MAGNETIC ANOMALIES NORTHEAST OF SHATSKY PLATEAU

A Thesis

by

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ABSTRACT

Magnetic Anomalies Northeast of Shatsky Plateau. (May 1982)

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The previously mapped east-west trending magnetic lineations northeast of Shatsky Plateau are reinterpreted to be northwest trending lineations of Early Cretaceous age. These lineations were formed along the Pacific-Farallon (P-F) spreading ridge system and are part of the Hawaiian lineation set. The northwest trending Hawaiian lineations meet the northeast trending Japanese lineations to form a magnetic bight north of Shatsky Plateau. The bight is interpreted to be evidence of a ridge-ridge-ridge (RRR) triple junction which existed from about 124 MYBP (anomaly M10N time) into the Cretaceous Quiet Period.

A ridge-fault-fault (RFF) triple junction existed at Shatsky Plateau for about 17 MY (anomalies M19-M10N time). The plate boundaries were: a Pacific-Farallon (P-F) transform fault, a Pacific-Kula (P-K) spreading ridge, and a Kula-Farallon (K-F) transform fault. The RFF geometry predicts the observed northeasterly migration of the triple junction and increasing offset, with age, of the Japanese and Hawaiian lineations. A stable RFF implies the K-F spreading rate equalled the P-F rate (35.3 mm/yr half rate) and, for mid-range values of P-K spreading (30 mm/yr at N23°W), the direction of K-F spreading was east-west.

At about anomaly M10N time, the relative motion between the Pacific and Farallon plates changed. This change produced instability at the RFF triple junction and it reverted back to an RRR north of Shatsky Plateau. This triple junction reorganization was accompanied by fracturing and initiation of spreading along the old P-F transform fault.

The Mesozoic geomagnetic reversal model younger than M3 (114 MYBP) has been modified to reflect the presence of an extra interval of reversed polarity observed on the anomaly profiles of the study area and the Phoenix and Keathley lineations. The added interval, between M1 and CL or M0, is labelled CL1 and the time bounds are 111.5 to 112.0 MYBP.

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Special thanks to Chao-Shing Lee, Waris Warsi, and Mike Carnes for their assistance in developing the computer programs used for this study and for their advice at many stages of my research.

Seiya Uyeda kindly provided me with Japanese bathymetry maps including soundings of my study area. The suggestions of Tracy Vallier were very helpful to my research.

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INTRODUCTION

General

The Northwest Pacific Ocean crust in the vicinity of the Shatsky Plateau contains key information regarding the evolution of the Pacific plate. This region is the site of the Late Mesozoic triple junction or intersection of the Pacific-Kula-Farallon (P-K-F) plates (Hilde et al., 1976). Reconstructions of the Pacific plate evolution for Mesozoic time rely heavily on the resolution and interpretation of the magnetic anomalies in the region of Shatsky Plateau. The complementary record of spreading on the Kula and Farallon plates has since been destroyed and cannot be used to deduce the spreading history of the Pacific plate.

The term plateau will be used in lieu of "rise", as in Shatsky Rise, in this thesis. During early sea floor mapping, the term "rise" was popularly used to describe any large, shallow feature regardless of its origin. Recently, there has been an effort to distinguish between spreading ridges referred to as rises, and isolated platform-like arches rising above the surrounding sea floor (Jones et al., 1979). The latter feature is more appropriately described as a plateau. Hence, the term plateau is used for large, isolated bathymetric features that are significantly higher than the surrounding sea

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floor but not now associated with active spreading ridges.

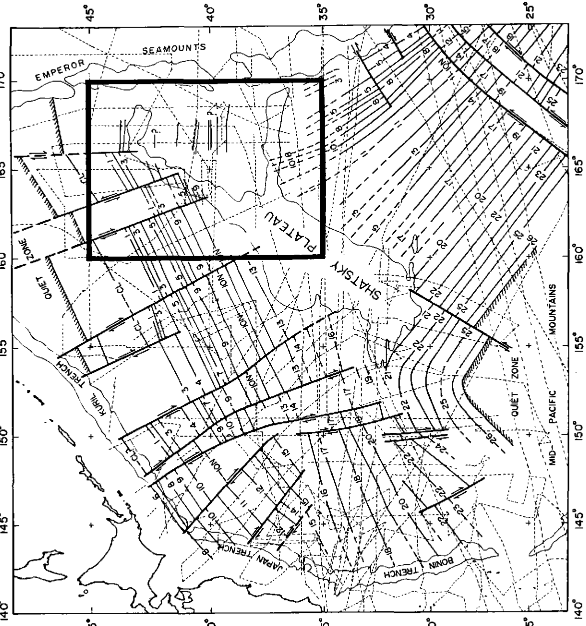
A major source of uncertainty concerning the nature of the intersection of the Pacific, Kula, and Farallon plates is Shatsky Plateau. The projections of the northwest trending Hawaiian lineations and the northeast trending Japanese lineations indicate that Shatsky Plateau straddles the site of the Cretaceous triple junction. However, the magnetic anomalies are perturbed and attenuated over the plateau making it difficult, if not impossible, to map the details of the magnetic bight. Therefore, deciphering the spreading history of the Late Mesozoic P-K-F boundary in this region depends on mapping and interpreting the magnetic anomalies around the plateau.

Magnetic lineations, representing the Cretaceous northern boundary of the Pacific plate, have been mapped around Shatsky Plateau except at the northeast end of the plateau. Hilde (1973) and Hilde et al. (1976) examined some magnetic anomalies northeast of the plateau and mapped them as east-west lineations. They reported their east-west lineations with reservations because they do not fit the regional patterns. Isezaki and Miki (1978) have also questioned the east-west trending lineations.

Objectives

The objectives of this study were to determine the age, orientation, and origin of the magnetic anomaly lineations northeast of Shatsky Plateau in the Northwest Pacific (Figure 1). The previously mapped magnetic lineations were contrary to the general trends of others observed in this part of the Pacific. The final objective was

Fig. 1. Location of the study area (enclosed) with Mesozoic magnetic anomaly lineations in the northwest Pacific Ocean. Solid lines are the anomaly correlations. Heavy solid lines are fracture zones. Dashed portions of these lines mean either a projection of the correlation or less than positive identification. Light dashed lines are ship tracks for the magnetic data used in mapping the pattern. Arrows on the fracture zone indicate offset of the lineations, not fault motion. The Japanese lineations are between Shatsky Plateau and Japan, the Hawaiian lineations are located in the southeast corner of the figure. (After Hilde et al., 1976).


EMPEROR
SEAMOUNTS
SHATSKY
PLATEAU
KURIL TRENCH
JAPAN TRENCH
BONIN TRENCH
QUIET ZONE
MID-PACIFIC MOUNTAINS
140°
145°
150°
155°
160°
165°
170°
25°
30°
35°
40°
45°

to evaluate the implications these magnetic lineations have for the evolution of the Northwest Pacific in the area of Shatsky Plateau.

Previous Work

The pioneering work on marine magnetics data by Heezen et al. (1953), Adams and Christoffel (1962), Mason and Raff (1961), and Raff and Mason (1961) focussed the attention of marine researchers on the linearity of marine magnetic anomalies. In addition, geomagnetic polarity reversals were recognized from the study of basalts on land (Matuyama, 1929; Cox, 1959; Cox and Doell, 1960).

Vine and Matthews (1963) associated the long linear magnetic anomaly trends mapped by previous investigators with the phenomenon of reversals of the Earth's magnetic field. They proposed that the oceanic crust becomes magnetized in the direction of the Earth's prevailing magnetic field as it cools below the Curie temperature during formation at spreading ridges. They envisioned an oceanic crust composed of long, narrow blocks of alternating magnetic polarity.

Heirtzler et al. (1968) derived a geomagnetic reversal time scale for the Cenozoic by applying the hypothesis of Vine and Matthews (1963) to marine magnetic anomalies that were mapped by Pitman et al. (1968) (South and North Pacific Ocean), Dickson et al. (1968) (South Atlantic Ocean), and Le Pichon and Heirtzler (1968) (South Indian Ocean). Heirtzler et al. (1968) examined magnetic anomaly profiles and some crustal dates from each ocean and selected the South Atlantic profile as being representative of uniform sea floor spreading. The youngest part of the South Atlantic profile was dated to the end of the Gilbert

Reversal Epoch, 3.35 million years before present (MYBP). By assuming a constant spreading rate of 1.9 cm/yr for the South Atlantic, and extrapolating the dated sequence to the end of the recorded anomaly profile, Heirtzler et al. (1968) obtained dates for magnetic reversals to 80 MYBP. The establishment of a geomagnetic reversal time scale provided researchers with a means to date the oceanic crust wherever Cenozoic magnetic anomalies could be identified.

Hayes and Pitman (1970) mapped a set of magnetic anomalies west of the Hawaiian Ridge and concluded that these anomalies did not fit the geomagnetic time scale of Heirtzler et al. (1968). They proposed a Jurassic age for the oceanic crust in the northwestern Pacific and, based on the opposing trends of the Japanese lineations (Uyeda et al., 1967) and Hawaiian lineations, a magnetic bight (bend) in the vicinity of Shatsky Plateau.

Larson and Chase (1972) identified additional anomalies and fracture zones in the western Pacific. They grouped the anomalies into three sets and named them the Japanese, Hawaiian, and Phoenix lineations for their proximity to Japan, the Hawaiian Ridge, and the Phoenix Islands respectively. Larson and Chase (1972) were able to model and date the magnetic anomalies of the three sets by using the geomagnetic time scale that Larson and Pitman (1972) had devised for the Late Jurassic and Cretaceous.

The magnetic lineation patterns in the western Pacific led Larson and Chase (1972) to speculate that the Pacific plate grew as crust accreted along the spreading ridges that formed two triple junctions during the Late Mesozoic. The northern triple junction was placed near Shatsky Plateau based on the apparent intersection of the northeast trending Japanese lineations and the northwest trending Hawaiian lineations (Figure 1, p. 4). Their model of Pacific plate evolution had the northern triple junction migrate northward through Shatsky Plateau until 100 MYBP. At about 100 MYBP, the plates reorganized to produce a triple junction 2000 km to the southeast at the Mendocino Fracture Zone near Hess Plateau.

Hilde (1973) extended the Japanese and Hawaiian lineations back in time with the identification of the Mesozoic anomalies M22 (148 MYBP) to M26 (155 MYBP). He was able to connect the lineations of the two sets to form a magnetic bight on older crust south of Shatsky Plateau. He interpreted the bight as evidence of a ridge-ridge-ridge (RRR) triple junction which changed to a ridge-ridge-transform fault (RRF) triple junction (which is an unstable configuration by the criteria of McKenzie and Morgan, 1969) at anomaly M20 (143 MYBP) and then back to a stable RRR triple junction at anomaly M4 (116 MYBP) (Hilde, 1973; Hilde et al., 1976).

In addition to mapping the magnetic bight south of Shatsky Plateau, Hilde (1973) refined the Mesozoic geomagnetic reversal model with the identification of anomalies M10N (124 MYBP) and CL or M0 (108 MYBP). Subsequently, using the results of Hilde (1973) and other data, Larson and Hilde (1975) revised the Mesozoic geomagnetic reversal time scale.

Hilde et al. (1976) predicted that between M20 (143 MYBP) and M4 (116 MYBP), the Pacific-Farallon ridge northeast of Shatsky Plateau had a northwesterly orientation described by the projected trends of the Hawaiian lineations. However, the anomalies northeast of Shatsky Plateau, as mapped by Hilde (1973), strike roughly east-west and do not fit the regional lineation patterns. Hilde et al. (1976) recognized this problem and postulated "interplate" spreading northeast of Shatsky Plateau at about 110 MYBP.

The problem is compounded by 1) the likelihood that the magnetic anomalies were created near the paleomagnetic equator and moved 40° north to their present position (Larson and Chase, 1972; Hilde et al., 1976), 2) the anomalies were apparently created near the time boundary of the Cretaceous Quiet Period, and 3) the complexity of the crustal structure as seen in the bathymetry (Map 2, inside back cover). This thesis addresses the problem of resolving the lineations at the northeast end of Shatsky Plateau and evaluating the implications of this resolution for the Early Cretaceous evolution of the Pacific plate.

DATA AND METHODS

Data

Data for this thesis came from several sources. A magnetic tape containing geophysical data in MGD77 format was obtained from the National Geophysical and Solar Terrestrial Data Center (NGSDC) in Boulder, Colorado. The data of seventeen cruises from six institutions were included on the tape. In addition, a magnetic data tape with two cruises was obtained from the Hawaii Institute of Geophysics (HIG). Table 1 is a listing of cruises and associated data used for this study. Map 1 (inside back cover) is the track chart of the cruises listed in Table 1. Figure 2 is the index to selected tracks which correspond to profiles of bathymetry, seismic reflection data and magnetic anomalies discussed later.

A typical data record on tape included: the cruise identification, the position, depth in two-way travel time and/or corrected meters, total magnetic field, and magnetic anomaly. The range of magnetic anomaly values is predominantly ± 500 gammas with a few isolated peaks and troughs exceeding 500 gammas. Bathymetry data for two Japanese cruises (KH6803 and KH7002) consisted of corrected meters only, with an unspecified correction formula.

Bathymetry charts with soundings were obtained from the Hydrographic Department, Maritime Safety Agency, Japan (courtesy of Dr. Seiya Uyeda) and were used to advantage in areas of poor primary data coverage.

Table 1. Inventory and sources of data used for this thesis. Data type codes represent: B-bathymetry, M-magnetic anomalies, S-seismic reflection profiles.

Institution	Vessel	Cruise ID	Year	Data Type
Scripps Institution of Oceanography	Spencer Baird	JAPANYON Leg 2	1961	B M
	Argo	LUSIAD Leg 1	1962	B M
	Argo	ZETES Leg 3	1966	B M
	Melville	GEOSECS Leg C	1973	B M
	Thomas Washington	INDOPAC Leg 1	1976	B M
	Glomar Challenger	GC Leg 55	1977	B M S
Lamont-Doherty Geological Observatory	Vema	V2110	1965	B M S
	Conrad	C1008	1966	B M S
	Conrad	C1108	1967	B M S
	Conrad	C1207	1968	B M S
	Conrad	C1219	1969	B M S
Naval Oceanographic Office	Staten Island	SI343625	1976	B M
National Oceanographic and Atmospheric Administration	Surveyor	POL6829	1968	B M
	Oceanographer	POL68	1968	M
	Oceanographer	POL7004	1970	B M
Ocean Research Institute of the University of Tokyo	Hakuho Maru	KH6701	1967	M
	Hakuho Maru	KH6803	1968	B M S
	Hakuho Maru	KH7002	1970	B M S
Hawaii Institute of Geophysics	Kana Keoki	KK760806 Leg 2	1976	B M
	Kana Keoki	KK770317 Leg 5	1977	B M

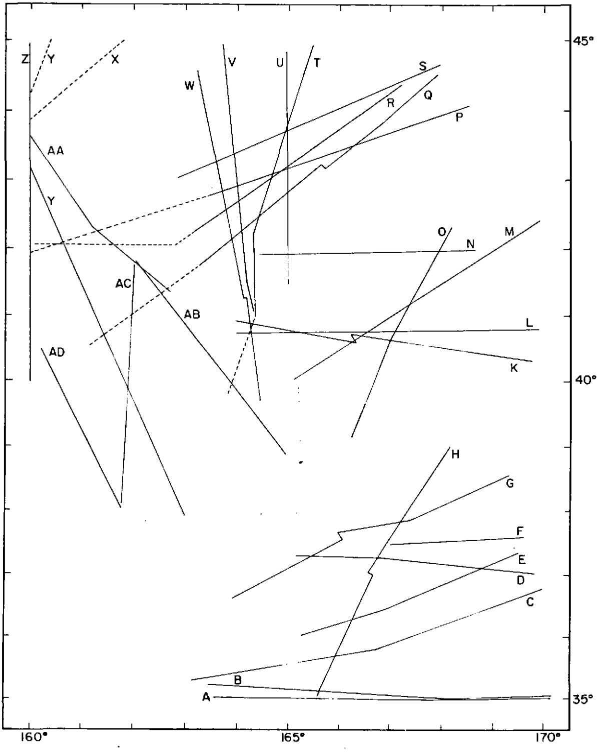


Fig. 2. Index to tracks of selected data profiles. Solid lines indicate magnetic anomaly data with or without bathymetry and seismic reflection data. Dashed lines indicate only bathymetry and/or seismic reflection data. Letter designations are used in place of cruise identification.

Methods

Several computer programs were written in FORTRAN for an Amdahl 470 computer to manipulate and display the bathymetry and magnetic anomaly data in a variety of ways. Plots were made using a Versatec 1200A electrostatic plotter and a Houston Instrument DP8-S pen plotter. The Mercator projection was used for all chart plots.

The ship tracks were plotted for inspection in Mercator projection at 1.2 inches/degree of longitude. Major course changes were flagged in order to control the plotting of magnetic anomaly profiles along the ship's track. Depths were calculated from two-way travel times by assuming a sound speed of 1500 meters/second (m/s), plotted along the ship's tracks at a working scale of 4.8 inches/degree of longitude and contoured at 250 meter intervals to show maximum bathymetric definition at the working scale.

The Japanese bathymetric data (corrected meters-unspecified correction formula, corrected meters-Kuwahara Tables and H.D. 282 (Matthews Tables, 1939), and wire soundings) were contoured in uncorrected meters (1500 m/s). The wire soundings were discarded where they conflicted with depths calculated from echo soundings. Corrected depths were converted to uncorrected meters using the Matthews Tables (1939). Depth corrections for the study area are less than 40 meters; for a depth of 5000 meters, the adjustment is nearly zero.

A portion of the Japanyon,2 (1961) track line was shifted 16 km to the east to reconcile the Japanyon,2 depths with depths of more recent cruises (presumably with better navigation). Map 2 (inside back cover) is a revised bathymetric chart of the study area.

Magnetic anomaly values were plotted perpendicular to the ship's track using the track as the zero line. The magnetic scale was 500 gammas per inch and the chart scale was 2.0 inches/degree of longitude (Map 3, inside back cover). The northern portion of the Zetes,3 (1966) cruise was adjusted southeast to better match the bathymetry and magnetic anomalies of the POL7004 (1970) cruise.

To aid the correlation and identification of the magnetic anomalies and to view the sea floor in cross section, profiles of magnetic anomalies were plotted above profiles of bathymetry versus distance along the ship's track. Bathymetric effects contributing to the magnetic anomalies were readily apparent with this type of display. In addition, bathymetry profiles were examined for evidence of fracture zones. Some distinctive bathymetric features associated with fracture zones are: an increase in sea floor roughness, regional depth differences across the fracture zone, and ridges and seamounts flanking a trough or valley (Menard and Atwater, 1969; Bonatti, 1973; Francheteau et al., 1976). Though all of the characteristics of a fracture zone might not be present, any one is indicative. The profiles could be adjusted and compared to each other independent of their map orientation. After establishing lineation directions, the magnetic anomalies were also projected normal to the direction of spreading to appropriately foreshorten the long wavelength anomalies that were recorded at an oblique angle to the spreading direction.

Seismic reflection data (microfilm and photographic prints) (see Table 1, p. 10) were analyzed for evidence of fracture zones. The fracture zones observed on the seismic records were plotted on a map for comparison with fracture zones suspected from the offsets of the magnetic anomaly correlations. The seismic records and bathymetry profiles were used as primary evidence for fracture zones in areas where the magnetic anomaly correlations were incomplete.

Several representative magnetic anomaly profiles were deskewed using the transformation to the pole procedure of Blakely and Cox (1972). This procedure uses phase shifting of the Fourier Transform to eliminate the skewness inherent to mid-latitude magnetic anomalies. The system function, which causes the phase shifting, does not depend on the shape or location of the magnetized source, and it gives constant amplification and phase shift at all wave numbers. This process transforms skewed magnetic anomalies to anomalies that would have formed by the same source with vertical magnetization and vertical regional field. The system function depends on five angles at two locations, the place of origin and the pole. The angles are: the declination and inclination of the regional field; the declination and inclination of the remanent field; and the strike of the magnetized crustal blocks.

The Fourier Transform requires equally spaced points, so the raw data were projected normal to the direction of assumed spreading and interpolated at a spacing of 1 km. Several transformed profiles were produced to find the most deskewed profile. The latitude of formation (hence the remanent inclination) was systematically varied while the other angles were held constant for a series of calculations. The approximate latitude of formation is inferred from the profile that exhibits the least amount of skewness. Frequently, more than one set of parameters were necessary to deskew all of the anomalies of a single profile, resulting in a range of formation latitudes.

The transformation to the pole technique removes anomaly asymmetries that result from nonvertical or nonhorizontal remanent magnetization. The shape of the observed anomalies can be significantly different from that produced by vertical magnetization in a vertical regional field, making correlations and identifications difficult or misleading. This procedure also enchances each anomaly by positioning its maximum or minimum directly over the source. Because individual anomalies are enhanced, it is possible to identify short polarity events otherwise obscured by dominant, asymmetric anomalies. This study used the transformation to the pole procedure to give confidence to the correlations and identifications of the magnetic anomalies, not to identify short reversal events or construct a model.

The magnetic anomaly models were computer generated based on the method of Talwani and Heirtzler (1964) and the Larson and Hilde (1975) magnetic reversal time scale. Identification of the anomalies was based on comparing the projected and transformed profiles to the Cenozoic and Mesozoic magnetic reversal models. The best match was with the Mesozoic model.

REGIONAL GEOLOGY

Age of the Northwest Pacific

The Northwest Pacific basin is Late Jurassic and Cretaceous in age, based on a combination of seismic stratigraphy, ocean crust coring, and magnetic anomaly mapping. The extent of the Late Jurassic crust appears to be confined to the old nucleus of the Pacific plate just east of the Mariana Trench. The Pacific plate becomes younger to the north and east of the Jurassic nucleus; the remainder of the Northwest Pacific crust is Cretaceous in age.

J. Ewing et al. (1968) collected seismic reflection profiles of the Pacific crust and noted an acoustically opaque sedimentary unit on the Northwest Pacific profiles. They obtained a minimum age of Albian for Shatsky Plateau using fossils recovered from a core which sampled the opaque layer on a flank of the plateau (M. Ewing et al., 1966). The opaque layer has been subsequently sampled at several sites (46, 51, 195, 307, and 452) in the Northwest Pacific (Deep Sea Drilling Project (DSDP) legs 6, 20, 32, and 60) and Cretaceous ages have been substantiated for this cherty layer in this region.

Oceanic basement in the deep ocean basin is believed to have been sampled at DSDP sites 197, 304, and 307. Site 304 (430 km west of the study area) is located on anomaly M9 of the Japanese lineations with a minimum age of Hauterivian (122 MYBP). Site 307 (720 km south of the study area) lies on anomaly M21 of the Hawaiian lineations and has a minimum age of Berriasian (138 MYBP). Site 197 (1275 km southwest of the study area) is located nearest the Jurassic nucleus of the plate and is at least 138 MY old (Berriasian). Minimum ages for the crust at the three sites are based on the fossils recovered from the basal sediments. A Cretaceous age is inferred for the crust in the study area based on the ubiquitous opaque layer mapped by Ewing et al. (1968) and the results of DSDP legs 6, 20, and 32 (Figure 3).

Magnetic anomalies have been used to predict the age of the crust in areas where fossils and/or radiometric dates are lacking. A few widely separated samples of the crust have been used to date the magnetic lineations of the Northwest Pacific. Specifically, fossils from DSDP-Northwest Pacific sites 166, 303, 304 and Atlantic site 105 were used by Larson and Hilde (1975) to construct a geomagnetic time scale for the Mesozoic anomalies. Application of the Mesozoic time scale to the magnetic anomaly patterns of the Northwest Pacific yields isochrons of crustal age. Cretaceous ages are expected for the crust northeast of Shatsky Plateau if the magnetic isochrons of Figure 1 (p. 4) are projected into the study area.

The Emperor Seamounts

The Emperor Seamounts represent a sequence of Cenozoic volcanoes that were erupted onto Mesozoic Pacific crust as that crust moved northward over the fixed, Hawaiian "hot spot". This conclusion is based on several lines of evidence. Basalts from the seamounts have been radiometrically dated as Cenozoic (Dalrymple et al., 1980) and show an age progression, becoming younger to the south (see Figure 3). The paleomagnetic latitude of formation for Suiko Seamount (45°N, 170°E),

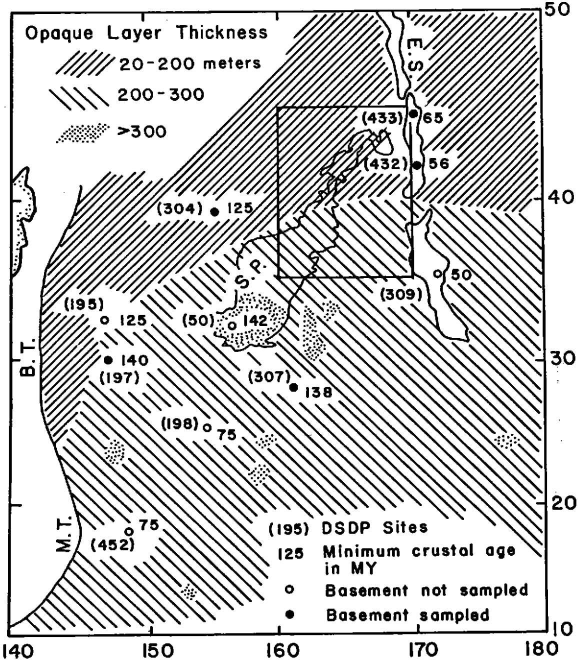


Fig. 3. Age of the Northwestern Pacific based on the distribution of the opaque layer mapped by J. Ewing et al. (1968) and the results of DSDP legs 6, 20, 32, and 55. Site numbers are in parentheses. M.T. is the Mariana Trench, B.T. the Bonin Trench, E.S. the Emperor Seamounts, and S.P. is Shatsky Plateau. The study area is outlined. Map is modified from J. Ewing et al. (1968).

formed 64.7 MYBP, is 27°N ± 3.5° (Kono, 1980). Marshall (1978) reported a paleolatitude of formation of 19.2°N ± 4.1° for Meiji Guyot (53°N, 165°E) which was formed 72 MYBP. These latitudes are close to the latitude (19.5°N) of the presently active Hawaiian volcanoes. Finally, Emperor Seamount basalts are petrologically very similar to basalts of the Hawaiian Islands (Kirkpatrick et al., 1980) and distinctly different from basalts of normal ocean crust (Hubbard, 1969).

These data are evidence that the Emperor Seamounts had a common origin in the vicinity of the presently active Hawaiian volcanoes. The seamounts are then a volcanic record of the motion of the Pacific plate relative to this hot spot (Wilson, 1963; Morgan, 1972). Hence, the Emperor Seamounts are considerably younger than the crust on which they rest.

Shatsky Plateau

Shatsky Plateau is the largest individual bathymetric feature of the Northwest Pacific basin. Unlike the Emperor Seamounts, the origin and evolution of the plateau is poorly understood. The plateau is elongate with its major axis striking NE-SW. The plateau's elongate shape and coincidence with a regional magnetic bight (Figure 1, p. 4) suggest a genetic relationship between the plateau and crustal accretion at a triple junction (Hilde et al., 1976; Sharman, 1979).

Although a number of DSDP holes have been drilled on the plateau (sites 47, 48, 49, 50, 305, 306), none have penetrated the basement. Much of the sedimentary section has been cored and the oldest recovered fossils (site 50) were dated as Kimmeridgian to Tithonian (about 142

MYBP). The crest of Shatsky Plateau is covered by more than 1 km of carbonates indicating that the plateau remained above the carbonate compensation depth (CCD) for most of its existence. The highest sedimentation rates measured on the plateau occurred between 65 and 105 MYBP with a maximum at about 90 MYBP (Lancelot and Larson, 1975). The maximum in sedimentation probably correlates with the plateau passing beneath the equatorial high productivity zone. The sedimentary record on the plateau, as well as data from other DSDP sites, suggests that this portion of the Pacific plate formed south of the equator. This is consistent with other models based on magnetics data (Larson and Chase, 1972; Hilde et al., 1976).

Chen (personal communication), in his study of seismic records across Shatsky Plateau, has found extensive normal faulting and slumping associated with the early tectonic history of the plateau. The largest faults bound the southern portion of the plateau with the plateau on the upthrown side relative to the ocean basin. He supposes the marginal faults are due to the isostatic adjustment of the plateau because very small free air gravity anomalies (about +30 mgals) are observed over the plateau.

Hilde et al. (1976), as an alternative explanation for the origin of Shatsky Plateau, suggested a model of local convergence for the origin of the plateau in an attempt to explain its great thickness (Den et al., 1969). However, geological features typical of convergent zones are not observed in the region around Shatsky Plateau. Gettrust et al. (1980) have confirmed an abnormal thickness of at least 26 km for Shatsky Plateau and inferred a very dense mantle beneath the plateau to account for the observed isostasy.

Shatsky Plateau might have been built in stages. Vallier et al. (1982) suggested the possibility of renewed magmatism on southern Hess Plateau (a feature similar to Shatsky Plateau). Their evidence for late stage volcanism on the plateau includes rounded alkalic pebbles in an Upper Cretaceous and Lower Tertiary nannofossil ooze (Hess Plateau is at least 30 MY older than this ooze), and the present depth of the southern plateau is shallower than expected if it had followed normal subsidence. A similar history might apply to Shatsky Plateau. Henderson and Gordon (1981) have proposed that many major volcanic edifices in the Pacific Ocean (e.g. Shatsky and Hess Plateaus) were constructed by intersecting hot spot tracks. Their model is consistent with the post-formation uplift and renewed magmatism of Hess Plateau cited by Vallier et al. (1982).

BATHYMETRY AND SEISMIC REFLECTION DATA

The author has revised the bathymetry northeast of Shatsky Plateau, using all available bathymetric data. The resulting chart is Map 2 (inside back cover) covering 35° to 45°N and 160° to 170°E. Several new features were discovered, mostly in the center of the study area, and some previously mapped features have been modified to reflect the additional data.

Five physiographic provinces are delineated (Figure 4). Clockwise from the southwest corner of the study area the five provinces are: 1) the Plateau, 2) Northwest (NW) Basin, 3) Central Region, 4) Seamount Range, and 5) Southern Region. Each region has distinct morphologic and magnetic characteristics.

The Plateau is the northern extension of the larger part of Shatsky Plateau to the southwest, rising above the 5000 m isobath on Map 2 (inside back cover). The southern portion of the plateau mapped by this study is a dome 225 km in breadth with a relief of 2300 m. It encompasses most of the southwestern corner of the study area and has many peaks on its flanks. The magnetic anomalies directly over this part of the Plateau are generally subdued, difficult to correlate, and probably unreliable as indicators of sea floor spreading.

The Plateau narrows abruptly at 40°N to an irregularly shaped ridge approximately 50 km wide. This northern ridge extends eastward and nearly meets the Emperor Seamounts at 43°N. This northern ridge of the Plateau does not affect the magnetic anomalies as much as the Plateau to the south. In general, magnetic anomalies over this ridge

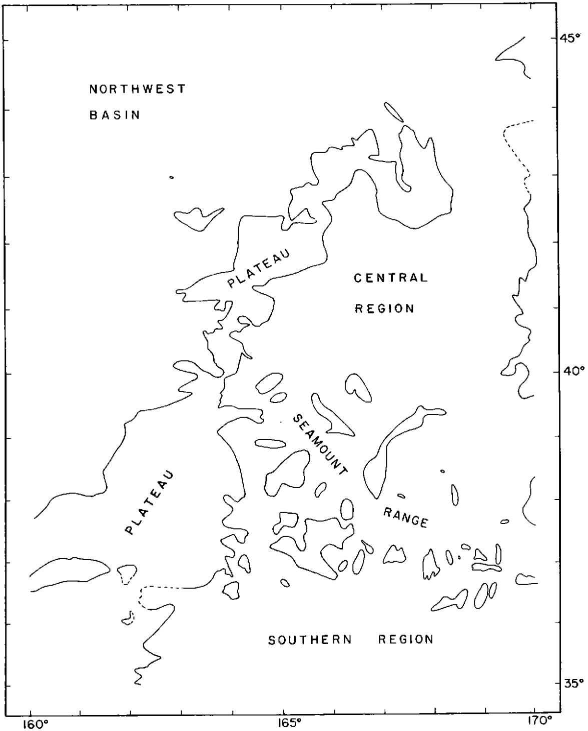


Fig. 4. The five physiographic provinces of the study area. The 5000 m isobath shown serves to delineate the provinces.

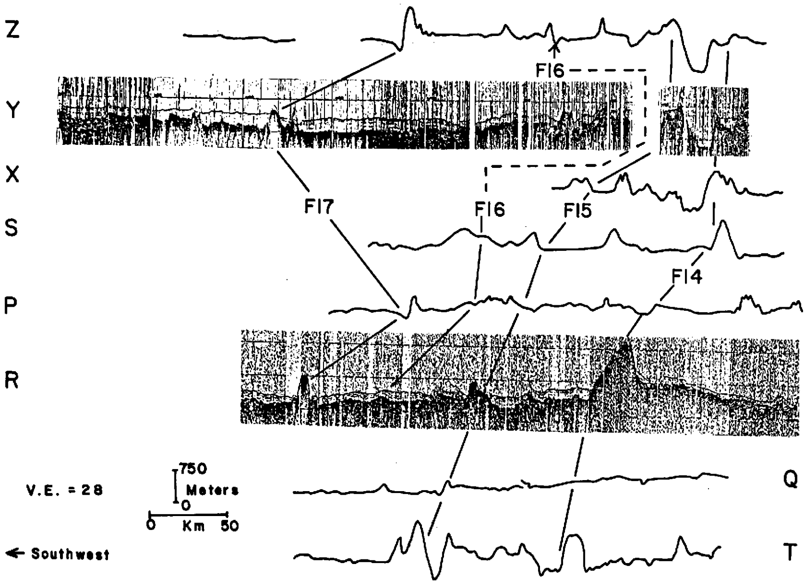
can be correlated.

The Northwest Basin, north and northwest of the Plateau, is generally flat at about 5500 m. There is a northwest trending zone of rugged topography extending from the southern tip of the Plateau's northern ridge at 40°N, 164°E to 44.5°N, 160°E. This zone of roughness is delineated on Figure 6 (p. 31) by two heavy lines suggesting two fracture zones (F14 and F15), but the zone might be one large fracture zone or many small ones. Figure 5 shows the rough morphology and flanking seamounts and ridges of the fracture zones in cross section. The most pronounced scarps and trough are located in the extreme northwest corner of the area and can be seen on profiles X, Y, and Z. These well developed scarps coincide with the bend in the Hokkaido Trough (Green and Fleischer, 1980), also known as the Hokkaido Fracture Zone (Chase, 1975).

The Central and Southern Regions are similar to the Northwest Basin in that they are almost uniformly flat. The Central Region is a 5500-5700 m deep basin bounded on the east by the Emperor Seamounts, the north and west by the northern ridge of the Plateau and on the south by the Seamount Range, a zone of seamounts and ridges. The Southern Region is south of the Seamount Range and gradually deepens to 5800 m at the southern edge of the study area.

The age-depth relationship of Parsons and Sclater (1977) suggests that the flat regions northeast of Shatsky Plateau are 90-110 MY old if normal crustal subsidence is assumed. This range is reasonable for only the youngest crust in the study area. Hence, the oldest crust in this region is too shallow for its age (excluding the

Fig. 5. Bathymetric and seismic profiles of the Northwest Basin showing four fracture zones. Lines connecting the profiles indicate where fracture zones cross the profiles. Fracture zones are labelled on the lines with an F followed by a number. For fracture zone locations, see Figure 6 (p. 31). See Figure 2 (p. 11) for index to profiles. Vertical exaggeration is 28.


Z
Y
X
S
P
R
Q
T
F16
F17
F16
F15
F14
V.E. = 28
750
Meters
0
0 Km 50
Southwest

Plateau). A possible explanation for the discrepancy between the depth-age curve and the observed depths is that the curve gives a large range of ages for small changes in depth, for oceanic crust deeper than 5500 m. Another possibility is that the crust has not subsided like normal ocean crust.

Mammerickx (1982) has also found discrepancies between depths predicted for the Mesozoic crust of the Northwest Pacific and the age-depth curve of Parsons and Sclater (1977). She attributes the anomalous depths to intraplate volcanism, deformation of the plate around large volcanic piles and near trenches, and domes which did not mature to spreading ridges. It is possible that one or more of these processes has affected the crust northeast of Shatsky Plateau making the depth an unreliable indicator of crustal age in this area.

The fidelity of the crust as a recorder of geomagnetic polarity reversals does not appear to have been altered in the Northwest Basin, Central Region or Southern Region. There are no seamounts or other unusual features in these regions. As a result, the magnetic anomalies from these flat regions are expected to be only associated with geomagnetic polarity reversals recorded by the crust at the time of formation. The magnetic anomalies of the Northwest Basin, Central Region and Southern Region are considered to be uncontaminated records of the spreading history northeast of Shatsky Plateau.

The Seamount Range is a group of seamounts and ridges which extends southeastward between 36°-40°N from the Plateau to the Emperor Seamounts (Figure 4, p. 23). Many of the small seamounts and ridges comprising the southeast end of this range are associated with fracture zones. The shallow depression that is flanked by large seamounts and ridges in the center of this range (Map 2, inside back cover) is interpreted to be a fracture zone (F6, Figure 6, p. 31). Although this area has a typical fracture zone morphology it does not appear to have significant regional differences in depth.

There are several possible reasons for this. Perhaps because the crust is more than 80 MY old, it has come to equilibrium (Parsons and Sclater, 1977). If the original offset was small, then there would not have been a significant vertical offset for this fracture zone (Menard and Atwater, 1969). Alternately, the total vertical offset of the fracture zone could be distributed over many smaller faults resulting in a wide fracture zone with no single significant offset in depth (Francheteau et al., 1976). There are other fracture zones in the study area that are associated with scarps (Figures 5 and 8, pp. 26 and 36), and there appears to be a minimum of 100 km of lateral offset across fracture zone 6. The apparent lack of a regional depth difference is probably due to many small faults, distributed over a wide zone, obscuring the total vertical offset.

The 200 km offset between similar magnetic anomalies of the Central and Southern Regions supports the fracture zone interpretation for these features. In addition to the proposed fracture zones, the contributions of the seamounts and ridges of the Seamount Range to the total magnetic field are probably masking sea floor spreading anomalies. Consequently, the anomalies in this zone cannot be used with confidence to map the lineations between the Central and Southern Regions.

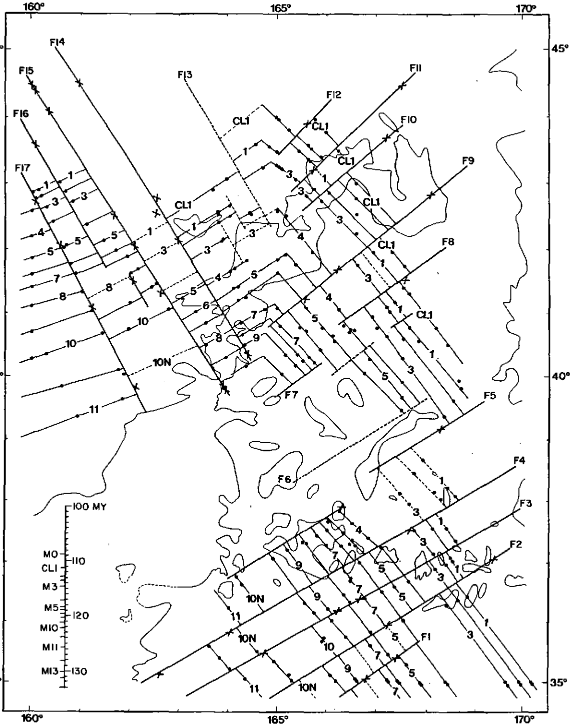
MAGNETIC ANOMALIES

General

The Mesozoic geomagnetic reversal sequence M3 to M5 was well developed and easily correlated throughout the study area. Lineation trends were established by the correlations of M3 and M5, and corroborated by the diagnostic anomalies M10-M11. Anomaly M11 (125 MYBP) is the oldest and M1 (112 MYBP) the youngest anomaly, within the region studied, that are identified with certainty. Anomaly M3 displays the most variability of any anomaly. The shape ranges from a large peak and shoulder to a broad, low amplitude signal. Identification of M3, as well as the other anomalies, is based on its relative position in a sequence. Figure 6 and Map 4 (inside back cover) show the correlations and identifications for the study area. The following discussion uses letter designations (Figure 2, p. 11) for selected profiles.

The portion of the Pacific plate investigated in this study formed near the equator; 5°N-5°S as determined from the parameters that gave the most deskewed anomaly profiles using the transformation to the pole procedure (Blakely and Cox, 1972). The latitude of crustal formation is one of the input variables to the transformation procedure, thus the formation latitude is determined directly by association with the most deskewed anomaly profile. Figure 7 is an example of anomaly profile M transformed to the pole, given different latitudes of formation. The fact that the magnetic anomalies of the study area could be matched with the Mesozoic reversal model for the

Fig. 6. Magnetic lineations chart with Mesozoic anomaly identifications. Dashed lines are inferred lineations or fracture zones. Heavy solid lines are fracture zones (labelled with an F followed by a number). Light solid lines are magnetic lineations. Dots are magnetic anomaly data control. X's are bathymetric and/or seismic data control for fracture zones. The 5000 m isobath is shown for physiographic reference.


160°
165°
170°
45°
40°
35°
F14
F15
F16
F17
F13
F12
F11
F10
F9
F8
F7
F6
F5
F4
F3
F2
F1
CL1
10N
11
100 MY
110
120
130
M0
CL1
M3
M5
M10
M11
M13

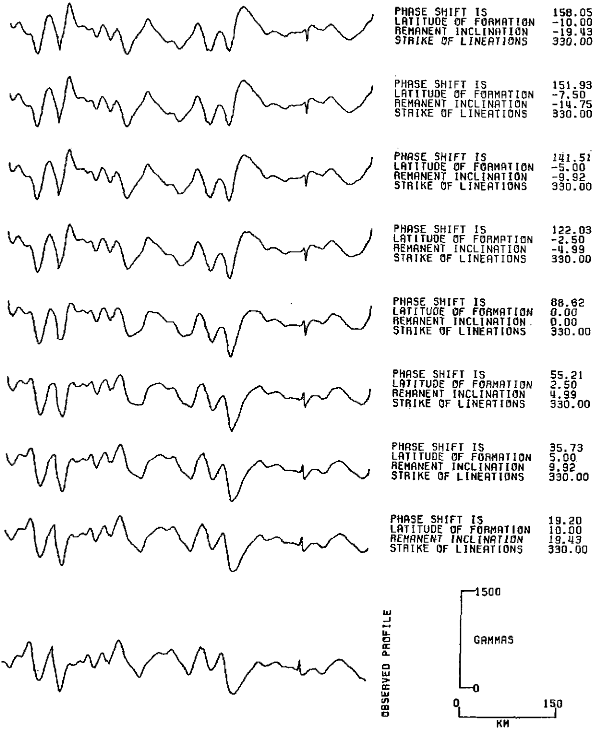


Fig. 7. An example of profile M transformed to the pole. The latitude of formation is 5°N-5°S as indicated by the most deskewed profiles. The latitude of formation was the only parameter varied in this example. Parameters: remanent declination 0°; strike of lineations, N330°E; remanent inclination, variable with latitude of formation.

southern hemisphere substantiates a southern latitude of formation for this part of the Pacific plate.

This is in agreement with the conclusions of several other investigators and lines of evidence. Larson and Chase (1972) and Larson and Pitman (1972) postulated 40° of net northward movement for the Pacific plate based on magnetic anomaly studies. Hilde et al. (1976) confirmed such a displacement from their magnetic modelling results. Lancelot and Larson (1975) examined the sedimentary record of the northwestern Pacific (sites 303A and 304) and concluded that it had crossed the equator about 100 MY ago. Paleomagnetic inclination studies on the basalts at sites 303A and 304 gave paleolatitudes of 5.8°S and 11°S respectively (Larson and Lowrie, 1975). According to the rotations described by Henderson and Gordon (1981) for the Pacific plate relative to eight fixed hot spots, the Northwest Pacific was south of the equator at least 100 MY ago.

The Northwest Pacific crust that formed south of the paleomagnetic equator during a reversed polarity period would have a remanent magnetization in the same sense of direction as the present regional field in the northern hemisphere. The two fields are then additive and measured with a magnetometer as the total field, giving a positive magnetic anomaly. Hence, positive anomalies are presently observed over reversely magnetized crust in the Northwest Pacific. Both positive and negative magnetic anomalies are numbered in the Larson and Hilde (1975) model. Mesozoic anomalies M2 and M4 correspond to normal polarity events (negative anomalies) and the rest of the numbered anomalies correspond to reversed polarity intervals (positive anomalies).

Hawaiian Lineations: Southern Region

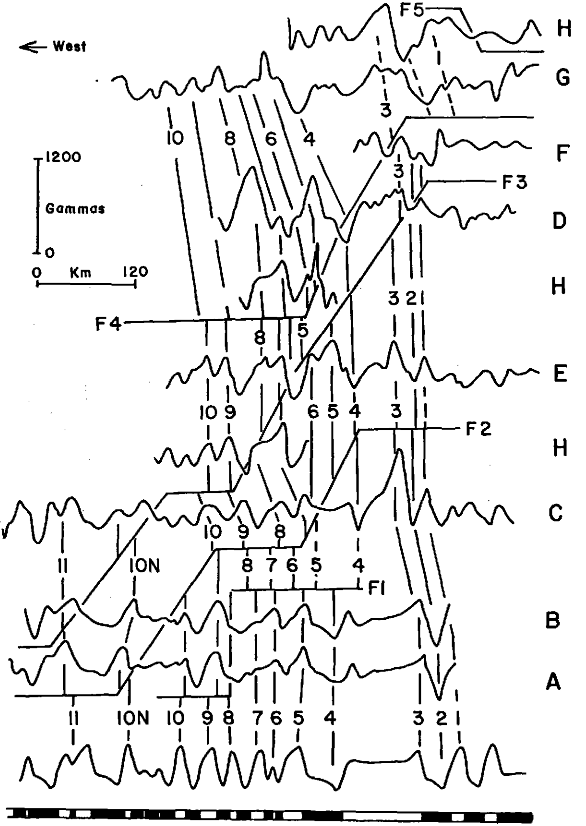
The magnetic lineations in the Southern Region have the same trend as the Hawaiian lineations south of the study area. Hilde (1973) suggested the existence of Hawaiian lineations in this region but did not map them. The anomalies are interpreted to be the northern extension of the Hawaiian lineations, formed on crust created along the Pacific-Farallon spreading ridge during the Cretaceous period.

The key anomaly used to establish this trend was the large prominent peak identified as anomaly M5 (Figure 8). The shape of anomaly M5 persists over most of the Southern Region making it a good marker anomaly. Anomalies M7 and M8 frequently appeared as one wide anomaly. Profile H in Figure 8 is an example.

The sequence M11-M1 is nearly complete on lines A and B. M6 and M7 are interpreted to be combined into one broad anomaly west of M5. M8 is missing on these profiles and a fracture zone (F1) is proposed. A rough sea floor at the location of the missing M8 is bathymetric evidence for F1. Anomalies west of M11 (near and over the Plateau) are indistinct and were not correlated.

The anomalies on the eastern half of profile G and northern half of profile H (between F4 and F5 on Figure 6, p. 31) have unusual shapes and do not appear to fit the model. The correlations are shown dashed between F4 and F5. These anomalies are not affected by the bathymetry. There might be two short fracture zones near F5 disrupting the sequence of M3-CL1. The sea floor is a little rougher near M3 on profile G than east of M3, indicating there could be one or more fracture zones here. However, a sequence could not be

Fig. 8. Magnetic anomaly correlations for the Southern Region. See Figure 2 (p. 11) for the index to profiles. F followed by a number refers to a fracture zone (for locations, see Figure 6, p. 31). Anomalies are projected normal to the spreading direction (N60°E). Numbers on the correlations refer to identified Mesozoic magnetic anomalies. Magnetic model is from the magnetic reversal time scale of Larson and Hilde (1975), with the addition of CL1 (115 to 112.0 MYBP). Model parameters are: magnetic susceptibility, 0.009; magnetic intensity 35000 gammas; depth to the top of the modelling layer and its thickness, 6 km and 1 km respectively; constant spreading rate, 37 mm/yr; magnetization inclination, -10°; azimuth of spreading, N60°E; and declination 10°. Shaded blocks correspond to normal magnetic polarity.



West
1200
Gammas
0
0 Km 120
F5
H
G
F
F3
D
H
F4
E
F2
H
C
F1
B
A
11
10N
10
9
8
7
6
5
4
3
2
1

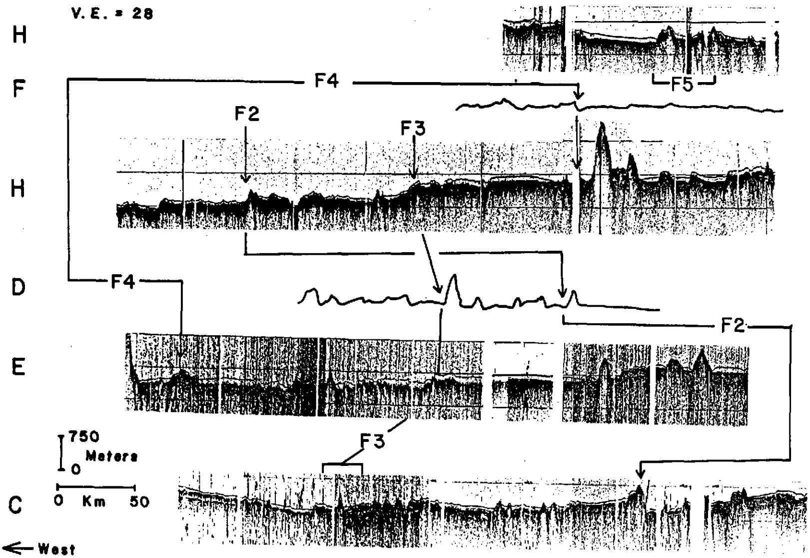
established in the Seamount Range immediately north of these anomalies, thus precluding definite mapping near F5.

Several fracture zones have been mapped in the Southern Region on the basis of disruptions of the magnetic anomalies, offsets of magnetic lineations, and significant changes in the character of the sea floor as seen on bathymetric and seismic reflection profiles. Some spreading anomaly patterns have been disturbed where fracture zones have been crossed. For instance, the absence of anomalies M5 and M6 on profile C in Figure 8 is attributed to a northeast trending fracture zone (F2). The anomaly sequences on both sides of the fracture zone are easily modelled confirming the identity of the missing peaks as M5 and M6. This fracture zone can be seen on seismic reflection profile C in Figure 9 as a prominent scarp separating crust of different age.

Another fracture zone (F3) is indicated on profile C (Figure 8) where the diagnostic sequence of M10-M11 is disrupted by two positive anomalies occupying the position of M10N. The easternmost anomaly of the pair is interpreted to be caused by a fracture zone because M10N is not repeated on this line. The relative positions of M10N north and south of the fracture zone are established by M11. This fracture zone is associated with the small fault and nearby peak seen at the west end of profile C in Figure 9.

The west end of F4 is associated with a small feature that protrudes from an otherwise flat sea floor (profile E, Figure 9). The eastern extension of this fracture zone is clearly visible as a change in the regional depth on profile F, Figure 9. It also produces a distinct negative magnetic anomaly in place of the expected broad

Fig. 9. Bathymetric and seismic profiles of the Southern Region showing four fracture zones. Conventions are the same as in Figure 5 (p. 26).


V.E. = 28
H
F
H
D
E
C
F4
F5
F2
F3
F4
F2
F3
750
Meters
0
0 Km 50
West

anomaly M3 (profile F, Figure 8, p. 36).

The offsets of magnetic lineations support the existence of the proposed fracture zones in the Southern Region with the exception of the two middle fracture zones (F3 and F4). There is zero or very small offset across these fracture zones for lineations M4-M10. Significant offsets of lineations M3 (20 km) and M10N (60 km) suggest that these fracture zones are continuous between these anomalies. The southern fracture zone of this pair is associated with a rough sea floor and regional depth differences on crust where zero offset is observed (profiles E and H in Figure 9). The northern member does not have a prominent signature in the crust for the time of zero offset.

The two transform faults (F3 and F4) that separated three short ridges at anomaly M10N (124 MYBP) must have persisted as zones of weakness (zero offset transforms, Schouten and White, 1980) for the next 7 MY in spite of the colinearity of the individual spreading segments. By anomaly M3 (117 MYBP), the transform faults were again part of a 20 km, right-lateral offset of the ridges. Schouten and White (1980) found similar cases of persistent decoupling of spreading ridges in the Atlantic even though magnetic lineations are not offset. They cite changes in plate motion as causing variable and asymmetric spreading resulting in variable offsets across the zones of decoupling.

The reorganization of the ridges from M10N to M3 through a transition of zero ridge offset indicates the Pacific-Farallon plate boundary was experiencing variations in its relative motion. Indeed, there are differences in spreading rates for each ridge segment (Figure 6, p. 31) and there is a reduction in the spreading rate after M4 on profiles C, D, E, and F. As seen in Figure 8 (p. 36), a modelled spreading rate of 37 mm/yr results in marked divergence of correlations for anomalies M4-CL1 on most profiles. This divergence indicates the actual spreading rate was slower than modelled. A representative spreading rate for these anomalies is 20 mm/yr. The reduced and variable spreading rates could have altered the ridge configuration from M4 to that of M3.

Hawaiian Lineations: Central Region

Hilde (1973) mapped east-west trending lineations in the Central Region on the basis of three north-south track lines. Additional data has made it possible to reinterpret the magnetic anomalies of this region as belonging to the Hawaiian lineations. The strongest correlations are among east-west trending track lines (K, L, M, and O). The lack of east-west tracks in the lower part of the Central Region and the topographic effects of the Seamount Range precluded continuous mapping of the Hawaiian lineations between the Central and Southern Regions.

Figure 10 shows the correlations of individual anomalies. The best match with the model (Larson and Hilde, 1975) is for anomalies M3 to M6. The identification of the anomalies west of M6 is tenuous, those east of M3 uncertain because they do not fit the reversal model of Larson and Hilde (1975). The broad positive anomaly west of M6 on profile M is identified as anomalies M7-M9 because of its position with respect to M6 and by analogy with the combined anomalies M7 and M8 of profile H in the Southern Region. The anomalies in the center

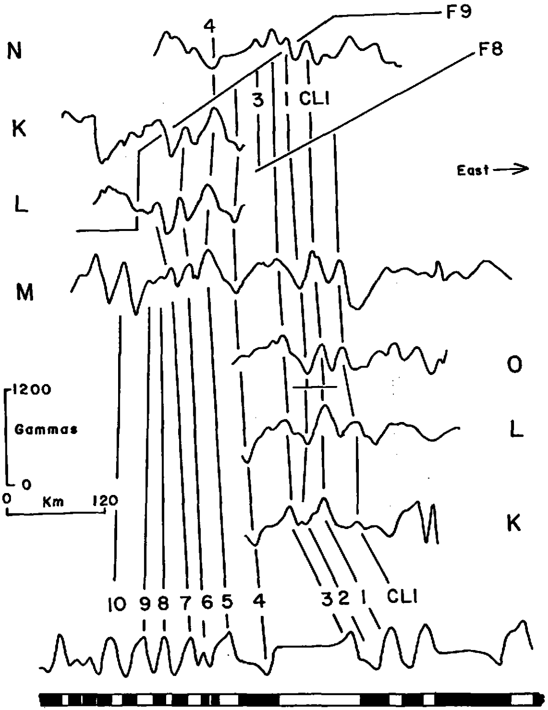


Fig. 10. Magnetic anomaly correlations for the Central Region. Anomalies are projected normal to the spreading direction (N60°E). Conventions are the same as in Figure 8 (p. 36).

of the study area (40°N, 165°E) are difficult to correlate and identify because the wavelengths of the anomalies appear to be nearly the same regardless of the track orientation. Rough topography is probably masking some of the spreading anomalies in this area. The existence of the magnetic bight in this area could account for anomalies with similar wavelengths on tracks that have significantly different orientations.

There is also a lack of east-west tracks in the northern part of the Central Region. The anomaly sequences on the north-south tracks showed a lot of variability and a reversal sequence could not be established. The identification of anomalies M2-CL1, in this part of the Central Region, depends on the identification of M3 on profile N and anomaly patterns on profiles P, Q, R, and S.

The anomaly sequence younger than M3 has a peculiar pattern that is difficult to reconcile with the model of Larson and Hilde (1975). A ridge jump seems to be the obvious explanation if the model is considered complete. However, the bathymetry is flat in this region; the deep trough and flanking ridges expected of an abandoned spreading center (Tamaki et al., 1979; Mammerickx, 1980) are absent. Consequently, I have modelled the profiles of the Central Region with an additional reversal interval (CL1) between anomalies M1 and CL (M0) to account for the observed anomaly patterns. Similar anomaly patterns exist in the area of the magnetic bight and the Southern Region.

Fracture zones are mapped primarily on the basis of magnetic anomalies in the Central Region. For instance, the steep slope and broad shape of the anomaly west of M6 on profile K and the dissimilarity of the same anomaly on the adjacent line L are interpreted to be a fracture zone (F9). The same fracture zone produces vertical offset in the sea floor to the northeast.

Japanese Lineations

The magnetic anomalies in the Northwest Basin are distinct and easily correlated (Figure 11). The major bathymetric features are confined to the wide northwest trending fracture zone discussed on page 24. The sequence M1-M11 is complete in this region. Anomalies south of M11 lie near or over the Plateau and are, therefore, probably affected by the Plateau. They show variable character from line to line and do not exhibit linear trends.

Larson and Chase (1972) and Hilde (1973) had correlated the anomalies of this region and included them with the Japanese lineations. The Japanese lineations formed along the Pacific-Kula ridge system. This study agrees with the earlier correlations and identifications.

Additional data available for this study allowed detailed correlations which revealed two long fracture zones (F16 and F17, Figure 6, p. 31) not mapped in previous studies. Supporting evidence for the fracture zones can be seen on the bathymetric and seismic profiles of Figure 5 (p. 26). F17 has a well developed trough with a flanking ridge or seamount on profile Z and a ridge without a trough on profiles P, R, and Y. F16 is typified by a rough sea floor on profiles S and Z but has no surface or basement expression on profiles P and R. The offset of magnetic lineations M5 and M6 justifies extending this

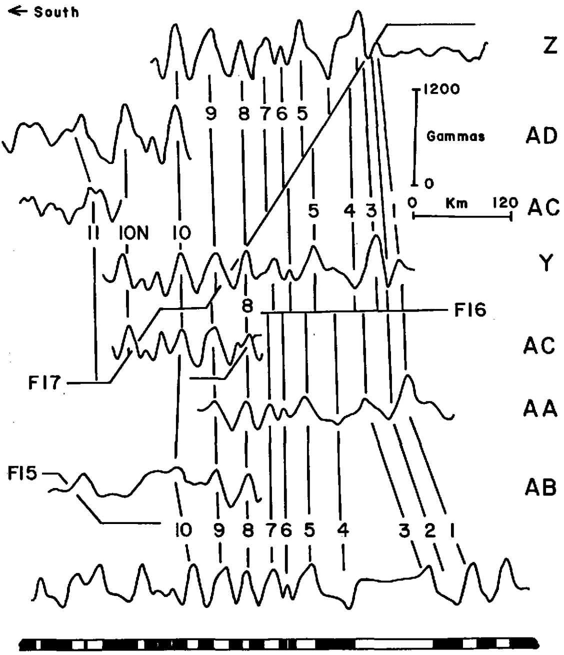


Fig. 11. Magnetic anomaly correlations for the Northwest Basin. Anomalies are projected normal to the spreading direction (150°E). Conventions are the same as in Figure 8 (p. 36), except for azimuth of spreading, N330°E.

fracture zone southward to 41.8°N. The short fracture zone south of F16 is mapped on the basis of an extra, small positive anomaly between anomalies M8 and M9 (profile AC in Figure 11) and an offset in the sea floor with attendant seamount.

The Japanese lineations were not mapped extensively in the Northwest Basin between 161°E and 163°E because of a lack of sufficient trackline control. The lineations between F14 and F15 are extrapolations of the identified anomalies M6-M9 at the south end of these fracture zones.

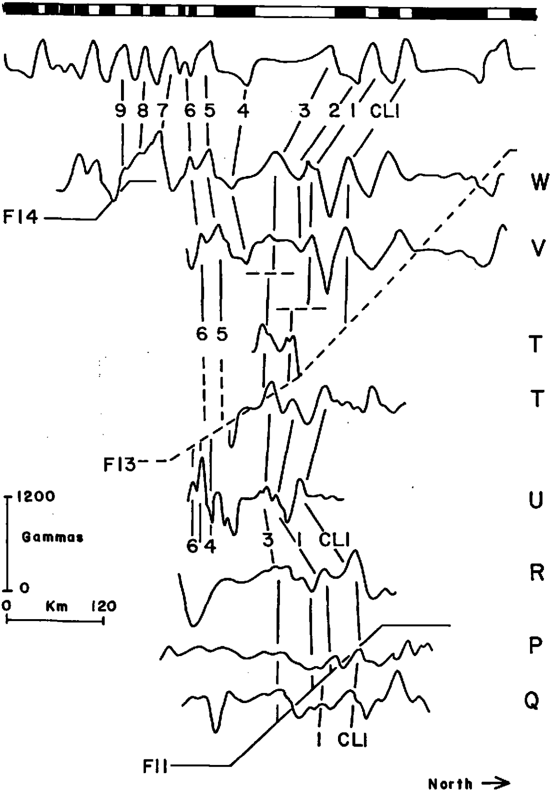
The Magnetic Bight

A magnetic bight is located where the well mapped Hawaiian and Japanese lineations meet north of 40°N. The northeast trending Japanese lineations are mapped on lines V and W, and the Mesozoic reversal sequence M3-M6 is identified with confidence (Figure 12). Anomaly M3 is the primary anomaly used to extend the Hawaiian lineations to the bight north of 42°N.

The shape of anomaly M3 of the Japanese lineations is distinctive on profile W and it is used as a marker anomaly in the area of the bight. The shape of M3 on profile W is duplicated exactly on profile T which establishes the position of anomaly M3 on line T. Anomaly M3 becomes broad on profiles Q, R, and U immediately southeast of line T (Figure 12). Still further southeast of line T, M3 of the Hawaiian lineations narrows again to its more common shape of a prominent peak flanked by a broad shoulder (Map 3, inside back cover).

Identifications of anomalies younger than M3, in the region of the

Fig. 12. Magnetic anomaly correlations for the region of the magnetic bight northeast of Shatsky Plateau. Anomalies of profiles V and W are projected N150°E and the anomalies of the remaining profiles are projected N60°E. Dashed lines indicate uncertain correlations or questionable fracture zones. Conventions are the same as in Figure 8 (p. 36).


9 8 7 6 5 4 3 2 1 CLI
W
F14
V
6 5
T
T
F13
U
1200
Gammas
0
0 Km 120
6 4 3 1 CLI
R
P
Q
1 CLI
F11
North →

bight, are based on their similarities with profiles in the Central Region (K, L, M, and O). Anomalies M1 and CL1 are well developed on profiles V and W. Hilde (1973) had identified anomaly CL1 as M1 repeated by a northwest trending fracture zone on line V. This fracture zone or a combination of fracture zones cannot be used to duplicate M1 on line V and the adjacent line W. M1 and CL1 are considered to be individual spreading anomalies. This is supported by similarities between these profiles and profiles of the Central Region.

The negative anomaly identified as M2 in Figure 12 does not have the character expected for this anomaly. Consequently, it appears that it, and the following peak could be considered as part of M3. However, the overall anomaly pattern younger than M3 (two positive anomalies and a long magnetically flat zone) is the same as in the Central Region where M2 is distinct. This supports the identifications of M3-CL1 in Figure 12.

Anomaly CL (M0), of the Japanese lineations, is north of the study area (Hilde, 1973). It may be present, as part of the Hawaiian lineations, in the northeast corner of the study area. There are similarities between the youngest anomaly sequence of the bight and those in the northeast corner, suggesting CL is nearby. The magnetic effects of the Emperor Seamounts may, however, be obscuring CL.

Anomaly M3 was successfully used to establish the outline of the bight. However, the details remain to be mapped because there are difficulties with simply projecting the Japanese and Hawaiian lineations until they meet. For example, there are strong correlations among anomalies younger than (north of) M3 on profiles V and W and anomalies supposedly older than (south of) M3 on profiles Q, R, T, and U. The resulting magnetic bight younger than anomaly M3 would map southwest of its position on Figure 6 (p. 31). This mapping contradicts the presence of the distinctive anomaly M3 on line T because then M3 is associated with crust younger than M1. The apparent discrepancy is tentatively resolved by northwest trending fracture zones (dashed, including F13) that offset the diagnostic anomaly M3 on lines T, V, and W.

The difficulties with mapping the details of the bight may be related to changes in the Pacific plate boundaries. The RRR triple junction was migrating N12°E relative to the Pacific plate until 117 MYBP (M4). After that time, the path of the triple junction was N13°W, as measured by a line drawn roughly through the center of the bight. The change in plate motion was apparently restricted to a change in the spreading rates. The fracture zones offsetting anomalies younger that M4, in the region of the bight, have the same trend as fracture zones offsetting older anomalies on the flanks of the bight, suggesting no significant change in the spreading direction.

There is a dramatic change in the spreading rates after M5 which is evident on most profiles in the study area. The sequence M5 to M11 (on all profiles) matches the magnetic reversal model very well for a half spreading rate of 37 mm/yr. However, the correlations between the model and profiles of anomalies M4 to CL1 show divergence (with the exception of profiles V and W). As pointed out earlier, this divergence of the correlations indicates the actual spreading rate was slower than modelled.

Spreading was faster for M4-CL1 on the Pacific-Kula spreading limb near the bight than on the Pacific-Farallon limb (Figures 6 and 12, pp. 31 and 48). Faster spreading on the Pacific-Kula limb of the triple junction resulted in its northwesterly migration. Hence, the complications encountered in mapping the bight may be the result of the change in the direction of triple junction migration.

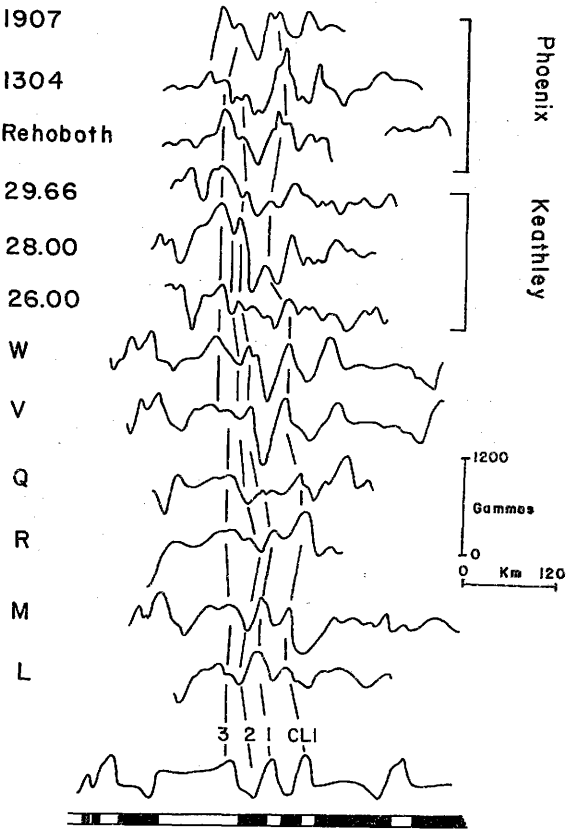
Mesozoic Reversal Model Modifications

There is a recurrent and significant mismatch between the youngest part of the Mesozoic geomagnetic model of Larson and Hilde (1975) and several anomaly profiles in the study area (O, Q, R, V, and W, in Figures 10 and 12, pp. 42 and 48). According to this model, the first peak on the younger side of anomaly M3 is M1 which is followed by a long normal polarity period. However, on the profiles listed above, there are two peaks observed between anomaly M3 and the magnetically flat zone.

Magnetic anomaly profiles from other parts of the world were examined and several profiles were found from the Phoenix lineations (Central Pacific) (Larson et al., 1972) and Keathley lineations (Western Atlantic) (Vogt et al., 1971) that exhibit the same character as profiles in this study area (Figure 13). The anomalies of the Phoenix and Keathley lineations do not appear to be bathymetry related or offset by fracture zones.

Possible explanations for the extra peak observed on the profiles in Figure 13 are: 1) local crustal anomalies not observed in the bathymetry are perturbing the normal anomaly patterns, 2) a ridge jump

Fig. 13. Revised Mesozoic magnetic reversal model. Anomaly CL1, 111.5-112.0 MYBP, has been added to account for the observed anomaly patterns younger than M3 on profiles of the study area, Phoenix lineations, and Keathley lineations. North Atlantic-Keathley anomalies were inverted to compare with the Pacific magnetic anomalies that were created south of the equator. Conventions are the same as in Figure 8 (p. 36).



1907
1304
Rehoboth
29.66
28.00
26.00
W
V
Q
R
M
L
Phoenix
Keathley
1200
Gammas
0
0
Km
120
3
2
1
CL1

shortly after anomaly M1 time left two M1 anomalies, or 3) the model is deficient for anomalies younger than M3.

The extra reversals observed on the profiles of the magnetic bight might be related to bathymetry or an unrecognized triple junction geometry, but neither situation exists for the profiles of the Central Region. Bathymetric and magnetic anomaly evidence for a ridge jump is lacking in the Central Region and in the area of the bight. Furthermore, the Mesozoic model for anomalies M0 (or CL) to M3 was based on profiles collected over the Hawaiian Ridge. The seamounts of the Hawaiian Ridge undoubtedly affected the magnetic anomaly patterns and would have obscured spreading anomaly patterns. The most reasonable alternative is to modify part of the Mesozoic reversal model to account for the observed anomaly patterns younger than M3.

The possibility of additional reversals not included in the model is substantiated by the work of Keating and Helsley (1978). They derived a composite reversal sequence from sediments cored at DSDP sites 361, 363, 364, 369, 386, and 391. Their composite has at least eight reversed polarity intervals between anomaly M3 and the Cretaceous Quiet Period; twice as many reversed intervals as the present reversal sequence (Larson and Hilde, 1975).

These combined data suggest the addition of a reversed polarity interval to the Mesozoic model immediately following (younger than) anomaly M1. The time bounds of the new reversed period, called CL1, are approximately 111.5 MYBP and 112.0 MYBP based on an assumed fixed spreading rate for the Central Region.

DISCUSSION

The Japanese and Hawaiian lineations in the study area are offset by many fracture zones. This pattern probably reflects some readjustments of the Pacific-Kula-Farallon relative plate motions during the Early Cretaceous. Changes in the plate motions would have initiated fracturing at zones of weakness and caused the reorganization of the ridges (Menard and Atwater, 1969).

An extension of this observation to the unmapped area on Shatsky Plateau might suggest the bight is continuous from M25 (153 MYBP) to M0 (108 MYBP). However, there remains the problem of the northeasterly migration of the triple junction, and the progressive increase in offset, with age, between the Hawaiian and Japanese lineations, along the length of the plateau, from M20 (143 MYBP) to M11 (125 MYBP). As pointed out by Sharman and Feeley (1979), the RRR triple junction southwest of Shatsky Plateau should have moved north at 48 mm/yr (Figure 14). Given the triple junction geometry depicted by the velocity diagram in Figure 14, a northeasterly migrating RRR triple junction would have required nonorthogonal and/or asymmetric spreading on the three spreading limbs or very fast spreading on the Pacific-Farallon ridge.

A much more attractive triple junction configuration at Shatsky Plateau is a ridge-fault-fault (RFF). The plate boundaries were: a Pacific-Farallon (P-F) transform fault, a Pacific-Kula (P-K) spreading ridge, and a Kula-Farallon (K-F) transform fault (Figure 15a). Hilde (1973) had suggested the existence of the P-F fault and the P-K

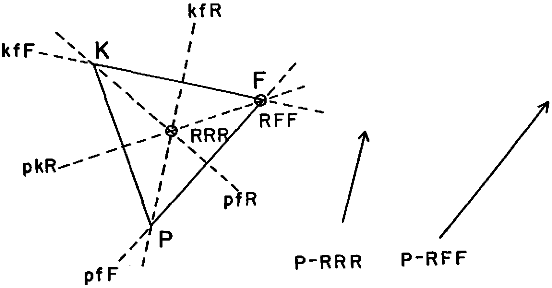
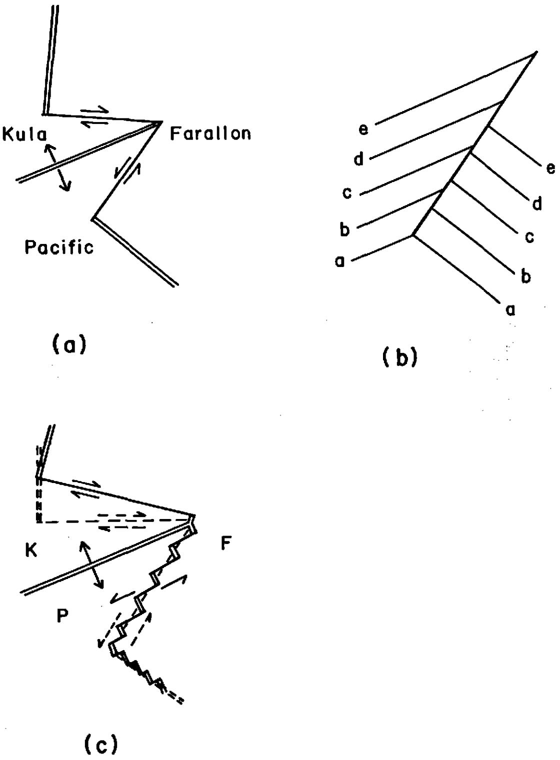


Fig. 14. A schematic velocity diagram of the Pacific (P), Farallon (F), and Kula (K) plates including the location of an RRR and an RFF triple junction. Solid lines connecting P, K, and F represent the full velocity (spreading rate and direction of motion) between a pair of plates. The dashed lines represent the velocity constraints imposed by the plate boundaries and labelled with lower case letters followed by an upper case letter designating the type of boundary. For example, pkF represents the Pacific-Kula spreading limb of the RFF triple junction. Spreading is assumed to be symmetric and orthogonal. The vectors to the right of the velocity diagram represent the motion of the triple junction with respect to the Pacific plate.

Fig. 15. The Late Mesozoic RFF triple junction at Shatsky Plateau. (a) The plate boundaries are shown and the arrows indicate relative motion between plates. (b) The magnetic lineation pattern produced by progressive offset of the Pacific-Farallon (P-F) ridges with time. This increase in offset of the lineations is a consequence of the lengthening of the (P-F) transform fault as the triple junction moves away from the Pacific plate at the P-F full spreading rate while the P-F spreading center only moves away at the P-F half spreading rate. (c) A schematic representation of the evolution of the lineation and fracture zone pattern as the triple junction changed from an RFF to an RRR northeast of Shatsky Plateau. Dashed lines represent old boundaries and directions of motion.


Kula
Farallon
Pacific
(a)
e
d
c
b
a
e
d
c
b
a
(b)
K
F
P
(c)

spreading ridge but misinterpreted the third limb (K-F) as a ridge. His resulting RRF geometry is not stable and could not have been sustained for the supposed 25 MY. On the other hand, an RFF triple junction can be stable or maintained if the rates of slip on the two faults are equal. The resulting lineation pattern on the Pacific plate would look just as Hilde (1973) had mapped (Figure 1, p. 4). Evidently, the spreading rates on the K-F and P-F ridges were sufficiently equal for a long time because it appears this triple junction configuration persisted for 17 MY (M19-M10N).

Several unique aspects of the proposed RFF triple junction are consonant with the magnetic lineation and fracture zone patterns in the region of Shatsky Plateau. Because such a triple junction would be fixed with respect to the Farallon plate (Figure 14, p. 56), it would migrate in the direction of the P-F transform fault (along the major axis of Shatsky Plateau, N35°E). Thus, the RFF triple junction geometry predicts the northeasterly migration of the Shatsky triple junction.

In addition, this RFF triple junction predicts an increasing separation for progressively younger anomalies between the Japanese lineations and the Hawaiian lineations. The growth of the offset between the lineations is a consequence of the lengthening of the P-F transform fault as the triple junction moved with the Farallon plate, away from the Pacific plate (Figure 15b). The increasing separation, with age, between the Japanese and Hawaiian lineations is observed for anomalies M19-M13 if the lineations of the two sets are projected onto Shatsky Plateau.

As noted above, the RFF geometry requires the spreading rates on the K-F ridge to be the same on the P-F ridge. Spreading along the P-F ridge was 35.3 mm/yr (half rate) at N40°E, as measured between anomalies M14 and M17 of the well mapped Hawaiian lineations. Therefore, the half spreading rate on the K-F ridge was 35.3 mm/yr in an undetermined direction (spreading anomalies associated with this ridge have been supposedly lost to subduction).

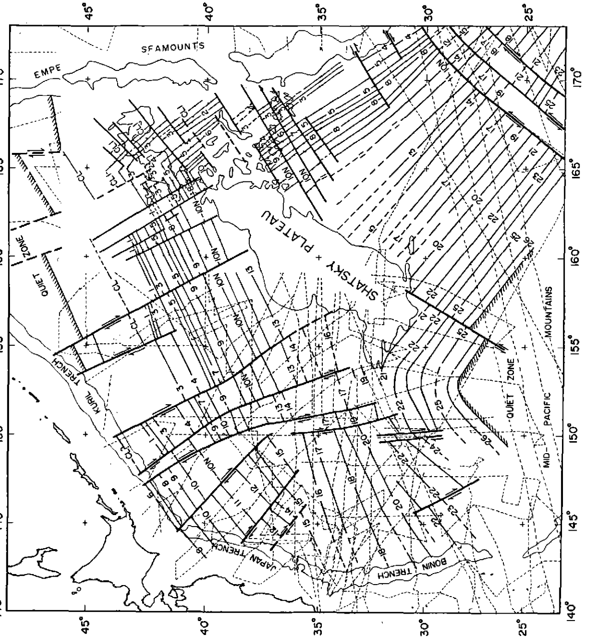
The direction of K-F spreading can be estimated from the directions and rates observed in the Japanese and Hawaiian lineations for the P-K and P-F ridges respectively. However, P-K rates and directions are poorly determined from the mapped fracture zones and Japanese lineations. Consequently, a range of possible rates and directions for P-K spreading combined with the RFF model proposed here yields a range of directions for K-F spreading.

The fracture zone directions for the Japanese lineations M14-M17 range from N11°W to N38°W. Assuming the fracture zones indicate the direction of plate motion, spreading is orthogonal to the ridges, and spreading on K-F is 35.3 mm/yr, then, calculated P-K half spreading rate limits are 14.7 mm/yr to 44.4 mm/yr. Observed half rates of P-K spreading for anomalies M11 to M19 range from 25.4 to 50.9 mm/yr, largely overlapping the calculated range. These observations were based on the sparse data of the Japanese lineations near Shatsky Plateau. A mid-range value for P-K spreading (30 mm/yr, half rate) implies east-west spreading along the K-F boundary.

The RFF geometry would have been sustained until the plate motion changed such that the slip rates on the faults were different, rendering the triple junction unstable. In this case, the RFF changed to an RRR triple junction shortly before anomaly M10 (122 MYBP). Hilde (1973) noted a change in the spreading direction of the Pacific plate between M13 and M10, as reflected in a change in strike of the Hawaiian lineations. The plate motion change would have induced new fracturing and plate separation along the P-F transform fault in a manner similar to the creation of the zed-pattern described by Menard and Atwater (1969). The transform fault would have been resolved into several ridges and transform faults as this zone of weakness responded to readjustments in plate motion (Figure 15c, p. 58). The breakup of the P-F fault would have resulted in numerous small ridges and transform faults as seen in the magnetic lineation and fracture zone patterns mapped by this study.

Figure 16 is a composite magnetic lineations map for the Northwest Pacific. It is based on the magnetic anomaly mapping by Hilde (1973) and this study. Some ambiguities remain around Shatsky Plateau but the overall growth pattern of the Northwest Pacific can be seen. The northwestern part of the Pacific plate grew along two limbs of an RRR triple junction from 155 (M26) to 141 (M19) MY ago. At about 141 MYBP, the Pacific plate motion changed and the triple junction reorganized to an RFF. The special stability requirement of equal slip rates on the two faults (P-F and K-F) appears to have been satisfied for about 17 MY. Readjustments of the Pacific plate's motion rendered the triple junction unstable and an RRR configuration again emerged 122 MY ago (M10). The long, P-F transform fault broke into many ridges and transform faults, as seen in the magnetic lineation pattern of Figure 6 (p. 31). Further changes to the Pacific plate's motion relative to the

Fig. 16. Composite Mesozoic magnetic lineations in the Northwest Pacific Ocean. Figures 1 and 6 (pp. 4 and 31) were combined. The respective labelling conventions apply.



EMPE
SEAMOUNTS
SHATSKY + PLATEAU
QUIET
ZONE
KURIL
TRENCH
JAPAN TRENCH
BONIN TRENCH
QUIET ZONE
MID-PACIFIC MOUNTAINS

triple junction at 117 MYBP resulted in changing the triple junction's direction of motion from N12°E to N13°W.

Future studies of this area should include crustal and seamount coring and collecting long range side scan sonar data in addition to the usual underway geophysical data. The drilling program could be used to verify the anomaly identifications and establish the age gradient in the Central Region by coring the crust at anomaly CL1 and perhaps anomaly M5. Cores from the seamounts of the Seamount Range would provide dates which would set a minimum age for the underlying crust and paleomagnetic information could be used to determine the paleomagnetic latitude of formation (expected to be south of the equator if the range was formed contemporaneously with the surrounding crust and north of the equator if they formed after 100 MYBP).

The long range side scan sonar system could be best used to map the tectonic grain of the magnetic bight north of Shatsky Plateau. This type of data provides continuity and guidance in mapping the crustal fabric as structural lineaments and bathymetric trends. A track line collecting side scan sonar data run to 43°N in a zig-zag pattern centered on 167°E and then west over the bight would greatly enhance the interpretation of the magnetic anomalies in this area. The fracture zones in the Southern and Central Regions would be crossed oblique to their trends making them highly visible on the records. The sea floor grain is expected to change trends on the sonar records as the inverted V on the bight is traversed. Side scan data on the crust north and east of the bight may provide valuable information concerning the evolution of the Pacific crust during the Mesozoic Quiet Period.

CONCLUSION

Using a revised bathymetric map and the magnetic anomaly data, five physiographic provinces were defined, on the basis of different morphologic and magnetic characteristics. The Northwest Basin, Central Region, and Southern Region are nearly flat making them the most reliable sources of sea floor spreading magnetic anomalies. In contrast, magnetic reversal anomalies associated with crustal accretion are obscured by the effects of the Plateau and Seamount Range.

The magnetic anomalies of the Southern Region are interpreted to be part of the Hawaiian lineations. Anomalies M1-M11 have been identified. The northwest trending lineations are offset by five fracture zones. In this region, the Pacific-Farallon ridge system was four small ridges until 122 MYBP when the ridges became nearly aligned. The ridges were approximately colinear for 7 MY until M3 time when the ridges again were offset about 20 km. The fluctuating ridge configurations observed in the lineations suggest slight changes in the Pacific-Farallon plate motion.

The east-west trending lineations of Hilde (1973) and Hilde et al. (1976) are reinterpreted as northwest trending lineations produced by the Pacific-Farallon spreading system. Anomalies M1-M6 are well developed and easily identified in the Central Region. The correlations were extended northward to a magnetic bight with a series of easterly offsets.

The northeast trending Japanese lineations in the northwestern part of the study area meet with the northwest trending Hawaiian lineations of the Central Region to form a magnetic bight north of Shatsky Plateau. The bight represents a ridge-ridge-ridge triple junction. The complicated anomaly patterns younger than M5, at the bight, probably reflect the change in triple junction migration (N12°E to N13°W at M4). The direction change was probably the result of a reduction in the spreading rate on the P-F ridge at M4 time, a decrease in spreading evident in the magnetic reversal lineations in the Central and Southern Regions.

The RRR triple junction southwest of Shatsky Plateau changed to an RFF triple junction about 142 MY ago (M19). The stability requirements of equal slip rates on the two transform faults were evidently satisfied for 17 MY (M19-M10N). The RFF geometry predicts the observed northeasterly migration of the triple junction and, because the triple junction was fixed with respect to the Farallon plate, the P-F transform fault grew at the P-F half spreading rate. The lengthening of the transform fault produced a progressively greater separation of the P-K and P-F ridges, resulting in an increasing offset, with age, of the Japanese and Hawaiian lineations.

A stable RFF implies the K-F spreading rate equaled the P-F rate (35.3 mm/yr half rate). This condition is satisfied if the half spreading rate on the P-K ridge was between 14.7 mm/yr and 44.4 mm/yr with a range of relative directions of motion between N11°W and N38°W. Mid-range values for the half rate and direction of P-K spreading imply east-west K-F spreading.

At about anomaly M10N time, the relative motion between the Pacific and Farallon plates changed. This change rendered the RFF triple junction unstable, and it reverted back to an RRR configuration north of Shatsky Plateau. The change in relative motion also caused fracturing and initiation of spreading along the old P-F transform fault. The resulting ridge and fault pattern that developed is reflected in the lineation and fracture zone pattern mapped by this study.

The Mesozoic geomagnetic reversal model younger than M3 (114 MYBP) has been modified to reflect the presence of an extra interval of reversed polarity observed on the anomaly profiles of the bight and Central Region. Some profiles of the Phoenix and Keathley lineations exhibit this same character. The added interval, between M1 and CL or M0, is labelled CL1. The time bounds are 111.5 MYBP to 112.0 MYBP. Anomaly CL1 was not detected by Larson and Hilde (1975) probably because it was obscured by the effects on the Hawaiian Ridge.

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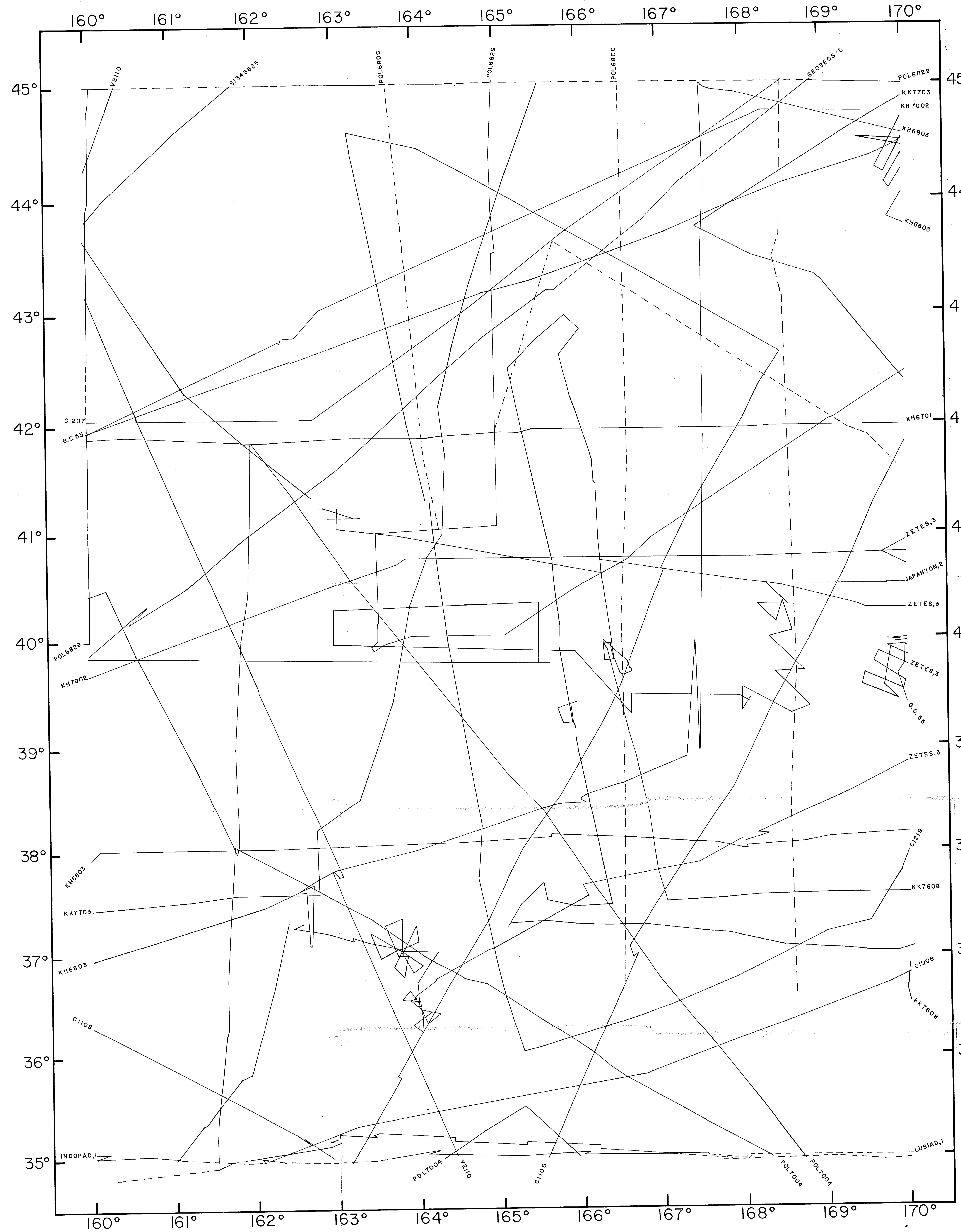
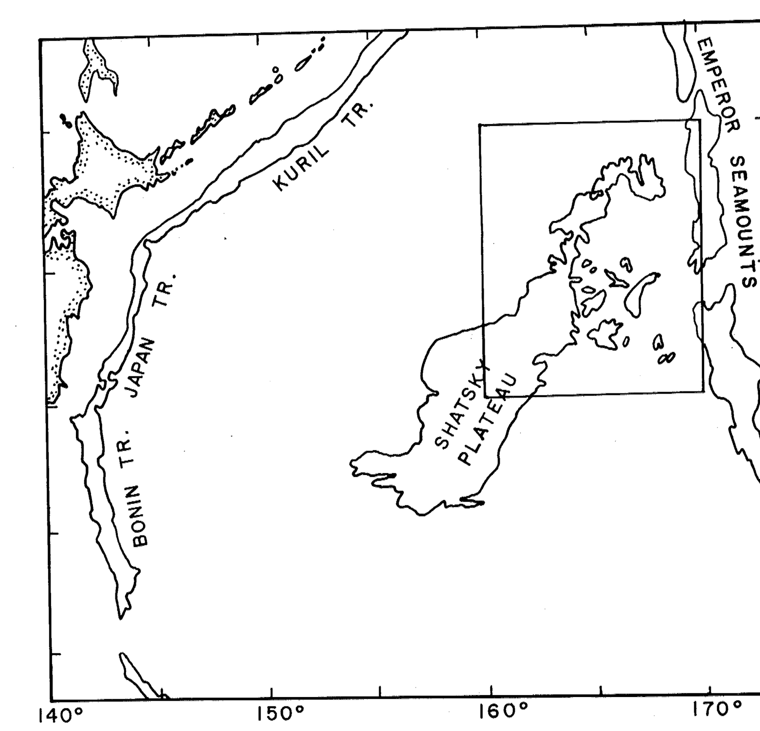




Index of study area (enclosed) for Maps 1, 2, 3, and 4.

Solid tracks were received in digital form.

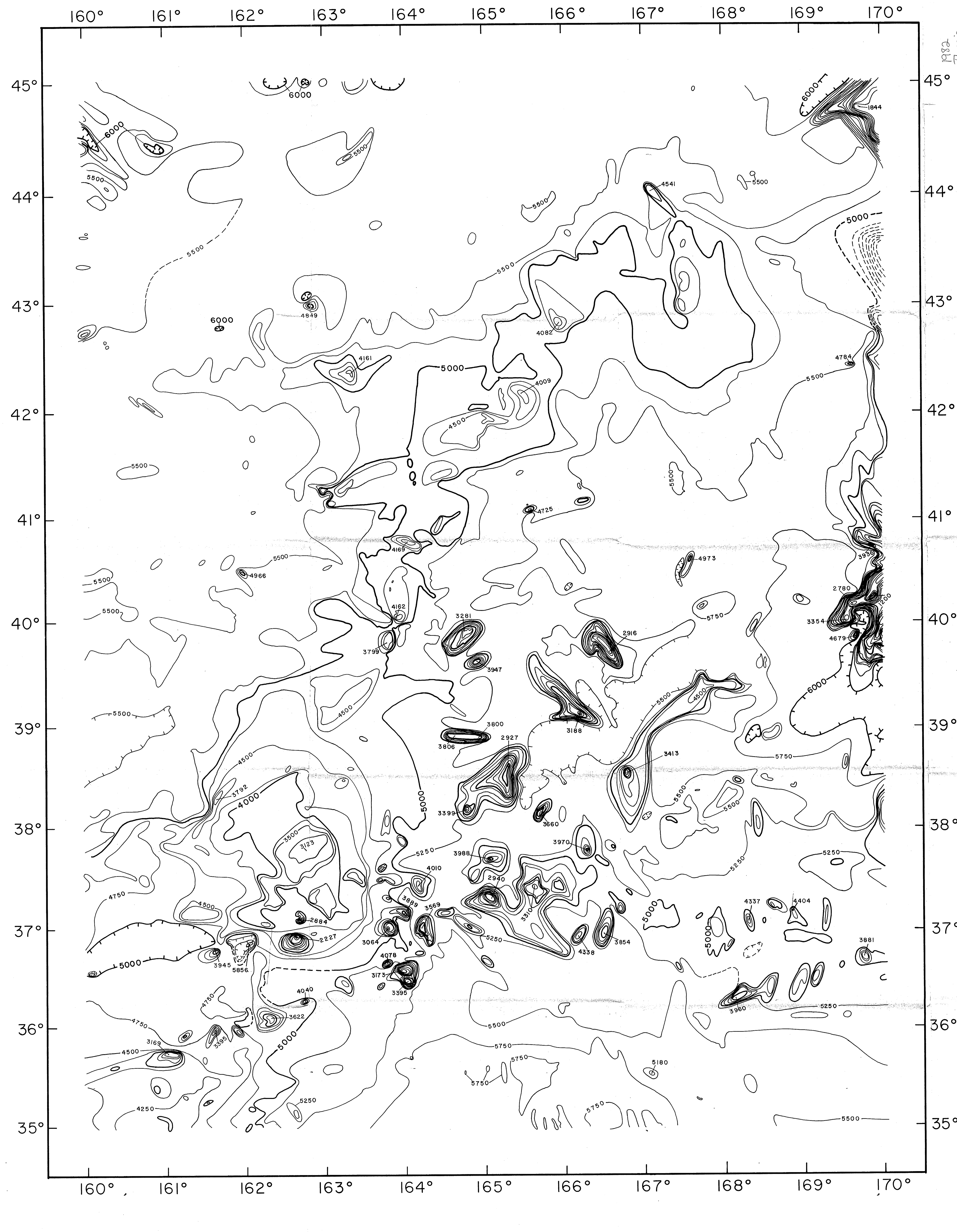
Dashed tracks taken from Scripps Magnetic Chart no. 7 and a Pacific Ocean Labs magnetics chart.

Mercator Projection

MAP I

TRACK CHART OF AREA
NORTHEAST OF SHATSKY PLATEAU

RISCH, 1982



Contour interval: 250 m.

Assumed sound speed: 1500 m s.

Contours taken from Japanese Hydrographic Department charts.

Depression contour.

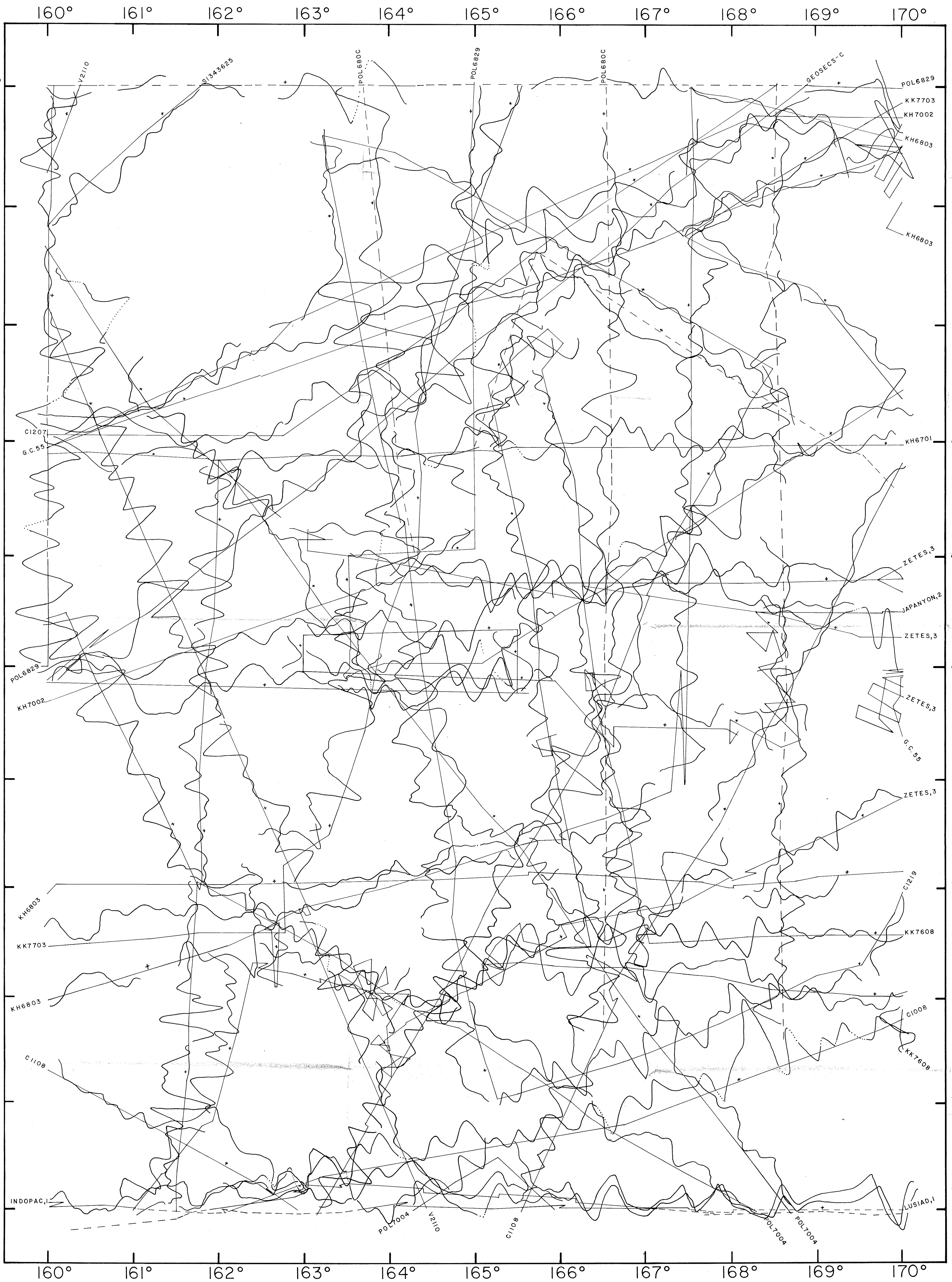
4000 m contour.

5250 m contour.

MAP 2

BATHYMETRIC CHART— NORTHEAST OF SHATSKY PLATEAU

RISCH, 1982



See Map1 for explanation of tracks.

Magnetic anomalies are plotted normal to ship tracks with the track taken as zero intensity.

\+ Positive anomalies.

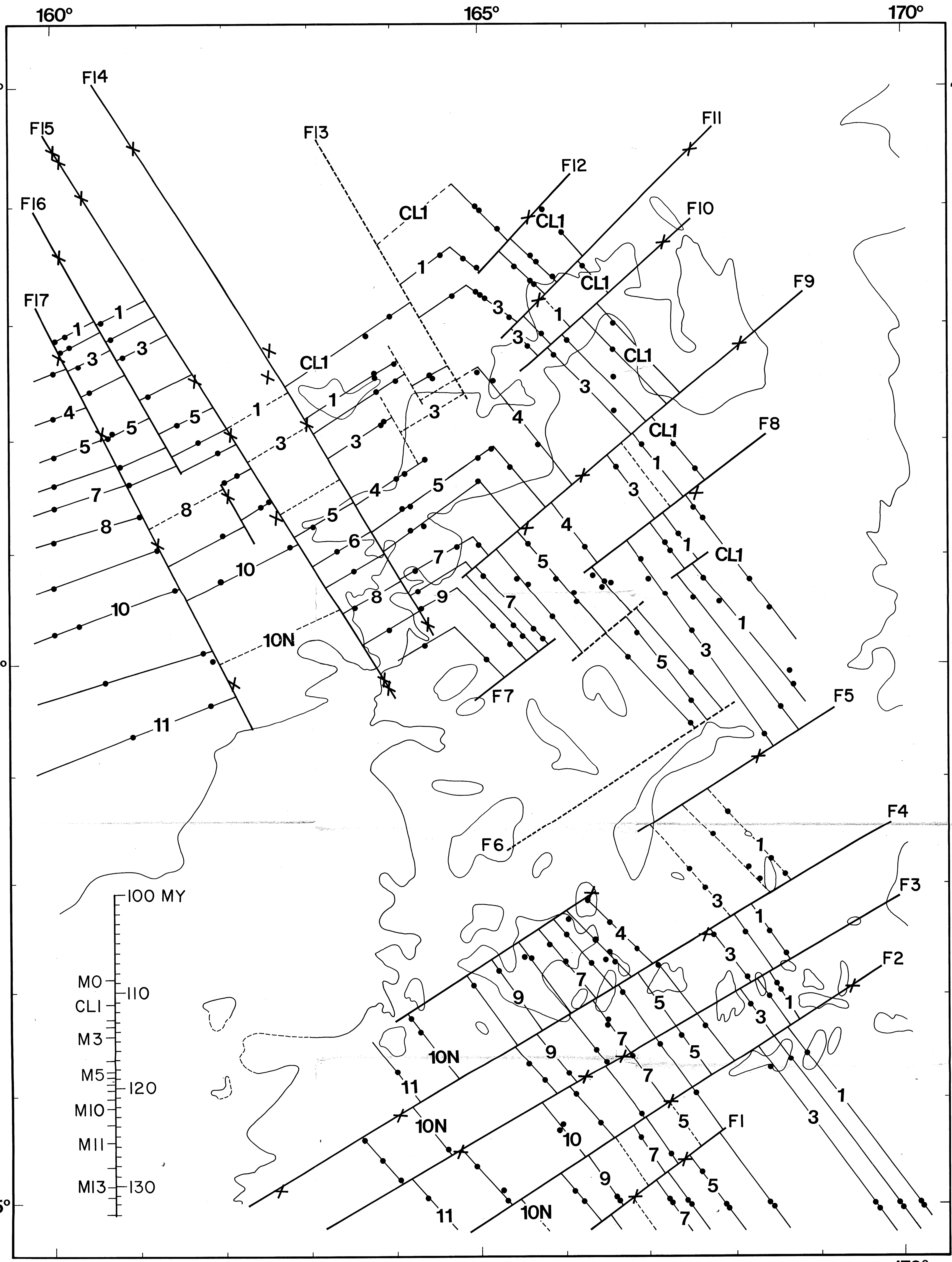
··· Inferred anomalies.

500 Gammas 0

MAP 3

MAGNETIC ANOMALY CHART — NORTHEAST OF SHATSKY PLATEAU

RISCH, 1982



- ● Magnetic anomaly data control.
- X Bathymetric and/or seismic data control for fracture zones.
- Magnetic lineations.
- Fracture zones.
- Inferred lineations or fracture zones.

Numbers on the lineations are Mesozoic anomaly identifications.

5000 m bathymetry contour shown.

MAP 4

MAGNETIC LINEATIONS CHART — NORTHEAST OF SHATSKY PLATEAU

RISCH, 1982