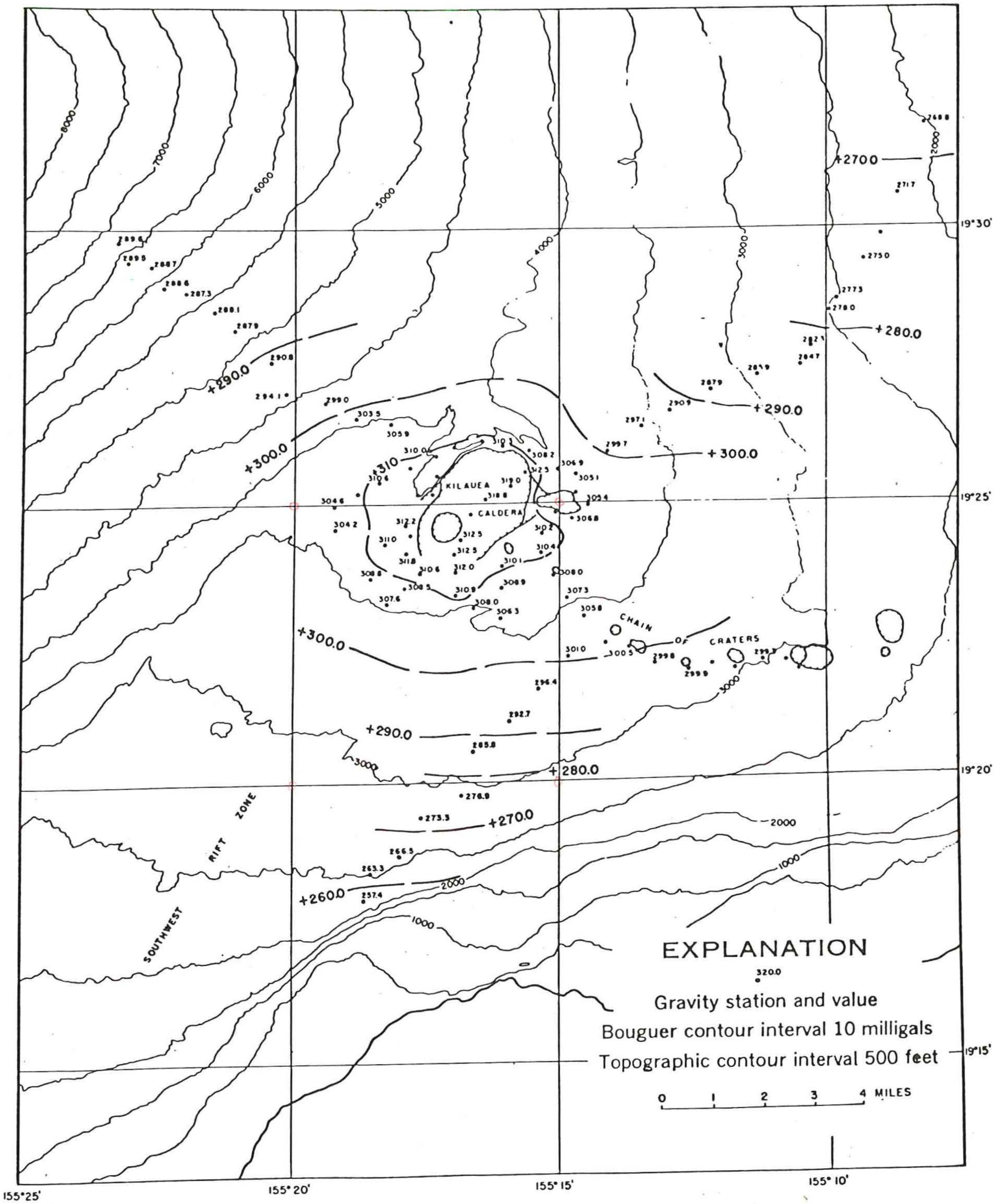

FIGURE 360.1.—Positive Bouguer gravity anomalies (heavy broken lines) for the summit region of Kilauea volcano. Some gravity values have been omitted for sake of clarity.

March–April gravity data together with elevations determined in May and June 1960 for summit bench marks.

Gravity work in the Puna area (fig. 360.2) was completed in February 1960, during the east-rift eruption. Elevations used in the reduction of these data are based on the survey of 1958. Eight hours before the Kapoho eruption vertical displacements on the order of several feet were observed along the two border faults at the Kapoho graben. About a dozen bench marks in this vicinity were buried by 1960 lava. It is possible that data computed for these points, based on uncertain

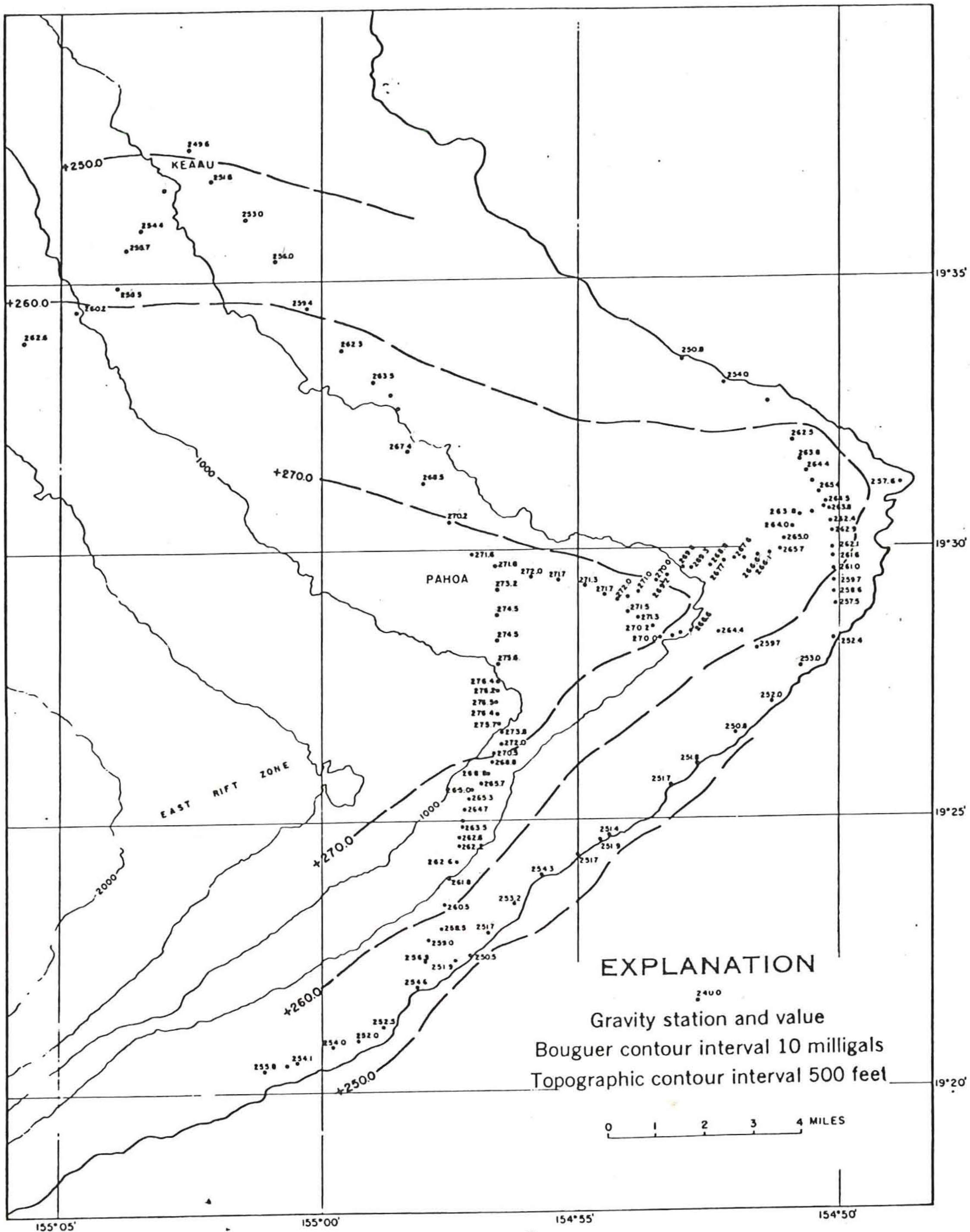

FIGURE 360.2.—Positive Bouguer gravity anomalies (heavy broken lines) for the east flank (Puna area) of Kilauea volcano. Some gravity values have been omitted for sake of clarity.

elevation, might be in error by three or four tenths of a milligal.

A value of 2.3 g per cm³ obtained by Woollard (1951) for Oahu was adopted for the average density of the island mass in computing Bouguer anomalies. Bouguer anomalies so computed for the Kilauea summit and Puna regions reflect the topography of the volcano as does Woollard's Bouguer anomaly for Waianae volcano on Oahu. Thus, the anomaly contours are parallel to the topographic contours along Kilauea's southeastern coast, where both are also parallel to the east rift zone. North of the rift zone, however, Bouguer anomaly contours cut sharply across the topography and follow the rift zone. To reduce the apparent correlation between

Bouguer anomaly and topography, where it exists, it might seem reasonable to adopt a bulk density closer to the conventional value of 2.9 g per cm³ for dense basalt. This might be justified for lavas erupted beneath the sea under pressures that restrict the formation of vesicles. However, there is little reason to believe that the parts of the volcanoes above sea level, which alone are involved in the Bouguer reduction, have been so constrained. Indeed, estimates of the bulk density of basalt once covered by several thousand feet of younger lavas and later exposed by erosion are close to the value of 2.3 g cm³ found by Woollard for the entire ridge when he applied gravity-profiling theory to Vening Meinesz' submarine profile.

The Bouguer anomaly rises from about +250 milligals along Kilauea's southeastern coast to +320 milligals at the center of Kilauea caldera at an elevation of about 3,600 feet. It then drops off steadily northwestward over the southeastern flank of Mauna Loa to +290 milligals at an elevation of about 4,800 feet. Beyond this point the anomaly remains virtually constant to an elevation of 6,700 feet, where the present survey ends.

In accordance with Wollard's interpretation of the large positive Bouguer anomalies around the two main eruptive centers on Oahu, it is likely that the strong positive anomaly that is centered at Kilauea caldera and extends out along the east rift zone is largely caused by a complex of dense dikes at the core of Kilauea. It is also possible that the shallow reservoir beneath the caldera, which is revealed by the pattern of elevation changes and tilt accompanying eruptive activity, is responsible for part of the anomaly. Additional gravity measurements on Kilauea volcano may help define the physical boundaries of this dike system.

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EXTRATERRESTRIAL STUDIES

361. THICKNESS OF THE PROCELLARIAN SYSTEM, LETRONNE REGION OF THE MOON

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Work done on behalf of the National Aeronautics and Space Administration

The stratigraphy of the Letronne region of the Moon is being investigated as part of a study of the lunar surface. The region lies in the general target area for a number of hard-landing lunar capsules to be launched as part of the National Aeronautics and Space Administration Ranger Program. The Procellarian system is the most extensively exposed stratigraphic unit in part of the target area.

Stratigraphic units exposed in the Letronne region include the major units thus far recognized on the Moon (Shoemaker and Hackman, 1960); these are pre-Imbrian material and the Imbrian, Procellarian, Eratosthenian and Copernican systems (Shoemaker, in press). The Imbrian system and pre-Imbrian material, the lowest stratigraphic units, cover much of the southern quarter of the Letronne region and are exposed in numerous widely scattered smaller areas (fig. 361.1). These units have a medium albedo and underlie a generally irregular surface upon which are craters ranging from less than 1 km to 130 km across. Most of the isolated exposures of the Imbrian and pre-Imbrian are the rims of large craters that have been partly buried beneath higher stratigraphic units, belonging chiefly to the Procellarian system.

The Procellarian system is characterized by low albedo and underlies extensive areas of generally low relief that occupy 82 percent of the Letronne region. Ridges of low amplitude, which have been interpreted as anticlines, and a few low domes and shallow valleys termed rilles are present on the surface of the Procellarian. The estimated thickness of the Procellarian varies from a featheredge to several thousand meters;