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During the North Pacific cruise of the R/V Yaquina in 1966, total magnetic field intensity was measured in the Andreanof group of the Aleutian Islands. Three north-south track lines were made across the Aleutian Trench and ridge between longitudes 175° W and 180°.

Three small scale magnetic profiles across the trench and ridge and one large scale profile over the crest of the ridge were constructed from the data. Total field and anomaly contour maps were drawn from the profiles. The data reveal:

1. A strong east-west trend of the contours present south of the ridge but absent north of the ridge which suggests that the Aleutian ridge is the boundary of two different magnetic provinces.
2. Large anomalies south of the trench which appear to be continuous for a distance of about 500 miles. The

anomalies result from shallow structures and are considered to be ocean floor magnetic lineations.

3. Large anomalies north of the trench which result from deep-seated structures, probably strongly magnetic intrusions.

4. Short wavelength anomalies on the crest of the ridge which may result from dike intrusions parallel to the trend of the ridge.

5. A local magnetic gradient of about 800 gammas after removal of the regional geomagnetic field. The residual gradient is "low" over the trench and "high" over the ridge. The magnetic variation may be related to changes in the depth of the Curie temperature isotherm.

Magnetic Profiles Across the Aleutian Trench and Ridge

by

Allan Jerome Skorpen

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INTRODUCTION

Yaloc-66

In the spring and summer of 1966, an extended cruise in the North Pacific was undertaken by the Research Vessel *Yaquina* of Oregon State University. This cruise was designated Yaloc-66. One objective of the cruise was a program of geophysical observations which included continuous measurement of the magnetic total field intensity over the Aleutian Trench and ridge near Adak Island in the Andreanof group. The survey area lies between longitudes 175° W and 180° W and between latitudes 49° N and 53° N (Figure 1).

The density of coverage usually required for a magnetic analysis of crustal structure could not be obtained in the time available. However, the track lines include several crossings of the trench and ridge. While the data are not extensive enough for a precise analysis or quantitative results, they are of interest because they apply to an island arc system.

It is the purpose of this paper to present the magnetic data collected in the Aleutian arc in the vicinity of the Andreanof Islands and to make qualitative comments on the implied geology when possible. A brief discussion of island arcs is included and related where

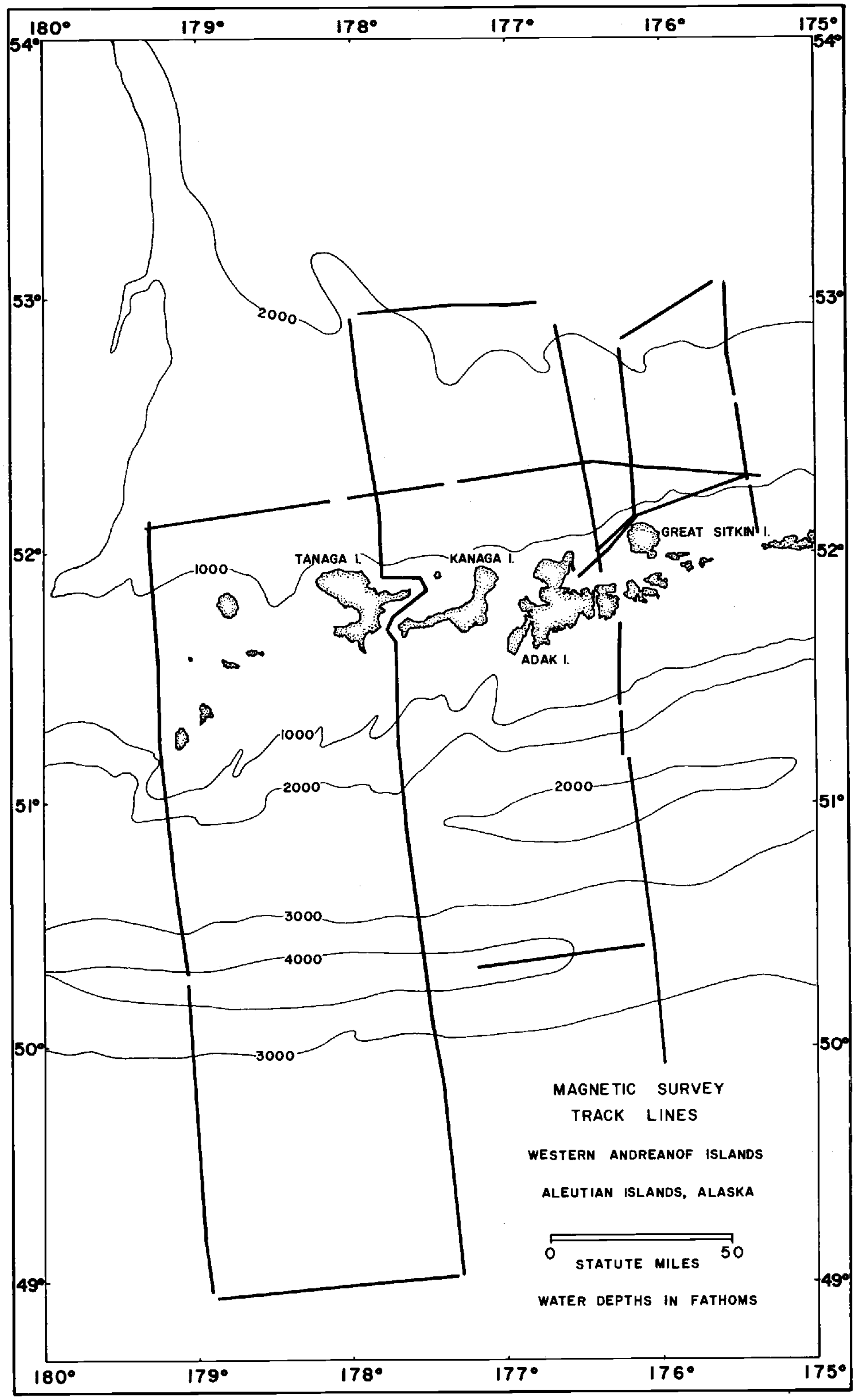

Figure 1. Survey area map showing ship track lines.

possible to the Aleutian arc.

Equipment and Field Technique

The data were recorded with a proton precession magnetometer patterned after the Packard-Varian model (Warren and Vacquier, 1961). The operation of the magnetometer depends upon the behavior of protons in a magnetic field. Hydrogen nuclei in a water sample provide a source of protons. In practice the sample of water is subjected to a polarizing field of about 400 gauss for a few seconds, causing about 10^{-7} of the protons in the sample to become aligned along the field. When the polarizing field is shut off, the sample remains in the earth's ambient field, and the aligned protons precess about this latter field in the manner of a symmetrical top in a gravity field. The frequency of precession is proportional to the intensity of the ambient field and is

$$f = \frac{\gamma H}{2\pi}$$

where H = field intensity and γ is the gyromagnetic ratio of the proton, which has been precisely determined by laboratory experiments.

The precessing protons induce an alternating emf in a coil surrounding the water sample. The emf is amplified and its frequency is measured. With the known relationship and the measured signal frequency, the intensity of the local field is found by solving the expression for H. As the signal is at a maximum when the applied field and pick-up coils are at right angles to the earth's field, a pair of perpendicular coils is connected in series to give adequate sensitivity regardless of orientation. The proton magnetometer requires no calibration and is independent of all environmental and instrumental influences.

The samples and coils are contained in a "fish" which is towed 250 feet astern of the vessel. The signal induced in the coils results in shipboard output of a number equal to one-fifth the local field in gammas (gamma = 10^{-5} oersted). This number is analog recorded as a continuous trace on a magnetogram and displayed visually on a counter from which the value is periodically noted on the magnetogram to facilitate digitizing the analog record.

Data Reduction

In order to reduce the measured total intensity data to an anomaly field, the regional gradient must be removed. There are several techniques for accomplishing this task. In this case the gradient of the geomagnetic field, as presented on charts of the U. S. Naval Oceanographic Office, was plotted across the area under investigation. Linearity was assumed between 100 gamma isodynamics, and the resulting profiles were plotted along the ship track lines. The regional gradient was corrected for annual variation (the charts employed were 1955 issue) and then removed through point-by-point subtraction from profiles of the raw data.

No attempt was made to correct the data for diurnal variations. Indeed, track line crossings are too few to permit assessment of such variations. The magnetic observatory at Sitka, Alaska, recorded diurnal variations of approximately 50 gammas during the summer months of 1963 (USCGS, 1965). Assuming that this range provides a fair measure of the diurnal change in the survey area, it is felt that such a variation did not cause appreciable errors in the gradients recorded along track lines covering about 200 miles in a day. Furthermore, absolute values are not of crucial importance here as the data are such that only qualitative conclusions are possible.

As can be seen from the profiles (Figure 7) of anomalous magnetic intensity and bathymetry, a general gradient of the magnetic field remains which roughly follows the bottom topography. This would not occur if the regional field removed were constructed artificially by averaging the measured total intensity over areas large with respect to an anomaly but small with respect to the transverse dimensions of the arc. The quantity of data was judged insufficient for such an averaging technique to be meaningfully performed.

Navigational control was by Loran A and radar. Limits of accuracy of fixes range from about one-fourth mile near the islands where radar was used to about two miles at the greatest distances from land.

Island Arc Structure

A brief outline of the principal ideas of island arc structure as summarized by Fisher and Hess (1963) is as follows:

Vening Meinesz proposed elastic downbuckle of oceanic crust to account for large negative isostatic gravity anomalies found just shoreward of the axes of ocean trenches. This structure was demonstrated in model studies by Kuenen and called "tectogene" by him. Later, Vening Meinesz modified his theory and postulated plastic, rather than elastic, downbuckle for consistency with considerations of the properties of crustal materials.

Benioff, from studies of circum-Pacific earthquakes, proposed that great reverse faults or fracture zones dip shoreward along island arcs. The ocean trench and uplifted shoreward block are considered to be surface expressions of reverse motions along the faults or fracture zones.

Hodgson opposes a thrust fault explanation of deep focus earthquakes associated with island arcs. From analysis of specific examples of deep focus earthquakes originating beneath island arcs, he finds that the plane of motion is nearly vertical and that the displacement is of a strike-slip nature. His solutions give two possible planes of motion, one essentially parallel to the trend of the arc and the other essentially perpendicular to it; Hodgson considers the parallel solutions to be the more likely.

McIntyre and Christie analyzed Hodgson's data from the Tonga-Kermadec arc and suggest that the parallel solutions are to be preferred.

Hess and Maxwell had previously suggested strike-slip faults in the Tonga-Kermadec area perpendicular to the trend of the trench and still hold to this view.

M. Ewing, Worzel, Shurbet, Heezen, Talwani, and others from Lamont Geological Observatory suggest that trenches are tensional features and consider the crust to have been pulled apart with subcrustal material flowing upward into the fissure formed.

The Aleutian Arc

The Aleutian chain extends westward from the Alaska peninsula about 1200 miles. Structurally, the arc is even longer and stretches from the Alaska range to the Kamchatka peninsula. The four island groups which comprise the Aleutian chain -- the Fox, Andreanof, Rat, and Near Islands -- all lie between latitudes 52° N and 55° N and between longitudes 172° E and 163° W, thus forming the northern boundary of the Pacific Ocean and separating that body of water from the Bering Sea.

The Aleutian Trench lies south of the ridge and on the convex side of the arc, as is typical of island arc and trench systems. The Aleutian arc is also typical in that the slope of the ocean side of the trench is gentle, with steeper slopes landward up to the ridge. Among the trenches of the world, the AleutianTrench is listed sixteenth in order of depth (Fisher and Hess, 1963) with an uncorrected maximum depth of about 4200 fathoms. The islands, composed primarily of Tertiary volcanics and volcanogenic sediments where exposed, have generally rugged relief. In the survey area, Mt. Moffet on Adak Island rises to an elevation of 3876 feet (Coats, 1956) and Great Sitkin volcano on Great Sitkin Island reaches a height of 5740 feet (Simons and Mathewson, 1955).

Gates and Gibson (1956) define the following four geologic provinces based on bathymetry:

1. The crest of the ridge, including islands, insular shelf to 70 fathoms, and ridge shelf to 100-150 fathoms.
2. Insular slope forming the sides of the ridge. The long, steep north slope is considered a linear scarp probably marking a major crustal fracture, while the south insular slope is considered a broad, faulted and warped arch.
3. The Aleutian bench, which is suggested by a prominent

step in the slope from the ridge to the trench.

4. The arcuate Aleutian Trench with steep north side and flat floor at 4000 fathoms.

The Aleutian arc is part of the seismically active circum-Pacific belt with earthquake distribution typical for island arcs, the foci being progressively deeper landward from the trench. Shallow shocks occur beneath the trench and just shoreward of the axis, while intermediate focal depths of 100 km are found beneath the line of active volcanoes which form the north sides of many of the islands. Still deeper shocks originate north of the chain, but earthquakes defined as "deep" (focal depth equal to or greater than 300 km) are not known from the Aleutian arc.

Petrographic data are available for some of the Andreanof Islands, and they reflect the volcanic nature of the rocks. On southern Adak and adjacent Kagalaska the most abundant rocks are the Finger Bay volcanics, which consist of an altered andesitic and basaltic sequence of marine pyroclastic deposits and lava flows with minor argillite and graywacke beds. This sequence is intruded by composite granodiorite, quartz-diorite, and diorite and gabbro plutons of probable Tertiary age. Aphanitic and generally altered dikes and sills are present (Fraser and Synder, 1959). Three basaltic volcanic cones of Tertiary or Quaternary age lie at the extreme northern end of Adak Island. Slightly to the south are five domes of andesite porphyry, apparently unrelated to the basaltic cones (Coats, 1956).

Coats (1956) assigns an age of late Paleozoic (?) to the Finger Bay volcanics in the northern part of Adak Island. This date was determined by assuming a correlation with a volcanic sandstone unit found on the northwest side of Adak which contains leaf fossils of Pennsylvanian or Permian age. Fraser and Snyder (1959) prefer correlating the Finger Bay volcanics, which they consider to be marine, with a volcanic and sedimentary sequence on Kanaga Island which contains Miocene fossils. Relationships among the formations are uncertain.

The exposed portion of Great Sitkin Island is composed of basaltic and andesitic pyroclastics and flows. The three principal sequences are the Finger Bay volcanics, the Sand Bay volcanics, and the Great Sitkin volcanics, all of roughly the same composition but progressively younger (Simons and Mathewson, 1955).

The Aleutian Islands represent a very small portion of the ridge and offer little evidence of the tectonic forces that have shaped the arc. Most faults known in the Aleutian arc have been inferred from topographic evidence, and even where they are mapped the direction of motion is generally conjectural. The existing evidence suggests that faults trending parallel to the arc are few (Coats, 1962).

Interpretations of the Aleutian Arc

Gates and Gibson (1956) interpret the Aleutian ridge as a southward-advancing wedge bounded on the north by a normal fault zone dipping steeply north and on the south by a thrust zone dipping more gently north from the bottom of the trench. The crest of the ridge is considered to be an erosion surface with the exception of the stratovolcanoes. They suggest that the wedge probably began to form in middle Tertiary.

Coats (1962) presents an interpretation of the arc (Figure 2) in conjunction with his explanation of andesite in an area where no sialic crust is available. The initial stage is the development of a thrust zone with volcanoes building the arc from the sea floor. The upper plate rides over and depresses the footwall resulting in a trench which traps sediment. Later the center of volcanic activity shifts away from the trench. Sedimentary and igneous debris carried down the thrust is buried to a depth where it is added to eruptible basaltic magma. The sialic magma thus formed results in the observed volcanic rocks at the surface.

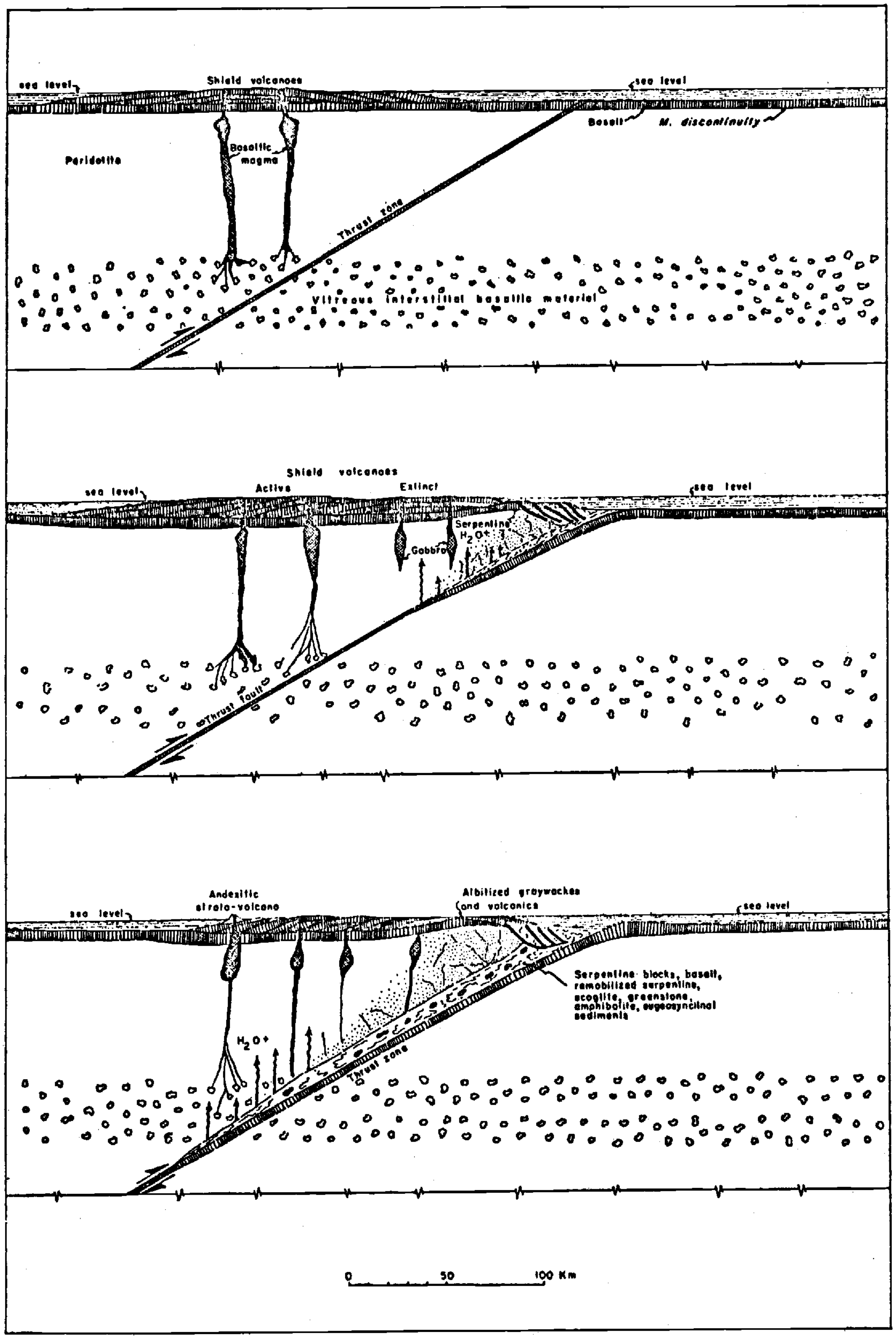

Figure 2. Time-sequential development of an island arc. (After Coats, 1962)

RELATED GEOPHYSICAL STUDIES

Work in the Aleutian Area

In 1947 aeromagnetic surveys were made of Adak and Great Sitkin Islands and eight widely spaced profiles were flown across the trench as part of a larger survey called Project Volcano (Keller, Meuschke, and Alldredge, 1954). Anomalies over the islands are thought to reflect primarily the topography with no correlation to individual volcanic centers. The profiles over the trench (Figure 3) were made by point-by-point subtraction of the earth's field from measured total intensity. The authors conclude that the anomalies in the trench do not correlate with any known topographic or geologic features and suggest that they must result from susceptibility contrasts.

The aeromagnetic maps of Adak Island were employed for calculations of depth to basement (Vacquier, *et al.*, 1951). The analyses yield depths to basement which average to the flight elevation, although there are differences among the individual values. Since the depth to basement is the flight elevation, the magnetic effects originate at the surface, indicative of the magnetic nature of the surface rocks.

Seismic refraction studies were made in the Aleutian area in 1956-57 (Shor, 1962). These studies give depths to the mantle of 13

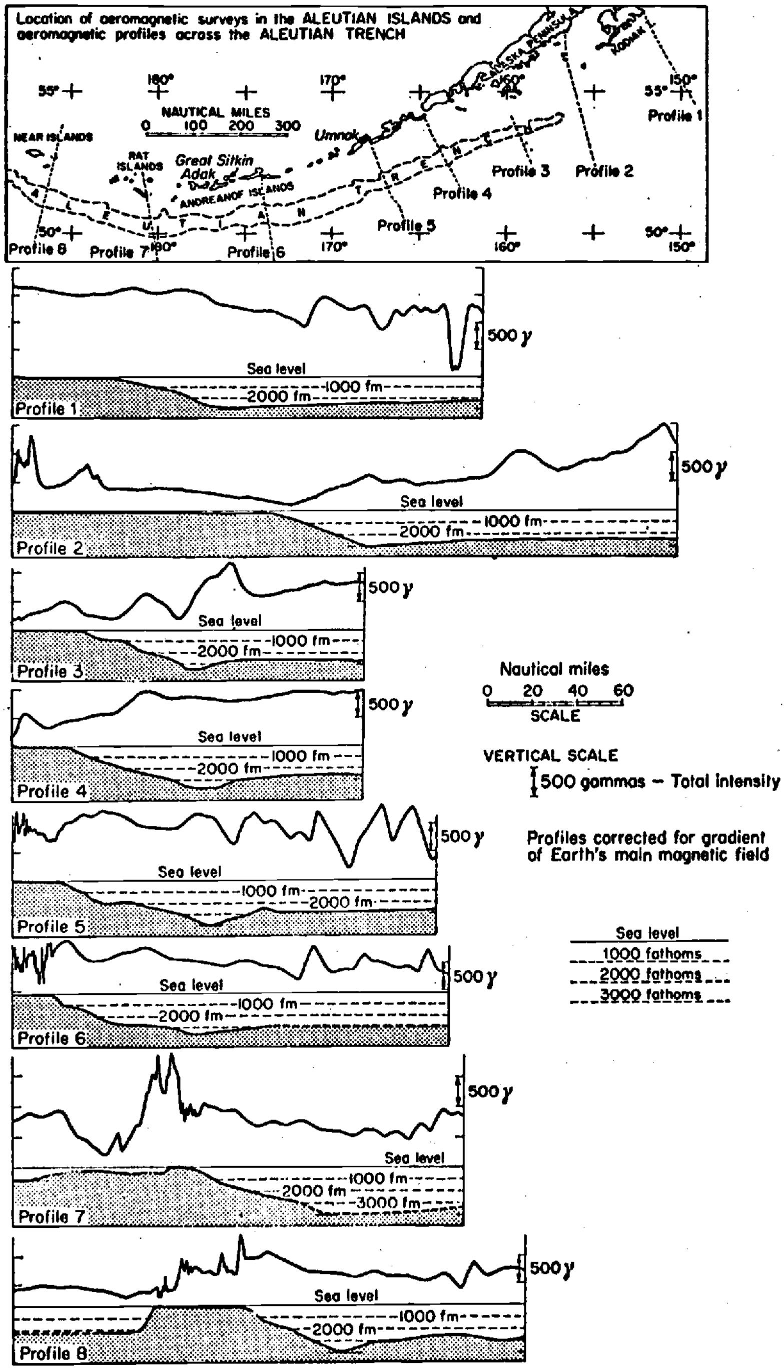

Figure 3. Magnetic and bathymetric profiles across the Aleutian Trench. (After Keller, Meuschke, and Alldredge, 1954)

to 14 km under the trench and the Aleutian basin north of the ridge. In each case the maximum compressional wave velocity recorded was about 7.6 km/sec, somewhat lower than normal mantle velocities. The mantle was not reached beneath the ridge, but this was perhaps due partially to the short refraction line. If the Mohorovicic discontinuity were at a depth of 24 km with the normal compressional wave velocity in the mantle below that depth, waves refracted into the mantle could not have been received with the shot and recorder separation employed.

Results of further refraction shooting in 1961 (Shor, 1964) give normal mantle velocities in the Aleutian basin (7.8 to 8.3 km/sec) and indicate a dip in the Mohorovicic discontinuity that accounts for the low velocity seen in the previous study. The data again suggest greater mantle depths beneath the ridge than beneath the trench or the basin. One station on the north edge of the ridge gives a mantle depth of 22 km.

Heat flow data were also obtained which indicate that heat flow is in the normal range between the Aleutian ridge and the Pribilof Islands. Measured values are from 0.9 to 1.3 $\mu cal/cm^2$ sec.

Fault plane solutions, made mostly by Hodgson, for Aleutian earthquakes were compiled by Coats (1962). Due to the ambiguity of direction of first motion of P waves, each solution gives rise to two orthogonal planes which were presented as separate groups, one roughly parallel to the trend of the arc and one roughly perpendicular to it. The parallel solutions show a slight predominance of dextral motions while the transverse solutions naturally show a similar predominance of sinistral motions, although both types of motions occur in each group.

Geophysical investigations performed in the western Andreanof Islands area on the Yaloc-66 cruise include measurement of gravity with a LaCoste-Romberg ship-borne gravity meter. The gravity data show free air anomalies of about -175 mgal just shoreward of the trench axis and about +150 mgal centered over the ridge. Preliminary analysis of the data suggests one model which accounts for the gravity anomalies that includes structure dipping gently north beneath the ridge (Couch, 1967).

Recent magnetic work in the Aleutian area includes a survey of the area from latitudes 45° N to 55° N and longitudes 156° W to 164° W (Elvers, Peter, and Moses, 1967). Contour maps were made for an area 1100 km long and 600 km wide. The maps show that the anomaly lineations, which trend NNW-SSE in this part of the Pacific, turn westward and continue in a nearly east-west direction (for magnetic lineations in the eastern Pacific, see Mason and Raff, 1961). Preliminary analysis suggests that the lineations terminate near the axis of the trench and nowhere correlate with the bathymetry.

Other Related Work

Heirtzler and Hayes (1967) present evidence for a magnetic boundary on each side of the Atlantic basin lying 2000 to 2500 km from the axis of the Mid-Atlantic ridge and roughly equidistant from it. The boundary separates a magnetically disturbed area toward the center of the basin from a relatively undisturbed area along the continent. The authors suggest that, under the assumption of sea-floor spreading, the undisturbed region could represent the long period of no magnetic reversals in late Permian.

In view of the uncertainties involved, any relationship of the magnetic boundaries in the Atlantic to the termination of magnetic lineations at the Aleutian Trench is questionable.

Two magnetic profiles, approximately 350 km in length, over the Tonga Trench were obtained as part of a more general geophysical survey (Raitt, Fisher, and Mason, 1955) (Figure 4). Depths to basement were estimated by the magnetic anomaly half-width technique, although the authors comment that this method generally overestimates. Results indicate that the inferred basement shown in Figure 4 is overlain by as much as two km of sediment. Seismic refraction data indicates a mantle depth of 20 km below sea level with a normal mantle velocity.

Comparison of observed and computed magnetic profiles shows

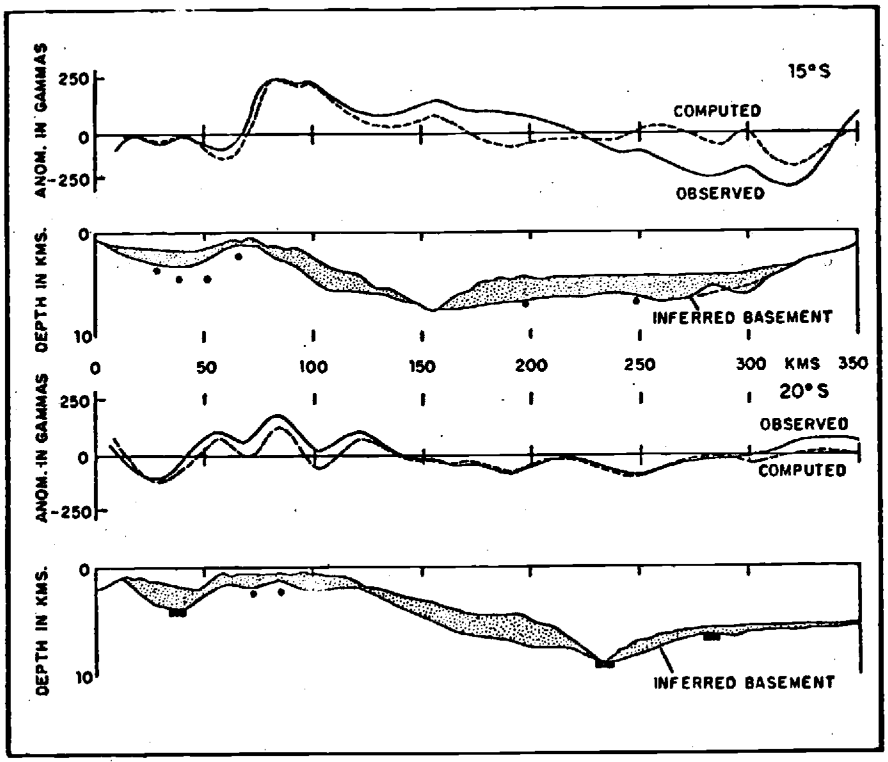

Figure 4. Magnetic and bathymetric profiles across the Tonga Trench with inferred basement. (After Raitt, Fisher, and Mason, 1955)

an excess of magnetism on the west side of the trench and a deficiency on the east side not easily accounted for by any reasonable basement configuration. The authors suggest as possible explanations:

1. a gradual variation in magnetic susceptibility;
2. changes in the levels of the various interfaces indicated by the seismic data;
3. a downwarp of the Curie temperature isotherm toward the ridge.

RESULTS OF THE SURVEY

Contour Maps

The total field and magnetic anomaly values obtained along the track lines have been used to construct rough contour maps of the area. The anomaly contour map (Figure 5) shows that south of the Aleutian ridge a pattern of linear features parallel to the trend of the arc is evident. The east-west trend of the contours is much less evident north of the islands, which suggests that the ridge is the boundary between two distinct magnetic provinces. The east-west trend is based upon correlation of values across three widely spaced lines of data and detailed features existing between the lines could have been overlooked.

As is indicated by the east-west trend of the contours, the data show that relatively steep north-south variations in magnetic intensity occur south of the ridge while east-west gradients are small. The anomalies on the south slope of the ridge which were crossed by only one line have been contoured to be consistent with this picture of the gradients. Without additional data the shape of the anomalies is conjectural, and it may be significant that where data exist between the profile lines, east-west gradients are introduced.

The total field map (Figure 6) and the anomaly map have a rather similar general appearance. Removal of the earth's field

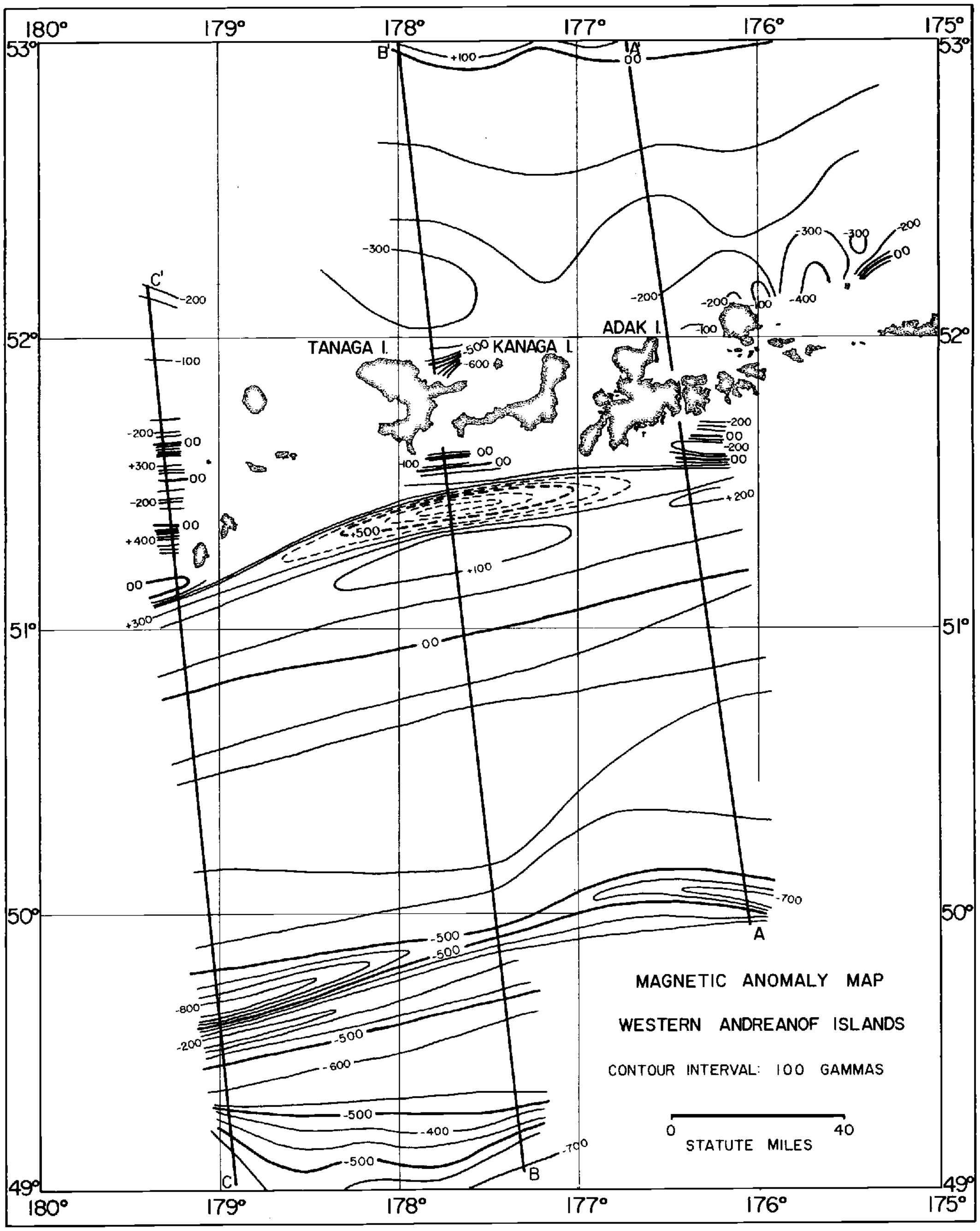

Figure 5. Magnetic anomaly contour map.

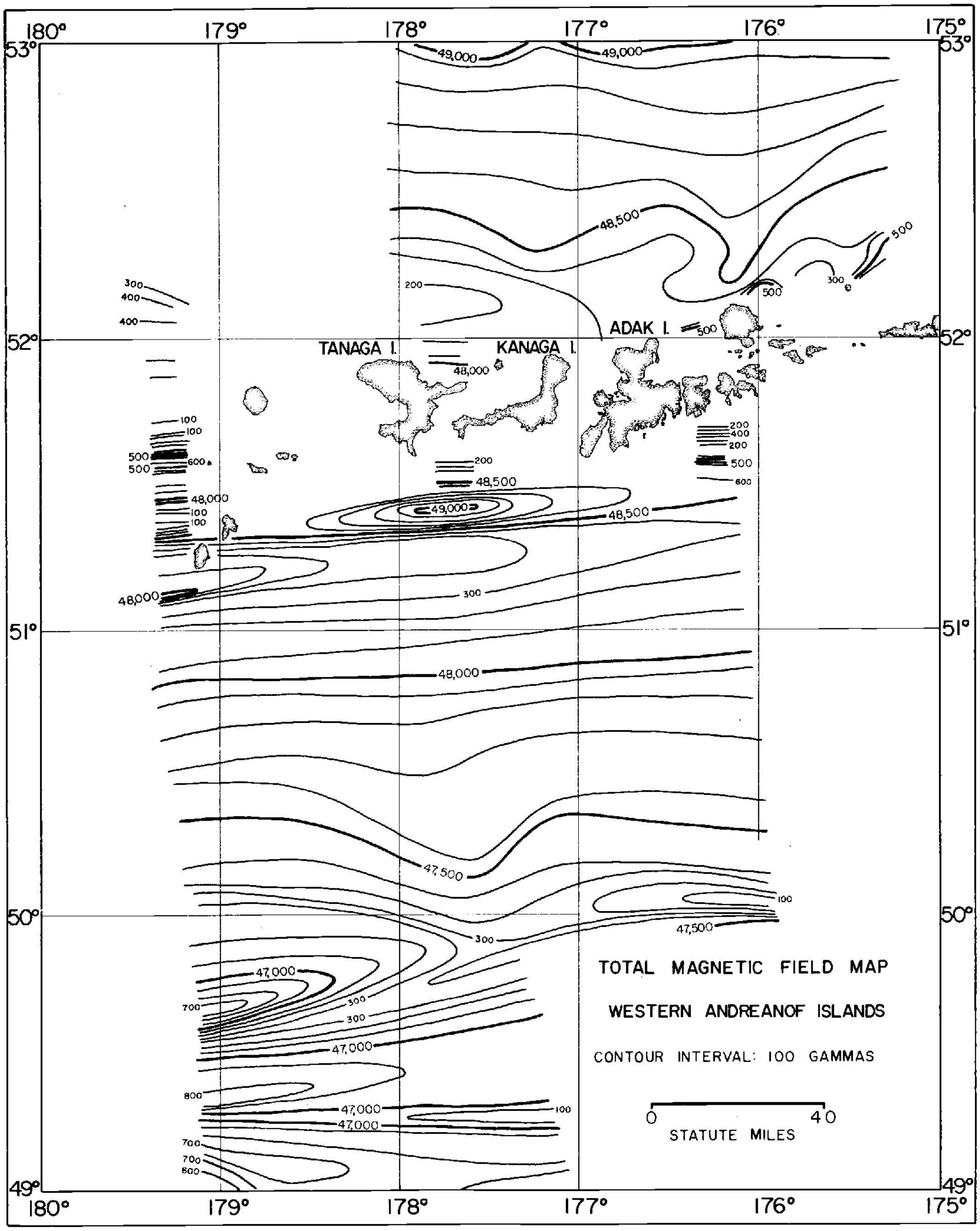

Figure 6. Total magnetic field contour map.

lessened, but did not eliminate, the presence of a north-south gradient across the trench and shifted slightly the direction of the contour trend. The shift causes the anomaly contour trend to lie more nearly parallel to the trend of the arc.

According to Heirtzler (1965), many, if not most, ocean areas have great linear magnetic anomalies which parallel coastlines and major structural features such as island arcs. The Aleutian data are in excellent agreement with this general picture.

In the passes over the spine of the ridge along profiles AA' and BB' the anomaly frequency is too high for inclusion in the regional map. Values are given for the intensities on the ridge along profile CC', but no attempt was made to contour the data, as high density coverage is required to adequately define the rapid variations.

Anomalies South of the Trench

The pair of anomalies at the southern end of profiles BB' and CC' (Figure 7) show a similarity which suggests that they arise from continuous features. The northernmost of the two is probably also responsible for the anomaly at the southern extremity of profile AA'. Profile 6 (Figure 3) from the work of Keller, Meuschke, and Alldredge (1954) includes a pair of anomalies south of the trench which shows a striking similarity to the pair found in this survey. This latter profile lies at about 173° W longitude, so that if these profiles have all

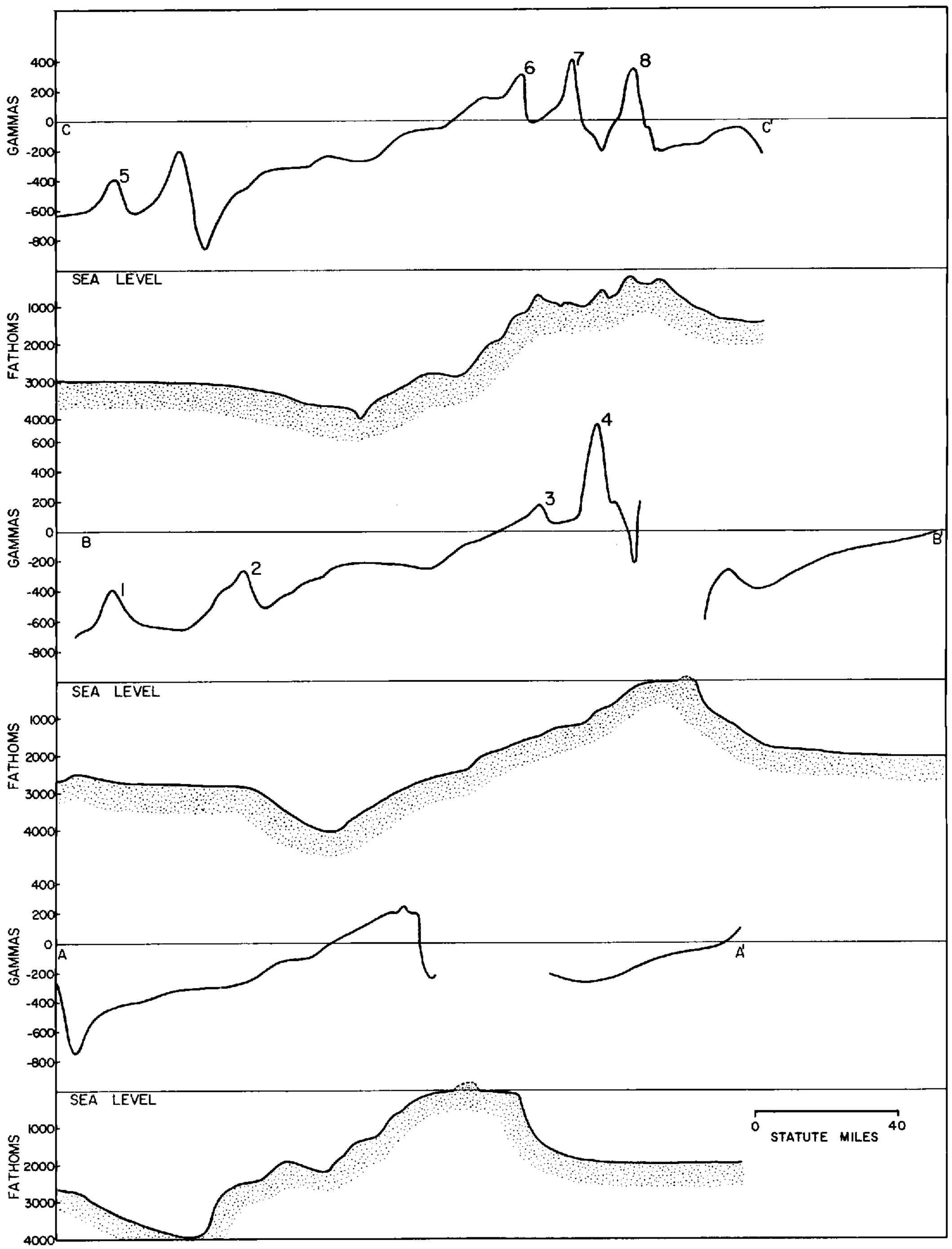

Figure 7. Magnetic and bathymetric profiles of the Aleutian arc.

crossed the same feature, then the implied linear anomaly must have a length of nearly 500 miles. Such length, along with the observed amplitudes of several hundred gammas, makes the feature comparable to the magnetic lineations found elsewhere in the North Pacific.

The findings of Elvers, Peter, and Moses (1967), in a survey east of the region under discussion, that the magnetic lineations of the sea floor change direction from N-S to E-W and die out on the south lip of the trench, strongly suggest that the anomaly pair observed is an expression of the sea floor magnetic lineations.

Estimations of depth to basement were made for these anomalies with the width from peak to half-maximum method and assuming line pole sources and isolated anomalies (Henderson and Zietz, 1948). The features appear to satisfy these conditions, with the exception of the more northern anomaly in profile CC' for which a depth estimate was not made. Accuracy in this technique requires that the shape and orientation of the anomaly be known, since the peak to half-maximum width is measured perpendicular to the long dimension of the anomaly and the angle between the long dimension and magnetic north enters the calculations. This requirement is met by assuming the anomalies are parallel to the trend of the arc, as appears to be the case. Errors may be introduced into the estimations by this assumption since the exact orientation of the anomalies cannot be known without more extensive data.

In profile BB', depth to source for anomaly 1 yields 19,400 feet in a water depth of about 17,000 feet. Anomaly 2 gives a slightly shallower depth of 17,500 feet in a water depth of 17,000 feet. Anomaly 5 of profile CC' gives a depth of 17,900 feet, also in 17,000 feet of water. These depths are estimates only and must be considered approximate. Raitt, Fisher, and Mason (1955) have commented that the anomaly half-width technique of source-depth estimation generally overestimates. In spite of the uncertainties, the estimated depths can probably be taken as a fairly reliable indication of a shallow source for the magnetic anomalies, perhaps in the upper 1000 feet of the sub-oceanic crust or even shallower.

Another value for source depth can be obtained by the Peters (1949) technique based on anomaly slope. Applying this method to anomaly 5 of profile CC' gives a depth to source of 13,000 feet. The water depth here is 17,000 feet, so the value is obviously incorrect as it is less than the distance to the ocean floor. While the estimate is clearly wrong, it is again perhaps an indication of a shallow source.

The qualitative result of these estimations is that the magnetic anomalies have shallow sources. This implies that the geologic structure responsible for the anomalies lies very near the surface of the oceanic crust, perhaps even at the surface. A shallow depth to source is typical of ocean floor magnetic lineations (Mason and Raff, 1961). Thus, this determination, although it must be taken as only approximate, strengthens the case for interpreting the anomaly pair as an expression of magnetic lineations.

Large Anomalies North of the Trench

Profiles BB' and CC' show the presence of relatively large anomalies north of the trench for which estimates of depth to source were made. Again line pole sources and isolated anomalies were assumed in the application of the Henderson-Zietz method. Anomalies 3 and 4 of profile BB' each give depths of 14,900 feet, occuring in water depths of 8,500 feet and 5000 feet respectively. The assumptions involved are open to question and the results are very rough, but the depths indicate that the anomalies probably arise from deep seated sources. Applying the Peters slope method to anomaly 4 produces a depth of 13,000 feet, which agrees with the previous estimate in suggesting a deep source.

The anomaly width to half-maximum method applied to anomalies 6, 7, and 8 of profile CC' gives depths of 9000 feet, 12,000 feet, and 14,500 feet respectively, in water depths of 2000 feet, 5000 feet, and 1500 feet respectively. Here also the suggestion is that the sources are relatively deep.

For each of these anomalies there is but a single crossing for control. The shape of the anomalies is therefore not known and the assumption of line sources parallel to the arc trend must be suspect.

No attempt was made to contour the anomalies on profile CC', but the anomalies on profile BB' are shown as having much greater east-west extent than north-south. The apparent correlation of contours across all three profiles suggests small east-west gradients on the south slope of the ridge and the anomalies were contoured to be consistent with this picture. However, it is possible that the anomalies introduce local east-west gradients and are not elongate but broadly oval or even round. Even if the assumptions are wrong, the qualitative result that the anomalies reflect sources that are deep rather than shallow is probably still valid.

If a depth to source of 15,000 feet is assumed correct for anomaly 4 of profile BB', a check on the assumptions can be made by calculating a theoretical anomaly for a vertical dike extending to great depth. This structure frequently produces an anomaly which can be considered due to a line pole source. The theoretical anomaly is calculated with Nettleton's formula (Dobrin, 1960) for a vertical dike,

$$V = 2 \cdot 10^5 \, k \, H \, t \left[\frac{1}{Z_1} - \frac{1}{Z_2} \right]$$

where V = vertical anomaly intensity, H = geomagnetic field strength = 0.5 oersted, k = magnetic susceptibility of dike, t = width of dike, Z_1 = depth to top of dike = 15,000 feet, Z_2 = depth to bottom of dike (here considered infinite). Remanent magnetization is ignored. A value for the susceptibility can be obtained from petrographic data on rocks of Adak Island (Fraser and Snyder, 1959) and Slichter's method (Dobrin, 1960) of computing susceptibility as the product of the volume percentage of magnetite in the rock and the susceptibility of magnetite (taken to be 0.3 cgs). Susceptibilities thus computed for a diorite pluton and an intrusive gabbro sill, each sampled at Bay of Waterfalls, Adak Island, are .003 cgs and .021 cgs respectively. The latter value is unusually high as a result of the abundant magnetite in the gabbro. Occasional small chips could be picked up with a magnet (Fraser and Snyder, 1959). Using the susceptibility contrast of the Adak rocks, .018 cgs, in Nettleton's formula with an assumed dike width of 6000 feet gives an anomaly of 700 gammas, in good agreement with the observed anomaly of 600 gammas.

Many geologic configurations could be devised to account for the observed anomalies. It appears likely that they arise from deep seated structures, probably 5000 to 10,000 feet beneath the ocean floor.

Kanaga Pass Profile

The character of the magnetics over the crest of the ridge is shown in the plot of magnetic intensity and bathymetry as a function of time along the Kanaga Pass track in Figure 8. Corresponding geographic positions can be obtained from Figure 9, in which the track line is plotted as a function of time. Anomalies will be referred to by the time to which they correspond. Since the profile includes numerous changes of speed and course, the horizontal distance scale is not constant.

The anomaly spacing over the crest of the ridge is too dense for inclusion in the small scale profiles, and several frequencies are evident. On the north side of the ridge crest the anomalies appear to be generally about one mile in length, although obvious overlap of adjacent features makes a general statement questionable. On the south side of the crest of the ridge anomalies of one mile length are also present, but more obvious are steeper peaks .25 to .5 miles in length. A larger anomaly is present at 1940 with smaller features superimposed. Perhaps the most curious portion of the profile is the relatively undisturbed section in the center of the ridge.

The aeromagnetic profiles of Keller, Meuschke and Alldredge (1954) (Figure 3) also show high frequency anomalies over the crest of the ridge, especially profiles 5 and 6 from a flight elevation of 500 feet. The Kanaga Pass profile (Figure 8) indicates that correlation of magnetic features with individual topographic peaks is generally poor. Furthermore, the bottom topography is almost uniformly smooth over the center and southern edge of the ridge,

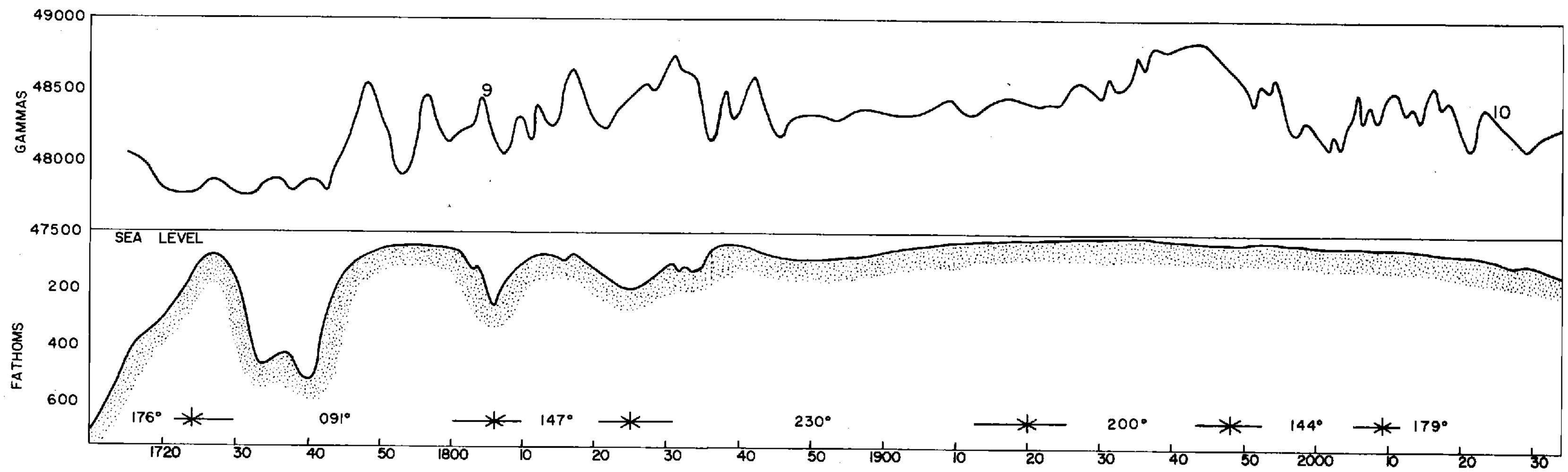

Figure 8. Magnetic and bathymetric profile of Kanaga Pass. Horizontal scale is local time. Course heading between arrows is ship direction for the corresponding time interval.

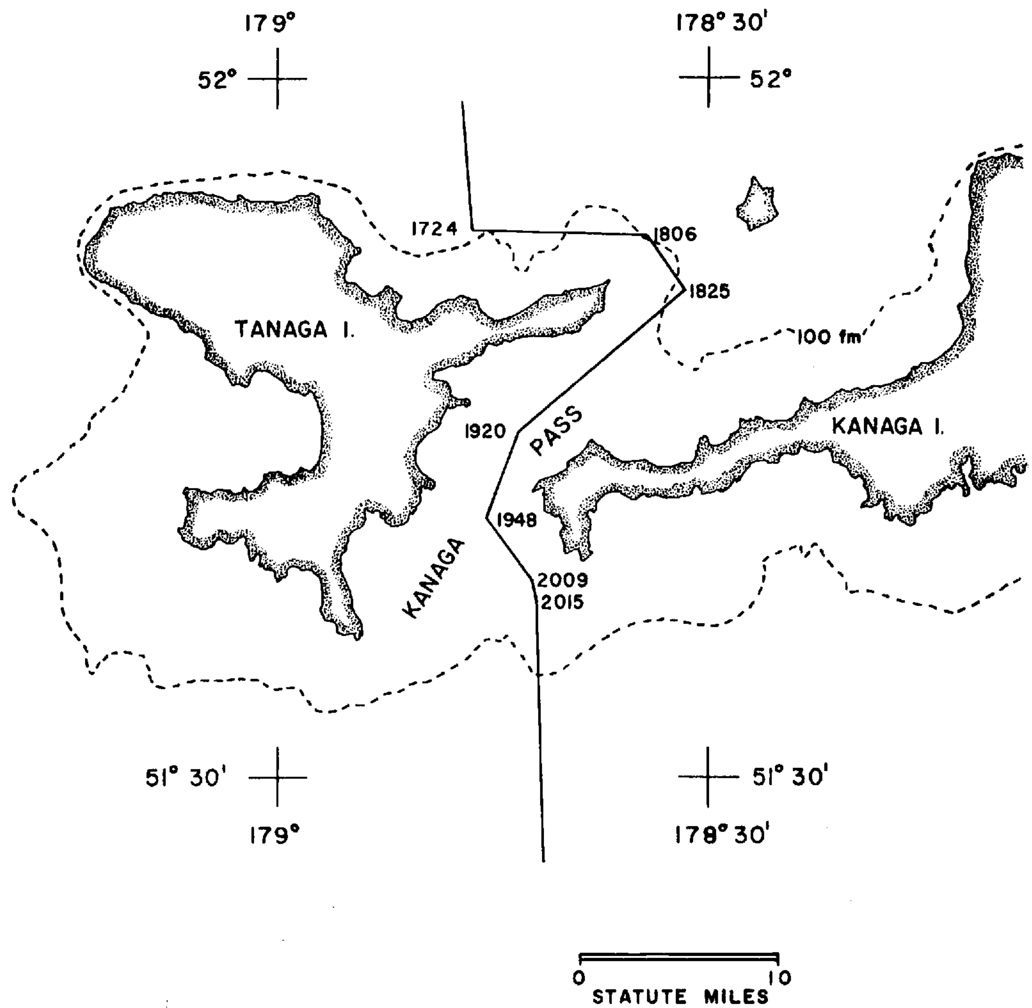

Figure 9. Kanaga Pass showing ship track with local time noted at corners.

although the character of the magnetics changes from "calm" to "noisy."

There are a few instances on the north side of the crest where anomalies appear to correlate with bottom topography, although a causal relationship is not necessarily implied. The sudden increase in magnetic intensity at 1742 coincides with the rapid shoaling of the bottom; however, the magnetic record describes a peak rather than a general increase in intensity. The anomalies at 1804 and 1831 coincide with minor topographic peaks.

Estimating the depth to basement for anomaly 9 at 1804 by the Henderson and Zietz (1948) method, based on the anomaly width from peak to half-maximum with the assumption of a line-pole source, gives a depth of 775 feet. Accuracy in this method of estimation requires an elongate, isolated anomaly of known trend. Since these conditions are not known to be satisfied, the depth must be considered approximate. Nonetheless, with the water depth of 720 feet, the depth estimation can probably be taken as a reliable indication of a shallow source. The topographic peak at 1804 is not large enough for the magnetic anomaly to be a terrain effect, but perhaps the peak is the surface expression of an intrusive structure which also causes the magnetic anomaly.

The anomaly half-width technique will predict deeper sources for broader anomalies. For example, anomaly 10 at 2023 occurring over smooth topography on the south edge of the crest yields a depth to source of 1200 feet in 600 feet of water. The assumption of a line source was again made. If the depth estimation is accepted, then the structure responsible for the anomaly has either been buried by sediment and volcanic material to a depth of 600 feet or else never reached the surface.

A possible explanation for the relatively flat magnetic record from 1845 to 1925 can be derived from the fact that it occurs along a course of 230 degrees, the portion of the track most closely aligned to the trend of the ridge. If the magnetic anomalies on the ridge crest arise from geologic structures which result in line sources parallel to the trend of the ridge (for example, dikes), then a profile sub-parallel to this trend would give sharply reduced anomaly frequency. The apparently reduced amplitude of the peaks is not accounted for by this explanation, but amplitudes are sufficiently varied along the profile that the reduction is perhaps not real. It can be seen that magnetic peaks occur in the first ten minutes of this leg, but it must be remembered that a ship requires some room to turn. Thus, the first minutes of the leg do not lie along the plotted azimuth.

The magnetic record indicates that the high frequency anomalies die out on the flanks of the crest, but a change in geologic structure is not necessarily implied. According to Bullard and Mason (1963), suboceanic magnetic anomalies are attenuated by the depth of sea water by a factor of

$$e^{\frac{-2\pi h}{\lambda}}$$

where h = depth of water and λ = anomaly wavelength. Thus if λ = 4h for a 200 gamma anomaly, a threefold increase in water depth would reduce the feature to less than 10 gammas. The disappearance of the high frequency anomalies can be interpreted as a result of the deepening water.

Local Magnetic Gradient

Each of the three profiles in Figure 7 shows that after removal of the earth's field a local gradient remains from south of the trench to the south edge of the ridge crest. A smooth average through the magnetic profiles shows that the traverses are remarkably similar in that they have an 800 gamma variation from a low of -600 gammas south of the trench to a high of +200 gammas at the crest of the ridge.

The bottom topography parallels the magnetic gradient in a general manner, reaching a high at the same place as the magnetic intensity. However it seems very unlikely that the observed gradient is a simple result of bottom topography. The effect of magnetic terrain can be estimated by considering the effect of an isolated magnetic pole at the ocean floor for various depths of water. A magnetic pole that would cause an 800 gamma anomaly in 100 fathoms of water would drop to 32 gammas in 500 fathoms of water, as the intensity varies inversely as the square of source and sensor separation. The observed gradient does not show this rapid drop-off on the upper slope of the ridge but rather appears to vary smoothly, and almost linearly, suggesting a deep effect. The gradient, moreover, shows no expression of the trench, in that it does not dip over this topographic low, and the expanded profile of the magnetics in the shallow water of Kanaga Pass (Figure 8) indicates generally poor correlation of magnetic intensity with bathymetry.

The local gradient found in the Tonga Trench by Raitt, Fisher, and Mason (1955) (Figure 4) was qualitatively very similar to that discovered in the Aleutian arc. The gradient measured over the Tonga Trench varied from a low seaward of the trench to a high over the ridge. The authors suggest three possible explanations:

1. a gradual increase in magnetic susceptibility from the trench to the ridge;
2. changes in the levels of the various interfaces indicated by seismic refraction;
3. downwarp of the Curie point isotherm beneath the ridge.

Of these three the authors consider the third to be consistent with the seismic refraction data.

Heirtzler and LePichon (1965), in their study of magnetic profiles over the Mid-Atlantic ridge, find evidence for a very long wavelength magnetic variation which they interpret as reflecting changes in the level of the Curie temperature isotherm.

Downwarp of the Curie temperature isotherm beneath the ridge could also be the explanation of the magnetic gradient found in the Aleutian arc. If true in general for island arcs, such a downwarp would certainly be an interesting addition to the geophysical phenomena associated with these crustal features. The feasibility of such a variation in the Curie temperature isotherm remains to be demonstrated and will probably be difficult to demonstrate.

If the Curie temperature isotherm dips from the trench to the ridge, one would not expect heat flow to be low in the trench. Presumably heat flow rates would vary inversely as the Curie point isotherm depth and hence would decrease from trench to ridge. The few heat flow measurements available from ocean trenches are not sufficient to establish a pattern for island arcs. The average of 16 measurements from Pacific trenches listed by Lee and Uyeda (1965) is 0.94 $\mu cal/cm^2$ sec. This somewhat lower than normal, but without additional data low heat flow in trenches cannot be considered an established fact. Twenty measurements in the trench off Sumatra averaged 1.23 $\mu cal/cm^2$ sec while 37 measurements outside the trench to seaward averaged 1.57 $\mu cal/cm^2$ sec (Lee and Uyeda, 1965). These data suggest the possibility of decreasing heat flow landward. Two values are listed from the Aleutian trench near 165° W longitude, a high of 2.7 μcal/cm^2 sec in the trench and a low of 0.4 μcal/cm^2 sec on the bench north of the trench. Again, decreasing heat flow landward from the trench is suggested, although two measurements are hardly conclusive. The available heat flow data do not compel acceptance or rejection of the possibility that the Curie temperature isotherm dips beneath island arcs. There simply is not enough information.

The magnetic profiles of Keller, Meuschke, and Alldredge (1954) (Figure 3) present a rather serious difficulty for the postulated dip of the Curie point isotherm. Profiles 6 and 7, lying just to the east and west respectively of the survey area described in this paper, show a similar trend of increasing magnetization from the trench to the south edge of the ridge. However, profiles 3 and 4, lying near longitudes 160° W and 165° W respectively, show reversed gradients with magnetic intensity decreasing toward the ridge. It appears very unlikely that these observations will be explained by a simple general statement. Trying to account for local magnetic gradients by postulating variations in Curie temperature isotherm depth can only be speculative.

Summary of Results

A review of estimated depths to source of magnetic anomalies is presented in Table I.

Table I. Depths to source and locations of magnetic anomalies.

Anomaly	Source Depth in Feet	Water Depth in Feet	Location
1	19,400	17,000	south of trench
2	17,500	17,000	south of trench
3	14,900	8,500	south slope of ridge
4	14,900	5,000	south slope of ridge
5	17,900	17,000	south of trench
6	9,000	2,000	south edge of ridge
7	12,000	5,000	crest of ridge
8	14,500	1,500	crest of ridge
9	775	720	crest of ridge
10	1,200	600	crest of ridge

The results of this survey may be summarized as follows:

1. The change in the character of the magnetics suggests that the ridge is the boundary of two distinct magnetic provinces, a magnetically "calm" region to the north and a more disturbed region to the south. These provinces are probably tectonic as well as magnetic.

2. Anomalies of great east-west extent and very shallow source south of the trench are very likely expressions of sea-floor magnetic lineations.

3. Large anomalies on the south slope and crest of the ridge appear to have a relatively deep source of strongly magnetic material.

4. High frequency anomalies found on the crest of the ridge suggest a direction-oriented source which could indicate extensive dikes.
5. A strong regional magnetic gradient is found across the arc with a variation of 800 gammas from a low south of the trench to a high on the south side of the ridge crest. This gradient seems to reflect a deep effect which could be related to the level of the Curie temperature isotherm.

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