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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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JUL 28 1970
DIV. MINES & GEOLOGY

INTERPRETATION OF AN AEROMAGNETIC SURVEY OF THE AMCHITKA ISLAND AREA, ALASKA

By

G. D. Bath, W. J. Carr, L. M. Gard, Jr.,
and W. D. Quinlivan

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ABSTRACT

An aeromagnetic survey of about 1,800 square miles flown over Amchitka Island and the adjacent insular shelf has provided information on Tertiary volcanic, intrusive, and sedimentary rocks, including identification of rocks that cause anomalies and the lateral extents, structures, and approximate depths of those rocks. Near proposed drill sites, anomalies were examined for features that might be related to faulting. The survey was facilitated by data on the magnetic properties for 347 rock specimens collected from surface exposures and 216 from drill core, and by plots of 25 miles of ground magnetic traverse. The data on magnetic properties furnished bases upon which anomalies were related to geologic features; ground surveys provided identification of near-surface rocks as either lava or breccia.

The total magnetization of volcanic breccia, tuff breccia, volcanic sandstone, and siltstone averages about $7.0X10^{-4}$ gauss with an effective direction generally along the earth's magnetic field. This value is designated as the ambient magnetization level for the area. The prominent anomalies come directly from lava flows and thick sills that have total magnetizations which differ from the ambient level for the island, and they come indirectly from large bodies of intrusive rock that have altered and destroyed the magnetite content of overlying flowrocks. The average for 219 surface and 81 core specimens of lava is $14.2X10^{-4}$ gauss induced intensity and $12.8X10^{-4}$ gauss remanent intensity. Lavas of the Chitka Point Formation have normal remanent polarities and produce positive anomalies. The basalt lavas of the Banjo Point Formation and the pillow lavas and breccias of Kirilof Point of the upper part of the Amchitka Formation, have both normal and intermediate polarities and produce positive and negative anomalies. Individual samples of breccia of the Banjo Point Formation and the lower part of the Amchitka Formation have significant values of remanent intensity, but directions vary so greatly from sample to sample that a thick section of breccia does not give a magnetic anomaly. Although dikes and small sills have total magnetizations well above the ambient level, their thicknesses are too small to give a significant effect at the datum plane 1,600 feet above sea level. The normal polarity of the White House Cove intrusive and the reversed polarity of the East Cape intrusive confirm that these intrusives are separate features emplaced at different geologic times.

Computation of the effects of sheetlike models shows that the steeper gradients of theoretical anomalies are positioned near the ends of flows or sills that have been terminated by faulting. Drill sites were selected in areas away from gradients considered to be fault related.

Nearly all prominent anomalies over land and many over water can be reasonably interpreted and can be correlated with known geologic features. Anomalies and geologic data suggest that the magma of the Chitka Point Formation originated in a large volcanic center on western Amchitka and eastern Rat Island. Faults that are well delineated by aeromagnetic contours on Amchitka do not appear to extend very far seaward, and marked submarine trenches that have the same general trend are not well defined magnetically.

INTRODUCTION

An aeromagnetic survey of Amchitka and Rat Islands and the adjacent insular shelf was made during December 1966 and January 1967 to gain information on the structure and subsurface distribution of Tertiary extrusive and intrusive rocks. An area of about 1,800 square miles was covered by the aeromagnetic survey, and the resulting data were supplemented by laboratory data on the magnetic properties of 347 rock specimens collected from surface exposures and of 216 from drill core, and by plots of 25 miles of ground magnetic traverse.

The main purpose of the study was to investigate anomalies found near proposed drill sites (fig. 1), with particular emphasis placed on recognizing features that might be related to faulting and on detecting large intrusive bodies at depth. Major faults may control the initial deposition or emplacement of magnetized rock or may displace rock boundaries and their associated magnetic anomalies. Anomalies in random pattern seldom indicate structure, but those that have dominant or drawn-out trends or abrupt terminations suggest a relation to faulting.

To identify near-surface rock sources, positions of anomalies were compared with geologic units as mapped by Carr and Quinlivan (1969), and the magnetic properties of surface and drill-core rock samples were investigated to determine whether the geologic units possess magnetic properties that could cause anomalies.

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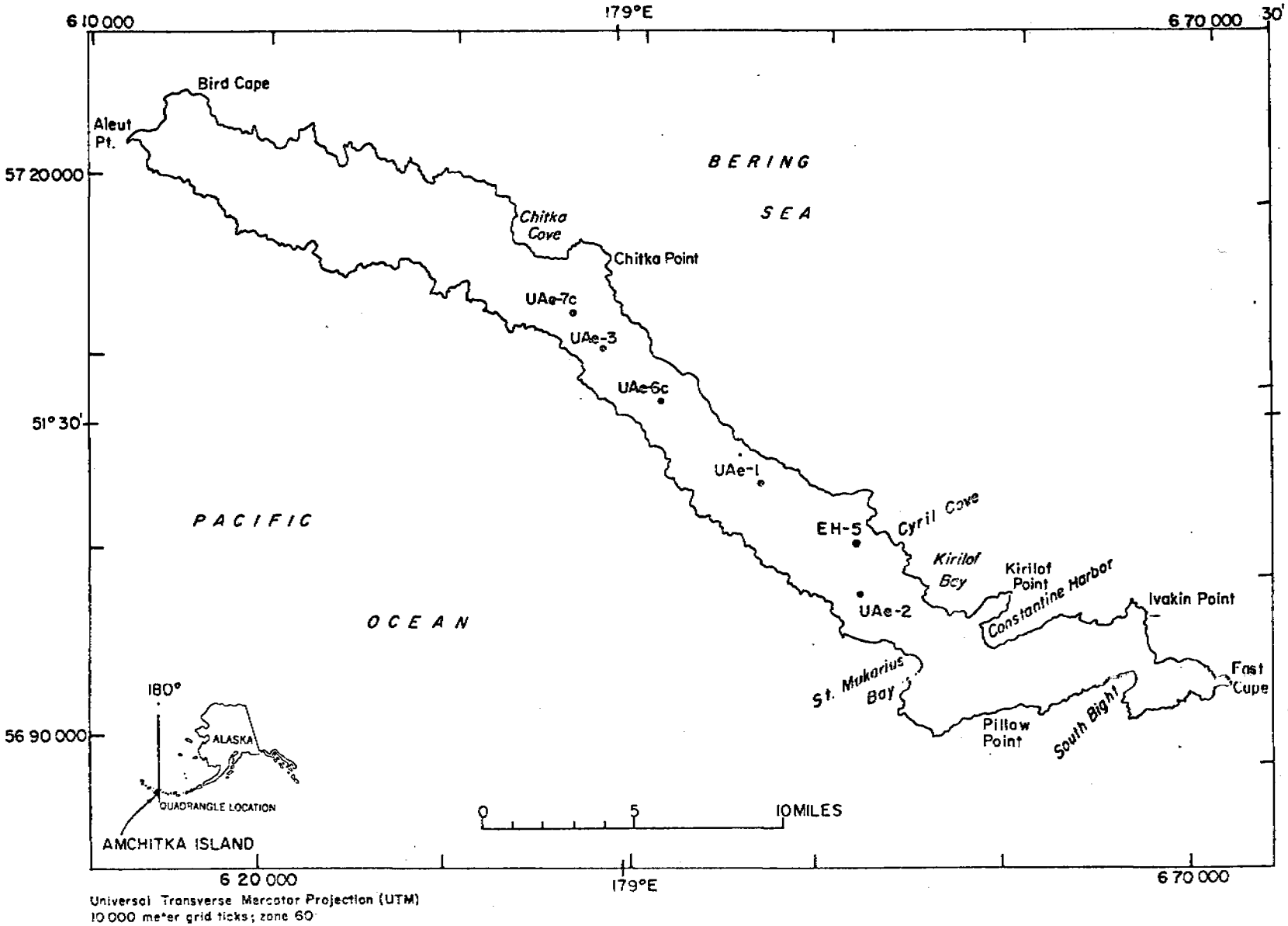

Figure 1.--Index map of Amchitka Island showing drill-hole sites.

PREVIOUS MAGNETIC SURVEYS

One of the most exciting investigations in recent years followed the discovery by Mason (1958) that the floor of the Pacific Ocean produces remarkably regular magnetic anomalies, or magnetic lineations, which form parallel patterns that often extend for distances of several hundred miles. Since then, studies by numerous investigators have resulted in the discovery of similar anomalies in the Atlantic and Indian Oceans and in the development of comprehensive new theories that make use of the concepts of paleomagnetism (Cox and others, 1964), sea-floor spreading (Vine, 1966), and continental drift (LePichon, 1968) to explain the geologic history of oceanic areas.

Magnetic lineations are present south of Amchitka beyond the Aleutian trench, and Hayes and Heirtzler (1968) have discussed the relation of these lineations to the Aleutian Islands arc and trench. Abrupt changes in continuity of the anomalies south of the trench suggest large north-south displacements or faults in the sea floor that have offset anomaly patterns as much as 150 miles. The limited data now available from shipborne surveys do not indicate that any displacements trend toward Amchitka Island. Grim and Erickson (1968) inferred a small north-south offset in the magnetic pattern near long 177° W., 175 miles east of Amchitka, which they called the Adak fracture zone. Hayes and Heirtzler inferred a large north-south fracture zone at long 176° E., 100 miles west of Amchitka.

No anomaly lineations have been reported over the oceans north of the Aleutian trench, and neither the magnetic anomalies nor the magnetic properties at Amchitka resemble those from ocean areas. In a study of 94 submarine lava samples, Ade-Hall (1964) found that 67.5 percent of the samples had magnetic susceptibilities less than $10X10^{-4}$ gauss/oersted and that 61 had Konigsberger ratios greater than 10. On Amchitka, less than 10 percent of the andesitic and basaltic lavas (see histograms, figs. 17, 18) had susceptibilities less than $10X10^{-4}$ gauss/oersted or Konigsberger ratios greater than 10. Although basaltic lavas do show high Konigsberger ratios, their susceptibilities are also high, averaging about $40X10^{-4}$ gauss/oersted.

Keller, Meuschke, and Alldredge (1954) have published aeromagnetic survey data for northern Adak Island, part of Umnak Island, and all of Great Sitkin Island. Magnetic properties are unknown for the volcanic formations on these islands, and the anomalies cannot be discussed in terms of geologic features. The fairly large number of positive anomalies suggests the presence of normally magnetized lava, like the Chitka Point lavas on Amchitka. Richards, Vacquier, and Van Voorhis (1967) have computed the direction and intensity of magnetism for the Quaternary volcanic rocks that form the topographic relief of Great Sitkin volcano, Mount Adagdak, Mount Moffett, and a parasitic cone on the northeastern side of Mount Moffett. Directions of magnetization for the four volcanoes are quite different, indicating that the anomaly-producing rocks are products of separate eruptive episodes.

AEROMAGNETIC SURVEY

As shown on the aeromagnetic map (fig. 2), more than 66 flight lines were flown: 12 long lines and a few short lines were flown northwest and southeast at about a half-mile spacing along the axis of the island, and 51 long lines were flown northeast and southwest at about a 1-mile spacing; two tielines were flown in the northwest direction, one over the north insular slope and one over the south insular slope. A barometric elevation of about 1,600 feet was maintained throughout the survey by means of a continuously recording radio altimeter. The magnetic measurements were made by a continuously recording Gulf fluxgate magnetometer, installed in a DC-3 aircraft outfitted with Loran and Doppler navigational systems. Aero Service Corp. performed the aerial survey and compiled the data shown on figure 2.

Reduction of data

The observed data consist of those on both residual and regional magnetic anomalies. The residual anomalies are of particular interest because they come from geologic features that are near surface or buried only a mile or two. The regional anomaly is not important in this study because it comes from the northward increase in the geomagnetic field and from deep-seated rock sources too deep to investigate by drilling. A least-squares method (Richards and others, 1967) was used to either eliminate the regional anomaly or reduce its contribution to a minimum in the small area of the survey.

It was assumed that a planar surface would best fit the data and represent the regional anomaly to be discarded, and the observed data of figure 2 were plotted on a rectangular grid 50 miles long in the x-direction (S. 55° E. along the island axis) and 30 miles wide in the y-direction. On the basis of 1,500 data samples taken at 1-mile grid intervals, the least-squares adjustment arrived at by means of an electronic computer provided the following equation for the regional anomaly:

$$T(x,y) = C_1x + C_2y + C_3.$$

$T(x,y)$ is the regional anomaly in gammas computed for coordinates x, y; C_1 equals 1.70 gammas per mile, C_2 equals -9.64 gammas per mile, and C_3 equals 4,304.6 gammas at lat 51°54.6' N. and long 178°56.0' E.

The residual anomaly, which is the near-surface magnetic expression of a geologic feature, was determined by a graphical method by subtracting data on the regional anomaly from the observed data. The 250-gamma contours of figure 3 show generalized residual anomalies for most of the area of the survey at a scale of 1:100,000, and the 50-gamma contours of figures 4 through 11 show detailed residual anomalies along the island area at a scale of 1:63,360.

1 0 1 2 3 4 MILES

CONTOUR INTERVAL 50 GAMMAS

FIGURE 4 THROUGH FIGURE 11 — Residual magnetic anomaly maps showing contours in detail along the island area. Map positions are shown in Figure 2.

EXPLANATION

-177 X Measured value of maximum or minimum intensity

C39-67 Sample site showing sample number

E Proposed drill site

UAe-1 Drill hole

12 Infantry road and Clevenger road showing mile stations of ground magnetic traverses.

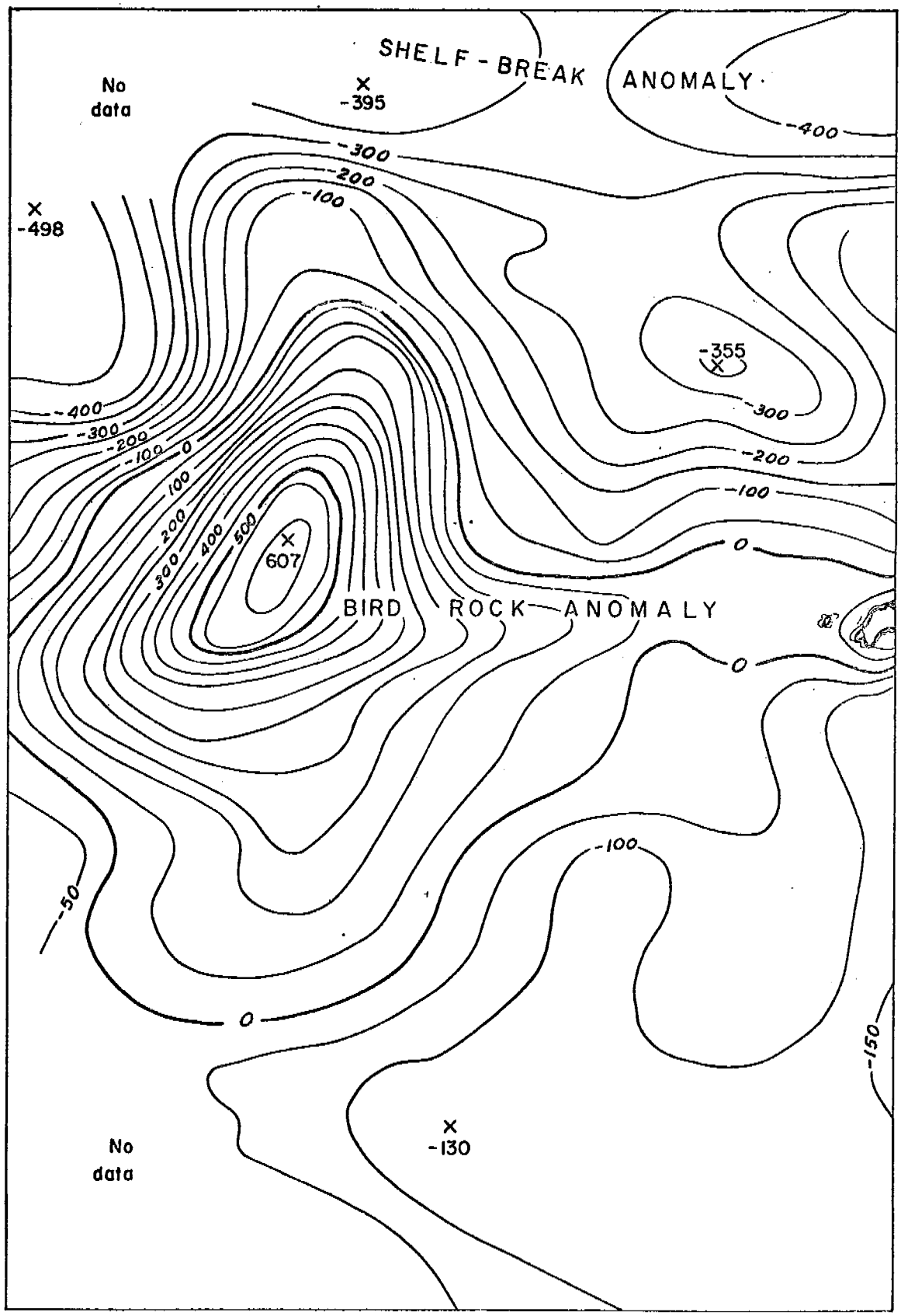
SHELF-BREAK ANOMALY
No data
-395
-400
-300
-200
-100
-498
-355
-300
-400
-300
-200
-100
0
100
200
300
400
500
607
-200
-100
0
BIRD ROCK ANOMALY
0
-100
-50
0
-150
-130
No data

Figure 4

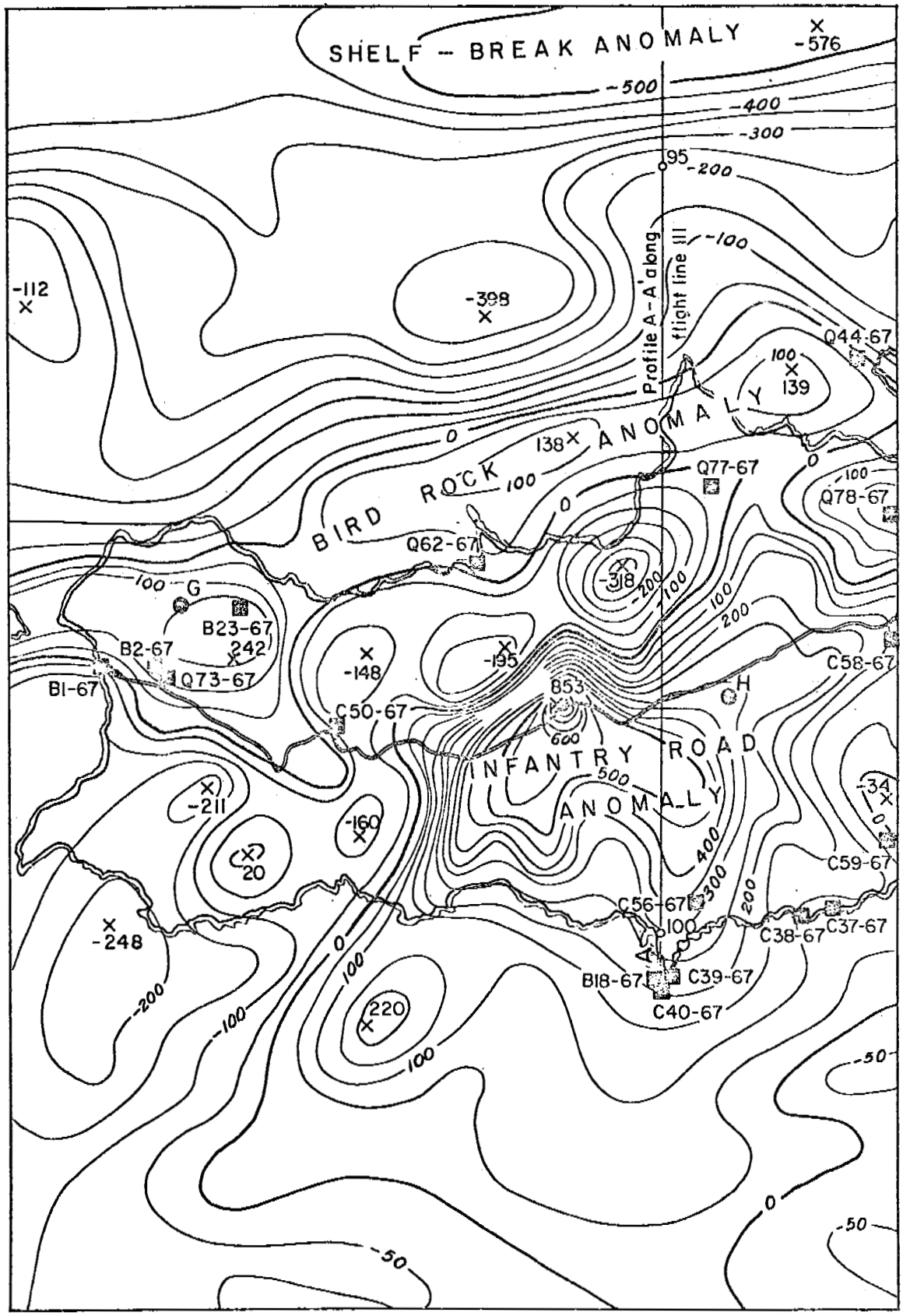
SHELF - BREAK ANOMALY
-576
-500
-400
-300
-200
-100
95
Profile A-A' along flight line III
-112
-398
Q44-67
100
139
BIRD ROCK ANOMALY
138
0
Q77-67
Q78-67
Q62-67
-318
G
B23-67
242
B2-67
Q73-67
B1-67
-148
-195
853
C58-67
H
C50-67
600
INFANTRY ROAD ANOMALY
500
-211
-160
20
-34
C59-67
400
300
200
C56-67
100
C38-67
C37-67
-248
B18-67
C39-67
C40-67
220
-50

Figure 5

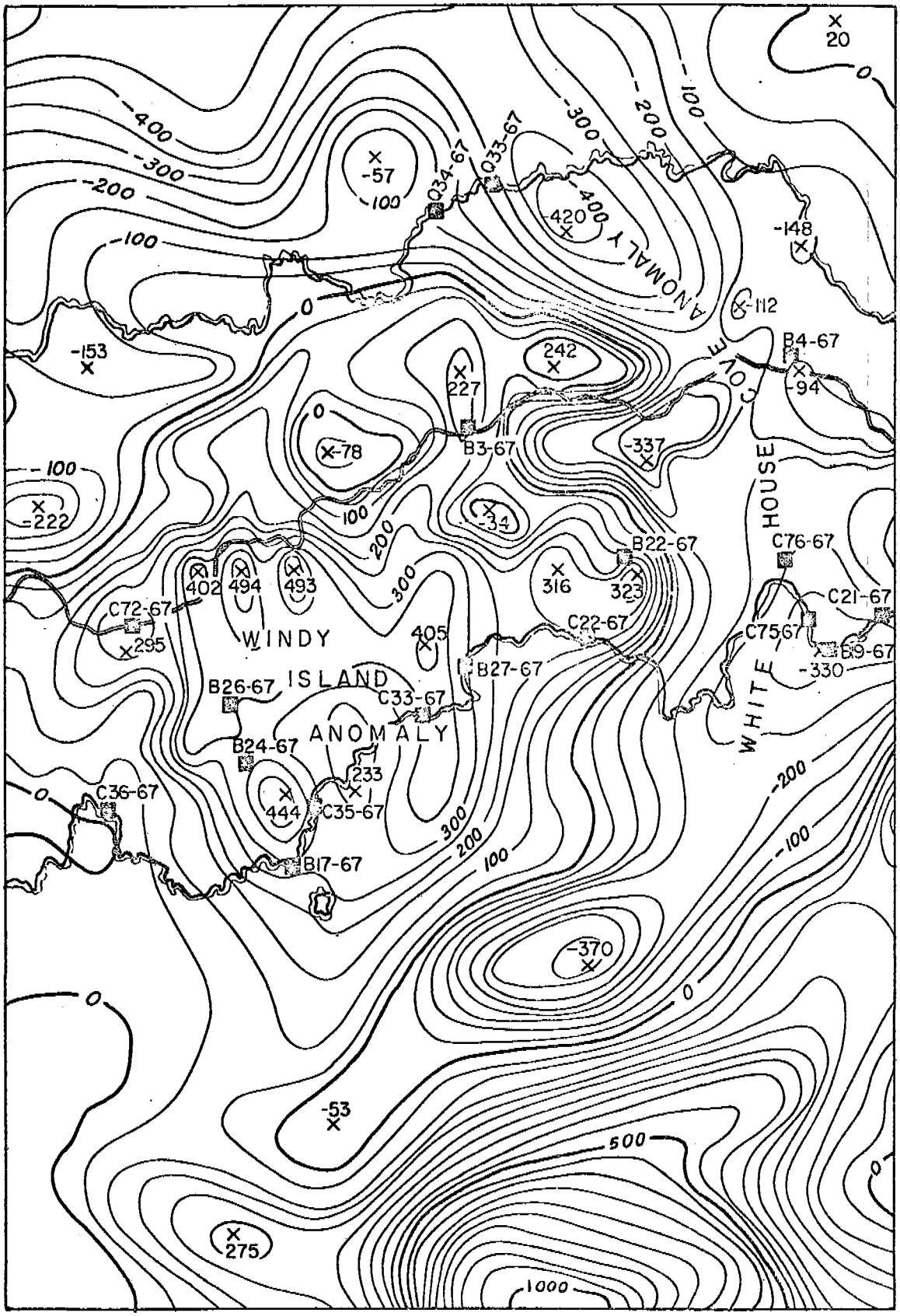
WINDY ISLAND ANOMALY
WHITE HOUSE ANOMALY
C34-67
C33-67
B3-67
B4-67
B22-67
C76-67
C21-67
C75-67
B9-67
C22-67
B27-67
C72-67
B26-67
C33-67
B24-67
C36-67
C35-67
B17-67
20
-57
-100
420
-148
-112
-153
242
227
-94
-78
-337
-222
34
402
494
493
316
323
295
405
-330
233
444
-370
-53
275
0
100
200
300
400
500
1000

Figure 6

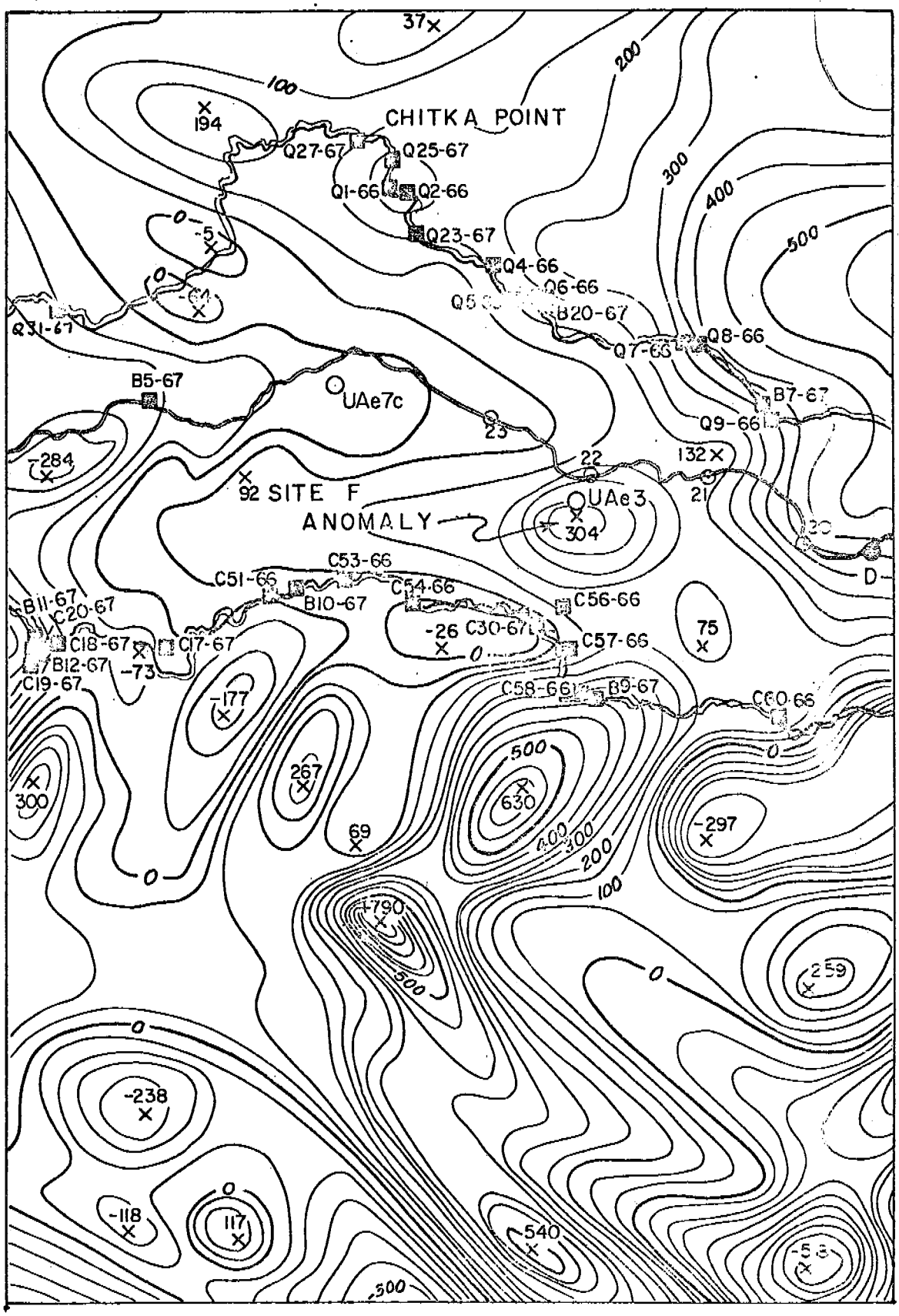
CHITKA POINT
SITE F
ANOMALY
UAe7c
UAe3
Q27-67
Q25-67
Q1-66
Q2-66
Q23-67
Q4-66
Q6-66
B20-67
Q7-66
Q8-66
B7-67
Q9-66
Q31-67
B5-67
C53-66
C51-66
C54-66
B10-67
C56-66
C30-67
C57-66
B11-67
C20-67
C18-67
C17-67
B12-67
C19-67
C58-66
B9-67
C60-66
D
37
194
-5
-64
-284
92
23
22
132
21
20
304
75
-26
-73
-177
267
69
300
630
-297
1790
259
-238
-118
117
540
-58
100
200
300
400
500
0

Figure 7

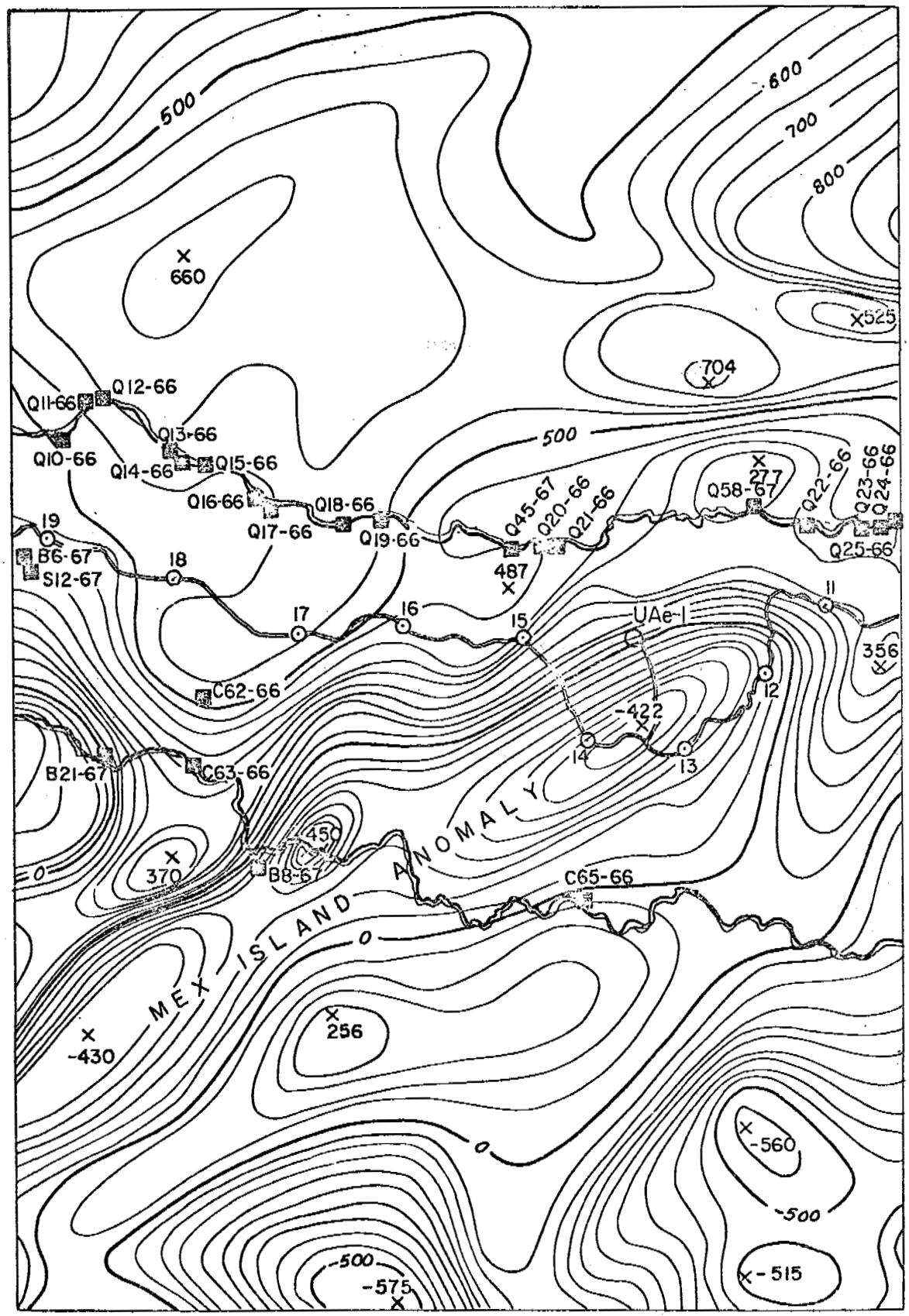
500
600
700
800
660
525
704
Q12-66
Q11-66
Q13-66
Q10-66
Q14-66
Q15-66
Q16-66
Q18-66
Q17-66
Q19-66
Q45-67
Q20-66
Q21-66
Q58-67
277
Q22-66
Q23-66
Q24-66
Q25-66
19
B6-67
S12-67
18
487
17
16
15
UAe-1
11
356
C62-66
12
-422
14
13
B21-67
C63-66
450
370
B8-67
C65-66
MEX ISLAND ANOMALY
0
256
-430
-560
-500
-515
-575

Figure 8

[redacted]

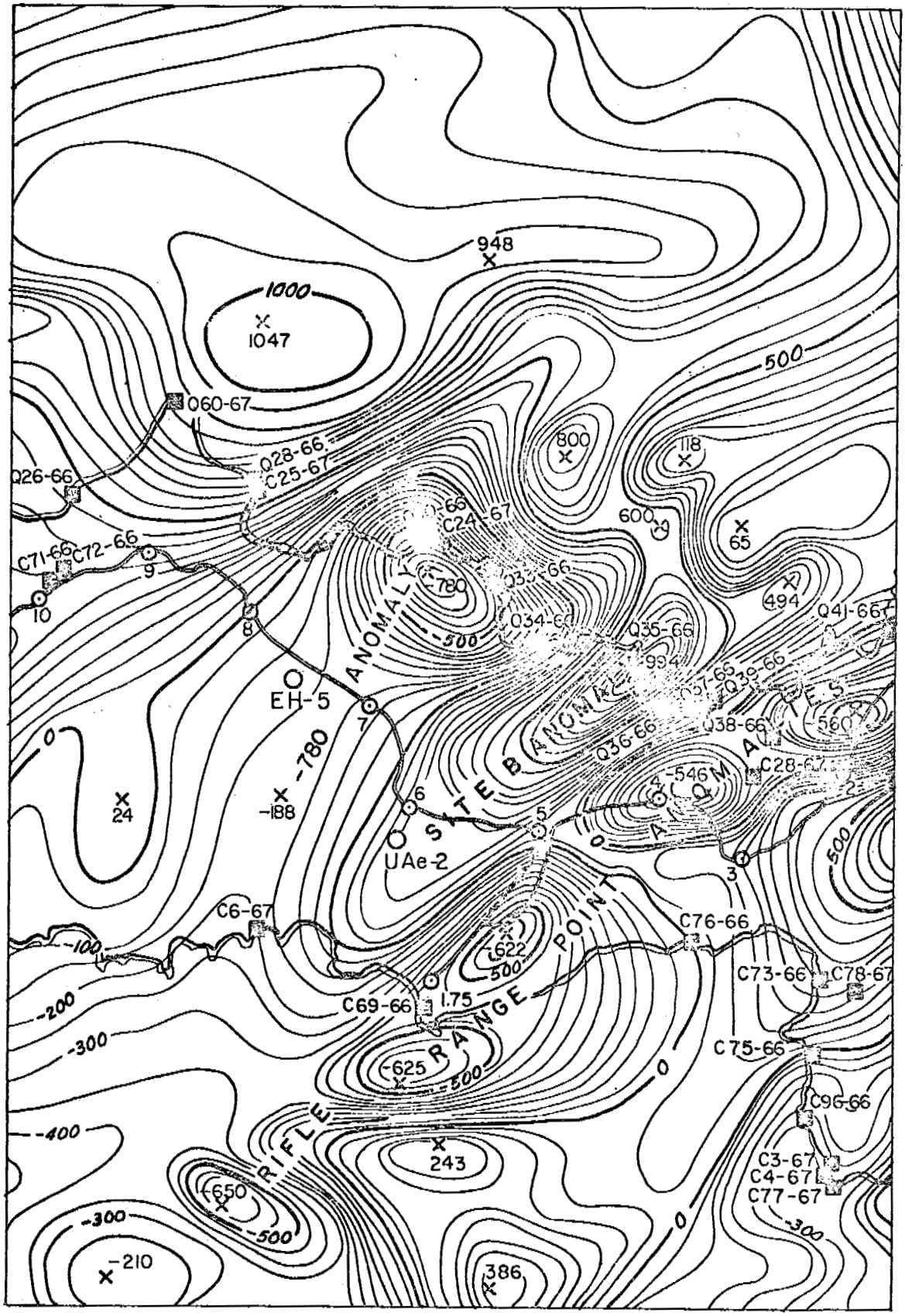

Figure 9

[redacted]

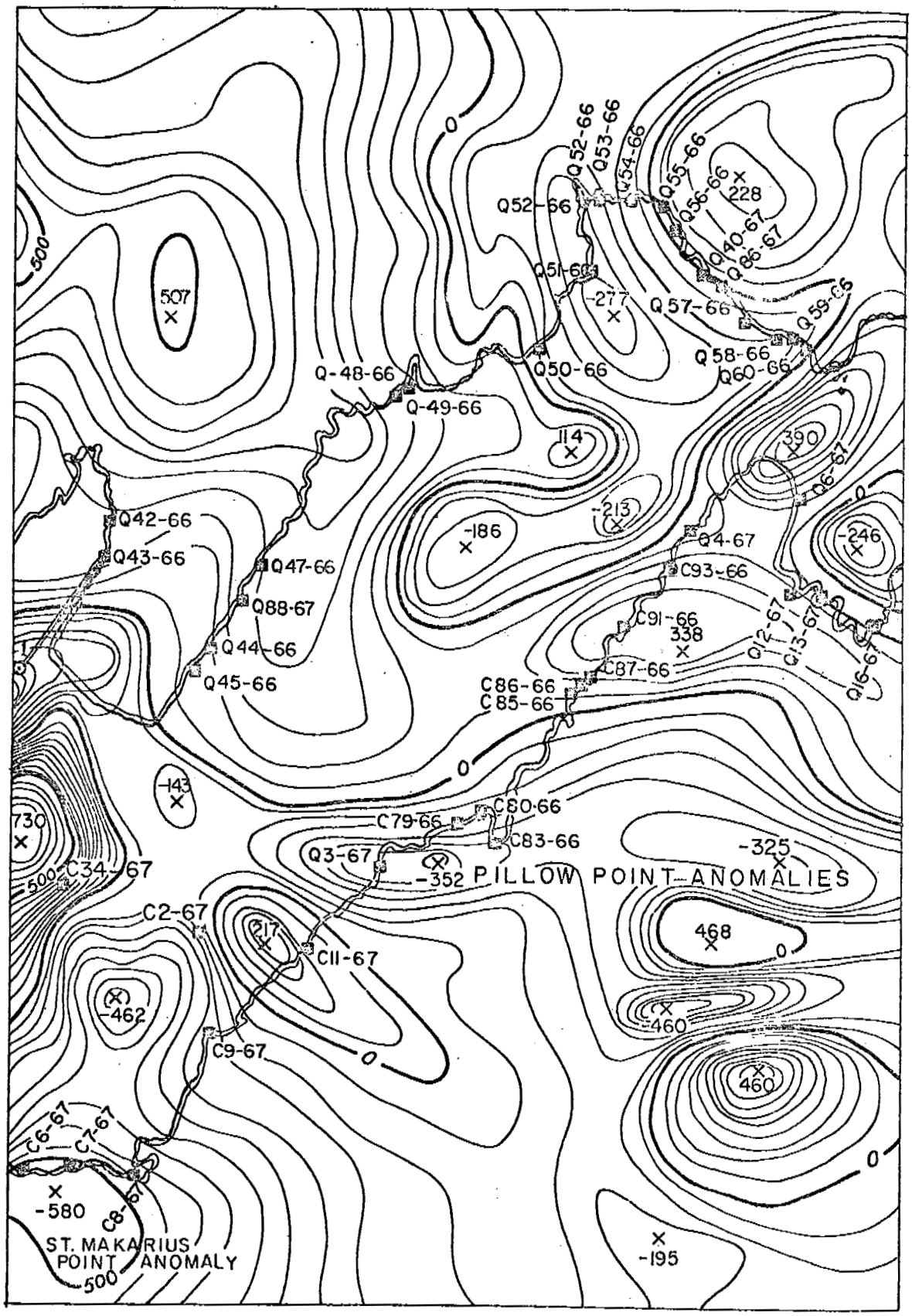

Figure 10

[redacted]

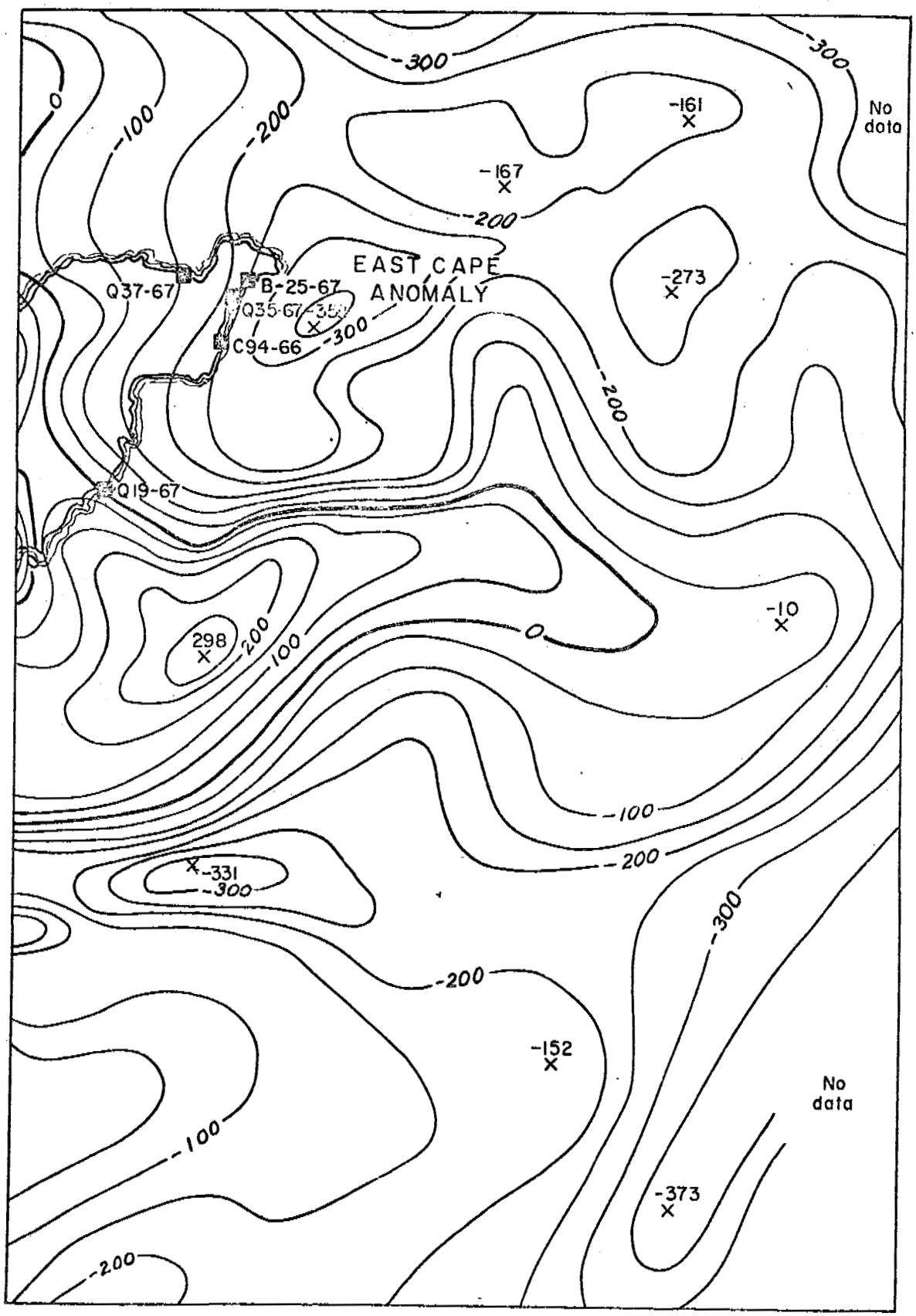

Figure 11

GROUND MAGNETIC SURVEYS

Ground magnetic surveys, which were made along roads, were conducted to determine if significant differences in anomaly patterns are present over volcanic breccia and over basaltic lava flows and to provide more detail on and to better delineate the aeromagnetic anomalies. Figure 12 shows the residual magnetic anomaly and standard error data obtained from stations 0.1 mile apart along the Infantry Road from mile 0 on Kirilof Point to mile 23 northwest of drill hole UAe-3, along Clevenger Road and along the access road to drill hole UAe-1. At each station, five observations were taken 5 feet apart and the values averaged to give the magnetic anomaly at that station. Anomaly-producing rocks are close to the surface beneath the tundra, and the proximity of strongly magnetized rock introduces extreme local anomalies. A measure of these effects is shown by computing the standard error of the five observations and plotting the error as a bar as done in the lower diagram "Standard Error (gammas)," of figure 12.

The Sharpe MF-1 fluxgate magnetometer used in the survey provided values of the vertical component of the earth's magnetic field. Owing to the effects of temperature changes and other factors, readings could be repeated only to within ± 20 gammas. Four base stations were established, and one base was reoccupied about every 3 hours to correct for large changes in the earth's diurnal field.

MAGNETIC PROPERTIES OF ROCK SAMPLES

A magnetic survey detects those geologic features that have magnetic properties unusual enough to cause a disturbance, or an anomaly, in the earth's magnetic field. The anomaly arises when a feature has a total magnetization that is significantly different from the total magnetization of the surrounding rocks.

The average total magnetization of a uniformly magnetized rock mass, denoted as the vector $\vec{J}_t$, is defined as the vector sum of the induced magnetization $\vec{J}_i$ and remanent magnetization $\vec{J}_r$ of the mass,

$$\vec{J}_t = \vec{J}_i + \vec{J}_r. \tag{1}$$

The direction of induced magnetization is assumed along the earth's field, and the intensity of induced magnetization is a function of the magnetic susceptibility, k, and the strength, H_o, of the earth's field,

$$J_i = kH_o. \tag{2}$$

The direction and intensity of the earth's magnetic field are known for Amchitka (explanation, fig. 2); therefore it is magnetic susceptibility, direction, and intensity of remanent magnetization that must be measured to evaluate total magnetization. For this study, the dry bulk density of each sample was measured in order to provide an independent parameter that could be used to help determine whether the selected rock samples were representative.

The histograms in figures 13-18 give magnetic properties and densities for 563 rock specimens collected from surface outcrops and drill core. Numbers and types of rock specimens used were: 85 surface and 74 drill-core specimens of volcanic breccia; 61 drill-core specimens of volcanic sandstone, siltstone, and tuff breccia; 43 surface specimens of intrusive rock; and 219 surface and 81 drill-core specimens of andesitic and basaltic flows, sills, and dikes. Konigsberger ratios (the ratios of remanent to induced intensities of rock samples) are also included as a histogram. Site locations for the surface samples are shown in figures 5 through 11.

In reporting units of magnetic intensity the authors have followed Collinson, Creer, and Runcorn (1967) in their attempt to specify electromagnetic units more precisely. Gauss/oersted is used for magnetic susceptibility, and gauss is used for induced, remanent, and total intensity.

The extreme scatter found in magnetic property data obtained by the usual procedure of using an arithmetic mean indicates that this method results in an assignment of too much weight to large values and this in turn results in an average value that is greater than the true average of a geologic feature. Statistical studies by Irving, Molyneux, and Runcorn (1966) suggest that histograms of magnetic properties may conform more closely to a normal distribution when the abscissas are plotted as logarithms. Our studies, although incomplete, tend to confirm their conclusions, and the histograms included in this report were therefore plotted with logarithmic abscissas.

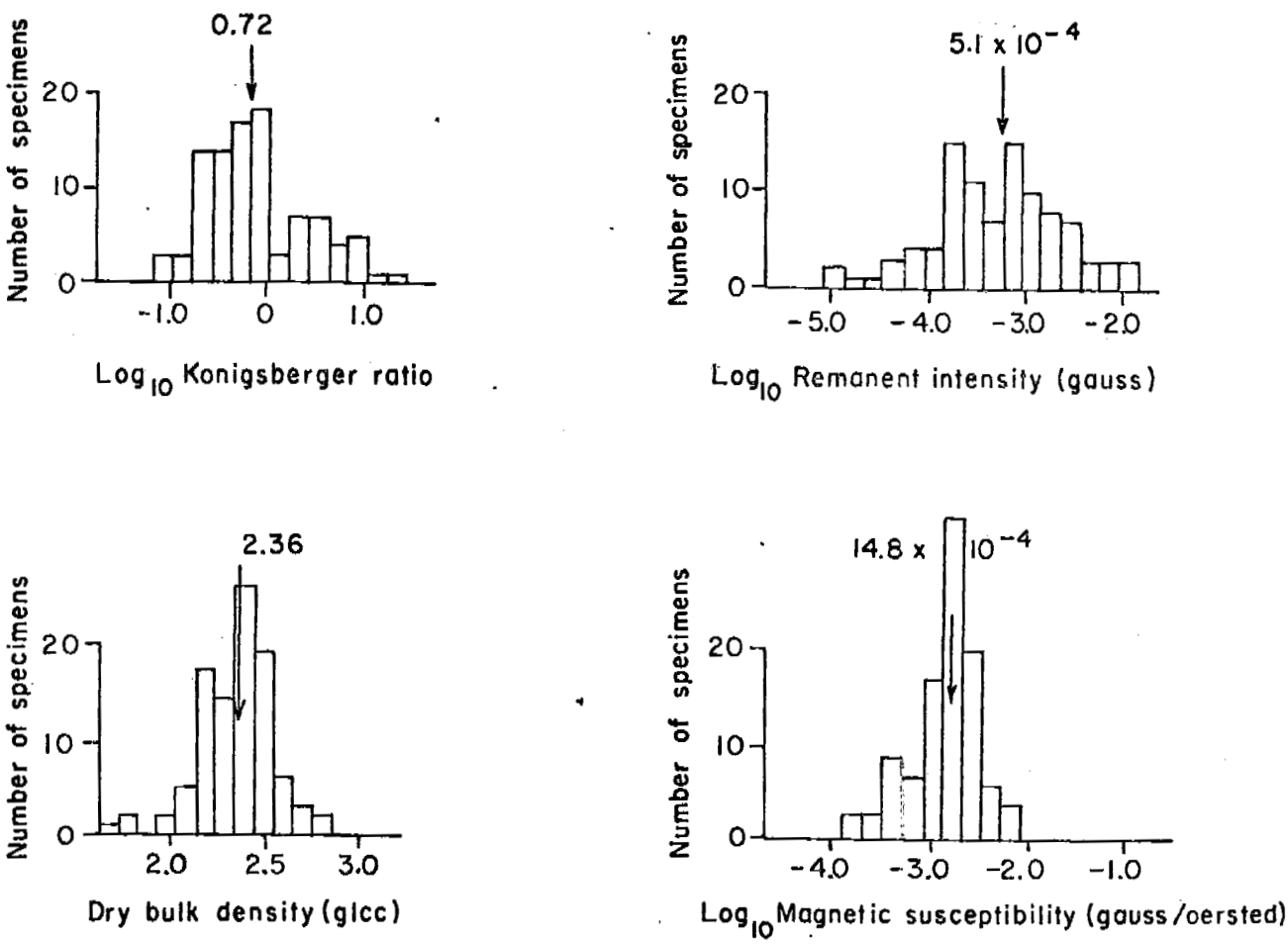

Figure 13.--Histograms of Konigsberger ratio, density, remanent intensity, and magnetic susceptibility for 97 specimens of volcanic breccia. Arrow indicates average value.

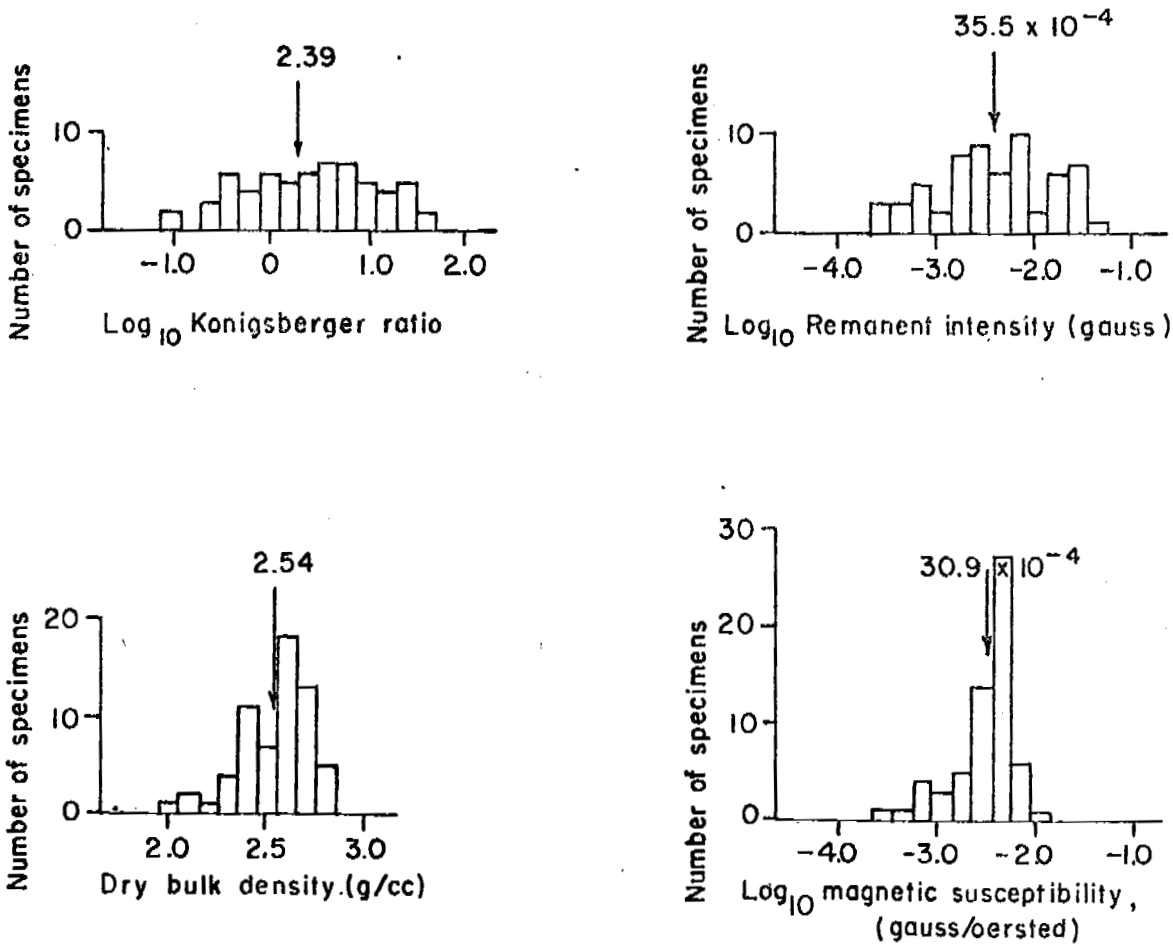

Figure 14.--Histograms of Konigsberger ratio, density, remanent intensity, and magnetic susceptibility for 6[illegible] specimens of volcanic breccia fragments. Arrow indicates average value.

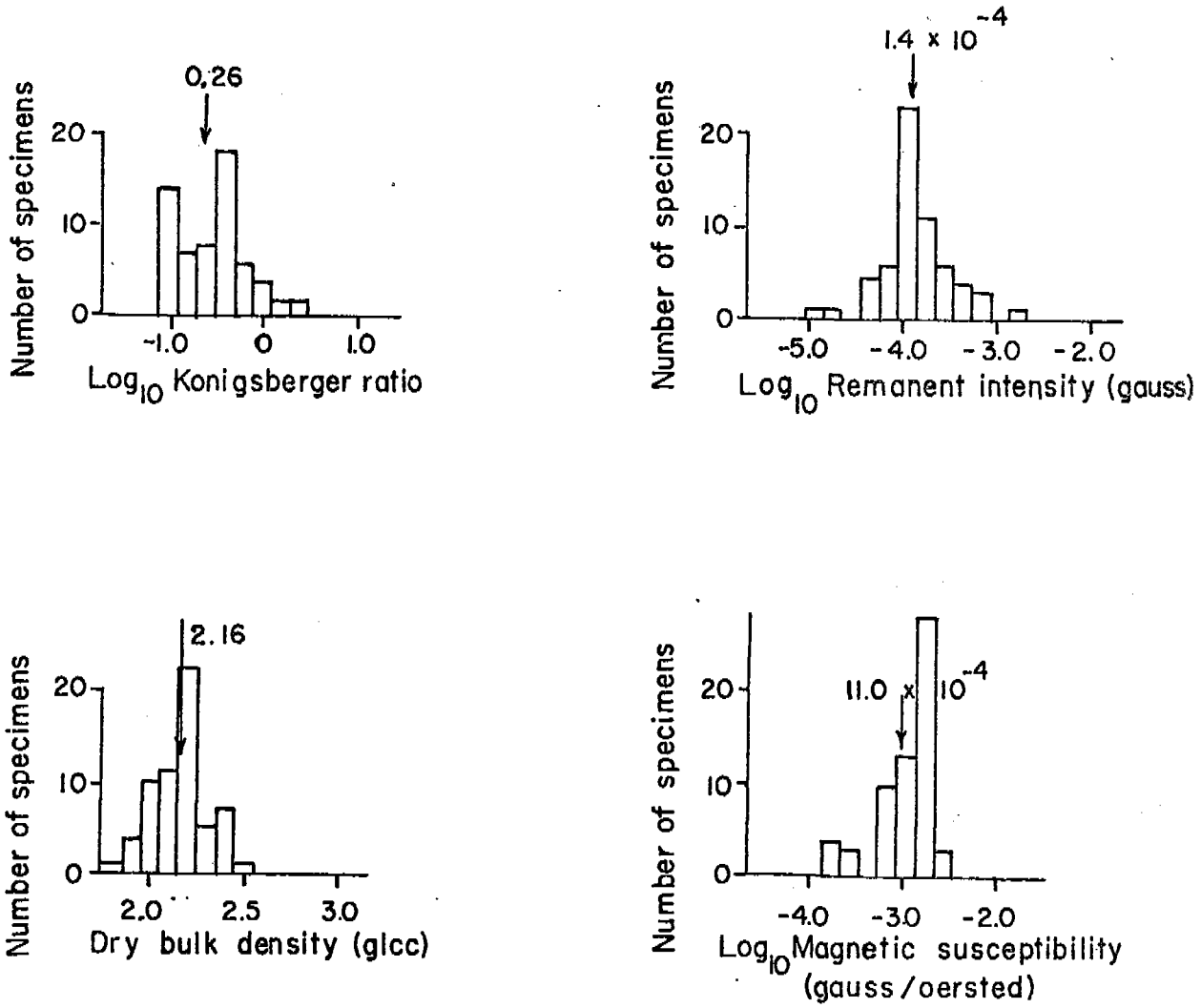

Figure 15.--Histograms of Konigsberger ratio, density, remanent intensity, and magnetic susceptibility for 61 specimens of volcanic sandstone, siltstone, and tuff breccia. Arrow indicates average value.

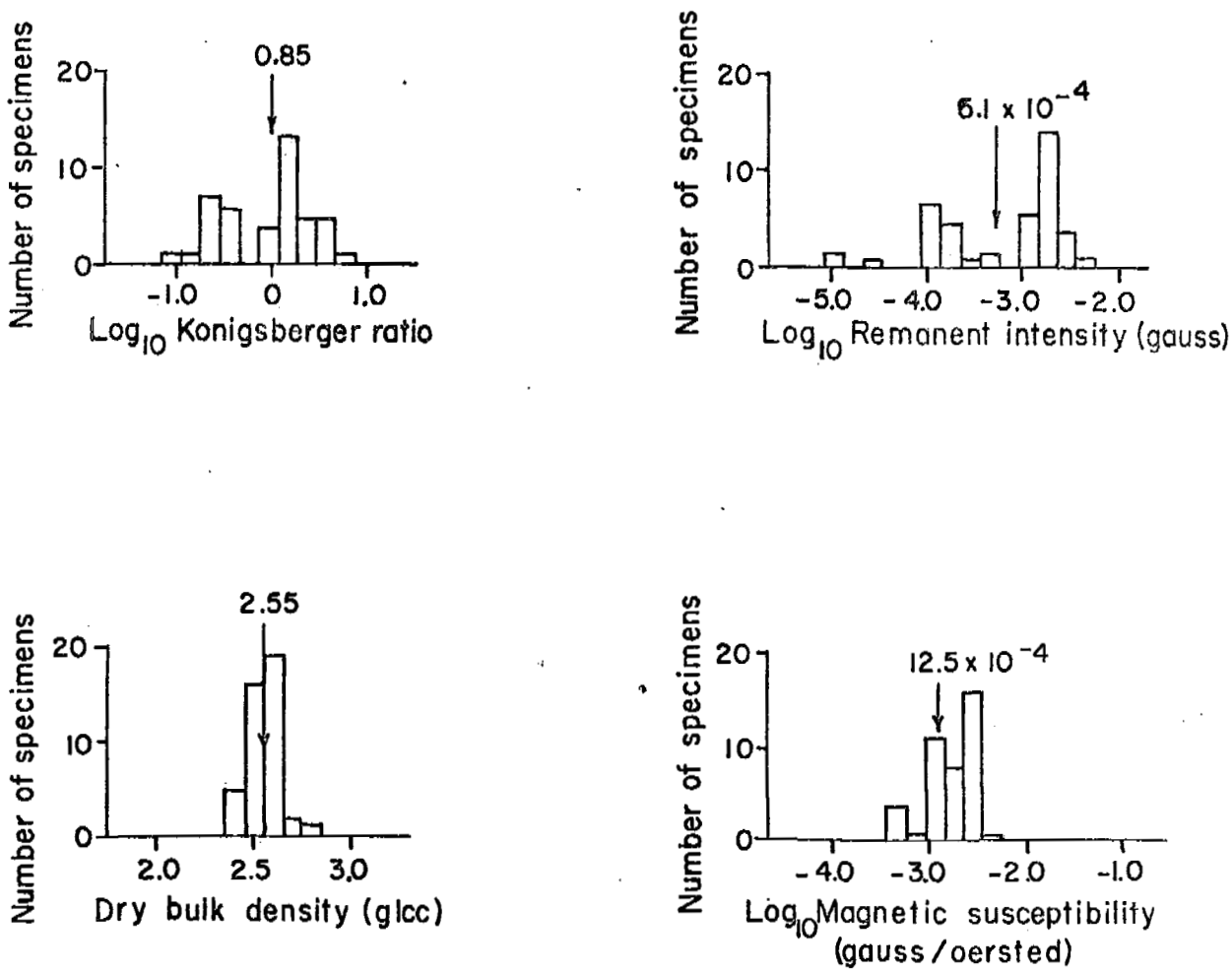

Figure 16.--Histograms of Konigsberger ratio, density, remanent intensity, and magnetic susceptibility for 43 specimens of intrusive rock. Arrow indicates average value.

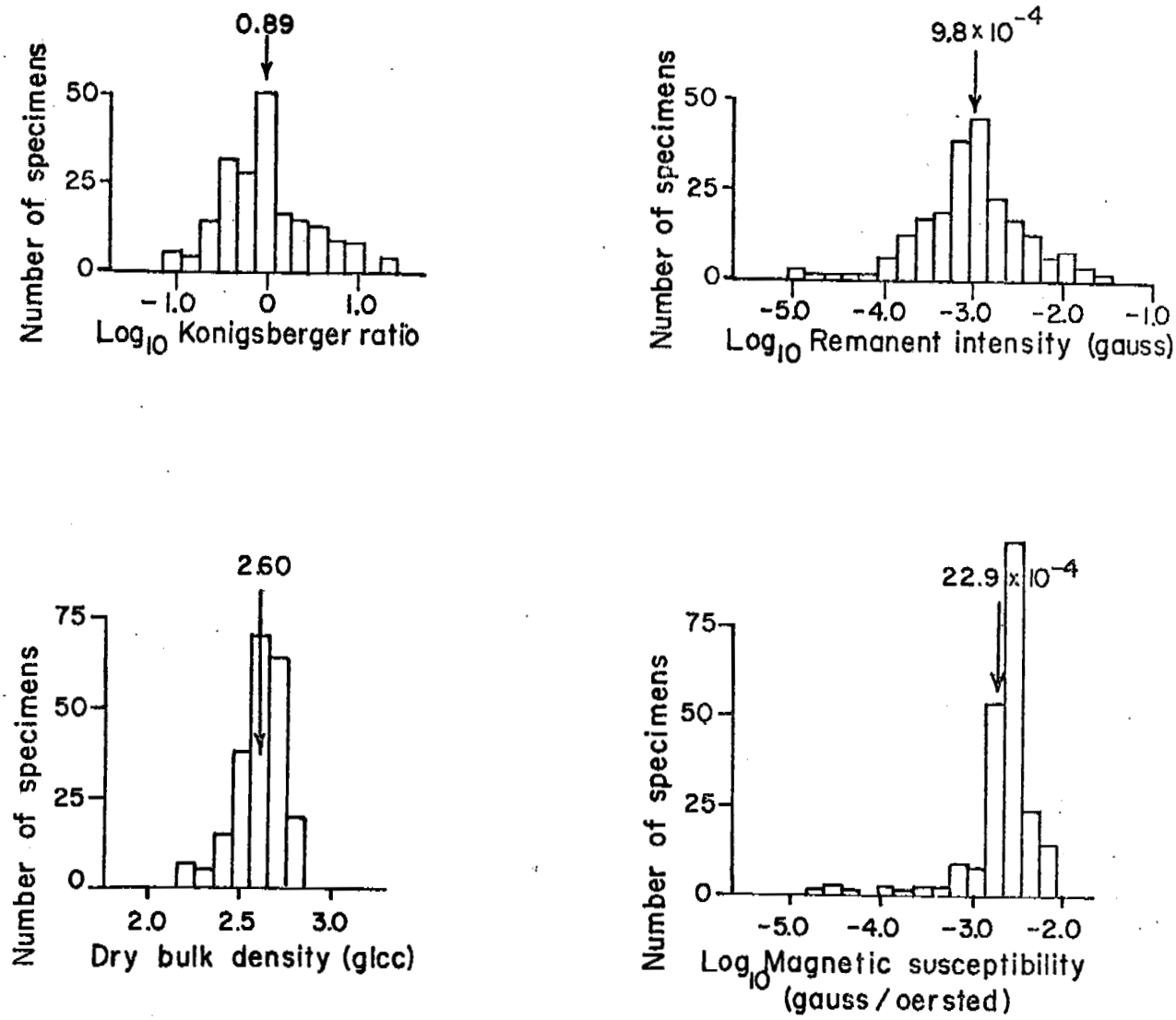

Figure 17.--Histograms of Konigsberger ratio, density, remanent intensity, and magnetic susceptibility for 219 surface specimens of andesitic and basaltic flows, sills, and dikes. Arrow indicates average value.

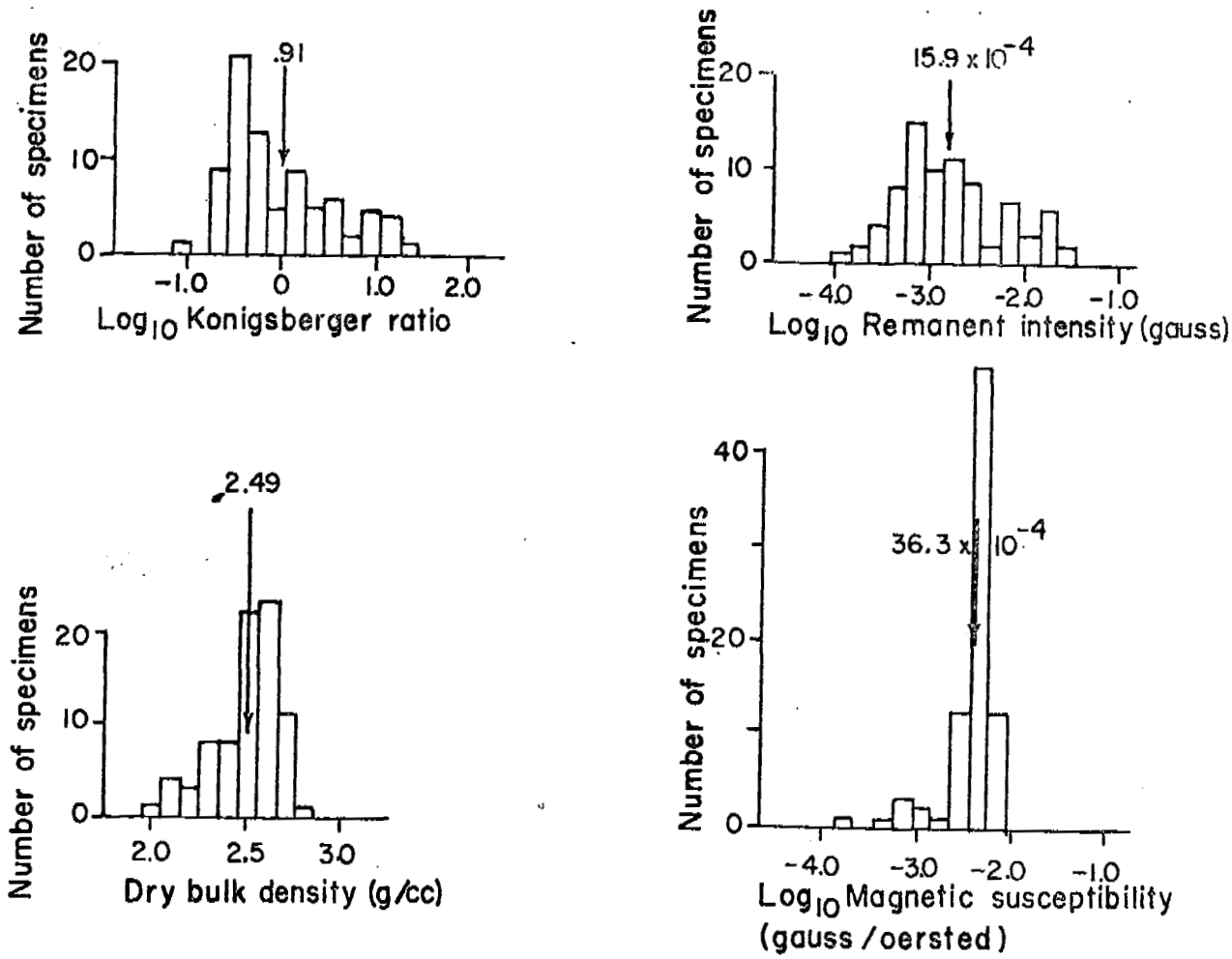

Figure 18.--Histograms of Konigsberger ratio, density, remanent intensity, and magnetic susceptibility for 81 drill-core specimens of andesitic and basaltic flows, sills, and dikes. Arrow indicates average value.

The reader will note the usage of the words "sample," "specimen," and "sampling site." Rock samples were collected from points separated by at least 50 feet. Specimens were taken closer together vertically, coming from the same core run of 10-foot length, or from two or three pieces drilled from the same surface sample. Sampling sites were as much as 1 mile apart. For example, each landing of the helicopter used to collect the "B" samples (figs. 5-11) was designated a sampling site.

Measuring magnetic susceptibility

Reversible magnetic susceptibilities were determined by inserting samples into one of a pair of matched Helmholtz coils connected to an induction comparison bridge. For large roughhewn samples, coils with inside diameter of 8 1/4 inches were used; and for small 1-inch diameter by 1-inch length drilled plugs, coils with inside diameter of 2 1/2 inches were used. Meter deflections were calibrated against a commercially available alternating-current bridge by using a set of standard samples.

Measuring remanent magnetization

The intensity, azimuth, and inclination of remanent magnetization were determined for both large roughhewn and small drilled plugs by means of a commercially available fluxgate-type clip-on milliammeter, modified to function as a magnetometer. Jahren and Bath (1967) have described the procedure that we used.

Surface samples were oriented before they were removed from the outcrop by marking a north arrow on the sample top and a horizontal line on two or more sides. An arrow pointing upward was marked on all pieces of drill core immediately after the core was taken from the core barrel. Although the geographic azimuth is unknown, the intensity and inclination of remanent magnetization were obtained for core from vertical holes. Most of the samples collected during the geological reconnaissance were not oriented; however, the remanent intensity was determined for many of them.

At the Nevada Test Site (Bath, 1967) lightning introduces a relatively strong component of remanent magnetism that is confined to near-surface rocks. Tabulation of data from these samples will not give a true value of average magnetism for a geologic feature under study. In Nevada, data were used from underground samples that were free from these effects and from surface samples in which remanent direction remained constant during partial alternating-field demagnetization in the laboratory. Although lightning has rarely been observed during historic time on Amchitka, the possibility of contamination effects cannot be ignored because parts of the island have been above sea level for perhaps 1 million years (Powers and others, 1960). We partially demagnetized 24 surface and 7 drill-core samples of andesitic and basaltic lava in an alternating-current field of 100 and 200 oersteds and found no significant directional changes in the moderately to strongly magnetized rocks that produce the aeromagnetic anomalies. Some of the weakly magnetized rocks did show changes in their remanent directions. This change is explained as being the result of a component of viscous magnetization or the remanent effect acquired when a rock remains in the earth's magnetic field over a long period of time.

In this study, it has been assumed that lightning has not introduced a significant error in the magnetization values.

GEOLOGIC SETTING

The stratigraphy and structure of Amchitka are now fairly well known as the result of recent studies by Carr and Quinlivan (1969) and earlier work by Powers, Coats, and Nelson (1960). As shown on the generalized geologic map (fig. 3), the rocks are divided into (1) the Amchitka Formation, which comprises a lower unit of older breccias and an upper unit of the pillow lavas and breccias of Kirilof Point; (2) the Banjo Point Formation; and (3) the Chitka Point Formation.

The lower Tertiary Amchitka Formation is the oldest formation exposed on the island. Rocks in the northwestern part of Amchitka formerly mapped as Amchitka Formation are now included in the Chitka Point Formation (W. J. Carr, unpub. data) and rocks on eastern Amchitka are included either in the older breccias or in the pillow lavas and breccias of Kirilof Point.

The older breccias of the Amchitka Formation are restricted in outcrop to the eastern part of Amchitka, mainly between Constantine Harbor and the quartz diorite intrusive rocks of East Cape. Inliers of hornfels occur within the intrusive masses. The unit consists of fine- to coarse-grained sedimentary breccias interbedded with minor amounts of sandstone, siltstone, and claystone which contain volcanic debris. Most of the rocks are propylitically altered. The degree of alteration increases erratically eastward toward the intrusive complex, and strongly metamorphosed older breccias occur adjacent to the intrusive masses. The upper contact of the older breccias is placed at the base of a locally glassy lava sequence and at the top of a thin interval of sedimentary rocks. Numerous dikes, including many of hornblende andesite, cut the breccias on the eastern part of Amchitka. A maximum thickness of about 4,000 feet of the older breccias may be exposed, but because of the thickness of the numerous dikes and sills that intrude the section and the possibility of fault repetition, this estimate is probably too high.

The rocks of Kirilof Point are glassy breccias, most of which are monolithologic, subordinate pillow lava flows, and a very minor amount of bedded volcanic sedimentary rocks, all of which were probably deposited in a submarine environment. Compositionally, the rocks of the Kirilof Point are less mafic than others known on Amchitka; Powers, Coats, and Nelson (1960) have published an analysis of hydrated glassy breccia from Kirilof Point which indicates that the rock is a latite. The Kirilof Point rocks are about 3,500 feet thick in the vicinity of Pillow Point.

The Banjo Point Formation overlies the Amchitka Formation, apparently with only minor unconformity, and consists mainly of basaltic breccias, minor pillow lavas, and volcaniclastic sedimentary rocks, all of submarine deposition. Hornblende-andesite and basalt sills are present locally. Largely because of a major erosional unconformity at the top, no complete section of the Banjo Point is exposed. The formation is probably between 2,000 and 5,000 feet thick. It is late Eocene or Oligocene in age (W. J. Carr, unpub. data).

The Chitka Point Formation overlies the Banjo Point Formation with major unconformity and is restricted (G. D. Bath, unpub. data) to subaerial hornblende- and pyroxene-andesite lava flows, breccias, tuffs, and conglomerate in the northwestern part of Amchitka (fig. 3). Included in the Chitka Point Formation by the present authors are all rocks previously mapped by Powers, Coats, and Nelson (1960) as Amchitka Formation on the northwestern part of the island and some rocks in small areas along the Bering Sea coast between about lat 51°30' N. and Cyril Cove previously mapped by them as Banjo Point Formation. The Chitka Point ranges in thickness from 0 near the middle of Amchitka to at least 2,000 feet in the vicinity of Top Side in northwestern Amchitka. On the basis of a K:Ar date and other evidence the Chitka Point is determined to be Miocene (G. D. Bath, unpub. data).

Dioritic intrusive rocks cut the Chitka Point Formation on the western part of Amchitka and the older breccias of the Amchitka Formation on the eastern part of the island. Intense hydrothermal alteration of the Chitka Point in the Chitka Cove area may be related to the diorite that crops out at White House Cove (fig. 3). Weak to strong propylitic alteration affects much of the Chitka Point Formation and the older breccias of the Amchitka Formation. Alteration minerals include epidote, quartz, calcite, chlorite, and pyrite. In addition to causing locally intense alteration the intrusives gently tilt the invaded rocks at White House Cove and on the eastern part of Amchitka east of St. Makarius Point.

Although faults are not as abundant as aerial photograph lineaments suggest, there are perhaps a dozen major fault zones, a few of which may have a width of several thousand feet and within which the rocks may be highly fractured. Most of the major faults trend about N. 70° E. and dip northwest at 75°-90°. Although some of the movement appears to be lateral, some faults have stratigraphic displacement of as much as 4,000 ft. The middle third of the island is a series of fault blocks that repeat the southeastward-dipping section. Most of the major faulting predates the Chitka Point Formation.

Within the area of the aeromagnetic survey are three important submarine fault systems. One lies 5-10 km north of Amchitka and Rat Islands along a prominent escarpment. In addition to outlining the escarpment, faults of this system also border the basins and ridges between Amchitka and Semisopochnoi Islands. Most of these structural features appear to be younger than the Chitka Point Formation. Southeast of Amchitka on the slopes descending into Amchitka Canyon and Ward Basin are east-northeast-trending faults that parallel those on Amchitka and probably have the same general sense of displacement. South of Amchitka on the insular slope are several sharply incised asymmetric submarine canyons. These mark northeast-trending faults, downthrown on the northwest. These faults cannot be confidently connected with any exposed on Amchitka.

VOLCANIC BRECCIA

Breccias are an important part of the entire stratigraphic section on Amchitka; most of the samples were collected from the Banjo Point Formation. L. M. Gard and W. E. Hale (unpub. data, 1964) showed that the Banjo Point consists of a thick series of submarine basaltic breccias, lapilli tuffs, and conglomerates and a minor number of intercalated beds of volcanic sandstone, siltstone, shale, and tuff.

Magnetic properties

The volcanic breccia consists mostly of coarse fragments of volcanic material that was rapidly deposited at low temperature as submarine landslides. During deposition, the earth's magnetic field alines smaller magnetized fragments so that they settle to the ocean bottom in a consistent direction of remanent magnetization. On the assumption that this alinement is maintained throughout consolidation and cementation, a deposit consisting mainly of small fragments will acquire a bulk magnetization that is directed along the magnetic field. The earth's field could not, however, affect larger pieces of magnetized material, especially those emplaced by a rapid depositional process, and these larger pieces, therefore, would give the breccia a random remanent magnetization.

Experiments with breccia cores of the Banjo Point from exploratory drill hole UAe-1 verify that the remanent directions are basically random. Measurements on 15 core pieces from core run 1 (Gard and others, 1969), oriented with arrows pointing upward, gave seven upward or negative inclinations, six downward or positive inclinations, and two nearly horizontal inclinations. Inclinations for the 14 pieces of breccia from core 2 were: seven negative, five positive, and two horizontal. Other breccia core gave similar results.

It is concluded by the present authors that this wide scatter effect of disoriented breccia fragments on remanent magnetization will cancel most of the remanent contribution to the total magnetization of a large breccia deposit. Equation (1) then reduces to

$$\vec{J}_t \approx \vec{J}_i$$

The histograms of figure 13 present data from 97 breccia specimens, all of the breccia measured to date. Logarithmic averages are 14.8×10^{-4} gauss/oersted for magnetic susceptibility, 5.1×10^{-4} gauss for remanent intensity, and 0.72 for Konigsberger ratio. The average density is 2.36 g/cc. Formulas (2) and (3) determine that the total magnetization becomes 7.1×10^{-4} gauss in the direction of the earth's magnetic field. Because breccia is the predominant lithology of Amchitka, we have designated this total magnetism of breccia as the ambient level for the island. A large geologic structure with a magnetization that differs in intensity or direction from the ambient level should, therefore, produce a residual magnetic anomaly.

The 41 core samples from the Long Shot drill hole EH-5, collected at depths from 76 to 1,999 feet, are considered to be representative of breccia of the Banjo Point Formation. Data from these samples have the following averages: dry bulk density, 2.36 g/cc; magnetic susceptibility, 19.8×10^{-4} gauss/oersted; remanent intensity, 16.0×10^{-4} gauss; and total intensity, 9.5×10^{-4} gauss in the direction of the earth's magnetic field. The relatively high remanence of these pieces of core is apparently caused by a few large breccia fragments, and is not the remanence of the rock as a whole.

Histograms (fig. 14) list properties for 62 lithic fragments removed from two surface samples of the breccia of the Banjo Point Formation. Most of the pieces are from lava flows that were probably originally emplaced away from the present island area.

On the basis of core from UAe-1, the breccia of Kirilof Point and the underlying older breccias are seen to have quite different average total magnetizations. Thirteen samples of breccia of Kirilof Point from depths of 2,415-4,925 feet gave averages of 2.32 g/cc for density, $4.9X10^{-4}$ gauss/oersted for magnetic susceptibility, $5.1X10^{-4}$ gauss for remanent intensity, and $2.4X10^{-4}$ gauss for total intensity. Thirteen samples of older breccia from depths of 5,756-6,997 feet gave averages of 2.45 g/cc for density, $33.9X10^{-4}$ gauss/oersted for magnetic susceptibility, $5.9X10^{-4}$ gauss for remanent intensity, and $16.2X10^{-4}$ gauss for total intensity.

Aeromagnetic anomalies

Aeromagnetic traverses over the large area of Banjo Point breccias and the older breccias (fig. 3) show an anomaly level that is generally above the regional value but is interrupted by several prominent and many local negative and positive anomalies. In the area of the Banjo Point Formation the marked negative anomalies have been named Mex Island, -780, and Rifle Range Point anomalies. The most marked positive effect is named the Site B anomaly. As will be pointed out in a following section, the marked positive and negative anomalies come from lava flows or sills and do not represent the magnetic effect of breccia. After removing lava-related anomalies, the resulting magnetic field becomes fairly uniform.

Ground survey anomalies

A striking difference in average anomaly amplitude and standard error is present over breccia and lava flows. The magnetic expressions of the breccia are relatively uniform and have lower values than the lavas, except that the contrast is not great between the Chitka Point lava flows and the Banjo Point breccias. In the Infantry Road traverse (fig. 12), the 8 1/2 miles over the Banjo Point Formation from mile 8 to mile 16.5, and the 6 1/2 miles over the Chitka Point Formation from mile 16.5 to mile 23, gave averages that are less than 1,000 gammas for anomaly amplitude and less than 50 gammas for standard error. Low values of standard error come from near-surface breccia, and high values from small near-surface features such as flows, dikes, or sills.

From mile 0 to mile 5, the pillow lavas and breccias of Kirilof Point as mapped by Carr and Quinlivan (1969) show extreme magnetic effects. Anomaly amplitudes reach values of 5,000 gammas and show standard errors of 600 gammas over near-surface and strongly magnetized lava flows. From the data of figure 12 the following near-surface source rocks may be identified: lava from mile 0 to mile 0.7, breccia from 0.8 to 1.1, mostly lava from 1.2 to 2.1, mostly breccia from 2.2 to 3.0, and mostly lava from 3.1 to 4.

The short traverse along the access road to drill hole UAe-1 presents an excellent example of the characteristic low values of standard error that are found over near-surface breccia. The traverse also locates the Mex Island anomaly more accurately than does the aeromagnetic survey. The ground data place the anomaly minimum at 0.3 mile from UAe-1--not at 0.6 mile as indicated by the aeromagnetic data of figure 8.

VOLCANIC SANDSTONE, SILTSTONE, AND TUFF BRECCIA

Although Carr and Quinlivan (1969) reported interbedded sedimentary rocks in the Chitka Point and Banjo Point Formations and in the older breccias of the Amchitka Formation, the beds are too thin to be mapped at the 1:100,000 scale, and the outcrop areas are too small to be correlated with individual aeromagnetic anomalies. Sedimentary rocks may be more extensive in some areas offshore as suggested by the abrupt change of the character of the magnetic field (fig. 2) in the area of the broad positive anomaly located about 10 miles north of Chitka Point. A thick deposit of rocks with consonant total magnetizations is required to explain the uniform nature of the field.

The histogram of figure 15 presents data from 30 core specimens of volcanic sandstone and siltstone and 31 specimens of tuff breccia collected at depths varying from 543 to 2,225 feet in drill hole EH-5. Logarithmic averages are 11.0×10^{-4} gauss/oersted for magnetic susceptibility, 1.4×10^{-4} gauss for remanent intensity, and 0.26 for Konigsberger ratio. The average density is 2.16 g/cc. Except for remanent direction, average values are similar for the volcanic sandstone and siltstone and the tuff breccia.

We assumed no structural tilting and obtained true values of remanent inclinations by measurement of drill core that was referenced to a vertical drill hole. Remanent azimuths are unknown, but we obtained a measurement of variation by referencing azimuth to a line marked along seven continuous lengths of drill core before these lengths were cut into several specimens. Figure 19 gives inclinations and variations in azimuth for drill-core samples collected from EH-5. The low average inclination of 27° for 16 specimens of volcanic sandstone and siltstone is difficult to explain. One possible explanation is the tendency of platy magnetic particles to settle horizontally and thus be only partially alined by the earth's magnetic field. Most of these samples are from graded beds or fine-grained rapidly deposited sediments. For 17 specimens of tuff breccia, the average inclination is 67° or close to the 62° value for the geomagnetic field, which suggests the effect of a viscous magnetization acquired after emplacement.

The total magnetization of volcanic sandstone, siltstone, and tuff breccia is controlled by magnetic susceptibility, or induced magnetism. The low Konigsberger ratio of 0.26 shows that the contribution of remanent magnetism is relatively unimportant. We therefore assign these fine-grained sedimentary rocks an average total magnetization of 6.5×10^{-4} gauss in the direction of the geomagnetic field.

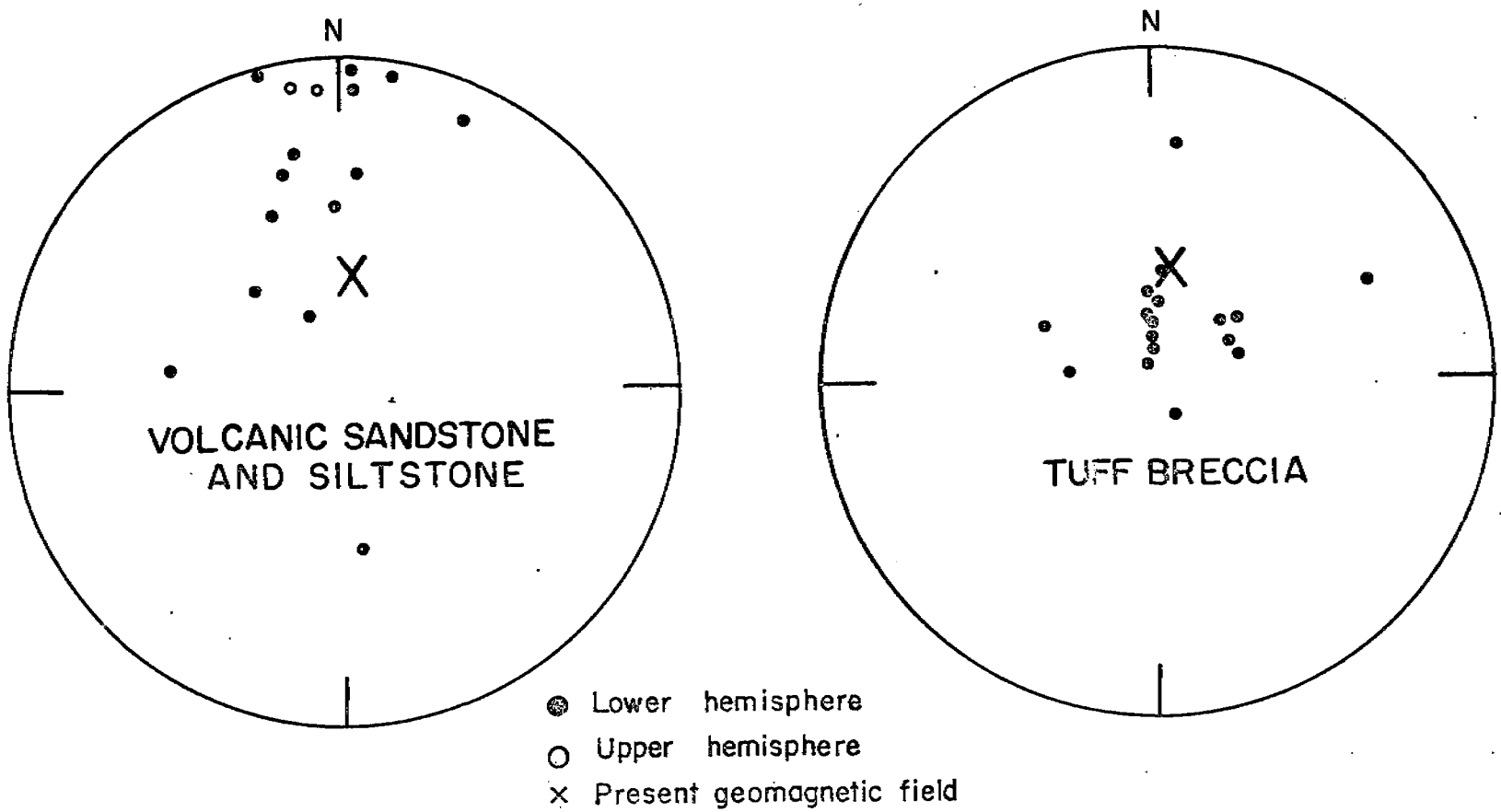

Figure 19.--Equal-area projections of remanent directions of magnetization for 16 specimens of volcanic sandstone and siltstone, and 17 specimens of tuff breccia cut from continuous lengths of core from drill hole EH-5. Differences in azimuth are referenced to an arbitrary line marked along the core before it was cut. The average of all azimuths is assumed northward, but inclinations are referenced to a vertical drill hole and they are, therefore, true values.

DIKES AND SMALL SILLS

The presence of dikes and sills beneath prominent aeromagnetic anomalies suggests that the magnetic contribution of several of these small features is sufficient to explain some of the anomalies. For example, the -780 and St. Makarius Point anomalies shown on figures 3, 9, and 10 are over complexes of basaltic dikes and small sills intruded into the Banjo Point Formation. Most of the dikes and sills exposed in these areas have thicknesses that are less than 50 feet. From the geologic detail shown by Carr and Quinlivan (1969), it seems clear that these features should be considered as possible source rocks. The St. Makarius Point and -780 anomalies are discussed in more detail under the section on interpretation of anomalies.

Data are available for 30 surface samples collected from dikes and small sills in the areas of figures 5 through 11. Logarithmic averages are 25.7×10^{-4} gauss/oersted for magnetic susceptibility, 5.5×10^{-4} gauss for remanent intensity, and 0.45 for Konigsberger ratio. A maximum value of 17.8×10^{-4} gauss for total magnetization is computed from these data. Subtracting the ambient level value (7.0×10^{-4}) from 17.8×10^{-4} gauss, the effective total magnetization for the 30 samples collected from dikes and small sills becomes 10.8×10^{-4} gauss. A single dike or small sill that has this value of effective total magnetization will produce an aeromagnetic anomaly of little importance at the datum plane 1,600 feet above sea level. Assuming a thickness, ε, of 50 feet and a depth, t, of 1,200 feet, computations using the equation

$$\Delta T_{max} = \frac{2\ J_t\ \varepsilon\ 10^5}{t} \text{ gammas,} \qquad (3)$$

gives a maximum anomaly ΔT_{max} of only 9 gammas for a total magnetization J_t of 10.8×10^{-4} gauss. Referring to figures 25 and 26, computation for a sill 50 feet thick at a depth of 1,200 feet,

$$\Delta T_{max} = \frac{2.4\ J_t\ \varepsilon\ 10^5}{t} \text{ gammas,} \qquad (4)$$

gives a maximum anomaly of only 11 gammas. Because the effect of a single dike is small, we have concluded that a complex of many dikes is required to explain a prominent aeromagnetic anomaly.

INTRUSIVE ROCKS

Samples of intrusive rock were collected from the complex of diorites and andesites exposed on the eastern part of the island, from exposures on White House Cove, Chapel Cove, and Ivakin Point, and from intrusive features that are too small to be shown on figure 3.

Magnetic properties

The histograms of figure 16 present data from 43 specimens of intrusive rock. Logarithmic averages are 12.5×10^{-4} gauss/oersted for magnetic susceptibility, 5.1×10^{-4} gauss for remanent intensity, and 0.85 for Konigsberger ratio. The average density is 2.55 g/cc. The broad spectrum of values shown in the remanent intensity histogram indicates the presence of more than one pluton. A closer inspection of the data reveals that the lower values come from the complex exposed on the eastern part of the island, including Ivakin Point. Table 1 shows an average remanent intensity of 1.3×10^{-4} gauss for eight specimens from the East Cape pluton, and 19.7×10^{-4} gauss for 16 specimens from the White House Cove intrusive.

Table 1.--Average for eight specimens collected from the East Cape pluton, and 16 specimens collected from the White House Cove intrusive

	East Cape pluton	White House Cove intrusive
Density (g/cc)	2.58	2.50
Magnetic susceptibility ($\times 10^4$ gauss/oersted)	11.9	20.8
Induced intensity ($\times 10^4$ gauss)	5.7	10.0
Induced direction		
Declination (degrees)	7	7
Inclination (degrees)	62	62
Remanent intensity ($\times 10^4$ gauss)	1.3	19.7
Remanent direction		
Declination (degrees)	181	5
Inclination (degrees)	75	69
Total intensity ($\times 10^4$ gauss)	6.6	29.6
Total direction		
Declination (degrees)	8	6
Inclination (degrees)	69	66

Difference of directions of remanent magnetism supports the concept of two separate episodes of intrusion. Experts in paleomagnetic investigations of remanent directions now generally agree that during cooling and crystallization of igneous rocks the magnetic minerals in them become magnetized in the direction of the earth's magnetic field. In the geologic past, the earth's magnetic field has changed direction and has undergone numerous complete reversals of polarity (Cox and others, 1964). Directions for 16 specimens collected from the White House Cove intrusive (fig. 20) have a normal polarity that averages 5° in declination and 69° in inclination, a direction that approximates the 7° declination and 62° inclination of the present geomagnetic field on Amchitka. Partial demagnetization of three of the specimens in alternating fields of 100 and 200 oersteds did not result in a significant change in direction, and the natural-state magnetism appears to be stable and related to the direction of an ancient geomagnetic field.

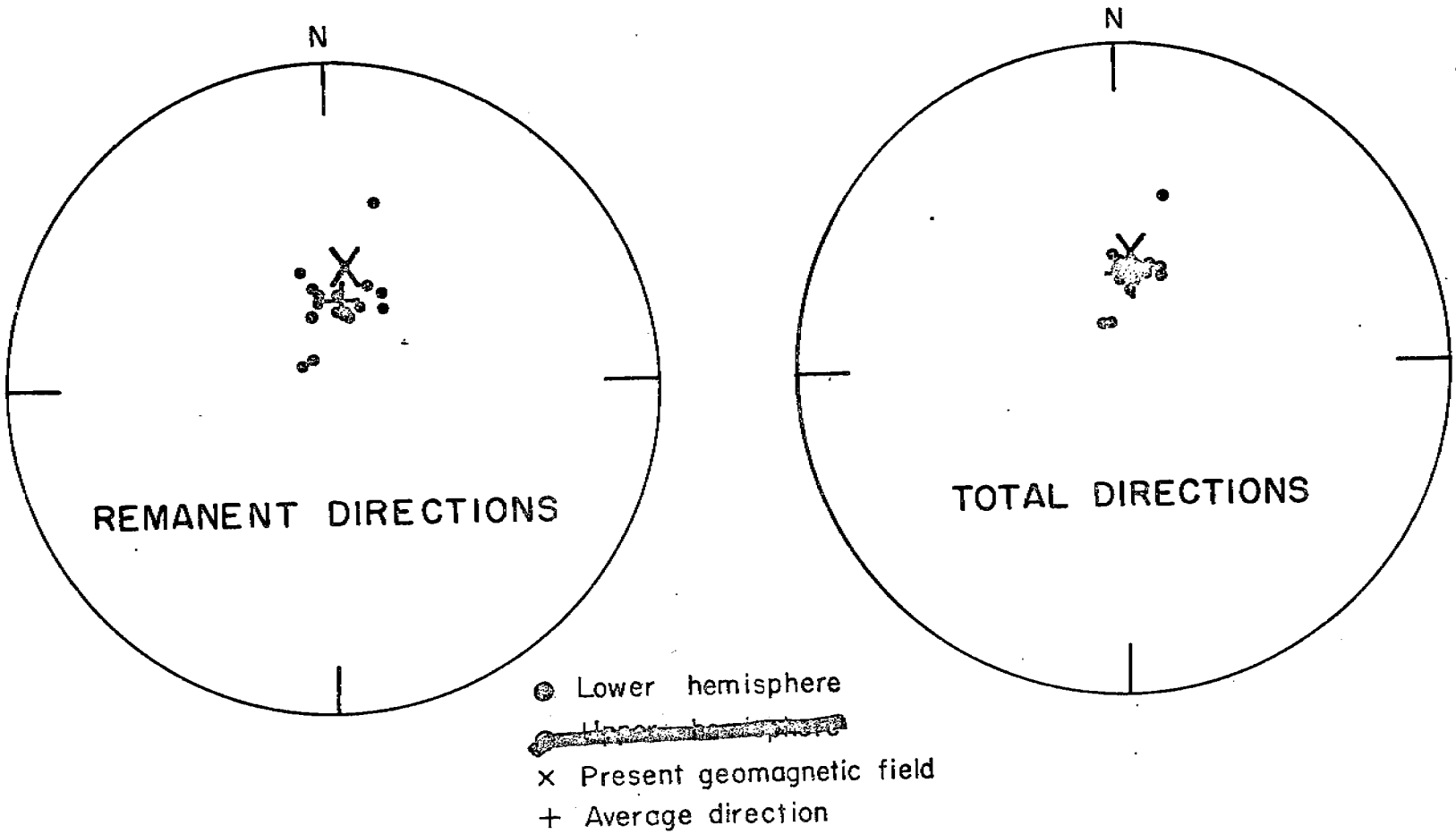

Figure 20.--Equal-area projections of remanent directions of magnetization and total directions of magnetization for 16 specimens of intrusive rock collected from surface exposures of the White House Cove intrusive.

In marked contrast, the remanent data of figure 21 from eight specimens of the East Cape pluton show an intermediate polarity with an average declination of 181° and an inclination of 75°. The natural-state magnetism contains an unstable component of viscous remanent magnetization which was removed by partial demagnetization. At 100 oersteds (table 2), inclination changed from plus to minus. The average direction for three specimens at 200 oersteds gives a reversed polarity, or a declination of 188° and an inclination of -49°.

Table 1 gives the total magnetization values that are used in the interpretive studies of the two plutons. The reader may be surprised to find that even with the reversed direction of fossil remanent magnetization for the East Cape pluton, the average direction of total magnetization, shown on figure 21, is normal and approximates the present earth's magnetic field. This is the result of the low 0.23 value of Konigsberger ratio. The remanent effect becomes trivial when it is added vectorially to the induced effect.

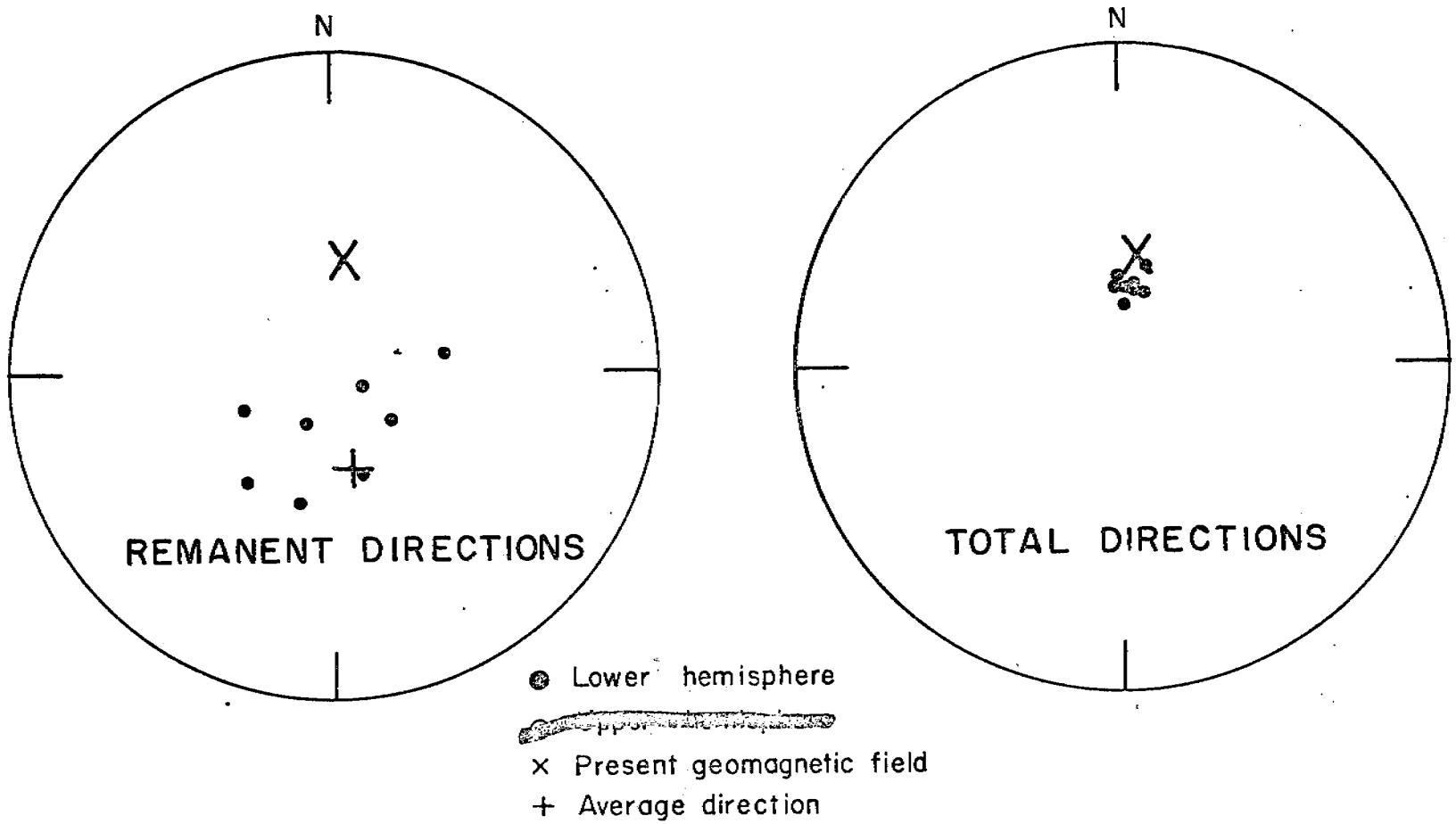

Figure 21.-- Equal-area projections of remanent directions of magnetization and total directions of magnetization for 8 specimens of intrusive rock collected from surface exposures of the East Cape intrusive.

Table 2.--Average remanent directions and intensities for three specimens collected from the East Cape pluton, measured at natural state and after partial alternating field demagnetization to 100 and 200 oersteds

	Natural state	Demagnetization level	
		100 oersted	200 oersted
Specimen B25A1-67			
Declination (degrees)	189	199	203
Inclination (degrees)	44	-49	-58
Intensity (x 10^4 gauss)	3.3	3.0	2.9
Specimen B25A2-67			
Declination (degrees)	169	187	184
Inclination (degrees)	66	-45	-45
Intensity (x 10^4 gauss)	1.5	0.7	0.7
Specimen B25C1-67			
Declination (degrees)	128	170	178
Inclination (degrees)	72	-40	-45
Intensity (x 10^4 gauss)	1.7	0.4	0.3

Aeromagnetic anomalies

The positions of several aeromagnetic anomalies that have values well below the regional level correlate with the positions of large exposures of intrusive rock. The East Cape negative anomaly is over a complex of diorites on the eastern end of the island (fig. 3). The White House Cove negative anomalies are over exposures of intrusive rock at White House and Chapel Coves. A less pronounced low occurs near the intrusive complex at Ivakin Point.

LAVA FLOWS AND THICK SILLS

Lava flows and thick sills produce most of the pronounced aeromagnetic anomalies. Of particular importance are the thick andesite lava flows of the Chitka Point Formation, the andesitic and basaltic lavas within the Banjo Point Formation, and the latitic pillow lavas of Kirilof Point in the Amchitka Formation.

Magnetic properties

The histograms of figures 17 and 18 present data from 219 surface and 81 drill-core specimens of lava flows, sills, and dikes. The surface samples were collected from all areas of the island except the areas of undivided intrusive rocks (fig. 3). Their logarithmic averages are 22.9×10^{-4} gauss/oersted for magnetic susceptibility, 9.8×10^{-4} gauss for remanent intensity, and 0.89 for Konigsberger ratio. The average density is 2.60 g/cc. The subsurface data consist of those on 30 specimens from drill hole EH-5, 12 from UAe-1, 24 from UAe-2, 10 from UAe-3, and 5 from UAe-7c. Their logarithmic averages are 36.3×10^{-4} gauss/oersted for magnetic susceptibility, 15.9×10^{-4} gauss for remanent intensity, and 0.91 for Konigsberger ratio. The average density is 2.49 g/cc.

Although remanent directions at Amchitka appear generally constant throughout individual flows or sills, average directions may change from formation to formation, and even within some formations. For example, all pieces of the pillow lavas of Kirilof Point from core runs 4, 5, 6, 16, and 18 of UAe-1 (Gard and others, 1969) have negative inclinations that average about -60°. The change from formation to formation is demonstrated by the data from drill hole UAe-2, located about 5 miles southeast of UAe-1. Four core samples of lava collected from the Banjo Point Formation at depths of 2,578-3,103 feet have positive rather than negative inclinations that average 68°. However, not all units in the Banjo Point have the same magnetic characteristics, as illustrated by the negative inclinations of lava samples at depths of 2,227-2,244 feet in drill hole EH-5.

Small changes in remanent inclination can be interpreted in a similar manner. Inclinations of andesite core from EH-5 have the following averages and 95-percent confidence intervals: 76±6° for seven samples from 2,340.8- to 2,342.2-foot depth; 55±11° for eight samples from 2,466- to 2,468.3-foot depth; and 41±4° for five samples from 2,479.7- to 2,480.9-foot depth. The 76° average differs significantly from the 55° and 41° averages, and we thus assume that the andesite at the more shallow depth was emplaced at a different time.

The remanent data plotted on figure 22 indicate that the thick lava flows of the Chitka Point Formation have normal polarities. The 58 surface specimens collected from 26 samples at 11 sampling sites average 26.4×10^{-4} gauss/oersted for magnetic susceptibility, and 15.1×10^{-4} gauss for remanent intensity. Average total magnetization is 27.4×10^{-4} gauss with a direction that approximates the present geomagnetic field.

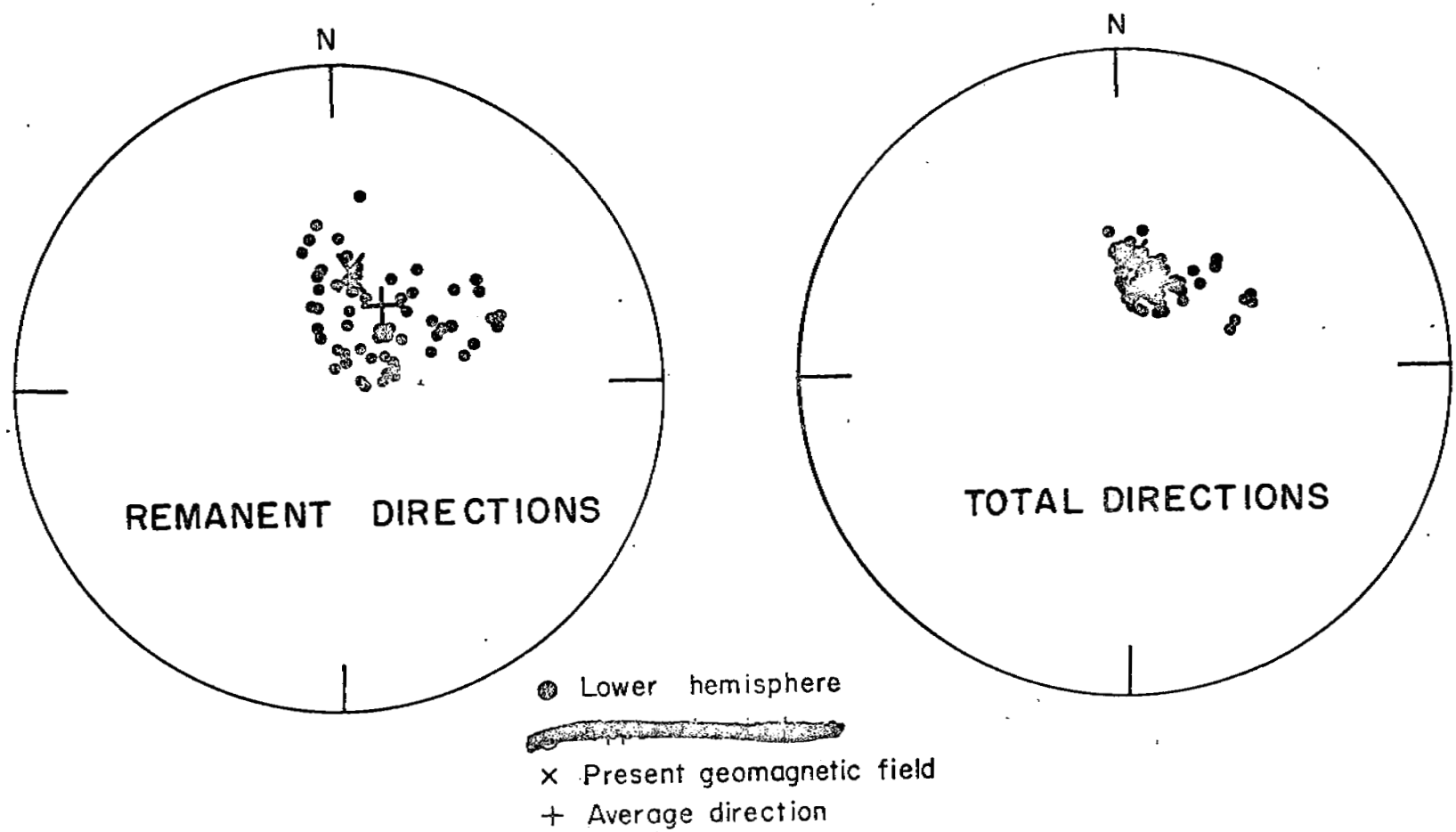

Figure 22.--Equal-area projections of remanent directions of magnetization and total directions of magnetization for 58 specimens of andesitic lava collected from surface exposures of the Chitka Point Formation.

A few strongly magnetized surface samples that we have collected to date show intermediate remanent polarities. For example, the 10 surface specimens of basalt collected from five samples at four sampling sites in the Banjo Point Formation average 29.1×10^{-4} gauss/oersted for magnetic susceptibility, and 114.6×10^{-4} gauss for remanent intensity.

The intermediate directional data for these samples are shown on figure 23. The average total magnetization for these samples is 111.5×10^{-4} gauss with a declination of 316° and an inclination of -26°.

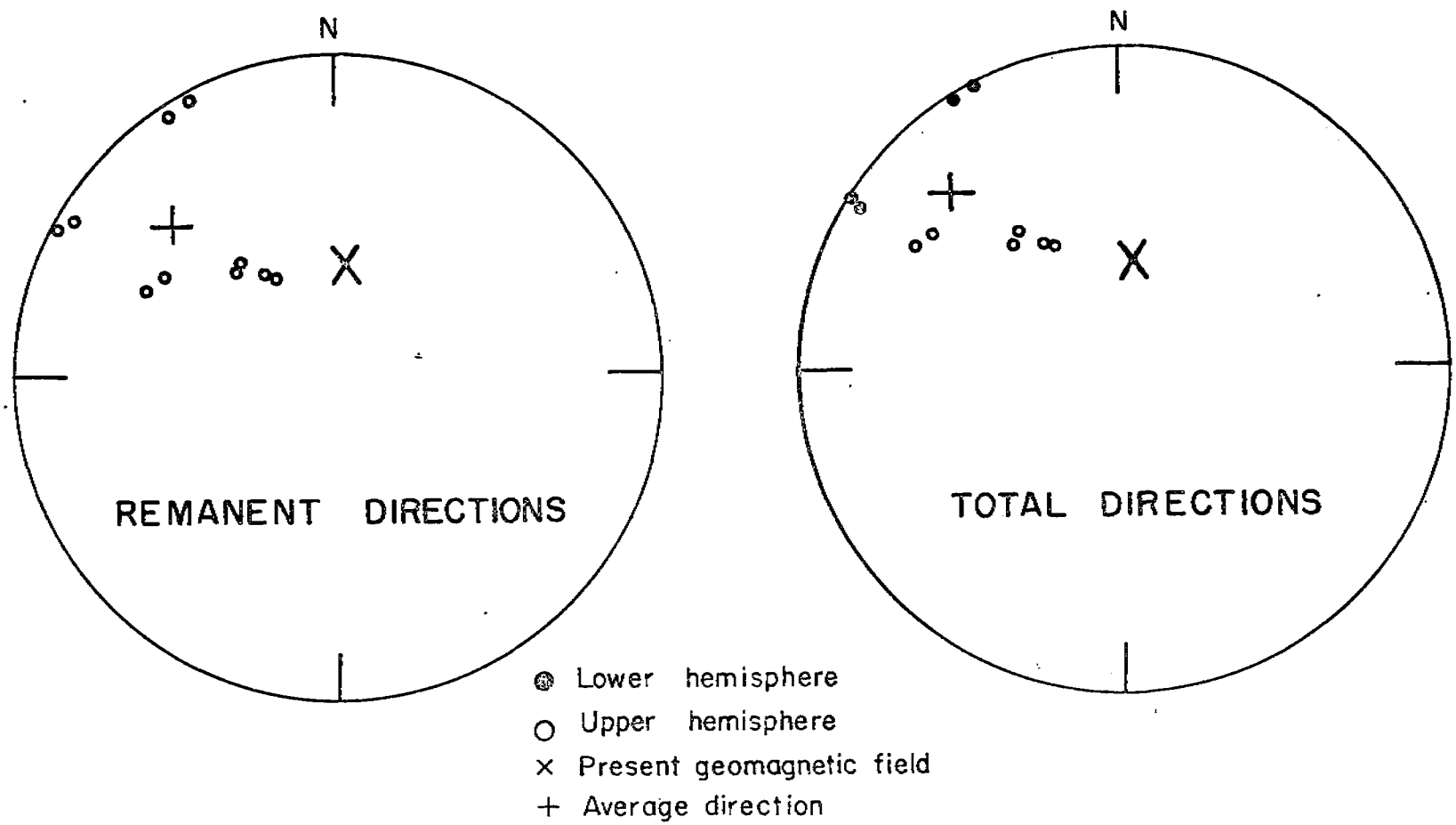

Figure 23.--Equal-area projections of remanent directions of magnetization and total directions of magnetization for 10 specimens of basaltic lava collected from surface exposures of the Banjo Point Formation.

Aeromagnetic anomalies

The positions of several aeromagnetic anomalies with values well above the regional anomaly correlate with the positions of known exposures of relatively young andesite lava flows of the Chitka Point Formation. Bird Rock, Windy Island, and Site F positive anomalies are over these flows on the northwestern part of the island (fig. 3). The Infantry Road anomaly is over exposures that are mainly breccia, but flows probably lie beneath the breccia. The edge of the large positive feature named the Chitka Point-Constantine Point anomaly is also over the flows. It has been previously pointed out (p. 37) that the positive Site B anomaly and the negative Mex Island, -780, and Rifle Range Point, and Pillow Point anomalies are at least partly related to older lavas that are buried within or beneath the Banjo Point Formation.

Ground survey anomalies

The data obtained from the traverses and plotted on figure 12 show the characteristic irregular pattern of magnetic anomalies over lava. Weiss (1949) was perhaps the first investigator to point out the extreme variations found in the ground anomalies beneath the aeromagnetic anomalies caused by near-surface and reversely magnetized rocks.

Data obtained from the short traverse along Clevenger Road illustrate the effects of strongly magnetized rock buried beneath nonmagnetic rock. The irregular and negative residual anomalies indicate rocks with strong remanent intensities and reverse polarities that are assumed to be the pillow lavas of Kirilof Point. The low values of standard error indicate near-surface rocks that are considered nonmagnetic, such as breccia or alluvium.

ANALYSIS OF MAGNETIC ANOMALIES

A detailed investigation of the complex anomaly patterns given in the Amchitka aeromagnetic survey is possible in areas where individual anomalies stand out so clearly that they can be separated from neighboring magnetic effects. By means of our understanding of geologic structure and magnetic properties of the rocks on the island, we are able to identify many of the anomaly-producing features, compute estimates of depths to their tops, and make inference about their lateral extents and thicknesses.

The identification of anomaly-producing features becomes more difficult over the insular shelf where little is known about marine geology. However, considerations of magnetic properties and magnetic anomalies over the island units permit a qualitative analysis of many of the anomalies shown in figures 4-11. The most likely causes of complex anomaly patterns are the strongly magnetized lava flows and thick sills within the Amchitka and Banjo Point Formations; the positive anomalies being related to rocks with positive inclinations of remanent direction, and the negative anomalies to rocks with negative inclinations of remanent direction. Most of the broad positive anomalies with the more moderate anomaly patterns are undoubtedly produced by normally magnetized lava flows of the Chitka Point Formation. Areas of relatively uniform anomaly could overlie large volumes of either intrusive rock, sedimentary rock, or volcanic breccia.

Depth estimates

Several investigators working in petroleum-rich areas have pointed out the advantage of using aeromagnetic data to obtain preliminary estimates of the thickness of the sedimentary section throughout extensive areas (Steenland, 1965; Henderson and Zietz, 1958). Their premise is that sedimentary rocks are nonmagnetic and any magnetic anomalies must originate from the underlying igneous rocks. Calculation of depth to the magnetic rock therefore yields a thickness estimate for the sedimentary rocks.

On Amchitka, the igneous rocks are at or very near the surface and our premise is that some rocks, such as volcanic breccia, are relatively nonmagnetic and do not significantly distort aeromagnetic anomalies arising from deeper, strongly magnetized rocks. These magnetic anomalies were analyzed to determine thicknesses of breccia, some lava flows, and other rocks with low magnetizations. Also, computed depths were compared with the actual depths of known geologic features that have been obtained by drilling.

In general, shallow sources give sharp anomalies with short wave lengths, and deep sources give broad anomalies with long wave lengths. Numerous simple rules have been introduced to determine depth or some other dimension of the anomaly source (Vacquier and others, 1951; Grant and West, 1965). Most rules are made in accordance with some property of an anomaly calculated for models of varying depth, length, width, thickness, magnetization, or geomagnetic latitude. Often the property consists of the horizontal distance between two critical points of the anomaly. For most Amchitka anomalies, computations were made for horizontal sheet and dipole models: first, the extent of maximum slope (Vacquier and others, 1951), second, the interval between the one-half maximum slope intersections with the anomaly curve (Peters, 1949), and third, the interval between inflection points (Bean, 1966). Comparison of these computed anomaly properties with similar properties of an actual anomaly will yield the depth estimate.

Figure 25 was prepared to illustrate observed data from magnetometer records, anomalies produced by near-surface rocks, and an anomaly produced by rocks below sea level. The data were recorded at a scale of about 1:30,000, and the distance from airplane to ground and water surface was obtained by radio altimeter. Anomaly analysis indicates that the rocks causing the shelf-break anomaly are along the shelf break and 1,100 feet below sea level, those causing Bird Rock anomaly are at the ground surface, those causing the two dipole anomalies on the north side of Infantry Road anomaly are at the ground surface, and those causing the Infantry Road anomaly and the dipole anomaly on its south side are buried 500 feet beneath the ground surface.

Dipole and sheetlike models

In spite of the complexity of the earth's magnetic field at a barometric elevation of 1,600 feet (fig. 2), certain individual anomalies do stand out (fig. 3) and they appear to represent the effect of single, magnetized bodies. For these anomalies, a quantitative method of interpretation may give information on the length, width, and thickness of the magnetic feature. The method consists of finding the model, or models, that are both reasonable geologically and capable of causing an effect equivalent to the anomaly.

A sharp anomaly with an interval of only about one depth unit, or less, between maximum and minimum values as the effect of a point dipole model was considered. One depth unit is equal to the distance from airplane to anomaly-producing rocks. Such a model represents a fairly small geologic feature that has dimensions roughly the same in all directions. Experimental examples of dipoles are the three small anomalies shown superimposed on the Infantry Road anomaly of figure 25, and theoretical examples are data on the five traverses shown on figure 26. The dipole anomaly portrays the limiting case that gives no information on the dimensions of the source. A strongly magnetized body that measures only a few feet on a side will produce the same anomaly configuration as a body with dimensions up to about half a depth unit. Larger dimensions will distort the anomaly and thus show a shape effect.

To investigate the dipole effect, anomalies for five directions of traverse over a dipole source were computed from $\frac{\Delta T t^3}{\mu}$ (equation (8) of Hall (1959, p. 1947)), as shown on figure 26. The depth from datum line to source is designated t, and traverse distance, x, is expressed in depth units. The direction of total magnetization is parallel to the earth's magnetic field at Amchitka, μ is the dipole moment, and ΔT is the anomalous total magnetic field measured by the airborne magnetometer.

Lava flows frequently occur as well-defined magnetic bodies that have dimensions that nearly approach those of a horizontal sheetlike model. The sheet model has practical importance also, because its anomaly does not change in shape for the sake of increases in thickness up to about one depth unit. The anomaly pattern does change for increases in length as shown on figure 27 and for increases in width as shown on figure 28. Also, when the average total magnetization of the body is known, calculations based on the anomaly amplitude will give an estimate of thickness.

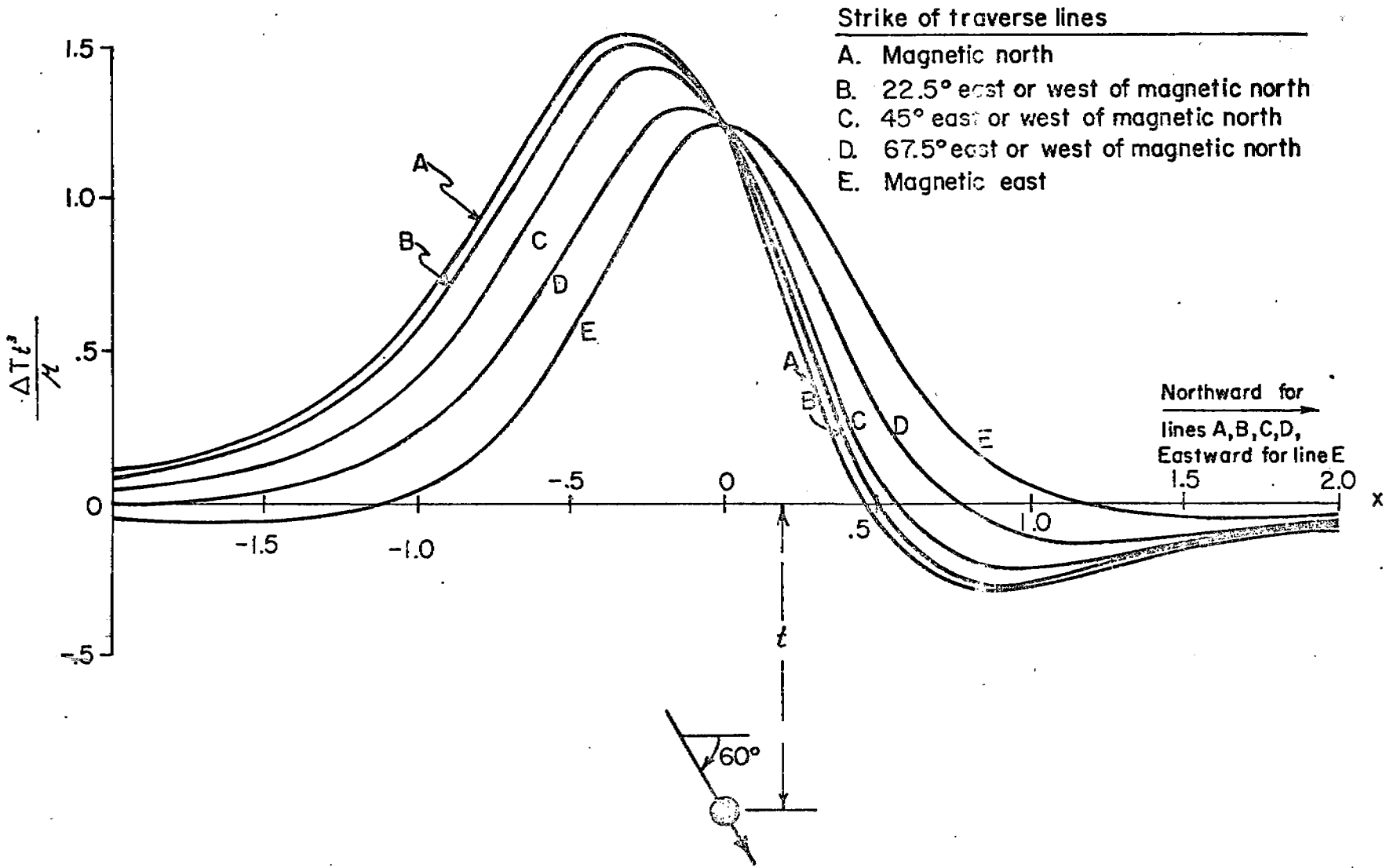

Figure 26.--Theoretical magnetic anomalies computed for five directions of traverse over a dipole source magnetized along the geomagnetic field with an inclination of 60°.

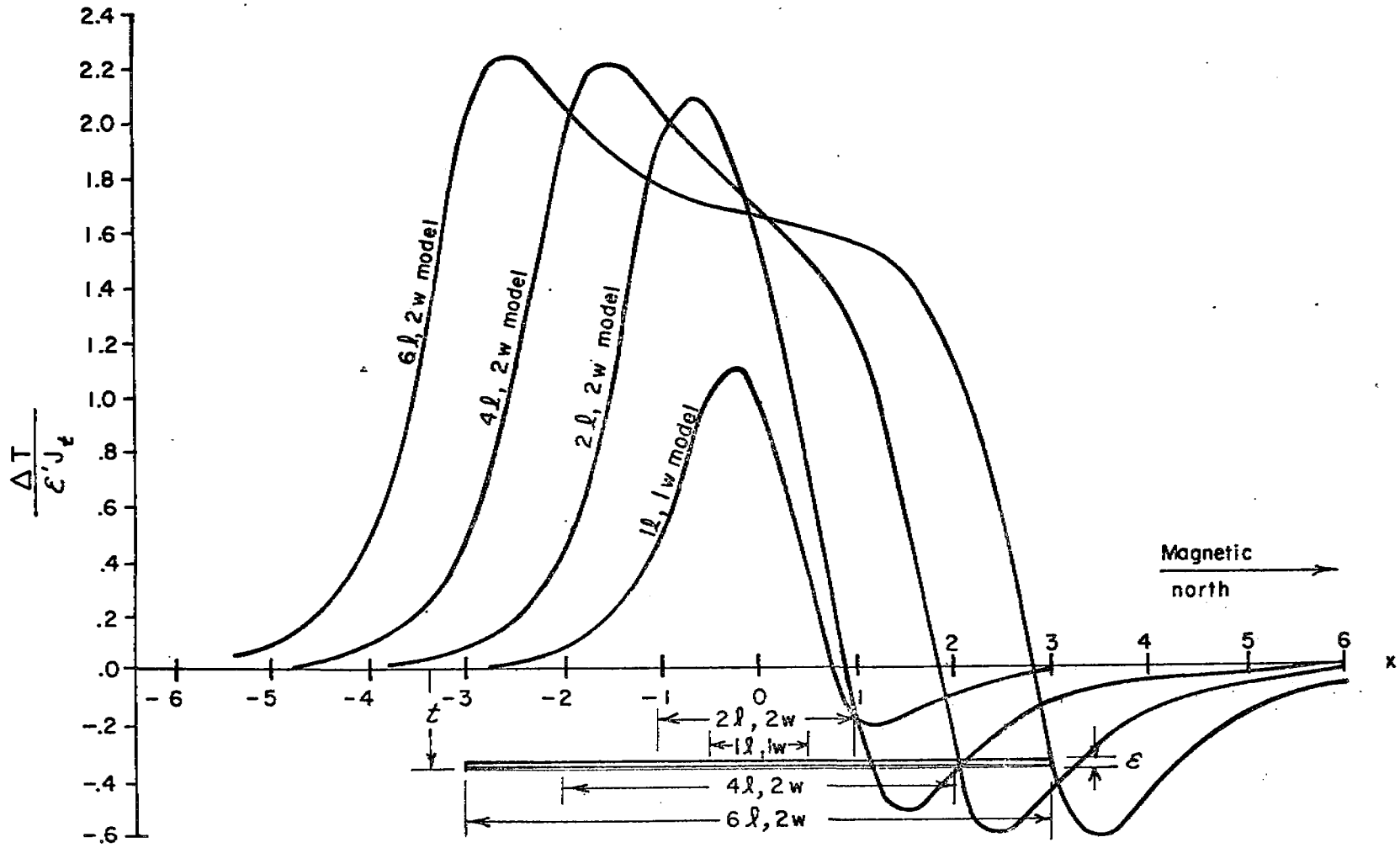

Figure 27.--Theoretical magnetic anomalies computed for traverses striking magnetic north over the centers of four rectangular sheet models magnetized along the geomagnetic field with an inclination of 60°. Model length l, width W, thickness ε, and traverse distance X are expressed in units of depth t.

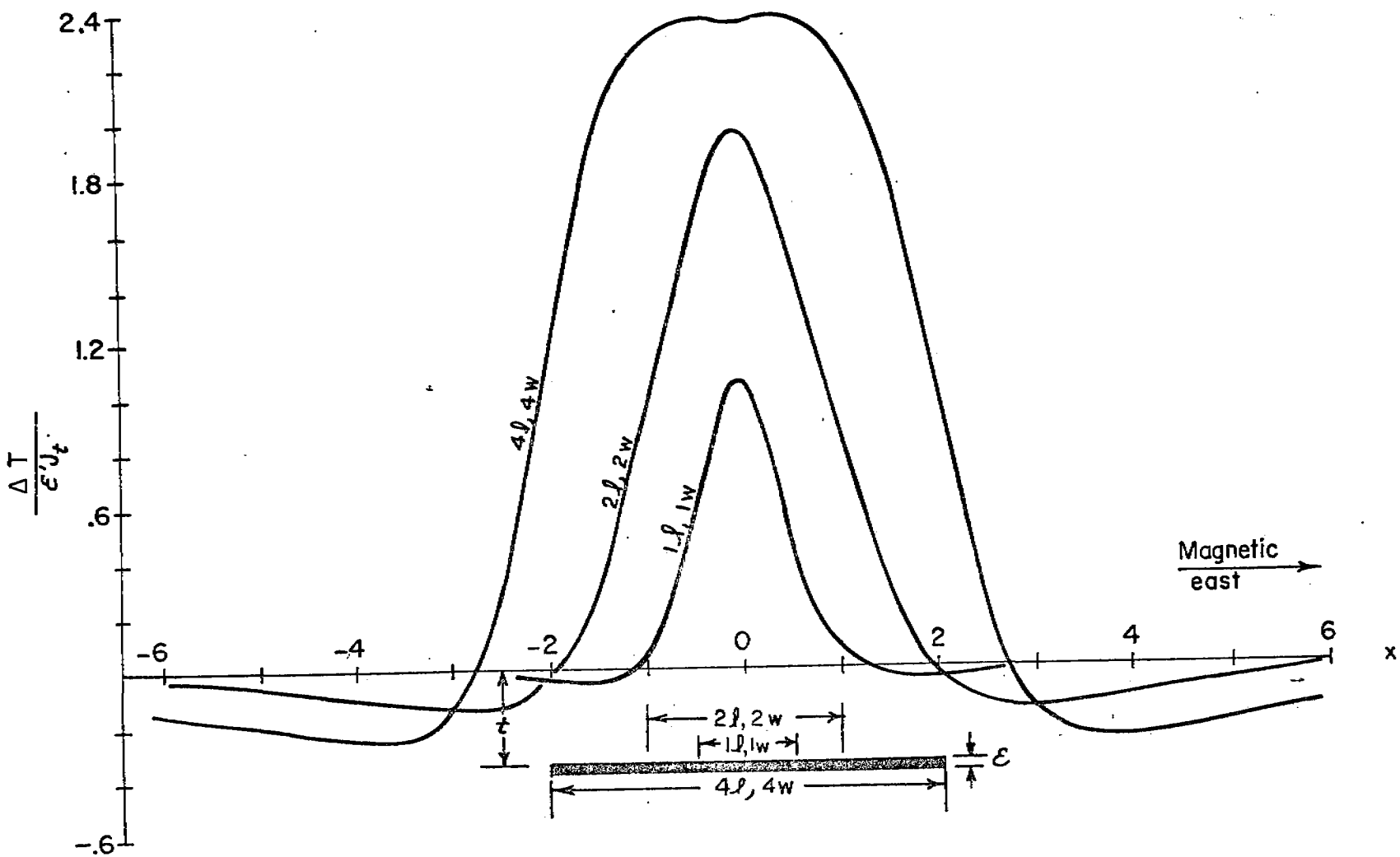

Figure 28.--Theoretical magnetic anomalies computed for traverses striking magnetic east over the centers of three square sheet-like models magnetized along the geomagnetic field with an inclination of 60°. Model length l, width W, thickness ε, and traverse distance X are expressed in units of depth t.

The anomalies of figure 27 were computed from equations 4.3a and 4.3b of Werner (1953, p. 17), and the anomalies of figure 28 from the prismatic models of Vacquier, Steenland, Henderson, and Zietz (1951) by using a thickness of one-third depth unit and then converting to the sheet notation. The direction of total magnetization $\vec{J}_t$ is parallel to the earth's magnetic field at Amchitka, and the thickness of the sheet model, ε, is expressed in depth units ε', where $\varepsilon' = \frac{\varepsilon}{t}$. The model length l, and width w, and the traverse distance x are also expressed in units of depth t.

INTERPRETATION OF ANOMALIES

The following discussion deals with some of the magnetic anomalies that can be explained by known geologic facts. Also discussed are some anomalies and anomaly patterns that are subject to more conjectural interpretations.

The lava flows and thick sills produce most of the anomalies found in the aeromagnetic survey. The theoretical magnetic anomalies plotted on figures 27 and 28 show steeper gradients near the boundaries of models, which represent simplified configurations for flows or sills with horizontal attitudes. Most drill holes are located away from the strong anomalies that have dominant trends or are terminated abruptly. Termination may also be caused by erosion or other geologic processes, and the present authors have relied heavily on geological evidence before designating a feature as fault related.

Remanent magnetization exerts the most marked influence on the total magnetization of flows and sills, and remanent direction thereby becomes a dominant factor in determining anomaly configurations. The Konigsberger ratio, $Q = J_r/J_i$, averages 0.9 for all the measured andesite and basalt specimens, and the ratio increases for many anomaly-producing formations. For example, the 58 specimens from the Chitka Point lavas (fig. 22) have a ratio of 1.2, and 10 specimens of basalt (fig. 23) have a ratio of 14.0.

East Cape anomaly

At East Cape, Pillow Point, and Ivakin Point the diorite complex intrudes the older breccias and the pillow lavas and breccias of Kirilof Point. Contact metamorphism has locally changed some of the wallrock to hornfels. Explanation of the broad negative anomaly in the area of East Cape is based on the very low remanent intensity of the diorite and the somewhat higher values of the intruded breccia. Eight specimens of diorite (table 1) have a low average total intensity of 6.6×10^{-4} gauss along the direction of the geomagnetic field, which is a value just under the ambient level for the island. Thirteen samples of breccia, dikes, and sills from the area mapped as older breccia and hornfels (fig. 3) have somewhat higher average values: 4.4×10^{-4} gauss for remanent intensity, and 10.0×10^{-4} gauss for induced intensity, but the contrast is probably insufficient to explain the anomaly. We therefore conclude that lava flows in the older breccia are strongly enough magnetized to cause the contrast. Examples are samples Q57-66 and Q12-67 (fig. 10) which have high average remanent and induced intensities of 156×10^{-4} and 24.5×10^{-4} gauss. Drill hole UAe-2 at site B penetrated several thick bodies of mafic magnetic rock in this general part of the section. For example, a hornblende-andesite sample, collected at a depth of 6,002 feet, has remanent and induced magnetizations of 14.0×10^{-4} and 20.9×10^{-4} gauss.

White House Cove and shelf break anomalies

Another prominent negative anomaly related to intrusive rock is at White House Cove directly over outcrops of diorite porphyry that intrude the Banjo Point Formation and probably the Chitka Point Formation. The anomaly curves across the island to the Bering Sea side of Amchitka where there is a small outcrop of diorite (Carr and Quinlivan, 1969).

Two possibilities that require relatively low values of magnetization to explain the negative anomalies were considered. The first assumes that the White House Cove intrusive has a total magnetization lower than that of the adjacent rocks. The limited sample data now available do not support this concept. According to table 1, the diorite has a total intensity which is well above the ambient level for the island and which is about equal to the total intensity of the Chitka Point lavas. This relatively high value of magnetism would result in a positive rather than a negative anomaly relative to the Banjo Point, and practically no anomaly relative to the Chitka Point.

The second possible explanation of the anomaly seems to be more reasonable. It requires a local decrease of magnetism in the near-surface volcanic rocks that overlie the pluton, and it requires a laccolithic structure that would give the pluton a thickness about equal to the total thickness of the Chitka Point lavas. A thicker intrusive could change the anomaly from negative to positive. The anomaly also extends over intensely altered lava flows of the Chitka Point Formation (fig. 3). This hydrothermally altered rock is represented by samples B4-67, B5-67, and Q30-67, which have an extremely low total average magnetization of 0.5×10^{-4} gauss, indicating almost complete destruction of magnetite. Lava and breccia samples collected beneath the anomaly, but outside the intensely altered zone, such as samples C75-67, C76-67, and B19-67, have an average total magnetization of 5×10^{-4} gauss, which is also well below the regional level. Much of this area has weak to strong propylitic alteration, the chief minerals of which are pyrite, chlorite, and quartz.

Figure 2 shows that the White House Cove anomaly is only part of a much bigger negative anomaly that extends from the Bering Sea coast of Amchitka northwestward more than 25 miles, culminating in a very pronounced negative anomaly over the eastern part of Rat Island. The part north of the northwestern tip of Amchitka is designated as the shelf-break anomaly on figure 3. Its termination may be related to faulting along the shelf break, the escarpment that parallels Rat Island and Amchitka Island on the north. On Rat Island the anomaly is over diorite porphyry that appears to be identical to the diorite on Amchitka. Alteration is also locally intense on this part of Rat Island. The total pattern of the anomaly thus tends to be an elongated partial oval inside of which are located lavas and probably source vents for the Chitka Point andesite lava flows. Gravity data (Miller and others, 1969) show that the western end of Amchitka is a gravity low. In addition, remanent directions shown on figures 18 and 22 are very similar for the White House Cove intrusive and the surrounding Chitka Point lava flows, indicating the possibility that these rocks may be nearly contemporaneous. The two rocks--intrusive and lava--are also similar petrographically. All these data, though sketchy, suggest that the western end of Amchitka and the eastern end of Rat Island may constitute a large volcanic center related to the Chitka Point Formation and that the diorite porphyry may be a series of large ring dikes related to the volcanic center.

Pillow Point and Rifle Range Point anomalies

Analysis of the negative anomalies that trend southeastward from Pillow Point (figs. 3, 10, and 11) indicates source rocks that are (1) near surface, (2) magnetized in a negative or upward direction, and (3) elongated in the direction of strike. The anomaly is less than 2,000 feet wide, but extends southeast from the island 6 miles. At the shoreline of Amchitka the anomaly correlates with pillow lavas of Kirilof Point as mapped by Carr and Quinlivan (1969). The anomaly is also over intrusive rocks at Pillow Point. Although intrusive rock samples C83-66 and Q79-66 (fig. 10) were not oriented to determine remanent direction, other data show that they do not have the required total magnetization and have a negative or upward direction. Their average induced intensity (20.1×10^{-4} gauss) is greater than the remanent intensity (17.8×10^{-4} gauss), and this will result in a total magnetization with a downward direction. The pillow lavas of Kirilof Point, however, are known to have upward total direction, and these rocks crop out beneath the anomaly and have a strike that is nearly the same as the anomaly.

Part of the Rifle Range Point anomaly (fig. 3) correlates fairly well with the same pillow lavas of the Kirilof Point that are presumed responsible for the Pillow Point anomaly. However, the anomaly diverges from outcrops of the pillow lavas and appears to follow the southeast side of the Rifle Range fault out into the Pacific. The rocks that cause this part of the anomaly have not been identified, but a possible explanation is given in the following discussion of the St. Makarius Point anomaly.

St. Makarius Point anomaly

The downward inclination of the total magnetization of the five samples collected from dikes and sills beneath the St. Makarius Point negative anomaly (figs. 9 and 10) shows that these are not source rocks. Depth estimates support this interpretation. The depth estimated from the negative anomaly on profile T-16 (fig. 2) is at least 500 feet below the surface. The anomaly is near the axis of a gentle syncline that trends northeast. This fold may be a result of uplift due to intrusion of the diorite to the east. It seems reasonable to assume that the St. Makarius Point anomaly is caused by reversely magnetized but locally thicker pillow lavas near the top of the Kirilof Point rocks. These would lie between 1,000 and 1,500 feet below the surface at the location of the anomaly. The apparent thickening of this reversely magnetized lava in a structural depression further suggests that this depression was present in late Kirilof Point time, which means that structural movements may have begun in Kirilof Point time. Support for this concept is also found in the previously mentioned Rifle Range Point anomaly wherein source rocks of the strongest negative anomalies are buried and displaced away from the trend of the present strike of these lavas. Here, too, the only rocks known to be capable of causing the anomaly are pillow lavas of Kirilof Point. These may be thicker and structurally localized in the Rifle Range Point area, just as they are thought to be in the St. Makarius Point area. Furthermore, the largest and most intense negative anomalies on or near Amchitka lie offshore (fig. 2) south and west of the Rifle Range Point anomaly where one string of negative anomalies projects seaward, culminating in a large negative anomaly about 4 miles southwest of Rifle Range Point.

Mex Island anomaly

This negative anomaly appears to be another that is attributable to the pillow lavas of Kirilof Point. It occupies a position on the upthrown side of a major fault, like those anomalies at Rifle Range and St. Makarius Points. Although the Kirilof Point does not crop out in this area, drill hole UAe-1 encountered pillow lavas of the Kirilof Point at a depth of about 1,400 feet. The depth estimated from the anomalies on profiles T-130 and T-8 (fig. 2) is 1,300 feet to the top of the source rocks. A considerable portion of the section penetrated between 1,400 and 6,100 feet in UAe-1 is reversely magnetized, although at most depths the remanence is weak. Like the Rifle Range Point anomaly, the Mex Island anomaly extends seaward several miles to a large pronounced low over the ocean floor (fig. 3).

Relation of submarine structure south of Amchitka to aeromagnetic anomalies

A comparison of figures 2 and 24 with the generalized geologic map (fig. 3), which shows possible submarine faults beneath the Pacific Ocean, indicates that landward projections of the pronounced submarine canyons on which the existence of these faults is inferred do not show a consistent relationship with aeromagnetic contours. Many of the hypothetical faults cross the aeromagnetic contours at fairly large angles. Although there is a suggestion of local parallelism between aeromagnetic contours and inferred submarine faults above the submarine terrace at about 325 feet below sea level, most faults on Amchitka, such as the pronounced Rifle Range fault (fig. 3), apparently either die out seaward or become overlapped by anomaly-producing rocks. A fault inferred from submarine contours by Carr and Quinlivan (1969) to trend northeast through South Bight would have to cross the Pillow Point anomaly without producing any marked effect on the aeromagnetic pattern.

The erratic distribution of anomalies with respect to submarine topography (fig. 24) south of Amchitka might be explained by an intersecting fault system, by interruption of faults by intrusive masses, or a combination of both.

Bird Rock, Windy Island, Chitka Point-Constantine Point anomalies

The Chitka Point andesite lava flows are normally magnetized, and where relatively thick or high in total intensity, they produce positive anomalies. Examples are the Bird Rock, Windy Island, and Chitka Point-Constantine Point anomalies (fig. 3). Almost all oriented samples collected beneath these anomalies have positive remanent inclinations. The one notable exception which has a high negative inclination value, sample B7-67 (fig. 7), was collected from a feature that is probably too small to give an aeromagnetic anomaly.

The Windy Island anomaly corresponds with a pile of fairly young subaerial andesite lava flows that make up the highest part of Amchitka. These flows dip seaward from the high points of the island and the aeromagnetic data suggest that they extend well out into the ocean, particularly south of Windy Island. As previously described, the White House Cove anomaly, a result of alteration associated with intrusive rock, appears to cut across the anomaly produced by the less altered lavas of the Chitka Point Formation.

The Chitka Point-Constantine Point anomaly is mostly over water, but at the northwestern end it is over lava flows of the Chitka Point Formation. It seems reasonable to assume that these lavas, which appear to dip seaward, thicken or are less altered northeast of Amchitka in the area of the anomaly. It is also possible that the southeastern part of the anomaly may be due to basaltic rocks in the Banjo Point Formation.

The Infantry Road anomaly, which is also over the Chitka Point Formation, is mostly over altered andesitic breccias that are not highly magnetic. It is possible that the anomaly results from andesite lava flows buried beneath the breccias. Andesite is reported at a depth of about 80 feet in a drill hole in the eastern part of this area.

Site B anomaly

This anomaly just north and on the downthrown side of the Rifle Range fault is an example of several positive anomalies over fault-block wedges of Banjo Point Formation. Another unnamed anomaly lies in a similar position north of the major fault from St. Makarius Bay to Constantine Harbor.

-780 anomaly

This negative anomaly appears to be produced by a reversely magnetized near-surface lava flow or sill in the Banjo Point Formation. The body is represented by sample C24-67 (fig. 9). It has a magnetic susceptibility of 35.5×10^{-4} gauss/oersted, a remanent intensity of 37.5×10^{-4} gauss, a remanent declination of 210°, and a remanent inclination of -57°.

Site F anomaly

The anomalies discussed so far stand out clearly from those in neighboring areas, and they are reflected by data taken on several aeromagnetic traverses. The Site F anomaly is one of the numerous small anomalies that relate to only one or two traverses. The anomaly has an amplitude of 150 gammas in the aeromagnetic survey (fig. 7) and 500 gammas in the ground magnetic survey (fig. 12).

A depth estimate from profile T-123 (fig. 2) places the anomaly-producing rocks at about 100 feet below the ground surface. Drill hole UAe-3, which started in breccia, penetrated Chitka Point andesite at a depth of 180 feet (Lee, 1969). Four drill-core specimens of the lava average 36.0×10^{-4} gauss/oersted for magnetic susceptibility, 3.9×10^{-4} gauss for remanent intensity, and 68° for remanent inclination. If we assume a northward declination, the average total magnetization becomes 21.2×10^{-4} gauss for intensity, 6° for declination, and 64° for inclination.

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