

Paleogene history of the Kula plate: Offshore evidence and onshore implications

PETER LONSDALE *Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093*

ABSTRACT

Paleocene to middle Eocene magnetic anomalies were mapped over oceanic crust that accreted at the Kula-Pacific spreading center and is now obliquely entering the western Aleutian Trench between 179°E and 168°E. The strike of anomalies and the pattern of abyssal hills and fracture zones changed abruptly during 56–55 Ma, when north-south spreading veered to northwest-southeast (310°–130°). Kula-Pacific spreading ceased in 43 Ma. A 75-km-long section of the fossil Kula Rift axis has avoided subduction, although it now intersects the trench axis (almost orthogonally) near 171.5°E. A narrow remnant of the former Kula plate, northwest of this fossil spreading center, is bounded by a fossil Kula-Pacific transform with a high transverse ridge alongside a sediment-filled transform valley. Anomalies on this remnant show that Eocene Kula-Pacific spreading was highly asymmetric (2:1).

The 56–55 Ma change in Kula plate rotation inferred from the change in spreading direction coincided with birth of the Aleutian subduction zone, and was probably a consequence of the resulting change in slab-pull stresses on the oceanic lithosphere. The change in direction of Kula-North American motion is a plausible explanation for the detachment of continental terranes from the Pacific Northwest and their migration around the Gulf of Alaska, and for the early Eocene demise of Alaska Range arc volcanism. The cessation of Kula-Pacific spreading coincides with a major change in Pacific-plate rotation, and the subsequent direction of convergence of the Pacific plate with the Aleutian arc was similar to the 55–43 Ma direction of Kula-plate convergence.

INTRODUCTION

Soon after the present pattern of lithospheric plates had been delineated by mapping the characteristic structures and seismicity of their boundaries, Pitman and Hayes (1968) recognized that east-west-striking, southward-aging, magnetic anomalies south of the Aleutian Trench implied the former existence of a now-vanished plate, part of the North Pacific floor that had moved northward faster than had the Pacific plate. Grow and Atwater (1970), believing that the hypothetical plate had been entirely consumed at subduction zones, named it Kula (= all gone); it was the first recognized of several such plates (Izanagi, Aluk, and others) now known to have been involved in accretion of the present Pacific floor and in the creation of plate-boundary structures that survive around its rim.

The magnetic anomalies that require the existence of the Kula plate also constrain the time of its birth and its subsequent motion. The plate originated by splitting from the Farallon plate during Late Cretaceous rifting (Rea and Dixon, 1983), but almost all of the crust accreted by Kula-Farallon spreading was later subducted beneath North America, and only Kula-Pacific motion has left a usable magnetic record. Chinnook Trough (Fig. 1) was one site of initial Kula-Pacific rifting (Erickson and others, 1969; Woods and Davies, 1982), and the Upper Cretaceous and Paleocene crust between this rift valley and the Aleutian Trench represents the truncated southern flank of a Kula-Pacific rise, the Kula Ridge of Grow and Atwater (1970). A dense coverage of bathymetric and magnetic data, including results from the systematic SEAMAP surveys (Erickson and Grim, 1969; Peter and others, 1970), allowed Grim and Erickson (1969) and Hayes and Heirtzler (1968) to estimate that the rise had spread almost exactly north-south with an average "half-rate" of

45–35 mm/yr until the time of Anomaly 25 (late Paleocene, 59 Ma, according to the DNAG time scale of Berggren and others, 1985, that is used throughout this paper). The "half-rate" is the rate of accretion to the Pacific plate; by assuming that spreading had been symmetric, Engebretson and others (1984, 1985) were able to use these data for quantitative modeling of the 82–59 Ma motion of the Kula plate relative to the Pacific plate and its hot spots, and thereby relative to the other plates that had bounded it (Farallon, North American, Eurasia). It is clear from these models, and from similar earlier reconstructions (for example, Jackson and others, 1978), that the Kula plate did not "die" by obliteration when its trailing edge entered the trench and spreading was stifled, as Pitman and Hayes (1968), Grow and Atwater (1970), and deLong and others (1978) had inferred. Instead it lost its separate identity sometime in the Eocene by fusing with the Pacific plate while most of the Kula-Pacific boundary was still far from any trench, leaving a fossil Kula Ridge to be subsequently subducted.

No direct information on when Kula-Pacific spreading ceased has been obtained from the well-mapped truncated rise flank south of the eastern Aleutian Trench, because no fossil spreading axes have been recognized, and no anomalies younger than Anomaly 25 have avoided subduction, except for a tentatively identified Anomaly 24 now in the trench east of 160°W (Peter and others, 1970). Byrne (1979) inferred a 56 Ma date for cessation of Kula Ridge spreading, based on the mapped pattern of Pacific-Farallon anomalies in the Gulf of Alaska. Engebretson and others (1984) speculated that spreading continued until the Pacific plate changed direction at 43 Ma; in which case, the Kula plate had an undetermined 15-m.y. Eocene history.

In 1986 we explored the Pacific floor south of

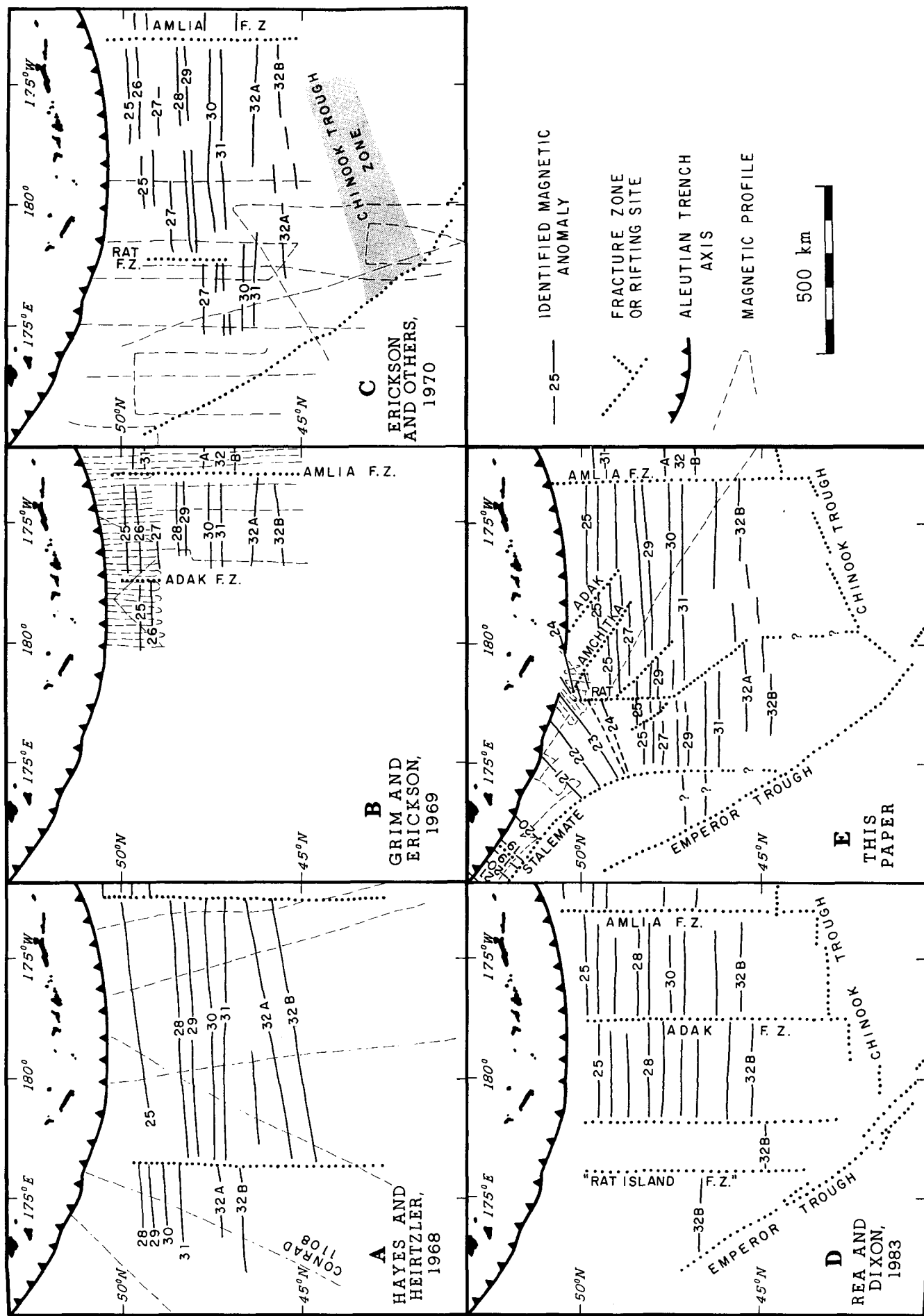


Figure 1. Successive interpretations of crustal patterns south of the western Aleutian Trench, based on increasing amounts of data. Favored interpretation E relies on a few additional post-1970 magnetic and bathymetric profiles, as well as the new data along the Seabeam track (dashed line).

the western Aleutian Ridge, where there were two reasons for suspecting that more of the later history of Kula-Pacific spreading might be preserved, even though the extent of the Tertiary crust was poorly known. First, the western part of the trench has consumed only a small area of ocean crust since 43 Ma, because of its high obliquity to Pacific-North American motion (McKenzie and Parker, 1967). Second, Erickson and others (1970) mapped a large left-lateral offset of magnetic anomalies near 178°E, which brought the late Paleocene crust west of their "Rat fracture zone" more than 300 km south of the trench axis (Fig. 1C). The pioneering study of Hayes and Heirtzler (1968), however, assigned a right-lateral offset to the large fracture zone, leaving less room for Paleogene crust south of the western part of the trench (Fig. 1A), and this interpretation was followed by Rea and Dixon (1983). Our most novel results, including definition of the western boundary of Tertiary crust and discovery of a fossil Kula-Pacific spreading center attached to a sizeable remnant of Kula plate, come from west of Rat fracture zone. New data farther east are also important for documenting the response of the Kula-Pacific spreading center to changes in relative plate motions.

METHODS OF STUDY

The 1986 field program was conducted from R/V *Thomas Washington*, with a SEABEAM multi-narrow-beam echo-sounder (Renard and Allenou, 1979), a 3.5-kHz acoustic profiler, a single-channel seismic profiler, and a magnetometer. Navigation was by Transit and Global Positioning System satellites and LORAN C. A thorough Seabeam survey straddled the intersection of Rat fracture zone with the trench, from 179.5°E to 176.5°E, and reconnaissance tracks were made over the trench outer rise and slope from 176.5°E to 170°E (Fig. 2). Abyssal hill orientations measured on Seabeam swaths helped establish the trend of magnetic lineations even in areas of few tracks, but on the trench slope, care was required to distinguish original crustal structures from recent fault blocks created near the modern convergent plate boundary. On the outer rise, minimal recent faulting and uniform pelagic deposition allow bedrock topography diagnostic of the spreading direction to be expressed in a smoother but still highly lineated sea-floor relief despite a 400-m-thick sediment blanket (Fig. 3).

Interpreting the new Seabeam, profiler, and magnetic observations required integrating them with data already used by Hayes and Heirtzler (1968), Grim and Erickson (1969), and Erickson and others (1970). Re-examination of the old data was particularly important for establishing the limits of the study area by determining

the extent of early Tertiary crust in the northwest Pacific.

THE BOUNDARIES OF TERTIARY CRUST IN THE NORTHWEST PACIFIC

The Cretaceous/Tertiary crustal boundary on the south flank of Kula Ridge is marked by the east-west line of Chron 30, 300–500 km south of the trench axis (Figs. 1E, 4). No east-west Tertiary anomalies have been identified beyond 174.8°E, even on the well-placed north-south magnetic profiles of Erickson and others (1970) (Fig. 1C). The implication is that the Paleocene Kula Ridge was bounded on the west by a major transform fault whose trace (labeled "Stalemate fracture zone" on Profile C of Fig. 5) is now near 174.5°E. A set of magnetic lineations west of this meridian, tentatively identified with Chron 32 (for example, on the Conrad 1108 profile Figs. 1A, 4), could be evidence that Kula-Pacific spreading extended farther west during the Early Cretaceous. If so, a fossil Kula-Pacific spreading center may exist in the poorly surveyed region east of the northern Emperor Trough, which is itself interpreted as a fossil Upper Cretaceous axis of Pacific-Farallon spreading (Rea and Dixon, 1983).

Stalemate fracture zone bends to a northwesterly strike north of 49°N and forms the southwest boundary of a narrow triangle of Eocene crust that extends alongside the Aleutian Trench as far as 168.3°E (Fig. 6). The deeper, rougher crust southwest of the fracture zone has a thicker sediment layer, including a basal layer (the "older pelagics" of Buffington, 1973) that is absent northeast of the ridge (Fig. 5, profiles A and B). It also appears to lack magnetic lineations and is therefore assigned to the Cretaceous Magnetic Quiet Zone (Fig. 6). The northwest-striking section of the fracture zone has major structural relief, with a narrow 1- to 2-km-high ridge (Stalemate Ridge) northeast of a 25-km-wide trough (Fig. 2). These features produce a narrow anomaly in the satellite-measured gravity field (Haxby, 1987), which helped me interpolate the fracture zone's location between widely spaced ship crossings.

The western Aleutian Trench is an active plate boundary zone in which the Tertiary oceanic crust is intensely deformed by normal faulting and deeply buried by turbidite deposition before it is obliquely subducted. These processes destroy or obscure structures inherited from the time of crustal formation, although the crust's magnetic signature is still readable up to 50 km landward of the trench axis (Peter and others, 1970; Grow, 1972). Our Seabeam data indicate that in the eastern part of the study area the normal faulting induced by bending of the downgoing lithosphere proceeds by rejuvenation

of old abyssal-hill faults. West of 178°E, however, where the pre-existing faults strike into the trench at a high angle (parallel to the magnetic stripes in Fig. 6), new fractures are formed, and the abyssal hill relief is obliterated by deep grabens subparallel to the trench axis (for example, northeast end of profile C, Fig. 5).

STRUCTURAL PATTERNS OF PALEOGENE CRUST SOUTH OF THE WESTERN ALEUTIAN RIDGE

Paleocene Crust East of 178°E

My maps of crustal patterns east of Rat fracture zone (Figs. 1E, 6) differ from previous interpretations in showing a set of oblique, northwest-trending fracture zones, none of which intersects our Seabeam swath between the normal Rat and Amlia fracture zones, although they cause repetition of anomalies on north-south tracks. Hayes and Heirtzler (1968, p. 4642) could not explain this phenomenon with any "reasonable orientation" of fracture zones, but oblique fracture zones were subsequently recognized as common features elsewhere in the North Pacific (Bassinger and others, 1969; Shih and Molnar, 1975; Hey and Wilson, 1982). The oblique nature of Adak fracture zone is apparent from close inspection of the SEAMAP data that first revealed its existence (Grim and Erickson, 1969). A parallel fracture zone, here named for the island of Amchitka, obliquely offsets Chron 26-25 in the SEAMAP survey (Figs. 4, 7C) and extends across the outer rise to the Seabeam survey of the trench outer slope (Figs. 7B, 8).

On bathymetric profiles (for example, Fig. 5D), the magnetically identified oblique fracture zones are shallow depressions at small steps in the regional depth. Grim and Erickson's (1969) survey of Adak fracture zone shows an irregular line of troughs and small seamounts, and the section of Amchitka fracture zone within our Seabeam survey has similar relief.

Rat Fracture Zone

Rat fracture zone strikes normal to Paleocene Anomalies 28–25 and offsets them 80 km left laterally at a trough along 177.7°E (Figs. 2, 4, 6). Farther north, where it offsets Anomaly 24 and was profiled with Seabeam, the fracture-zone valley strikes 357° and is bounded on the east by a 2-km-high scarp, the side of a 60-km-long transverse ridge of locally uplifted crust like those along many other fracture zones (Bonatti, 1978; Lonsdale, 1986). Beyond a saddle at 50°N, the ridge changes to a more symmetric feature with gentler lobate sides indicative of a volcanic origin. This ridge ends abruptly part-way down the outer slope of the trench, where

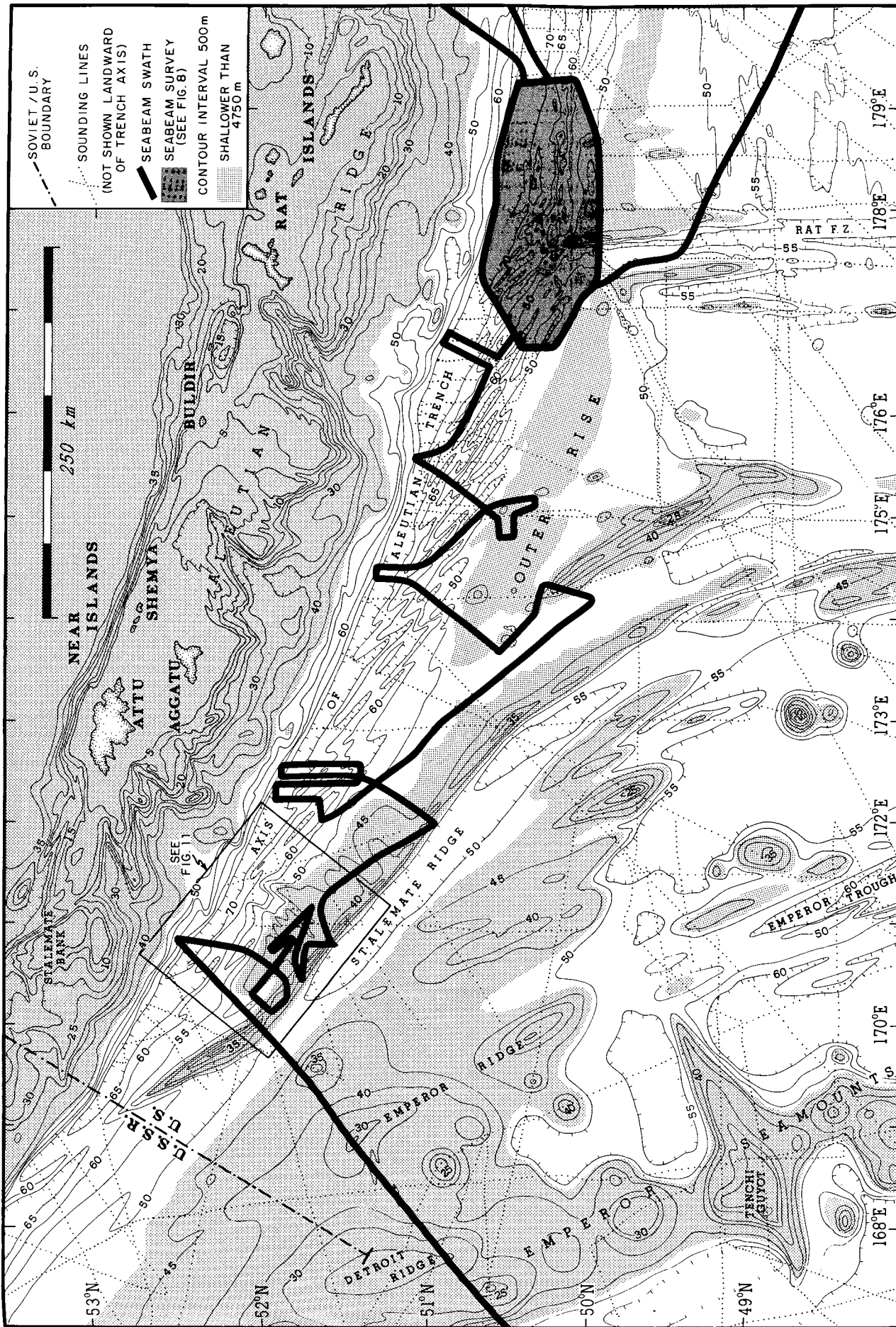


Figure 2. Regional bathymetry. Contours on the Aleutian Ridge are after Nichols and Perry (1966).

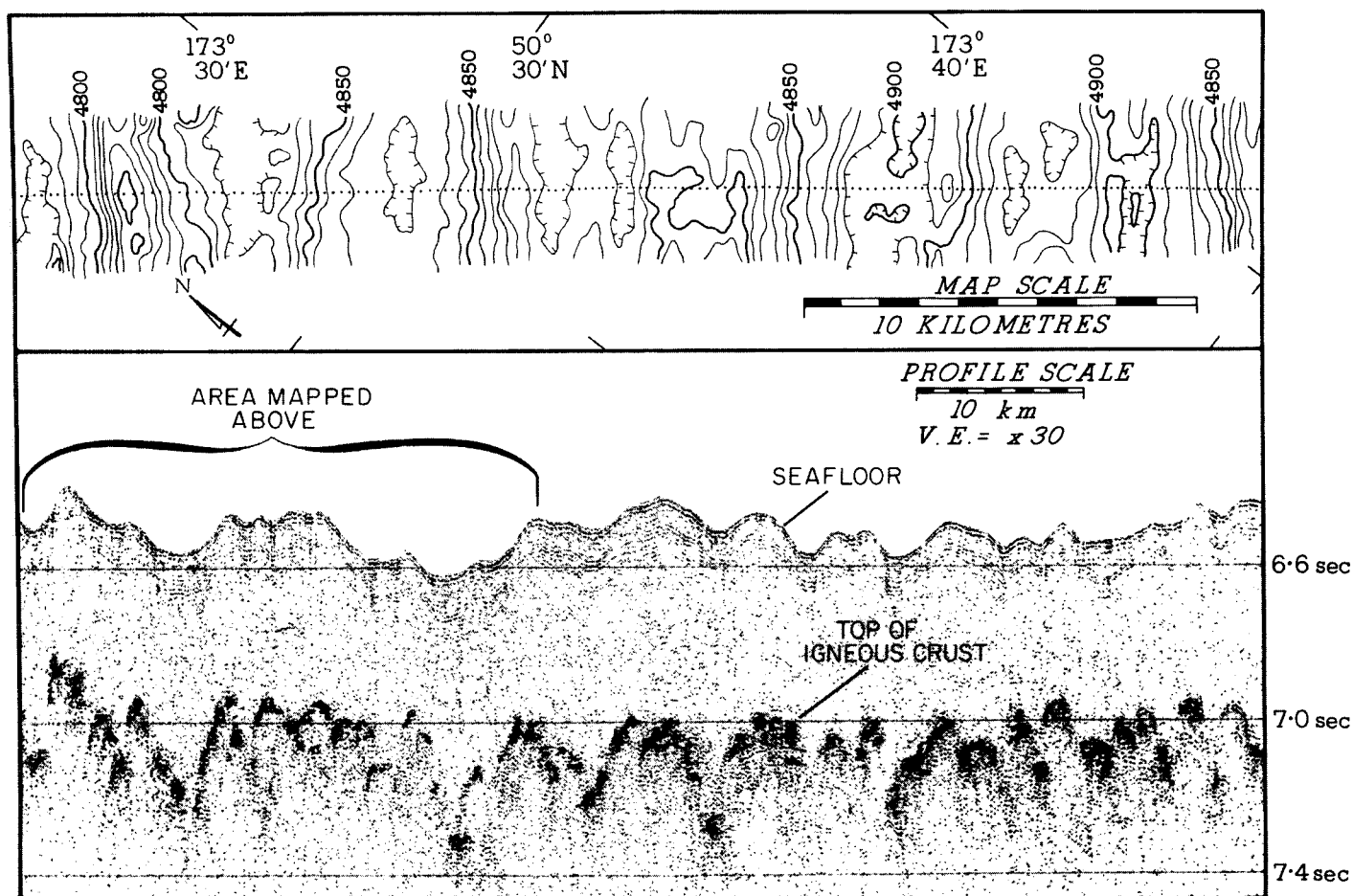


Figure 3. Samples of a seismic reflection profile and a simultaneously collected Seabeam swath, on 50-m.y.-old crust seaward of the Aleutian Trench near 174°E (located in Fig. 9). Note that the low-amplitude abyssal-hill relief of the igneous basement has a persistent effect on bathymetry, despite its burial by several hundred metres of sediment.

truncation by Anomaly 23 (Fig. 8) demonstrates termination of the fracture zone.

Eocene Pacific Crust 171°E–178°E

A 60,000-km² area of lithosphere that accreted to the Pacific flank of the Kula Ridge 55–43 Ma (Chronos 23–19) remains unsubducted west of 178°E (Fig. 6), in a region where the few earlier magnetic profiles had been misidentified (for example, on the Conrad 1108 track; Hayes and Heirtzler, 1968) or were oriented parallel to the magnetic stripes and therefore inferred to be in the magnetic quiet zone (for example, Vema 2006; Fig. 4). More than half of this narrow wedge of crust has already reached the outer slope of the trench and been severely deformed by recent extensional faulting. Fortunately for the interpretation of the rather sparse available data (Fig. 4), the initial crustal structure was simple in comparison to the complex crustal age patterns of pre-55 Ma crust, with its close-spaced fracture zones. If Chronos 23–20 are un-

broken between the trench axis and Stalemate fracture zone, as available data (Fig. 4) suggest, the intervening Buldir Ridge cannot be a fracture zone trace, despite its parallelism to Stalemate Ridge. Seabeam swaths across the northwest end of Buldir Ridge show a row of coalesced 25-km-high volcanoes.

The Kula Plate Remnant and Its Fossil Boundaries

The northwest boundary of the Pacific flank of the Eocene Kula Ridge is Kula Rift, which strikes 040° down the outer slope of the trench and is a 43 Ma fossil spreading center (Fig. 4). This identification is based on the reversal of magnetically determined age gradients across the rift (Fig. 9), the characteristic cross section revealed by the profiler (Figs. 10B, 10C), and the right-angle intersection with a fossil transform fault (Fig. 11). Kula Rift had an original relief of 1 km from its uplifted shoulders (“rift mountains”) to the rift floor, which is now over-

lain by 500–600 m of sediment. A buried ridge along the axis of the rift valley resembles the volcanic “central high” common to most rifted mid-ocean ridges. The fault trough can be tentatively mapped, using old sounding lines and profile B30 of Buffington (1973) (Fig. 5A), for 70 km from Stalemate Ridge to the trench axis near 171.4°E (Fig. 11). Our new Seabeam and magnetic data are restricted to its southwest end, where the rift valley is unaffected by later trench-slope faulting.

The segment of Stalemate Ridge northwest of its intersection with Kula Rift follows a fossil Kula-Pacific transform fault. By analogy with better known modern transform faults of similar slip rate (for example, in the Eltanin fault system; Lonsdale, 1986), the principal site of strike-slip faulting was probably the floor of the 500- to 1,000-m-deep transform valley, now deeply filled with sediment (Fig. 10A), on the northeast side of the ridge. As at the Eltanin transforms, the Stalemate transform valley is closed off near the Kula Rift intersection by oblique ridges,

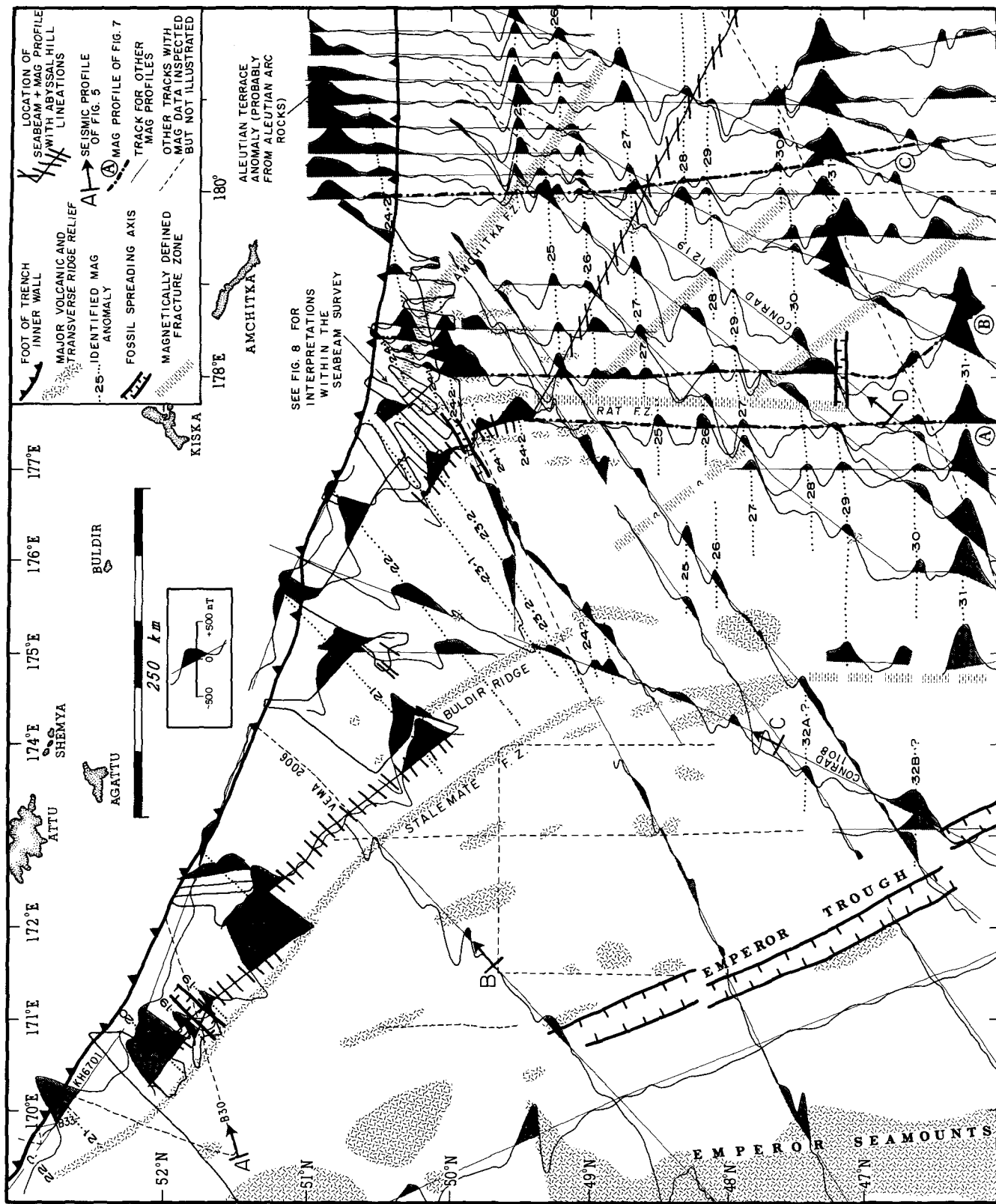


Figure 4. Magnetic anomalies, projected 090° for Anomaly 23 and older and 050° for Anomaly 24 and younger, and abyssal hill lineations mapped within the Seabeam swath.

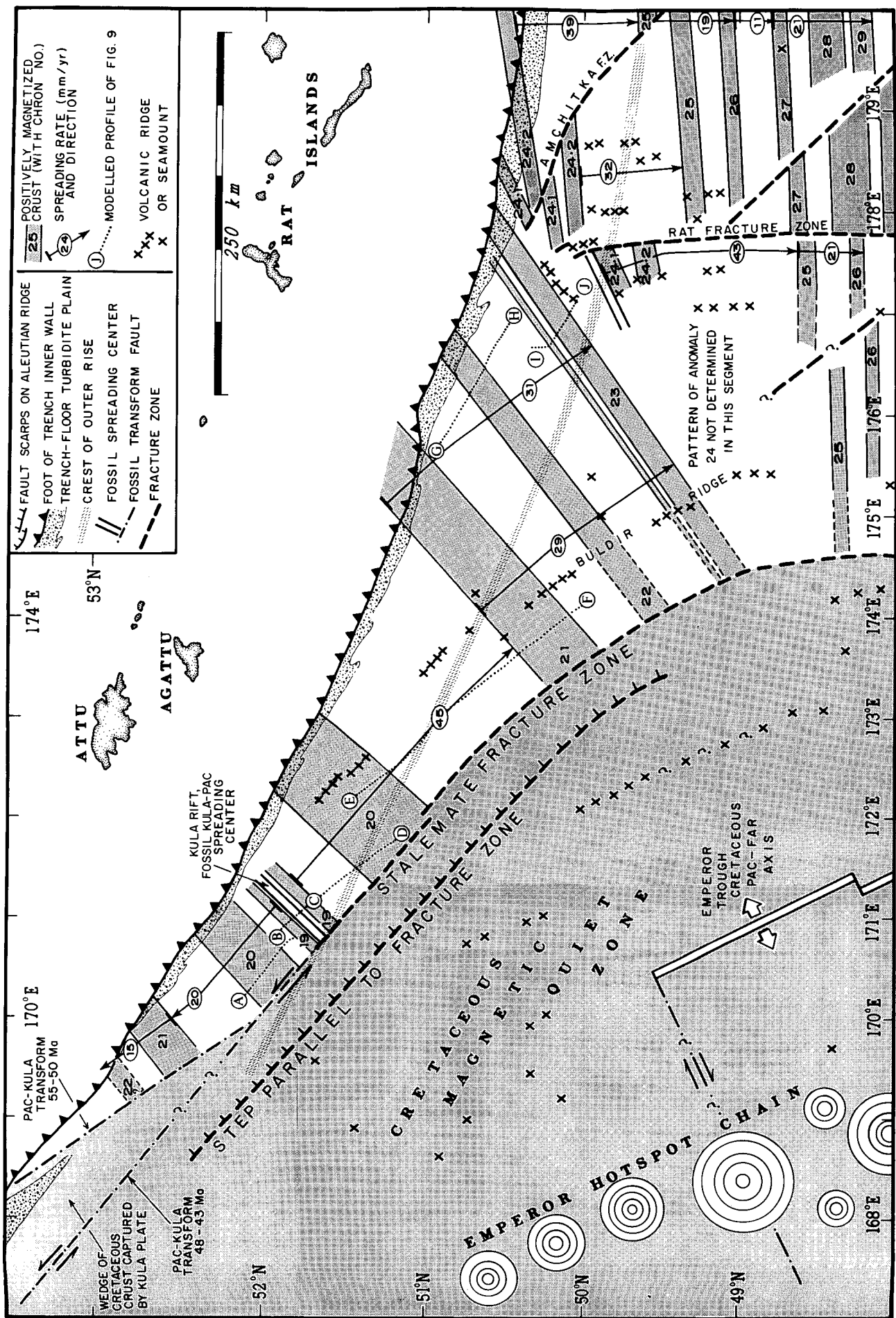


Figure 6. Interpretation of magnetic stripes, based on the magnetic anomalies of Figure 4 and the bathymetry of Figure 2. Symbolic portrayal of Emperor Seamounts is not meant to imply that they are all negatively magnetized.

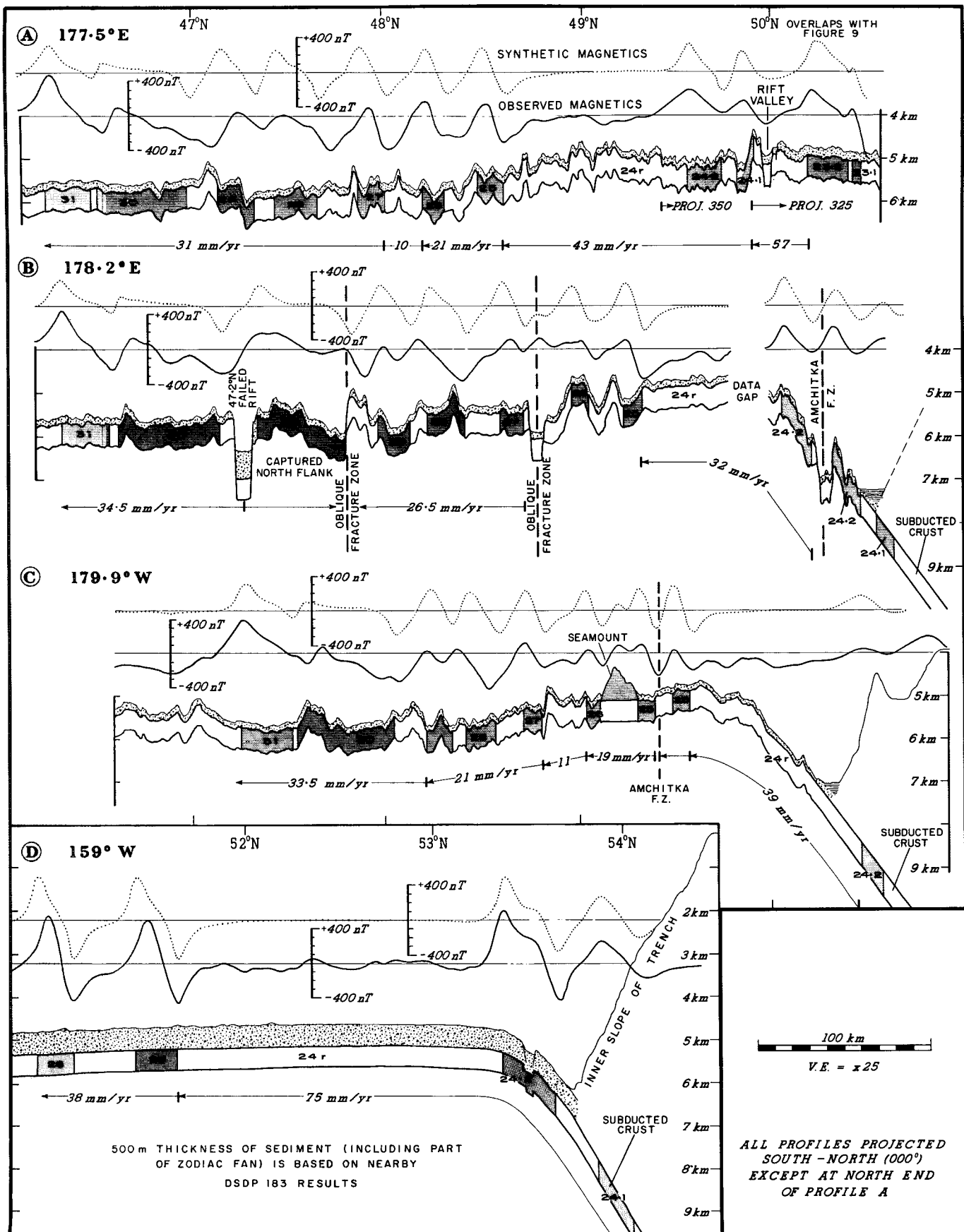


Figure 7. Observed magnetic profiles, projected north-south (except as noted for profile A) and modeled assuming a 150-m sediment blanket (500 m for profile D) over a 500-m-thick 10 A/m magnetic layer (15 A/m for profile D). Profiles A-C are correctly aligned east-west and are located in Figure 4. Profile D is one of the south-north SEAMAP profiles (Erickson and Grim, 1969), crossing Anomaly 24.2 about 75 km west of the fossil triple junction south of the eastern Aleutian Trench. Spreading rates given, in mm/yr, are those derived from the imperfect forward modeling.

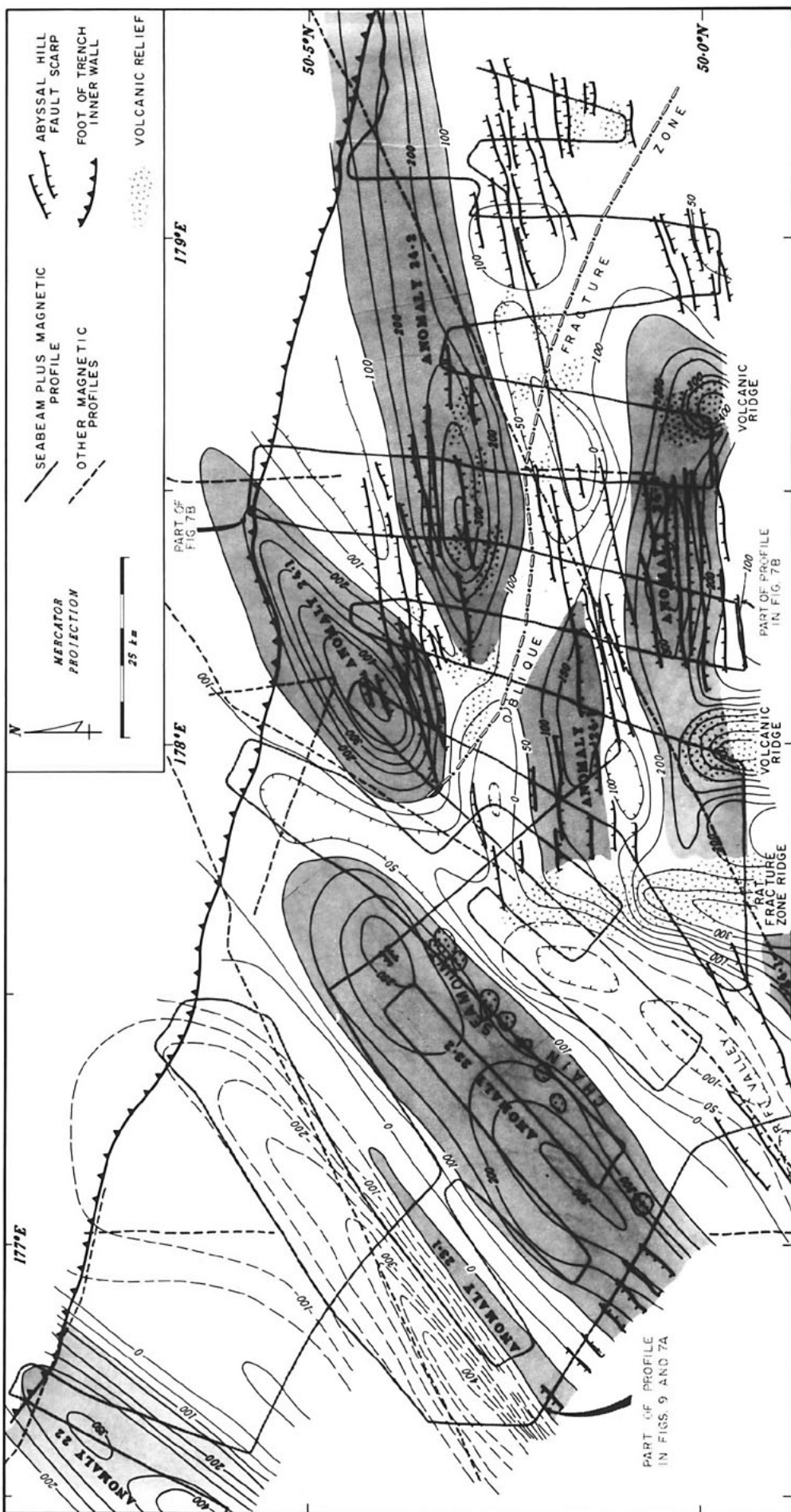


Figure 8. Magnetic total-intensity anomaly map of the Seabeam survey area at the northern end of Rat fracture zone based on data collected along the tracks shown. Positive anomalies are stippled; note that at this latitude they are displaced south and southeast of the strips of positively magnetized crust responsible for the anomalies (see Fig. 7). Only the fault scarps oriented approximately parallel to magnetically determined isochrons, and thereby plausibly inherited from the time of lithosphere accretion, are shown.

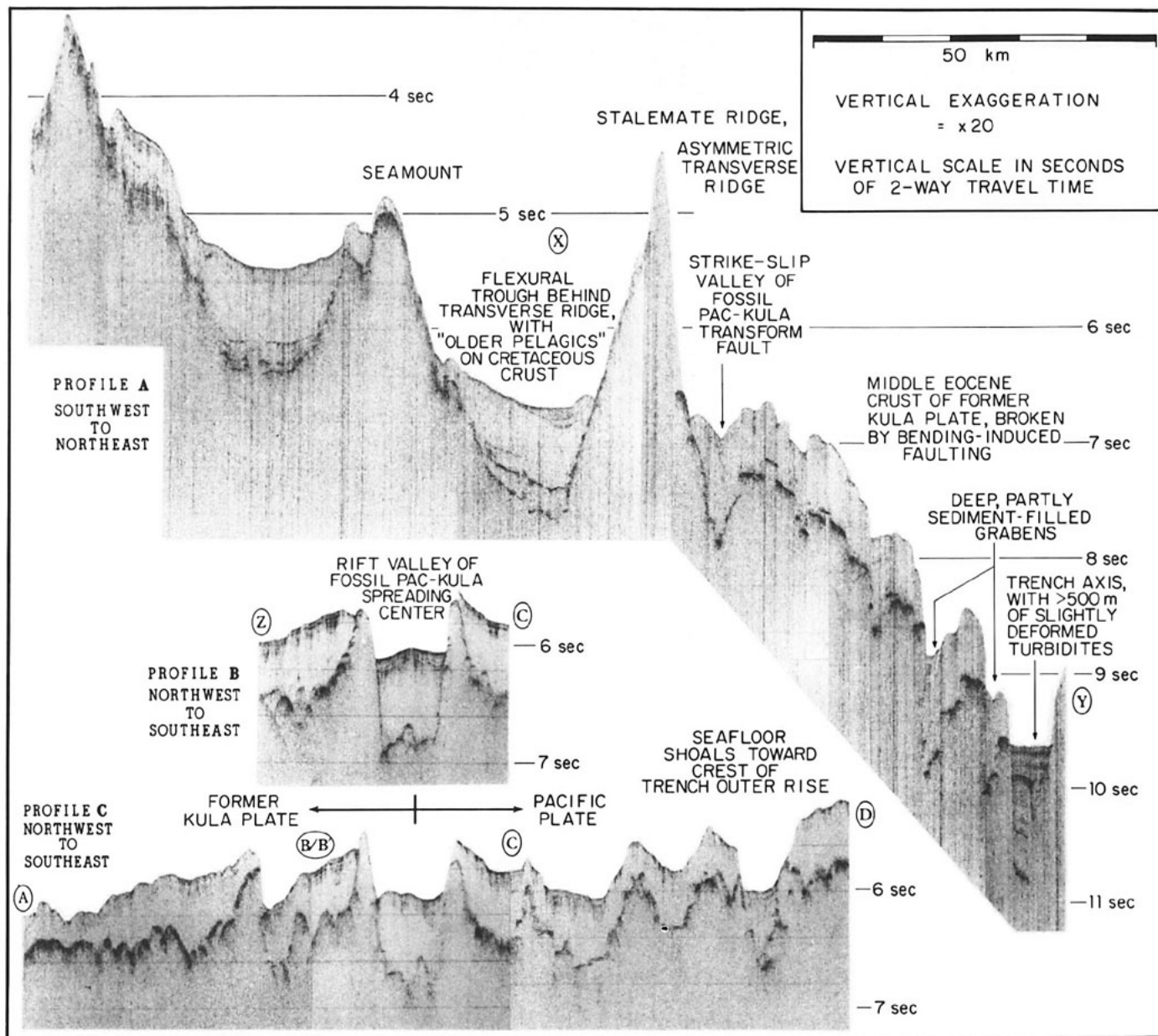


Figure 10. Single-channel watergun profiles across the Kula-Pacific transform fault (profile A) and spreading center (profiles B, C) that ceased activity at 43 Ma. Profiles are located on Figure 11.

which prolong the rift shoulders. Stalemate Ridge itself is an asymmetric transverse ridge, similar to the one along the northern part of Rat fracture zone, but larger: its crest is 2.5 km above the transform valley floor, and almost as high above the older (Cretaceous) crust on its southwest flank. The broad structural trough on the old side of the fault, which continues along most of Stalemate fracture zone (Figs. 2, 5B) is identified as a flexural depression like those alongside many other transverse ridges (Lonsdale, 1986; Collette, 1986). This interpretation is

consistent with its appearance on gravity maps (Haxby, 1987) as a deep gravity low that strikes obliquely across the outer rise gravity high.

Where they orthogonally truncate Kula Rift and Chrons 19–20, the transform valley and transverse ridge strike 310° (Fig. 11). Beyond our northwesternmost Seabeam crossing at 170°E , sparse conventional sounding lines suggest that Stalemate Ridge veers northward to about 325° and crosses the trench axis between 168°E and 169°E (Fig. 12), where the axial turbidite plain is absent and there is a hump in the

trench long profile (Scholl, 1974). Another line of partly buried basement ridges that seem to prolong the 310° trend, however, can be traced within Cretaceous crust along the outer slope of the westernmost Aleutian Trench, past the Komandorski Islands [where they form the "Prodol'noye horst-anticlinorium" of Gnibidenko and others (1983)], to the northern end of the Kamchatka Trench (Fig. 12). These ridges might have grown along Eocene transform faults, as they appear younger than the Cretaceous crust they cross, being overlain only by the

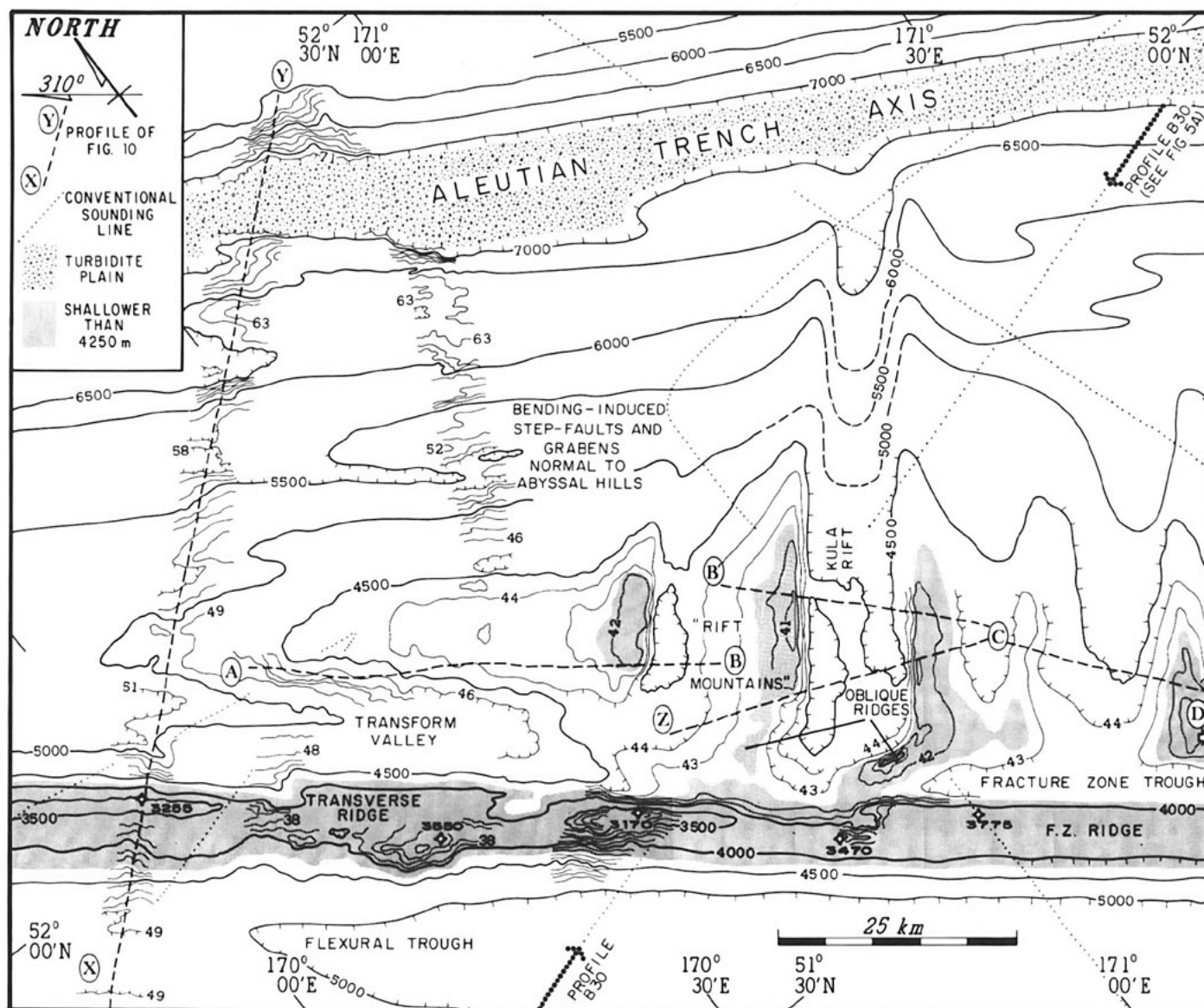


Figure 11. Bathymetry of Kula Rift and its intersection with the fossil Stalemate transform fault. Contour interval is 50 m within the area covered by Seabeam swaths, 500 m elsewhere. This chart is located in Figure 2.

upper (Neogene) sedimentary unit, not by the Paleogene and Cretaceous "older pelagics" (see profiles of Fig. 12).

If the northwestern end of Stalemate Ridge has been correctly located, about 10,000 km² of northwest-aging crust that accreted to the Kula plate during the Eocene survives northwest of Kula Rift. Most of it lies within 40 km of the trench axis, and its original plate fabric has been obliterated by bending-induced faulting (Fig. 10A). Magnetic mapping is incomplete, but crust at least as old as 50 m.y. (Chron 21) is included.

A REVISED INTERPRETATION OF PACIFIC-KULA SPREADING HISTORY

Before 58.6 Ma: North-South Spreading with Propagating Rifts

The pattern of east-west anomalies and oblique fracture zones on Upper Cretaceous and Paleozoic crust (Figs. 4, 6) records north-south spreading from segments of the Kula-Pacific spreading center that were systematically propagating westward, causing westward migration of

the offsets between the spreading segments. One large (80-km) offset stopped migrating at about Chron 29 and thereby changed into the stable transform fault that produced the Rat fracture zone (Fig. 13A). This change coincided with a 25%–35% decrease in the south-flank spreading rate (Figs. 7B, 7C). Conversion of large migrating nontransform offsets to stationary transform faults at a slow-down of spreading has occurred on other rise flanks (Lonsdale, 1986) and is qualitatively explained by the fracture mechanics model of Phipps Morgan and Parmentier (1985). The initiation near Chron 27 of a stair-

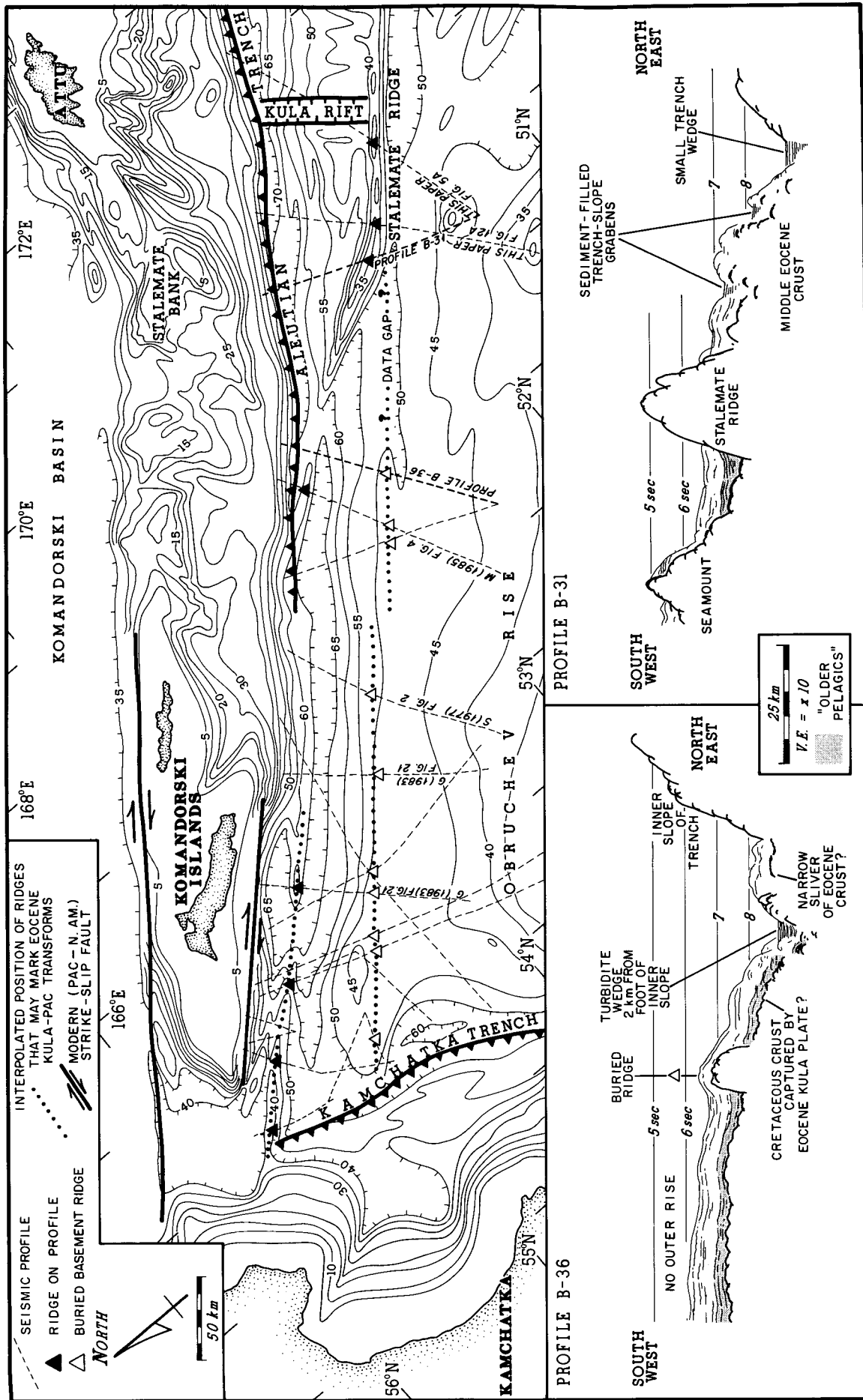


Figure 12. Bathymetry northwest of Kula Rift, indicating the possible location of fossil Kula-Pacific transform faults that connect to this fossil spreading center. Several of the profiles that reveal ridges that may mark these faults have been published: G(1983) = Gnibidenko and others (1983); S(1977) = Scholl and others (1977); M(1985) = Mannerickx (1985). The line drawings of profiles B-36 and B-31 are from Buffington (1973); the "Older Pelagics" are believed to be mainly Cretaceous in age.

case of similar offsets (Adak, Amchitka, and perhaps the one west of Rat transform) suggests that at that time of further spreading deceleration (Fig. 7) there may also have been a small rotation in spreading direction.

Westward migration of left-lateral offsets transferred young crust from the Kula to the Pacific plate, thereby causing long-term asymmetry in crustal accretion, consistent with the prediction of Stein and others (1977) that accretion favors the trailing plate when a spreading axis drifts with respect to the asthenosphere. The Kula Ridge crest had an unusually high "absolute" velocity because it separated two plates which were both moving north (in the hotspot reference frame) at more than 50 mm/yr (Engelbreton and others, 1985), and so a correspondingly high degree of asymmetry is to be expected. At the Pacific-Antarctic Ridge, asymmetric accretion in accordance with Stein and others' (1977) model has occurred both by rift propagation and by an unevenness in the spreading processes that results in broader magnetic stripes on the trailing-plate rise flanks (Lonsdale, 1986). The total degree of asymmetry of the Paleocene Kula Ridge cannot be assessed because of the loss to subduction of its north flank, but significant primary asymmetry, varying in degree from one spreading segment to the next, is the simplest explanation for the unsystematic along-strike variation in south flank spreading rates prior to Chron 24r (Figs. 6 and 7). The general secular trend in these spreading rates is for a decrease to below 30 mm/yr at the end of the Cretaceous, with rates less than 12 mm/yr for the Chron 27–26 interval on several profiles, followed by an acceleration that began near the end of the Paleocene (Chron 26–25).

Elsewhere in the Pacific, oblique fracture zones often separate sequences of magnetic stripes that differ in azimuth by 2°–8° (Hey and others, 1980), although whether the inferred differences in spreading-axis strike are a cause or a consequence of rift propagation is in doubt (Wilson and others, 1984; Phipps Morgan and Parmentier, 1985). The only area where our Kula Ridge data are dense enough to document such a pattern is either side of Amchitka fracture zone. East of this oblique fracture zone, Anomalies 26 and 25 strike almost exactly east-west (Fig. 4; Erickson and Grim, 1969), whereas to the west, these same anomalies, and the abyssal hills mapped by Seabeam, strike 085°.

58.6–55 Ma: Change in Spreading Direction and Elimination of Transform Faults

Anomaly 24.1 differs in strike by 7°–8° from Anomaly 25, both east of Amchitka fracture zone near 180° longitude (Fig. 4) and at the eastern end of Kula Ridge near 160°W (Fig. 14), probably because of a 7°–8° anticlockwise

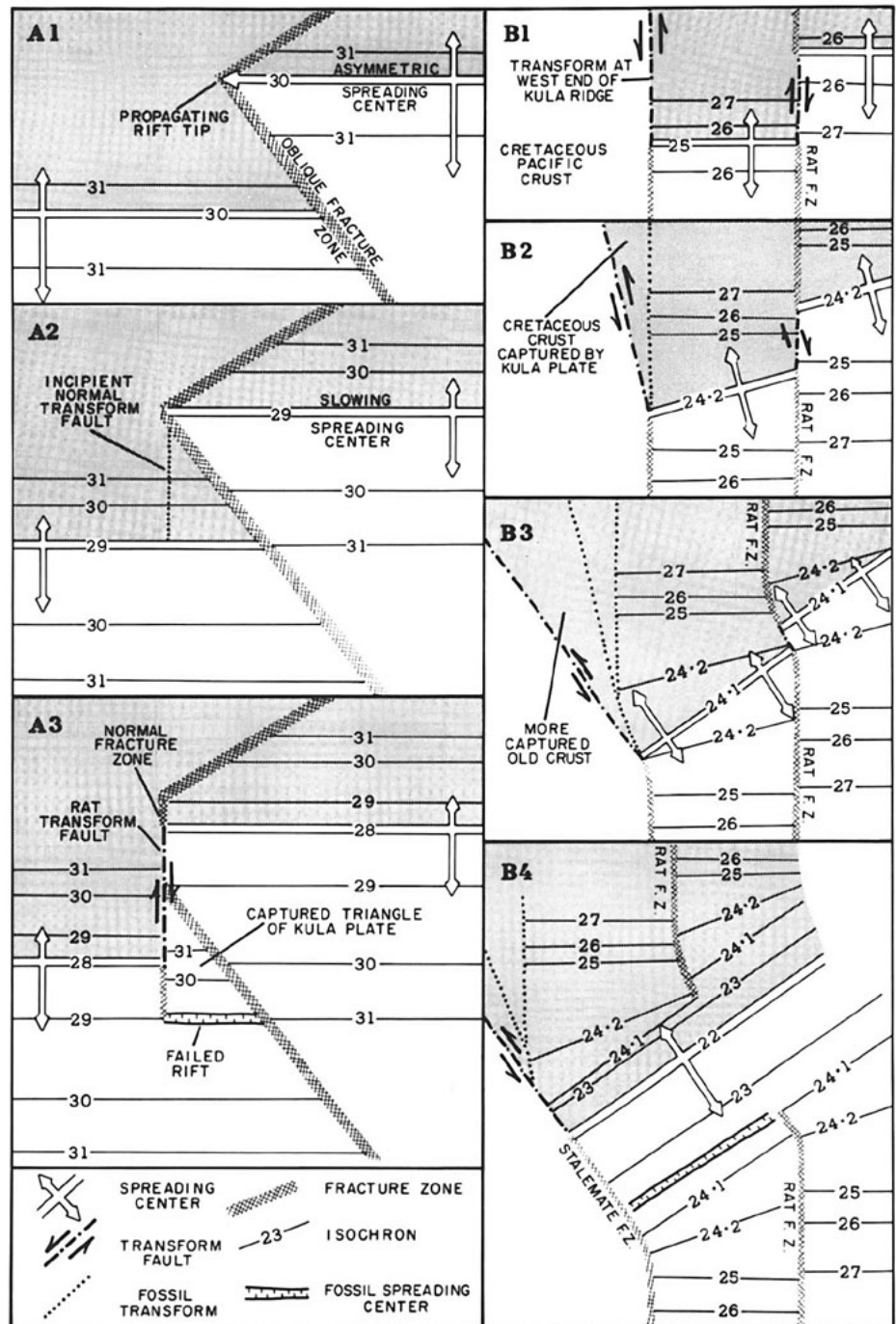


Figure 13. Sequential sketch maps showing reorganizations of the Kula-Pacific boundary when Rat transform fault was born, as a descendant of a westward-migrating offset (A1–A3), and when it was eliminated, during the early Eocene change in spreading direction (B1–B4). Area of Kula plate (shaded) has been entirely lost by subduction, except for fragments captured by the Pacific plate, as in A3. Complexities during the elimination of Rat transform fault include a period of oblique extension of the shortened transform (B2), and apparent propagation of the spreading center northeast to southwest across the transform shortly before Chron 23 (between B3 and B4). Note progressive capture by the Kula plate of sectors of old Cretaceous crust during rotation of the transform fault at the west end of the Kula Ridge (B2–B3).

rotation of the spreading direction during the 2.5 m.y. between the end of Chron 25 (58.6 Ma) and the beginning of Chron 24.1. East of Amchitka fracture zone and west of Rat fracture

zone, the strike of abyssal hills and magnetic lineations rotated a further 20°–25° during the 1 m.y. of Chron 24. This realignment was necessarily accomplished by along-strike varia-

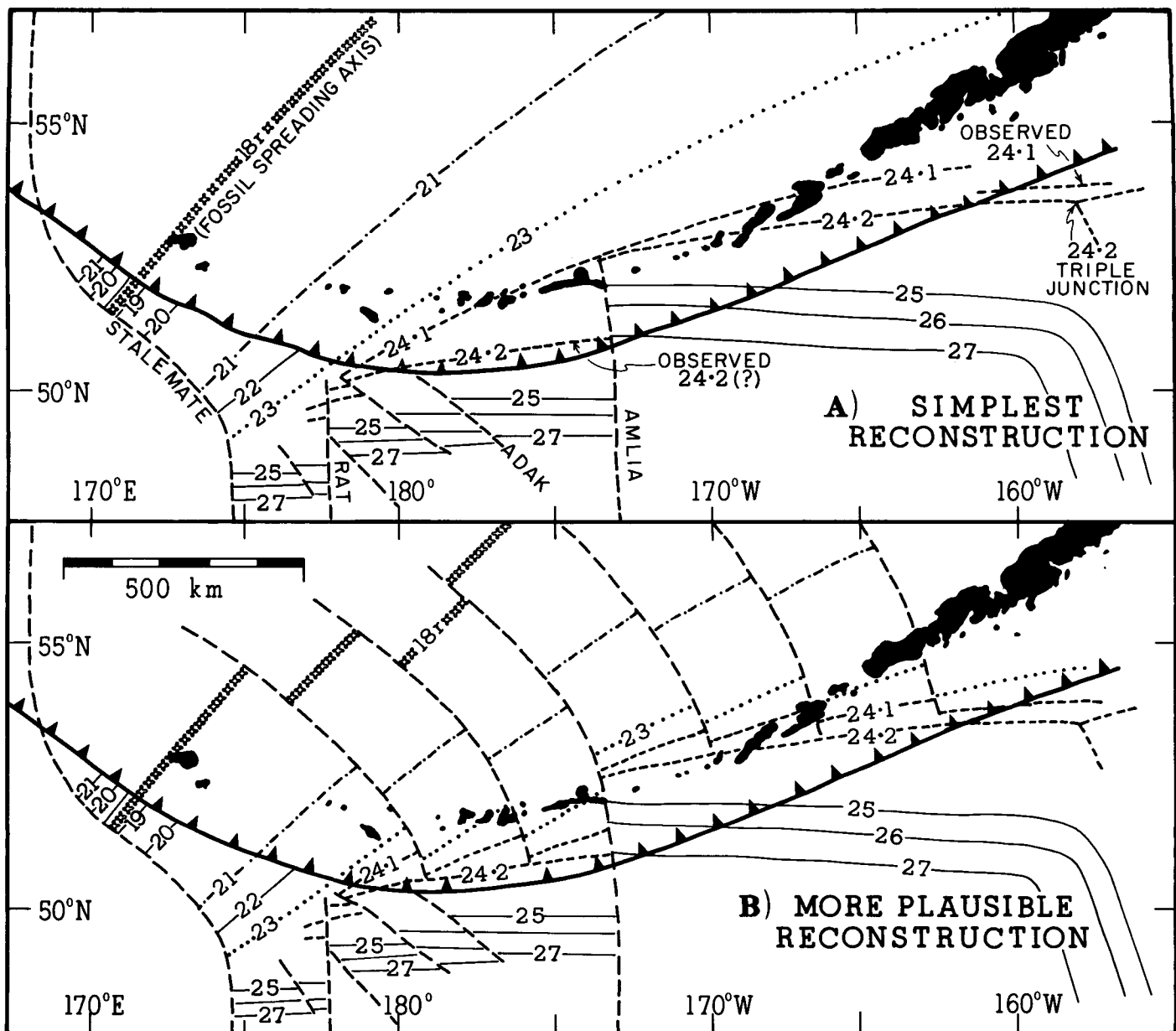


Figure 14. Hypothetical reconstructions of the pattern of Kula-Pacific chrons and fracture zones on the subducted slab beneath the Aleutian arc, based on extrapolation from the observed unsubducted crust. Note that the lineations have not been projected vertically from their actual position on the steeply dipping subducted slab, but are shown in their original pattern on a horizontal plate surface. In reconstruction A, isochrons have been extrapolated in straight lines (that is, great circles) from their observed location. The implication that rotations in spreading directions were accommodated entirely by highly asymmetric spreading leads to implausible fast spreading rates at some sites (for example, between Chrons 24.1 and 24.2). The assumption in reconstruction B is that counterclockwise rotation of long spreading axes was facilitated by segmentation into shorter axes. Spacing of the new right-offset transform faults created by this process (Nelson, 1981) is unknown but is depicted here as 200–250 km.

tion in the degree of asymmetric spreading, with the fastest south-flank accretion at the eastern ends of spreading segments (Menard and Atwater, 1968). The initial geometry of the plate boundary thereby helps explain why the south-flank spreading rate on the west side of Rat fracture zone was 35% greater than on the east

side (Fig. 7, profiles A and B). Still higher Chron 24r spreading rates can be inferred for immediately west of Amlia fracture zone (54 mm/yr) and near the Kula-Pacific-Farallon triple junction. At the latter site, about 66 km of the 186 km of south flank crust accreted during Chron 24r (Engelbreton and others, 1984) is attributa-

ble to a 7.5° rotation of the 1,000-km-long spreading segment between Amlia fracture zone and the triple junction.

The structural geomorphology of the northern part of Rat fracture zone supports the hypothesis of an anticlockwise rotation of the spreading direction. For a left-offset transform, a rotation of

this sense causes extension across the transform fault, and a decrease in its total offset (Menard and Atwater, 1969). The section of Rat fracture zone that was an active transform fault during Chron 24.2, when rotation-induced extension should have started, has a high transverse ridge. On the modern Pacific-Antarctic Ridge (where spreading rates are similar to Eocene Kula Ridge rates), such landforms are characteristic of transform fault zones that have acquired a component of extension from small rotations in relative plate motion (Lonsdale, 1986). With continued rotation-induced extension, Menard and Atwater (1968, 1969) predicted that the transform fault zone would become eruptive, and the volcanic ridge near the northern end of Rat fracture zone (Fig. 8) may overlie a leaky transform fault that by Chron 24.1 had become oblique to the new spreading direction (Fig. 13B).

Shortening of the Rat offset by rotation of the spreading axes was complete soon after Chron 24.1, and the transform fault was obliterated, as shown by the northern termination of Rat fracture zone (Fig. 8). This could have been accomplished by the spreading axes east and west of the transform simply rotating around (in response to the changing direction of spreading) until they were aligned, and then linking up. Structural details in the Seabeam survey (Fig. 8) favor a more complicated process in which just before Chron 23 an axis orthogonal to the new spreading direction propagated rapidly southwestward across the diminishing offset and the young rise flank on its west side (Fig. 13B). A rift valley striking 065° within the broad strip of negatively magnetized crust between Chrons 23 and 24 (Figs. 7A, 8) is tentatively identified as the failed spreading center, and a 055° chain of small volcanoes 20 km to the northwest (Fig. 8) may record the initial location of the new axis, as a variant of the high volcanic relief found at major rift-initiation sites (Mammerickx and Sandwell, 1986).

The counterclockwise rotation of spreading probably eliminated the small offset of Adak fracture zone as early as Chron 24.2. Evidence for this is the alignment of a positive magnetic anomaly over the trench inner slope west of Amlia fracture zone and 135 km north of Anomaly 25 (Peter and others, 1970) with the segment of Anomaly 24.2 that obliquely crosses the trench axis near 179°E (Fig. 14). Amlia transform fault, where the Paleocene ridge crest was displaced left laterally by 220 km, probably persisted throughout the change in spreading direction, although with a reduced offset and a new azimuth. As depicted in Figure 14, conversion of the long east-striking rise axes that existed during Paleocene north-south spreading to northeast-striking axes orthogonal to the new spreading direction probably required creation of new right-offset transforms on the Kula

Ridge. Another effect of reorientation of the Kula Ridge was a jump in the Kula-Pacific-Farallon triple junction; the fossil junction still survives south of the Aleutian Trench at the T-shaped Anomaly 24.2 near 53°20'N, 158°W (Fig. 14; Engebretson and others, 1984). All traces of the new triple junction and new Kula-Pacific transform faults have been subducted, but the latter would have been copolar with the extant Stalemate fracture zone, which formed the western boundary of the Kula Ridge. The northwest-trending part of this fracture zone must be descended from a new strike-slip fracture which in response to the 20°–25° change in the local direction of Kula-Pacific motion during 56–55 Ma broke through Cretaceous crust of the part of Pacific plate that had bounded the Kula plate on the west (Fig. 13B).

55–44 Ma: Northwest-Southeast Asymmetric Spreading

Magnetic stripes on Eocene crust at 178°E–173°E (Fig. 6) show an almost constant speed and direction of spreading on the southeast flank of the Kula Ridge from the beginning of Chron 23 to the end of Chron 21, as the rise crest migrated northwestward along the new transform boundary of the Kula plate. The gradual veering from 055° to 048° of the stripes and abyssal hills created during this stage might be caused by fanning around a fixed Kula-Pacific Euler pole, but continuation of the change in relative plate motion is more compatible with the strike of Anomaly 21 and Stalemate fracture zone on the northwest flank of Kula Rift. Near the start of Chron 20r (about 48 Ma), the spreading direction seems to have stabilized at 310°–130°, and the rate increased by 50% (Fig. 9). From the beginning of Chron 21, we finally have direct evidence for the degree of asymmetry of Kula-Pacific spreading, because both flanks of the ridge survive (Fig. 6). During Chron 21, plate accretion favored the southeast (Pacific) flank by about 2:1, and during the next 4.5 m.y., the ratio was even higher (2.25 to Pacific: 1 to Kula).

Continued counterclockwise rotation of the spreading direction after Chron 23, to the 310° orientation recorded by the best mapped part of Stalemate Ridge (Fig. 11), would cause renewed compression along the southwest boundary of the Kula plate, probably relieved by creation of new strike-slip faults parallel to the new spreading direction. These new faults would redefine the boundary of the Kula plate by further capture of small wedges of Pacific lithosphere, repeating the process that occurred during 56–55 Ma (Fig. 13B). Traces of these transform faults, diverging from the main crustal age boundary (Stalemate Ridge), may be preserved in the lines of ridges that extend across Cretaceous litho-

sphere to the Kamchatka Trench (Fig. 12). Before the crest of the Kula Ridge had migrated very far toward this trench, Kula-Pacific spreading came to a halt.

44–43 Ma: Cessation of Spreading

Magnetic anomalies across Kula Rift (Fig. 9) show that spreading did not begin to slow before the start of Chron 19 (44.1 Ma), but had stopped within about 1 m.y., with crustal accretion ceasing during Chron 18r (43.6–42.7 Ma). As the full spreading rate declined from 65 mm/yr to zero, the degree of asymmetry also declined, so that Anomaly 19 is almost the same width on both flanks. A change to symmetric accretion during the demise of a medium-fast asymmetric spreading center has also been described at Malpelo Rift in the eastern Pacific (Lonsdale and Klitgord, 1978), although that spreading center took about 3 m.y. to shut down.

The rifted nature of fossil spreading centers presumably results from rise-crests acquiring characteristics of slow-spreading ridges as their opening rates decline. Slow-down of spreading can also affect the relief of crust that has already accreted. The high-relief crust that extends up to 30 km southeast of Kula Rift (Fig. 9) may have been as smooth initially as crust elsewhere that accreted at the same high rate inferred from the magnetics, only to be roughened later by extensional faulting in a broad plate boundary zone during a final spasm of plate separation.

Direct evidence for a 43 Ma cessation of Kula Ridge spreading exists only at the short westernmost segment that has avoided subduction. It is possible that other segments, since subducted, continued to spread after this time, just as parts of the Cocos-Nazca boundary have continued to spread long after the demise of the Malpelo Rift segment (Lonsdale and Klitgord, 1978). One argument for the simpler interpretation that the entire Kula plate fused to the Pacific plate during Chron 18r is that 43 Ma was the time of a major change in Pacific plate motion. The principle that a strong connection exists between changes in a plate's velocity and changes in the geometry of its boundaries, which led Engebretson and others (1984) to *predict* a 43 Ma date for demise of the Kula Ridge, is vindicated by our magnetic dating of Kula Rift.

INFERRED MOTIONS AND EXTENT OF THE KULA PLATE

Chronology of Plate Rotations

The orientation of Paleocene lineations on the western part of the Kula Ridge is consistent with the 18°N, 111°E Kula-Pacific pole proposed by Engebretson and others (1984). I regard the ro-

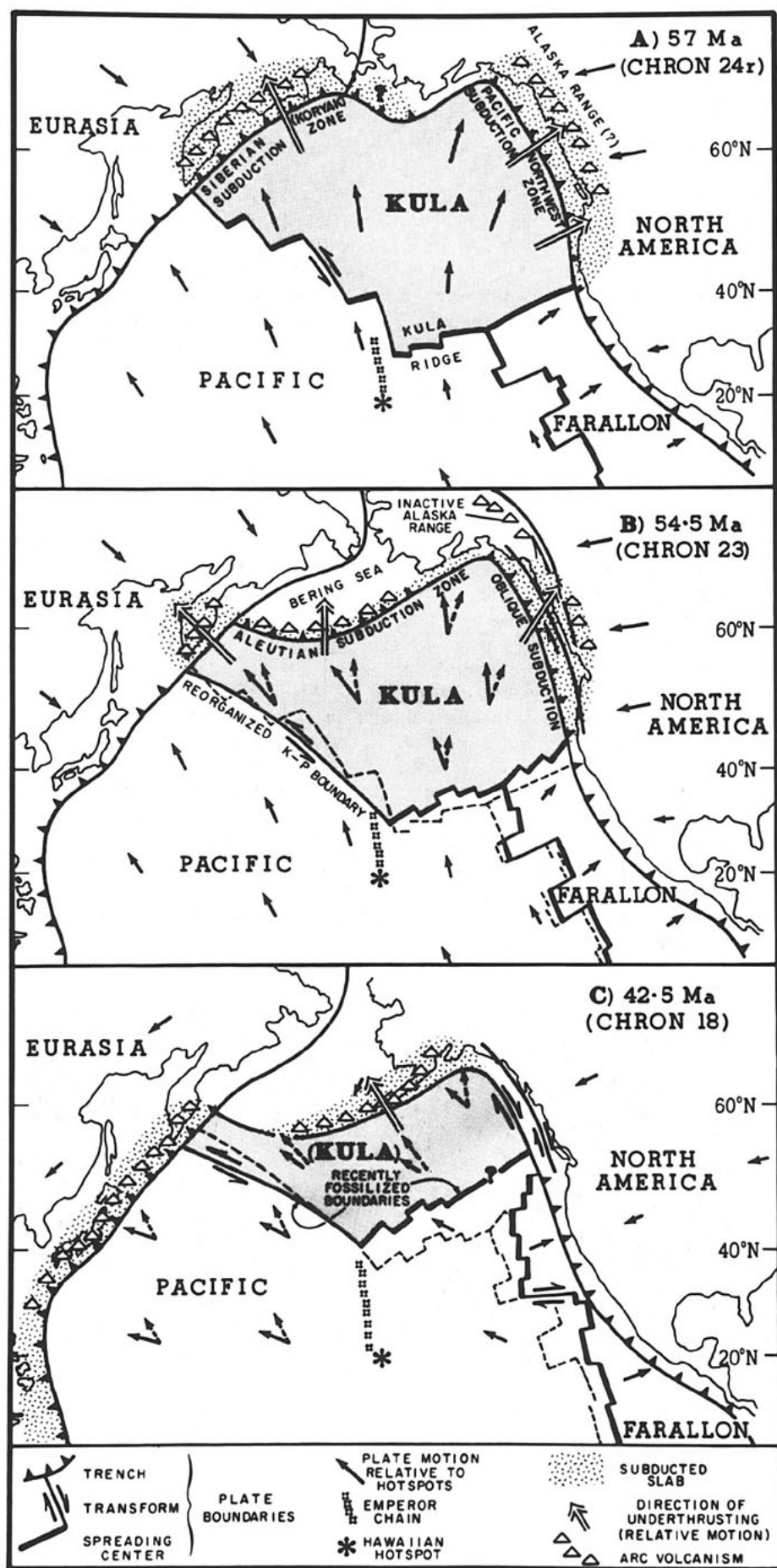


Figure 15. Hypothetical reconstructions and motions of the Kula plate, just before (A) and after (B) its early Eocene westward swerve, and just after its middle Eocene fusion with the Pacific plate (C). Dashed lines and arrows show boundaries and motions in preceding panel. Initial reconstruction (A) is slightly modified from Engebretson and others (1985), with a slower northward motion of the Kula plate causing more orthogonal subduction on the North American margin. The more oblique subduction at this margin after 55 Ma (B) caused development of strike-slip faults (shown schematically) and rapid northward rafting of continental slivers. Absolute Kula motion during this period was estimated by adding a poorly constrained Kula-Pacific motion ($0.68^\circ/\text{m.y.}$ about 1°N , 37°E) to a Pacific hot-spot rotation of $0.61^\circ/\text{m.y.}$ about 17°N , 107°W (Duncan and Clague, 1985). The change in local direction of the Kula plate after its annexation by the Pacific plate (C) was most marked in the Gulf of Alaska, where arc volcanism began in the Alaskan Peninsula and the eastern margin was converted to purely strike-slip (parts of this margin might have been in strike-slip contact with the Pacific plate before this 43 Ma event). In all panels, the position of the Kula-Pacific-Eurasia triple junction is purely speculative.

tation rate around this pole as poorly constrained, because of the unknown degree of asymmetric spreading; if plate accretion was 2.25:1 Pacific: Kula, as in the middle Eocene, then rotation rates calculated with the assumption of symmetric spreading (Engebretson and others, 1984) would be too high by almost 40%. The secular trend of a decreasing rate of accretion to the Pacific plate, until Chron 26, however, probably does reflect a declining rate of Kula-Pacific rotation, rather than implausible changes in the sense of Kula Ridge asymmetry.

The Kula-Pacific rotation pole shifted during the early Eocene, with its most rapid motion at 56–55 Ma. If the change in direction of plate motion was complete by Chron 23, and the mapped anomalies 23–21 are assumed to accurately record meridians that converge on the new rotation pole, its location can be calculated as 39°N , 159°E . As noted above, however, this convergence more likely results from a continuing drift of the rotation pole. For the Chron 20–18r stage, the best constraint on the location of the Kula-Pacific pole comes from the azimuth of the fossil Stalemate transform fault. If the transform was as far from the Kula-Pacific pole as it had been during the Paleocene, the middle Eocene pole would be at 1°N , 138°E , and the rotation rate would be $0.68^\circ/\text{m.y.}$ Improved mapping of the curvature of this sole surviving

Eocene Kula-Pacific transform is needed to refine these estimates.

There is no evidence from hotspot trails such as the Emperor Seamounts that the Pacific plate's "absolute" motion (that is, its rotation in the hotspot reference frame) changed at the end of the Paleocene. The changes in Kula-Pacific motion prior to 44 Ma are therefore attributable to changes in absolute velocity of the Kula plate and are evidence for changes in the motion of this plate relative to the other plates with which it interacted (Eurasia, North America, Farallon). In contrast, the rapid cessation of Kula-Pacific motion during 44–43 Ma coincides with the change in absolute Pacific motion that is recorded by the elbow in the Emperor-Hawaiian hotspot chain. Detailed bathymetry of that feature (Smoot, 1985) shows that the chain starts to bend about 70 km northwest of the mid-point of the elbow, where seamount lavas have been dated at 43.4 ± 1.6 Ma and 42.4 ± 2.3 Ma (Duncan and Clague, 1985). These data suggest that the swerve in Pacific plate motion took about 2 m.y., centered near 43 Ma.

Plate Dimensions

Throughout its history, the Kula plate decreased in latitudinal extent because of the migration of its southern, accreting, boundary toward the subducting continental margins around the northern rim of the Pacific Basin. A sudden decrease occurred in the Paleogene, when the northernmost 1.5×10^6 km² of the plate, now underlying the Bering Sea, was captured by the continental plates as subduction shifted south to the intra-oceanic Aleutian Trench (Scholl and others, 1975, 1986). Even after this event, however, the crest of the Kula Ridge remained many hundred kilometres south of any trenches (Fig. 15B). The Paleogene rearrangements of the Kula-Pacific plate boundary that are now recorded in a narrow zone along the present Aleutian Trench were not caused by fragmentation and pivoting of the Kula plate as its trailing edge approached the Aleutian subduction zone, a process that accounts for the complex pattern of anomalies left by Pacific-Farallon spreading in the eastern Pacific (Menard, 1978). The Kula plate still occupied a significant fraction of the North Pacific until it was captured by the Pacific plate at 43 Ma.

The westward extent of the Kula plate is poorly constrained. Whether the Paleocene Stalemate transform fault extended unbroken to the Siberian trench (as depicted by Engebretson and others, 1985) or was part of a staircase that linked additional Kula-Pacific spreading centers (Jurdy and Gordon, 1984) cannot be determined directly, because the evidence has been subducted. Figure 15A hypothesizes a staircase with an overall northwesterly trend, which min-

imizes the amount of transfer between Pacific and Kula plates during the subsequent reorganization to northwest-southeast Kula-Pacific motion (Fig. 15B).

The location of the southeastern margin of the Kula plate, the ridge-crest boundary with the Farallon plate, is also poorly determined. The only direct evidence surviving on the ocean floor is the short length of Kula-Farallon Anomaly 24.2 that strikes northeast (078°) from the fossil 56 Ma triple junction at 53°20'N, 158°W (Fig. 14). The geometry of this boundary would have changed during the early Eocene as the direction of the Kula plate changed. Motion of the Farallon plate also changed significantly during 59–50 Ma, as shown by the rotation of Pacific-Farallon lineations between Anomalies 25 and 21 (Atwater and Menard, 1970; Engebretson and others, 1984). Byrne (1979) interpreted this rotation (and the northward extension of Pacific-Farallon spreading) as evidence for a 59–56 Ma capture of the Kula plate by the Pacific plate, a notion inconsistent with Kula-Pacific Anomalies 24–19 that we mapped. An alternative interpretation of the change in Farallon plate motion is that the plate-driving forces acting on its margins changed because of changes in the location and pattern of the Kula-Farallon boundary, involving a northward jump of the Kula-Pacific-Farallon triple junction and reorientation of spreading segments. These were ultimately caused by the changes in Kula plate motion that are inferred from the spreading record of the Kula-Pacific boundary.

Speculation on the Causes of the Changes in Kula Plate Motion

Because the principal factor controlling the absolute velocity of a plate is the magnitude and distribution of slab pull forces (Forsythe and Uyeda, 1975), the change in absolute velocity of the Kula plate at the end of the Paleocene is most plausibly related to a rearrangement of the plate's subducting boundaries. Most geologic evidence places initiation of the Aleutian subduction zone, which replaced the Siberian (Koryak) subduction zone as the northern margin of the Kula plate, at about 55 Ma (Scholl and others, 1983, 1986). Detachment of the Bering Sea lithosphere would have resulted in sudden loss to the Kula plate of the northward pull along its northern margin. This loss would not be replaced by the pull of the slab descending beneath the new Aleutian Ridge until that slab had penetrated hundreds of kilometres into the asthenosphere. Meanwhile, the pull of the slab of old lithosphere that continued to descend the northwestern (Kamchatka) subduction zone would have exerted relatively greater influence on the resultant Kula plate motion, causing the plate to swerve northwest. The external cause of

the subduction zone jump inferred to have initiated this evolution may have been collision of a hard-to-subduct oceanic plateau with the Bering Sea margin (Ben-Avraham and Cooper, 1981).

The fusion of the Kula and Pacific plates at 44–43 Ma coincided with other major readjustments in plate boundaries and changes in plate velocities. Most significant was the great acceleration of the northward motion of Australia (Cande and Mutter, 1982) as the Australian and Indian plates fused together following the collision of Indian with Eurasia (Liu and others, 1983). Development of subduction zones along the southwest margin of the Pacific plate because of the accelerated convergence of Australia created new slab pull forces on that plate. Its westward swerve recorded by the Emperor-Hawaiian elbow was probably a response to the addition of a southwesterly pull to the pre-existing northwesterly pull down trenches at the Eurasian margin (Gordon and others, 1978). The loss of independence by the Kula plate was most likely caused by this change in absolute Pacific motion, which brought the velocity along the northern margin of the Pacific plate close enough to that of the Kula plate that spreading between them ceased. The Pacific plate's capture of the Aleutian Trench and its northward pulling slab would have served to limit the extent of the plate's southwestward veering and may thereby be responsible for the abruptness of the Hawaiian-Emperor elbow.

SOME IMPLICATIONS OF THE REVISED HISTORY FOR INTERPRETATIONS OF CONTINENTAL MARGIN GEOLOGY

Limitations of the Sea-Floor Record of Kula Plate Motion

The new marine observations of the rates and directions of Paleogene Kula-Pacific spreading are incompatible with models of Kula plate motion that have been used to help interpret the onshore geology of the North Pacific rim. The magnetic record on the newly discovered remnant of the north flank of the Kula Ridge shows that the assumption of symmetric Kula-Pacific spreading which is a basic feature of most such reconstructions (for example, Engebretson and others, 1984; Jurdy and Gordon, 1984; Rea and Duncan, 1986) is invalid. The large mapped changes in spreading axis and transform-fault orientation prove that Engebretson and others (1984) specific assumption of a fixed Euler pole throughout the history of the Kula-Pacific separation is also invalid. So much of the record of Kula-Pacific spreading has been lost by subduction, however, that accurate replacements for these simplifying assumptions—specifying the degree of asymmetry in Paleocene plate accre-

tion, and the locations of Eocene Euler poles—cannot be made. Lacking confidence in guesses of Kula-Pacific rotation parameters, I hesitate to use them to calculate new estimates for the Kula–North America and Kula–Farallon rotations, which would quantitatively describe the changing speeds and directions of plate convergence and divergence along the northern and eastern boundaries of the Kula plate. Some qualitative differences from published estimates of Kula–North America and Kula–Farallon interactions, however, can be inferred from my Kula-Pacific revisions:

1. Paleocene Kula–North America convergence vectors would be rotated clockwise relative to previous estimates that exaggerated the northward velocity of the Kula plate by assuming symmetric Kula-Pacific spreading. A slower Kula plate would also imply a counterclockwise rotation of the Kula–Farallon divergence vectors, unless the eastward motion of the Farallon plate has also been overestimated because of asymmetric spreading.

2. The lack of a huge northward acceleration of the Kula plate during Chron 24r eliminates the need for a dramatic increase in Alaskan subduction rates at this time and for a complete reorientation of the axes of Kula–Farallon spreading (Wells and others, 1984).

3. The northwest swerve of the Kula plate, beginning about 59 Ma and concentrated in the 56–55 Ma interval, would cause counterclockwise rotation of Kula–Farallon, Kula–North America, and Kula-Pacific vectors and would result in some reorientation and relocation of Kula–Farallon and Kula-Pacific spreading centers.

4. Fusion of the Kula and Pacific plates at 43 Ma did not mean that a fast north-drifting oceanic plate (Kula) was suddenly replaced along the Aleutian subducting margin with a slow northwest-drifting one (Pacific), although it did cause a significant change in the direction of underthrusting at the eastern part of this boundary (Fig. 15C).

Implications for Paleogene Arc Volcanism and Terrane Displacement

Key dates in the history of arc magmatism in mainland Alaska are 75 Ma, initiation of the Alaska Range and Coast Mountains batholith; 55 Ma, cessation of Alaska Range volcanism; and 45–42 Ma, cessation of Coast Mountains magmatism and initiation of Aleutian Arc volcanism (Wallace and Engebretson, 1984). The correspondence to the dates for birth, mid-life swerve, and death (capture) of the Kula plate are so close that a genetic connection seems likely. The modifications proposed for the history of Kula plate motion require few changes in

the speculative model of Wallace and Engebretson (1984) that the Paleocene growth of a northwest-trending Alaskan arc was caused by north-northeasterly convergence of the Kula plate and was followed by a period between 56–43 Ma more oblique subduction that caused strike-slip dislocation of the arc and northwest translation of the Alaska Range portion out of the zone of continued arc volcanism. If the northward velocity of the Kula plate was slower than previously estimated, however, the Late Cretaceous to Paleocene Kula–North America convergence may have been normal to the continental margin of the Pacific Northwest. The cause of the subsequent rotation to oblique convergence was probably the documented westward swerve of the Kula plate, rather than a postulated northward acceleration that would have made the 12-m.y. hiatus in arc volcanism after 55 Ma coincident with an acme in the subduction rate (Wallace and Engebretson, 1984).

The increasingly oblique convergence of the Kula and North American plates in 55–43 Ma provided a suitable tectonic setting for the rafting of continental slivers (microplates) along the continental margin into the Gulf of Alaska. Kodiak Islands and adjacent parts of the Prince William and Chugach terranes moved northward with respect to North America by about 25° during this period (Moore and others, 1983; von Huene and others, 1985). One tectonic model compatible with modern analogs (for example, Fitch, 1972) is that oblique convergence of the major plates was resolved into more normal convergence with a fast-moving continental microplate that had a strike-slip boundary with a major continental plate. Alternatively, the continental terrane may have rode part-way firmly attached to the Kula plate, like the modern Yakutat terrane on the Pacific plate (Davis and Plafker, 1986).

Implications for Interactions of Spreading Axes and Seamounts with the North American Margin

Volcanic and plutonic rocks within the Prince William and Chugach terranes, dated at 62–56 Ma and with paleolatitudes of $40^{\circ} \pm 6^{\circ}\text{N}$, are believed to have formed during intersection of a spreading axis and a subduction complex at the Kula–Farallon–North American triple junction (Moore and others, 1983). Simple extrapolation of an unsegmented spreading axis from the fossil (56 Ma) Kula–Farallon–Pacific triple junction along the 078° trend of Anomaly 24.2 would place the landward end of the Kula–Farallon axis near 40°N at this time (Fig. 15A). For most of its history, this spreading center, the trailing edge of the Kula plate, was sweeping rapidly

northward along the subducting margin. The brief slowdown of Kula plate motion ca. 60 Ma, inferred from the slow south-flank spreading rates on the Kula-Pacific boundary (Fig. 7), would cause temporary stagnation of the Kula–Farallon–North American triple junction; it may have led to a short-lived increase in spreading-center–subduction–complex interaction.

Apart from stimulating a few such *ad hoc* suggestions, plate-rotation models that must start with dubious assumptions about symmetry of spreading and constancy of Euler poles provide few useful constraints on detailed geologic interpretations of convergent margins. For example, a group of obducted seamounts and former volcanic islands now exposed in the Oregon/Washington Coast Ranges (Snively and others, 1968) were interpreted by Duncan (1982) as an oceanic chain built by the Yellowstone hotspot about 62–48 Ma and accreted to the continent soon after. Duncan's (1982) inference from the pattern of radiometric dates that the hotspot chain was centered on the Kula–Farallon ridge and grew symmetrically on both plates was challenged by Wells and others (1984) as being difficult to reconcile with their estimates of Eocene relative and absolute plate motions. Some of their objections (for example, that a hotspot chain on the northeast-moving Farallon plate would not age southward) are probably still valid even if their plate-rotation model, which fails the test of predicting Eocene Kula-Pacific spreading, is wrong. It is difficult, however, to evaluate the alternative suggestions (Wells and others, 1984) that the Coast Range seamounts formed along segments of the Kula–Farallon boundary during repeated reorganizations, or at a prolongation of this spreading center into the North American continent, because the direct offshore evidence for the orientation, location, and migration rate of this boundary is almost nonexistent; and the indirect evidence, the partial record of Kula-Pacific, Farallon-Pacific, and Pacific hot-spot motions, requires rash assumptions before it is applicable to the geography of the Kula–Farallon boundary.

Implications for the History of the Aleutian Ridge and Its Modern Volcanism and Tectonics

The Aleutian Ridge was built as a by-product of the subduction that consumed most of the Kula plate and the north flank of the fossil Kula Ridge. Its evolution may therefore have been strongly influenced by temporal changes in the motion of the oceanic plates, and perhaps by spatial changes in their composition. The known history of the ridge (Scholl and others, 1975, 1983) includes an initial period of voluminous submarine volcanism until 45–40 Ma, followed

by a long period with limited volcanism but widespread tectonic uplift and subaerial erosion until the middle Miocene (ca. 15 Ma), when an episode of renewed but mainly intrusive magmatism affected the whole ridge. A later mainly Plio-Pleistocene episode of arc volcanism has built a chain of subaerial cones in the eastern and central parts of the ridge (to Buldir Island at 176°E); the western part of the ridge has had limited Plio-Pleistocene volcanism (Scholl and others, 1976) and is being dismembered by extensional faulting.

The late Eocene decline in ridge-building volcanism may be related to a change in the speed or direction of convergence of oceanic lithosphere after the capture of the Kula plate by the Pacific plate. Subsequent events are more difficult to reconcile with the plate-tectonic history. Grow and Atwater (1970) hypothesized that the Miocene magmatic event was caused by entry of the (active) Kula Ridge into the subduction zone. In DeLong and others' (1978) elaboration of this suggestion, subduction of young Kula Ridge crust and the active spreading center (at 30–35 Ma) was held responsible for the mid-Tertiary hiatus in arc magmatism, together with uplift and regional metamorphism of the Aleutian Ridge; the 15 Ma revival of arc volcanism was attributed to the waning influence of the subducted ridge. Extrapolation of the 43 Ma crest of Kula Ridge across the subducted slab from Kula Rift (Fig. 14), however, indicates that it has only just arrived beneath Attu and Agattu, which were the source of most of the geologic evidence for DeLong and others' (1978) interpretation. Less than 500–700 km of crust has been subducted at the central Aleutian Trench since entry of segments of the fossil spreading center there (Fig. 14B), representing only 6–9 m.y. of plate convergence. When the Kula Ridge axis was beneath the axis of the central Aleutian arc, just 4–6 Ma, it had been welded shut for almost 40 m.y. I doubt that the presence of this old plate boundary had any major influence on arc volcanism, but if it did, the timing suggests that the effects should be sought in the Plio-Pleistocene volcanic resurgence, rather than in Oligocene metamorphism or Miocene plutonism.

The revised history of Kula-Pacific spreading also means that the topography of the lithospheric slab now underlying the Aleutian arc is different than had been assumed by simple northward extrapolation of north-south fracture zones and east-west isochrons. Segmentation of the arc, as mapped by the boundaries between the aftershock regions of major thrust-zone earthquakes, the location of summit basins and transverse canyons of tectonic origin, and the spatial pattern and chemistry of young volcanoes, has been attributed to the supposed pres-

ence of Rat, Adak, and Amlia fracture zones in the subducted slab (Spence, 1977; Grim and Erickson, 1969; Kay and others, 1982). Even if these fracture zones did have subducted north-south extensions, correspondence with transverse boundaries in the Aleutian Ridge is plausible only for the most modern features (for example, seismicity), because the obliqueness of north-south structures to the direction of plate convergence would cause them to sweep westward along the arc (at about 50 km/m.y. for Amlia fracture zone). My new data (Fig. 7) and interpretations (Fig. 14) indicate that only the Amlia fracture zone actually extends north to underlie the Aleutian arc, although there may be other fracture zones (produced by hypothetical right-offset transforms initiated in an unknown pattern at the 56–55 Ma change in spreading direction) which have recently been entirely subducted (Fig. 14B) but could still play a role in bounding interplate seismic zones. The evidence for any such control, however, is thin. Sykes (1971) emphasized that not even Amlia fracture zone acted as a boundary for the rupture zone of the large 1957 earthquake, although Mogi (1969) recognized an influence of the fracture zone in the pattern of this event's aftershocks.

SUMMARY OF CONCLUSIONS

1. A triangular area of middle Eocene oceanic crust that preserves a record of the final stage of Kula-Pacific plate motion remains unsubducted south of the obliquely convergent western Aleutian Trench. The spreading record is more complete than for earlier stages because parts of both flanks of the Kula Ridge have survived, either side of a rift valley that marks the fossil ridge crest. Post-56 Ma Kula-Pacific spreading was directed northwest-southeast, with an asymmetry of more than 2:1 in favor of the northwest (Kula) flank. It ceased at 43 Ma.

2. The fossil Kula Rift and an orthogonally intersecting fossil transform fault zone bound a part of the Kula plate, which had been thought "all gone" down the trench. The surviving fragment probably includes some Cretaceous crust that was captured from the Pacific plate during Eocene changes in relative plate motion, as well as some of the northwest flank of the Kula Ridge.

3. Spreading on the Paleocene Kula Ridge was north-south, but most of the fracture zones that displace east-west magnetic lineations strike obliquely northwest, showing that small offsets of the ridge crest migrated west. Rat fracture zone, a 80-km normal displacement at 177.7°E, was produced by a stable transform fault that evolved from a westward-migrating offset when spreading slowed at the end of the Cretaceous.

4. The change between Paleocene and middle Eocene spreading directions, concentrated at 56–55 Ma, eliminated the Rat transform fault and other small left-stepping offsets and caused a jump in the Kula-Pacific-Farallon triple junction.

5. The 56–55 Ma rotation of Kula-Pacific spreading was caused by a westward swerve of the Kula plate, perhaps because most of its northward slab pull was temporarily eliminated when subduction shifted from the Siberian margin to the Aleutian Trench. Kula-Pacific spreading probably ceased when changes in the motion of the Pacific plate, caused by events elsewhere on its periphery, brought the velocity of its northern margin close to that of the adjacent Kula plate.

6. Insufficient data exist for accurate determination of the pole of Kula-Pacific rotation during the Eocene or the rate of rotation during the Paleocene, mainly because most of the crust created by Kula-Pacific spreading has been subducted. There is almost no direct ocean-floor record of the motion of the Kula plate with respect to any plates other than the Pacific, or to the hotspot reference frame. There is, therefore, a weak foundation for derivative estimates of relative motions at the northern and eastern boundaries of the Kula plate, which would clarify the nature of Paleogene plate interactions at the Eurasian and North American continental margins. Some qualitative changes to previous plate-interaction models can be suggested.

7. The structural fabric of the oceanic plate now underlying the Aleutian arc cannot be described by simple northward extrapolation from the exposed Pacific floor. Models of arc segmentation that rely on such descriptions are false. The long-inactive crest of the Kula Ridge moved beneath most of the Aleutian arc in the past 6 m.y. and is just now beneath Attu. Interpretations of mid-Tertiary tectonic and magmatic events that rely on overriding of a spreading center are false.

ACKNOWLEDGMENTS

For help at sea, I am indebted to the officers and crew of R/V *Thomas Washington* (T. Desjardins, captain) and the scientific party of Expedition Papatua Leg 11, especially T. Hylas (Seabeam engineer), R. Comer (acting seismic engineer), and K. L. Smith (co-chief scientist). I thank S. Miller (University of California, Santa Barbara) for a magnetism modeling program. Financial support for ship time came from the State of California; for seismic reflection profiling, from National Science Foundation Grant OCE 83-15354; and for analysis of oblique and normal fracture zones, from Office of Naval Research contract N00014-80-C-0104.

REFERENCES CITED

- Atwater, T., and Menard, H. W., 1970, Magnetic lineations in the north-east Pacific: *Earth and Planetary Science Letters*, v. 7, p. 445-450.
- Bassinger, B. G., deWald, O. E., and Peter, G., 1969, Interpretation of the magnetic anomalies off central California: *Journal of Geophysical Research*, v. 74, p. 1484-1487.
- Ben-avraham, Z., and Cooper, A. K., 1981, Early evolution of the Bering Sea by collision of oceanic rises and North Pacific subduction zones: *Geological Society of America Bulletin*, v. 92, p. 485-495.
- Berggren, W. A., Kent, D. V., Flynn, J. J., and van Couvering, J. A., 1985, Cenozoic geochronology: *Geological Society of America Bulletin*, v. 96, p. 1407-1418.
- Bonatti, E., 1978, Vertical tectonism in oceanic fracture zones: *Earth and Planetary Science Letters*, v. 37, p. 369-379.
- Buffington, E. C., 1973, The Aleutian-Kamchatka Trench convergence [Ph.D. dissert.]: Los Angeles, California, University of Southern California, 363 p.
- Byrne, T., 1979, Late Paleocene demise of the Kula-Pacific spreading center: *Geology*, v. 7, p. 341-344.
- Cande, S. C., and Mutter, J. C., 1982, A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica: *Earth and Planetary Science Letters*, v. 58, p. 151-160.
- Collette, B. J., 1986, Fracture zones in the North Atlantic: Morphology and a model: *Geological Society of London Journal*, v. 143, p. 763-774.
- Davis, A. S., and Plafker, G., 1986, Eocene basalts from the Yakutat terrane: Evidence for the origin of an accreting terrane in southern Alaska: *Geology*, v. 14, p. 963-966.
- DeLong, S., Fox, P. J., and McDowell, F., 1978, Subduction of the Kula ridge at the Aleutian Trench: *Geological Society of America Bulletin*, v. 89, p. 83-95.
- Duncan, R. A., 1982, A captured island chain in the Coast Range of Oregon and Washington: *Journal of Geophysical Research*, v. 87, p. 827-837.
- Duncan, R. A., and Clague, D. A., 1985, Pacific plate motions recorded by linear volcanic chains, in Nairn, A. E., Stehli, F. G., and Uyeda, S., eds., *The ocean basins and margins, Volume 7A: The Pacific Ocean*: New York, Plenum Press, p. 89-121.
- Engelbreton, D. C., Cox, A., and Gordon, R. G., 1984, Relative motions between oceanic plates of the Pacific Basin: *Journal of Geophysical Research*, v. 89, p. 10291-10310.
- , 1985, Relative motions between oceanic and continental plates in the Pacific Basin: *Geological Society of America Special paper* 206, 59 p.
- Erickson, B. H., and Grim, P. J., 1969, Profiles of magnetic anomalies south of the Aleutian island arc: *Geological Society of America Bulletin*, v. 80, p. 1387-1390.
- Erickson, B. H., Rea, D. K., and Naugler, F. P., 1969, Chinook Trough: A probable consequence of north-south sea-floor spreading: *EOS (American Geophysical Union Transactions)*, v. 50, p. 633.
- Erickson, B. H., Naugler, F. P., and Lucas, W. H., 1970, Emperor fracture zone: A newly discovered feature in the central North Pacific: *Nature*, v. 225, p. 53-54.
- Fitch, T. J., 1972, Plate convergence, transcurent faults, and internal deformation adjacent to southeast Asia and western Pacific: *Journal of Geophysical Research*, v. 77, p. 4432-4461.
- Forsythe, D., and Uyeda, S., 1975, On the relative importance of the driving forces of plate motion: *Royal Astronomical Society Geophysical Journal*, v. 43, p. 163-200.
- Gnibidenko, H., Bykova, T. G., Veselov, O. V., Vorobiev, V. M., and Svarichevsky, A. S., 1983, The tectonics of the Kuril-Kamchatka deep-sea trench, in Hilde, T. W. C., and Uyeda, S., eds., *Geodynamics of the western Pacific—Indonesian region*: Washington, D.C., American Geophysical Union Geodynamics Series, v. 11, p. 249-286.
- Gordon, R. G., Cox, A., and Harter, C. E., 1978, Absolute motion of an individual plate estimated from its ridge and trench boundaries: *Nature*, v. 274, p. 752-755.
- Grim, P. J., and Erickson, B. H., 1969, Fracture zones and magnetic anomalies south of the Aleutian Trench: *Journal of Geophysical Research*, v. 74, p. 1488-1494.
- Grow, J. A., 1972, A geophysical study of the central Aleutian Arc [Ph.D. thesis]: La Jolla, California, Scripps Institution of Oceanography, University of California, San Diego, p. 132.
- Grow, J. A., and Atwater, T., 1970, Mid-Tertiary tectonic transition in the Aleutian arc: *Geological Society of America Bulletin*, v. 81, p. 3715-3722.
- Haxby, W. F., 1987, Gravity field of the world's oceans: Boulder, Colorado, Marine Geology and Geophysics Report MGG-3, National Geophysical Data Center, scale 1:40,000,000.
- Hayes, D. E., and Heitzler, J. R., 1968, Magnetic anomalies and the relation to the Aleutian island arc: *Journal of Geophysical Research*, v. 73, p. 4637-4646.
- Hey, R. N., and Wilson, D. S., 1982, Propagating rift explanation for the tectonic evolution of the northeast Pacific—The pseudomovie: *Earth and Planetary Science Letters*, v. 58, p. 167-188.
- Hey, R. N., Duennbeier, F. K., and Morgan, W. J., 1980, Propagating rifts on mid-ocean ridges: *Journal of Geophysical Research*, v. 85, p. 3647-3658.
- Jackson, E. D., and others, 1978, Drilling confirms hot spot origins: *Geotimes*, v. 23, p. 23-26.
- Jurdy, D. M., and Gordon, R. G., 1984, Global plate motions relative to the hot spots 4 to 56 Ma: *Journal of Geophysical Research*, v. 89, p. 9927-9936.
- Kay, S. M., Kay, R. W., and Citron, G. P., 1982, Tectonic controls on tholeiitic and calc-alkaline magmatism in the Aleutian arc: *Journal of Geophysical Research*, v. 87, p. 4051-4072.
- Liu, C. S., Curran, J. R., and McDonald, J. M., 1983, New constraints on the tectonic evolution of the eastern Indian Ocean: *Earth and Planetary Science Letters*, v. 65, p. 331-342.
- Lonsdale, P., 1986, Tectonic and magmatic ridges in the Eltanin fault system, South Pacific: *Marine Geophysical Research*, v. 8, p. 203-242.
- Lonsdale, P., and Klitgord, K. D., 1978, Structure and tectonic history of the eastern Panama Basin: *Geological Society of America Bulletin*, v. 89, p. 981-999.
- Mammerickx, J., 1985, A deep-sea thermohaline flow path in the northwest Pacific: *Marine Geology*, v. 65, p. 1-19.
- Mammerickx, J., and Sandwell, D., 1986, Rifting of old oceanic lithosphere: *Journal of Geophysical Research*, v. 91, p. 1975-1988.
- McKenzie, D., and Parker, R. L., 1967, The North Pacific: An example of tectonics on a sphere: *Nature*, v. 216, p. 1276-1280.
- Menard, H. W., 1978, Fragmentation of the Farallon Plate by pivoting subduction: *Journal of Geology*, v. 86, p. 99-110.
- Menard, H. W., and Atwater, T., 1968, Changes in direction of sea floor spreading: *Nature*, v. 219, p. 463-467.
- , 1969, Origin of fracture zone topography: *Nature*, v. 222, p. 1037-1040.
- Mogi, K., 1969, Relationship between the occurrence of great earthquakes and tectonic structures: *Bulletin of the Earthquake Research Institute of Tokyo University*, v. 47, p. 429-451.
- Moore, J. C., Byrne, T., Plumley, P. W., Reid, M., Gibbons, H., and Coe, R. S., 1983, Paleogene evolution of the Kodiak Islands, Alaska: Consequences of ridge-trench interaction in a more southerly latitude: *Tectonics*, v. 2, p. 265-293.
- Nichols, H., and Perry, R. B., 1966, Bathymetry of the Aleutian arc: ESSA Monograph 3, Rockville, Maryland, U.S. Department of Commerce, scale 1:400,000.
- Peter, G., Erickson, B. H., and Grim, P. J., 1970, Magnetic structure of the Aleutian Trench and northeast Pacific basin, in Maxwell, A. E., ed., *The sea, Volume 4, Part II*: New York, Interscience, p. 191-222.
- Phipps, Morgan J., and Parmentier, E. M., 1985, Causes and rate-limiting mechanisms of ridge propagation: A fracture mechanics model: *Journal of Geophysical Research*, v. 90, p. 8603-8612.
- Pitman, W. C., and Hayes, D. E., 1968, Seafloor spreading in the Gulf of Alaska: *Journal of Geophysical Research*, v. 73, p. 6571-6580.
- Rea, D. K., and Dixon, J. M., 1983, Late Cretaceous and Paleogene tectonic evolution of the north Pacific Ocean: *Earth and Planetary Science Letters*, v. 64, p. 67-73.
- Rea, D. K., and Duncan, R. A., 1986, North Pacific plate convergence: A quantitative record of the past 140 m.y.: *Geology*, v. 14, p. 373-376.
- Renard, V., and Allenou, J. P., 1979, Sea Beam, multi-beam echo-sounding in "Jean Charcot": *International Hydrographic Review*, v. 56, p. 35-67.
- Scholl, D. W., 1974, Sedimentary sequences in the North Pacific trenches, in Burk, C. A., and Drake, C. L., eds., *The geology of continental margins*: New York, Springer-Verlag, p. 493-504.
- Scholl, D. W., Buffington, E. C., and Marlow, M. S., 1975, Plate tectonics and the structural evolution of the Aleutian-Bering Sea region: *Geological Society of America Special Paper* 131, p. 1-31.
- Scholl, D. W., Marlow, M. S., MacLeod, N. S., and Buffington, E. C., 1976, Episodic Aleutian Ridge igneous activity: Implications of Miocene and younger submarine volcanism west of Buldir Island: *Geological Society of America Bulletin*, v. 87, p. 547-554.
- Scholl, D. W., Hein, J. R., Marlow, M., and Buffington, E. C., 1977, Meiji sediment tongue: North Pacific evidence for limited movement between the Pacific and North American plates: *Geological Society of America Bulletin*, v. 88, p. 1567-1576.
- Scholl, D. W., Vallier, T. L., and Stevenson, A. J., 1983, Geologic evolution of the Aleutian Ridge—Implications for petroleum resources: *Alaska Geological Society Journal*, v. 3, p. 33-46.
- Scholl, D. W., Vallier, T. L., and Stevenson, A. J., 1986, Terrane accretion, production, and continental growth: A perspective based on the origin and tectonic fate of the Aleutian-Bering Sea region: *Geology*, v. 14, p. 43-47.
- Shih, J., and Molnar, P., 1975, Analysis and implications of the sequence of ridge jumps that eliminated the Surveyor transform fault: *Journal of Geophysical Research*, v. 80, p. 4815-4822.
- Smoot, N. C., 1985, Guyot and seamount morphology and tectonics of the Hawaiian-Emperor elbow by multi-beam sonar: *Marine Geology*, v. 64, p. 203-215.
- Snively, P. D., MacLeod, N. S., and Wagner, H. C., 1968, Tholeiitic and alkalic basalts of the Eocene Siletz River Volcanics, Oregon Coast Range: *American Journal of Science*, v. 266, p. 454-481.
- Spence, W., 1977, The Aleutian arc: Tectonic blocks, episodic subduction, strain diffusion, and magma generation: *Journal of Geophysical Research*, v. 82, p. 213-230.
- Stein, S., Melosh, H. J., and Minster, J. B., 1977, Ridge migration and asymmetric sea-floor spreading: *Earth and Planetary Science Letters*, v. 36, p. 51-62.
- Sykes, L. R., 1971, Aftershock zones of great earthquakes, seismicity gaps, and earthquake prediction for Alaska and the Aleutians: *Journal of Geophysical Research*, v. 76, p. 8021-8041.
- von Huene, R., Keller, G., Bruns, T. R., and McDougall, K., 1985, Cenozoic migration of Alaskan terranes indicated by paleontologic study, in Howell, D. G., ed., *Tectonostratigraphic terranes of the circum-Pacific region*: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, p. 581.
- Wallace, W. K., and Engelbreton, D. C., 1984, Relationships between plate motions and late Cretaceous to Paleogene magmatism in southwestern Alaska: *Tectonics*, v. 3, p. 295-315.
- Wells, R. E., Engelbreton, D. C., Snively, P. D., and Coe, R. S., 1984, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington: *Tectonics*, v. 3, p. 275-294.
- Wilson, D. S., Hey, R. N., and Nishimura, C., 1984, Propagation as a mechanism of reorientation of the Juan de Fuca Ridge: *Journal of Geophysical Research*, v. 89, p. 9215-9225.
- Woods, M. T., and Davies, G. F., 1982, Late Cretaceous genesis of the Kula plate: *Earth and Planetary Science Letters*, v. 58, p. 161-166.

MANUSCRIPT RECEIVED BY THE SOCIETY MARCH 27, 1987

REVISED MANUSCRIPT RECEIVED AUGUST 20, 1987

MANUSCRIPT ACCEPTED SEPTEMBER 15, 1987