JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. B3, PAGES 3489-3500, MARCH 10, 1986

MULTIBEAM STUDY OF THE FLORES BACKARC THRUST BELT, INDONESIA

Eli A. Silver, Nancy A. Breen, and Hardi Prasetyo

Earth Sciences and Institute of Marine Sciences, University of California, Santa Cruz

Donald M. Hussong

Hawaii Institute of Geophysics, University of Hawaii, Honolulu

Abstract. Using the SeaMARC II seafloor mapping tool in conjunction with closely spaced seismic reflection profiles, we have mapped a segment of the Flores back arc thrust zone. Structural irregularities along the deformation front of the thust zone result from changing stratigraphy and basement structure of the lower plate. NE trending faults cutting the outer slope of the Flores basin are easily mapped because they truncate dense drainage patterns obliquely. Mud diapirs, probably indicating elevated fluid pressures, have formed throughout the accretionary wedge but appear to be concentrated (as do back arc thrust earthquakes) at the ends of thrust faults. The overall orientation of the deformation front of the accretionary wedge is 100°, suggesting a NNE sense of thrust motion and supporting an origin of the thrust zone by collision of the arc with Australia rather than by magmatic forcing or gravitational sliding or spreading. Orientations of faults and folds close to the arc are not consistent with the trends of the frontal thrusts, however, and the difference may be due to either different initial orientations or to later rotations of structural features as the accretionary wedge grew.

Introduction

Numerous hypotheses have been proposed for the initiation and driving mechanism of thrust belts. These include gravitational body forces as the sole mechanism [Hubbert and Rubey, 1959; Elliott, 1976], gravity spreading as a result of existing relief [Price and Mountjoy, 1970] or injection of magma in the volcanic arc [Hamilton, 1979], low-angle subduction resulting in back arc thrusting [Barazangi and Isacks, 1976; Jordan et al., 1983; Dalmayrac and Molnar, 1981], and collisional tectonics [Dewey and Bird, 1970; Hamilton, 1979; etc.].

As a result of a seismic reflection study north of the eastern Sunda arc, Silver et al. [1983] concluded that the Hubbert-Rubey and the Price-Mountjoy mechanisms were unlikely to be of primary significance in the development of this zone of young back arc thrusting, although the stress generated by the surface slope of the back arc may have significant secondary importance in determining the location of thrusting [Dalmayrac and Molnar, 1981]. Subduction is not low angle in the eastern Sunda arc [Cardwell and Isacks, 1978]. Neither collision nor magmatism could be ruled out as driving mechanisms for the thrusts on the basis of existing structural data, although magmatism appeared unlikely as the primary cause of the Wetar thrust zone (Figure 1) because the arc is volcanically inactive in that segment. The Flores thrust zone, however (Figure 1), lies north of a volcanically active part of the arc, and we concluded that magmatic heating may allow much easier fracturing of the lithosphere (in agreement with Armstrong [1974] and Burchfiel and Davis [1975]).

In order to further refine our understanding of the process of thrust belt initiation, we carried out a detailed geophysical study of part of the thrust belt north of Flores island, using the SeaMARC II swath-mapping tool in conjuction with seismic reflection data. We hypothesized that if collision were the dominant mechanism for initiating and driving the thrusts, then any directional indicators for thrust movement should be consistent with those observed at the collisional interface south of the arc. If, on the other hand, magmatic forcing were of primary importance, then we should see movement indicators directed radially away from the centers of intrusion, largely unrelated to collisional directions. Finally, whatever the primary cause of the thrusting, the SeaMARC II survey should provide us with a wealth of information on the lateral structural geometry of a young thrust belt, and this information might be applied to understanding of the growth and development of thrust systems in general.

Regional Tectonic Setting

The island of Flores, Indonesia, is in the process of collision with the northern continental margin of Australia (Figure 1 [Hamilton, 1979]). Although subduction of the Indian-Australian plate continues [Cardwell and Isacks, 1978] south of the Sunda arc (Figure 1), two discontinuous zones of thrusting are developed north of the arc, the Wetar and Flores thrust zones [Silver et al., 1983]. Subduction of the Indian Ocean plate beneath the eastern Sunda arc is very steep, as indicated by the Benioff zone [Cardwell and Isacks, 1978], reflecting the great age of Indian ocean lithosphere in this region [Larson and Pitman, 1985; Molnar and Atwater, 1978].

Volcanism is discontinuous in the arc. The most prominent volcanic gap lies just south of the Wetar thrust zone, on the islands of Alor, Wetar, and Romang (Figure 1). Volcanic activity occurs north of the Wetar thrust, however, on the island of Gunung Api [Hamilton, 1979] and on a small seamount adjacent to the thrust off the NW margin of Wetar, dated at 0.40 ± 0.01 Ma [Silver et al., 1985]. Western Flores (Figure 1) is a region of

Paper number 4B5295.
0148-0227/86/004B-5295$05.00

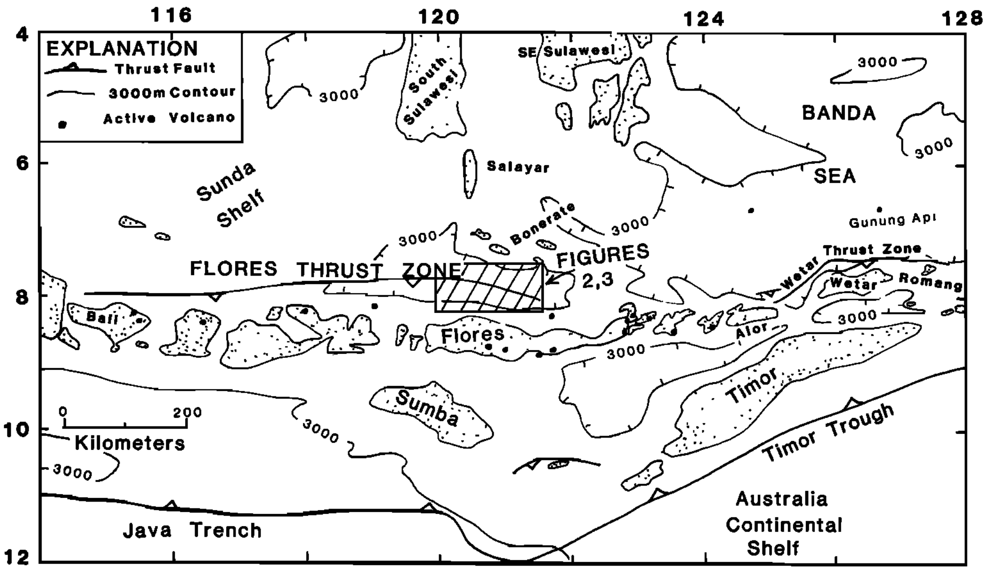

Fig. 1. Location of SeaMARC II survey (Plate 1 and Figures 2) and geographic features discussed in text. Triangles on upper plates of thrust zones.

low volcanic activity. The volcanic centers shown on the map are not volcanoes but localized solfatara fields [Simkin et al., 1981; R. Varne, oral communication based on unpublished field work, 1983]. The volcanic arc is cut by a number of cross-arc structures that show up as linear straits between islands and as lineations on side-looking airborne radar (SLAR) images [Silver et al., 1983]. In western Flores, just south of the zone of our SeaMARC II survey (Plate 1 and Figure 2), both NW and NE trending lineations cut the arc.

Seismicity is associated with both northward subduction of the Australian plate [Cardwell and Isacks, 1978; McCaffrey et al., 1985] and southward thrusting of the Flores basin beneath the arc [McCaffrey and Nabelek, 1984]. Focal mechanism solutions for earthquakes north of Bali [Cardwell et al., 1981; R. McCaffrey, written communication, 1985) and north of Flores [McCaffrey and Nabelek, 1984] indicate north trending slip vectors. Best estimates of the fault plane suggest a thrust fault dipping 30° to the south. The fault plane published by McCaffrey and Nabelek (December 23, 1978; m_b = 5.8) was located at 8.33°S, 121.34°E, at a depth of 11 km. This

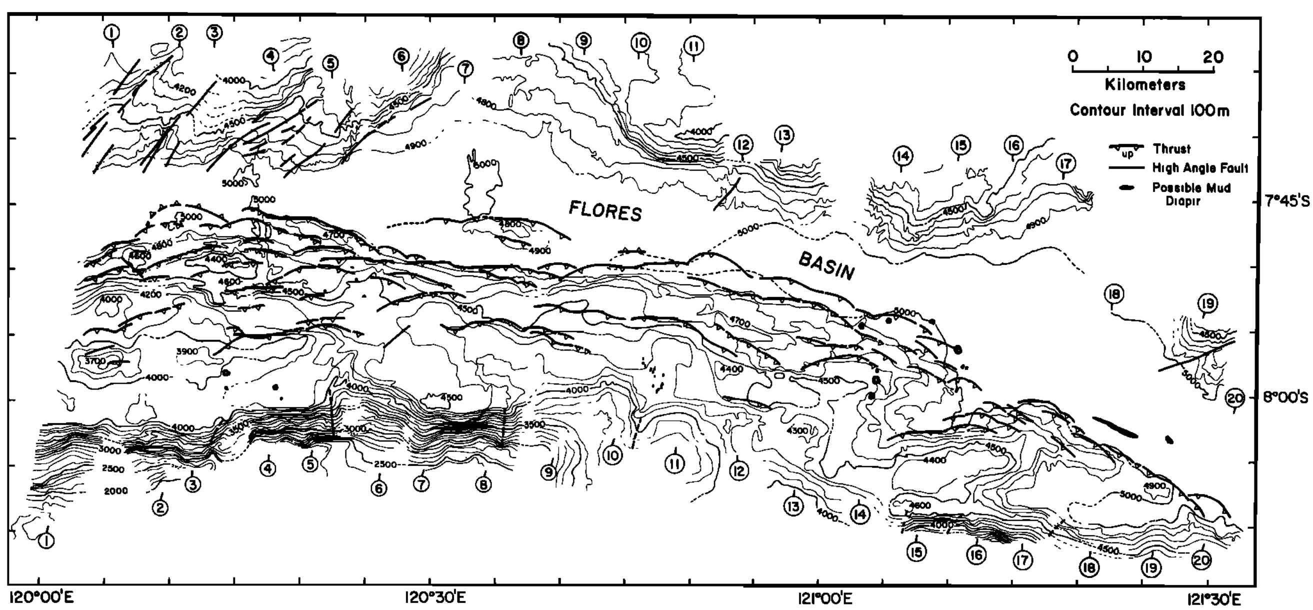

Fig. 2. Bathymetry, faults, and mud diapirs of the central Flores thrust zone, based on interpretation of SeaMARC II data and seismic reflection profiles. Shown also are locations (circled numbers) of all seismic profiles. Mud diapirs are solid black. Triangles on upper plates of thrust faults.

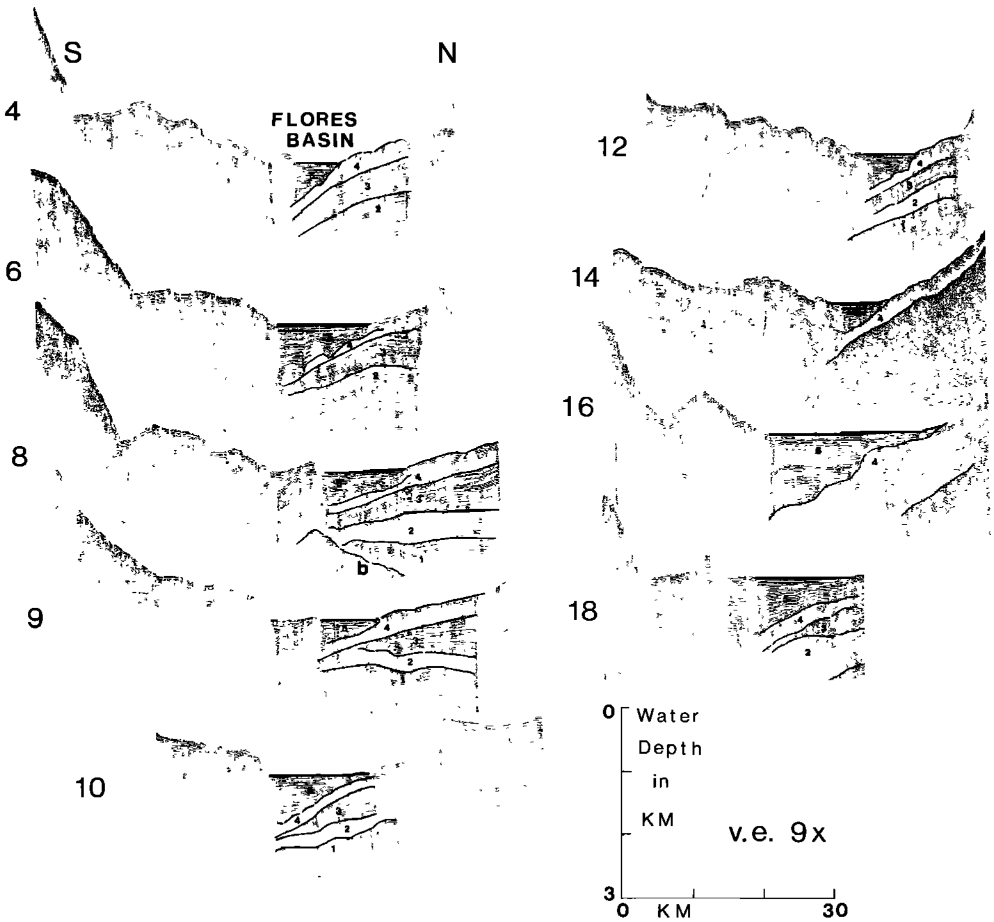

Fig. 3. Seismic profiles 4, 6, 8, 9, 10, 12, 14, 16, and 18, located on Figure 2. Vertical exaggeration (V.E.) approximately 9x. Seismic units 1-5 located on most profiles, where reasonably clear.

location is 10 km south of the south end of profile 18 (Figure 3). R. McCaffrey (written communication, 1985) has determined a similar solution (focal depth 16 km) for the March 3, 1976, earthquake, located a few kilometers to the SE. Shallow focus earthquakes on western Flores are transcurrent, with NW and NE trending focal planes.

The age of collision of the arc by the Australian continental margin is difficult to determine, but estimates of the rate of convergence between the Australian and Southeast Asian plates [Hamilton, 1979], together with the suspected length of continental margin already subducted [Chamalaun et al., 1976; Jacobson et al., 1979] indicates an age of initial collision of about 3 Ma. Although excellent estimates are available for the convergence rate and direction between the Australian and Eurasian plates [Minster and Jordan, 1978; Chase, 1978], the eastern Sunda collision is between the Australian plate and Southeast Asia. The latter is a region of complex, non rigid tectonic behavior [Molnar and Tapponnier, 1975; Tapponnier et al., 1982], and therefore rigid plate assumptions do not apply. The north directed slip vectors for earthquakes north of Bali and Flores, discussed above, are up to 30^{o} off the expected rigid plate orientation for Australia relative to Eurasia. We have estimated the convergence direction on the basis of structural studies using SeaMARC II in the forearc [Breen et al., 1983], and these correspond more closely with the earthquake slip vectors (approximately due N).

Definition of the Flores Thrust Zone

Before discussing the structure in more detail, it is important to define how we are using the terms "deformation front" and "frontal thrust" and to define the term "Flores thrust zone." The deformation front of the accretionary wedge represents the forwardmost deformation (either folds or faults) above a decollement. The frontal thrust is the forwardmost thrust to reach the surface above the decollement. It may or may not coincide with the deformation front because the latter could be defined by folds rather than faults. When viewed in map form, frontal thrusts are laterally changing, overlapping features, and the frontal thrust on one section may be a secondary thrust along strike.

Profile 15 (Figure 4) illustrates these differences. The deformation front (DF) is marked by a buried fold. The frontal thrust (FT) extends to the surface, though its internal structure may

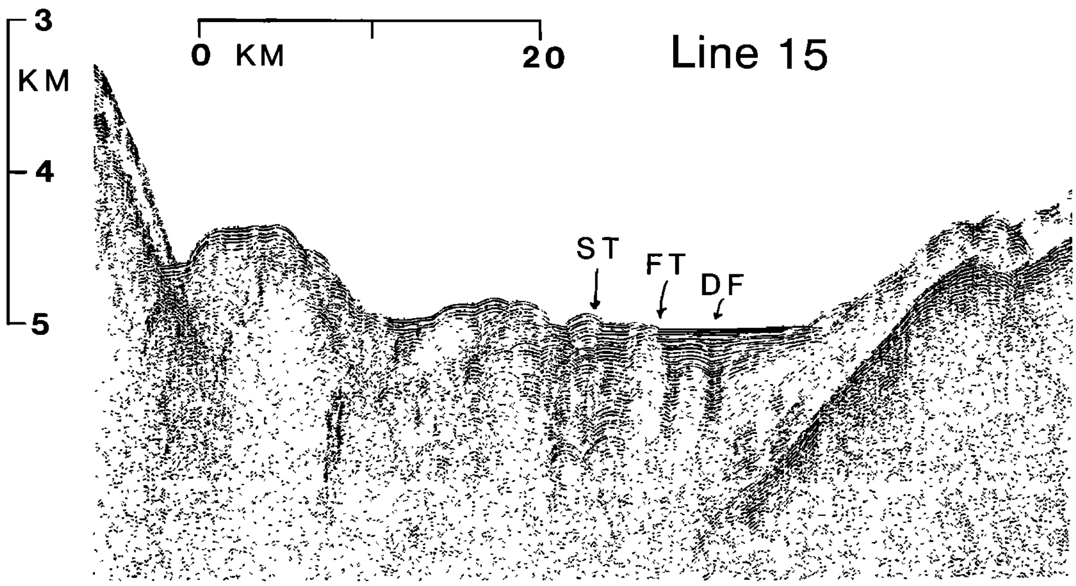

Fig. 4. Seismic profile 15, located on Figure 2. DF, deformation front; FT, frontal thrust; ST, secondary thrust. V.E. 9x. Vertical scale is water depth.

be complicated by sedimentary volcanism (see Figure 2). The secondary thrust (ST) continues eastward to become the frontal thrust.

Silver et al. [1983] used the term "Flores thrust" to map what they felt was the frontal thrust of the zone of back arc thrusting north of Flores Island. That term is not useful on the scale at which we are focusing here, however, because the Flores thrust includes a number of separate thrust segments, which are probably better named independently. Lacking sufficiently high-quality seismic data and any drill information, we have avoided naming specific thrust segments. We suggest that the Flores thrust of Silver et al. [1983] be termed the Flores thrust zone. Standard usage of named thrusts refers to specific fault surfaces, whereas "fault zone" includes more than one related fault as mapped at the surface, with the general expectation that such a zone connects to a surface of slip at depth. The term "accretionary wedge" or "accretionary complex" would be appropriate over some but not all of the thrust zone, and morphologic terms such as "trench" are best avoided when referring to structures such as thrust zones which may produce or be associated with a variety of morphologies.

Field Program and SeaMARC II Explanation

The study was carried out aboard the R/V Kana Keoki of the University of Hawaii in March, 1983. Swath mapping bathymetry and side scan were done with the SeaMARC II, in conjunction with standard underway seismic reflection, gravity, and 3.5-kHz surface bathymetry. Line spacing was approximately 8 km to allow a 2-km overlap between adjacent SeaMARC swaths. Processed, true scale side scan sonographs were formed into a mosaic (Plate 1). We used this mosaic and the seismic reflection profiles to construct a tectonic map of the area, shown in Figure 2. The ship's location was determined primarily by satellite navigation, but minor adjustments in track location were made by aligning reflectors on overlapping SeaMARC swaths.

The SeaMARC II (Sea Mapping and Remote Characterization) submarine mapping device was developed initially by International Submarine Technology, Ltd., but modified extensively by the Hawaii Institute of Geophysics. It is a long-range (10 km swath) side scanning acoustic imaging tool, towed near the surface (100-m depth) at speeds up to 18 km/h, and operates at 12 kHz. It produces a geometrically correct side scan image of the seafloor 10 km wide in water depths of 2 km or greater. Bathymetry is determined by a phase difference technique [Hussong and Fryor, 1983] and is contoured at 100-m intervals.

Acquisition of both side scan images and detailed bathymetry, combined with seismic reflection data, allowed us to map the extent of individual thrusts and folds, to separate these features from mud volcanoes or slumps, to determine cross cutting relationships between faults, and to determine the role of structure in controlling drainage patterns on the seafloor.

Previous studies of subduction zones using other swath-mapping devices, such as Sea Beam [e.g., Aubouin et al., 1982; Bijou-Duval et al., 1982; Le Pichon et al., 1982; Lewis et al., 1984; Moore et al., 1984], a narrow beam bathymetric tool, have proven very successful and have begun to show both the complexity of these zones and the interpretive power of swath mapping techniques in conjunction with seismic reflection data. Other side scan studies of subduction zones have been carried out with the very wide swath (50 km) GLORIA instrument, which has proven to be an excellent reconnaissance tool [Kenyon et al., 1982; Stride et al., 1982]. Interpretations made using GLORIA [Kenyon et al., 1982], however, sometimes conflict with those made using Seabeam [Le Pichon et al., 1982]. The SeaMARC II provides significantly more detail than GLORIA (though in a smaller region) and gives both side scan and bathymetry (100-m contour interval), compared to only bathymetry (but at 10-m interval) for Sea Beam.

Results and Interpretation

The combination of SeaMARC 2 and seismic reflection data allowed us to analyze a number of aspects concerning the early development of submarine thrust belts. What is the nature of the thrust front? Is it smooth, lobate, or offset? Are mud ridges and volcanoes common, dominant, or rare? How does the front propagate? Is thrust propagation related to the megastructure of the regional setting? Can we see cross faults within the accretionary wedge or any relation to faults or irregularities of the arc edifice? Do the observed structures tell us about the direction of convergence or of the principal stresses? We will begin to address these questions by interpretation of the tectonic map and reflection profiles.

Construction of the tectonic map in Figure 2 was based in part on interpretation of reflection profiles to locate the main surface thrust(s) along each profile and other major features, such as the Flores turbidite basin and its margins. We then extended these features laterally using the reflection pattern in the SeaMARC mosaic (Plate 1). We were able to locate the source of the reflection on the side scan image more precisely with respect to the seismic profile by use of combined SeaMARC and 3.5-kHz data and by use of raw side scan. The advantage of plotting 3.5-kHz data and side-scan on the same chart is that reflectors on the side scan can be tied directly to a surface point on the profile. The 3.5-kHz record, in turn, can be tied directly to features on the seismic profile.

Structure and Stratigraphy of the Lower Plate

The lower plate structure and stratigraphy are critial to understanding the development of the thrust belt. The rocks of the lower plate originated in a variety of environments, and facies transitions occur in the region studied here. West of 120° 30′ the Flores basin is bounded by the NE trending slope of the Sunda shelf. East of this longitude the basin is bounded by the Salayar-Bonerate ridge that projects onto South Sulawesi (Figure 1). The western part of the ridge is composed of Neogene volcanic and sedimentary rocks that dip to the west and southwest. The eastern part is a line of coral atolls built on a low submarine ridge which trends to the eastern end of Flores Island [Hamilton, 1979; van Bemmelen, 1949].

The outer slope and trench sediments can be divided into five recognizable seismic stratigraphic units (Figure 3), though not all are present in all sections. The lowest reflector (B), seen on a few sections, is irregular, hummocky, and considered to be acoustic basement. It is seen in lines 8, 14, and 15 but may be present in others. The nature of "basement" may not be the same on lines 8 and 14 because only a part of the stratigraphic sequence overlies basement on line 14, whereas the whole sequence is seen on line 8. Because it occurs just south of several volcanic islands (the Bonerate group) the basement in line 14 (and possibly 15) may be composed of young (Pliocene?) lava flows.

The basal unit 1 overlying basement is highly reflective and variable in thickness. It is defined clearly in lines 8-12, is absent in lines 14-16, and may thicken westward in line 4. Above 1 is a poorly reflective unit 2 that we infer to represent pelagic or hemipelagic deposition. The unit is well developed in lines 8-12. In lines 2-6 the layer is replaced by more prominent reflective units. Above 2 in some but not all sections is a well-layered unit 3 of variable thickness, which we interpret as a turbidite deposit. It is present in profiles 6-12 and absent in lines 14-16. It appears to be present also in line 18. Another pooly bedded, hemipelagic layer (unit 4) generally forms the top of the slope sequence and is present in all profiles. Locally (lines 15-16), it appears to be very thick, but otherwise its thickness is constant at a few hundred meters. Unit 4 is overlain by the trench turbidites (unit 5) which are present in all profiles but vary greatly in thickness and width.

Unit 3 is the most variable of the group and may record changes in local source rocks and tectonics. The unit thins eastward, and it pinches out locally in the Flores basin (profile 9, Figure 3). The easternmost lines (profiles 16 and 18, Figure 3) show a significantly thicker trench fill and unit 3 is either missing or very minor. The major change in the slope stratigraphy occurs just south of the westernmost end of the Salayar-Bonerate ridge (profile 14, Figure 3), which is consistent with the expectation that the basements and source rocks to the east and west of this point are very different.

The outer slope sequence (units 1-4) is cut by a series of faults which show up exceedingly well on the SeaMARC mosaic (Plate 1 and Figure 2). They are prominent because slope gullies terminate sharply along them (Figure 2). They are more prominent in the western lines 1-6 where they trend uniformly northeast and cut units 1-4. Layer 5 is not offset by the faults in the underlying outer slope sequence, implying that the outer slope faults are not active at present.

The faults cutting the lower plate sediments may represent a reactivation of older basement faults because they are parallel to buried basement faults mapped in the Java Sea (E. Scheibner, Tectonic map of the circum-Pacific region, scale 1:10,000,000, southwest quadrant, Am. Assoc. Pet. Geol., 1987). Possibly the collision acted to reactivate the faults north of the Flores thrust zone. The reactivation may have been a bending response to the development of the Flores trough. Usually such faults are parallel or subparallel to the trench axis, but Aubouin et al. [1982] showed in the mid-America trench that trench axis faults tend to form along old lines of crustal weakness. An alternative mechanism might be strike slip faulting related to the collision because the trend of the faults is nearly 30° off the expected direction of convergence. Lacking earthquakes on these faults we cannot resolve the mechanism at present.

Back Arc Accretionary Wedge

The structural geometry of the back arc thrust belt should provide discriminating clues as to whether its origin were related primarily to magmatism or collision. Magmatic forcing should produce fold and thrust packages oriented concentrically away from the intrusive centers; collision effects might show irregularities associated with the margin of the back arc, but overall deformation trends should reflect the collision direction, as measured independently by other techniques.

The average orientation of the deformation front between profiles 2 and 14 (Plate 1) is 100°. That direction is normal to convergence determined by Breen et al., [1983] south of Sumba Island, and it is consistent with slip vectors for back arc thrust earthquakes, discussed earlier. Because we lack detailed knowledge of the magmatic history of Flores, we cannot rule out all possible scenarios for magmatic forcing. However, the consistency between the back arc thrust structures and the expected convergence direction favors the collision hypothesis as the primary driving force for the Flores thrust zone.

A primary characteristic of the deformation front (Plate 1) is its irregular or scalloped appearance. This irregularity may arise from one or more of the following factors. First, as discussed in the previous section, the stratigraphy within the Flores basin changes from east to west along it. These changes can affect the strength of the material entering the deformation front and therefore the maximum width of the thrust sheet (measured normal to the thrust fault) that can be formed [Davis et al., 1983]. Changing stratigraphy may result in changes in the level of the decollement and thus changes in the thickness of sediment accreted to the accretionary wedge. Also, differences in basal friction of the thrusts, derived for example, from changing clay mineralogy or changing fluid pressures, could significantly affect the width of the frontal thrusts [Davis et al., 1983]. Basement irregularities or faulting also may be important in the development of the thrust.

Relatively little attention has been paid to the process by which new thrust sheets are initiated [Boyer and Elliott, 1982; Leith and Alvarez, 1985]. Here we have an example of a new frontal thrust in the process of formation. The frontal thrust in profile 8 appears to be a new feature, located about 5 km north of the main thrust. Seismic profile 8 (Figure 3) shows that part of the Flores turbidite basin has been transformed to the hanging wall behind the new thrust. The new thrust produces a bathymetric ridge several hundred meters high (Figure 3), and layers 1-5 overlie a ridge in the basement (b) on profile 8 (Figure 3), which is not evident in profile 9 (Figure 3).

The coincidence of a basement feature exactly beneath the frontal thrust in profile 8 suggests a mechanical relationship, which could be manifested in one of several ways. For example, the sediments above the ridge may undergo microfracturing due to differential compaction, sufficient to act as a nucleus for the new frontal thrust. Alternatively, the ridge may be caused by an active basement fault, making this thrust not a frontal thrust but part of a foreland basement structure.

Whatever the explanation for the coincidence of the basement ridge and the thrust, it brings up the question of local effects on thrust propagation. A perfectly homogeneous layer of constant thickness would be expected to produce very regular fold/thrust packages, and we have observed this effect with clay deformation experiments. However, inhomogeneities in the sediment layer may act to localize the position of developing thrusts, and this effect may be observed by attempting to deform imperfectly layered clay.

Changing vergence direction can cause structural irregularities in the thrust front. Most of the thrusts verge northward, as indicated by the south side up sense of vertical offset on most faults, but two exceptions are seen on profiles 2 (Figure 5) and 10 (Figure 3). In these lines the frontal fault is very well displayed on the seismic record because it cuts the trench sediment section and the sense of offset is north side up. We interpret these as reverse faults because they dip to the north and the north (hanging) wall has moved up. This interpretation is supported by a processed digital seismic profile taken across the fault very close to the location of profile 2 (line 43, located by Silver et al. [1983]).

Why should these two regions show south verging reverse faults while all others appear to be north verging? Seely [1977] showed that opposite vergence is expected in wedges with very low basal traction, and in these cases, vergence could form either way. Where basal traction is higher, faults tend to verge uniformly toward the trench or foreland. Local variations in fluid pressure or sediment composition could be responsible for these differences in direction of fault dip.

The main thrust ends between profiles 15 (Figure 4) and 16 (Figure 3). Secondary thrusts in line 15 emerge eastward as frontal thrusts in lines 16 and 17. A series of mud diapirs (discussed below) are mapped at the east end of the frontal thrust near lines 14 and 15 (Figure 2), possibly indicating abnormally high fluid pressures associated with fault zone propagation. The abrupt change in width of the accretionary wedge as well as structural style between lines 15 and 16 (Figure 2) must be a function of both eastward decreasing convergence and changing facies within the Flores basin. This conclusion is based on the following reasoning.

A thick layer 5 would be expected to show a wider accretionary zone than a thin layer, if the amount of convergence were constant along the wedge. The observation that the eastern part of the wedge (profiles 16-18; Figure 3) is narrow and layer 5 is thick implies a significantly lower convergence in the eastern part (because incoming thickness [above the decollement] x total convergence = total accretion x % loss of pore fluids). We can rule out the possibility that the decollement is simply very shallow in the eastern part of the thrust zone because line 18 shows a very thick folded section.

The Flores thrust zone dies out to the east at 121°30'E. Despite the increased thickness of turbidites in the Flores basin here, the wedge diminishes dramatically in width to a single fault in line 20. The deformation front is composed of en echelon thrust segments in lines 16-17. We have found no evidence for tear faulting between lines 15 and 16 on the SeaMARC image. The apparent concentration of earthquakes on both the eastern and western (north of Bali) ends of the Flores thrust zone might be explained by stress

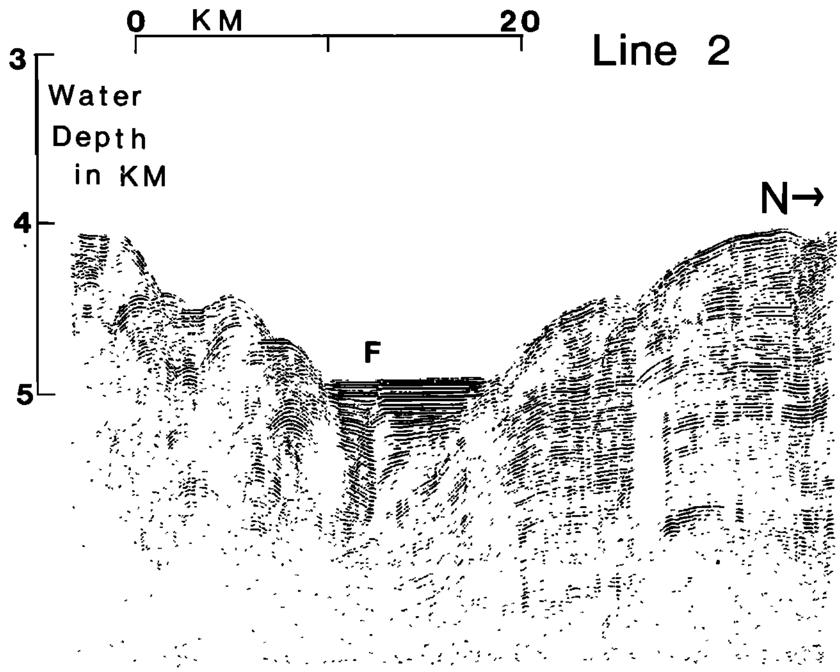

Fig. 5. Seismic profile 2, located on Figure 2. Northward dipping reverse fault located below the letter F. V.E. 9x.

concentrations at the thrust tips. A long-term seismic monitoring study may be needed, however, to document that this pattern is not simply an artifact of the short duration of seismic observation.

Structural trends in the inner (southern) parts of the wedge are not always parallel to those in the frontal (northern) parts. The orientation of the frontal thrust at profile 4 (Figure 2) is WNW, close to the average trend of the wedge as a whole. Structures 20 km south of the frontal thrust, however, trend ENE. The ENE trend can be seen in the region crossed by profiles 1-7, at one location between profiles 13 and 14, and in a prominent ridge outlined by the 4400-m contour between profiles 14 and 16. The younger (northern) faults in nearly all the profiles (3-20) trend WNW and they may indicate the most recent (NE to NNE) sense of local relative motion. It is not clear whether the ENE trends formed early in the development of the thrust belt or were rotated from a WNW trend. Discriminating these alternatives will be difficult for submarine thrust belts.

Mud Diapirs

Abnormally high fluid pressures are indicated by the presence of a number of mud diaprirs (Figure 2). Scattered diapirs occur in all parts of the wedge between lines 1 and 6, adjacent to the arc slope between lines 10 and 11, in the front (north) part of the wedge between lines 14 and 15, and in front of the wedge between lines 18 and 19. The apparent concentration in the eastern part of the wedge may indicate abnormally high fluid pressures associated with lateral propagation of the thrust zone.

A mud diapir approximately 10 km long lies parallel to the easternmost end of the thrust, about 5 km beyond the front (Figure 2). The diapir is crossed in profile 18 (Figure 3), and it disrupts the sediments but does not fold them. The extent of the diapir can be mapped by the SeaMARC mosaic, as a faint but discernable reflector. A frontal diapir is also crossed on profile 19 (located on Figure 2) but it is not continuous with the diapiric ridge crossed by profile 18.

The presence of circular mud volcanoes in the inner part of the wedge (Figure 2) indicates that they have formed in their present setting, rather than at the toe of the wedge. The reasons are first that the diapirs cut basinal sediments which are deposited over the deformed rocks of the wedge (profile 4, Figure 3) and second that wedge material tends to be squeezed during deformation, so mud volcanoes that formed initially at the toe should be elongated parallel to the wedge front as they accrete. This process would make them difficult to distinguish from folds. Thus it is very likely that the number of mud volcanoes interpreted on Figure 2 is a minimum.

The simplest interpretation of the distribution of mud volcanoes is that they form continually within and in front of the accretionary wedge, with a tendency to form more toward the toe than the rear of the wedge. As older ones become deformed by strain within the wedge they become elongate and therefore difficult (for us) to distinguish from nondiapiric folds. Some of the diapirs form initially as diapiric ridges, such as that developed north of the frontal thrust in line 18 (Figures 2 and 3) and the ridges mapped south of Sumba Island [Breen et al., 1983]. In order for the circular shape of the mud volcanoes to be preserved, they must not have undergone significant deformation. Those near the rear of the wedge are expected to show less deformation than those near the toe. As we see no clear concentration of diapirs toward the rear we suspect that their rate of formation is not uniform across the wedge, but rather concentrated more toward the toe.

Mud diapirs reported from the Lesser Antilles accretionary wedge appear to be concentrated in the southern part, where the thickness of trench strata is great [Westbrook and Smith, 1982; Stride et al., 1982]. The diapirs are found both seaward and landward of the frontal thrust, as we find behind Flores. Sedimentary volcanism is well known also on Trinidad [Kugler, 1967] and within the Scotland district of Barbados [Larue and Speed, 1984]. We [Breen et al., 1983] have mapped a wide field of elongate mud diapirs south of the frontal thrust off Sumba island, in the zone of initial collision of the arc with the Australian continent.

Triassic diapiric structures from the central Dolomites of northern Italy [Doglioni, 1984] range in cross-sectional dimension from hundreds to thousands of meters, are internally sheared, and are generally separated from surrounding rocks by faults. Diapiric cored folds [Lebedeva, 1965] on the Kerch peninsula on the northern shore of the Black Sea range in size from hundreds of meters to several kilometers in width, and as much as 23 km in length. Diapiric fields tens of kilometers across in north central Irian Jaya, Indonesia [Williams et al., 1984], make up 30% of the rocks in this mobile belt, and Williams et al. suggested that mud diapirism represents an important mechanism for the formation of melanges in accretionary wedges.

Sedimentary volcansim is very common in the eastern Sunda and Banda forearc, especially in the islands of Timor, Tanimbar, and Kai. Rapidly buried shale sequences, tectonic convergence, and high seismicity may all contribute to the development of the sedimentary volcanism.

Conclusions

Detailed study of a segment of the Flores thrust zone indicates that the most likely mechanism for the development of the thrusting is collision, rather than volcanic forcing of the arc. The orientations of folds and faults in the accretionary wedge are not those of expansion from local point sources in the arc, as would be expected from magmatic intrusions. Structural observations of the accretionary wedge can not rule out continuous longitudinal intrusions along the arc axis, but earlier observations showing cross-arc trends of volcanic vents [Silver et al., 1983] makes this an unlikely possibility.

Irregular growth of the frontal thrust zone can be traced to several factors. One is the local development of a new frontal thrust, the location of which may be facilited by the presence of a buried ridge in the crust that may or may not be related to active basement faulting. The basement ridge could act as a mechanical inhomogeneity to nucleate the new thrust. The second major change occurs at the eastern end of the main thrust, east of which a secondary thrust becomes the frontal thrust. Here the thickness of lower plate sediments increases significantly eastward, whereas the width of the wedge decreases eastward. The decrease in width of the wedge reflects decreased convergence eastward.

Mud diapirs are common throughout the accretionary wedge, but they appear to be especially numerous at the eastern end of the thrust zone. In addition, the two documented thrust earthquake mechanisms by McCaffrey occur close together near the eastern end of the zone. The other region where back arc thrust earthquakes are documented is north of Bali, near the west end of the zone. Forward propagation of the accretionary wedge is aided locally by inhomogeneities on the lower plate, and wedge growth is accompanied locally by mud diapirism. Circular mud volcanoes are also found on all parts of the wedge, indicating in situ growth because circular structures formed within or in front of the wedge would be deformed into parallelism with folds and faults on the wedge. For this reason, we expect that the number of mud volcanoes shown on Plate 1 is a minimum. Because deformation in wedges is expected to decrease toward the rear of the wedge, we would expect greater concentrations of circular mud volcanoes there if they developed uniformly across the wedge. As they are not more concentrated near the rear of the wedge, we infer that their rate of formation is greater near the toe. The most prominent structures on the lower plate are the NE trending faults that cut-off slope drainage systems. The faults are parallel to those mapped farther to the west in the subsurface and may be reactivated. These faults may not be active now because they do not cut the youngest turbidites in the Flores basin. Farther to the east, however, where back arc thrusting has not begun, cross-arc faults are presently active [Silver et al., 1983; van Bemmelen, 1949]. We suggest that in arc-continent collisions, back arc thrusting supercedes cross-arc faulting and reactivation of back arc faults.

Acknowledgments. Supported by National Science Foundation grant OCE82-14725 to E.A.S. We thank J. C. Moore, R. Speed, and P. Vogt for reviews. We are especially grateful to R. Speed for his exceptionally thorough review. J. Widartoyo, J. A. Katili, and H. M. S. Hartono were very helpful in arranging clearances and scientific support in Indonesia. We are grateful to K. Mansfield for the painstaking care required in processing the SeaMARC mosaic, to R. McCaffrey for sending us preprints and unpublished data from earthquake studies in the eastern Sunda arc, and to Captain Hayes and the crew and scientific party of the R/V Kana Keoki for their support.

References

Armstrong, R. L., Magmatism, orogenic timing, and orogenic diachronism in the Cordillera from Mexico to Canada, Nature, 247, 348-351, 1974.

Aubouin, J., J. Stephan, J. Roump, and V. Renard, The Middle America trench as an example of a subduction zone, Tectonophysics, 86, 113-132, 1982.

Barazangi, M., and B. L. Isacks, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America, Geology, 4, 686-692, 1976.

Bijou-Duval, B, P. Le Quellec, A. Mascle, V. Renard, and P. Valery, Multibeam bathymetric survey and high resolution seismic investigations on the Barbados ridge complex (eastern Caribbean): A key to the knowledge and

interpretaion of an accretionary wedge, Tectonophysics, 86, 275-304, 1982.
Boyer, S. E., and Elliott, D., Thrust systems, Am. Assoc. Petr. Geol. Bull., 66, 1196-1230, 1982.
Breen, N. A., E. A. Silver, and D. M. Hussong, SeaMARC 2 study of the transition between subducting continental and oceanic crust, Sunda arc, Indonesia (abstract), Eos, Trans. AGU, 64, 872, 1983.
Burchfiel, B. C., and G. A. Davis, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis, Am. J. Sci., 275A, 363-396, 1975.
Cardwell, R. K., and B. L. Isacks, Geometry of the subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions, J. Geophys. Res., 87, 2825-2838, 1978.
Cardwell, R. K., E. S. Kappel, M. S. Lawrence, and B. L. Isacks, Plate convergence along the Indonesian arc (abstract), Eos, Trans. AGU, 62, 404, 1981.
Chamalaun, F. H., K. Lockwood, and A. White, The Bouguer gravity field of eastern Timor, Tectonophysics, 30, 241-259, 1976.
Chase, C. G., Plate kinematics: the Americas, East Africa, and the rest of the world, Earth Planet. Sci. Lett., 37, 335-368, 1978.
Dalmayrac, B., and P. Molnar, Parallel thrust and normal faulting in Peru and constraints on the state of stress, Earth Planet. Sci. Lett., 55, 473-481, 1981.
Davis, D. M., J. Suppe, and F. A. Dahlen, Mechanics of fold-and-thrust belts and accretionary wedges, J. Geophys. Res., 88, 1153-1172, 1983.
Dewey, J. F., and J. M. Bird, Mountain belts and the new global tectonics, J. Geophys. Res., 75, 2625-2647, 1970.
Doglioni, C., Triassic diapiric structures in the central Dolomites (northern Italy); Eclogae Geol. Helv., 77, 261-285, 1984.
Elliott, D., The motion of thrust sheets, J. Geophys. Res., 81, 949-963, 1976.
Hamilton, W., Tectonics of the Indonesian region, U.S. Geol. Surv. Prof. Pap., 1078, 345 pp., 1979.
Hubbert, M. K. and W. W. Rubey, Role of fluid pressure in mechanics of overthrust faulting, 1, Mechanics of fluid-filled porous solids and its application to overthrust faulting, Geol. Soc. Am. Bull., 70, 115-166, 1959.
Hussong, D. M., and P. Fryor, Back-arc seamounts and the SeaMARC II seafloor mapping system, Eos, Trans. AGU, 64, 627-632, 1983.
Jacobson, R. S., G. G. Shor, Jr., R. M. Kieckhefer, and G. M. Purdy, Seismic refraction and reflection studies in the Timor-Aru trough system and Australian continental shelf, Mem. Am. Assoc. Pet. Geol., 29, 209-222, 1979.
Jordan, T. E., B. L. Isacks, R. W. Allmendinger, J. A. Brewer, V. A. Ramos, and C. J. Ando, Andean tectonics related to geometry of subducted Nazca plate, Geol. Soc. Am. Bull., 94, 341-361, 1983.
Kenyon, N. H., R. H. Belderson, and A. H. Stride, Detailed tectonic trends on the central part of the Hellenic outer ridge and in the Hellenic trench system, Trench-Forearc Geology, edited by J. K. Leggett, Geol. Soc. Spec. Publ., 10, 335-343, 1982.
Kugler, H. G., Sedimentary volcanism, Am. Assoc. Pet. Geol. Bull., 51, 55-64, 1967.
Larson, R. L., and W. C. Pitman III, The bedrock map of the world, scale 1:23,230,300, W.H. Freeman, New York, 1985.
Larue, D. K., and R. C. Speed, Structure of the accretionary complex of Barbados, II: Bissex Hill, Geol. Soc. Am. Bull., 95, 1360-1372, 1984.
Lebedeva, N. B., Certain problems relating to the mechanism of formation of the clay diapirs in the Kerch-Taman region, Folded Deformations in the Earth's Crust, Their Types and Origin, edited by V. V. Belousov and A.A. Sorskii, Israel Program for Scientific Translations, Jerusalem, 1965.
Leith, W., and W. Alvarez, Structure of the Vakhsh fold-and-thrust belt, Tadjik SSR: Geologic mapping on a Landsat image base, Geol. Soc. Am. Bull., 96, 875-885, 1985.
Le Pichon, X., N. Lyberis, J. Angelier, and V. Renard, Strain distribution over the east Mediterranean ridge: A synthesis incorporating new sea-beam data, Tectonophysics, 86, 243-274, 1982.
Lewis, S. D., J. W. Ladd, T. R. Bruns, D. E. Hayes, and R. von Huene, Growth patterns of submarine canyons and slope basins, eastern Aleutian trench, Alaska (abstract), Eos, Trans. AGU, 65, 1104, 1984.
McCaffrey, R., and J. Nabelek, The geometry of back arc thrusting along the eastern Sunda arc, Indonesia: Constraints from earthquake and gravity data, J. Geophys. Res., 89, 6171-6179, 1984.
McCaffrey, R., P. Molnar, S. W. Roecker, and Y. S. Joyodiwiryo, Microearthquake seismicity and fault plane solutions related to arc-continent collision in the eastern Sunda arc, Indonesia, J. Geophys. Res., 90, 4511-4528, 1985.
Minster, J. B. and T. H. Jordan, Present-day plate motions, J. Geophys. Res., 83, 5331-5354, 1978.
Molnar, P., and T. Atwater, Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere, Earth Planet. Sci. Lett., 41, 330-340, 1978.
Molnar, P., and P. Tapponnier, Cenozoic tectonics of Asia: effects of a continental collision, Science, 189, 419-426, 1975.
Moore, G. F., T. H. Shipley, and P. F. Lonsdale, Recent sediment offscraping at the toe of the middle America trench off Guatemala, Eos Trans. AGU, 65, 1088, 1984.
Price, R. A., and E. W. Mountjoy, Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca rivers-a progrss report, Structure of the Southern Canadian Cordillera, edited by J. O. Wheeler, Spec. Pap. Geol. Assoc. Can., 6, 7-25, 1970.
Seely, D. R., The significance of landward vergence and oblique structural trends on trench inner slopes, Island Arcs, Deep Sea Trenches, and Back-Arc Basins, Maurice Ewing Ser., vol. 1, edited by M. Talwani and W. C. Pitman III, pp. 187-198, AGU, Washington, D. C., 1977.
Silver, E. A., D. Reed, R. McCaffrey, and Y. Joyodiwiryo, Back arc thrusting in the eastern Sunda arc, Indonesia: A consequence of arc-continent collision, J. Geophys. Res., 88, 7429-7448, 1983.

Silver, E. A., J. B. Gill, D. Schwartz, H. Prasetyo, and R. A. Duncan, Evidence for a submerged and displaced continental borderland, North Banda Sea, Indonesia, Geology, 13, 687-691, 1985.

Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newhall, and J. H. Latter, Volcanoes of the World, 232 pp., Hutchinson Ross, Stroudsburg, Penn., 1981.

Stride, A. H., R. H. Belderson, and N. H. Kenyon, Structural grain, mud volcanoes and other features on the Barbados ridge complex revealed by Gloria long range side-scan sonar, Mar. Geol., 49, 187-196, 1982.

Tapponnier, P., G. Peltzer, A. Y. Le Dain, R. Armijo, and P. Cobbold, Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine, Geology, 10, 611-616, 1982.

van Bemmelen, R. W., The Geology of Indonesia, vol. 1A, 732 pp., Government Printing Office, The Hague, 1949.

Westbrook, G. K., and M. J. Smith, Long decollements and mud volcanoes: Evidence from the Barbados ridge complex for the role of high pore-fluid pressure in the development of an accretionary complex, Geology, 11, 279-283, 1982.

Williams, P. R., C. J. Pigram, and D. B. Dow, Melange production and the importance of shale diapirism in accretionary terrains, Nature, 309, 145-146, 1984.

N. A. Breen, H. Prasetyo, and E. A. Silver, Earth Sciences and Institute of Marine Sciences, University of California, Santa Cruz, CA 95064.

D. M. Hussong, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, HI 96822.

(Received October 1, 1984;
revised September 23, 1985;
accepted September 23, 1985.)

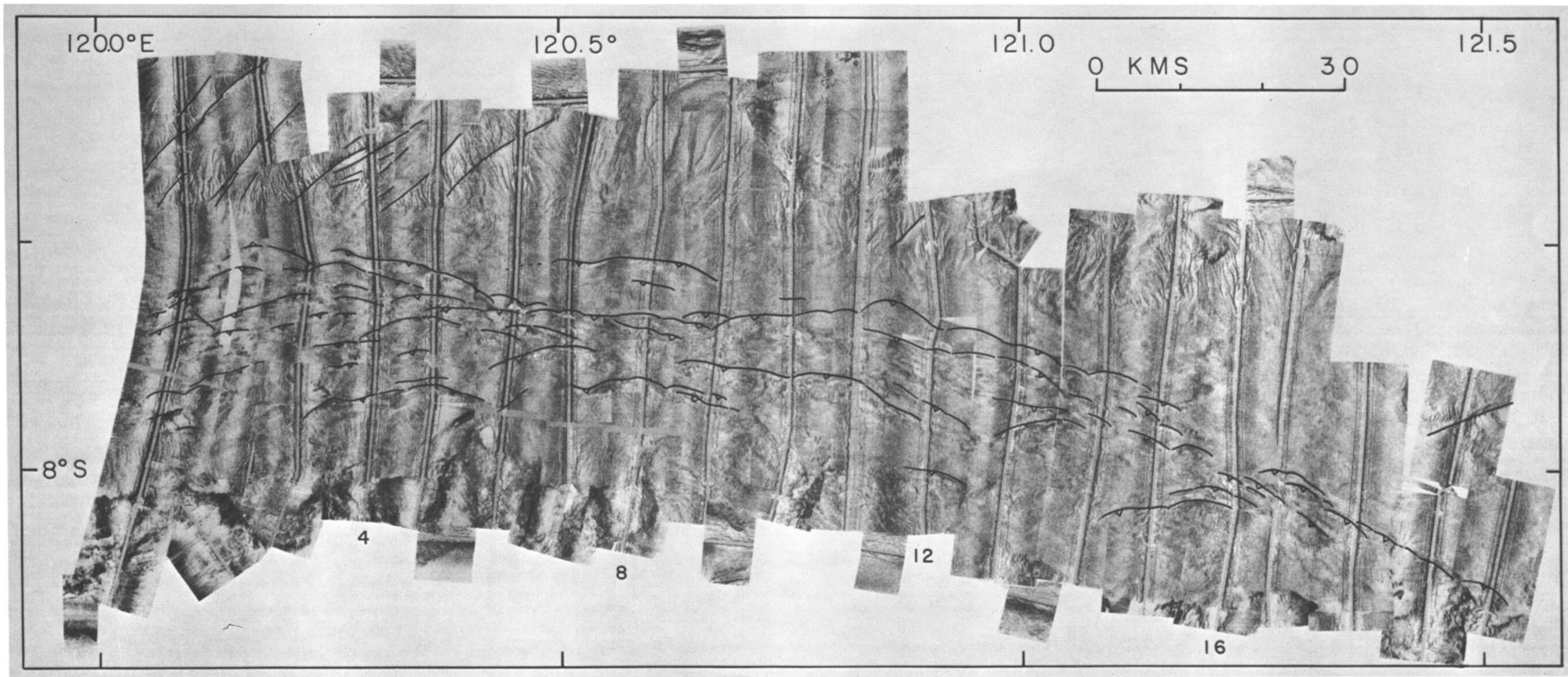

Plate 1. SeaMARC II side scan mosaic. Every fourth track line is labeled. Compare with Figure 2. Faults are located on the mosaic. Triangles on upper plates of thrust faults.