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Gravity Anomalies and Their Relation to Major Tectonic Features in the North-Central Pacific

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GRAVITY ANOMALIES AND THEIR RELATION TO MAJOR TECTONIC FEATURES IN THE NORTH-CENTRAL PACIFIC

William H. Lucas

Gravity anomalies in the north-central Pacific have been obtained aboard the USC&GS Ship SURVEYOR with a LaCoste and Romberg surface-ship gravity meter. The data lie along several profiles from the Hawaiian Archipelago to 39°N between 167°W and 173°30'W and extend across the north side of the Hawaiian Archipelago and portions of the Murray, Pioneer, Mendocino and Surveyor fracture zones. The accuracy of measurements is estimated to be within ± 5 mgal and the data are in agreement with those published by Worzel on the basis of 1948 submarine pendulum measurements. Maps of free-air and Bouguer anomalies are presented and some of their crustal structural implications are discussed.

1. INTRODUCTION

During 1963 and 1965 the USC&GS Ship SURVEYOR carried out marine surveys on the SEAMAP (Scientific Exploration and Mapping Program) project. The basic plan provided for continuous echo sounding, gravity and magnetic observations on a line spacing of 10 nautical miles (18.5 km) with Loran-C control. This report is concerned with data in the area of the Hawaiian Ridge between 167° and 174°W Longitude north to 39°N Latitude. Segments of the SURVEYOR's tracklines which provided reliable gravity measurements in this area and locations of the published pendulum stations and seismic refraction lines are shown (fig. 1). The area covers a complex portion of the North Pacific, where six major tectonic

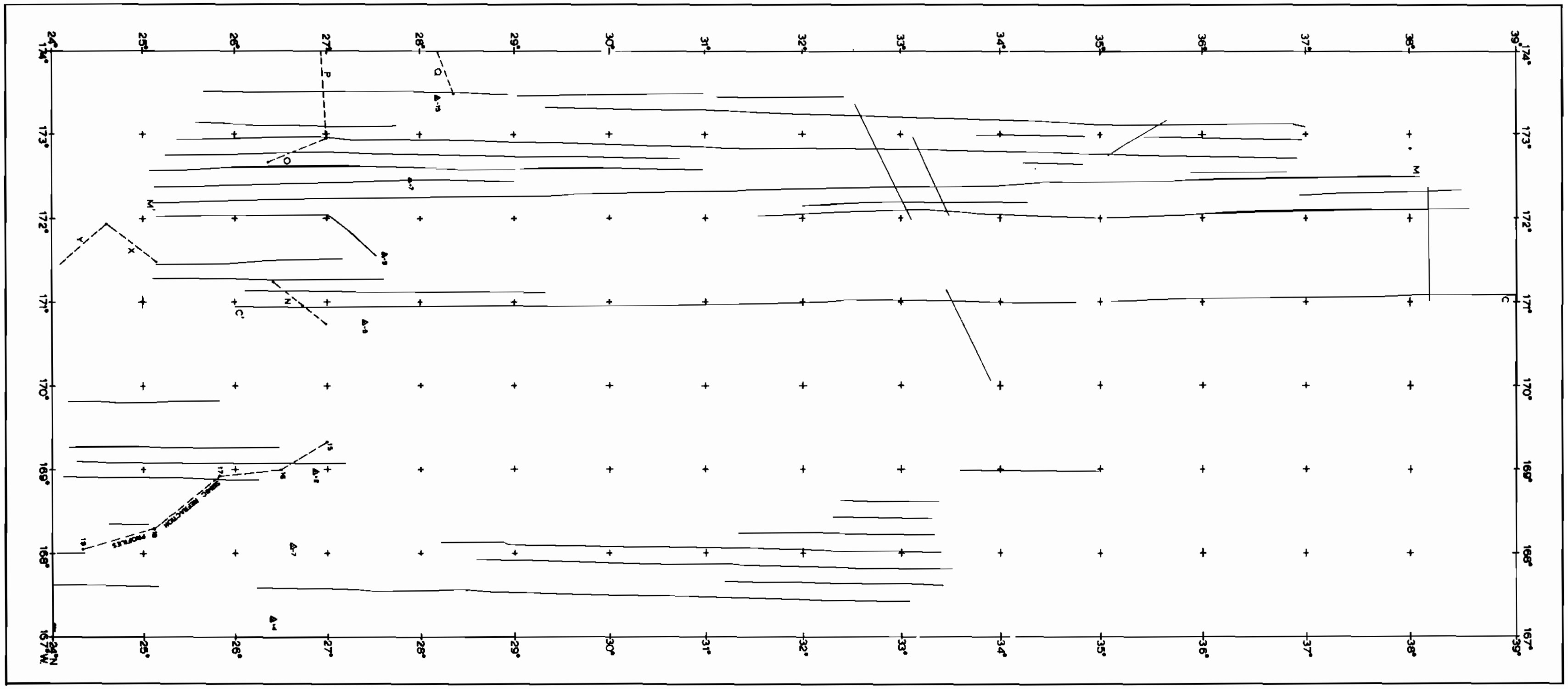

Figure 1. Location map of gravity profiles. The solid lines are the SURVEYOR tracks along which reliable gravity data were obtained. Refraction data (stations 15, 16, 17, 18, 19) near Gardner Pinnacles of Shor (1960) and lines (P, Z, X and Y) of Furumoto et al. (1971). Submarine pendulum measurements (small triangle) by Worzel (1965).

features, the Hawaiian Archipelago, the Murray, Pioneer, Mendocino and Surveyor fracture zones and a major seamount province, are the dominant structural elements.

This report is concerned with the free-air and Bouguer gravity anomalies. The results of hypothetical two-dimensional crustal sections that are consistent with bottom topography, seismic refraction data and free-air anomalies will be discussed in a later paper.

Gravity anomalies are affected by both bottom topography and geologic variations. Free-air anomalies generally give a direct representation to local topography. Exceptions occur mainly in association with the fracture zones and buried deeps. They normally show, however, only a minor expression to regional changes in the sea floor depth. The Bouguer anomaly values, on the other hand, generally show an inverse correlation with regional changes in topography but are often not correlative with local changes.

Hereafter, in this report, the term "normal relation" will refer to free-air anomalies that conform to the sea floor and/or Bouguer anomalies displaying an inverse correlation to topography. "Anomalous relation" will refer to free-air anomalies which do not conform to the sea floor and/or Bouguer anomalies having a direct correlation to topography.

The geophysical instruments used aboard the SURVEYOR were the LaCoste-Romberg sea gravimeter S-12, and a Varian V-4931 towed marine magnetometer (proton free precession). Soundings were obtained with a precision depth recorder (PDR).

2. TREATMENT OF DATA AND MEASUREMENT ACCURACY

For 1963 gravity data, the filtered beam position was continuously recorded on the beam chart. The filtered beam position was considerably noisy. For this reason, the derivative or slope, had to be measured over a finite time interval, generally 10 minutes. The result was an average gravity reading for this period.

At the end of the 1963 field season, meter S-12 was sent to the LaCoste-Romberg factory for a complete overhaul and to automate the equipment and computer system, so that instead of the filtered beam position, the beam trace represents a corrected gravity profile. The computer system for the 1965 gravity data was capable of converting the counter dial readings to corrected gravity, by feeding the beam derivative, the averaging period and the meter constant into the computer. This eliminated the need to measure slopes from the beam chart. The average beam position and the average meter counter setting were displayed, in analog form, on a potentiometer recorder. Two additional recorders displayed the short-period and the long-period horizontal accelerations, showing the nature of those affecting the meter. The observed gravity values were computed after the instrument variations were adjusted by ties to the absolute gravity base sites at Honolulu and Midway.

The gravity, magnetics and bathymetric data were further processed and edited at the Pacific Oceanographic Laboratory (POL), located at NOAA's Pacific Marine Center in Seattle, Washington. Following several edit procedures, the soundings, gravity, magnetic and navigation data were encoded on punch cards. From these cards, as a further edit procedure

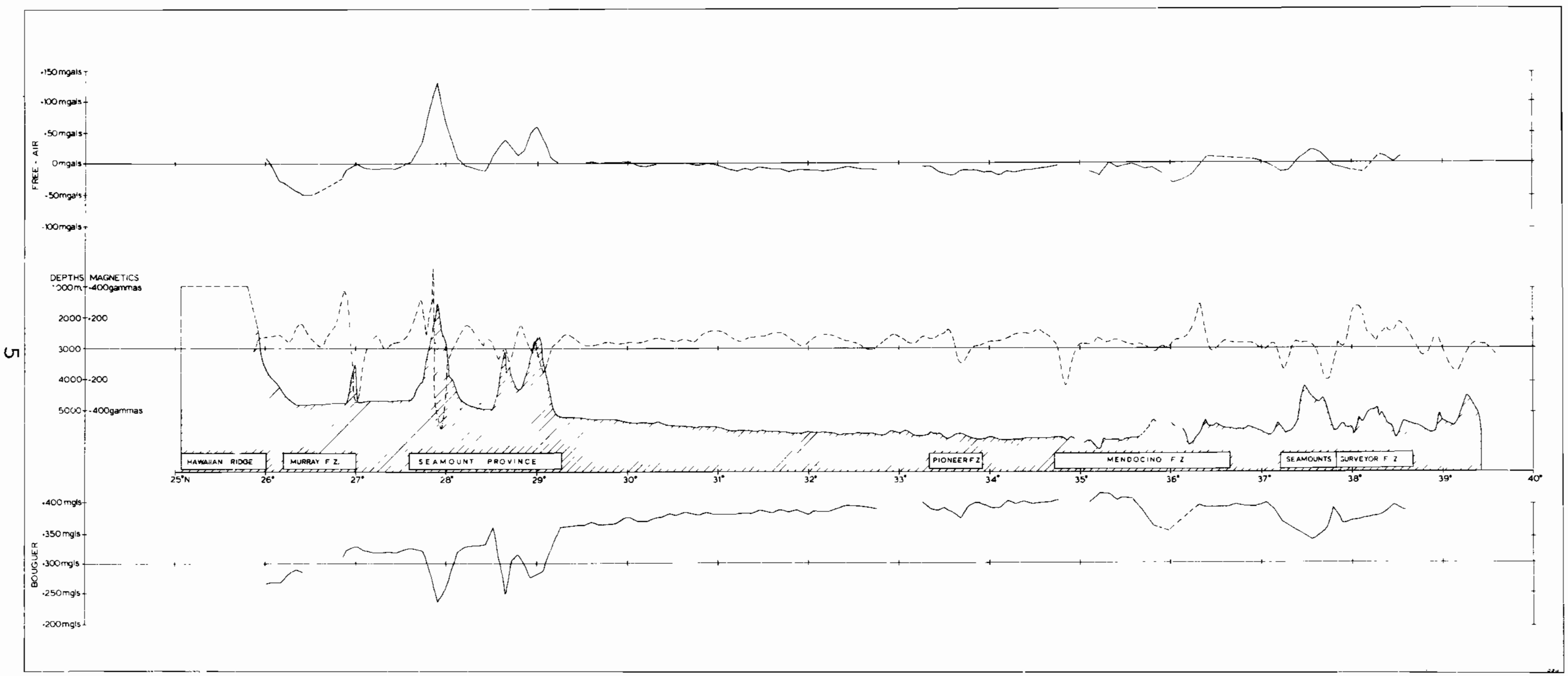

Figure 2. Gravity, magnetics and bathymetry profile along 171°W. Line c-c' (fig. 1) of SURVEYOR 1963 measurements.

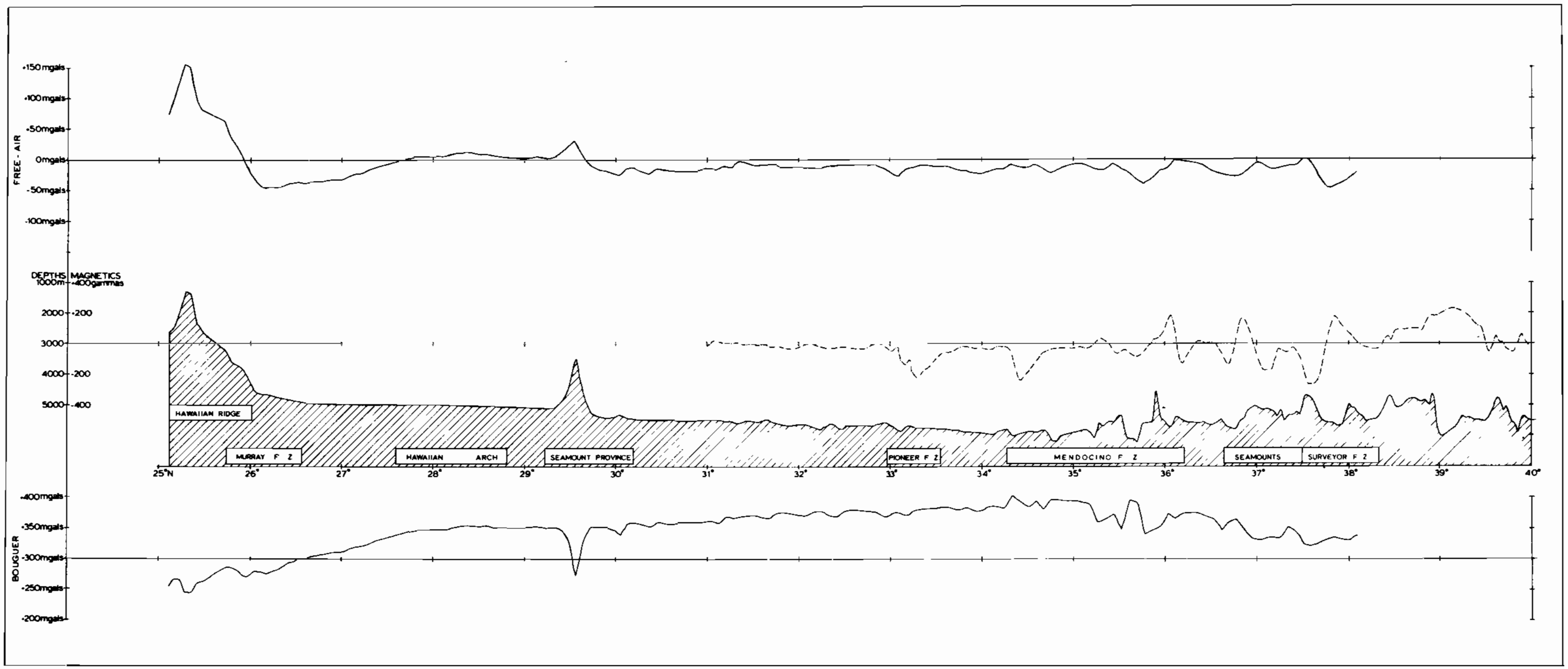

Figure 3. Gravity, magnetics and bathymetry profile along 172°20'W. Line m-m' (fig. 1) of SURVEYOR measurements.

the computed ship's velocity between successive fixes have been evaluated. The Pacific Marine Center's IBM 1620 computer was programmed to calculate positions for the geophysical data and soundings by time interpolation between navigation fixes and to apply sound velocity corrections to the soundings (Ryan and Grim, 1968). The gravity data was combined with the navigation and bathymetric data in computing free-air and Bouguer gravity anomalies. The Bouguer anomalies in the present report were calculated assuming an infinite flat slab and using an assumed sea water to rock density differential of (2.67 - 1.03) g/cc. The corrected data were plotted by a Gerber plotter (Mobley, 1965) on a Mercator projection at a scale of 5.5 inches equal to 1° of longitude. These anomalies were also plotted graphically as profiles by a computer plotting program. Figures 2 and 3 are examples of such a plot.

Certain observations have been made as to the sources of errors occurring in the field operations as well as on the test area. These errors fall under three categories: navigational control; sea conditions; and meter measurements.

2.1 Navigational Control

Navigation for the data used in this report was controlled by Loran-C, which under optimum conditions, gives a positioning accuracy of about 0.5 km. Most of the data were obtained along north-south headings with an estimated uncertainty in course heading of 1°, and in speed 0.2 knots.

The effects of north-south speed are less than one milligal for speeds below 16 knots, but while the measurements are not sensitive to small errors in northerly speed, they are sensitive to corresponding errors in heading. On near-northerly courses, a heading error of 1° results in an error of 1 mgal at 10 knots.

2.2 Sea Conditions

Generally, the meter functioned satisfactorily when the sea was not more than 5 ft. In greater sea states the course and speed are difficult to maintain, vertical accelerations are impulsive causing the Browne corrections to exceed 400-500 mgals and result in large errors. Only data with Browne corrections that were uniform and of low order (300 or less) were accepted.

2.3 Meter Measurements

Exclusive of the effect of navigation errors, gravity measurements can be accurate to within ± or 3 mgals. The controlling factor in reliability of measurements is the magnitude and uniformity of the accelertions. The sign and amount of error depends on the damping coefficient of the accelerometers.

For the data presented in this report the filtered accelerometer recordings were uniform and sinusoidal, and the beam recordings fairly straight and continuous with the Browne corrections under 300 mgals. In the final analysis every effort was made to eliminate errors greater than 10 mgals and to present only those values well under this tolerance.

Submarine gravity measurements were made by the USS CAPITAINE (SS336) in 1948, (Worzel, 1965). Seven of these pendulum measurements transect the study area near and roughly parallel to the Hawaiian Arch (fig. 1). The SURVEYOR tracklines passed almost directly over two pendulum stations where a difference of the order of 3 mgals was observed in free-air anomalies. The lines were not sufficiently close to the other five pendulum measurements to provide a direct comparison, however, anomalies at these stations could be contoured smoothly with a 10 mgal contour interval.

2.4 Base Ties

Base ties were made at Bishop Museum, Honolulu, Hawaii, and at Sand Field, Midway Islands. The SURVEYOR made ten base ties in 1963 and twelve in 1965. The average drift for meter S-12 was approximately 3.5 mgals per month in 1963 and 0.3 mgals per month in 1965 (Appendices A and B).

3. DISCUSSION

The anomaly maps (Plates 1 and 2) are based on measurements obtained along the traverses shown (fig. 1). They cover the western portion of the Hawaiian Ridge, the Murray, Pioneer, Mendocino and Surveyor fracture zones and the adjacent regions. The contour interval is 10 mgals; solid contour lines are based on reliable anomalies and dashed lines on widely spaced lines of data, where the values are interpolated. The contours strongly parallel the bathymetric (Plate 3) and magnetic features on the Hawaiian Ridge and the major fracture zones.

Free-air anomalies range from +240 mgals on the Hawaiian Ridge to -80 mgals over the Hawaiian Deep. Near-zero anomalies occur over most of the deep-water areas where the topography is relatively flat.

The Bouguer anomalies range from +170 mgals on the Hawaiian Ridge to +450 mgals in the deep ocean area north of the archipelago which has an average depth of 5000 meters. The maps show the following prominent features:

3.1 Hawaiian Ridge, Deep and Arch

The Hawaiian Ridge trends north-westerly across the southern portion of the area with the flat tops of several large seamounts defining the crest. These features have subsided relative to sea level, leaving two small volcanic islets, Gardner Pinnacles, and one small island, Laysan, as subaerial remnants.

A relative Bouguer gravity low of +170 to +200 mgals over the Hawaiian Ridge coinciding with the +150 to +250 mgal free-air anomalies, suggests a thickening crust. The large positive free-air anomalies over the ridge continue as very large positive Bouguer anomalies on Laysan Island (Kroenke and Woollard, 1965). The positive free-air anomalies are too large to be due to topography alone, indicating a large mass excess of volcanic material has accumulated along this lineation and apparently caused the ridge to sink in order to reestablish isostatic equilibrium. This has downwarped the surrounding sea floor and caused a peripheral depression or moat, and a compensating rise further seaward.

A series of seismic refraction lines made by Shor (1960) extend across a flat bank at Gardner Pinnacles, down the north side of the ridge and across the adjacent deep to the floor of the Pacific basin. Results show the total section is thickened and the Mohorovicic discontinuity depressed beneath the deep as well as beneath the ridge. The measurements indicates a depth to the mantle of 17 km which is very close to mantle depths estimated by Vening Meindez (1941), Worzel (1965) and Strange et al. (1965) at other parts of the Hawaiian Ridge.

Another series of refraction lines have recently been made by Furumoto et al. (1971). The lines that are within the area are shown (fig. 1). Their data near Laysan Island and other parts of the ridge show a Moho depth that was never greater than 15 km. They have proposed an hypothesis based on fluid dynamics of inverted densities to account for the inference that the area of subsidence was smaller for older volcanic islands than for the newer ones.

The deep which is associated with other parts of the archipelago is apparent in the eastern half of the area (plate 3) as a slight depression but the western half is very flat. There is, however, a very pronounced negative free-air anomaly ranging from -50 to -80 mgals extending along the north side of the ridge, which suggests the Hawaiian deep is structurally present but filled in with sediment (see plate 1). There is no recognizable expression for the deep in the Bouguer anomalies although the relation is normal along with the free-air for the Hawaiian Ridge.

Within the area of the deep there are places where the tops of seamounts protrude through the smooth flat surface. Most of these are confined to the area near the Murray fracture zone extension (Naugler and Erickson, 1968)(see also fig. 2). They are expressed normally in the free-air anomalies, but only to a minor extent. There are other places in the moat area where the same low amplitude free-air anomalies are found but the topography is flat suggesting the presence of seamounts which have been completely buried.

The Hawaiian arch (see fig. 3) lies north of the moat and is usually characterized by positive free-air anomalies with values between +10 and +30 mgals along the crest. However, west of the intersection of the Murray fracture zone and the arch, there is a normal expression of the arch in the free-air anomalies but they range from only -5 to +10 mgals.

3.2 Seamount Province

A group of large seamounts comprise a major volcanic province that trends northwesterly for more than 1000 km from the Hawaiian archipelago to the Hess Rise at 35°N, 177°E. The southern portion of the province lies within the map area and has about the same trend as the Musician Seamounts (Naugler, 1968) located further to the east. They are nearly circular to elongate in plan with the larger seamounts displaying no preferred direction for elongation. From the examination of the echograms these seamounts do not appear to have flat tops. Thus, in contrast with the mid-Pacific Mountain Range located south of the Hawaiian Ridge and characterized by numerous flat-top seamounts (or guyots), these apparently were never exposed to wave erosion at the sea surface. The seamounts are characterized by local free-air anomalies, ranging from +60 to +100 mgals with the largest anomalies occurring on the seamounts near the intersection of the Murray fracture zone and the Hawaiian arch.

3.3 Anomalies Over Flat Areas

The map shows areas north of the Hawaiian Arch which do not have any large topographic features. These areas have corresponding smooth gravity fields of near-zero free-air anomalies which indicate that they are nearly in isostatic equilibrium.

3.4 Pioneer Fracture Zone

The Pioneer fracture zone in this area (Rea, 1970) consists of a southern trough and a northern ridge characterized by a linear magnetic dipole anomaly, positive to the south. The Pioneer fracture zone in this area is not as well defined as the other fracture zones in the gravity anomalies, however there is a negative free-air anomaly that follows the general trend of the fracture.

3.5 Mendocino Fracture Zone

The Mendocino fracture zone appears as a 175 to 220 km wide band of asymmetric ridges and troughs trending at approximately 245° across the area. Broad linear magnetic anomalies essentially parallel the fracture zone. Rea (1970) has shown that the bathymetric trends along the northern portion of the Mendocino are slightly south of the magnetic trends.

The gravity data across the Mendocino fracture zone indicate many anomalous relations in both free-air and Bouguer anomalies implying block faulting and/or changes in crustal density. The most predominant feature is the broad negative free-air anomaly located on the north flank of the fracture zone and easily defined on all the graphic sections (figs. 2 and 3). Despite the presence of very rugged topography with pronounced peaks and troughs, their effect is completely cancelled on the free-air anomalies suggesting a decrease in crustal or upper mantle density associated with the north flank of the Mendocino.

3.6 Surveyor Fracture Zone

The Surveyor is about 70 km wide as it crosses the study area and consists of an intermittent northern ridge and a continuous linear dipole anomaly. The magnetics and bathymetry indicate that some bathymetric and, to a lesser extent, some magnetic lineations trend at about 235° in this area. If these topographic and magnetic trends of 235° do represent the Surveyor fracture zone, then the Surveyor and the Mendocino could merge at approximately 36°N, 173°W, and the structures thought to be the Surveyor fracture zone west to 180° would represent another fracture zone.

The gravity anomalies show these same trends (plates 1 and 2). There is, however, a difference in the relationship of the gravity anomalies to topography for these features. The structure trending at 235° shows generally a normal relation to topography in both the free-air and Bouguer anomalies. This is the same type of relationship indicated on the seamount province discussed earlier. The more east-west trending structure displays in the many places an anomalous relationship to topography in the Bouguer which is found on most of the other fracture zones. This would imply that the Surveyor fracture zone remains on the original trend (250°) and would correspond to a series of low ridges, relief about 300 m, and large magnetic anomaly, mostly negative located on the north slope of the Hess Rise at 179°W.

4. ACKNOWLEDGEMENTS

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5. APPENDIX A

Land Tie Summary - Meter S-12 - 1963

Date	Location	Drift (mgals)
Feb. 5, 1963	Seattle	0.0
Feb. 18, 1963	Honolulu	+5.8
March 25, 1963	Honolulu	+5.7
June 20, 1963	Seattle	+7.8
July 8, 1963	Seattle	-4.1
July 16, 1963	Oakland	+7.7
July 23, 1963	Oakland	-2.0
Sept. 7, 1963	Adak	+7.6
Oct. 4, 1963	Midway	-5.2
Oct. 27, 1963	Seattle	+8.4

6. APPENDIX B

Land Tie Summary - Meter S-12 - 1965

Date	Location	Drift (mgals)
Feb. 8, 1965	Seattle	0.0
Feb. 15, 1965	Oakland	-0.1
Feb. 27, 1965	Honolulu	+1.4
March 24, 1965	Honolulu	+2.8
March 30, 1965	Honolulu	+0.0
April 19, 1965	Honolulu	-0.9
May 3, 1965	Seattle	-0.9
June 7, 1965	Seattle	-0.8
June 24, 1965	San Francisco	+1.7
June 30, 1965	Seattle	-1.1
July 31, 1965	Kodiak	-1.2
Aug. 13, 1965	Kodiak	+1.5

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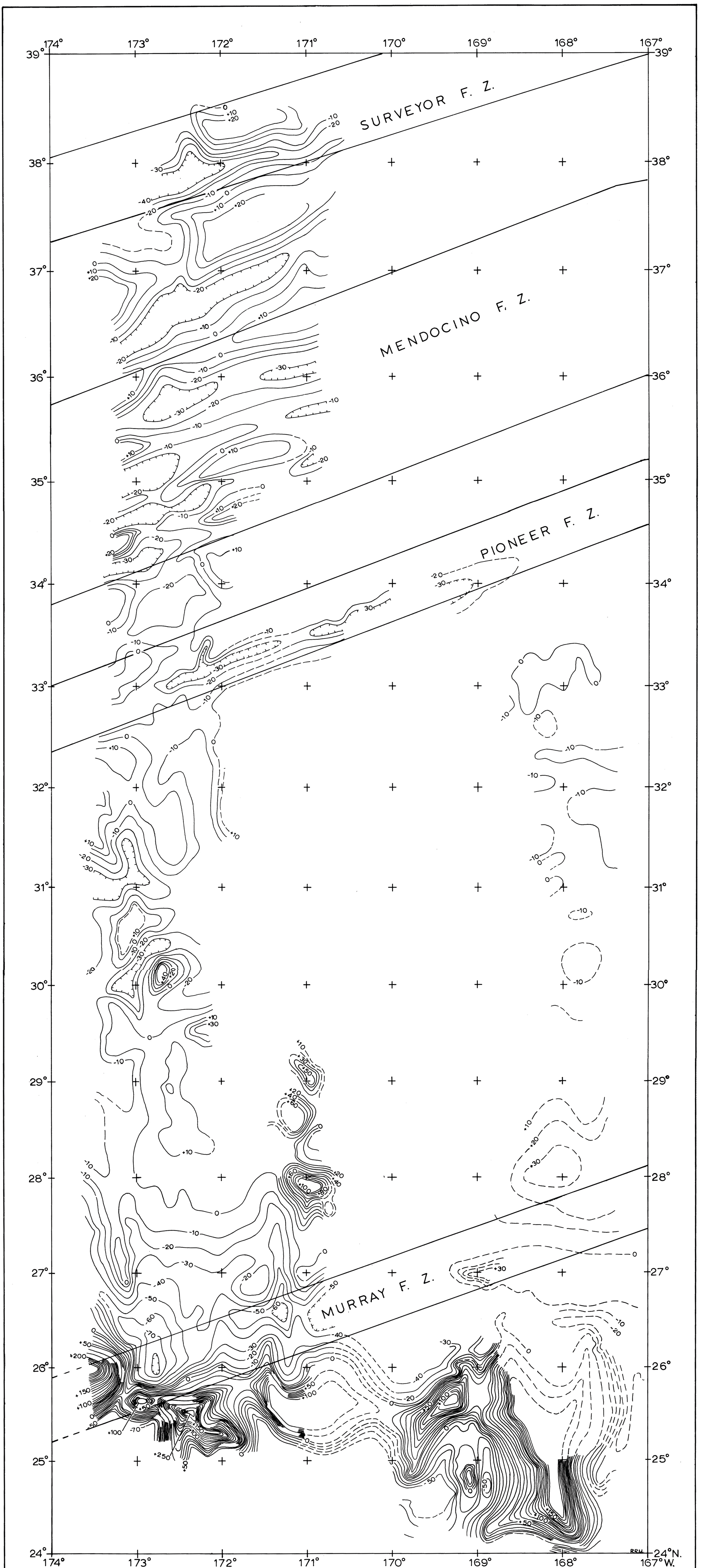

Plate 1. Free-air gravity anomaly map of the Hawaiian Archipelago and area north; contour interval, 10 mgal.

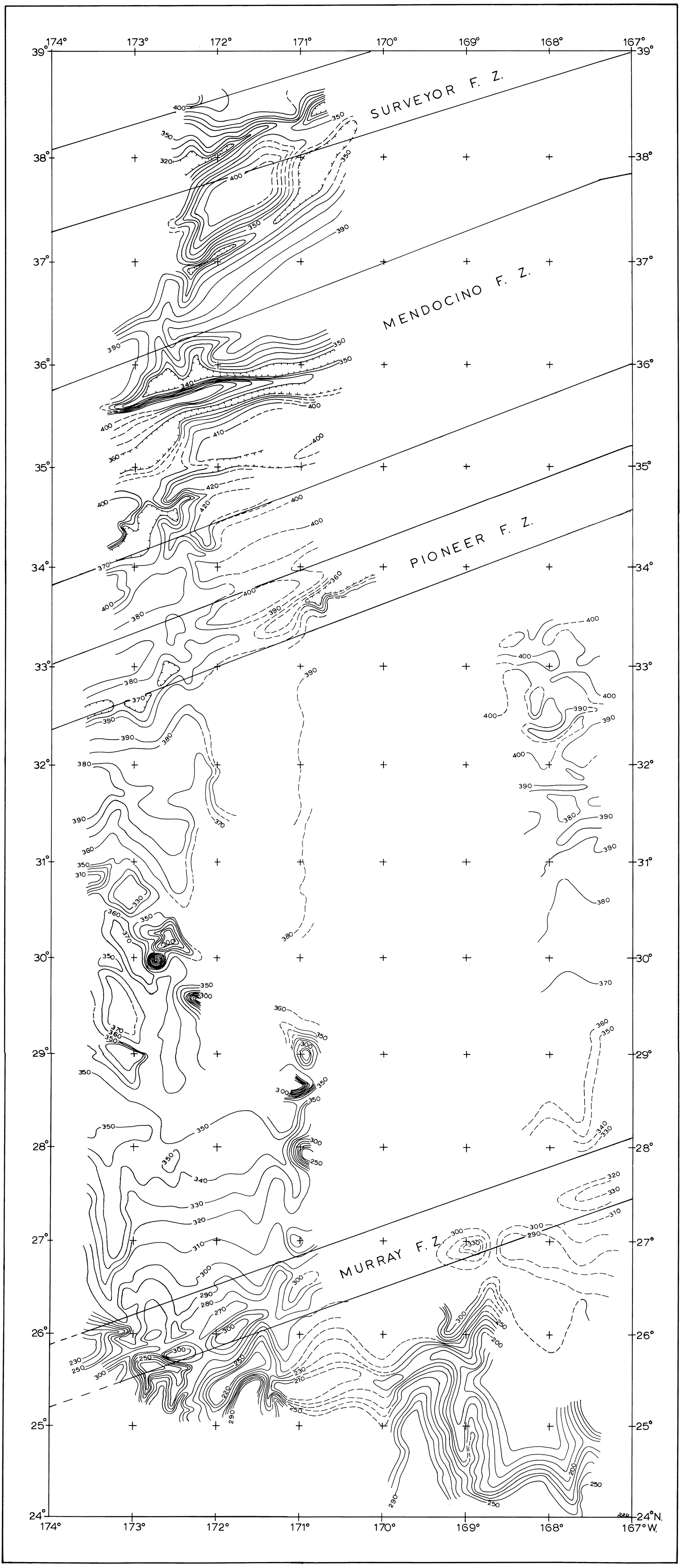

Plate 2. Bouguer gravity anomaly map of the Hawaiian Archipelago and area north; based on rock density of 2.67 gm/cm^3. Contour interval, 10 mgal.

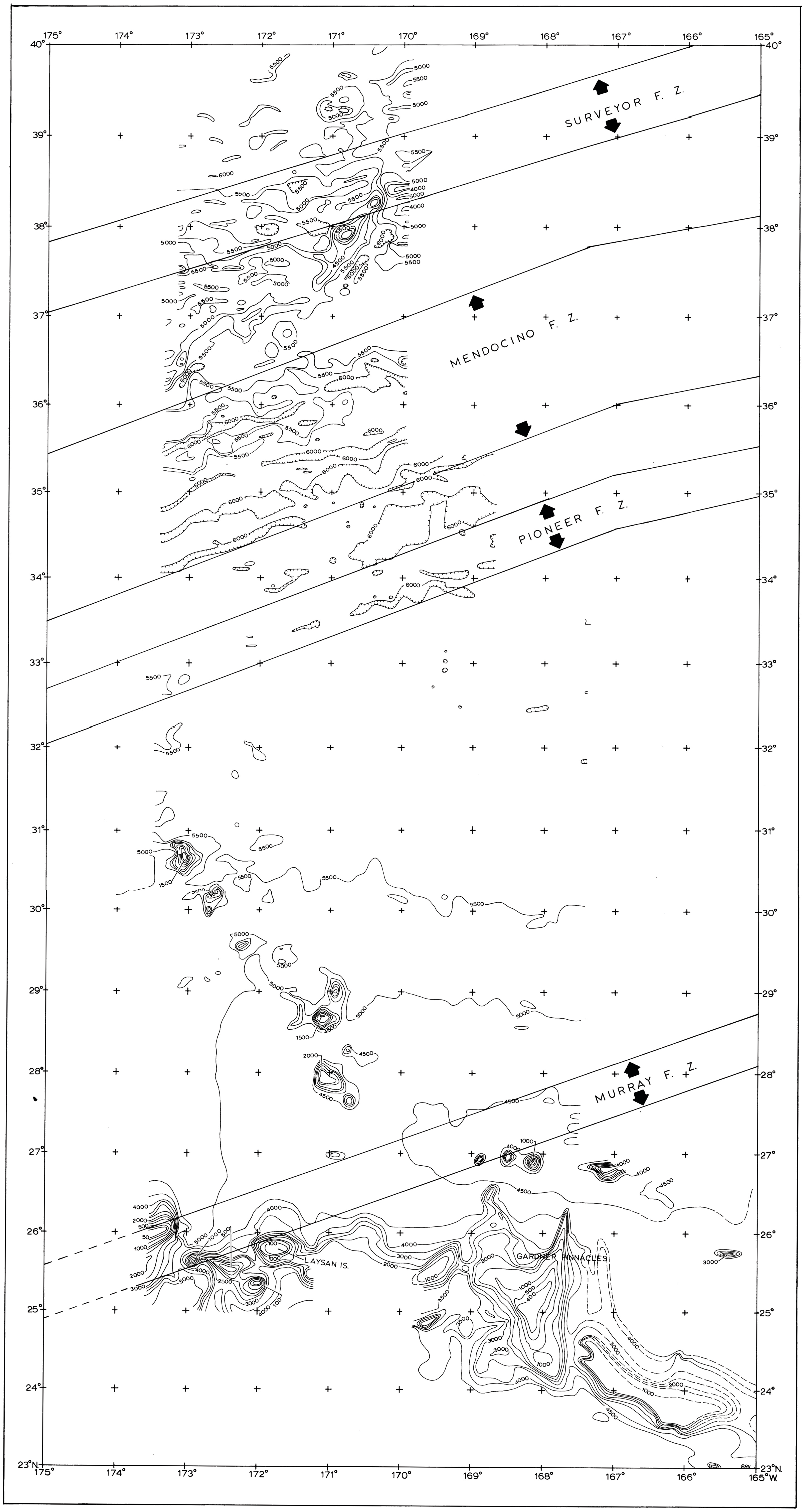

Plate 3. Bathymetric map of the Hawaiian Archipelago and area north; contour interval, 500 meters.