Solid Earth - Geomagnetism - Hawaii

ORIGIN OF MAGNETIC ANOMALIES OVER THE NORTHWESTERN PORTION OF THE HAWAIIAN RIDGE

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ABSTRACT

Aeromagnetic data were taken over the northwestern portion of the Hawaiian Ridge between French Frigate Shoals and Kure Island. Total force residual anomalies are usually in the form of bipoles which are elongate in the direction of the Hawaiian Ridge. In most of the bipoles the positive values are much higher than the negative values. Most of the features show a single bipole but the larger features show several magnetic bipoles located on the center and/or the flank of the features. About 30% of the anomalies are reversely magnetized. The terrain effects seldom exceed 200 gammas and do not substantially alter the amplitudes of the observed anomalies which sometimes reach 1200 gammas, suggesting highly magnetized bodies within the topographic features. The large mean absolute error from the three runs of Talwani's three-dimensional program of Midway Island indicates that the body is not uniformly magnetized, suggesting a plug or dike complex under the atoll. Analysis of terrain-corrected anomalies by Martin's method of characteristic curves, and Malahoff and Woollard's curves, gives a width of the body of 8 km, with the top of the body close to the surface, and a depth of 20 km to the base of the prism-shaped body. This agrees favorably with the model of the atoll computed from gravity and seismic studies. The magnetic anomalies observed over Midway also agree well

with those on the Project Magnet map. Analyses of the other bathymetric features show that the magnetic anomalies here may also be due to dike swarms and plugs which are sometimes found on the crests or on the flanks of the old volcanoes.

INTRODUCTION

Background of Research

In 1964, the Hawaii Institute of Geophysics began an extensive aeromagnetic coverage of the Hawaiian Ridge from the island of Hawaii in the southeast to Kure Island in the northwest. The work was funded by a National Science Foundation Grant GP 4001.

Malahoff and Woollard (1966a), working on the major Hawaiian Islands from Hawaii to Kauai, found that the regional distortion of the earth's magnetic field due to the topographic mass of the Hawaiian Ridge seldom exceeds 150 gammas. They also found that the anomalies trend eastward in the form of lenticular and circular dipoles over the islands. The lenticular anomalies were interpreted as related to crustal rifts that were invaded by magmatic material while the circular bipoles were associated with the dike complexes or plugs of volcanic eruption centers. The inferred crustal rifts sometimes have surface geologic expressions and can often be traced magnetically offshore for over 160 km. The Molokai Fracture Zone has a distinct magnetic expression which can be followed westward to the Hawaiian Ridge in the vicinity of Molokai Island, and across the Hawaiian Ridge to the southwest for an undetermined distance. The associated anomalies are mostly lenticular and parallel to the trend of the zone. The authors suggested that the areas where the strands of the east-west Molokai Fracture Zone intersect the northwest-southeast strike of the Hawaiian Ridge are the areas in which volcanism was localized.

Malahoff and McCoy (1967) made a detailed magnetic and bathymetric survey east of the island of Hawaii, along the Puna Submarine Ridge which is a seaward extension of the Puna Rift Zone of Kilauea Volcano. The submarine ridge has an elongate normally polarized magnetic anomaly with a maximum amplitude of 2270 gammas. The authors concluded that the anomaly is due to a magnetized intrusive body, such as a composite plug or a dike complex, 1 km beneath the ridge.

In a later paper, Malahoff and Woollard (1966b) described the magnetic anomalies over the volcanoes of the main Hawaiian Islands in terms of their volcanological implications. They noted that volcanic centers have magnetic amplitudes greater than 500 gammas and Bouguer gravity anomalies of 250-330 mgals. The anomalies appear to be related to intrusive rocks which have a higher apparent magnetic susceptibility than either the crustal host rock or the surface tholeeitic basalts. The depth analysis from magnetic studies agreed substantially with seismic depth data and gravity analysis. The magnetizing bodies beneath most of the volcanoes were found to be 0.3-2.4 km below the surface. The anomalies over three volcanoes in Maui and Hawaii yielded depth estimates of 4.0, 5.7, and 9.3 km. Almost all the anomalies are normally polarized, the lone reversely polarized anomaly being that of the Koolau volcano in Oahu. The magnetic and gravity anomalies are due to deep-seated, dense, highly magnetized volcanic plugs located beneath the volcanic centers.

Wellman (1966) studied the magnetic anomalies in the central portion of the Hawaiian Ridge between Kauai and French Frigate Shoals. He reported that the calculated effect of the Hawaiian Ridge is a southern positive peak of 210-280 gammas and a northern negative peak of 200-320 gammas. The major portion of the anomalies in the area can be explained by normal magnetization of the Hawaiian Ridge. Magnetic anomalies associated with seamounts had large amplitudes and were found to have a greater diameter than the bathymetric expression of the seamounts themselves. In areas of flat sea floor, Wellman found low-amplitude, subparallel anomalies which are apparently caused by shallow bodies.

Malahoff and Woollard (in press) later expanded their discussion of magnetic and tectonic trends to cover the Hawaiian Ridge northwest to French Frigate Shoals and related these to trends elsewhere. They noted that the magnetic anomalies are continuous from east of the Hawaiian Ridge, across the Ridge, to the area west of the Ridge. The strike and location of these anomalies closely parallel the

Murray and Molokai Fracture Zones. Over the Ridge itself, the east-west pattern of the anomalies is disturbed by a smaller-wavelength, northwest-southeast pattern of anomalies. The authors did not find any symmetry in the pattern of anomalies around the Murray and Molokai Fracture Zones, and noted that their anomalies were significantly different from those found over the Mid-Atlantic Ridge (Vine, 1966) and off the California coast (Vacquier, Raff, and Warren, 1961). Instead, there is direct relationship between the bathymetric expression of the fracture zones and the magnetic anomalies. They also found that the magnetic patterns at the intersection of the Marcus-Necker Ridge and the Hawaiian Ridge and along the two fracture zones are quite complex. These anomalies are thought to reflect large dike-intruded sections of the crust which have apparently been intruded by smaller bodies of more magnetic material.

This study is concerned with the aeromagnetic coverage of the Hawaiian Ridge farther northwest of the earlier studies, namely, the area between French Frigate Shoals and Kure Island. The only previous aeromagnetic work in the area was by Project Magnet of the U.S. Naval Oceanographic Office in 1963. From the data, Joyner (quoted in Blank, 1966) suggested that the topographic mass of the Midway Islands is not uniformly magnetized. His models of the magnetized body showed that a portion of the body, presumably an older cone, is reversely magnetized.

Other geophysical work in the area include a few seismic and gravity studies. At Gardner Pinnacles, Shor (1960) found four layers of velocities 3.5, 4.7, 6.9, and 8.3 km/sec. The Mohorovicic discontinuity is depressed to about 17 km below sea level beneath the Ridge. A Free Air and Bouguer anomaly map of the Pacific Basin compiled by Strange, Woollard, and Rose (1965) showed Free Air anomalies in this northwestern portion to be almost 0, while Bouguer anomalies range from +250 to +400 mgals. They inferred the mantle depth below sea level to be about 12 km. Kroenke and Woollard (1965) established about five gravity stations on the islands in the study area and found that the islands are characterized by high Bouguer gravity values approximating 300 mgals.

Elsewhere in the Pacific and Atlantic, some geophysical work has also been done on atolls, seamounts, and guyots such as are found in the study area. Alldredge and Dichtel (1949) attempted to interpret the aeromagnetic data over Bikini Island by assuming zero permanent magnetization and a uniform susceptibility of 0.008 cgs units and by measuring the magnetic anomalies over a working model with a miniature magnetometer. Their results showed that about 1.6 km northeast of Bikini Island the basement rock lies less than 1.6 km below sea level. They suggested that anomalies in that area are produced by a broad seamount with irregular subsurface features in the basement. Keller, Meuschke, and Alldredge (1954) aeromagnetically surveyed extensive areas over the Aleutian, Marshall, and Bermuda islands. They assumed that the coral atoll of Eniwetok is underlain by an old basaltic volcano. Their aeromagnetic map of the area showed that the crater of the underlying volcano is approximately under the center of the lagoon. In the Bermuda area, the magnetic anomalies were found to correlate with topography.

In a study of Jasper Seamount, four northeast Pacific seamounts, Eniwetok Atoll, Galicia Bank, and a seamount north of Madeira, Bullard and Mason (1966) found that the amplitude of magnetic anomalies increase greatly as the seamount approaches the surface. Most of these seamounts have dipole anomalies of several hundred gammas amplitude and all are positively polarized. The anomalies on Eniwetok are said to be of lower amplitude because of the great thickness of coral beneath the atoll. Also, as the anomaly over Galicia Bank is only about 150 gammas in amplitude, the authors concluded that it is not a basaltic volcano.

Miller and Ewing (1956) compared observed and computed magnetic anomalies over Caryn Seamount in the Atlantic. They found that the seamount body above the ocean floor would need a magnetization of 0.0058 cgs units and a susceptibility of 0.0107 cgs units to match the computed with the observed curves if the magnetization was by induction alone.

Heirtzler (1965), reviewing magnetic studies on seamounts, concluded that magnetization could not have been by induction alone and that remanent magnetization plays a very important part in the magnetization of seamounts. He added that seamount studies would be helped greatly if answers to questions such as how much of the seamount is volcanic, how much adjacent bottom structure is magnetic, and what constitutes a "best fit" between observed and computed anomalies, were better known.

Talwani (1965) utilized the Caryn Seamount anomalies to demonstrate his digital computation of magnetic anomalies using the three components of the magnetizing body. With additional subbottom data on the Caryn Seamount (Worzel, 1959; Hersey, 1962) showing an additional 1300 m of the seamount beneath sediments, Talwani was able to match the observed anomaly with the computed anomaly by assigning a susceptibility of 0.005 cgs units to the seamount and by assuming that magnetization was by induction alone.

Richards, Vacquier, and Van Voorhis (1967) presented a method of calculating the magnetization of seamounts by combining topographic and magnetic surveys. When the calculations were carried out on a group of seamounts near Hawaii, results showed that the poles of magnetization of these seamounts are significantly different from the present regional field. They also found the average intensity of magnetization to be 0.007 cgs units; seven of the 21 values are greater than 0.01 cgs units. These intensities are higher than those derived from rocks which they sampled on land.

According to them, these indicate strong remanent magnetization characteristic of "young" basic volcanics.

Schimke and Bufe (1968) made a detailed gravity and magnetic study of Chautauqua Seamount west of Kauai. Using Talwani's three-dimensional program and assuming uniform magnetization, they were able to match the observed and computed anomalies only if they extended the base of the seamount 1100 m below the ocean bottom. The computed magnetization was found to be roughly antiparallel to that of the earth's present field. The authors inferred that most of the growth of the seamount may have occurred during the Matuyama reversed polarity epoch between 0.85 ± 0.65 and 2.4 ± 0.1 million years ago.

Purpose of Study

The aim of this study is to analyze magnetic anomalies in the northwestern portion of the Hawaiian Ridge between French Frigate Shoals and Kure Island in terms of geologic structure. Magnetic anomaly patterns over specific structural features such as islands, atolls, coral reefs, banks, and guyot-like features in the area have been selected for analysis. The anomalies are analyzed in terms of the depth to the source of the magnetizing body. Centers of major volcanism which are now camouflaged by coral growth are determined as well as the polarization associated with each past volcanic center.

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METHODS

Data Collection

Survey

The aeromagnetic survey was carried out with a twin-engined Piper Apache airplane. Three of the five seats in the aircraft were removed to accommodate the scientific equipment and the extra fuel tank which extended the flying range of the airplane from 8 to 10 hours.

The flights were at altitudes of 7000 ft. (2135 m) or 8000 ft. (2440 m) depending on which airlane was made available by the Honolulu Office of the Federal Aviation Administration. Those altitudes were found to be optimum for good weather conditions and radio reception, and was close to the best altitude for magnetic measurements as described by Malahoff and Woollard (1966a). Flight lines were spaced 10-15 mi. (16-24 km) apart and were in a northwest-southeast direction. The best flight direction would have been perpendicular to the Hawaiian Ridge in a northeast-southwest direction but this was not possible because of the long distance between French Frigate Shoals and Midway, the limited flying range of the airplane, a limited supply of aviation fuel, and lack of time (as the survey was conducted in the middle of the Fall Semester 1966). The width of the area covered was 200 mi. (320 km).

A transistorized Loran A-Loran C set was installed in the airplane for navigation. A Loran fix was attempted every five minutes by crossing one Loran A line of position with a Loran C line of position. As flights were made during daylight hours, skywaves presented a navigational problem. Despite these difficulties, the navigation was found to be good to about ±3 mi. (4.8 km) as ascertained from agreement between magnetic intensities at the points where the flight lines crossed. The reefs and islands in the area were also used as visual flight navigational aids.

Instrumentation

Magnetic readings were taken with an Elsec proton magnetometer (Model 592/G). Scientific gear aboard the plane consisted of the magnetometer, an automatic recorder, two 12-volt batteries, and a "bird" housing the detector bottle which was towed 31 m behind the plane. The magnetometer measures the total magnetic vector to an absolute accuracy of one gamma, requires no leveling, and, for this project, was set to make one reading every five seconds (roughly equivalent to one reading every 880 ft. or 268 m). The fiberglass "bird" which houses the detector head was designed by Kenneth E. Culler. It was suspended from the airplane by a braided nylon rope which encased a coaxial cable connecting the magnetometer to the detector or sensing head. This "bird" had been tested and found to be aerodynamically stable up to an airspeed of 180 mph.

The detector head contains a one-quarter pint bottle of liquid. With the 12-volt battery providing the polarizing power supply, a current of one amp is passed through the measuring coil in the detector head, creating a magnetic field of several hundred gauss along its axis. This force acting on the protons in the bottle produces a net proton magnetic moment in the direction of the axis which is usually east-west. When the polarizing current is cut off, the protons precess about the earth's field, and this precession induces a voltage in the coil. After selective amplification the signal is squared and the frequency divided by the number of proton pulses (by 1024 in this survey), and then displayed digitally on a dial readout as proton counts. The counts are automatically recorded on the six-inch paper tape.

Data Reduction and Interpretation

The proton precession counts were converted to gammas by dividing these into 24051 (where 24051 is a constant numerator when the automatic magnetic measurements are made every five seconds) to give the anomaly values of the total intensity of the earth's magnetic force. These values were then plotted on the flight lines. Contours were drawn by connecting points of equal total force magnetic intensity. The earth's total force regional magnetic field was derived by "smoothing" out total force intensity values, i.e., drawing lines through areas where the total force intensities have little or no variation and continuing these lines through areas where the pattern of magnetic anomalies is more complex. No attempt was made to derive the total force regional field by the least squares fit or any other theoretical method, because Malahoff and Woollard (1966a) have found that the "smoothing" process agreed well with the theoretical methods (Bullard, Gellman, and Vixon, 1950) in the low magnetic latitude of the Hawaiian Islands. Next, a total force residual anomaly map was drawn by subtracting the total force regional intensity values from the total force intensity values.

During the aeromagnetic survey, no magnetic storms were detected by the U.S. Coast and Geodetic Survey in Honolulu while the flights were in progress. The diurnal magnetic variations were less than 30 gammas per 24 hours and no corrections were made for them.

The bathymetric map of the study area was compiled from several sources because the U.S. Naval Oceanographic Office's bathymetric chart of the area (BC 1805N), considered to have the best control, is classified. The bathymetry from French Frigate Shoals to Raita Bank was provided by the Naval Oceanographic Office chart BC 1705N and that from Raita Bank to Midway Islands was taken from Coast and Geodetic Survey charts 4182 and 4183. Unfortunately, the latter two maps were contoured only in the vicinity of the islands so that the rest of the area had to be contoured by the writer using the soundings listed on these charts.

Bathymetric profiles were drawn over selected areas for the computation of magnetization due to terrain. Magnetic profiles were also drawn across the structural features.

The two-dimensional program of Talwani and Heirtzler (1962) was used to compute the terrain effects of these bathymetric features. These terrain effects were then subtracted from the total force residual anomaly values over the same profiles to calculate the magnetic field intensities due to the magnetizing bodies. The terrain-corrected total force residual anomalies were then used to find the depth to the magnetizing bodies and their parameters by the method of Martin's characteristic curves (1964). Midway atoll had good bathymetric and aeromagnetic coverage so that Talwani's three-dimensional program (1965) was used to compute the magnetization of the topography and to compare these with the observed values.

GEOMORPHOLOGY AND STRUCTURE

Base Maps

As stated in the previous section, the bathymetric map of the region was compiled from the following sources: (1) U.S. Naval Oceanographic Office chart BC 1705N for the area between French Frigate Shoals and Raita Bank, and (2) U.S. Coast and Geodetic Survey charts 4182 and 4183 for that between Raita Bank and Kure Island. Areas in the latter charts which were not contoured by the Coast and Geodetic Survey were contoured by the writer using soundings printed on the charts. The bathymetry of the Midway area was obtained from an enlargement of the figure published by Ladd, Tracey, and Gross (1967).

The control of the bathymetry was fairly good around the islands and atolls. That in areas deeper than 500 fathoms between Raita Bank and Pearl and Hermes Reef, however, depends on the correctness of the sounding published by the Coast and Geodetic Survey.

Bathymetry

Plate 1 shows the bathymetry of the study area. The Hawaiian Arch, Deep, and Ridge as described by Dietz and Menard (1953) in the area of the major Hawaiian Islands can also be seen in parts of this northwestern area. The Hawaiian Ridge itself remains continuous to the area west of Lisianski

Island (about 175°W). The Ridge narrows down to a 32 km width between the Pioneer and Northampton Banks before widening again in the area of Lisianski Island and Pioneer Bank. West of Lisianski, the Ridge is broken from the rest of the western area by a 2800-fathom deep. In this western area, there are two ridge-like features trending almost east-west, one to the south of the other. These two ridges are also separated by another 2800-fathom deep. The southern ridge has five small banks rising to about 200 fathoms below sea level; the northern ridge includes the reefs and atolls of Kure, Midway, and Pearl and Hermes. These two ridges may have been offset by faults. Despite this offset, however, the Hawaiian Ridge maintains its northwest-southeast strike. The Hawaiian Deep can also be seen in the study area, specially in the area east of the Pearl and Hermes Reef complex, where depths down to 3000 fathoms have been reported. The Hawaiian Arch is not shown in the map and lies much farther to the north.

Most of the larger features in the area trend either parallel or perpendicular to the Ridge. The features perpendicular to the Ridge, such as Gardner, Raita, and Pioneer Banks can be seen mostly in the eastern half of the area, whereas parallel-trending features are located over the entire extent of the Ridge.

The 2800-fathom deep between Pearl and Hermes Reef and the Salmon Bank complex appears to indicate faulting in an east-northeast, west-southwest direction paralleling the general direction of a branch of the Murray Fracture Zone north of Necker Ridge. The fault in this area seems to indicate right lateral strike-slip movement of at least 300 km. Another right-lateral fault is also postulated bathymetrically striking 48 km south of Midway. The presence of these faults could explain the scattered topographic ridges and offset pattern of the Hawaiian Ridge in this western section.

Geology

It is the consensus among most geologists that the Hawaiian Islands were formed in sequence from the northwesternmost and oldest island of Kure to the youngest island of Hawaii in the southeast. Thus, the islands of the Hawaiian Ridge show a sequence in size which is inversely proportional to their age. They also show a gradation in elevation. Thus, the sand islands and atolls of the northwestern portion have maximum heights of 17 m above sea level; those of the central portion from French Frigate Shoals to Kaula range in height from 31 to 152 m above sea level; while the major islands southeast of these have mountains ranging in elevation from 305 to 4250 m above sea level.

Topographic features in this study area include many banks, a few seamounts, some reefs and atolls, and a few rock outcrops.

There are several banks less than 100 fathoms deep located along the Ridge from Midway Islands to French Frigate Shoals. The tops of these banks cover areas ranging from 16 to 48 km^2. In the section east of Gardner Pinnacles, there is a series of banks located on a 1000-fathom platform of the Ridge. In general, the banks in the western portion of the study area have greater heights from the sea floor (from the 2000-fathom contour) than the central area, where the banks begin from the 1000-fathom contour and the eastern area, where the banks rise from depths less than 500 fathoms.

A number of seamounts and guyot-like features occur in the southern portion of the Ridge in the region studied while the area north of the Ridge is bare of seamounts and is characterized by relatively flat areas containing a few deeps down to 3000 fathoms.

The reefs in this region are Maro Reef and Pearl and Hermes Reef, and the atolls are Midway Islands and Kure Island. The reefs usually rise no more than a few feet above sea level and cover extensive areas. The depth of water within the reefs seldom exceed a few fathoms. Midway and Kure atolls, on the other hand, encircle areas of water depth up to 10 fathoms.

The sandy islands in this region are Kure, Midway, Lisianski, and Laysan Islands. They constitute the highest features in this area, ranging in elevation from 7 m for Green Island in Kure Atoll to 17 m for Laysan Island. The islands are quite small with surface areas less than 8 km^2.

Laysan Island is characterized by a small lake in the center of the island.

A core from a hole drilled at Sand Island in Midway atoll showed unlithified material consisting mostly of aragonite and magnesian-calcite (Ladd, Tracey, and Gross, 1967). Calcite limestone was present below 200 ft. (60 m), and basalt was encountered at 516 ft. (155 m). Study of the fossils indicated ages from early Miocene to Recent. The gross petrographic features of the Midway basalts were found to closely resemble the lava flows of Oahu. K-Ar dating of two basalt samples indicated ages of 15.7 ± 0.9 and 16.6 ± 0.9 million years. These values are low for Miocene ages and were attributed to the weathering of the samples and the consequent loss of argon.

Vine (1968) analyzed an oriented drill core from Midway for paleomagnetic shifting and reported that the island may have been 15° south of its present latitude in the Oligocene.

The only exposed volcanic rocks are Gardner Pinnacles and La Perouse Rock in French Frigate Shoals. These islands represent the more resistant, dike-intruded portions of former basaltic islands.

RESULTS AND DISCUSSION

Trends and Description of Magnetic Anomalies

The total force residual magnetic anomalies (henceforth, "residual anomalies") over the topographic features are shown in Plate 3. No significant pattern of anomalies could be found for each "type" of topographic feature such as banks, reefs, and atolls. In general, however, the magnetic anomalies were in the form of bipoles with tendency towards elongation along the strike of the Hawaiian Ridge. The anomalies over individual ridges such as those directly east of Maro Reef are themselves elongate and parallel to the ridges.

Over banks, peak-to-peak amplitudes of terrain-corrected total force residual magnetic anomalies (henceforth referred to as "terrain-corrected anomalies") range from a low of 120 gammas over Raita Bank to 1015 gammas over Salmon Bank (Table 1). Over atolls and reefs, the total amplitudes vary considerably, ranging from 300 to 900 gammas. Lisianski Island has no significant magnetic anomaly associated with it.

The configurations of the magnetic bipoles also vary considerably (Plate 3). Most of the bipoles are composed of high positive anomalies associated with lower negative anomalies. However, there are cases, e.g. northeast of Pearl and Hermes Reef where the negative anomalies are twice as large as the positive anomalies.

Most of the features show a single magnetic bipole associated with them, but the larger features such as Maro Reef and Pearl and Hermes Reef show several magnetic bipoles

TABLE I

ANALYSIS OF TERRAIN-CORRECTED MAGNETIC ANOMALIES USING MARTIN'S METHOD OF CHARACTERISTIC CURVES

Body #	Name	Strike	Regional Field (gammas)	Peak to Peak Amplitude	Polarity	Length of Body (km)	Width of Body (km)	Depth below surface (km) (approx.)	Apparent Susceptibility Contrast x 10^{-3} cgs
1	Kure atoll-SE flank	0	36500	600	N	9.35	10.1	0	7.47
2	Midway atoll	35	36550	800	N	44.0	7.6	0	5.46
3	Seamount-E of Midway	0	36550	150	N	22.8	7.9	1	2.71
4	Bank-SW of Salmon Bank	0	36200	200	R	15.5	7.1	0	2.05
5	Salmon Bank	87	36230	1015	N	24.1	15.5	2	9.34
6	Southern Pearl and Hermes	45	36500	830	N	23.2	11.6	0	9.06
7	N of Pearl and Hermes	90	36610	500	N	22.8	22.8	0	2.87
8	Pearl and Hermes Reef	0	36550	450	N	14.2	3.86	0	7.95
9	SE of Pearl and Hermes	0	36480	200	R	12.9	8.7	1	3.91
10	Seamount-NE of Pearl	90	36580	975	N	36.1	25.7	0	4.10
11	Bank-NW of Lisianski	90	36130	850	N	26.7	16.7	4	8.25
12	Bank-S of Lisianski	90	35900	225	N	13.2	10.9	2	3.48
13	Pioneer Bank	45	36150	375	R	21.2	17.7	1	3.24
14	Ridge-NW of Northampton	45	36100	600	N	26.1	7.4	0	5.93
15	Northampton Bank	0	36050	620	R	25.1	6.1	0	10.1
16	Northampton Bank	0	36100	600	N	19.0	7.1	5	33.2
17	N of Northampton	45	36150	450	R	24.1	4.8	0	6.38
18	NW of Laysan Island	0	36210	500	R	27.7	17.4	0	3.03
19	Laysan Island	0	36200	400	R	12.5	4.8	0	3.14
20	Ridge-SW of Maro	0	36120	175	N	16.7	6.7	3	1.08
21	Ridge-SW of Maro	0	36180	200	N	10.9	7.4	0	3.35
22	Maro Reef	90	36200	850	N	19.3	12.3	0	3.65
23	Ridge-E of Maro	90	36170	525	N	24.3	18.0	0	2.13
24	Ridge-E of Maro	90	36230	620	R	24.2	5.8	0	5.52
25	Ridge-E of Maro	45	36170	650	N	33.5	6.7	0	10.5
26	Ridge-E of Maro	45	36200	600	R	38.6	9.0	0	6.76
27	Raita Bank	0	36400	120	N	23.5	19.6	4	2.35
28	W of Gardner Bank	0	36300	200	N	25.4	23.2	0	2.04
29	Brooks Banks	90	36100	375	N	54.8	10.9	1	2.73

located at the center and on the flanks. Also, while most of the anomalies may be found over the top of the bathymetric features, there are some cases, such as over Kure Island, where the anomalies are observed on the flank rather than on the top of the features.

No significant anomalies were observed over some of the smaller seamounts in the study area, but this could be due to our high level of observation and the wide-track spacing. Also, the linear magnetic anomalies characteristic of fracture zones in the southeast Hawaiian Ridge (Malahoff and Woollard, in press) were not found in the location of the Murray Fracture Zone or elsewhere.

About 30% of the anomalies in the study area are found to be reversely magnetized (Table 1). This marks a significant increase over the figure (10%) found by Malahoff and Woollard (in press) for the southeast Hawaiian Ridge and by Wellman (1966) for the central Hawaiian Ridge.

Source of Anomalies

The total force magnetic intensity measured by the magnetometer includes the regional field due to magnetohydrodynamic effects of the outer core (Bullard and Gellman, 1954; Elsasser, 1955), and the field due to the crustal effects. Magnetism in oceanic areas, as on land, is due to two processes: induced magnetization in the earth's present magnetic field, and natural remanent magnetization with paleomagnetic vectors. For rocks in oceanic areas, it has been shown that the natural remanent magnetization is much greater in magnitude than induced magnetization. The susceptibility and natural remanent magnetization of rocks are related to the amounts of magnetite and ilmenite present in them (Nagata, 1961). Magnetic anomalies over oceanic rocks may be due to compositional differences between rocks resulting from magmatic differentiation processes, to physical differences between rocks, and to paleomagnetic effects. The main contributions to the observed total force residual magnetic anomaly (henceforth, "observed anomaly") appear to originate from physical differences between extrusive rocks (which have low densities and are fine-grained) and intrusive rocks (high densities and coarse-grained), and from paleomagnetic effects such as natural remanent magnetization along a vector unlike that of the earth's present magnetic field.

The susceptibility contrasts between extrusive and intrusive volcanic rocks are probably the more important cause of observed anomalies in the Hawaiian Ridge. Table 2 from Malahoff and Woollard (1966a) shows that the natural remanent magnetization of intrusive rocks is three times greater than those of extrusive rocks. They found the average natural remanent magnetization for all rocks to be 0.005 cgs units. The apparent susceptibility computed by Malahoff and Woollard (in press) for extrusive rocks is 0.0075 cgs units. This value agrees with that used by

TABLE II

AVERAGE VALUES (x 10^{-3} cgs) OF SUSCEPTIBILITY (μ) AND NATURAL REMANENT MAGNETIZATION (NRM) FOR ROCKS OF THE HAWAIIAN ISLANDS*

FORMATION	NRM	μ	NRM	μ	NRM	μ
	(Tarling, 1965)		(Malahoff and Woollard, 1966a)		(Decker, 1963)	
Hawaii (Tholeiite)			11.0	3.2	10.0	1.0
Hawaii (Olivine-rich basalt)			5.0	0.5		
Hana (E. Maui)	17.31	4.63	-----	---		
Kula (E. Maui)	137.30	13.28	100.0	5.0		
Honomanu (E. Maui)	0.96	2.66	1.0	2.5		
Honolua intrusive rock			20.0	2.8		
Honolua (W. Maui)	14.34	2.74	15.0	2.7		
Wailuku intrusive rock			1.0	0.5		
Wailuku (W. Maui)	8.19	2.01	10.0	2.8		
Lanai	5.88	0.92				
East Molokai	19.43	2.13				
West Molokai	13.22	1.16				
Koolau dike rock			2.0	0.5		
Koolau (Oahu)	3.09	1.83	5.0	1.8		
Waianae (Oahu)	2.67	2.19	-----	---		
Honolulu (Oahu)	4.78	3.92	5.0	3.2		
Koloa (Kauai)	6.45	1.24	5.0	2.1		
Napali (Kauai)	4.21	1.01	5.0	2.0		

*From Malahoff and Woollard, 1966a

Richards, Vacquier, and Van Voorhis (1967) in calculating the magnetization of seamounts southwest of Hawaii. This same value is used in the terrain corrections in this study and may be thought of as the susceptibility contrast between sea water and oceanic basalt. Apparent susceptibility in this study is the derived value from natural remanent magnetization measured for the rock sample or obtained from the analysis of magnetic anomalies associated with known geological features (Nagata, 1961). That is:

$$J_{NRM} = k_A H_o$$

where J_{NRM} = intensity of natural remanent magnetization (NRM)

k_A = apparent susceptibility

H_o = intensity of the earth's magnetic field during the cooling of the magnetic source material to below Curie Point.

Terrain Correction

Bathymetric profiles were drawn over selected representative features in the study area. These profiles covered sections from the northern Deep, across the Ridge, to the southern Deep. The two-dimensional computer program of Talwani and Heirtzler (1962) was used to calculate the terrain effects across these profiles. Input data included: base level, or the deepest level of the profile; elevations from this base level of points where changes in bathymetric gradient occur; distances from the southern end (taken as 0 distance) of these points; the total force regional magnetic field (henceforth "regional field") of 36500 gammas; apparent susceptibility of 0.0075 cgs units; 40° inclination; and 10° declination. The computer then computed the total force intensity anomaly at field points every 4 km apart. These anomalies are described as "terrain effects" and were subtracted from the observed anomalies to give the terrain-corrected anomalies, i.e., anomalies due to some source other than terrain.

Figs. 1, 2, 3, and 4 show the bathymetry, observed anomaly, terrain effect, and terrain-corrected anomaly of profiles (Plate 2) of four features. The terrain effects seldom exceed 200 gammas and do not substantially change the amplitudes of the observed anomalies which sometimes reach up to 1200 gammas. Only in two cases, Lisianski Island (Fig. 3) and St. Rogatien Bank, do the observed anomalies match the computed terrain effects. In these cases, the magnetization is due entirely to the terrain effect. Assuming an apparent susceptibility of 0.0075 cgs units and multiplying this by the regional field of 36500 gammas would give the magnetization of the body to be 0.00275 cgs units.

Three-dimensional Model of Midway Islands

As the controls for both bathymetric and magnetic data

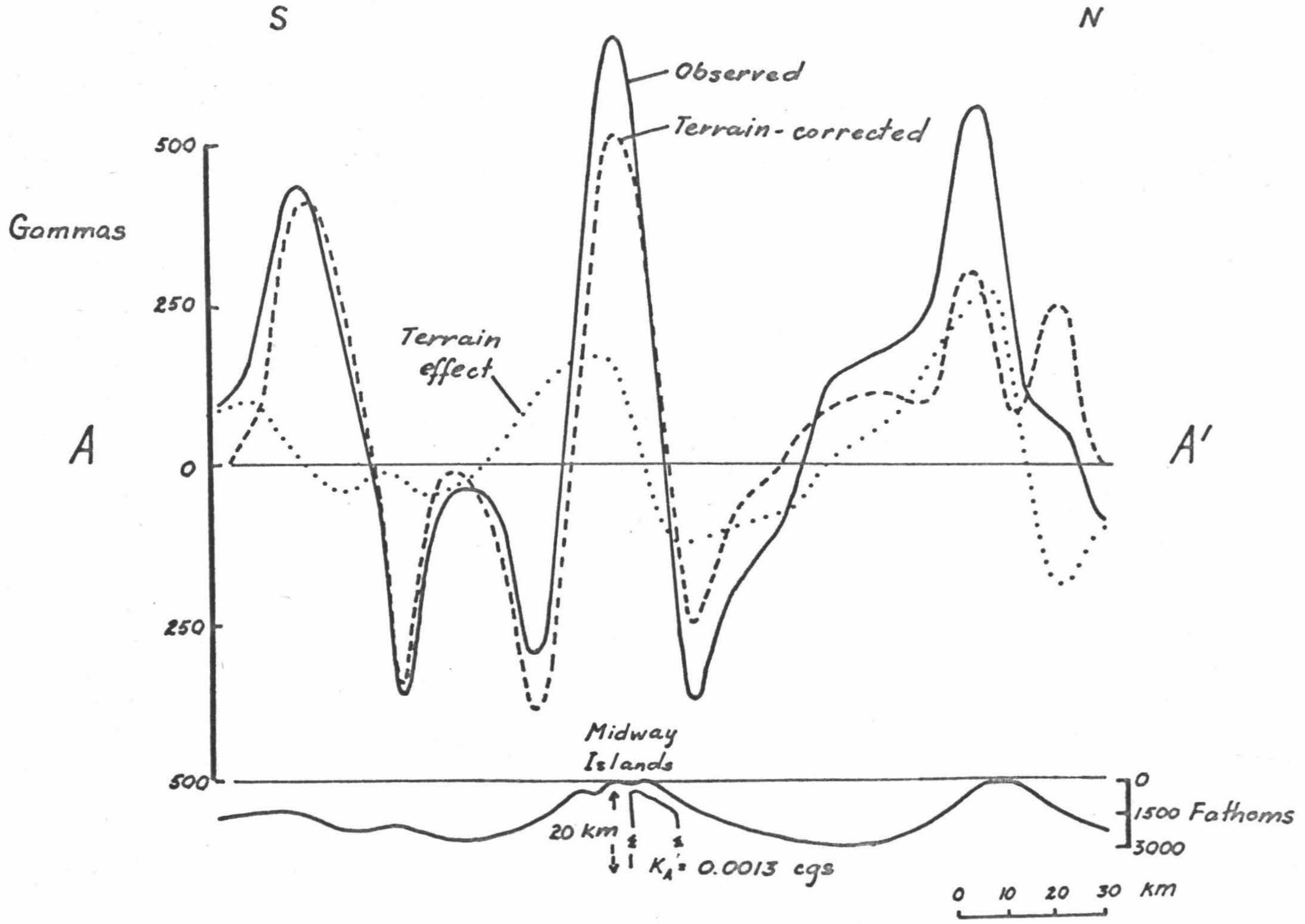


Fig. 1. Bathymetric and Magnetic Profile A-A' through Midway Islands. k_A is apparent susceptibility of the source body in cgs.

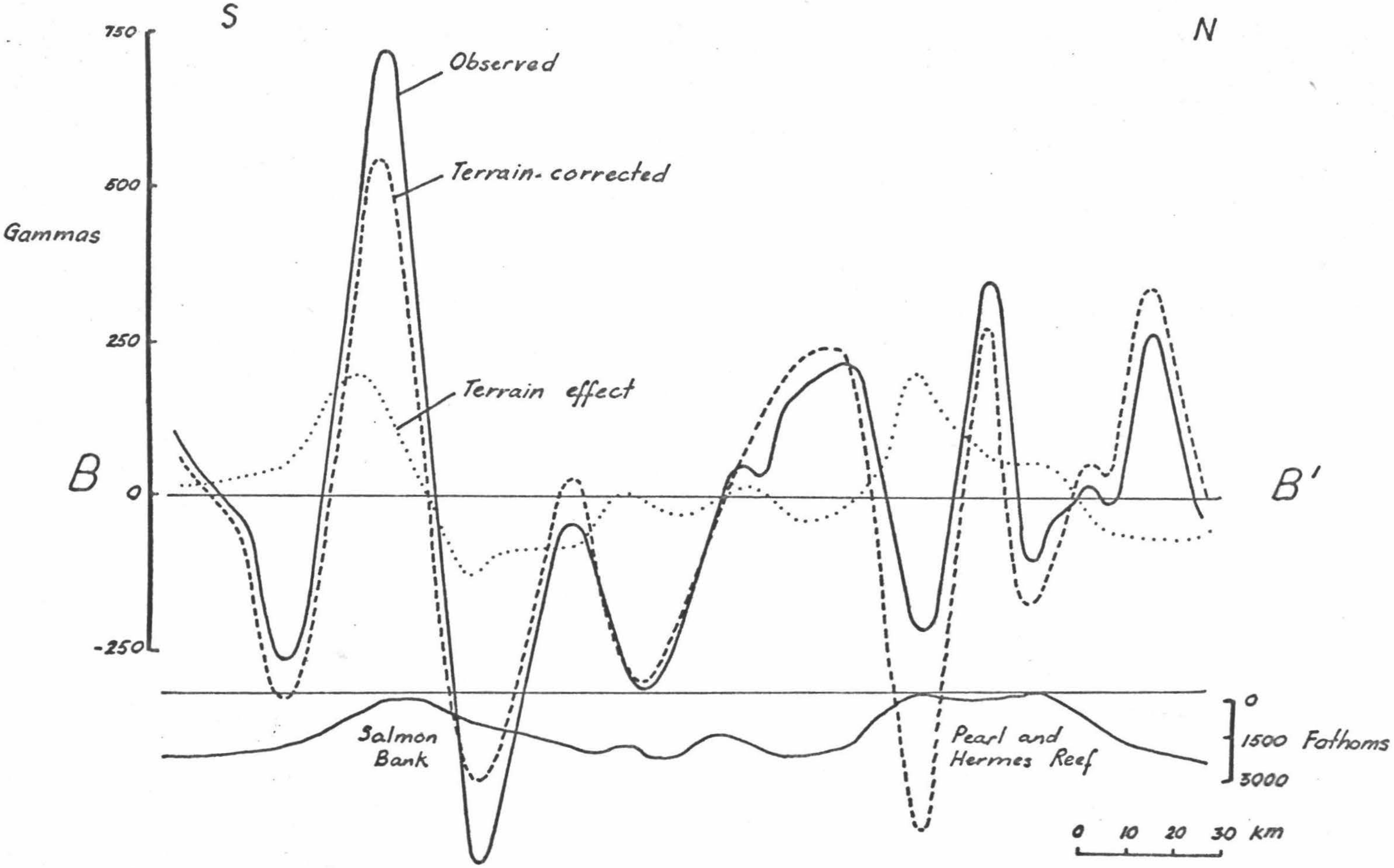


Fig. 2. Bathymetric and Magnetic Profile B-B' through Salmon Bank and Pearl and Hermes Reef.

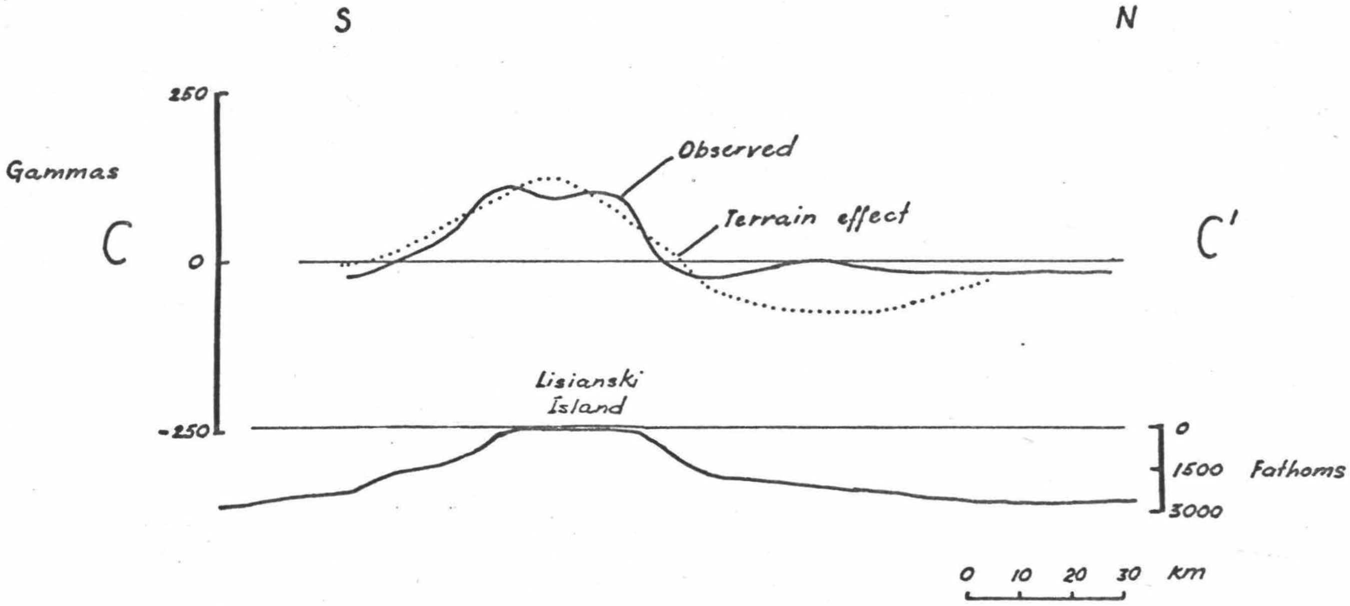


Fig. 3. Bathymetric and Magnetic Profile C-C' through Lisianski Island.

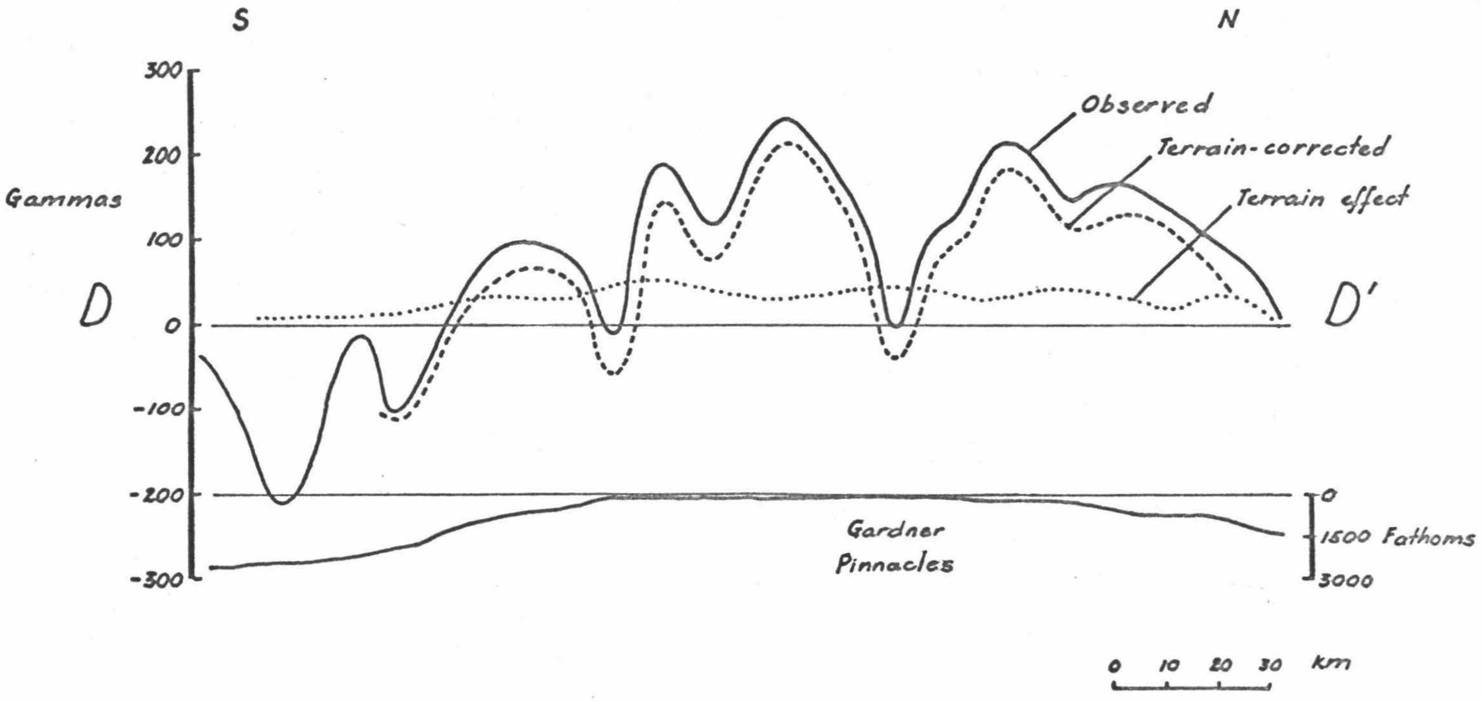


Fig. 4. Bathymetric and Magnetic Profile D-D' through Gardner Pinnacles.

for Midway are good, Midway was chosen for a special study utilizing Talwani's three-dimensional program (1965).

Figs. 5 and 6 show the bathymetry and the observed anomalies over Midway. The anomaly over Midway is a bipole with a +650 gamma high to the south and an elongate -350 gamma low to the north. The pattern is complicated by the presence of another negative anomaly of -350 gamma amplitude to the south of the large positive. However, this negative anomaly covers a much smaller area than the northern negative anomaly. The writer believes that the northern negative anomaly is associated with the positive anomaly, making the body normally polarized. The smaller southern negative anomaly could be due to minor dike injections during one of the reversals in the earth's magnetic field.

Briefly, Talwani's three-dimensional program obtains the three components of magnetization over a body and also the total force intensity anomaly. The body is assumed to be finite and homogeneously magnetized and is of arbitrary shape. No restriction may be made to the direction of magnetization.

The derivations for the equations are given by Talwani (1965) and only the final solutions to some of the equations are given here to show the principles of the program.

The body is described by contours, and the contours in turn are replaced by polygon laminas. The data entered include the coordinates of the field points taken at the

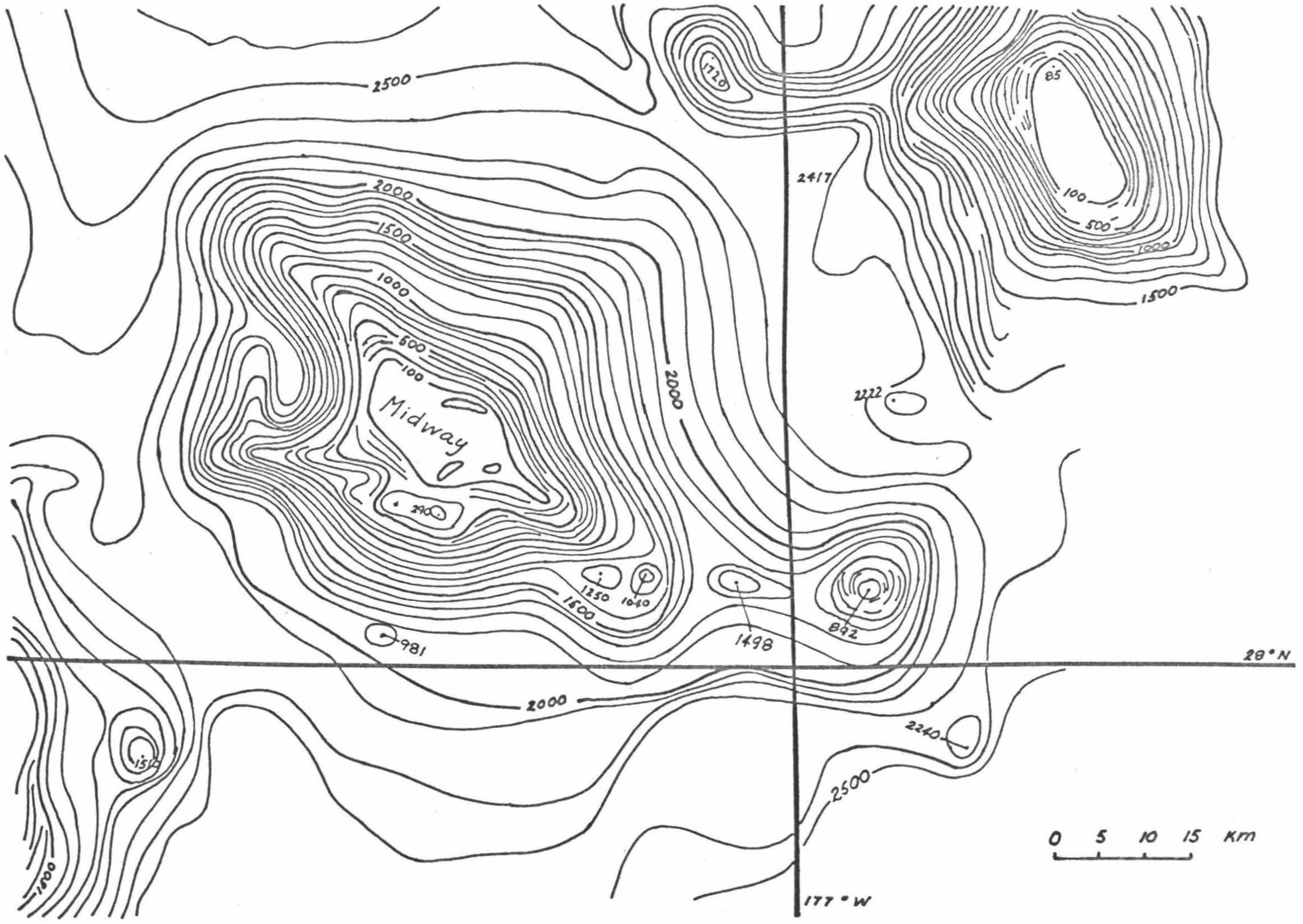


Fig. 5. Bathymetry of Midway Islands Area. Contour interval is 100 fathoms.

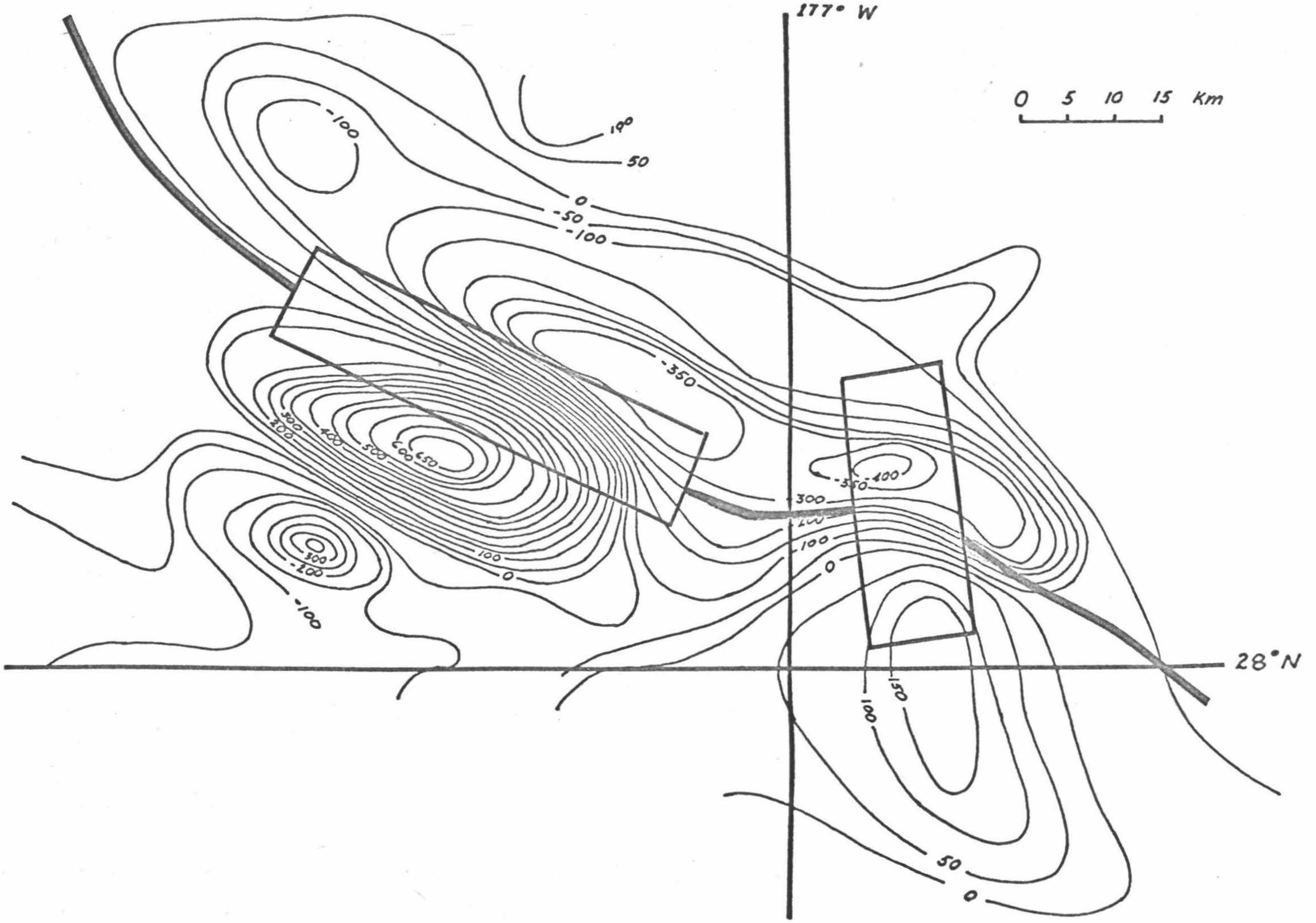


Fig. 6. Total Force Residual Magnetic Anomaly Map of Midway Islands. Contour interval is 50 gammas.

corner of the polygon laminas, the magnetic field point coordinates, and, for the induced magnetization run, the inclination and declination of the earth's field, the regional field, and apparent susceptibility. A double integration is carried out over the surface of each polygon lamina for each field point, and a numerical integration between the top and the bottom of the body gives the volume of the body. The computer then determines J_x, J_y, and J_z, the three components of the magnetization vector, by least squares fit. Once J_x, J_y, and J_z are known, Δx, Δy, and Δz, the three components of the total intensity anomaly, can be calculated:

$$\Delta x = J_x V_1 + J_1 V_2 + J_z V_3$$

$$\Delta y = J_x V_2 + J_y V_4 + J_z V_5$$

$$\Delta z = J_x V_3 + J_y V_5 + J_z V_6$$

Finally, the total intensity anomaly due to the magnetic body, ΔT, and the horizontal component of this total intensity anomaly, ΔH, are calculated:

$$\Delta T = \Delta X \cos D \cos I + \Delta Y \sin D \cos I + \Delta Z \sin I$$

$$\Delta H = \Delta X \cos D + \Delta Y \sin D$$

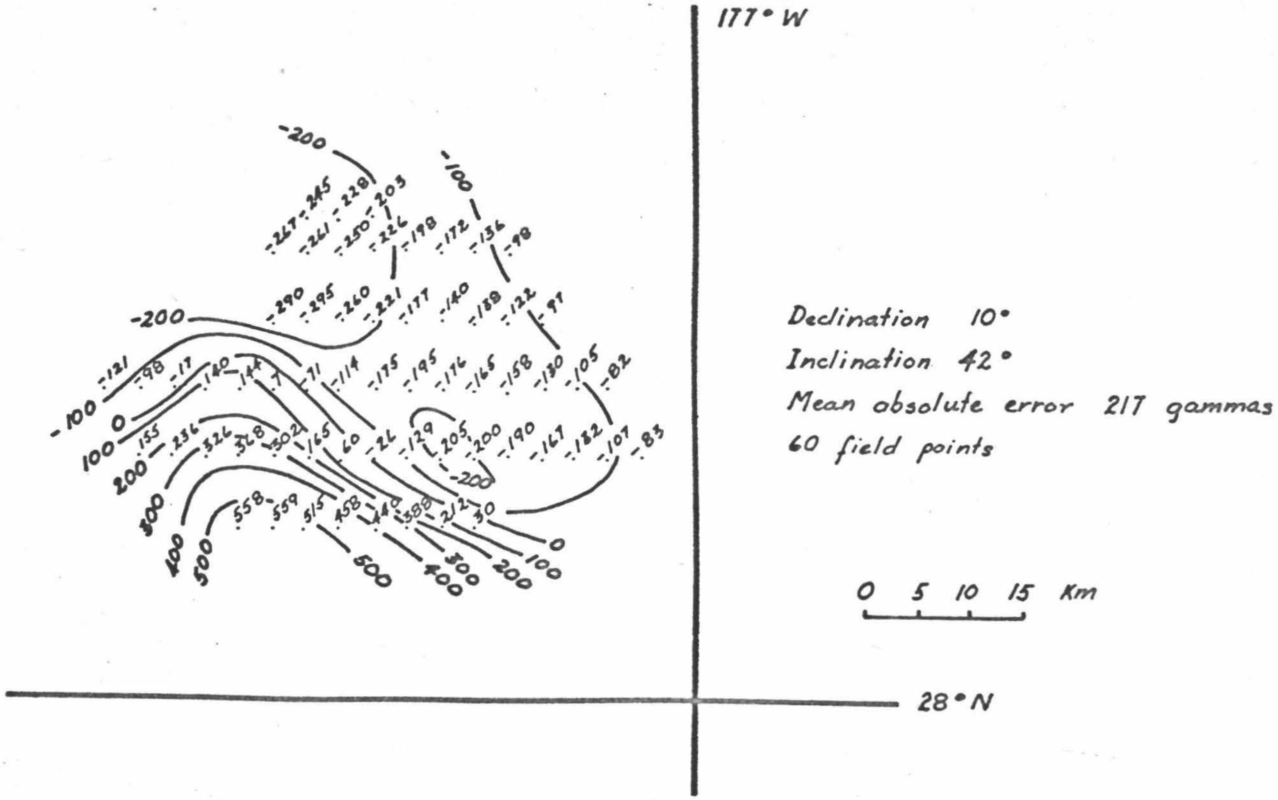
where D is declination and I is inclination.

The program was run three times on the IBM 360 of the University of Hawaii Computing Center.

For the first two runs, the field points were chosen to represent the normal bipole anomaly over the atoll with its large positive in the south and the smaller negative in the north. The depth contours of 10, 100, 500, 1000, 1500, and 2400 fathoms which define the bathymetric features of Midway were approximated by polygons. Sixty field points were chosen on these polygons.

In the first run, the body is assumed to be magnetized by induction alone in the present magnetic field of the earth. Thus, aside from the field points described above and their observed total intensities, the input included the following: declination of the earth's magnetic field, taken as 10°; inclination, 42°; the earth's regional field over Midway, 36500 gammas; apparent susceptibility of 0.14 cgs units, derived by dividing the average remanent magnetization value for Hawaiian rocks of 0.005 cgs units (Malahoff and Woollard, 1966a) by the earth's regional field over Midway, 36500 gammas.

The computed anomalies are shown in Fig. 7. Mean absolute error between observed and computed anomalies was found to be 217.0 gammas. A computed high of +550 gammas was found about 10 km south of the observed high, and a broad dislocation of the negative up to -250 gammas in amplitude was found over the northern side of the atoll. The gradient of the computed anomalies is highest at the location of the observed high. The large mean absolute error of 217.0 gammas between observed and computed anomalies suggests that the magnetization of the atoll is probably not due to induction



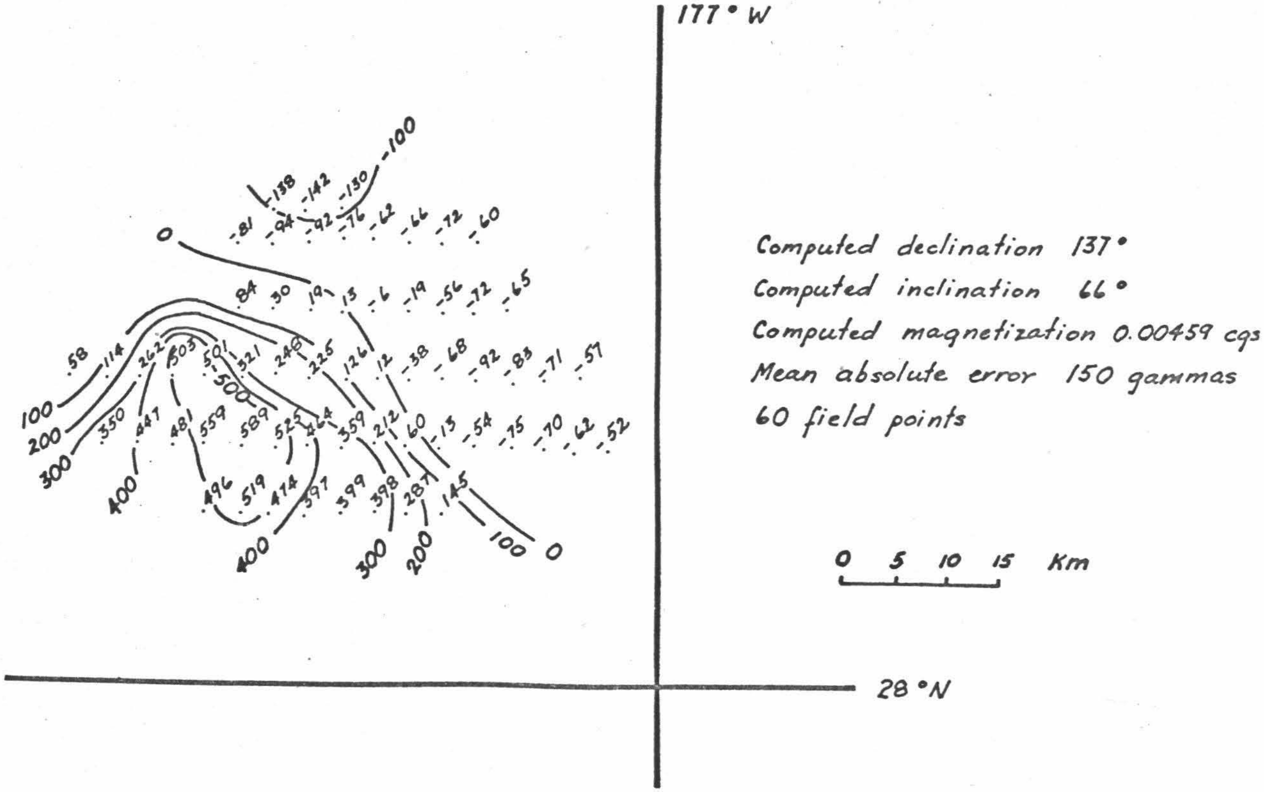
Declination 10°
Inclination 42°
Mean obsolute error 217 gammas
60 field points

Fig. 7. Computed Total Force Residual Magnetic Anomaly Map of Midway Islands (Magnetization by Induction). Contour interval is 100 gammas.

in the earth's present magnetic field.

The program was then run a second time, assuming that magnetization was not due to induction alone but to remanent or total magnetization. The field points used in this program were the same as those used in the first induction program. The computer used least squares fit to calculate the direction and intensity of natural remanent magnetization and the declination and inclination of the magnetization vector. The values calculated were: NRM = 0.004594 cgs units, declination = 136.6°, inclination = 66.3°, mean absolute error = 150 gammas. The computed anomalies (Fig. 8) show a high of +250 gammas to the south and a broad -140 gammas to the north. The location and trend of the anomalies roughly parallel the observed anomalies, although the configuration of the negative anomaly is quite different. The computed declination of 136° suggests that the paleomagnetic vector was quite different from the present vector during the formation of the atoll.

It was then decided to check the effect of the observed southern negative on the body. The program for remanent magnetization was run again with six extra field points representing the southern negative anomaly. The results of the run show that the computer apparently rejected the southern negative anomaly and instead expanded the breadth of the positive anomaly over the area (Fig. 9). The location of the computed anomalies does not differ much from the previous



Computed declination 137°
Computed inclination 66°
Computed magnetization 0.00459 cgs
Mean absolute error 150 gammas
60 field points

Fig. 8. Computed Total Force Residual Magnetic Anomaly Map of Midway Islands (Remanent or Total Magnetization), with 60 Field Points. Contour interval is 100 gammas.

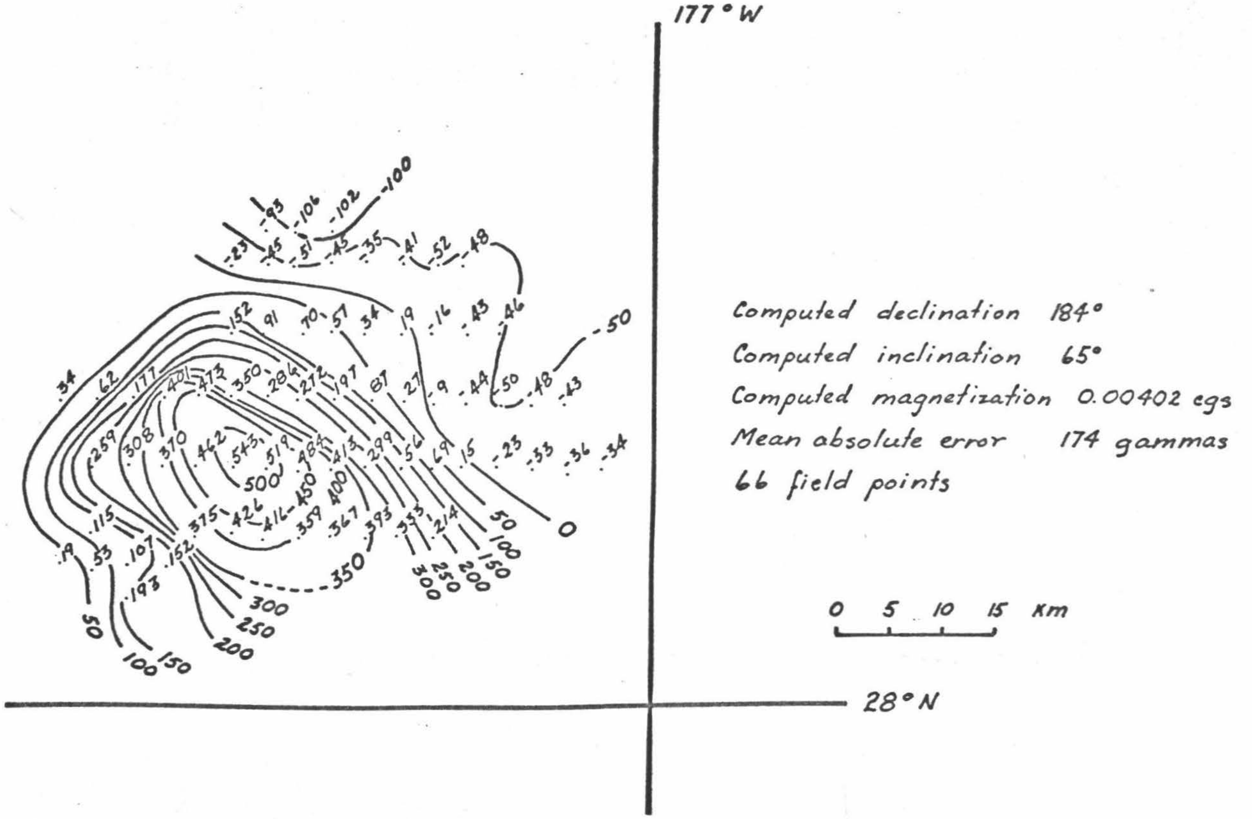


Fig. 9. Computed Total Force Residual Magnetic Anomaly Map of Midway Islands (Remanent or Total Magnetization), with 66 Field Points. Contour interval is 100 gammas.

run although the amplitude of the negative anomalies decrease to some extent. The NRM of the body decreased to 0.00402 cgs units, while the inclination change slightly to 65.2^{o}, and the declination swung farther to 184.3^{o}. The mean absolute error for this computation was 174.2 gammas.

Since the errors between the observed and computed anomalies were quite high in all three runs, these errors were plotted for comparison with the observed anomalies (Fig. 10, 11, and 12). These figures all have one surprising feature in common: they all show magnetic bipoles which do not appear in the computed anomalies and which closely resemble the configuration and trend of the observed anomalies over the atoll. From the high mean absolute error between the observed and computed magnetic anomalies, it is clear that the observed anomalies are not due to the geometrical configuration of the atoll. In other words, the basic assumption of the program that magnetization of the body is uniform is not true in the case of Midway (and apparently is also not true in the case of the other major bathymetric features in this study). It is more likely that the magnetic anomalies are due to a volcanic plug or dike complex underlying part of the atoll with greater magnetization than the surrounding body.

The two-dimensional top view of the plug or dike complex (Body #2, Fig. 4) can be derived from the configuration of the magnetic anomalies. The strike of the anomalies and

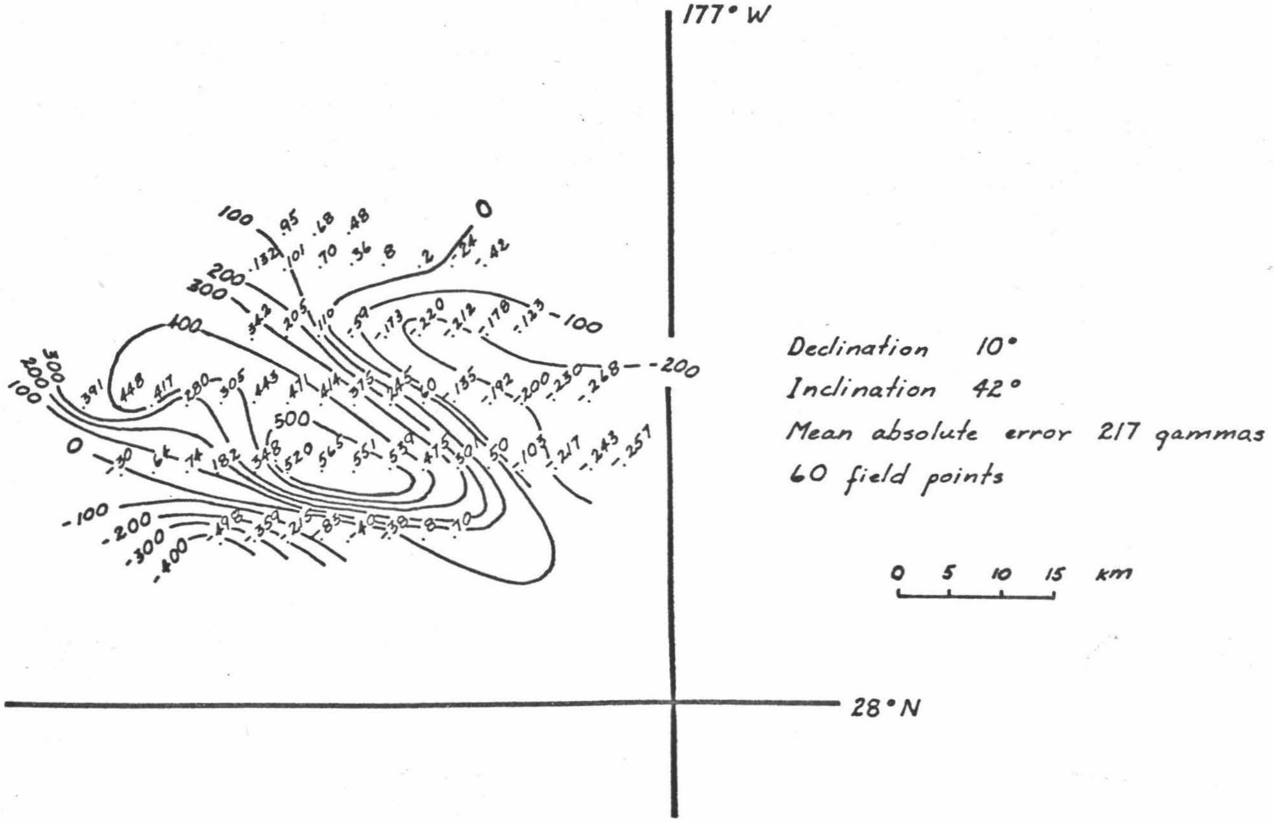


Fig. 10. Map of Errors (Observed-Computed), Induced Magnetization. Contour interval is 100 gammas.

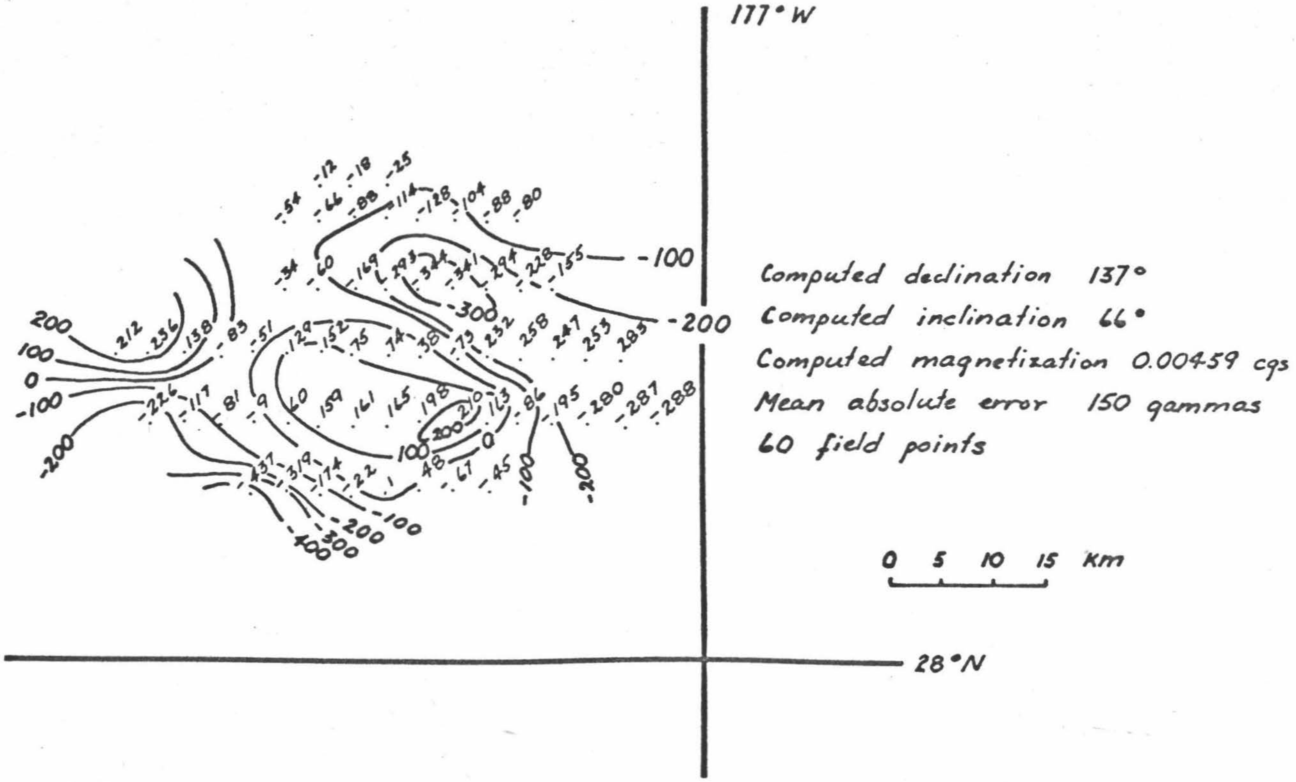
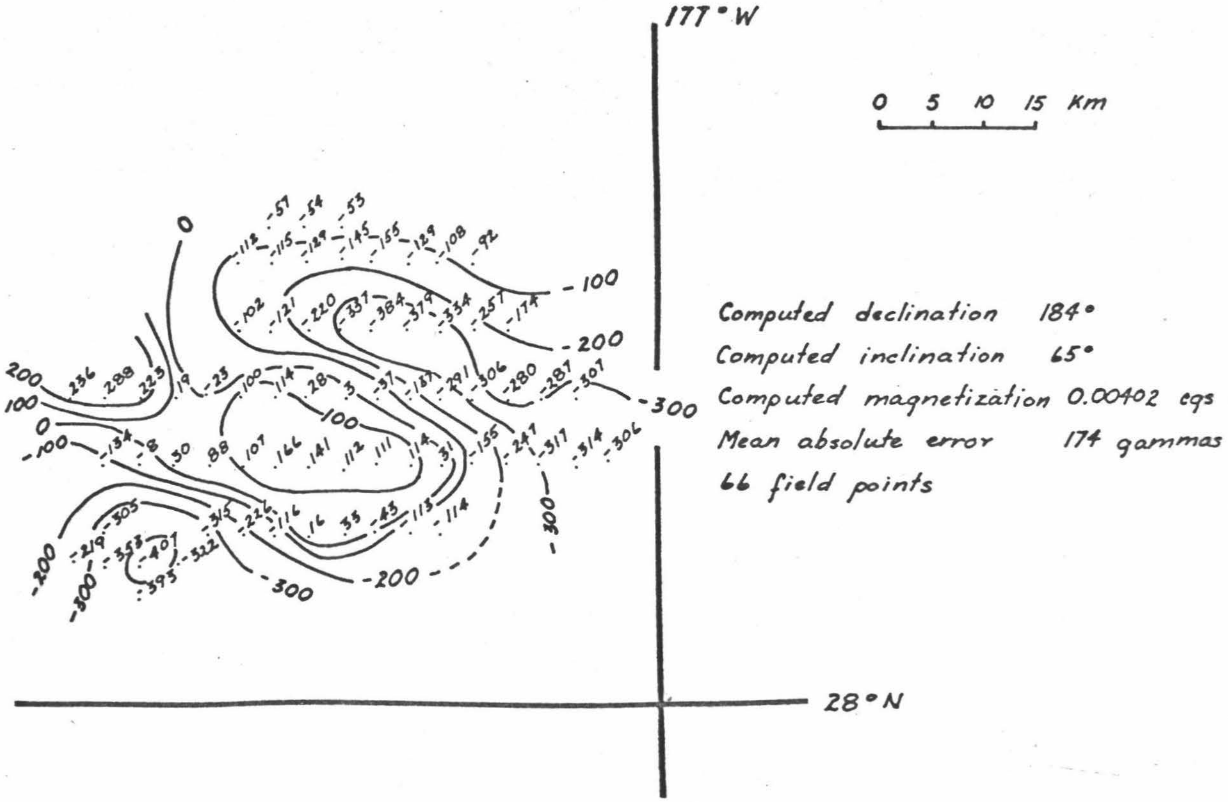


Fig. 11. Map of Errors (Observed-Computed), Remanent Magnetization, with 60 Field Points. Contour interval is 100 gammas.



Computed declination 184°
Computed inclination 65°
Computed magnetization 0.00402 cgs
Mean absolute error 174 gammas
66 field points

Fig. 12. Map of Errors (Observed-Computed), Remanent Magnetization, with 66 Field Points. Contour interval is 100 gammas.

the broad negative to the north suggest that the body is elongate, striking northwest-southeast, and is about 8 km wide (peak-to-peak distance of the magnetic anomalies). By using Martin's method of characteristic curves (1964), the depth to the top of the body was found to be 3.2 km (2 mi.) below the flight level which places the body fairly close to the surface of the atoll (Table 1). Martin's method also calculated a susceptibility of 0.00546 cgs units for the body.

Malahoff and Woollard (1966a) computed their own curves to derive magnetic anomalies due to vertical-sided prisms. Comparisons of observed anomalies and their set of curves showed that the profile of observed anomalies most closely matched Malahoff and Woollard's curves for a vertical-sided body 8 km (5 mi.) wide and 20 km (13 mi.) deep. Since the inclination and susceptibility of the observed body (42^{o} and 0.00546 cgs units, respectively) differed from those of Malahoff and Woollard (35^{o} and 0.001 cgs units), the curves were interpolated to match the observed profile. The resulting profile was surprisingly close to that of the terrain-corrected anomalies. From this interpolated profile, the body was postulated and is shown in Figs. 1 and 6. With an apparent susceptibility of 0.0075 cgs units used for surrounding rocks in the terrain correction, and an apparent susceptibility contrast between the body and surrounding rocks using Martin's method of 0.00546 cgs units, the apparent susceptibility of the intrusive body is 0.0013 cgs units.

The intrusive body inferred from the above magnetic analyses compares favorably with Kroenke, Walker, and Woollard's model of the atoll (in preparation) (Fig. 14). From well-controlled gravity data, they reported a Bouguer high of 310 mgals over the center of the lagoon (Fig. 13). Using computer techniques and incorporating Shor's (1964) seismic data and Ladd, Tracey, and Gross's (1967) drilling data, they arrived at a model which shows a plug with a density of 3.2 gm/cc, 5 km wide and 20 km deep, located about 2 km beneath the center of the lagoon.

The trends of the anomalies over Midway as given in the Project Magnet map (Fig. 15) closely reflect the anomalies found by the writer. The difference in amplitude was due to different flight elevations (152 m for Project Magnet, 2440 m for this survey). The presence of more anomalies of smaller scope on the Project Magnet map may be explained by the presence of smaller intrusives located beneath the atoll. The islands of the Hawaiian Chain commonly have many branching dikes which reach the surface at different locations on the islands. The magnetic anomalies over these smaller dikes are easier to detect from an altitude of 152 m than from 2440 m above sea level.

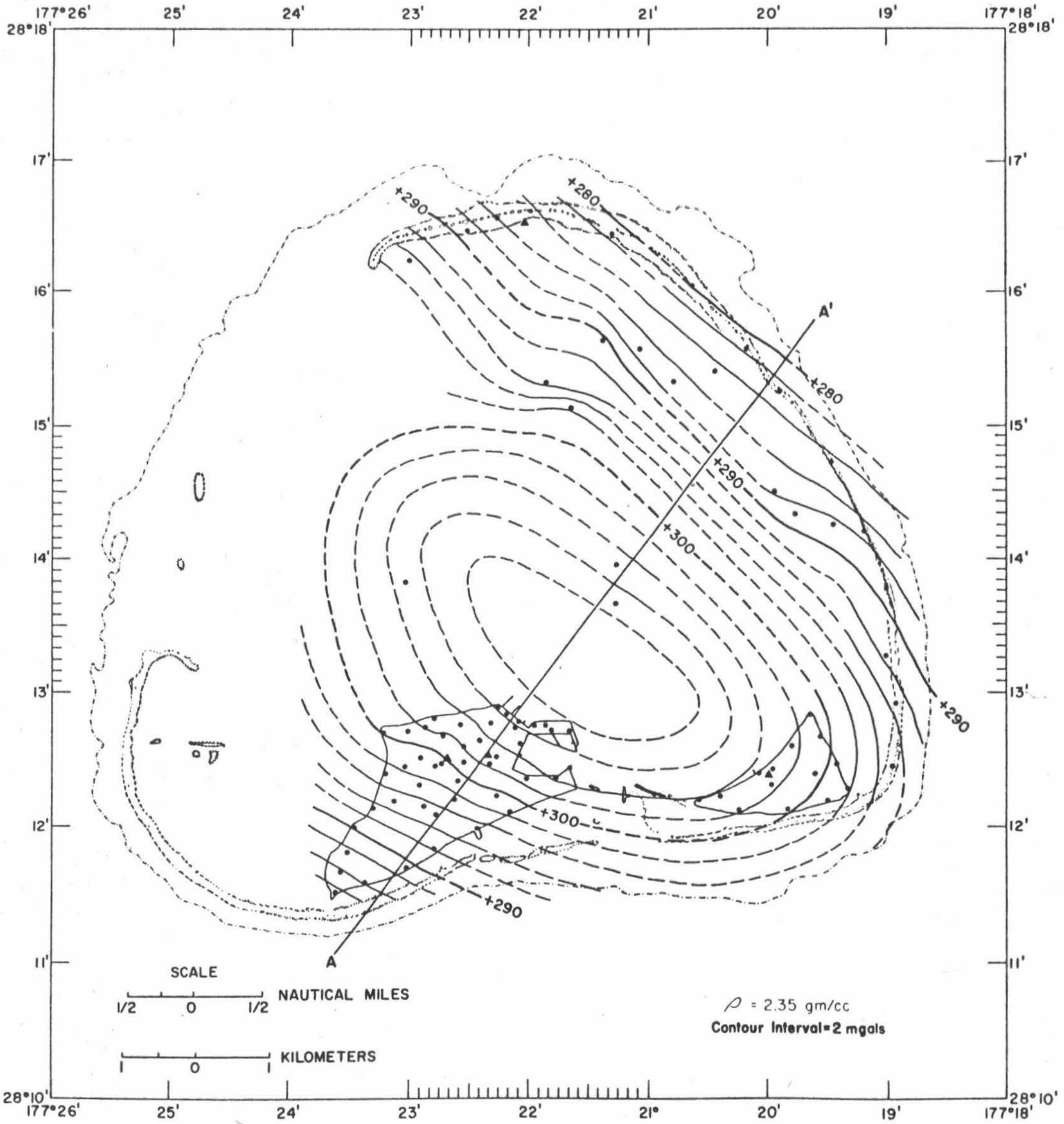


Fig. 13. Bouguer Anomaly Map of Midway Islands. Section A-A' refers to profile through Midway Islands showing model structure (Fig. 14). From Kroenke, Walker, and Woollard (in preparation).

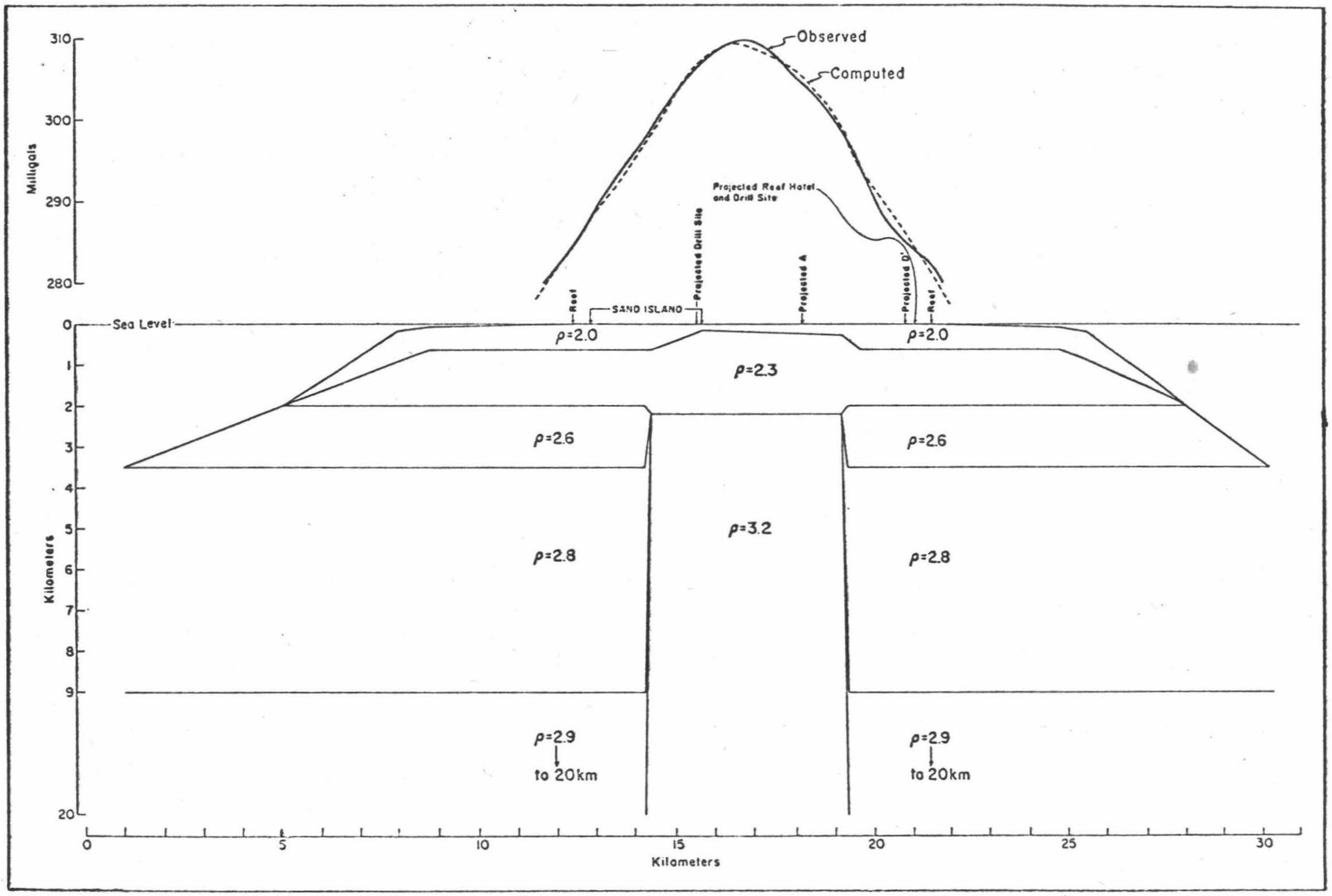


Fig. 14. Model of Midway Islands Structure from Gravity Studies. From Kroenke, Walker, and Woollard (in preparation).

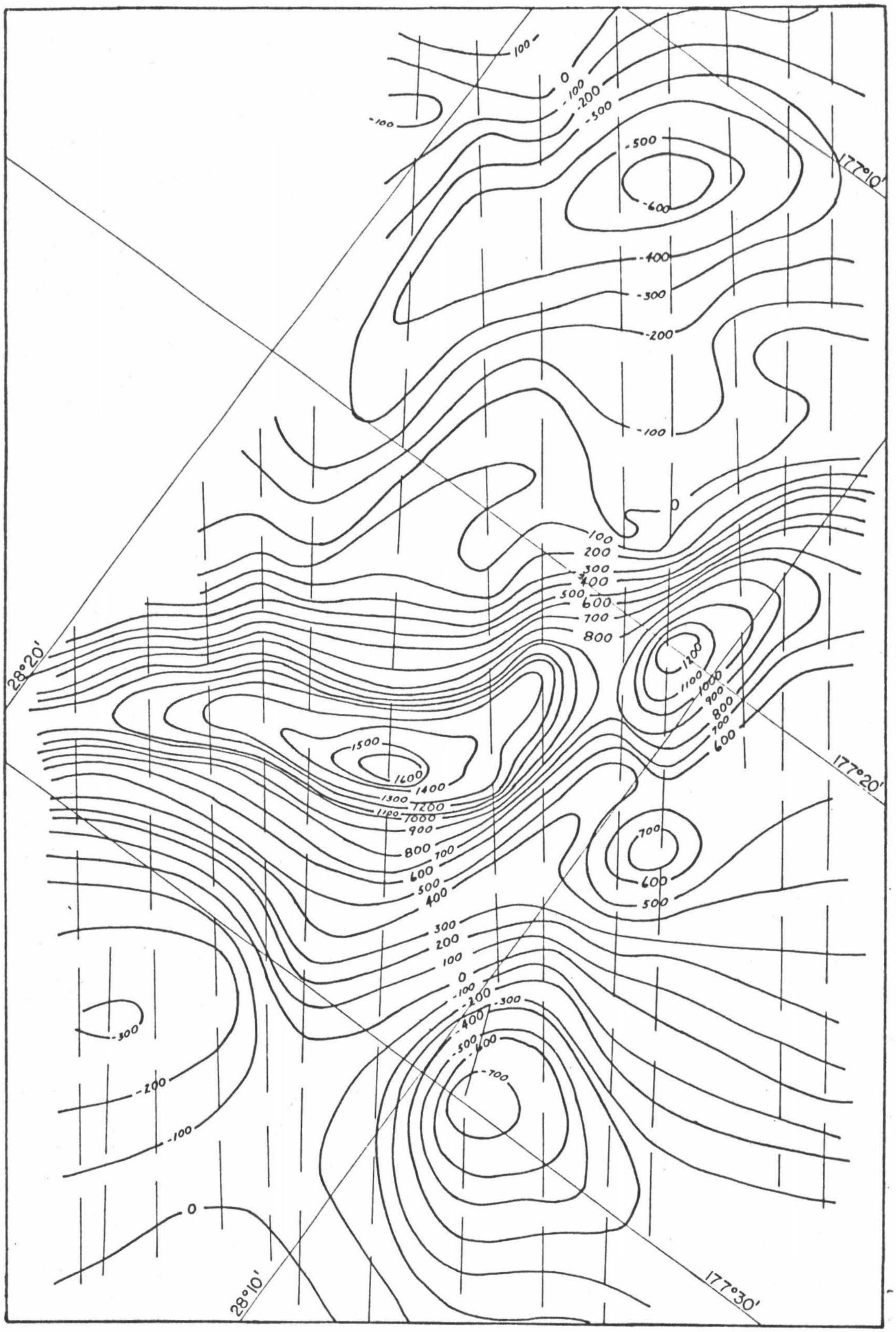


Fig. 15. Total Force Residual Magnetic Anomaly Map of Midway Islands Taken from Project Magnet Data. Contour interval is 100 gammas. ---refer to flight lines.

Other Features

The control of the bathymetric and magnetic data over topographic features of the study area other than Midway was not good enough to warrant three-dimensional computations of the magnetization of the body. In many cases, the aeromagnetic flight lines crossed over the top or the flank of the features only once.

In these cases, Martin's (1964) method of characteristic curves provides a quick and direct method of making depth estimates from aeromagnetic data with the least amount of numerical calculations. In his method, the theoretical anomaly from a simple geometric model such as a vertical prism is compared with terrain-corrected magnetic anomaly patterns by means of characteristic curves. In this procedure, the proper characteristic curves to be used for the interpretation of the terrain-corrected anomalies depend on the inclination of the magnetic field and the strike of the body relative to the magnetic north. Once the set of curves for each profile is isolated, it is a simple matter to measure such parameters as peak-to-peak amplitude of the terrain-corrected anomalies, width of the inflection points, width of the anomalies at certain amplitudes (such as 2/3 amplitude), the ground distance between the high and low values, etc., depending on the requirements of the particular set of curves. With these values and the regional field of the area, the method of characteristic curves gives the depth to the prism, the two dimensions of the top of the prism, and the susceptibility contrast between the prism and the surrounding rocks. The depth determinations in this study were accurate to about ±1.5 km. Table 1 gives the results of this method for several topographic features in the study area.

The magnetic anomalies over many of the bathymetric features are quite complex and difficult to interpret. Thus, only the features with clear bipole anomalies were chosen for analysis. Some of the latter topographic features have more than one bipole anomaly associated with them. For such cases, all the bipole anomalies associated with each feature were analyzed by Martin's method of characteristic curves. It is important to note that the bipole anomalies do not always occur over the top of the bathymetric features; sometimes they are found on the flanks, with a low-amplitude field existing on the surface of the features.

Plate 4 shows the locations and the top two-dimensional view of the magnetizing bodies as calculated by Martin's method and the pattern of rifting as inferred from the magnetic anomalies. Only the bodies which are directly associated with the topographic features studied are shown in the plate. The bodies are assumed to be plugs or dike swarms which probably extend down to the top of the mantle as shown by Kroenke, Walker, and Woollard (in preparation) for Midway Islands. The depths to the mantle has been found to be 20 km at Midway (Kroenke, Walker, and Woollard, in press) and about 17 km beneath the northern part of Gardner Pinnacles (Shor, 1960). Thus, it can be assumed that the plugs extend down for about 17-20 km.

Table 1 shows that in many cases, the surface of the bodies lies very close to the surface of the topographic features. A possible explanation for this may be found in the geologic history of the islands in this area. Because of the combined weight of the subaerial and submarine portions of the volcanoes on the crust, the islands began to sink isostatically. This rate of isostatic subsidence was probably slightly lower than the rate of leveling of the islands by subaerial erosion. The final planation of the subaerial portion of the volcanoes was probably done by ocean waves. Beyond this level, isostatic forces became the only factor in the sinking of the features. Thus the dike swarms or plugs are found close to the surface just beneath the coral growth. In those cases where sinking has occurred to greater depths, the depth to the source may have been controlled by greater thickness of coral and other sediment accumulated during periods of sinking.

The following is a more detailed analysis and interpretation of the anomalies over some of the more important features in the study area.

1. Maro Reef

Maro Reef is a broad complex topographic feature which rises from a depth of 2500 fathoms to sea level (Plate 1). The reef itself is roughly rectangular and covers an area of about 200 km^2. The anomalies associated with Maro Reef are elongate bipoles trending in the same direction as the Hawaiian Ridge (Plate 3). The main reef itself is characterized by a large +650 gamma anomaly over the center of the Ridge, accompanied by a very small -50 gamma anomaly directly to the north of the Ridge. This anomaly is probably due to a plug at the northeastern end of the reef (Body #22, Plate 4). The very small negative anomaly associated with the very large positive suggests that the body here is not uniformly magnetized. The source of the anomaly could be a cluster of smaller dike swarms which, because of our high altitude of observation, appear together as a single swarm. An alternative explanation is that the body was formed at a time when the paleomagnetic vector was different from the present vector and the angle of inclination was slightly higher. The other anomalies associated with this topographic feature are a bipole west of the Ridge and elongate bipoles over East Maro Reef.

Possible areas of rifting may be inferred from the direction of the strike of the magnetic anomalies as was done by Malahoff and Woollard (in press) for the southeast Hawaiian Ridge. Along Maro Reef, the rifts inferred from magnetic anomalies are connected to the ridges, showing that the ridges themselves may have been built by intrusions into the rift (Plate 4).

Table 1 shows that the source bodies for Maro Reef lie almost at the surface, probably just beneath the coral capping on the reef.

2. Pearl and Hermes Reef

Pearl and Hermes Reef is bathymetrically similar to Maro Reef and also has a complex pattern of magnetic bipoles (Plates 1 and 3). The peak-to-peak amplitude ranges from 450 to 900 gammas. The anomalies suggest a small dike swarm directly beneath the center of the reef, with larger dike swarms or plugs on the north and south of the reef. The location of Body #6 of Fig. 4 conforms with the location of the gravity high projected by Kroenke and Woollard (1965).

The anomaly with total amplitude of 900 gammas northeast of the reef is probably greatly affected by a seamount which rises 1500 fathoms high on the flank of the reef complex. The seamount anomaly appears to be affected by the reef complex because the positive side of the seamount anomaly is located on the side of the Pearl and Hermes Ridge. The size of the seamount may possibly be the cause of the large -600 gamma anomaly associated with the +300 gamma anomaly as shown in Plate 3.

3. Kure Island

Kure atoll, west of Midway Islands, has no apparent magnetic anomaly directly over the atoll, although a large bipole anomaly does occur over the flank of this feature (Plates 1 and 3). Plate 3 shows a possible rift zone connecting the atoll and the area on the flank over which the large anomaly occurs. This leads the writer to speculate that magma may have withdrawn from the center of the volcano by a flank eruption, although there could still be a plug beneath the center of the volcano and the lack of anomalies could possibly be explained by a small apparent susceptibility contrast with the surrounding rocks.

4. Laysan Island

The oval bank on which Laysan Island is situated is characterized by two bipole anomalies: West of Laysan, the bipole anomaly is normally polarized and has a long peak-to-peak wavelength, while the anomaly east of Laysan is a reversely magnetized bipole which may be caused by a narrow dike swarm (Fig. 2). The source bodies here probably are also beneath the coral growth (Plate 4, Table 1). The location of the magnetic anomalies does not conform with the Bouguer gravity high which Kroenke and Woollard (1965) found northeast of Laysan.

5. Salmon Banks

Salmon Banks rises from a depth of 2500 fathoms to about 30 fathoms beneath sea level (Plate 1). The anomalies associated with the banks are normally polarized bipoles with a peak-to-peak amplitude of 1250 gammas (Plate 3). A small reversely polarized anomaly occurs southwest of the bank. The steep gradient and the high amplitude of the anomalies suggest either a shallow source or a large susceptibility contrast between the body and the surrounding rocks. Table 1 shows that the body (#5) is actually located 2 km beneath the banks and has a susceptibility contrast of 0.00934 cgs units with the surrounding rocks. The susceptibility contrast suggests that the source body is a plug or dike swarm with a magnetization of 0.00334 cgs units.

6, 7. Lisianski Island and Gardner Pinnacles

These two topographic highs differ from the others by the absence of any appreciable magnetic anomalies in association with them (Plate 3). Instead, they have many small positive poles up to 300 gammas in amplitudes scattered over the banks without any associated negatives at all.

Lisianski Island bank is flanked by two other banks, Pioneer Bank to the east and an unnamed bank to the northwest (Plate 1). From the magnetic anomalies, three rifts can be postulated as heading out of Lisianski (Fig. 3): One rift connects with Pioneer Bank, the second rift with the northwest bank, and the third trends south. The source of the Pioneer Bank anomalies (Body #13) is located at a depth of 1 km whereas that of the northwest bank (Body #12) is at 4 km. At these depths, it is impossible to postulate that these banks are products of flank eruptions on the side of Lisianski.

A bipole anomaly also occurs on the western flank of the large bank around Gardner Pinnacles (Plate 3). The source body is probably a dike swarm close to the surface (Table 1, Body #28). Rifts from this anomaly area head north-northwest and south-southeast on the side of the bank (Plate 4).

8. Northampton Banks

Northampton Banks show complex bipole anomalies close together. A large +800 gamma pole seems to be shared by two surrounding negatives, suggesting the presence of plugs or dike swarms close together. However, the normally polarized anomaly has a depth source of 5.3 km with a very high susceptibility contrast of 0.0332 cgs units with the surrounding rocks, suggesting a very dense plug (Body #16). The other anomalies over the banks have source depths close to the surface (Bodies #14, 15).

9. St. Rogatien Bank

This bank occurs on a ridge in the easternmost part of the study area. As mentioned earlier, the anomaly over this body seems to be due entirely to terrain effects. The profile showing the observed anomalies and the terrain effect resemble that through Lisianski (Fig. 3).

10. Brooks Banks

This is a series of banks southeast of St. Rogatien Bank (Plate 1). Table 1 shows that the source of the anomalies (Body #29) lies 1.3 km beneath the banks and has a low apparent susceptibility contrast with the surrounding rocks. The configuration of the source body suggests a ridge formed by dike intrusion of a rift zone (Plate 4).

CONCLUSION AND SUMMARY

1. The magnetic anomalies over bathymetric features in the study area are usually found in the form of bipoles with tendency towards elongation along the strike of the Hawaiian Ridge. Whereas some of the anomalies are bipoles of equal magnitude, most of them have a high positive value associated with a lower negative value indicating normal polarization. Most of the topographic features show a single magnetic bipole but some show several magnetic bipoles located on the center and/or flanks of the topographic features. The topographic features are old volcanoes.

2. About 30% of the anomalies are found to be reversely magnetized.

3. The terrain effects seldom exceed 200 gammas and do not substantially change the amplitudes of the observed anomalies which sometimes reach 1200 gammas. Therefore, the anomalies probably originate from intrusive rocks at depth.

4. On Midway Islands the location of the computed anomalies as determined using Talwani's three-dimensional program do not differ significantly from the observed anomalies, although the configuration of the negative anomaly is quite different. The large mean absolute error between observed and computed anomalies over Midway (ranging from 150 to 217 gammas for the three runs) indicates that the magnetization of the body is not uniform, suggesting the

presence of a volcanic plug or dike complex under the atoll.

5. Martin's method of characteristic curves which gives a two-dimensional top view of the volcanic plug or dike complex under Midway gives a width of 8 km and shows that the plug is close to the top of the atoll. Using Malahoff and Woollard's curves, a depth of 20 km was derived for the base of the plug.

6. The shape of the intrusive body under Midway inferred from the magnetic analyses agrees well with gravity, seismic, and drilling information.

7. Martin's method applied to the other topographic features indicates that the source bodies of most of the anomalies lie close to the surface and only a few lie at greater depths. The magnetic anomalies over these features likewise suggest the presence of sub-surface dike swarms or intrusive plugs, which are sometimes beneath the crest and sometimes beneath the flanks of the old volcanoes.

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Plate 4. LOCATION OF SOURCE BODIES AND RIFTS IN STUDY AREA.

Plate 3. TOTAL FORCE RESIDUAL MAGNETIC ANOMALY MAP OF THE AREA BETWEEN FRENCH FRIGATE SHOALS AND KURE ISLAND.

CONTOUR INTERVAL IS 50 GAMMAS.

Plate 2. MAP OF STUDY AREA SHOWING TOTAL FORCE REGIONAL MAGNETIC FIELD, AND LOCATIONS OF FLIGHT LINES AND BATHYMETRIC AND MAGNETIC PROFILES.

Plate I. BATHYMETRY OF THE AREA BETWEEN FRENCH FRIGATE SHOALS AND KURE ISLAND.

CONTOUR INTERVAL IS 100 FATHOMS.