THE OPENING OF A BACK-ARC BASIN: NORTHERN MARIANA TROUGH

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN MARINE GEOPHYSICS

AUGUST 1987

By

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ACKNOWLEDGEMENTS

I would like to acknowledge a few key individuals who have assisted me through my graduate studies at the University of Hawaii. Donald M. Hussong recruited me from the University of California at Santa Barbara. He supported me throughout my career at UH with a research assistantship and served as my advisor and thesis committee chairman. Patricia Fryer offered much appreciated assistance and encouragement during my years at the university. I would also like to thank Fred Duennebier for insightful comments and suggestions. Last but not least I would like to express my appreciation to Naomi Tzur for unending moral support, particularly in the final stages.

ABSTRACT

SeaMARC II data from the northern Mariana Trough shows three stages of development for this marginal basin. The southern portion of the survey area has a series of three ridges interpreted as propagating rifts. These ridges propagate northwards and periodically step toward the arc so that the easternmost ridge is the youngest of these features. To the north the youngest ridge is sinistrally offset by a transform fault. This fault separates the southern zone of ridges from a central zone of large discreet volcanoes lying in the rift graben. While dredge samples from one of these volcanoes have yielded primitive back-arc basalt, the seamounts of this zone form symmetrical, conical edifices, as opposed to the linear ridges of the southern zone. The northernmost zone of the survey area has a well-developed rift graben in which lies an arc volcano. This zone exhibits a region of intrusive features, interpreted as dikes, seen on seismic reflection records. The features of these three zones are interpreted as characteristic of different stages in the development of this back-arc basin. The northernmost zone is the least developed, while the southernmost zone is nearly fully developed into a mature spreading center. Based on these data a model is proposed consisting of an orderly sequence of events associated with the opening history of the Mariana Trough.

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I. INTRODUCTION

The Mariana Trough is a mature back-arc basin of extensional origin. It is associated with the subduction of the Pacific Plate underneath the Philippine Sea Plate and is primarily a single rift, Lau-type basin (Tamaki, 1985; Hawkins et al., 1984). Using magnetic data, Bibee et al. (1980) determined that symmetrical spreading proceeds at approximately 1.5 cm/yr near the central portion of the trough ($\sim 18^{\circ}$N). Hussong and Uyeda (1981) suggested a rate of less than 2.15 cm/yr near 18°N based on drill core analysis and geophysical data.

This back-arc basin ranges from approximately 13°N to 23°N latitude and 143°E to 145°E longitude (Fig. 1). It is crescent shaped, bounded on the east by the active Mariana Arc, and on the west by the West Mariana Ridge, a remnant arc. These two ridges converge to the north and together form the Iwo Jima Ridge, which continues northward to Japan. Although the basin is closed on the northern end, there are extensional features in the Bonin area (Karig and Moore, 1975; Taylor et al., 1985) suggesting that the active arc north of the Mariana Trough is under tension.

The morphology of the Mariana Trough spreading system south of $22^{\circ}10'$N is similar to that of a slow spreading mid-ocean ridge (Fryer et al., in press, Fryer and Hussong, 1981). However, north of this latitude the spreading center is less well defined and it becomes unidentifiable at about 23°N. This change in character of the

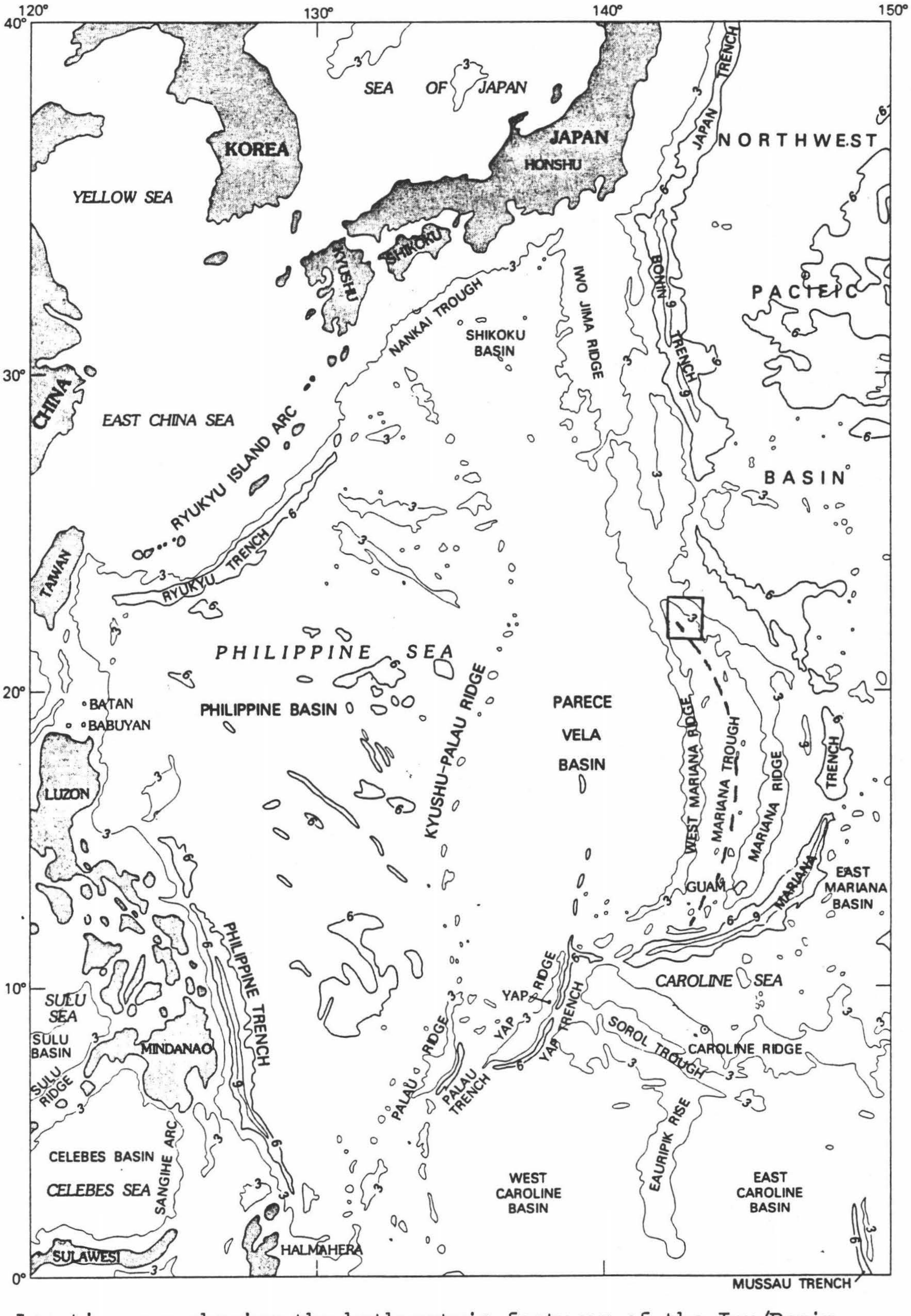


Fig. 1 Location map showing the bathymetric features of the Izu/Bonin regions, south of Japan. The contour interval is 1000m.

From Hamilton, 1979

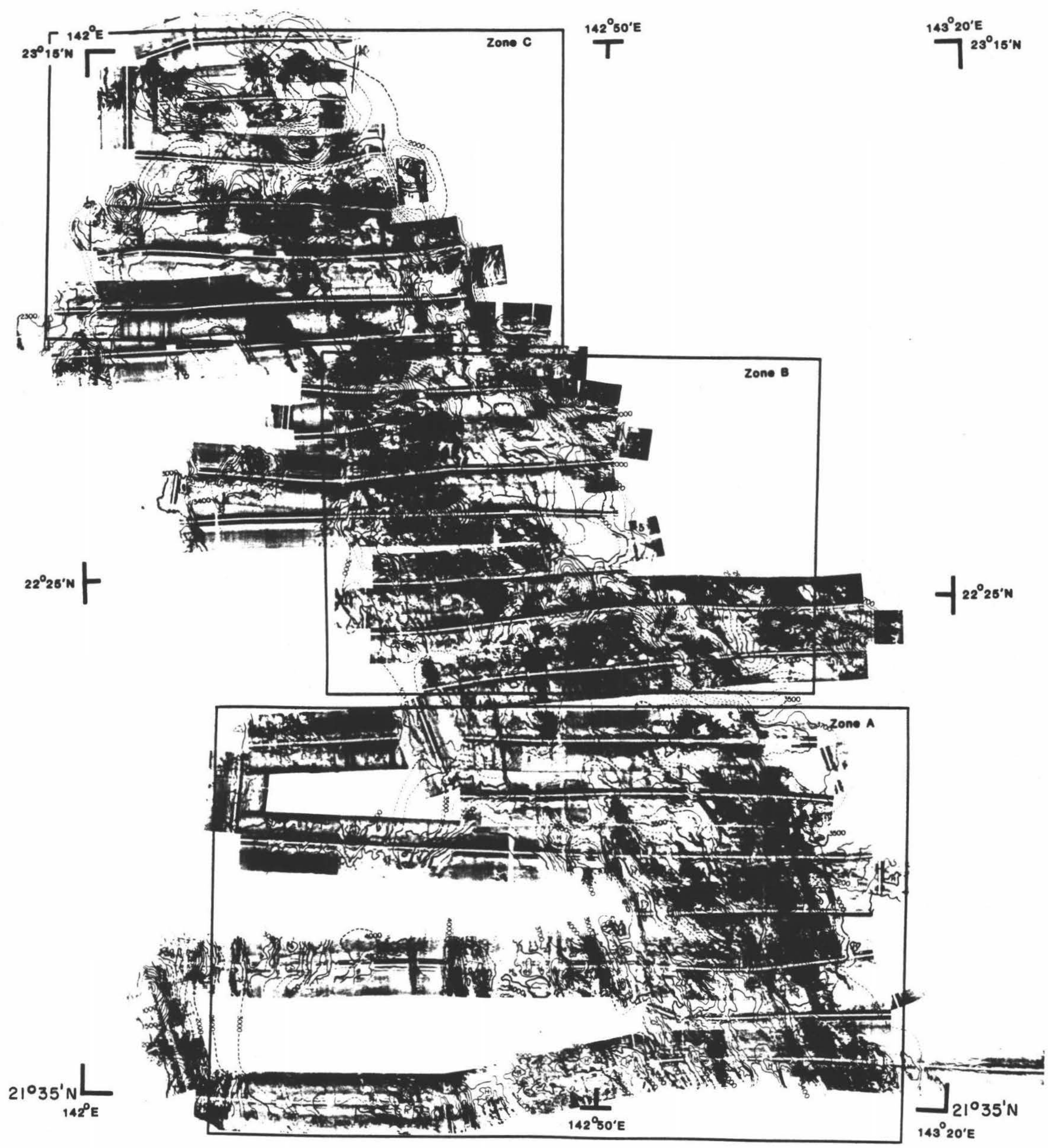
spreading axis has led to the suggestion that the northern portion of the survey area is still in the sundering and stretching stage, rather than in the seafloor spreading stage (Fryer et al., in press). This interpretation is consistent with a northward propagating extensional regime in the Mariana Trough.

Several models have been proposed for the opening history of the Mariana Trough (Bracey and Ogden, 1972; Le Pichon et al., 1975; Karig et al., 1978; Stern et al., 1984). However, none of these models attempt to discuss what processes occur in the initial stages of marginal basin formation. This paper will examine the events associated with the rifting of the northern Mariana Arc, and describe how the back-arc spreading system is propagating northwards. Some of the ideas presented here may be considered applicable to other areas of island arc rifting.

II. OBSERVED FEATURES

The survey area extends from $21^{\circ}35'$N to $23^{\circ}15'$N and $141^{\circ}55'$E to $143^{\circ}30'$E. The active rifting portions of the area have 100% coverage by SeaMARC II sidescan and bathymetry. Continuous seismic reflection data was recorded along ship's tracks. Based on morphology and subsurface features, the survey area has been divided into three zones, A, B, and C (Figs. 2a and 2b). Zone A (Fig. 3) includes an active segment of the back-arc spreading center. Zone B (Fig. 4) consists primarily of large, discreet volcanoes which lie in the back-arc rift graben. Zone C (Fig. 5) is in the rifting stage with evidence for subsurface intrusive activity but lacking evidence for an organized volcanic rift.

In the following discussion several conclusions are reached from the interpretation of the SeaMARC II sidescan data. These interpretations are based on backscatter characteristics of the submarine features and the response of the SeaMARC II system (Appendix) to these characteristics. Fresh lava flows have higher backscatter than sediment covered areas and thus appear darker on the mosaic. Dark returns are also caused by high backscatter and specular reflection from tilted surfaces, such as cliffs, when they face the sonar array. Thus, strong sonar echoes not associated with bottom relief are considered to be exposed lava flows and are interpreted as young features. An area with many closely spaced flows, seamounts, and smaller volcanoes forming a linear pattern parallel to the arc line is interpreted as a well established back-arc spreading center.



142°E
23°15'N
Zone C
142°50'E
143°20'E
23°15'N
Zone B
22°25'N
22°25'N
Zone A
21°35'N
142°E
142°50'E
21°35'N
143°20'E

Fig. 3 Sidescan data with bathymetry overlay of Zone A showing ridges 1, 2, and 3 and their associated depressions. Note the change in character of the spreading axis along strike.

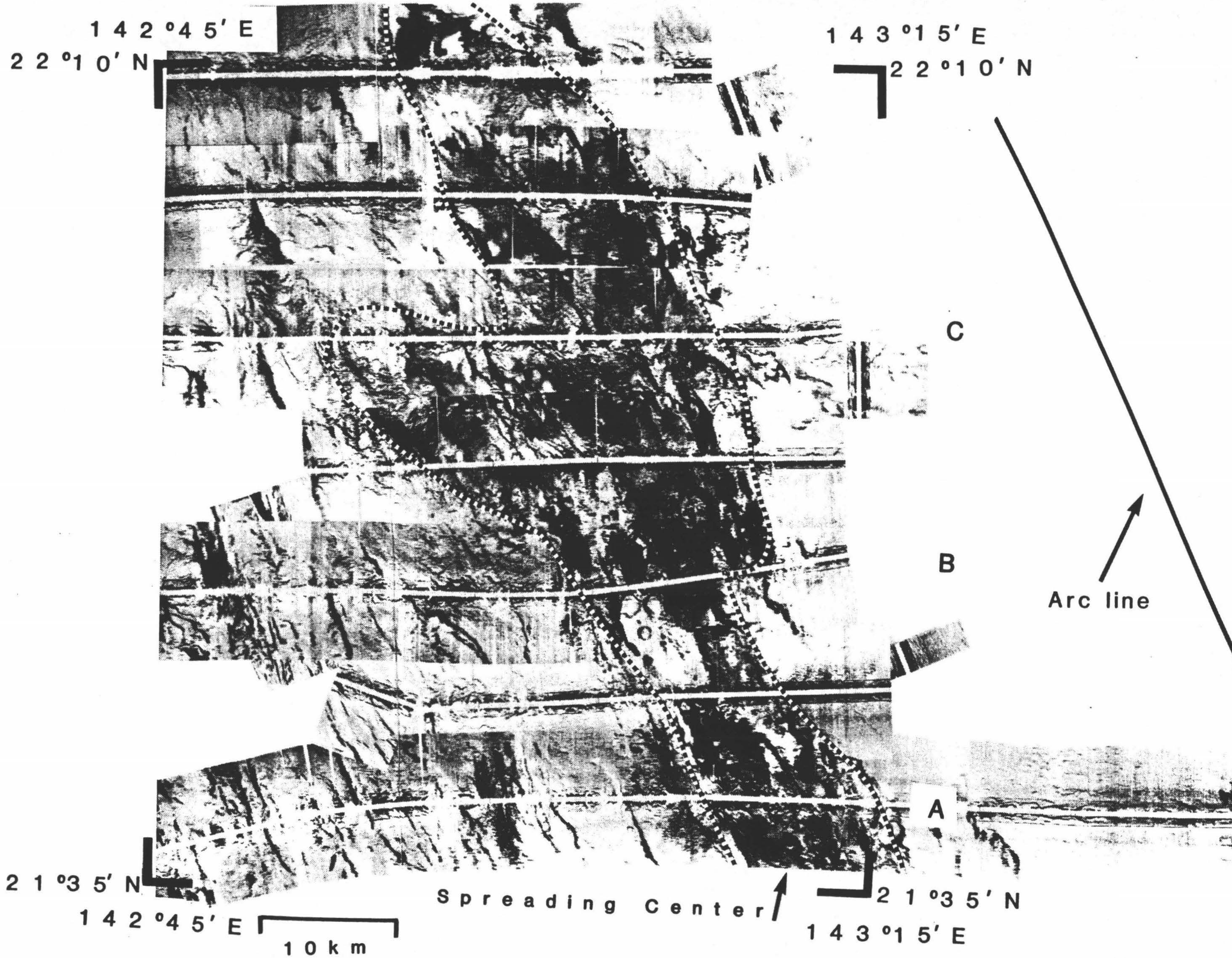
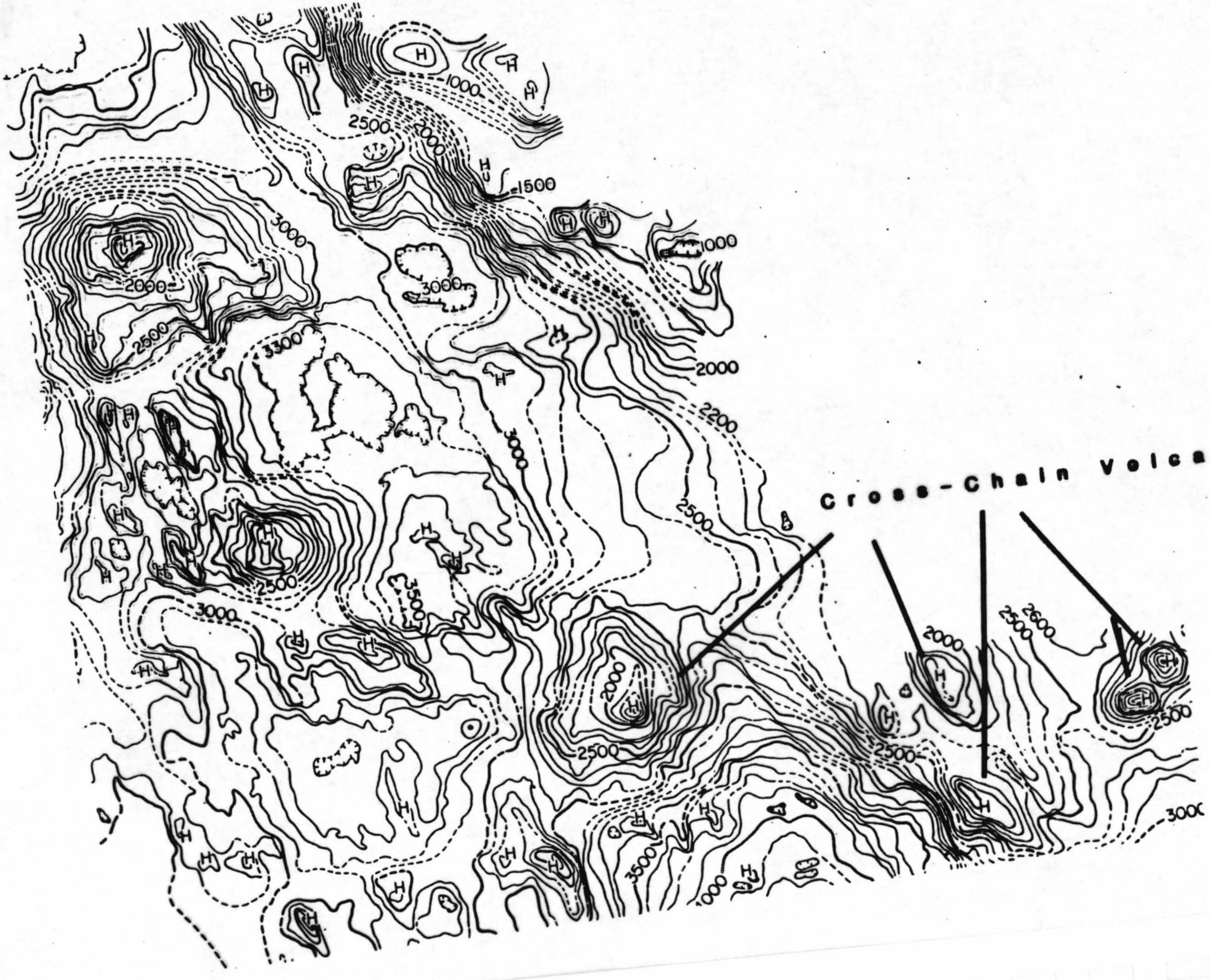
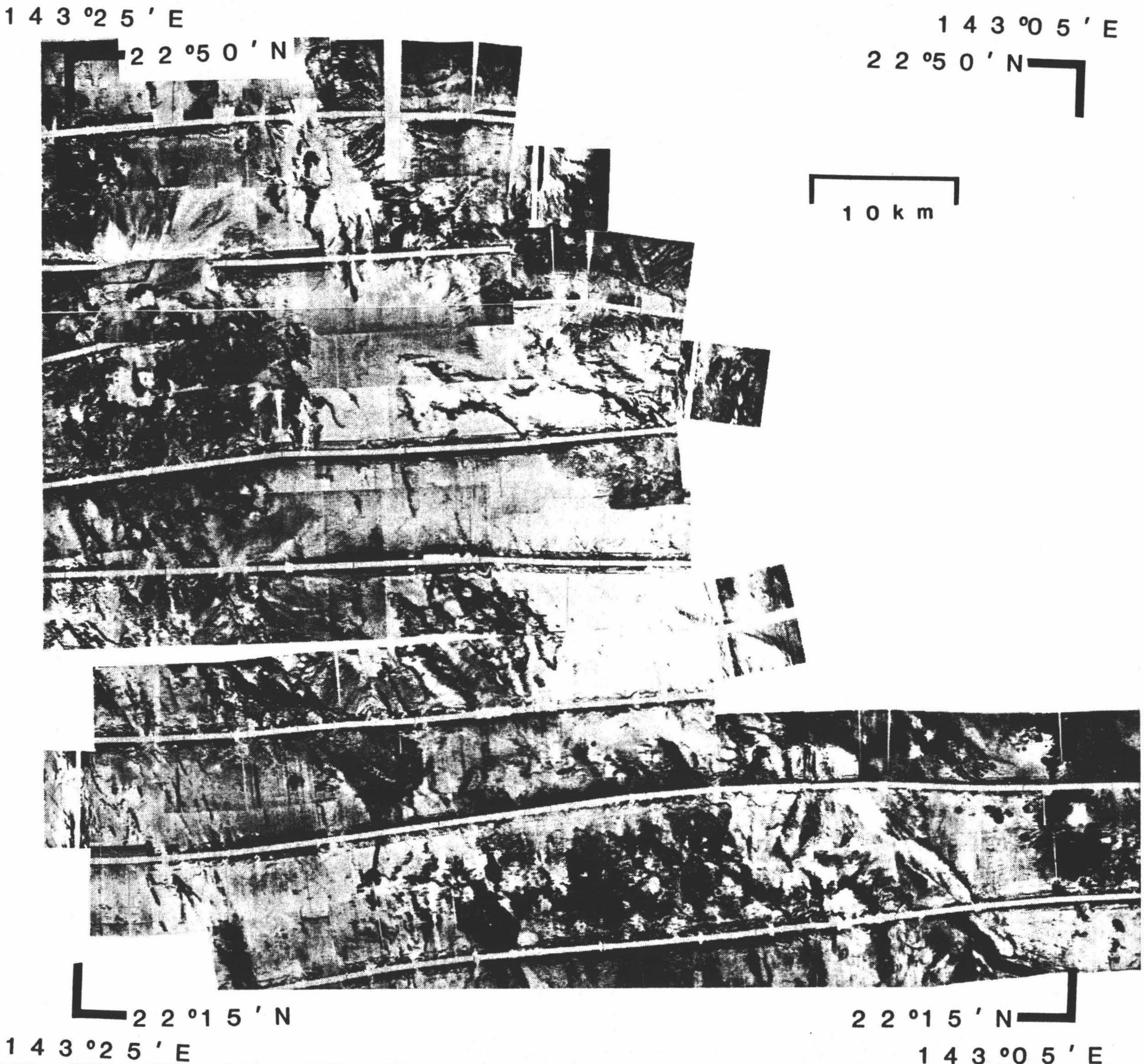

142°45'E
22°10'N
143°15'E
22°10'N
C
B
Arc line
A
21°35'N
142°45'E
10km
Spreading Center
21°35'N
143°15'E

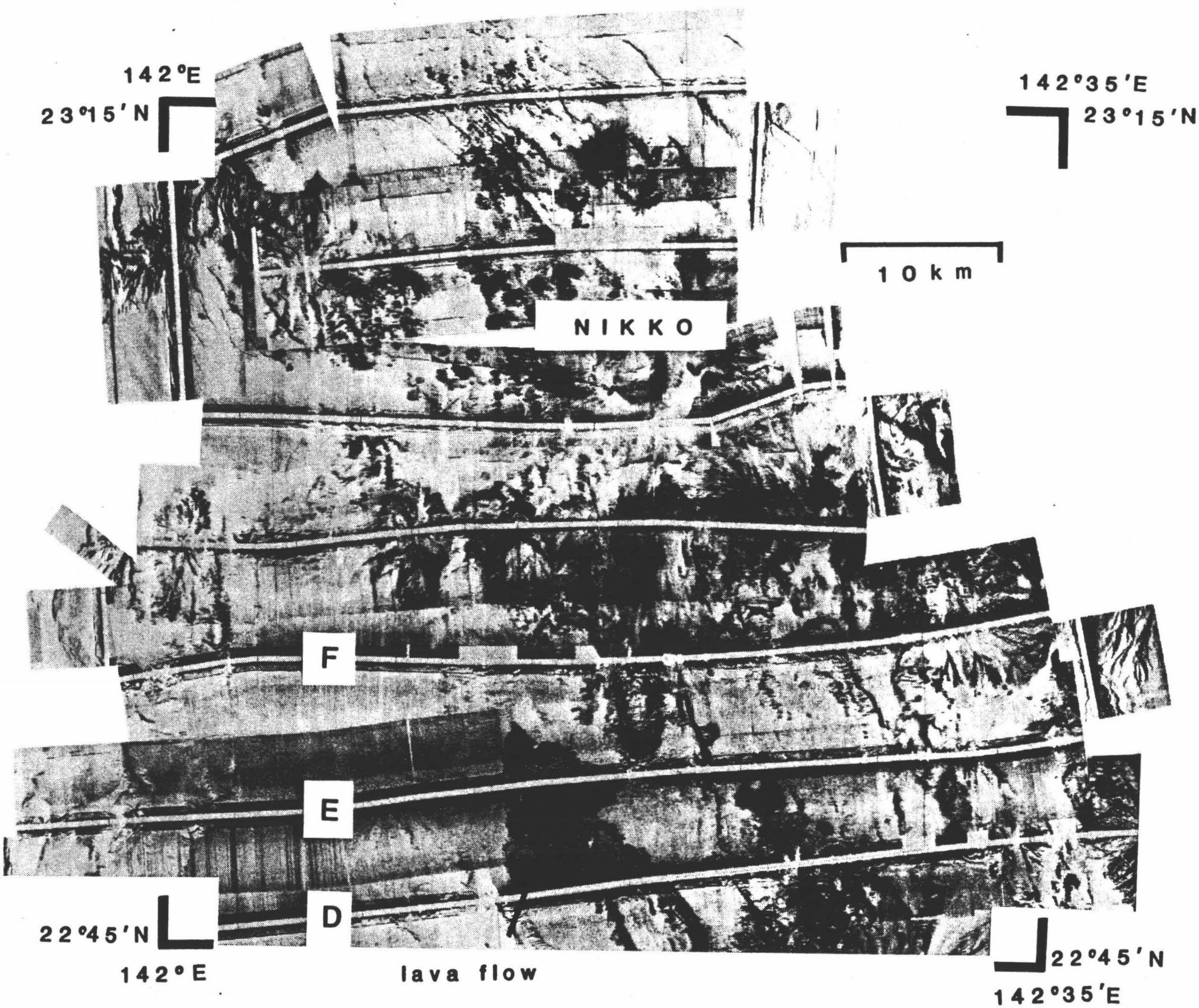
Fig. 4 Sidescan data with bathymetry overlay for Zone B showing the cross-chain of volcanoes in the southeastern corner and the large discreet volcanoes to the northwest.


Cross-Chain Volcanoes



143°25'E
22°50'N
143°05'E
22°50'N
10km
22°15'N
143°25'E
22°15'N
143°05'E

Fig. 5 Sidescan data with bathymetry overlay for Zone C showing the large lava flow at the bottom of the figure and Nikko, an arc-related volcano, in the center of the rift graben.


142°E
23°15'N
142°35'E
23°15'N
10km
NIKKO
F
E
D
22°45'N
142°E
lava flow
22°45'N
142°35'E

Zone A

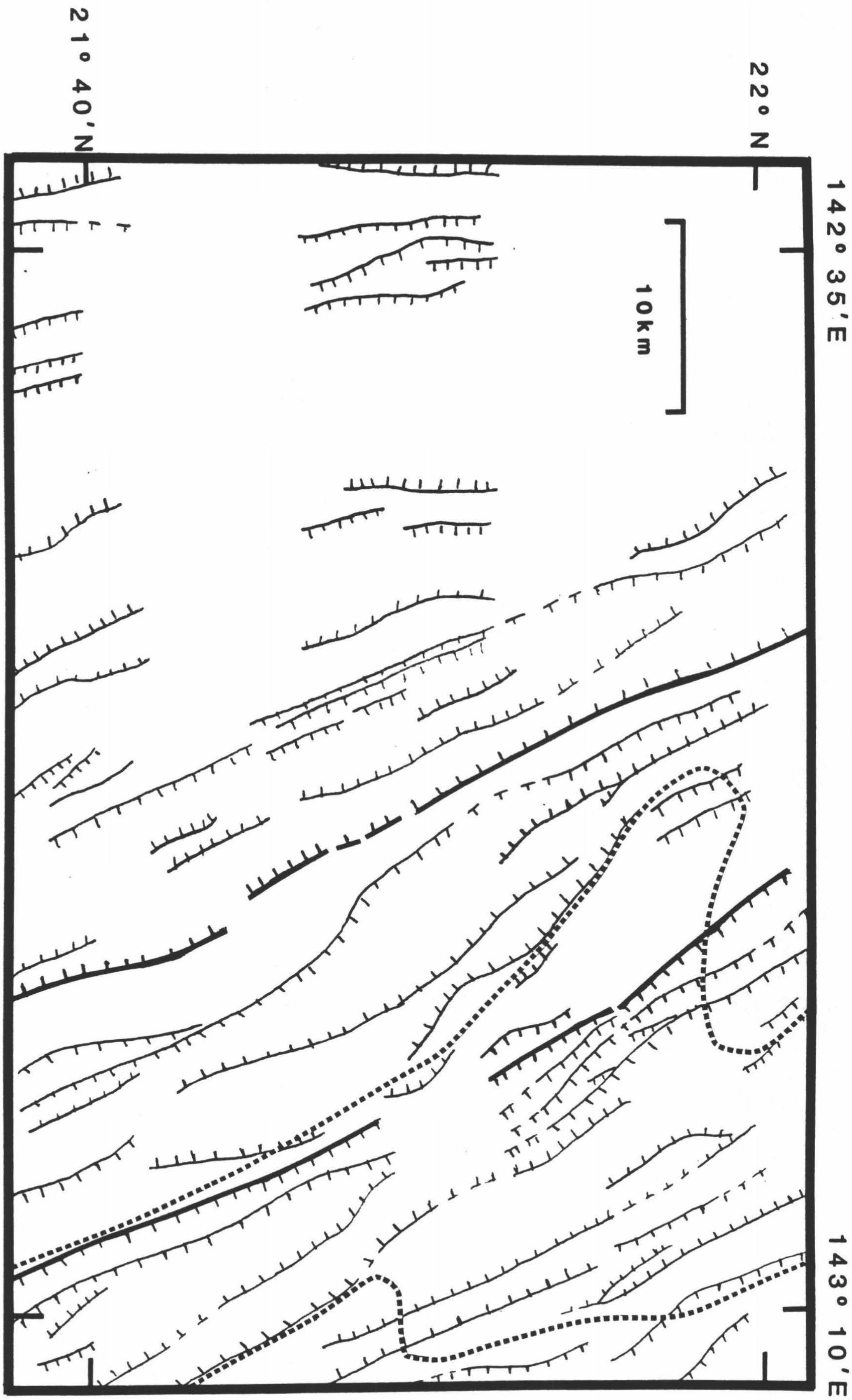
The morphology of Zone A is dominated by three ridges trending roughly parallel to the arc line (Fig. 3). Each of these ridges, labeled 1, 2, and 3 from west to east, has a depression associated with it just to the northwest tip of the ridge. These ridges are interpreted as propagating rifts associated with the back-arc spreading system.

Ridge 1 lies about 13 km west of the main axial zone. It is identified by two elongate seamounts extending to about 21°50'N where it dies out into its associated depression. While this ridge is associated with the back-arc spreading system it is no longer part of the main center.

Ridge 2 lies about 10 km east of ridge 1. It ranges from 21°35'N to 22°05'N. Although large faults bound this ridge (Fig. 6), it is believed to be constructed by volcanism rather than by faulting. Evidence for the volcanic nature of this feature include the presence of many vents and craters as seen on the SeaMARC II image (Fig. 7). While portions of this ridge are still active, the sediment-laden volcanic features seen in fig. 7 suggest that activity along this ridge may be waning.

Ridge 3 is the furthest east of these ridges. It is somewhat discontinuous but extends from 21°35'N to 22°10'N. Ridge 3 marks the primary location of the present day spreading axis. The depression associated with ridge 3 is the largest and deepest of the three depressions. There is evidence for volcanic activity in the eastern

Fig. 6 Major lineations of Zone A, interpreted as normal fault scarps, taken from side-scan record. Note change in orientation from NW in the eastern portion of the figure to N-S in the western portion. Bold lines denote the faults which bound Ridge 2. Dotted line outlines the spreading axis.


21° 40'N
22° N
142° 35'E
143° 10'E
10 km

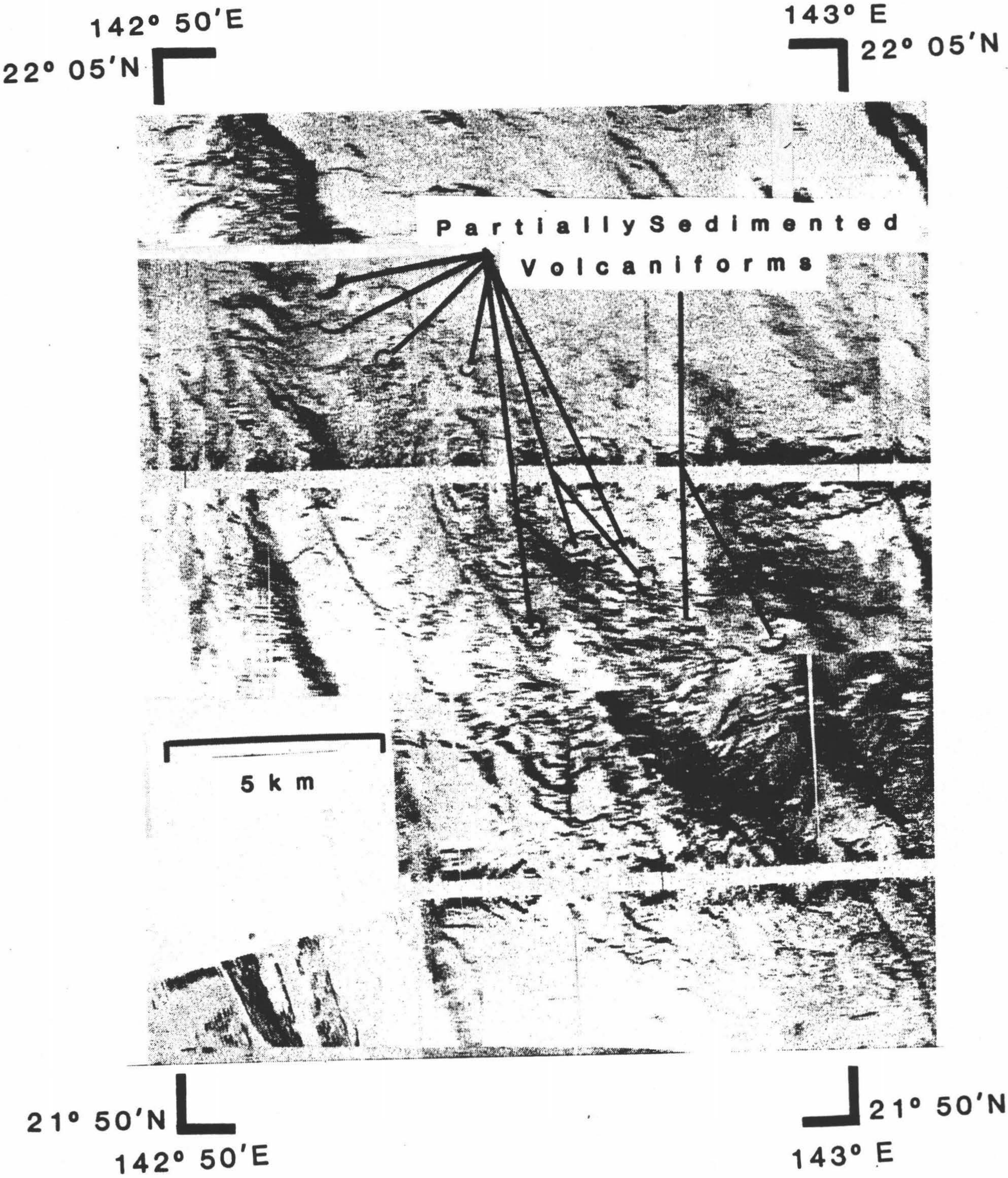


Fig. 7 Close-up of side-scan data from Ridge 2 showing partially sediment covered craters suggesting this ridge is of volcanic origin.

portion of this depression. This volcanism, which lies in line with the volcanic features of ridge 3, suggests that this ridge may still be actively propagating northwards.

Although the spreading axis of this zone continues uninterrupted 21°35'N to 22°20'N, it does change character significantly along strike. From 21°35'N to 21°50'N the main active spreading center is quite narrow (10-15 km). Many circular forms, identified as vents or volcanically related features, along with dark flows from fissures and small volcanoes, define this narrow rift zone. Dredge samples from this area include primitive and evolved back-arc basin basalts (Fryer et al., 1986). The abundance of volcanism associated with this segment of the spreading axis, coupled with the presence of evolved back-arc basin basalts, imply that this is a mature segment of the back-arc spreading system.

Just north of 21°50'N the spreading area widens considerably, up to 25 km, and appears to have activity that is concentrated on four seamounts. These seamounts are elongate roughly parallel to the trend of the spreading center. The two westernmost seamounts of this group are part of ridge 2, while the other two are part of ridge 3.

North of 21°55'N the primary locus of spreading becomes narrow once again (15 km) and is concentrated along ridge 3 up to 22°10'N. At this point the ridge dies out into a deep basin and the spreading system becomes offset to the west near 22°20'N. Although bathymetric and structural trends perpendicular to the rift are not observed in this transform zone, it is possible that such features may be buried by volcaniclastic sediment shed from the nearby arc.

An important off-axis feature of Zone A is an abrupt change in strike of the major lineations about 25km west of the axial rift. These features change from a N30W orientation near the spreading axis to a nearly N-S orientation further west (Fig. 6). This change may record a re-orientation of the stress pattern in the Mariana Trough, and consequently a modification of the opening direction of this basin. It is possible that the collision of the Ogasawara Plateau with the northern Mariana Arc (Smoot, 1983) caused this change in the stress regime of the Mariana Trough.

The bathymetry of Zone A shows greater water depths than are generally observed for Pacific crust of comparable age. A similar discrepency was noted by Louden (1980) for the entire Philippine Sea region. These unusually large water depths may be caused by a density anomaly in the upper mantle (Yoshii, 1973; Watanabe et al., 1977), depressed temperatures caused by the subducting slab (Louden, 1980), an unusually thin crust (LaTraille and Hussong, 1980; Louden, 1980), or a combination of these effects. Thus, although the spreading center often is expressed as a constructional bathymetric high in the Mariana Trough, it is deep compared to typical mid-ocean spreading centers and seems high only because the surrounding older crust is anomalously deep. In the occasional regions of the Mariana Trough where the spreading center is expressed as a rift graben, it occurs at water depths as great as 3600m or more.

Zone B

The morphology of Zone B, which ranges from $22^{O}20$'N to $22^{O}45$'N, is strikingly different from that of Zone A. This zone is dominated by large, symmetrical, discreet volcanoes rather than the continuous ridges observed in Zone A. Two relatively small, elongate features near the southwest corner of zone B are similar to the volcanoes of Zone A in reflection character, morphology, and orientation. Together they form a short, discontinuous ridge which diverges to the west and is overshadowed by the larger, more symmetrical volcanoes which dominate this segment of the spreading axis. This portion of the spreading system appears to be in a different stage of development than the portion contained in Zone A.

This zone also includes a cross-chain of arc volcanoes (described fully in Fryer et al., in press) at about $22^{O}20$'N. This cross-chain trends roughly N75W from $143^{O}05$'E to $142^{O}25$'E.

Zone C

The morphology of this zone, which extends from $22^{O}45$' N to $23^{O}15$'N, is dominated by Nikko, a large seamount from which both primitive arc basalts and dacites have been dredged (Jackson et al., 1987). Although Nikko is an arc volcano, it sits in the back-arc rift graben defined by a set of normal faults north and south of Nikko (Fig. 8).

Zone C is flat and well sedimented south of Nikko seamount. A large lava flow (60-70 km^2) lies in this sedimented portion of Zone C at about

Fig. 8 Major lineations of Zone C, interpreted as normal faults, taken from the side-scan record. The large circle depicts Nikko sitting in the back-arc rift graben. Dotted line outlines the rift graben as defined by faults north and south of Nikko.

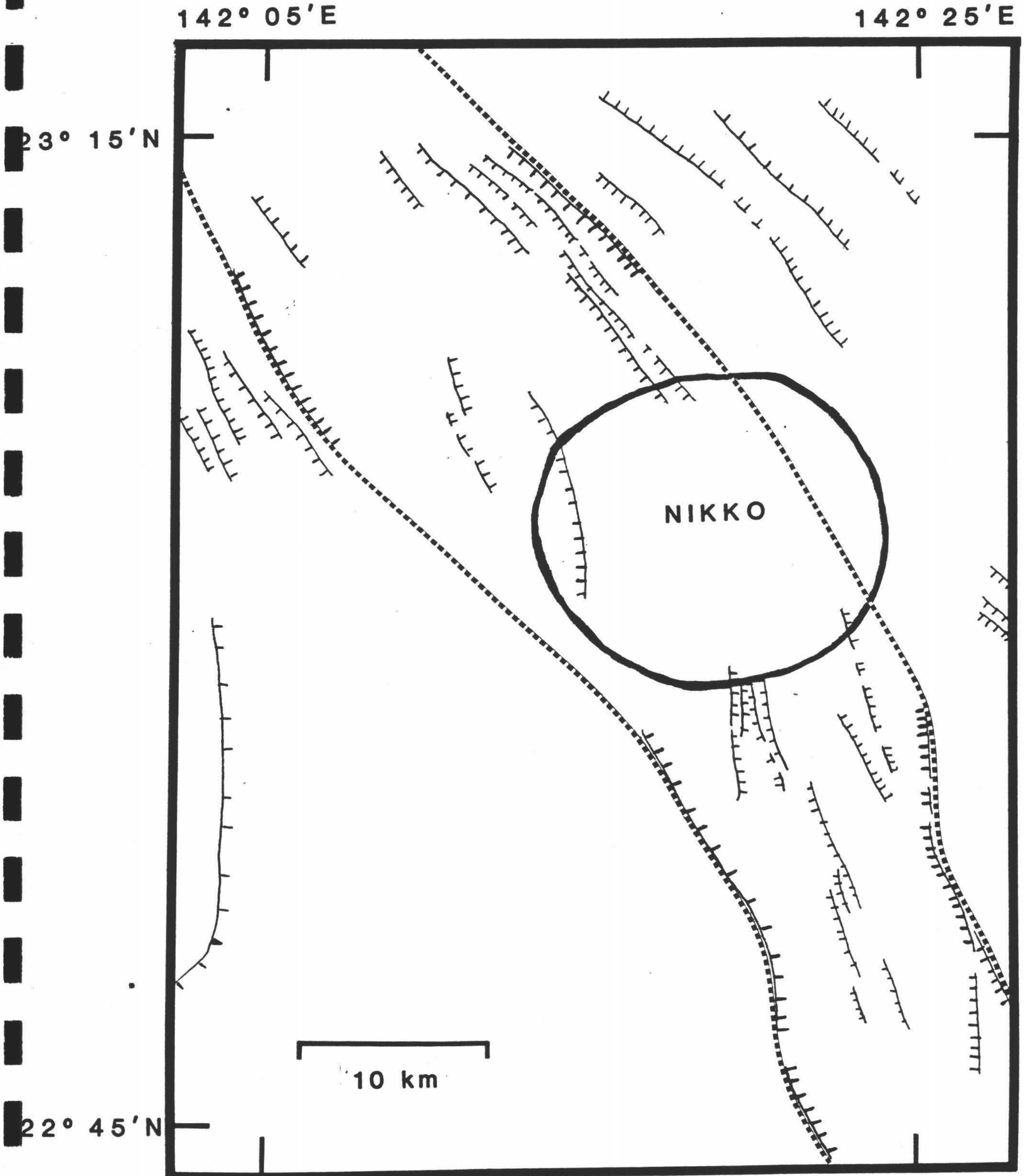
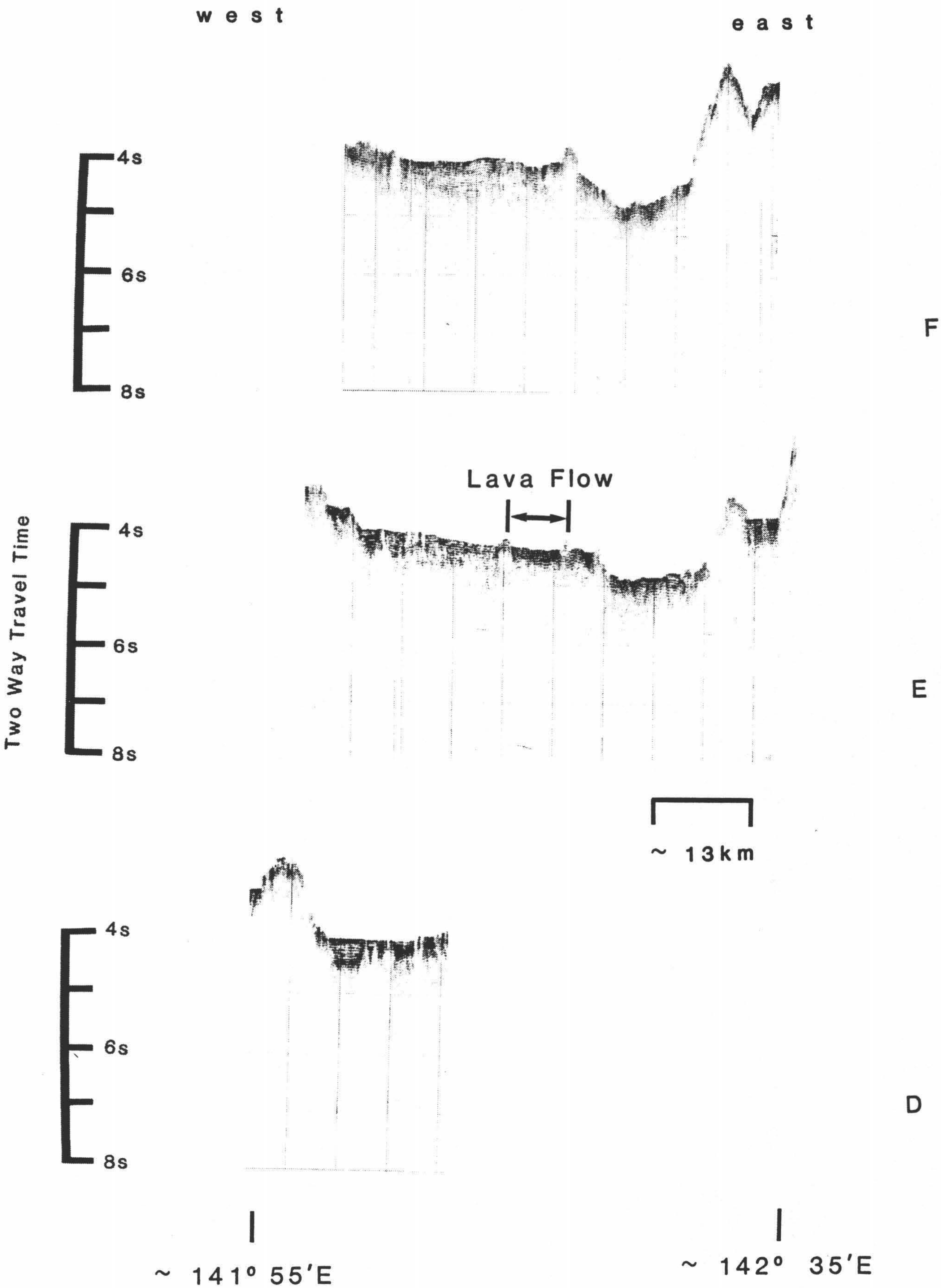

142° 05'E
142° 25'E
23° 15'N
NIKKO
10 km
22° 45'N

Fig. 9 Seismic reflection profiles from Zone C showing zone of intrusive dikes, considered to be precursors to the development of a volcanic rift. Dikes show up as light pillar-like features primarily in the western portion of the figures. Note that profile E displays such features in its eastern end. Note also that the back-arc rift graben lies slightly to the east of the main zone of intrusions.


west
east
4s
6s
8s
F
Lava Flow
Two Way Travel Time
4s
6s
8s
E
~ 13km
4s
6s
8s
D
~ 141° 55'E
~ 142° 35'E

$22^{O}50'N$, $142^{O}15'E$. Although this flow has a rather unusual composition, it does show some possible arc affinities (Jackson et al., 1987).

There is evidence in the reflection profiles for a fairly widespread region of intrusions. These piercement structures show up as light, pillar-like images on the reflection records (Fig. 9) and have been interpreted as dikes representing the earliest stages of back-arc crust formation. Very likely the lava flow in this zone emanated from one of these dikes which reached the surface. The unusual composition of this flow indicates that these dikes do not consist of true back-arc crust, but may instead be made of transitional material derived from a mixing of magma sources. Nevertheless, it seems that these dikes are important precursors to back-arc crust formation.

Another interesting characteristic of this zone revealed by the seismic reflection records is the wide extent of tectonic activity. Profile E shows a region approximately 65 km wide displaying subsurface intrusions and normal faulting. This widespread deformation is consistent with the idea that rifting of an island arc may be similar to the rifting of a continent (Fryer and Hussong, 1981) in that the rift is breaking through thick lithosphere and a correspondingly wide region of deformation is expected.

III. DISCUSSION

Regional tectonic stresses and local disturbances offer some plausible explanations for several intriguing characteristics of the northern Mariana Trough. Based on these SeaMARC II data, related geophysical data, and partially on previous work in the Bonin area (Karig and Moore, 1975; Taylor et al., 1984; Fryer et al., 1985), a model is proposed for the events associated with the early opening of the Mariana Trough (Fig. 10). While this model is aimed specifically at the processes involved with the opening of the Mariana Trough, some of these ideas may be appropriate for other areas of inter-arc basin formation.

One of the earliest events to transpire in the development of an inter-arc basin is the extension of the island arc. During this stage many normal faults develop aligned perpendicular to the direction of stretching. These faults lead to the development of a large rift valley in the vicinity of the active island arc (Karig and Moore, 1975; Taylor et al., 1984; Hawkins et al., 1984). The floors of the rift valleys are broken by normal faults, facilitating the emplacement of magmatic material. This is a very complicated stage in the process of forming a marginal basin and is not very well understood. Data from the Bonin area show that lavas with back-arc geochemical signatures can occur in the very early stages of rift valley formation (Fryer et al., 1985). However, the data from this survey area indicate that large amounts of extension can occur with arc-related volcanoes, such as Nikko, dominating the rift graben. The occurence of both back-arc and arc related volcanism in similar environments suggests that the network of

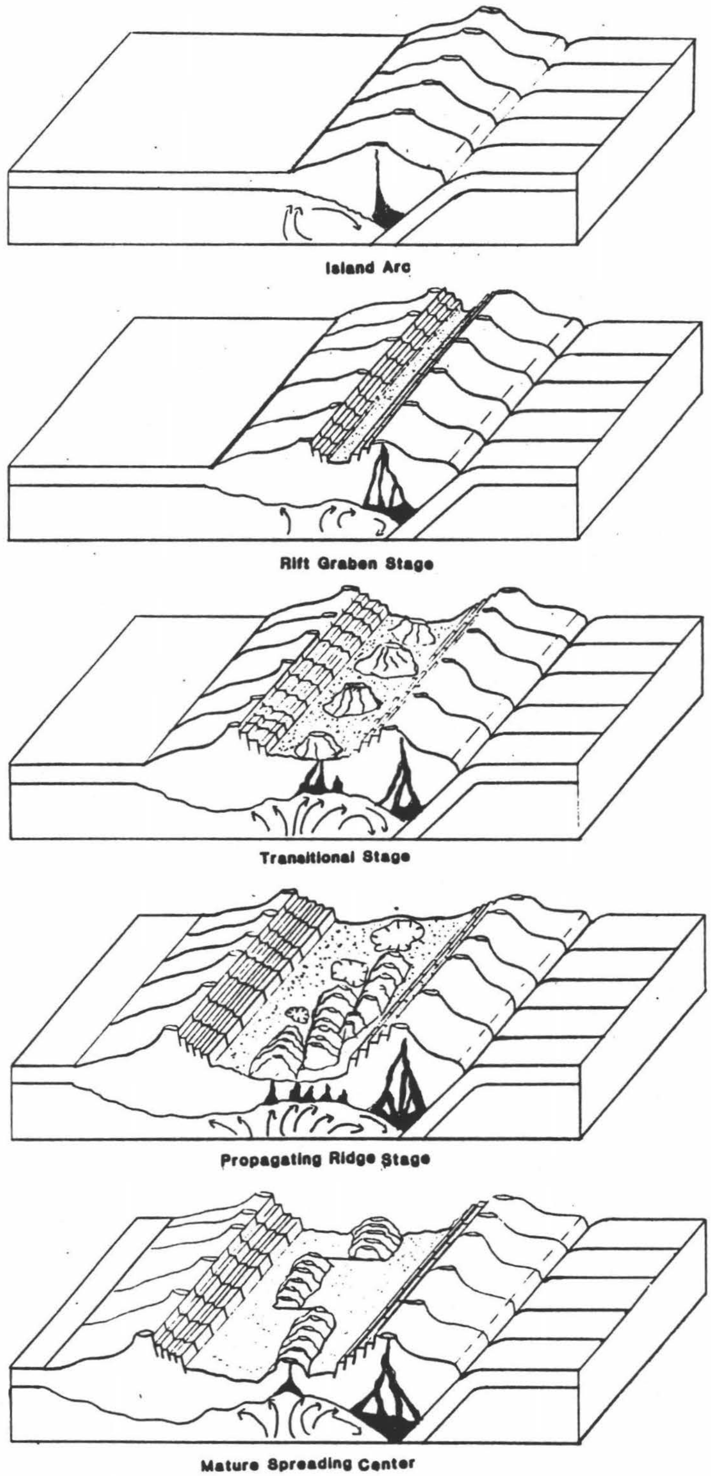


Fig. 10 Evolution of a back-arc basin.

faults controlling the subsurface plumbing of such regions has a large influence on the type of magmas that are extruded at different stages in the development of a back-arc basin.

In Zone C several normal faults north and south of Nikko define the back-arc rift graben (see fig. 8). The fact that Nikko sits in this graben indicates that in the early stages of back-arc basin formation, i.e. during the rifting of an island arc, it is not uncommon for the back-arc rift to overlap the line of active arc volcanoes. This is consistent with the possibility of magma mixing in young back-arc basins (Fryer et al., 1986).

The abundance of piercement structures in profiles D, E, and F suggest that the injection of dikes may be a precursor to the development of an axial volcanic rift. The fact that the zone of dike injection and normal faulting in this area is fairly wide (™65 km as seen on profile E of Fig. 9) suggests that the initial stages of back-arc formation are marked by diffuse tectonic activity similar to the concepts presented by Lawver and Hawkins (1978) to explain the incoherent magnetic patterns of some marginal basins.

The large lava flow in Zone C is mostly likely fed by a dike. Although this lava flow shows certain arc affinities, most notably a high K_2O content, its overall composition is not typical of arc material (Jackson et al., 1987). The unusual composition of this flow may indicate the effects of a back-arc magma source. Regardless of their composition, the injection of dikes appears to be an important preliminary process in the development of a back-arc volcanic rift.

A perplexing observation is that the area of abundant piercement structures lies well to the west of the rift graben defined above. This could be evidence that the locus of extension has periodically shifted east just as it appears to have shifted in Zone A.

With continued extension of the sundered arc, volcanoes develop on the rift valley floor. While these initial expressions of the back-arc spreading center are aligned roughly parallel to the trend of the arc, they do not form the long, continuous ridges characteristic of an established spreading center.

Zone B appears to be in this 'transition' stage, which occurs after the formation of the rift graben but before the establishment of a mature volcanic spreading center. The dominant features of Zone B are the large, discreet volcanoes lying in the back-arc rift graben (Fig. 4). Dredge samples from the northernmost of these volcanoes have yielded back-arc basin basalts (Jackson et al., 1987). The symmetrical nature of these volcanoes implies that they are fed from point sources as opposed to the fissure sources of zone A which result in long linear ridges. Such an interpretation leads to the inference that, while the volcanic rift zone is not fully established in this area, magmatic material is able to reach the surface through a few key points of weakness in Zone B.

This zone also includes a cross-chain of volcanoes, most likely arc-related, trending obliquely to the back-arc spreading system. Major lineations, interpreted as fault scarps, north and east of this feature show a similar orientation (Fig. 11). It is likely that the emplacement of the cross-chain is facilitated by such a fault.

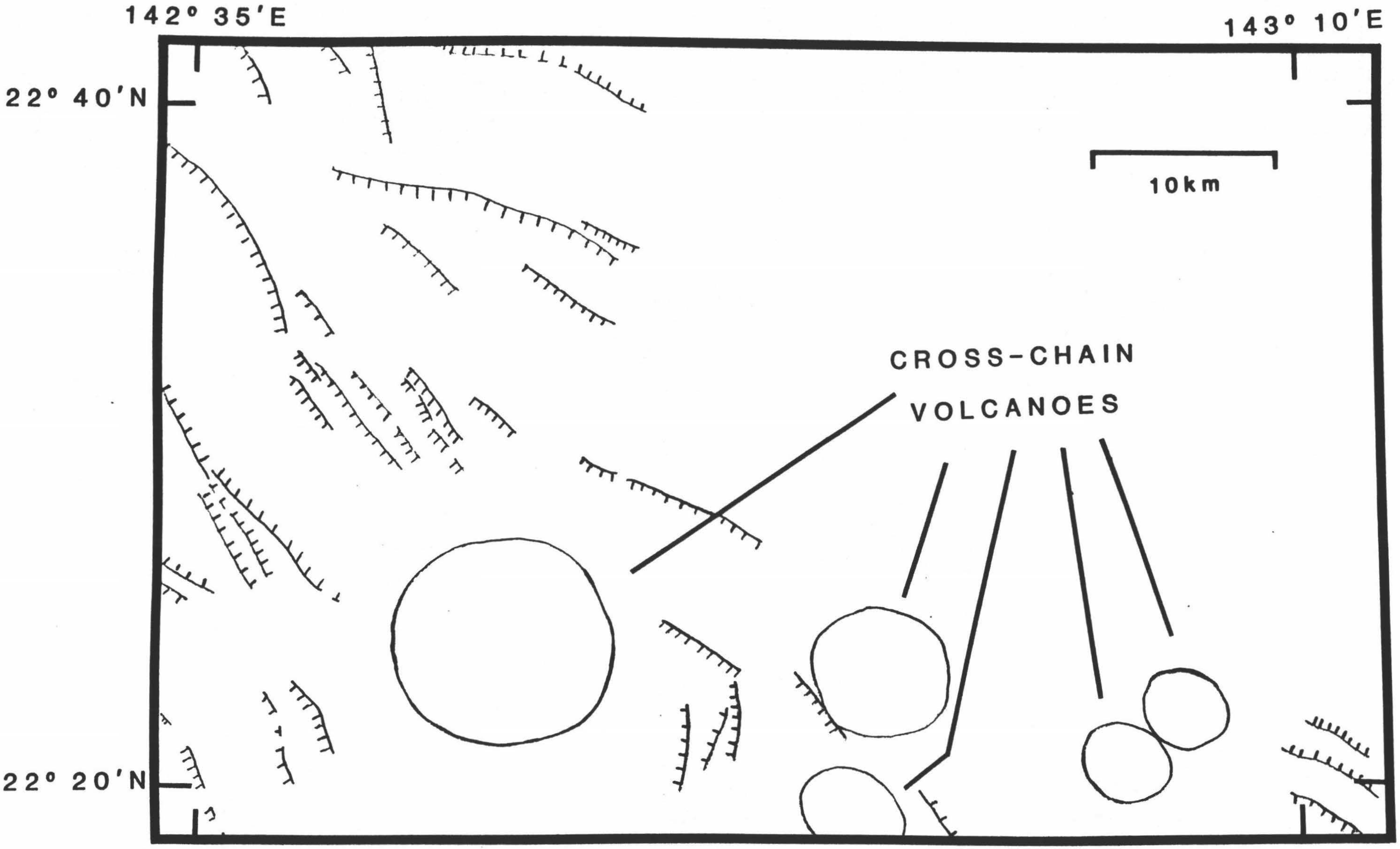


Fig. 11 Major lineations of Zone B and positions of cross-chain volcanoes. Note N75E lineations which roughly parallel the trend of the cross-chain.

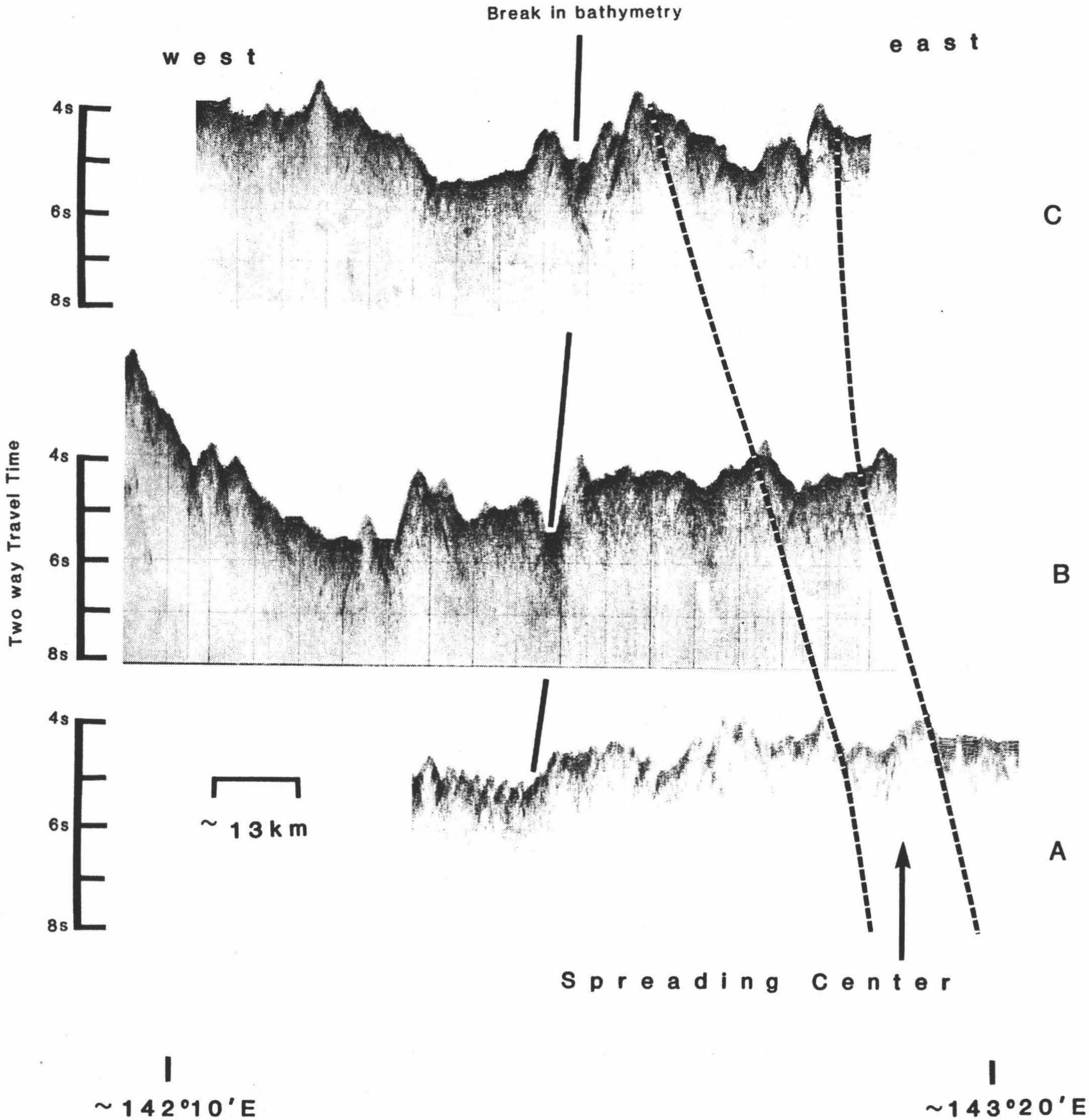
The origin of the N60W lineations is not clear. The majority of these features occur where there is a break in the line of active arc volcanoes. It is highly likely that these lineations are associated with the stress regime of the fore-arc region. This stress regime has created a very complicated fault pattern in the Mariana fore-arc. The relation- ship of this fault pattern to the opening history of the Mariana Trough is uncertain and beyond the scope of this thesis.

South of the cross-chain of Zone B lies the active spreading center of the Mariana Trough. This spreading center is considered to be propagating northward, resulting in a series of propagating ridges, numbered 1, 2, and 3 from west to east. These propagating rifts sequentially die out in favor of a new volcanic center slightly to the east.

Evidence for the propagating nature of this system is offered by figure 12. This figure shows three seismic reflection profiles, A, B, and C, which all exhibit a break in bathymetry west of the spreading axis. This break in bathymetry is interpreted to mark the border between fresh back-arc crust and old, rifted arc crust. This interpretation assumes that stretched and faulted material tends to subside while fresh oceanic crust forms axial ridges. The SeaMARC II data of this area supports this relationship. Given this interpretation, figure 12 exhibits a wedge of new back-arc crust which narrows to the north, suggesting that the spreading system has propagated northward.

Several features of Ridge 2 indicate that it is a dying segment of the back-arc spreading center. As mentioned, there are many circular

Fig. 12 Seismic reflection profiles from Zone A showing the bathymetric border between new back-arc crust and old sundered arc material in the southern portion of the survey area. Wedge of back-arc crust narrows to the north implying that the spreading system has propagated northwards


Break in bathymetry
west
east
4s
6s
8s
Two way Travel Time
C
B
A
~ 13km
Spreading Center
~142°10'E
~143°20'E

craters and vents along the length of this ridge. However, over 50% of these structures have been draped with sediment (Fig. 7) indicating a decline in recent volcanic activity along Ridge 2. Most likely there are several volcanic features which are so buried that they cannot be identified on the SeaMARC II mosaic. Therefore, it is estimated that between 50-75% of the volcanic features associated with this ridge have been quiescent for some time.

Sedimentation rates on Ridge 2 are a function of local volcanic activity. There are three sources of volcaniclastic sediment in this area: (1) the arc, 50-60 km to the east, (2) the cross-chain in zone B, more than 30 km to the north, and (3) Ridge 3, less than 20 km to the east. As a reference, holes 456 and 456A of DSDP leg 60 are approximately the same distance from the active arc as Ridge 2 and yielded recent (0-0.3 my) sediment accumulation rates of 1.9 $kg/cm^2/my$ and 1.3 $kg/cm^2/my$ respectively (Hussong and Uyeda et al., 1982)).

Ridge 3 is the most recently active volcanic rift in this survey area, as suggested by the large number of fissures, flows, and vents associated with it. However, it is somewhat smaller and less continuous than ridge 2, perhaps indicating that it is a younger, less developed feature.

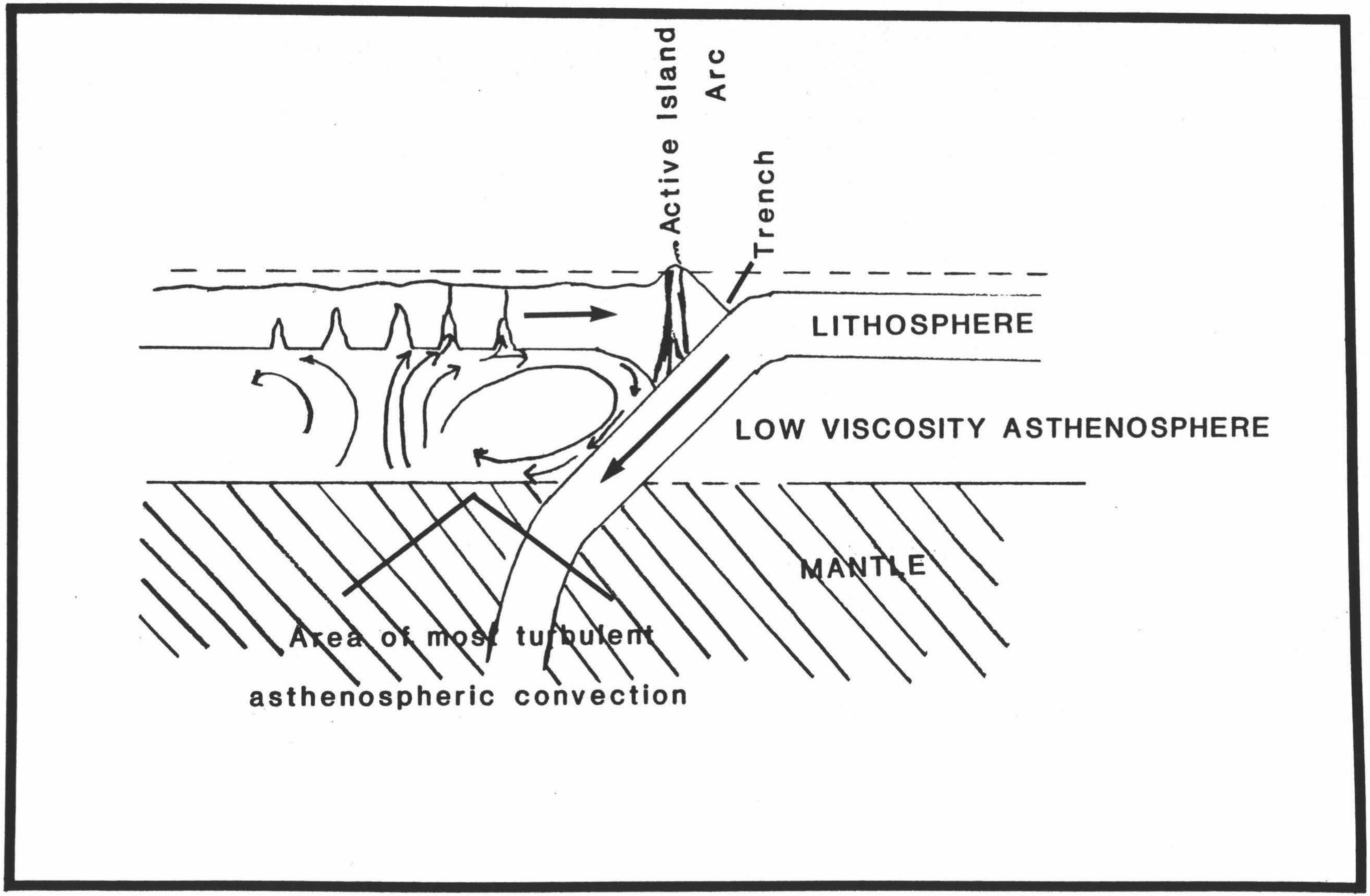
An interesting feature of all three ridges is the occurence of a depression just to the northwest of the tip of each ridge. A possible explanation for these deeps is that as the ridges propagate through the sundered arc, the old, cold crust inhibits the continuation of the rift.This is similar to the behavior of a mid-ocean ridge at a fracture zone (Sleep and Biehler, 1970; Parmentier and Forsyth, 1985). Hey et al. (1980) expanded this idea to include propagating rifts. They reasoned that the colder material through which the rift is propagating causes increased magma cooling, viscous head loss, and leads to the observed basin formation. The large basin in front of the active oceanic propagating rift in the Galapagos at $95^{o}30'$W is floored by new material behind the rift tip (Hey et al., 1986). Some older rifted material has been identified in the western portion of this basin near rift tip (R.N. Hey, personal communication). It is likely that the distribution of material that floors the depressions in Zone A is similar (i.e. new back-arc crust in the southeastern part of the basin, near the ridge tip, and older rifted arc material in the north part of the basin, away from the ridge tip). The observed flows in the southeastern portion of the basin associated with Ridge 3, coupled with the sedimented nature of the northern part of this basin, are evidence that this may be the case. The presence of fresh lava flows in the arc side of this basin supports the interpretation that Ridge 3 is actively propagating northward. The absence of volcanism in the western basins implies that the corresponding ridges have ceased propagating and are being abandoned.

The depression at the tip of a propagating rift tends to re-equilibrate with its surroundings by isostatic adjustment (Hey et al., 1986). Thus, the fact that the basins in Zone A are progressively deeper to the east implies that the corresponding ridges are progressively younger.

The stress regime associated with a back-arc basin is likely to be considerably different than that associated with a mid-ocean ridge propagator. In a mid-ocean ridge environment the stresses to be considered are regional and generally involve two large plates. This situation is quite different from a back-arc environment where stresses are localized and involve at least the subducting plate, the landward plate, and a small platelet between the back-arc rift and the deep-sea trench. In the case of the Mariana system the subduction occuring at the Philippine and Ryuku trenches also needs to be considered. All together, these local forces probably result in a variable stress regime causing frequent re-orientation of the propagating rift. This adjustment is demonstrated by the existence of three ridges of propagator origin within 30 km of each other.

One question arising out of this interpretation is why the ridges become offset to the east. Certainly the active arc is thicker than the sundered arc, so the tendency for the back-arc spreading ridge to re-locate closer to the arc is puzzling. The behavior is possibly the result of two factors: (1) local tensile stress, such as trench suction, may favor the formation of the rift zone nearer the trench (Forsyth and Uyeda, 1975; Bibee et al., 1980); and (2) mantle convection, as proposed by Sleep and Toksoz (1972) may concentrate the replenished mantle supply on the arc side of the rift graben, favoring the development of the spreading center closer to the arc. (Fig. 13). Once the rift is initiated it tends to propagate perpendicular to the direction of least compressive stress (parallel to the arc). This situation continues until thermo-mechanical conditions, such as replenished magma supply and

Fig. 13 Cartoon showing how mantle convection may concentrate the replenished magma supply closer to the arc causing the propagating ridges to migrate in this direction.



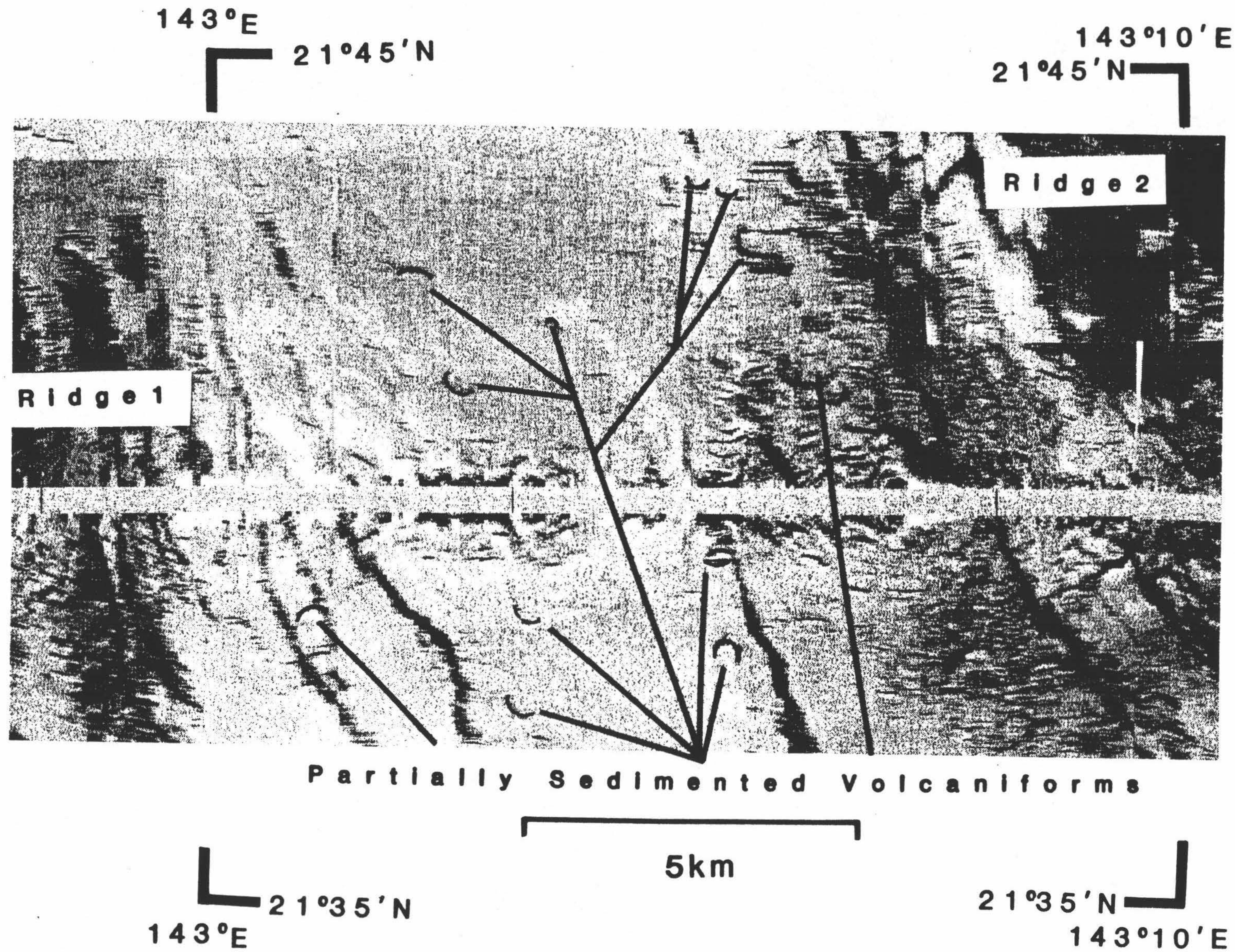
After Sleep and Toksöz, 1971

the state of the local stress field, favor shifting the ridge closer to the arc.

Spreading center relocation appears to be a gradual process based on information set forth here. The spreading center widens (up to 25 km), forming a broad zone of volcanic activity. Although the most prolific volcanism is concentrated about the dying and nascent ridges, there is a high propensity for volcanism between the two ridges at this time. This model is supported by the wide band of sediment draped volcanic features between ridges 1 and 2 (see Fig. 14) and by the zone of four seamounts near 21°55'N. The partially covered craters of Fig. 14 indicate that much of the area between ridges 1 and 2 has experienced volcanic activity. This activity is interpreted to have occured during the gradual relocation of the spreading axis from Ridge 1 to Ridge 2. The broad zone of active volcanism at 21°55'N represents the transfer of the spreading center from Ridge 2 to Ridge 3.

Transform faults occurring in the early stages of marginal basin formation are likely to be highly unstable. Such a transform occurs near 22°20'N where the spreading system is offset about 25 km to the west. Despite this offset, morphologic and bathymetric features perpendicular to the trend of the spreading system are not observed. The fact that Ridge 3 is propagating northward, considered in conjunction with the observations of Hussong and Sinton (1977) that the Pagan Fracture Zone may involve small ridge segments undergoing frequent re-orientation, suggests an unstable, highly variable geometry for this

Fig. 14 Close-up of side-scan data between Ridges 1 and 2 showing sediment laden craters suggesting that this area was once volcanically active. This supports the contention that the propagating ridges gradually shift to the east rather than making dicreet jumps.


143°E
21°45'N
143°10'E
21°45'N
Ridge 2
Ridge 1
Partially Sedimented Volcaniforms
5km
21°35'N
143°E
21°35'N
143°10'E

transform zone. This instability would decrease the tendency to form identifiable transform fault morphology.

Another feature of Zone A is the abrupt change in orientation of the lineations 35 km west of the spreading axis (see Fig. 6). These lineations, identified as normal faults associated with back-arc extension, change from roughly N-S oriented features in the western portion of the trough to N30W trending faults near the present spreading axis. This re-alignment indicates a change in the strike of the axis of minimum compression from roughly E-W to N60E, suggesting a change in the opening direction of the trough.

A possible explanation for the apparent change in the opening direction of the Mariana Trough is the collision of the Ogasawara Plateau with the active arc. Many people have argued that such collisions may cause island arcs to bend (Vogt, 1973; Larson et al., 1975; McCabe, 1984). A collision related bending of the arc would very likely have a considerable effect on the stress regime in the back-arc basin. Perhaps an OBS survey conducted on the Ogasawara Plateau might elucidate the processes involved in this portion of the subduction zone.

IV. CONCLUSIONS

Examination of this data set suggests an orderly sequence of events associated with the opening history of the Mariana Trough (Fig. 10). These events appear to be progressing from south to north, splitting the Iwo Jima ridge. Thus, different latitudes of the survey area are in different stages of development; the southern features being more mature than the northern features. While evidence for this sequence of events is drawn specifically from the northern Mariana Trough, it may be considered relevant to other areas of marginal basin formation.

First, the arc massif is subjected to a tensional stress regime. This causes stretching and thinning of the thick island arc crust. As a result, large normal faults develop and lead to the formation of the back-arc rift graben. Due to the thickness of the arc crust, this stage is similar to the rifting of a continent. As a result, a wide zone of deformation is developed.

As stretching continues and the arc becomes progressively more faulted, magmas migrate through an intricate plumbing system. At this very complicated stage in the development of the marginal basin, arc lava, back-arc lava, or any mixture of the two may penetrate the graben floor. Arc volcanoes, as well as dike swarms, may develop in the rift graben prior to the establishment of the back-arc volcanic rift. Data from this survey indicate that the zone of dike injection can be up to 65 km wide. This implies that the initial stages of back-arc crust generation are marked by diffuse magmatic activity.

With continued extension, back-arc volcanoes dominate the rift graben and a volcanic axis is established. In the early stages these volcanoes may be fed from near point sources and build symmetric, discreet structures as are seen in zone B. If the rate of extension is rather slow, these volcanoes will develop large edifices.

Eventually the volcanic axis becomes dominated by fissure flows forming semi-continuous ridges. These ridges propagate into the colder sundered arc material and typically have large depressions at their tips. Due to the variable stresses and complicated tectonic environment associated with marginal basin formation, these propagating rifts frequently become abandoned and the volcanic axis becomes re-established in a more favorable location. The data presented here suggest that this relocation tends to be closer to the active arc, but this may not be a universal trend.

The above is an admittedly simplified model. Several factors may impede the orderly progression from one stage of development to the next. Irregularities in the rift scar may impede the progress of the propagating rifts. As a rift impinges on the arc or intersects a cross-chain of volcanoes, a transform fault may be more mechanically feasible than continuing the rift. In the case of this survey area the transform fault may partially isolate zone A from zone B, allowing for a slower rate of extension to the north than to the south. The difference in extension (spreading?) rates may be taken up by fault splays in the fore-arc and the marginal basin. This lower rate appears to result in fewer vents and fissures. With continued extension a volcanic zone such as zone B will develop semi-continuous fissures which will split the larger volcanoes. In time these rifts may overcome the transform zone and develop a continuous back-arc spreading system.

The different stages of development observed in the northern Mariana Trough indicate a pole of rotation north of the survey area. A continuation of the rift scars on figure 15 results in an intersection at about $24^{\circ}05'$N, $141^{\circ}10'$E. The actual pole of rotation is probably located a little NW of this since the lithosphere is likely to be able to withstand the small amounts of stress required near the pole. The concept of a pole of rotation is based on the assumption of rigid plates. This assumption may have to be relaxed in the northern Mariana Trough where the marginal basin appears to be subjected to distributed strain as it rifts through the arc massif. The fact that the Bonin area has extensional features implies that there may be more than one 'pole of rotation' for the Mariana/Bonin arc system.

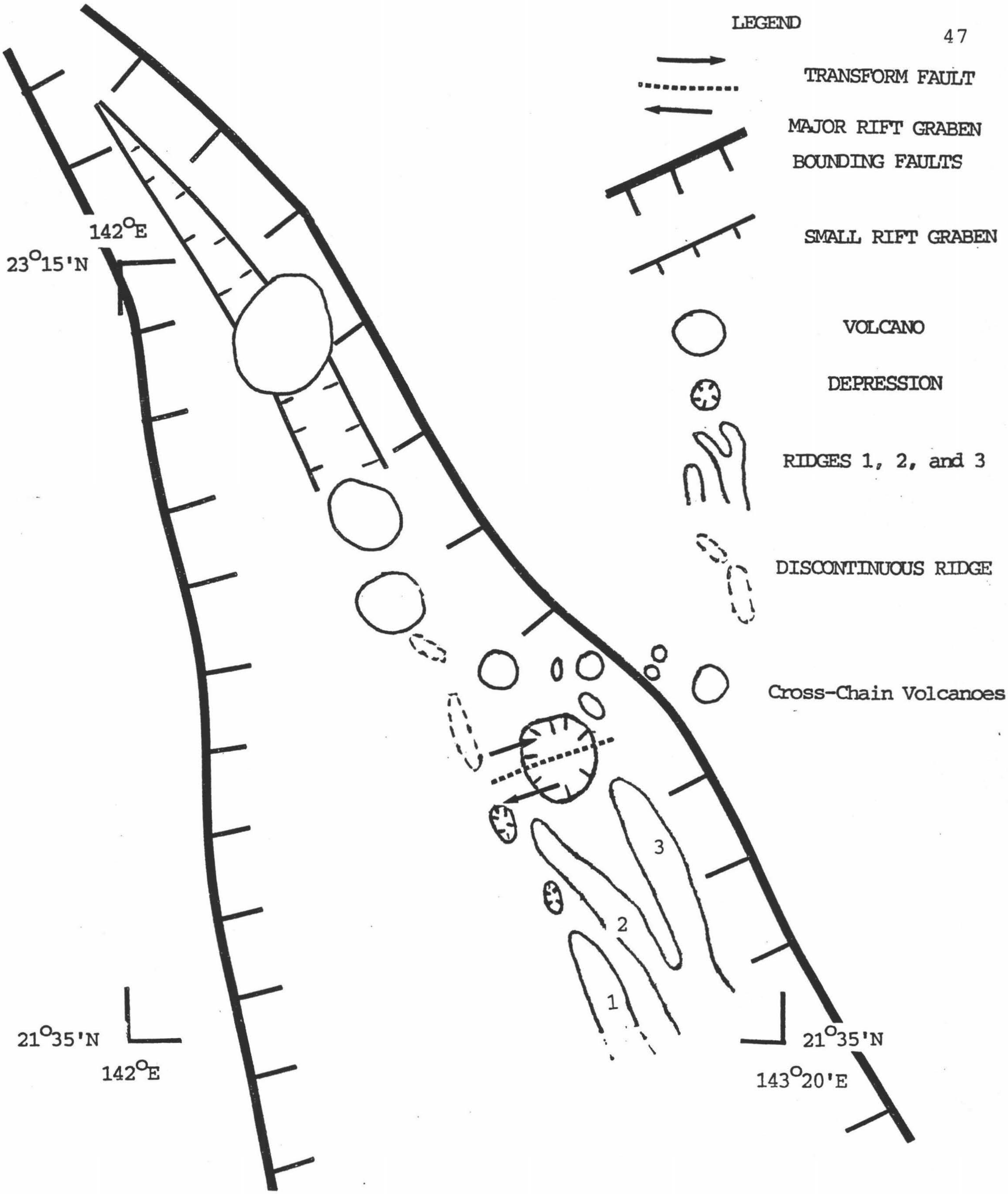


Fig. 15 Generalized tectonic map of the northern Mariana Trough.

REFERENCES

Bibee, Dale L., George G. Shor Jr., and Richard S. Lu, Inter-Arc Spreading in the Mariana Trough, Marine Geology, 35 183-197, 1980

Bracey, Dewey R., and Thomas A. Ogden, Southern Mariana Arc: Geophysical Observations and Hypothesis of Evolution, Geol. Soc. of America Bull., v. 83, p. 1509-1522, 1972

Forsyth, D. and S. Uyeda, On the Relative Importance of the Driving Forces of Plate Motion, Geophy. J. R. Astron. Soc., v. 43, p. 163-200, 1975

Frank, F.G., Curvature of Island Arcs, Nature, 220, 363, 1968

Fryer, Patricia, Kenton L. Beal, and Michael C. Jackson, Volcanism of the Northern Mariana Backarc Rift (abstract), EOS Trans. AGU, v. 67, No. 44, p. 1239, 1986

Fryer, Patricia and D.M. Hussong, Seafloor Spreading in the Mariana Trough: Results of Leg 60 Drill Site Selection Surveys, Deep Sea Drilling Project, Initial Rep. Deep Sea Drill. Proj., v. 60, p. 45-55, 1981

Fryer, Patricia, D.M. Hussong, and N.C. Smoot, Mariana Trough Morphology, In Press

Fryer, Patricia, C. Langmuir, B. Taylor, Y. Zhang, and D. Hussong, Rifting of the Izu Arc, III. Relationship of Chemistry to Tectonics (abstract), EOS, v. 66, 1985

Fuller, M., J.R. Dunn, G. Green, et al., Paleomagnetism of Truk Islands, Eastern Carolines and of Saipan, Marianas, In: D. Hayes (Editor), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Geophys. Monogr., Amer. Geophys. Union, v. 23, p. 235-245, 1980

Hawkins, James W., Sherman H. Bloomer, Cynthia A. Evans, and John T. Melchoir, Evolution of Intra-Oceanic Arc-Trench Systems, Tectonophysics, v. 102, p. 175-205, 1984

Hey, Richard, Frederick K. Duennebier, W. Jason Morgan, Propagating Rifts on Mid-Ocean Ridges, Journal of Geophysical Research, vol. 85, No. B7, p. 3647-3658, 1980

Hey, Richard, Martin Kleinrock, Steven Miller, Tanya Atwater, Rick Searle, Sea Beam/Deep-Tow Investigation of an Active Oceanic Propagating Rift System, Galapagos 95.5°W, Journal of Geophysical Research, vol. 91, No. B3, p. 3369-3393, 1986

Hsui, Albert T., and Sarah Youngquist, A Dynamic Model of the Curvature of the Mariana Trench, Nature, 318, no. 6045, 455-457, 1985

Hussong, Donald M., and John B. Sinton, Seismicity Associated With Back-Arc Crustal Spreading in the Central Mariana Trough, From: The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2, Edited by Dennis E. Hayes, Geophysical Monograph 27, American Geophysical Union, p. 236-254, 1983

Hussong, Donald M., and Seiya Uyeda, Tectonic Processes and the History of the Mariana Arc: A Synthesis of the Results of Deep Sea Drilling Project Leg 60, From: Initial Reports of the Deep Sea Drilling Project, vol. 60, 1982

Hussong, Donald M., Seiya Uyeda, et al., Site 456: East side of the Mariana Trough, From: Initial Reports of the Deep Sea Drilling Project, vol. 60, 1982

Jackson, Michael, Patricia Fryer, and Kenton Beal, Petrology of Northern Mariana Back-Arc Lavas, Abstract, GSA Cordilleran Meeting, Hilo, Hawaii, Spring, 1987

Karig, Daniel E., Structural History of the Mariana Island Arc System, Geol. Soc. of Amer. Bull., vol. 82, p. 323-344, 1971

Karig, Daniel E., Roger Anderson, L.D. Bibee, Characteristics of Back Arc Spreading in the Mariana Trough, J. Geophys. Res., vol. 83, No. B3, 1978

Karig, Daniel E., and G. F. Moore, Tectonic Complexities in the Bonin Arc System, Tectonophysics, vol. 27, p. 97-118, 1975

Laravie, J.A., Geometry and Lateral Strain of Subducted Plates in Island Arcs, Geology, 3, 484-486, 1975

Larson, E. E., R. L. Reynolds, M. Ozima, Y. Aoki, H. Kinoshita, S Zasshu, N. Kawai, T. Nakajima, K Hirooka, R. Merril, and S. Levi, Paleomagnetism of Miocene Volcanic Rocks of Guam and the Curvature of the Southern Mariana Island Arc, Geol. Soc. of America Bull., v. 86, No. 50309, p. 346-350, 1975

LaTraille, Sharon L., and Donald M. Hussong, Crustal Structure Across the Mariana Island Arc, The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Geophysical Monograph 23, AGU, 1980

Lawver, L. A., and J. W. Hawkins, Diffuse Magnetic Anomalies in Marginal Basins: Their Possible Tectonic and Petrologic Significance, Tectonophysics, 45, p. 323-339, 1978

LePichon, Xavier, Seafloor Spreading and Continental Drift, Jour. Geophys. Research, v. 73, p. 3661-3697, 1968

LePichon, Xavier, Jean Franchteau, and George F. Sharman III, Rigid Plate Accretion in an Inter-Arc Basin: Mariana Trough, J. Phys. Earth, 23, p. 251-256, 1975

Louden , Keith C., The Crustal and Lithospheric Thicknesses of the Philippine Sea as Compared to the Pacific, Earth and Planetary Science Letters, 50, P. 275-288, 1980

McCabe, R., Implications of Paleomagnetic Data on the Collision Related Bending of Island Arcs, 1984

Sinton, John B., and Donald M. Hussong, Crustal Structure of a Short Length Transform Fault in the Central Mariana Trough, in: The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2, edited by Dennis E. Hayes, Geophysical Monograph 27, American Geophysical Union, Washington D.C., p. 236-254, 1983

Sleep, Norman H., and S. Biehler, Topography and Tectonics at the Intersections of Fracture Zones With Central Rifts, J. Geophys. Res., v. 75, p. 2748-2752, 1970

Sleep, Norman H., and M. Nafi Toksoz, Evolution of Marginal Basins, Nature, v. 233, 1971

Smoot, N. Christian, Ogasawara Plateau: Multi-beam Sonar Bathymetry and Possible Tectonic Implications, Journal of Geology, vol. 91, p. 591-598, 1983

Stern, R. J., N. C. Smoot, and M. Rubin, Unzipping of the Volcano Arc, Japan, Tectonophysics, v. ?, 1984

Taylor, B., and G. D. Karner, On the Evolution of Marginal Basins, Reviews of Geophys. and Space Phys., v. 21. no. 8, p. 1727-1741, 1983

Tamaki, Kensaku, Two Modes of Back-Arc Spreading, Geology, v. 13, 1985

Watanabe, T., Langseth, M.G., znd R.N. Anderson, Heat Flow in back-arc basins of the Western Pacific in: Island Arcs, Deep Trenches and Back-Arc Basins, M. Talwani and W.C. zzzzpitman III, eds., American Geophysical Union, Maurice Ewing Series 1, 1977

Yoshii, T., Upper Mantle Structure Beneath the North Pacific and the Marginal Seas, Journal of the Physical Earth, 21, 1973

APPENDIX

SeaMARC II System Description

This description is paraphrased from a brochure on the SeaMARC II system distributed by the Hawaii Institute of Geophysics.

SeaMARC II is a long-range, high-resolution, side-scan sonar system with the capability of simultaneously measuring precise bathymetry of the surveyed seafloor. The system employs a transducer array that is towed at shallow depth, typically 100 m below the sea surface. Aside from avoiding the strong sound-speed gradients near the surface, towing the array provides greater stability than could be obtained were the array attached to the hull of a surface vessel. This is very important as the narrowness of the beam pattern requires that yaw or pitch of the transducer array be less than 1.5°. The system operates at 11 kHz on the port side and 12 kHz on the starboard side.

At seafloor depths greater than 1 km the system is generally configured to produce images 10 km wide. The minimum swath width for shallow water applications is 1 km and the minimum depth that can be surveyed is about 25 m below the array. The SeaMARC II side-scan images contain 1024 pixels in each half of the swath. The pixels are obtained by sampling the returning echoes to remove the slant range distortion and produce a geometrically correct plan view of the bottom. For a 10 km swath width each pixel represents the echo strength from an area 5 m wide across track. The along beam width of the towed transducer array is 2^{o}. At present the width of the bathymetric swath is limited to 3.4 times the water depth. Beyond this distance the bathymetric information suffers from bottom multiples.

As the wavelength of a 12 kHz signal is approximately 12 cm in water, the side-scan image is particularly sensitive to reflectivity changes caused by backscatter from seafloor relief on the order of 10 cm. Recognition of seafloor patterns, however, is a function of the type of feature causing the echoes. Typically, linear features such as channels or faults are recognizable if they have dimensions of only a few to several tens of meters, while three-dimensional features, such as small mounds or sediment ponds, must have dimensions on the order of 100 m or more before displaying a recognizable shape.

Monitor records of the side-scan data are produced on EPC and Raytheon variable density line scan recorders. A reduced scale (typically about 1 cm=2 km) monitor record of side-scan data and a simultaneously produced color-coded bathymetry swath monitor provide an image of the survey area. These monitor records can then be constructed into side-scan and bathymetry mosaics of the survey area (the quality of the fit is dependent on the available navigation). All side-scan data, fish attitude (depth, roll, pitch, and heading), bottom depth, operator switch settings, and the echo angle vectors are recorded on digital tape for further processing.

Post-acquisition data processing of the side-scan data from digital tapes includes further correction for ship speed after final navigation is available, compensation for undesirable gain variations, and pixel relocation for corrected bottom depths. The corrected side-scan strips are played out on a gray-scale recorder and used to prepare a spatially correct side-scan mosaic.

The depth resolution of SeaMARC II bathymetry is still improving as data processing algorithms continue to be modified. Under normal deep ocean situations an absolute repeatability, when compared to other high resolution multibeam bathymetry, of better than 35-75 m is obtained. This repeatability depends on local geologic and oceanographic characteristics. Relative depth variations, such as on abyssal hills with relief of a few tens of meters, are repeatable even when the average measured depth varies.

For a more complete description of the SeaMARC II system see Blackinton et al. (1983).