JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. B9, PAGES 7429-7448, SEPTEMBER 10, 1983

BACK ARC THRUSTING IN THE EASTERN SUNDA ARC, INDONESIA: A CONSEQUENCE OF ARC-CONTINENT COLLISION

Eli A. Silver, Donald Reed[1], and Robert McCaffrey[2]

Earth Sciences Board and Center for Coastal Marine Studies, University of California
Santa Cruz, California 95064

Yoko Joyodiwiryo

Geological Research and Development Center, Jalan Diponegoro 57, Bandung, Indonesia

Abstract. The structure of the eastern Sunda back arc region is dominated by two large north directed thrusts, the Wetar and Flores thrusts, and one or more minor thrusts, which may represent early stages of subduction polarity reversal of the arc. The relationships between thrusting and magmatic activity, surface slopes, cross-arc faulting, uplift, forearc structure, and collision by the Australian continental margin provide constraints on the likely driving mechanisms of thrust formation. Driving mechanisms are considered in two broad categories. One set of possible mechanisms originates within the upper plate and includes gravity sliding, gravity spreading, and magmatic intrusion. The other set focuses on stress propagation between the upper and lower plates, and for this arc system the major mechanism is that of continental collision. While no one mechanism explains the range of observations we see in the back arc region, all of these aspects play some role in the development of the thrusts. We can eliminate upper plate mechanisms as primary driving forces because slope effects are similar in areas of both thrusting and nonthrusting. In addition, the Wetar thrust shows a negative relation between thrusting and volcanism, and side-looking airborn radar images show no evidence of postvolcanic rifting that could accompany intrusion without volcanism. Collision between the arc and the Australian continent provides the clearest driving mechanism, but it does not explain the discontinuous nature or the particular location of the thrusts. We suggest a sequence that appears to account for the data and to provide insight into the controversies often associated with other such thrust belts. Thrusting was initiated in those areas where the crust of the forearc region was thick, a factor that facilitated stress propagation across the arc, and where the crust of the back arc was thin, which facilitated back arc thrusting. Thrusting concentrated at the base of the slope where the slope stress is maximum. The early thrusting may have been helped also by thermal weakening of the crust due to volcanism. As convergence proceeded, volcanism waned then ceased in the eastern part of the arc. The crust then strengthened, and thrusting required higher stress to maintain and propagate. This later stage should show higher seismic energy release, which appears to be the case for the Wetar thrust region. Displacement on the Flores thrust appears to be matched by deflection of the volcanic arc. We have estimated shortening in the back arc from interpretation of reflection profiles, and for the Flores thrust the value of approximately 30 km is consistent with that estimated for deflection of the arc. Compressional deformation continues west of the collision zone, across the Bali Basin and into Java. It is reported in NE Sumatra as well. This deformation involves much less convergence than the eastern Sunda thrusts, and it may be related to magmatic processes, to subduction of oceanic plateaus, such as the Roo Rise, or, in the case of the Bali Basin, to efficient lateral propagation of the Flores thrust.

Introduction

This paper presents the results of a geophysical study of the eastern Sunda back arc region, in which we have mapped the extent and character of deformation in the back arc, and presents our preliminary interpretations on the initiation and development of back arc thrusting in an arc-continent collision zone.

Back arc thrusting has been reported in a number of island and continental arc settings. It is found on the Caribbean side of the Central America arc behind Panama and SE Costa Rica [Edgar et al., 1971; Case and Holcomb, 1980], and there are indications that it occurs at present behind NW Japan [Yoshii, 1979; R. von Huene, oral communication, 1982]. Thrusting behind continental arcs is well documented behind the Andes of Peru and Chile [Coney, 1970; Barazangi and Isacks, 1976; Dalmayrac and Molnar, 1981; Megard and Philip, 1976; Jordan et al., 1981] and in the Canadian Rocky Mountains [Bally et al., 1966; Price, 1981].

Thrusting was first reported in the eastern Sunda back arc region (Figure 1) by Hamilton [1977, 1979] based on several reconnaissance Lamont-Doherty seismic reflection profiles and undisclosed other data. He recognized thrusting to be behind Alor and Pantar islands in the east and from central Flores to central Sumbawa in the west (Figure 2). Extension of the eastern zone to Wetar island was made by Usna et al. [1979], based on a Woods Hole seismic profile. We show here that the western zone extends into the Bali Basin.

[1]Now at Scripps Institution of Oceanography, La Jolla, California 92093.
[2]Now at Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

Paper number 3B0752.
0148-0227/83/003B-0752$05.00

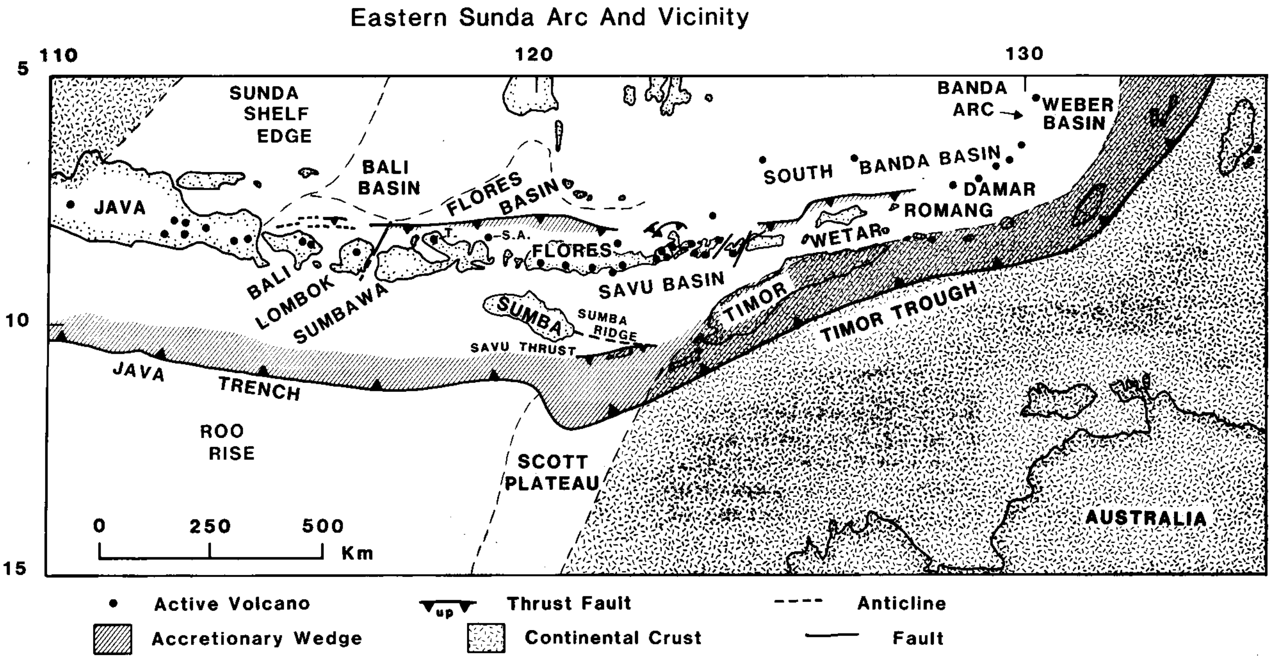

Fig. 1. Major tectonic features in the eastern Sunda arc. Locations of active volcanoes (from Simkin et al., 1981), major thrusts, accretionary wedges, and extent of continental crust. Forearc basin lies between the arc and the accretionary wedge. Modified from Hamilton [1979].

Hamilton interpreted these thrusts to represent an early stage of polarity reversal of the Sunda arc. Bowin et al. [1980], on the other hand, considered such thrusting to be part of a wide zone of distributed deformation across the Sunda arc, not necessarily indicating arc reversal. Van Bemmelen [1949] showed a schematic section across eastern Flores which could be construed as indicating thrusting on the north side of the arc. From his text it is clear, however, that if such was van Bemmelen's intention, it was meant to indicate gravity sliding within the upper crust, not deep-seated thrusting. Van Bemmelen rejected Brouwer's [in van Bemmelen, 1949] concept that the regional tectonics indicated convergence between Australia and the eastern Sunda arc. Compressional deformation is shown in Java [Hamilton, 1977] and reported for Sumatra [H. Wories, oral communication, 1982] north of the volcanic arc.

No general agreement exists as to the cause of back arc thrusting. Causes tend to be grouped into two main categories, those due to tectonic forces

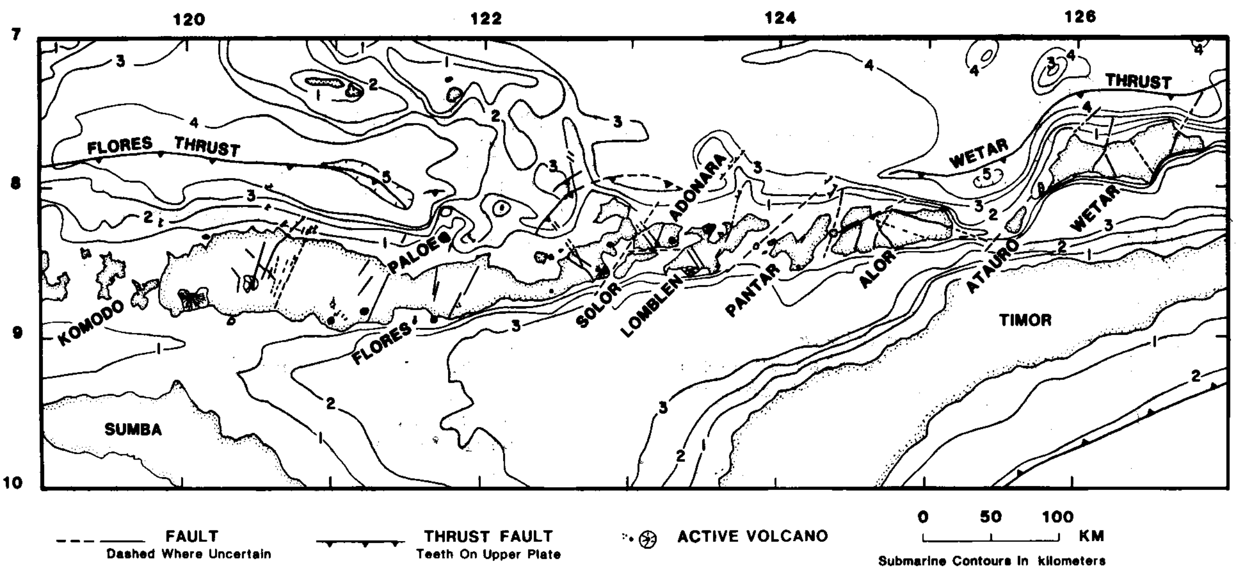

Fig. 2. Tectonic and bathymetric map of the eastern Sunda arc, from Komodo to Wetar. Faults on the islands were mapped from SLAR images of the volcanic arc. Offshore faults were mapped from Rama 12 seismic data, and bathymetry was largely from Rama 12, supplemented by the map of Mammerickx et al. [1976].

and those due to gravity gliding or spreading. Molnar and Atwater [1978] proposed that age of the subducting lithosphere provided a discriminator for distinguishing back arc thrusting (young lithosphere) from back arc spreading (old lithosphere). This idea appears satisfactory for thrusting in Central America and the Andes but not for the Sunda arc, where old lithosphere is being subducted. A number of workers have proposed that thrusting behind the arc occurs where the dip of the subducting lithosphere is shallow, in accord with the demonstration by Barazangi and Isacks [1976, 1979] of gently dipping subduction beneath several segments of the Andes. This idea works well for the Andes and Japan and may work for Central America (where the Benioff Zone is not, however, sufficiently well defined to test the idea), but it can not apply to the eastern Sunda arc, where the Benioff zone is well defined and very steep [Cardwell and Isacks, 1978]. We will argue that gravity sliding is not a primary factor in the development of these thrusts, but slope-generated stresses may play a role in localizing the thrusts. Magmatic intrusions may be important in thrust formation west of the collision zone, though our data are not sufficient to evaluate this idea effectively. Magmatic activity is probably important in weakening the crust, however, and in this way aiding thrust development in the collision region.

Regional Tectonic Setting

The tectonics of this region are dominated by the collision between Australia and the eastern Sunda arc. The western edge of the collision zone is just south of Sumba, where the Scott plateau is in thrust contact with the forearc accretionary wedge (Figure 1). Continental crust probably underlies Timor, based on interpretation of gravity data [Chamalaun et al., 1976]. The positive buoyancy of continental crust beneath the accretionary wedge could explain the uplift of Timor and the other outer islands to the east. Based on reconstructions by Hamilton [1979] and Bowin et al. [1980], collision should have begun in this region about 3 m.y. ago. These interpretations are based on backing off the estimated amount of continental subduction under Timor, using standard estimates of Australia-Eurasia motion [Minster and Jordan, 1978; Chase, 1978].

The back arc region is complex in eastern Indonesia. In the west the Bali Basin (Figure 1) is both narrow and shallow. From central Sumbawa to central Flores the Flores basin is deep, narrow, and underlain by oceanic crust [Raitt, 1967; Hayes et al., 1978]. The deepest part of the basin is along the south margin, and although it is filled with sediments, it has a trench like appearance in profile. This morphology is the result of thrusting behind Flores and Sumbawa. Separating the Flores and South Banda basins is a series of shallow ridges, localized north of eastern Flores. The South Banda Basin is of unknown age. From its depth and heat flow Hamilton [1979] feels it is of early to mid-Tertiary age, although Bowin et al., [1980] infer a Mesozoic age. Whether it is of back arc spreading origin [Hamilton, 1979] or has been trapped by the Sunda arc [Bowin et al., 1980] is not resolved.

The Volcanic Arc

The eastern Sunda arc was defined by van Bemmelen [1949] as that part of the Sunda arc system from Bali on the west to Romang on the east (Figure 1). It forms a position intermediate between the relatively wide islands of Sumatra and Java on the west, believed to be underlain by continental crust [Hamilton, 1979], and the Banda arc to the east, composed of small, active volcanoes rising above oceanic basement [Jacobson et al., 1979]. In addition to its intermediate morphologic position in the arc system, the eastern Sunda arc shows gradations in chemistry and structure as well, some of which may be tied closely to the effects of collision. The volcanic arc is inactive behind eastern Timor, on the islands of Romang, Wetar, Atauro, and Alor (see Figures 1 and 2). Cordierite-bearing granites on Wetar [van Bemmelen, 1949] may indicate melting of continental crust or continentally derived sediments. Relatively high $^{87}Sr/^{86}Sr$ ratios are reported widely from late Cenozoic volcanics in the eastern Sunda arc [Whitford et al., 1977]. The islands show high uplifted terraces (500 to 600 m), and Chappell and Veeh [1978] have determined uplift rates of about 0.5 mm/yr for parts of Atauro and northern Timor islands. Behind the volcanically inactive islands is a long back arc thrust, the Wetar thrust (Figure 2), which we describe below.

West of Alor, from the island of Pantar to eastern Flores (Figure 2), volcanic activity is high, back arc deformation is limited and developed only locally, and, as discussed below, cross-arc faulting seems to be well developed. In addition, terraces do not appear to reach the high elevations found to the east [van Bemmelen, 1949]. From central Flores to eastern Sumbawa, historical volcanism has occurred, and behind the arc is another long thrust, the Flores thrust. Terraces are high on the north coast and low or absent on the south, an observation that led van Bemmelen to infer N-S tilting of Flores island.

The volcanic line is continuous from Java to eastern Sumbawa, then appears to be offset southward to a line along southern Flores. Audley-Charles [1975] used this and other observations to suggest a 'Sumba Fracture Zone' crossing the arc between Flores and Sumbawa, but Cardwell and Isacks [1978] find no indication of a break in the seismic zone across this offset and available seismic reflection profiles have not documented its existence in the upper plate. Hamilton [1979] has explained the pattern as due to the modern volcanic axis trending obliquely across the Miocene axis rather than a discontinuous jump in the line of volcanoes.

The eastern Sunda arc may be cut by cross faults oblique to the trend of the arc. The north coast of Wetar is set off to the north of that of Alor, and the west coasts of Wetar and Atauro align in a NE trending lineament. Whether this morphologic offset implies a physical movement between the islands is unknown, though we see local faults in appropriate places on our reflection profiles. The straits between the islands of Alor, Pantar, Lomblen, and Adonara are aligned also in a NE trend, and that separating Adonara and Solor is E-W.

We have examined side-looking airborn radar

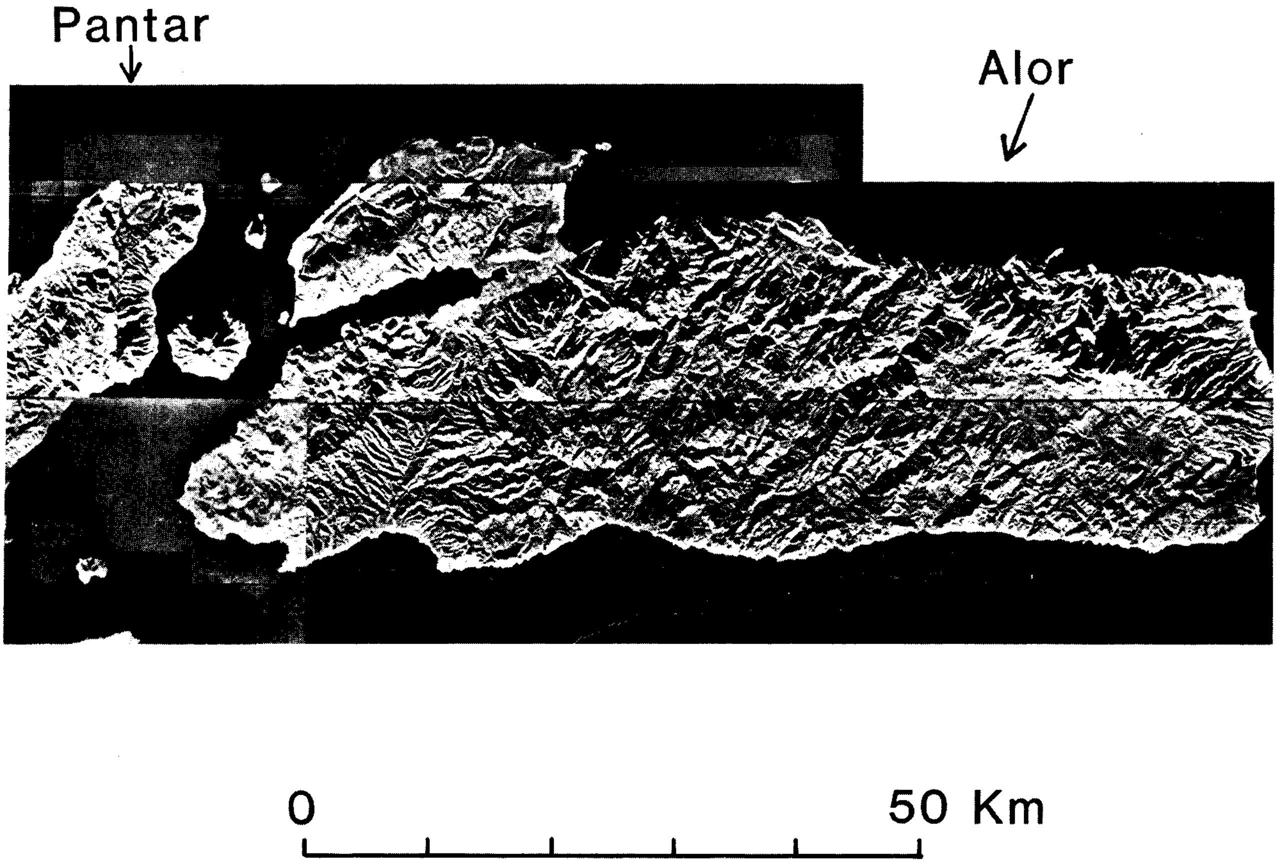

Fig. 3. SLAR image of the islands of Alor and eastern Pantar, showing topographic discontinuities. Interpretation of the faults are shown on Figure 2. Location on Figure 6.

(SLAR) images of the islands of Wetar westward to easternmost Sumbawa (obtained through the Geological Research and Development Center, Bandung) and have inferred a number of fault zones (Figure 2). These features separate distinctly different morphologic regions within the islands. Wetar displays a pronounced NE trending escarpment that is parallel to its west coast alignment, discussed above.

A number of faults cut the island of Alor (Figures 2 and 3). The most pronounced is an ENE trending feature that separates the northwestern peninsula of Alor from the main body of the island. Noteworthy is the fact that a large volcano lies in the intersection of this feature and the more northerly trending strait between the island and Pantar. Within this strait, four volcanoes lie along a straight line. A very pronounced fault trends NE, parallel to the Alor Strait, in the western part of the island. A pair of parallel faults trend WNW in the eastern part of the island, and the northern fault is marked by a major topographic escarpment.

Several NNE trending faults cross Flores island and, in the western part, appear to continue offshore to the north (Figure 2). NW trending faults cut eastern Flores and project into a zone of active volcanoes on the SE end. As a rule, cross-arc faults often are associated with volcanic centers. In west-central Flores we have located a field of about 18 small volcanic vents (Figure 4). Each is roughly 200 m across, and they appear as small cones on the SLAR images. The field has a N to NW trend and it is located on a broad plateau surface. The orientations of these vents may tell us something about the local stress gradients [Nakamura and Uyeda, 1980].

Seismicity

The eastern Sunda arc displays striking variations in the intensity of earthquake activity at shallow depth. Deep activity is continuous from western Java to the eastern Banda Sea and is parallel to the trench. Intermediate depth earthquakes are scarce in the region of the eastern Sunda arc [Cardwell and Isacks, 1978; Fitch, 1970; Hamilton, 1974].

Beneath Java and the eastern Sunda arc islands of Bali to Flores, earthquakes form a north dipping zone beginning at the Java trench. These earthquakes suggest that the Indian Ocean lithosphere subducts beneath the Indonesian Islands at the Java trench [Cardwell and Isacks, 1978]. In the vicinity of western Timor and to the east, however, there have been very few shallow earthquakes in the same time period (Figure 5). The increase in activity in the northeast corner of Figure 5 is concentrated mainly at intermediate depths and is due largely to a change in the stress orientation in the slab as it bends around to the north [Cardwell and Isacks, 1978].

Focal plane solutions for shallow earthquakes near the volcanic chain suggest that the arc may

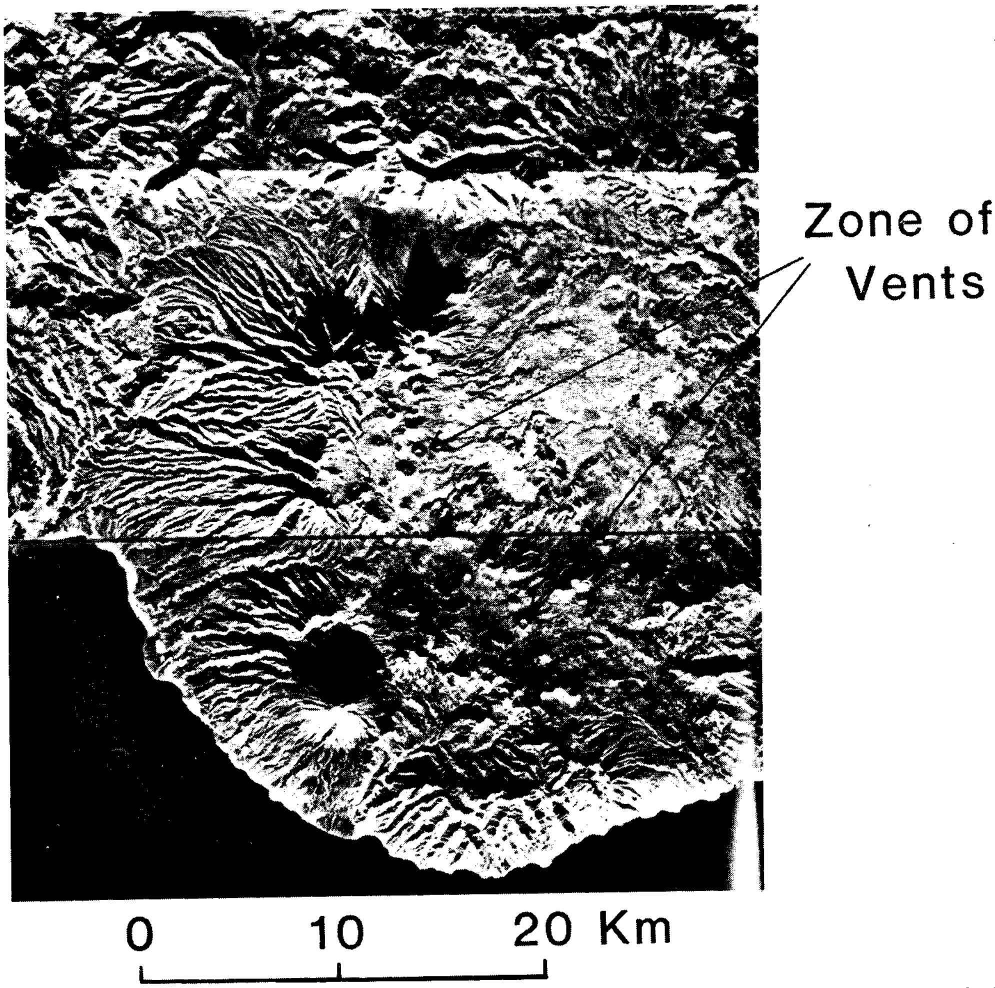

Fig. 4. Detail of SLAR image of part of the south coastal region of Flores island, showing a line or zone of small volcanic vents. Location on Figure 6. (Topographic features often appear clearer when photo is inverted.)

be under compression at the present time. Fitch [1970] determined a mechanism for an earthquake beneath the northeast coast of Bali which shows N-S compression but the focal planes are poorly constrained. Three other preliminary shallow focal plane solutions [R. McCaffrey, unpublished data, 1983] show N-S compression. Two of these mechanisms are from earthquakes north of central Flores, and one is between Wetar and Alor. All four earthquakes occurred where thrusting has been mapped by reflection profiling.

A conspicuous break in the pattern of shallow earthquake activity occurs near westernmost Timor (Figure 5). A small area of higher than normal levels of activity coincides with the break and may represent a tear in the subducted plate based on relocations of earthquakes and fault plane solutions [McCaffrey, 1981]. Also noticable at this longitude (~124° E)is a break in the line of active volcanoes and a change in the distribution of large ($M \geq 7.0$) shallow earthquakes. West of western Timor, only one large event has occurred in the past 80 years and that was the great normal faulting trench earthquake of 1977 [Stewart, 1978]. East of 124° E all large earthquakes occurred beneath or behind the volcanic arc. One of these (between Alor and Wetar) was very shallow (~10 km) and had a steep thrust mechanism [R. McCaffrey, unpublished data, 1983].

Field Program and Data Presentation

We examined the structure of the eastern Sunda back arc and forearc regions during April 1981, on the R/V Thomas Washington, Rama 12 expedition of Scripps Institution of Oceanography (Figure 6). The work involved largely marine geophysical investigations including seismic reflection and refraction, gravity, magnetics, and bathymetry. The seismic reflection study utilized a 550 cubic inch air gun, and the data were recorded digitally for later processing. Many of the seismic profiles were processed digitally by filtering and deconvolution and were plotted with automatic gain control (AGC) and variable area display. Additional data used were from Mara 9 expedition and published data from Woods Hole and Lamont-Doherty. Gravity and magnetics were recorded continuously during the cruise. Base ties for gravity were made at either end of the cruise, and total drift was negligible. Seven unreversed sonobuoy refraction profiles were run along the

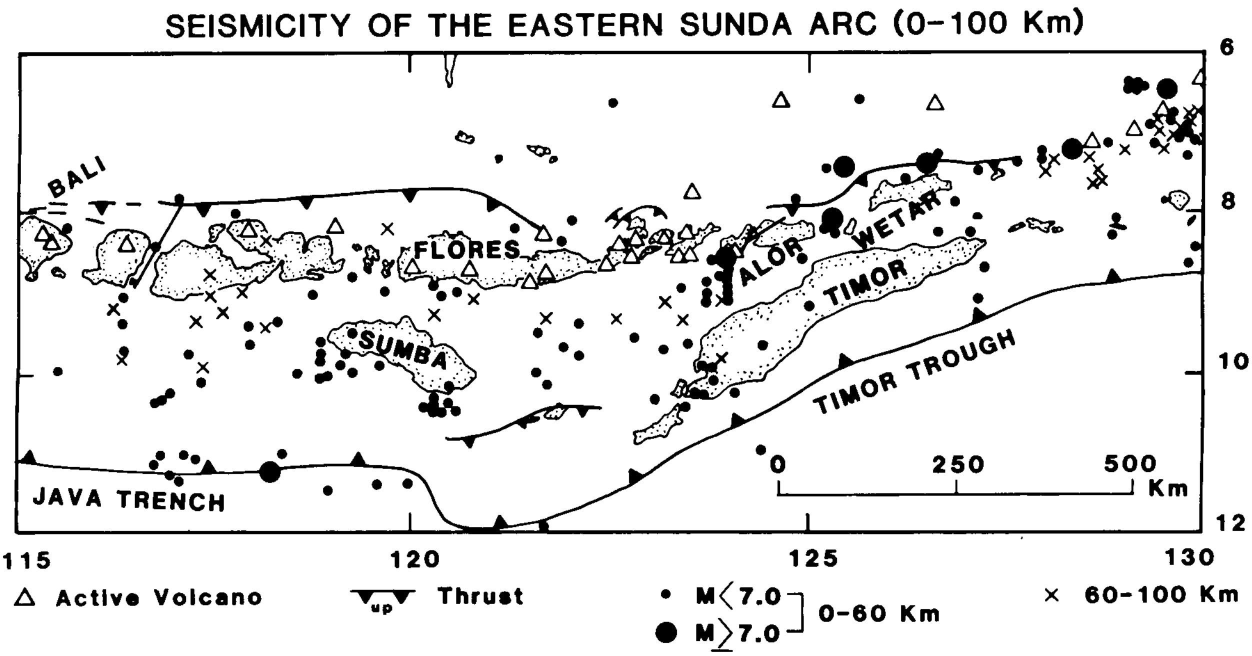

Fig. 5. Map of earthquake epicenters for shallow (h ≤ 100 km) events taken from ISC bulletins for the years 1964-1975. Events reported by 30 or more stations are shown. Large solid dots represent shallow events of M ≥ 7.0 which occurred between 1897 and 1977. Open triangles represent active volcanoes.

lines using the air gun source in both back arc and forearc regions.

Results of the Marine Program

We have studied the forearc and back arc regions of the eastern Sunda arc, though we focus largely on the back arc region in this paper. We rely most heavily on interpretation of digital seismic reflection profiles, but supplemental data are provided by gravity and magnetic anomalies, plus geological and seismological control discussed above.

Back Arc Region

We have mapped two major thrusts and several minor ones behind the eastern Sunda arc (Figures 1

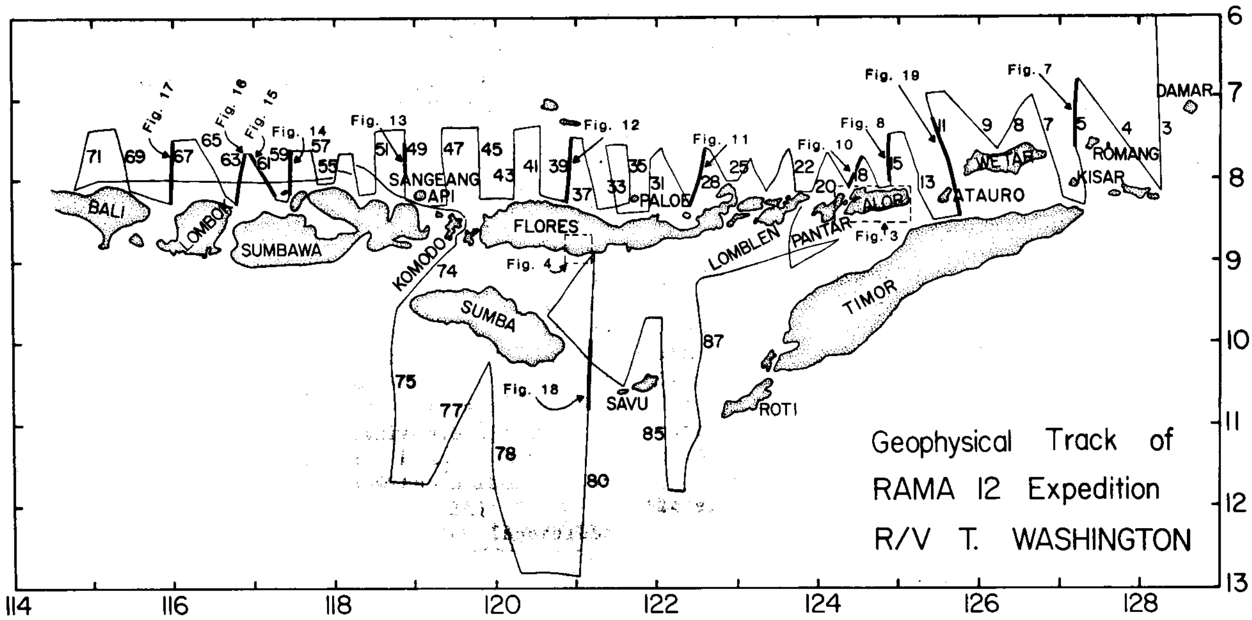

Fig. 6. Track of the R/V Thomas Washington during RAMA 12 expedition in the eastern Sunda arc, showing location of seismic profiles and control on gravity, bathymetry and magnetics. Map also indicates locations of Figures 3, 4, 7, 8 and 10-19. Navigation was by satellite, doppler sonar, and radar ranges and bearings near islands.

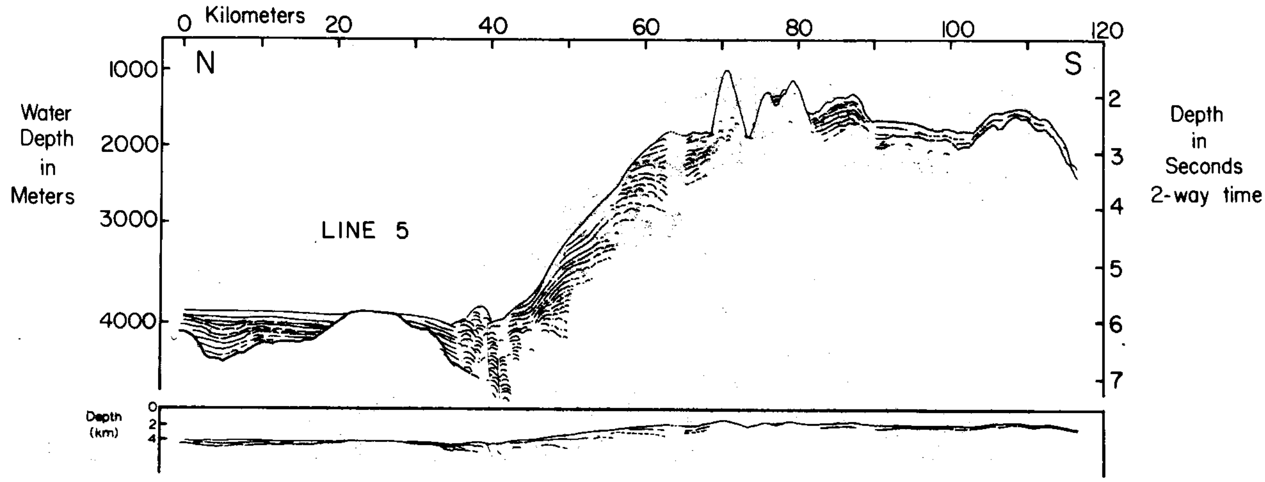

Fig. 7. Line drawing interpretation of seismic profile 5 crossing the eastern part of the Wetar thrust. Lower profile is plotted to true scale. Vertical exaggeration (V.E.) = 9.3x. See Figure 6 for location.

and 2). The eastern major thrust is named the Wetar thrust and is continuous (i.e., seen in each adjacent profile) from central Alor to NE of Romang (124° 40′E to 127° 40′E). The trace of the fault closely follows the bathymetric contours of the island ridges. The thrust does not continue behind Damar island, the first active volcano of the Banda arc.

The western thrust is named the Flores thrust, and it is continuous from central Flores to eastern Lombok, though its structure varies considerably along its length. From central Flores to central Alor we find local, discontinuous folds and faults and one minor thrust that curves around the east peninsula of Flores. West of eastern Lombok lies a complex series of folds which may project into the east Java fold belt.

The Wetar and Flores thrusts are roughly similar in length (300 and 400 km, respectively) but show differences in structural geometry due in part to the greater sediment thickness in the west. Additional differences may result from the fact that the volcanic arc in front of the Wetar thrust is inactive, whereas volcanism is still occurring on Flores, Sumbawa, and Lombok. The structure of these faults illustrates thrust development in an early stage.

<u>The Wetar Thrust</u>. The narrow accretionary wedge above the Wetar thrust (Figure 7) reflects both a small amount of total slip and a relatively thin sediment pile on the lower plate. The easternmost profile showing the fault is line 4, which has a structure similar to line 5 (Figure 7) but a narrower fault zone, only 1 or 2 km wide. In line 5 the thrust bounds a narrow (5 km) accretionary zone and the frontal thrust dips south at a low angle. The zone of accretion is bounded on the south side by a south dipping fault (Figure 7, 40 km). The width of the accretionary prism increases slowly westward to a maximum (18 km) in line 15 (Figure 8). This increase seems closely related to the thickness of sediment available for accretion on the Banda Sea basin to the north of the thrust.

In most profiles a basement high occurs just north of the frontal thrust. It isn't clear whether the high represents seamounts or a continuous feature, perhaps related to the development of the thrust. In line 15 (Figure 8) we see arching of the lower plate north of the

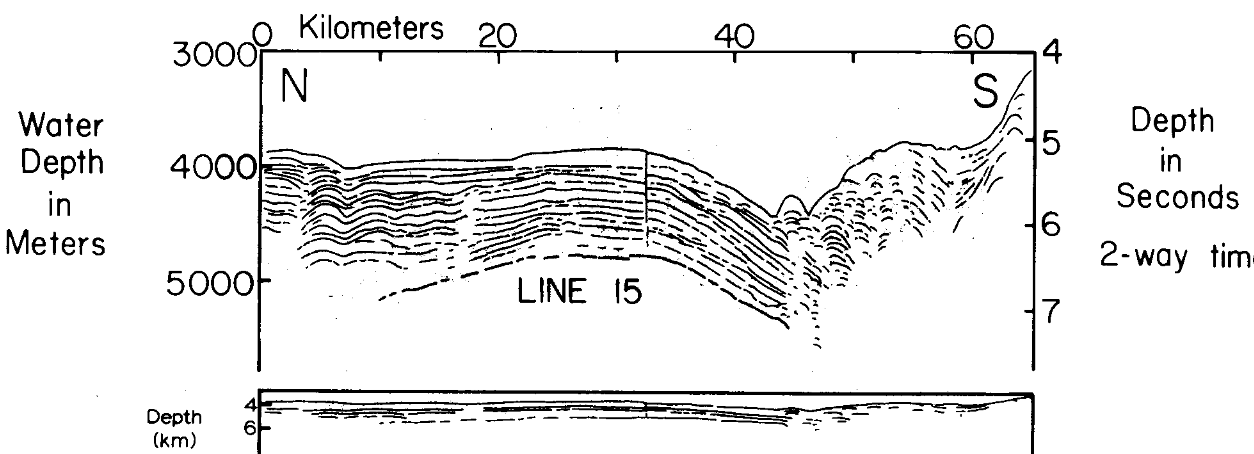

Fig. 8. Line drawing interpretation of seismic profile 15 crossing the western part of the Wetar thrust. Lower profile is plotted to true scale. V.E. = 9.3x.

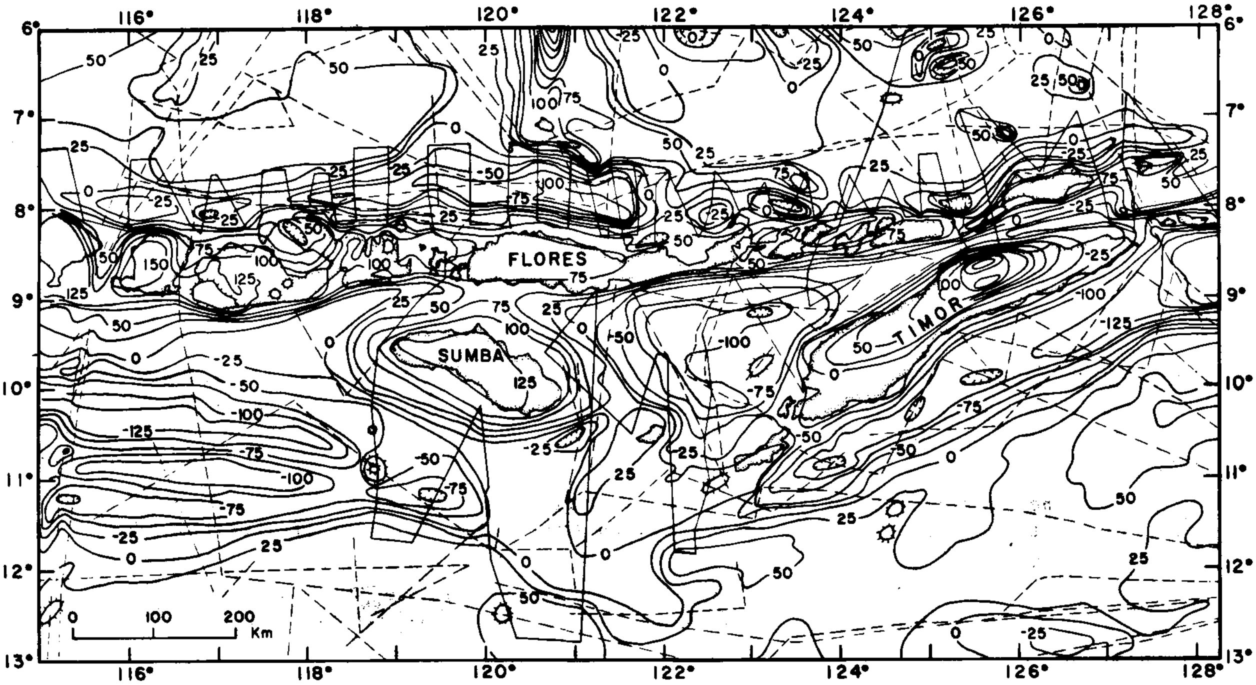

Fig. 9. Free-air gravity map of the eastern Sunda arc region, showing data control. Solid lines are from Rama 12 expedition, dashed lines are those used by Watts et al. [1978]. Island contours are Bouguer gravity.

trench. Also a small fault is developed over the arch within the sedimentary section. Similar outer swells may be developed in the other profiles, but their structure is complicated by the presence of seamounts or basement ridges.

Both gravity (Figure 9) and bathymetric (Figure 2) lows outline the position of the Wetar thrust, which is enclosed within the zero Mgal gravity contour. This gravity low is enhanced by the downbowing of the crust resulting from thrusting. As we move from eastern to western Alor, the magnitude of the low decreases markedly.

Alor to Central Flores. The back arc region from central Alor to central Flores is marked by local, discontinuous zones of folds and faults, separated by areas of non deformation. This region is characterized also by signficant cross-arc faulting and by numerous active volcanoes. The gravity map (Figure 9) shows several linear lows along the base of the arc slope, and these coincide with locally developed thrusts and bathymetric depressions (Figure 2).

We see no deformation behind western Alor and Pantar island (line 18, Figure 10). Local faulting and gentle folding are developed behind Lomblen and Adonara (Figure 2) and more intense faulting and folding is developed north of eastern Flores (line 28, Figure 11). In line 28 a large anticlinal ridge has undergone significant erosion on its northern flank. At 45 to 48 km is a small horst, possibly indicating initiation of thrusting. Small zones of folding and thrusting are seen in profiles around the eastern peninsula of Flores and off the north coast of Adonara. These features appear different from profile to profile and line 24 (not shown) displays a downbowed trench like structure at the base of the arc but no folds or thrusts. Whether these features represent a series of local folds and faults or a continuous zone is not clear, but we can map them along the trace of a smooth arc (Figure 2). The deformation does not continue east of line 24 or west of 29 (Figure 6).

Minor faulting is inferred at the base of Paloe volcano on its north side. It may be that the Flores thrust is just beginning to break to the surface in this region, and offset here is small. Alternatively (or in addition), it is possible that rapidly deposited volcanogenic material on the flanks of the volcano quickly bury the slowly deformed material above the thrust.

The Flores Thrust. West of Paloe the Flores thrust is essentially continuous north of the arc to NE Lombok. An accretionary wedge is developed behind Flores (Figure 12). The Flores basin is narrow in this area and the north margin of the basin is about 10 km from the frontal thrust. A small trench in front of the accretionary wedge is filled with younger turbidites. Much of the sediment accreted at the frontal thrust consists of these young turbidites because deeper layers can be followed beneath the outer part of the wedge (Figure 12). It appears that between 1 and 2 km of the sediment section are being accreted to the toe of the wedge.

The accretionary wedge is 25 to 30 km wide and we can discern at least eight thrust packets in the northern part of the wedge. A tiny slope basin is formed at the south edge of the wedge at its abrupt contact with the arc slope (Figure 12, 50 km). The strata in this basin dip gently southward, suggesting minor uplift on the north side; the uplift is likely due to the process of accretion, as observed commonly in forearc regions.

We can estimate roughly the total convergence represented by the accretionary wedge by making the following assumptions:

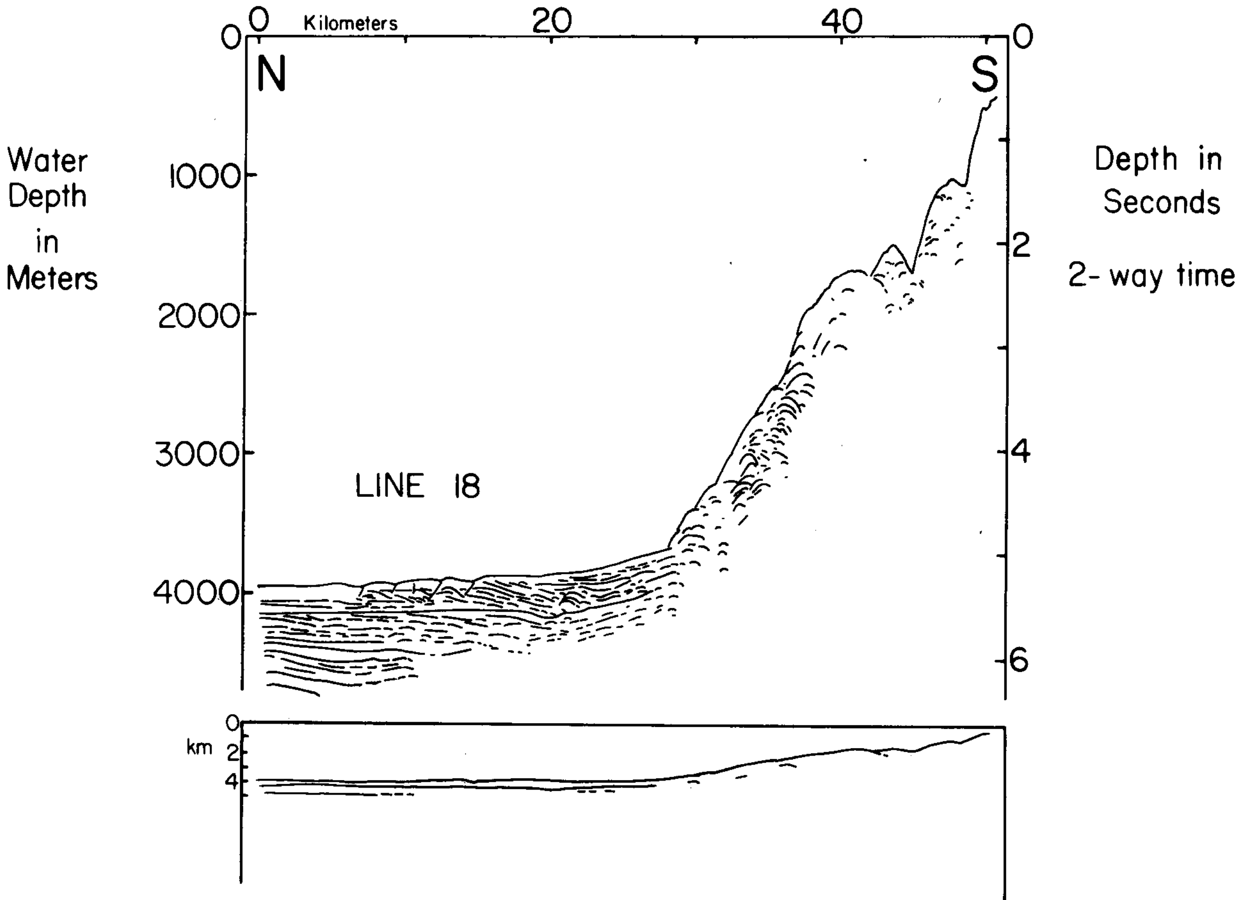

Fig. 10. Line drawing interpretation of seismic analog profile 18, which crosses the back arc region just to the west of the Wetar thrust. V.E. = 9.3x. Lower drawing to true scale.

1. The dip of the lower plate remains constant with depth beneath the accretionary wedge.
2. The change in volume on accretion is 33%.
3. The thickness of material being scraped off the lower plate is between 1.5 and 3 km. W. Hamilton [written communication, 1982] says that he has seen seismic data showing that the entire sedimentary section is involved in the deformation at depth within the wedge.

We measure a cross-sectional area for the wedge of about 68 km^2 using assumption 1, which yields an undeformed volume of about 100 km^2 using assumption 2. If 3 km of sediment are being scraped off the lower plate the indicated convergence is 30 km, whereas if 1.5 km are scraped off the convergence is 60 km. With better definition of the deep structure of the wedge this range might be narrowed or changed.

The accretionary zone is narrower behind the great volcanoes of Sangeang Api and Tambora than it is to either side of them. In line 49 behind Sangeang Api, convergence of the arc (south) and Sundaland (north) slopes has resulted in a buttress-type uplift of sediment wedges on either side (Figure 13). The acoustic stratigraphies of the sediment layers on either side are easily distinguished, and we are confident that the ridge on the north is Sunda slope sediment, whereas that on the south is arc derived.

Thrusting is shown by all profiles behind Sumbawa. Those north of central Sumbawa (51, 53, 55, 57) indicate a trench structure and minor sediment deformation but little or no accretionary wedge. In contrast, line 59 (Figure 14) off western Sumbawa shows clear accretionary structure. The structure here is similar to but smaller than that of line 39 (described above). The accretionary wedge is 10 km wide, and the small tubidite wedge in the trench is less than 0.5 km thick. The amount of sediment being accreted to the wedge is less than 1 km. The amount of convergence indicated here, using the same kinds of assumptions and uncertainties as discussed for profile 39 above is between 10 and 20 km. The small accretionary wedge in line 61 (Figure 15) is bounded sharply on the south by a steep, north side up fault. The fault is on line with the Lombok Strait and we infer continuity. Note the presence of a small buried ridge or seamount on the lower plate in the northern part of line 61 (Figure 15). Such features are common in the eastern Sunda back arc. In line 63 (Figure 16) we see a more prominent, partially buried seamount. Convergence is indicated by a series of gentle folds, which increase in amplitude and breadth southward. The north limbs of anticlines appear to be cut by south dipping thrust faults, but these do not extend to the surface. This structure implies that much of the southward thickening sediment wedge existed prior to

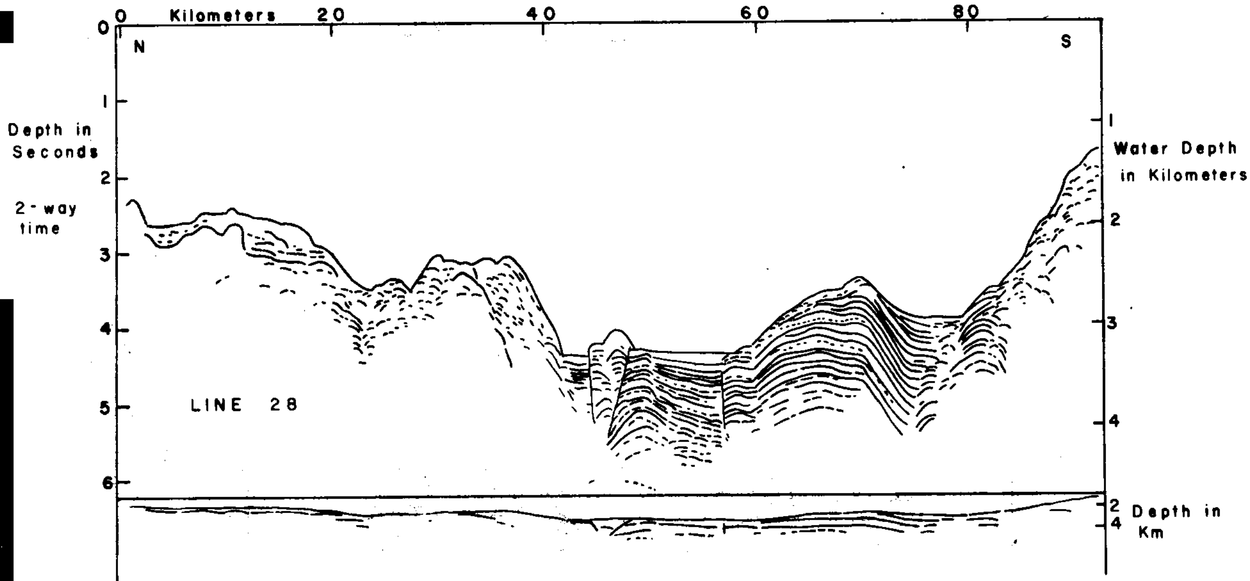

Fig. 11. Line drawing interpretation of seismic profile 28 crossing the back arc region behind eastern Flores. Lower profile to true scale. V.E. = 9.3x.

folding, as the wavelength of the folds increases with the thickness of the sediment. Deposition also occurred concurrently with deformation because the deeper layers under the largest fold are tilted more steeply than the shallow layers.

Bali Basin. Deformation is seen along the southern part of the Bali Basin in lines 67 (Figure 17), 69, and 71. This region is well west of the zone of collision. Deformation consists of four broad folds in line 67 which are successively wider southward (compare with line 63). In line 69 we see two gentle folds and in 71 only one. These folds are developed in a sedimentary section at least 2 km thick, yet produce litle morphologic effect; they represent little total convergence. Although the fold at 50 km is a candidate for diapirism, most of the folds in this region involve the whole sedimentary section and are not truncated. Fitch [1970] and Cardwell et al. [1981] have determined thrusttype shallow earthquakes from first-motion studies on the north side of Bali, consistent with tectonic rather than sedimentary processes causing the folding. We infer from these observations that the Flores thrust has propagated westward but that the amount of slip on the thrust behind Lombok and Bali is small. We do not see the trace of the thrust, but the sedimentary section must be shortened by decollement along a thrust surface at depth.

Structure of the Forearc Region

Here we examine briefly the salient aspects of the forearc region that might act to enhance or impede back arc thrusting. The forearc region can be divided simply into a forearc basin province and an accretionary wedge (Figure 1). The forearc basin province is highly variable. It is a wide basin between Sumba and central Timor, a narrow basin behind eastern Timor, and a wide, uplifted

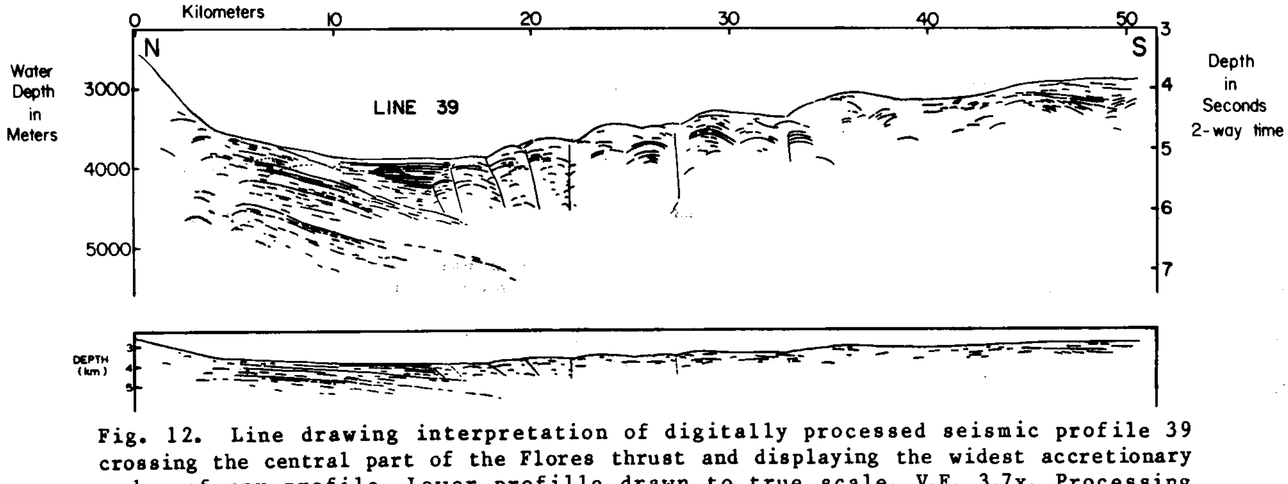

Fig. 12. Line drawing interpretation of digitally processed seismic profile 39 crossing the central part of the Flores thrust and displaying the widest accretionary wedge of any profile. Lower profille drawn to true scale. V.E. 3.7x. Processing included filtering, deconvolution, automatic gain control (AGC), and variable area display.

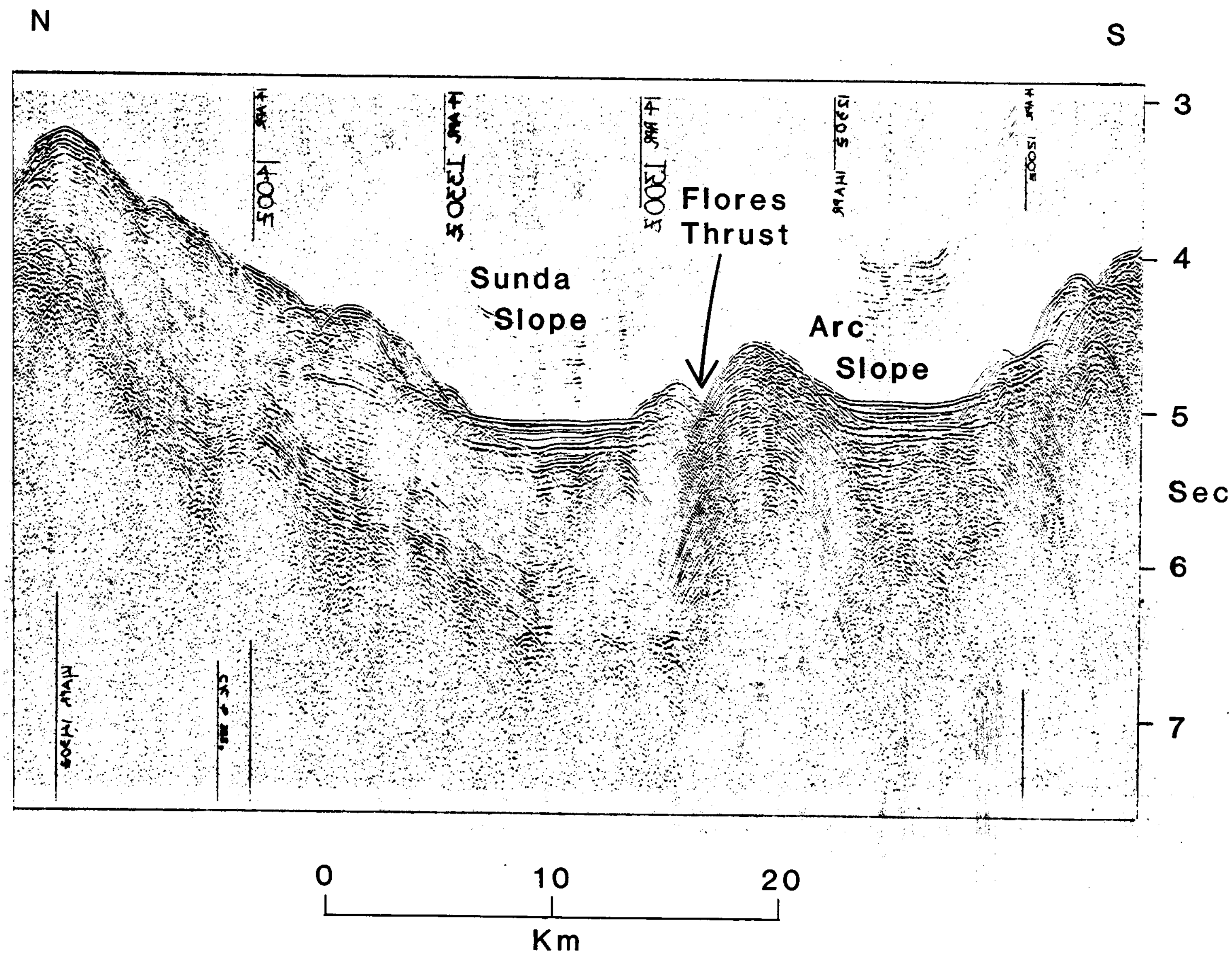

Fig. 13. Detail of analog seismic profile 49, which crosses the Flores thrust just to the east of Sangeang Api volcano. V.E. = 9.3x. North is to the left.

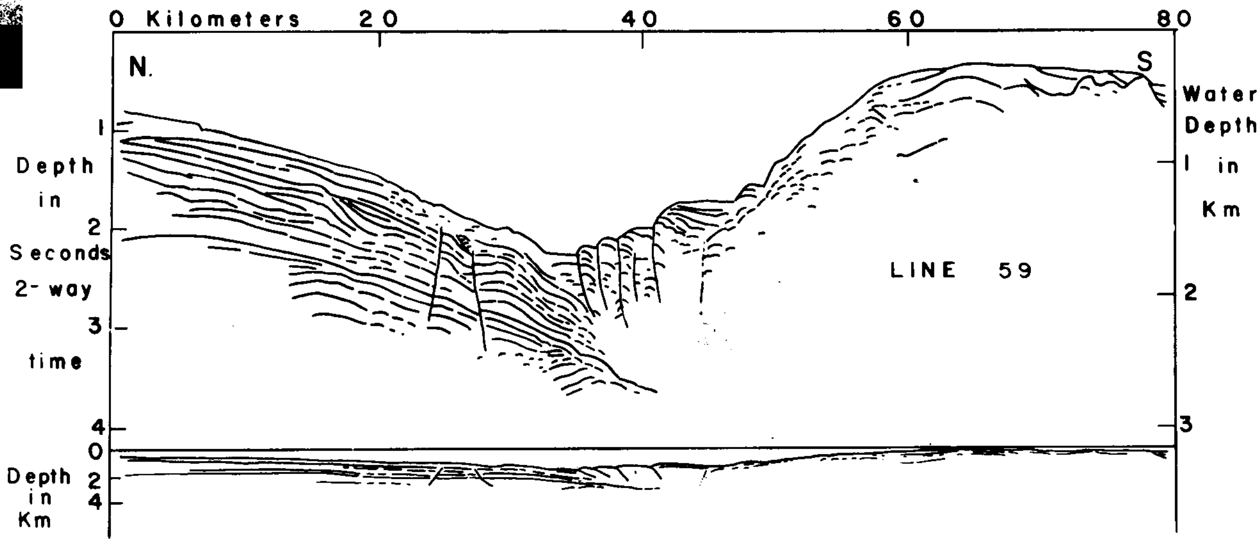

Fig. 14. Line drawing interpretation of seismic profile 59, which crosses the Flores thrust at the western end of Sumbawa island. Lower profile drawn to true scale. V.E. = 9.3x.

block at Sumba. The accretionary wedge in this region has been discussed by a number of workers recently [Bowin et al., 1980; Hamilton, 1979; Johnston and Bowin, 1981; Jacobson et al., 1979], and we will present our new results separately.

Between Timor and Sumba islands the forearc basin and accretionary wedge are separated by the Savu thrust, first documented by Crostella and Powell [1976] (see also Hamilton [1979]. On line 80 (Figure 18) the thrust cuts deeper layers of the south Savu basin, but it does not cut the upper 500 m. Possibly the thrust front is propagating northward, and its new location is in the center of the small basin, as shown in Figure 18. The Savu thrust crops out at the surface just east of the island of Savu (our profile 85 and Hamilton [1979] Fig. 72A). We have traced the Savu thrust westward to just south of eastern Sumba Island and eastward to just west of Roti (Figure 1). Profiles taken by industry between Roti and Timor show no sign of such faulting.

A major question concerns whether or not deformation occurs along the north coastal region of Timor [e.g., see Barber, 1979], in a location structurally analogous to that of the Savu thrust. Profile 11 (Figure 19) crosses a narrow (20 km) forearc basin which shows no sign of tectonism along either edge, aside from mild upwarping of deeper layers. Some controversy has arisen over the location of the main zone of convergence in the Timor region [see Audley-Charles and Milsom, 1974; Fitch and Hamilton, 1974]. This profile (Figure 19) and other profiles [Hamilton, 1979] document the lack of significant tectonic activity along the north margin of Timor, although minor deformation is present in this zone on line 13 (see Figure 6 for location). Although the extent of faulting behind Timor is not understood, our present data show that at most it is localized and discontinuous, and only one location is yet shown to have fault activity.

We infer a thick crust beneath Sumba island because of its elevation. Gravity studies on Timor [Chamalaun et al., 1976] are consistent with a crustal thickness of about 40 km. In contrast, the Savu basin reaches depths in excess of 3 km, and it is filled with up to 5 km of sediment. Removal of the sediment load would result in a water depth of over 4 km, indicating oceanic crustal density and thickness for the basement. The Savu thrust thus is best developed in the region of thin forearc basin crust, and the back arc thrusts are best developed where the forearc crust is thick. Conversely, the Savu thrust occurs in a region where the backarc thrusts are poorly developed.

Discussion

What is the cause of the back arc thrusts? Is more than one mechanism operating? Mechanisms have generally been divided into two broad catagories, those involving driving stresses confined to the upper plate and those involving stresses imparted to the upper plate by the lower plate. In the first group are (1) gravity sliding [Hubbert and Rubey, 1959]; (2) gravity spreading of material in the arc region toward the forearc as a result of uplift in the arc [Price and Mountjoy, 1970; Elliott, 1976], and (3) magmatic forcing due to intrusion in the arc [Hamilton, 1979; Smith, 1981].

The second group is dominated by collision tectonics in this region. In this case the thrusts are viewed to result directly from stresses propagated through the arc system to the back arc due to impingement on the arc by an externally colliding mass [McKenzie, 1969; Dewey and Bird, 1970], although in other arc settings low-angle subduction may play an important role [Barazangi and Isacks, 1979; Burchfiel and Davis, 1976; Dickinson and Snyder, 1978].

Gravity Sliding

Gravity sliding is dismissed as a primary cause of back arc thrusts in the eastern Sunda arc. First, the classical view of gravity sliding [Hubbert and Rubey, 1959] required a forward basal slope in the direction of motion. Our reflection profiles and the few available refraction lines

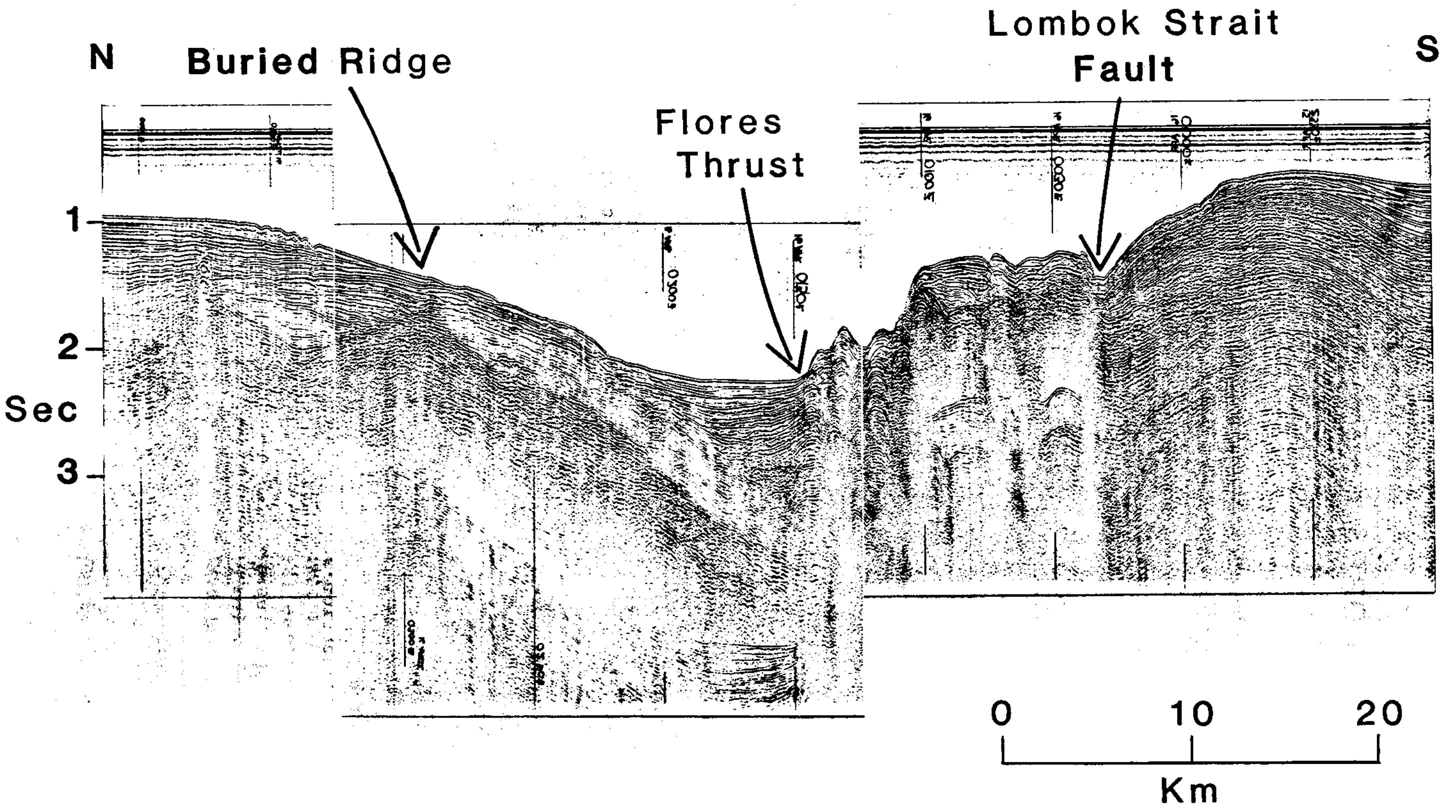

Fig. 15. Detail of analog seismic profile 61. This line crosses the back arc just NE of the Lombok Strait and crosses a major fault on-strike with strait. V.E. = 9.3x.

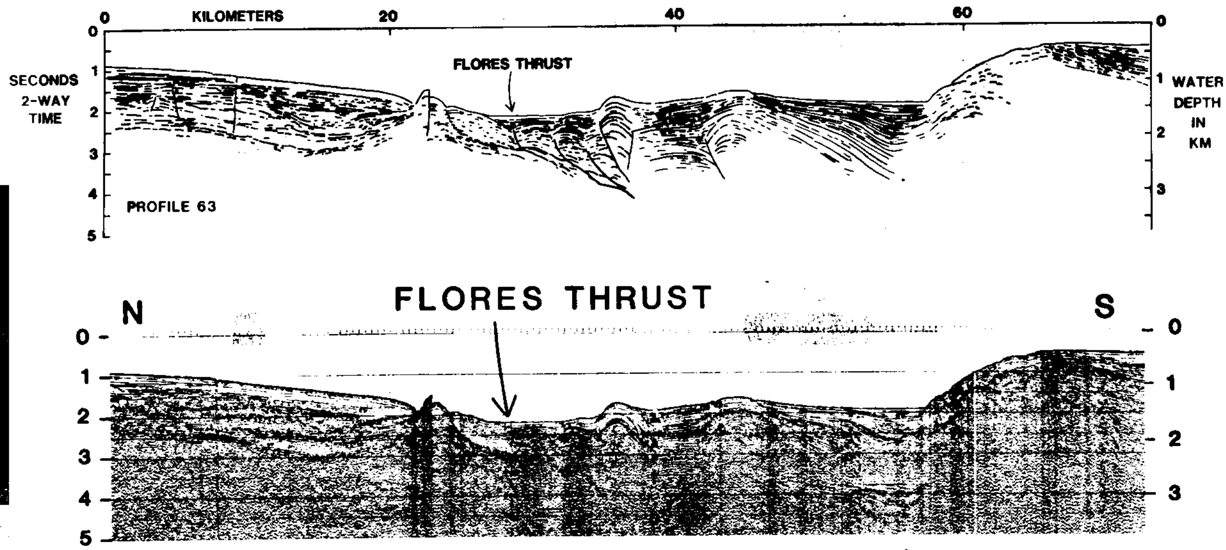

Fig. 16. Digitally processed seismic profile 63 (lower profile) which crosses the western part of the Flores thrust off the east coast of Lombok. Upper profile is line drawing interpretation. V.E. = 3.7x. Processing as discussed in Figure 12.

document that the basal thrust slopes arcward, as is observed in all active tectonic thrust environments. Second, gravity sliding requires an upslope source region for the overthrust mass. We do not observe an upslope region of extension on the seismic lines in the back arc, but we see abundant evidence of sediment accretion on the lower part of the back arc slopes.

Gravity Spreading

Elliott [1976] showed that a forward dipping basal slope was not necessary to provide the energy for thrust movement. The only requirement was a forward sloping surface. This demonstration seemed to lend support to earlier ideas of gravity spreading by Price and Mountjoy [1970] and Bucher [1956]. The method of Elliott [1976] may not apply to the back arc region discussed here, however, because his generalizations require a wedge thickness of 10 km, whereas for most of the back arc the wedge probably does not exceed 5 km thickness.

A second, more general difficulty is that Elliott did not consider a weak basal layer, yet a weak basal layer is common in subduction settings [Chapple, 1978; Davis et al., 1983; Suppe, 1980; Moore et al., 1982]. Elliott rejected a major influence of tectonics or pushing from the rear in driving thrust belts by assuming that the angle between the thrust and the maximum principal stress axis was larger than 32°. If this angle is less than 25°, then using his equations, the longitudinal stress term becomes significant. A weak basal layer will tend to decrease this angle [Chapple, 1978]. Davis et al. [1983] considered that the accretionary wedge acted as a stress guide, so that the maximum principal stress was nearly horizontal.

In the eastern Sunda back arc we note that the thrusts are not continuous, although the slopes are. A clear example of this change is seen in lines 15 and 18, both located on the north slope of Alor and both showing very similar arc slopes. The difference is that line 15 has a relatively wide zone of thrusting at the base of the slope and a well-developed outer arch just north of the thrust, whereas line 18 shows no sign of compressional deformation. Thus a forward surface slope is not a sufficient driving mechanism for the thrusts.

Hamilton [1979] also considered gravity

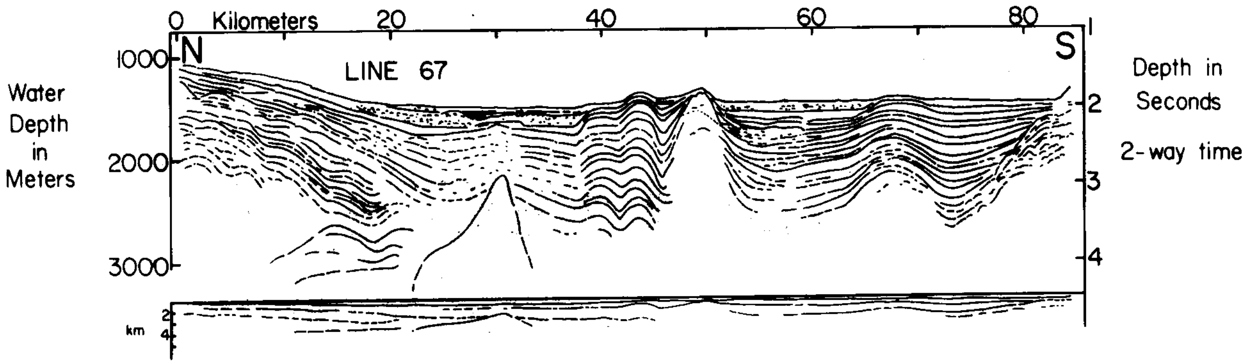

Fig. 17. Line drawing interpretaion of seismic profile 67, which crosses the backarc region between Bali and Lombok islands. V.E. = 9.3x. Lower drawing to true scale.

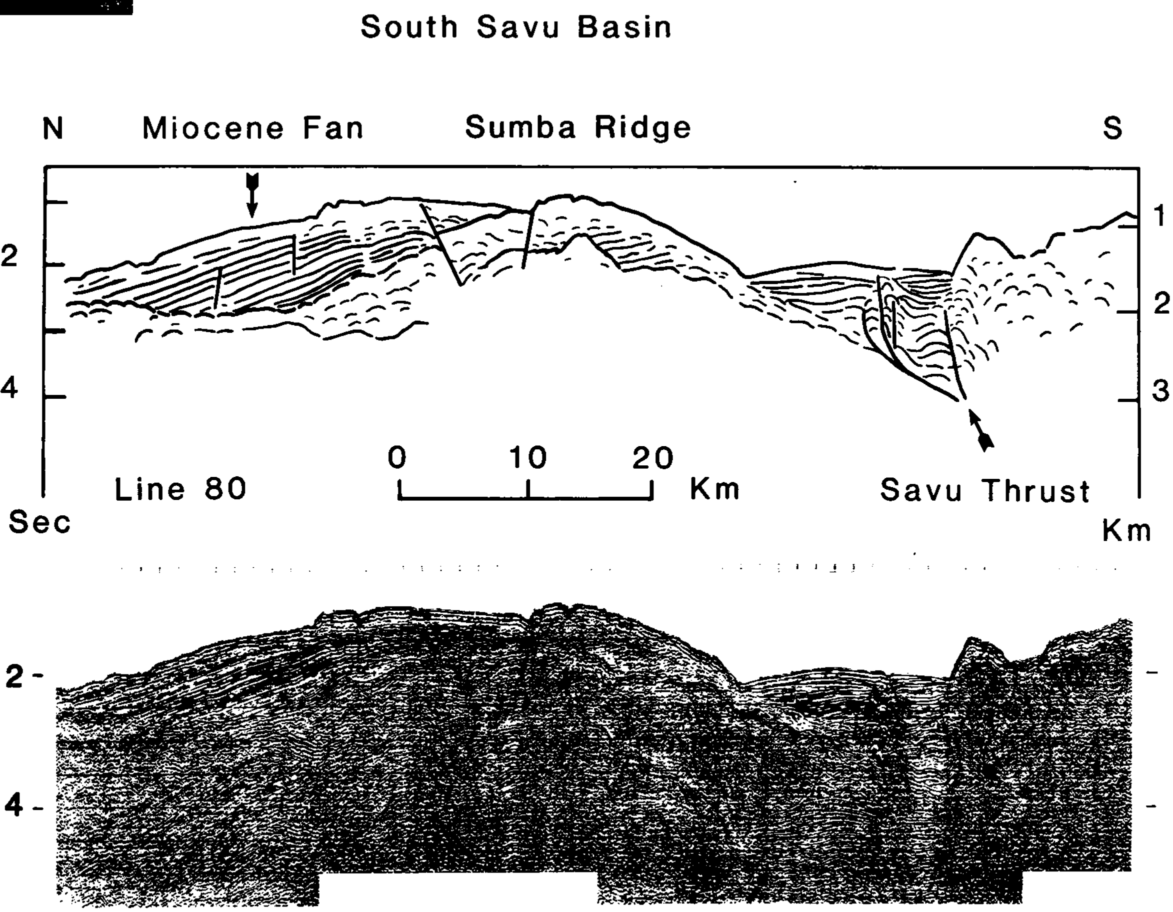

Fig. 18. North central part of profile 80, crossing the Savu thrust and the Sumba ridge. Lower photo is a digitally processed seismic profile with V.E. = 13.3x. Upper profile is a line drawing interpretation of the lower part, emphasizing the major structures. Processing as described in Figure 12.

spreading, but his treatment was not solely an upper plate mechanism. He viewed the thrusts as moving downslope and driven by gravity, but the slope itself was produced by accretion of material due to subduction. As all major quantitative treatments considered both gravity and boundary stresses acting on the thrust mass [Elliott, 1976; Chapple, 1978; Davis et al., 1983] it is difficult to know which view Hamilton was following or whether his was different from the others.

Gravitational stress on surface slopes may play an important role, however, in localizing the initial position of the thrust at the base of the arc slope. Topographic slopes must be maintained by the strength of the crust, and the greatest horizontal compressive stress occurs at the base of slopes (see Dalmayrac and Molnar [1981] for a good discussion of stress magnitudes in the Andean arc and back arc regions). As external stresses (for example, due to collision effects) increase across the arc, the base of the back arc slope will tend to be the first location where the strength of the crust is exceeded.

Magmatic Processes

Hamilton [1979] argued in favor of magmatic intrusion as a mechanism of back arc deformation in the northeast part of Java. He noted that compressional structures in Neogene materials tend to arc concentrically around, and to be directed outward from, large volcanic edifices. Such intricate associations of volcanic edifices and thrusts are expected from a magmatic mechanism for deformation. A collision origin could be considered as an alternative because Kelleher and McCann [1976] have pointed out that the Roo Rise is in a position of impingement against the Java Trench, which could produce collision effects. They used this observation to explain the absense of great earthquakes in the vicinity of Java. At present neither explanation (collision or magmatic influence) can be eliminated. The fold belt of east Java projects eastward to the Bali Basin and may be continuous with the gentle deformation that we observe there. Unfortunately, our line spacing is not sufficient to distinguish whether or not the folds follow the morphologic outlines of the Bali and Lombok volcanoes.

Farther to the east, however, the Wetar thrust shows a negative correlation with volcanism. The volcanically inactive region of the arc (the islands of Romang, Wetar, Atauro, and Alor) lies just south of the thrust. Thrusting ends abruptly on either end where arc volcanism is quite active. A counter argument, given by D. E. Karig [oral commununication, 1981], is that magmatic swelling might be greatest where volcanism is least

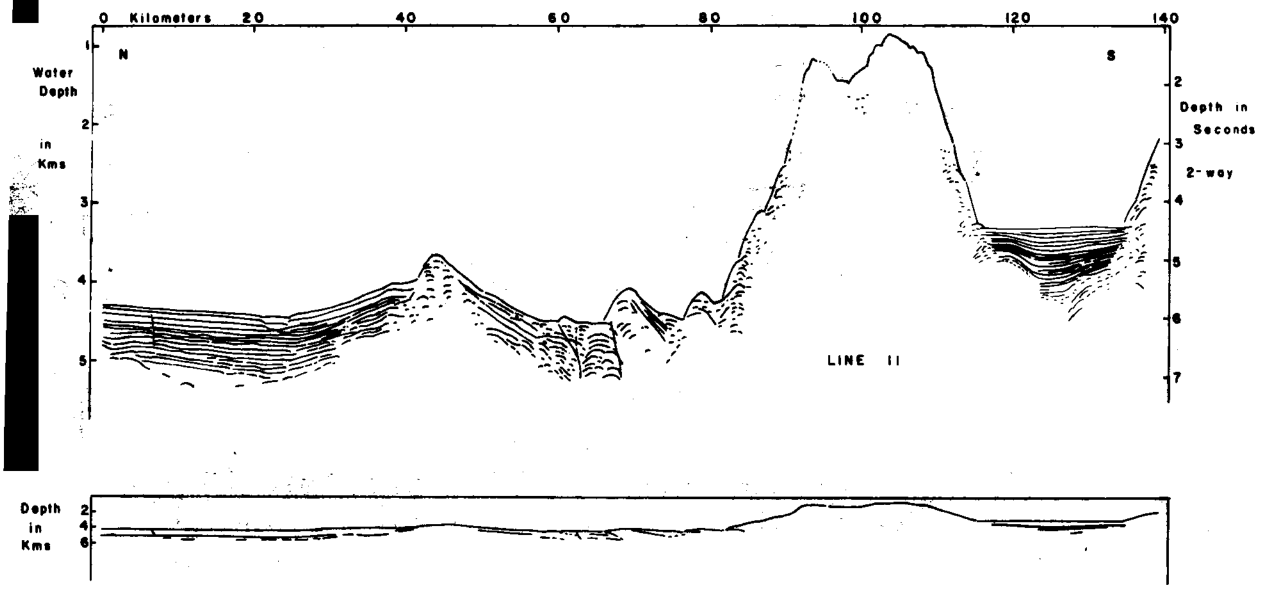

Fig. 19. Line drawing interpretation of analog seismic profile 11, which crosses the arc between Wetar and Atauro islands and shows the structure of the small forearc basin between the arc and Timor. Wetar thrust crops out at 60 km. V.E. = 10x. Lower drawing to true scale.

mportant and intrusions are dominant. Thus the olcanically inactive regions would be expanding ue to intrusion. In this case we should expect to ee some signs of crustal extension in the nactive part of the arc, including surface rifts. e have examined SLAR images of the arc from lores to Wetar, and we do not see evidence for uch structure. Wetar, in particular, shows orphologic structure of old eroded volcanic ones, and these are not overprinted by rift tructures. The island stands high, relief is ugged, and erosional terrace surfaces are pparent. Alor shows signs of younger faulting but ot clear rift morphology.

The region of greatest development of ccretionary thrusts is north of western Flores island. Here too the morphology is high and rugged, and we see no rift morphology. We can trace fault patterns obliquely across the island, and two trends appear to cross each other with little offset. Lines of small volcanoes trend northward in western Flores, indicating an E-W orientation of the local minimum principal stress. This direction is normal to that expected from development of E-W thrusts due to magmatic intrusion.

Magmatism may play a subsidiary role in allowing thrusting to occur, however, by thermally weakening the crust beneath the arc, an argument summarized by Dickinson [1979]. In this case, significantly lower stress levels would be required by collision to initiate and maintain thrusting than would be the case otherwise.

Collision Origin

As with many other ideas for the development of the complex tectonic setting of eastern Indonesia, Hamilton [1979] suggested a collision origin for the back arc thrusts. Evidence for a collision origin involves the location of the thrusts, the geometry of the arc with respect to the thrusts, and preliminary earthquake mechanism observations. The most direct observation is that the thrusts occur in the zone of collision between the arc and the Australian continent (Figure 1). Extension of the zone of deformation westward beyond the collision has been explained above as due to either magmatic processes or collision by the Roo Rise. A third alternative for the Bali Basin deformation is that it is related to the Australia collision zone and represents a very efficient lateral propagation phenomenon of the edge of the thrust. Whatever explanation is favored, it should be remembered that the deformation west of Sumbawa involves significantly less strain than is seen north of central Flores, for example.

The discontinuous nature of the thrusts suggests another reason to accept a collision origin for the Flores and Wetar thrusts. The thrusts are best developed behind the arc in those locations where the forearc basin is most narrow, behind the islands of Sumba and eastern Timor. Between these thrusts the Savu basin is wide and deep, and we have mapped a large south dipping thrust at the north edge of the accretionary wedge, the Savu thrust. Possibly this fault takes up some of the strain not found in the corresponding region of the back arc. Mechanically, this distribution of back arc thrusts makes sense if we consider the islands to overlie anomalously thick crust, and refraction [Jacobson et al., 1979] and gravity [Chamalaun et al., 1976] studies support this inference. We suggest that stresses imparted to the forearc region by collision of the Australian continent will transmit across the arc to the back arc region more efficiently in those regions where the crust is thicker. Those areas possessing forearcs with thin crust, such as the Savu and Weber basins, will have a greater tendency to deform by elastic flexure [see Hamilton, 1979] and will more readily absorb the effects of the collision in the forearc.

The gross morphology of the eastern Sunda arc can be explained using a collision origin for the thrusts. The Flores thrust is best developed behind western Flores and eastern Sumbawa. The gross trend of the arc from Java to Alor is a gentle convex southward arc, but this arc is interrupted at eastern Sumbawa and western Flores. Here the volcanic edifice is gently convex northward. If we assume that the arc was originally continuously convex southward from Java to Alor and that the convex northward segment resulted from the effect of collision, we can estimate the amount of collision. The maximum displacement measured by this assumption is about 30 km and occurs in westernmost Flores to easternmost Sumbawa. Displacement is predicted to decline both east and west from this zone. Our seismic reflection profiles clearly show this pattern of movement as measured by estimated convergence in the zone of back arc deformation. Our numerical estimates have a number of uncertainties and assumptions, but our best estimate gives a convergence of about 30 km, within a factor of 2, in the back arc of western Flores.

Gross geometrical indications of collision are apparent also behind eastern Timor, although the quantitative correspondence between arc offset and accretionary wedge is not good. Here the islands of Wetar and Romang are offset northeastward with respect to the western part of the arc. The morphologic offset occurs between Atauro and Wetar, and our seismic lines showed some evidence for fault zones cutting between these islands. The amount of convergence is somewhat more difficult to estimate here, but the westward increase in size of the accretionary wedge is not consistent with a large northward offset of Wetar with respect to the western part of the arc. On the other hand, the abrupt change from thrusting on line 15 to no thrusting on lines 17 and 18 might be explained by slip along the ENE trending fault that cuts northern Alor. We require further detailed study of the arc in the region of Atauro to resolve this puzzle.

Earthquake first-motion studies indicate N-S compression in the shallow Flores and Wetar thrust segments of the back arc. The focal depth of one thrust earthquake was about 40 km [McCaffrey, 1981], favoring a tectonic or gravity spreading origin over magmatic intrusion or gravity sliding.

Orogenic Implications

By inferring probable future configurations of the eastern Sunda arc we can explore implications for the interpretation of ancient mountain belts. As collision proceeds we would expect an eventual merging of the Wetar and Flores thrusts and their lateral propagation. The region between these thrusts could develop into a reentrant in the thrust front because this area is marked by topographic highs in the backarc region. Such reentrants are developed along ancient thrust belts, for example, the Uinta reentrant along the Rocky Mountain front [e.g. Beutner, 1977].

The Flores thrust is already impinging upon the Sunda shelf in its western part and should do so all along its present length in the near future. This thrust belt will then run up onto the shelf, becoming a foreland fold and thrust belt, because the positive buoyancy of the Sunda shelf should make it difficult to subduct. To the east, the Wetar thrust is overriding the Banda Basin oceanic crust, and the basin is about 400 km wide. Here arc polarity reversal is possible because of the potential negative buoyancy of the oceanic lithosphere of the Banda Basin (especially if Bowin et al.[1980] are correct in their assertion that the Banda Sea crust is Mesozoic in age), and a south dipping subduction zone might be initiated. Subduction could become self-sustaining (in the sense of McKenzie [1977]) when a deep enough slab of backarc basin crust is inserted into the mantle at a sufficiently rapid rate so that its negative buoyancy (plus any other driving stresses) is sufficient to overcome resistive stresses on the lower plate. Until that time, convergence must be driven by forces external to the Banda Sea crust, such as by collision between Australia and the eastern Sunda arc.

How can we distinguish whether the back arc thrusts represent the early stage of arc polarity reversal, as suggested by Hamilton [1979], or simply are part of a wide zone of distributed deformation [Bowin et al., 1980]? First, the wide region of old [Bowin et al., 1980], dense lithosphere in the Banda Sea which forms the rocks of the lower plate allows the possibility of future self sustaining subduction there, as discussed above. R. McCaffrey and J. Nableck (manuscript in preparation, 1983) show that the addition of thick sediment to the back arc trench increases the chances for development of self-sustaining subduction. Second, although we do not yet have a firm understanding of the temporal distribution of strain within the Timor accretionary wedge, those areas where convergence is clearly developed between the wedge and the arc (mainly the Savu thrust, plus one location of faulting behind Timor) are essentially restricted to the region where back arc thrusting is not developed. Third, studies of earthquakes in the back arc region indicate significant thrust activity on both the Flores and Wetar thrusts. Finally, regardless of how deformation is presently being taken up across the arc system, and we have tried to shed some light on that problem in this paper, eventual convergence between Australia and Southeast Asia must be accommodated along zones of weakness. The back arc thrusts are prime candidates for such zones.

These alternatives are not mutually exclusive. Recent studies of the strain distribution across accretionary wedges [Davis et al., 1983; Karig et al., 1980; Moore et al., 1981] show that while the highest rates of deformation are concentrated near the frontal thrust, deformation is distributed throughout the wedge, although toward the rear of the wedge the vertical component (uplift) becomes more important. The observations of significant Quaternary uplift of horizontal terraces on Timor [Tjia, 1981] support largely vertical motions of the older part of the wedge in the past 2 m.y. Thus we feel a reasonable case can be made for the possibility of future arc polarity reversal. A close ancient analog for this process is seen in New Guinea-Irian Jaya, in which a Miocene arc-continent collision has resulted in the development of a foreland fold and thrust belt in the central part of the island and arc polarity reversal along the north side [Hamilton, 1979].

The Timor trough may be evolving to what Dickinson [1977] refers to as a peripheral foreland basin. Continental crust already underlies the trough, and there is some indication that long, sled runner thrusts are beginning to develop just south of the trough [Montecchi, 1976]. In time, the eastern Sunda arc region could develop into a two-sided orogen, with foreland style thrust belts to the north and south of the arc. In the eastern part, the Wetar ′subduction zone′ could close the Banda Basin and carry the eastern part of the arc and the Banda arc NW to an eventual collision with Sulawesi and the south Molucca islands, initiating continent-continent collision.

Conclusions

We conclude that the dominant mechanism acting to drive back arc thrusting here is collision with Australia, but several additional factors aid or retard thrust development. One factor is crustal weakness due to thermal effects of magmatic intrusion, which allows the crust to deform more easily. A second factor is the effect of surface slope. While we ruled this out as a primary driving force, the effect of the slope is to concentrate compressive stress at its base. Though not sufficient in general to initiate thrusting alone, it is likely to localize thrust development when combined with additional cross-arc stresses.

An additional factor enabling thrusts to develop is efficiency of stress propagation across the arc system. Where the forearc crust is relatively thick (eastern Timor and Sumba), back arc thrusts are well-developed. Where the forearc crust is thin (Savu basin), back arc thrusts have developed weakly or not at all. The latter regions appear more prone to form thrusts on the inner edge of the forearc accretionary wedge (Savu thrust and local, small faults just north of Timor), taking up some of the strain that back arc thrusts do in the other areas.

As the thrusts develop, lateral propagation is probably energetically easier than initiation of the faults. The Bali Basin deformation may reflect such lateral propagation, although it may also (or alternatively) represent direct effects of magmatic intrusion (as suggested by Hamilton [1979] for east Java), or the subduction of buoyant oceanic plateaus such as the Roo Rise [Kelleher and McCann, 1976]. Thrusting is retarded by thickened crust in the back arc region.

We propose the following sequence of development for back arc activity during collision. In the early phases of collision the thermally weakened crust of the volcanic arc aids in the initiation of thrusting [e.g., Armstrong, 1974; Burchfiel and Davis, 1975; Dickinson, 1977]. In the case of the Flores thrust we must rationalize the concurrence of active volcanism and back arc thrusting. We suggest that the principal deviatoric stresses (S1, S2, and S3) are similar in magnitude in the arc and back arc at this stage. The different tectonic responses (volcanism versus thrusting) are produced by the slope of the back side of the arc which imparts an additional stress to the base of the slope. In the arc, S1 is vertical, but in the back arc at the base of the arc slope it is horizontal. As collision proceeds, the horizontal stress across the arc increases (Wetar region) and volcanism is retarded, becoming chemically altered by crustal contamination then finally eliminated. But as volcanism wanes, the crust strengthens, and greater stresses are required to fault the crust. In support of this idea, we observe that behind Timor in the Wetar thrust zone, all well-located large earthquakes ($M \geq 7$) occurred in the back arc region. In the Savu basin area, on the other hand, stresses are not propagated efficiently across the forearc basin, and S2 remains vertical for some time, resulting in the development of numerous cross faults but allowing volcanism to flourish well after it has stopped elsewhere. Because of the collision geometry, S3 lies along the arc axis, and lines of small volcanoes tend to trend N-S.

The sequence of development that we infer from the present structural and kinematic setting is formation of a two-sided foreland fold and thrust belt both north and south of the arc, possible arc polarity reversal along the Wetar thrust and its eventual extensions, and as proposed by Hamilton [1979], continent-continent collision between Australia and the complexly deformed margin of SE Asia.

Acknowledgments. We would like to thank the scientific party, ship′s crew and Captain Arsenault of RAMA 12 expedition for helping to make this study successful and enjoyable. We thank H.M.S. Hartono, John Katili and Joe Widartoyo for providing generous support within Indonesia; Dan Karig for very helpful discussions and disagreements, Peggy Plumley, and Audrey Wright for drafting; and Perry Crampton, Steve Box, and Holly Ryan for their efforts at various stages in this project. We are especially grateful to Ken Harris for painstaking interpretation of SLAR images of the arc. The paper was improved significantly by Warren Hamilton′s particularly thorough review. We thank him, G. F. Moore, R. K. Cardwell, and C. O. Bowin for reviews. This work was supported by NSF grant OCE80-18575.

REFERENCES

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

Audley-Charles, M. G., The Sumba fracture--A major discontinuity between eastern and western Indonesia, Tectonophysics, 26, 213-228, 1975.

Audley-Charles, M. G. and J. S. Milsom, Comment on ′Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the western Pacific′ by T. J. Fitch, J. Geophys. Res., 79, 4980-4981, 1974.

Bally, A. W., P. L. Gordy, and G. A. Stewart, Structure, seismic data, and orogenic evolution of the southern Canadian Rocky Mountains, Can. Pet. Geol. Bull., 14, 337-381, 1966.

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

Barazangi, M., and B. L. Isacks, Subduction of the Nazca plate beneath Peru: Evidence from spatial distribution of earthquakes, Geophys. J. R. Astron. Soc., 57, 537-555, 1979.

Barber, A. J., Structural interpretations of the island of Timor, Proc. Southeast Asia Pet. Explor. Soc., 4, 9-21, 1979.

Beutner, E. C., Causes and consequences of curvature in the Sevier orogenic belt, Utah and Montana, Rocky Mountain thrust belt geology and resources, edited by E. L. Heisey, D. E. Lawson, E. R. Norwood, P. H. Wach, and L. A. Hale, Joint Wyoming-Montana-Utah Geological Associations, Casper, Wyoming, 1977.

Bowin, C., G. M. Purdy, C. Johnston, G. G. Shor, L. Lawver, H. M. S. Hartono, and P. Jezek, Arc-continent collision in Banda Sea region, Am. Assoc. Pet. Geol. Bull., 64, 868-915, 1980.

Bucher, W. H., Role of gravity in orogenesis, Geol. Soc. Am. Bull., 67, 1295-1318, 1956.

Burchfiel, B. C. and G. A. Davis, Compression and crustal shortening in Andean-type orogenesis, Nature, 260, 693-694, 1976.

Burchfiel, B. C. and G. A. Davis, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis, Am. J Sci., 275-A, 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 (abs), Eos Trans. AGU, 62, 404, 1981.

Case, J. E. and T. L. Holcomb, Geologic-tectonic map of the Caribbean region, scale 1:2.5 million, U.S. Geol. Surv. Misc. Invest. Ser. Map I-1100, 1980.

Chamalaun, F. H., K. Lockwood, and A. White, The Bouguer gravity field of eastern Timor, Tectonophysics, 30, 241-259, 1976.

Chappell, J. and H. H. Veeh, Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island, Geol. Soc. Am. Bull., 89, 356-368, 1978.

Chapple, W. M., Mechanics of thin-skinned fold-and-thrust belts, Geol. Soc. Am. Bull., 89, 1189-1198, 1978.

Chase, C. G., Plate kinematics: The Americas, East Africa, and the rest of the world, Earth Planet. Sci. Lett., 37, 335-368, 1978.

Coney, P. J., Structural evolution of the cordillera Huayhuach, Andes of Peru, Geol. Soc. Am. Bull., 82, 1863-1884, 1970.

Crostella, A. A. and D. E. Powell, The geology and hydrocarbon prospects of the Timor area, paper presented at the Indonesian Petroleum Association 4th Annual Convention, Jakarta, 1976.

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.

Dickinson, W. R., Tectono-stratigraphic evolution of subduction-controlled sedimentary assemblages, in Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Ser., vol. 1, edited by M. Talwani and W. C. Pitman III, pp. 33-40, AGU, Washington, D. C., 1977.

Dickinson, W. R., Plate tectonic evolution of North Pacific rim, in Geodynamics of the Western Pacific, edited by S. Uyeda, R. W. Murphy, and K. Kobayashi, Japan Scientific Societies Press, Tokyo, 1979.

Dickinson, W. R. and W. S. Snyder, Plate tectonics of the Laramide orogeny, in Laramide Folding Associated with Basement Block Faulting in the Western United States, edited by V. Matthews III, Geol. Soc. Am. Mem. 151, 335-366, 1978.

Edgar, N. T., J. I. Ewing, and J. Hennion, Seismic refraction and reflection in Caribbean Sea, Am. Assoc. Pet. Geol. Bull., 55, 833-870, 1971.

Elliott, D., The motion of thrust sheets, J. Geophys. Res., 81, 949-963, 1976.

Fitch, T. J., Earthquake mechanisms and island arc tectonics in the Indonesian-Philippine region, Seismol. Soc. Am. Bull., 60, 565-591, 1970.

Fitch, T. J. and W. Hamilton, Reply, J. Geophys. Res., 79, 4982-4985, 1974.

Hamilton, W., Earthquake map of the Indonesian region, U.S. Geol. Surv. Misc. Invest. Ser. Map I-875-C, 1974.

Hamilton, W., Tectonics of the Indonesian region, in Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Ser., vol. 1, edited by M. Talwani and W. C. Pitman III, pp. 15-31, AGU, Washington, D. C., 1977.

Hamilton W., Tectonics of the Indonesian region, U.S. Geol. Surv. Prof. Pap. 1078, 345 pp., 1979.

Hayes, D. E., R. E. Houtz, R. D. Jarrard, C. L. Mrozowski, and T. Watanabe, Crustal Structure, in A Geophysical Atlas of the East and Southeast Asian Seas, Map Chart Ser. MC-25, Geological Society of America, Boulder, Colo., 1978.

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.

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.

Johnston, C. R. and C. O. Bowin, Crustal reactions resulting from the mid-Pliocene to Recent continent-island arc collision in the Timor region, BMR Jour. Aust. Geol. Geophys., 6, 223-243, 1981.

Jordan, T. E., B. L. Isacks, R. W. Allmendinger, J. A. Brewer, and C. J. Ando, Andean tectonics: Lateral segmentation of central Andes related to geometry of subducted plate (abstract), Geol. Soc. Am. Abstr. Programs, 13, 481, 1981.

Karig, D. E., G. F. Moore, J. R. Curray, and M. B. Lawrence, Morphology of the lower trench slope off Nias island, Sunda arc, in The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Geophys. Monogr. Ser. vol. 23, edited by D. E. Hayes, pp. 179-208, AGU, Washington, D. C., 1980.

Kelleher, J., and W. McCann, Buoyant zones, great earthquakes, and unstable boundaries of subduction, J. Geophys. Res., 81, 4885-4896, 1976.

Mammerickx, J., R. L. Fisher, F. J. Emmel, and S. M. Smith, Bathymetry of the east and southeast

Asian seas, Map Chart Ser. MC-17, Geological Society of America, Boulder, Colo., 1976.

cCaffrey, R., Evidence for lateral segmentation of the subducted Australian-Indian plate beneath the Banda arc near western Timor (abstract), Eos trans. AGU, 62, 949, 1981.

cKenzie, D. P., Speculations on the consequences and causes of plate motion, Geophys. J. R. Astron. Soc., 18, 1-18, 1969.

cKenzie, D. P., The initiation of trenches: a finite amplitude instability, in Island Arcs, Deep Sea Trenches and Back-arc Basins, Maurice Ewing Ser., vol. 1, edited by M. Talwani, and W. C. Pitman III, pp. 57-61, AGU, Washington, D. C., 1977.

egard, F. and H. Philip, Plio-Quaternary tectono-magmatic zonation and plate tectonics in the central Andes, Earth Planet Sci. Lett., 33, 231-238, 1976.

inster, J. B. and T. H. Jordan, Present-day plate motions, J. Geophys. Res., 83, 5331-5354, 1978.

olnar, 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.

ontecchi, P. A., Some shallow tectonic consequences of subduction and their meaning to the hydrocarbon explorationist, in Circum-Pacific energy and mineral resources, Mem. Am. Assoc. Pet. Geol. 25, 189-202, 1976.

oore, J. C., J. S. Watkins, and T. H. Shipley, Summary of accretionary processes, Deep Sea Drilling Project leg 66: Offscraping, underplating, and deformation of the slope apron Initial rep. Deep Sea Drill. Proj., 66, 825-836, 1981.

oore, J. C., Offscraping and underthrusting of sediment at the deformation front of the Barbados Ridge: Deep Sea Drilling Project leg 78A, Geol. Soc. Am. Bull., 93, 1065-1077, 1982.

akamura, K. and S. Uyeda, Stress gradient in arc-back arc regions and plate subduction, J. Geophys. Res., 85, 6419-6428, 1980.

rice, R. A., The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, in Thrust and Nappe Tectonics, Geol. Soc. London Spec. Publ., vol. 9, edited by K. R. McClay, and N. J. Price, pp. 427-448, Blackwell Scientific, London, 1981.

rice, R. A., and E. W. Mountjoy, Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca rivers--aprogress report, in Structure of the Southern Canadian Cordillera, edited by J. O. Wheeler, Spec. Pap. Geol. Assoc. Can., 6, 7-25, 1970.

Raitt, R. W., Marine seismic refraction studies of the Indonesian island arc (abstract), Eos Trans. AGU, 48, 217, 1967.

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.

Smith, A. G., Subduction and coeval thrust belts, with particular reference to North America, in Thrust and Nappe Tectonics, Geol. Soc. London Spec. Publ., vol. 9, edited by K. R. McClay and N. J. Price, pp. 111-124, Blackwell Scientific, London, 1981.

Stewart, G. S., Implications for plate-tectonics of the Aug. 19, 1977 Indonesian decoupling normal-fault earthquake (abstract), Eos Trans. AGU, 59, 326, 1978.

Suppe, J., Imbricated structure of western foot-hills belt, south-central Taiwan, Pet. Geol. Taiwan, 17, 1-16, 1980.

Usna, I., S. Tjokrosapoetro, S. Wiryosujono, Geological interpretation of a seismic reflection profile across the Banda Sea between Wetar and Buru islands, Geol. Res. Develop. Cent. Bull., 1, 7-15, 1979.

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

Watts, A. B., J. H. Bodine, and C. O. Bowin, Free air gravity field, in A Geophysical Atlas of East and Southeast Asian Seas, Map Chart Ser., MC-25, Geological Society of America, Boulder, Colo., 1978.

Whitford, D. G., W. Comston, I. A. Nicholls, and M. J. Abbott, Geochemistry of late Cenozoic lavas from estern Indonesia--Role of subducted sediments in petrogenesis, Geology, 5, 571-575, 1977.

Yoshii, T., A detailed cross-section of the deep seismic zone beneath northeastern Honshu, Japan, Tectonophysics, 55, 349-360, 1979.

(Received October 11, 1982
revised April 28, 1983;
accepted April 28, 1983.)