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COLLISION, ROTATION, AND THE INITIATION OF SUBDUCTION IN THE EVOLUTION OF SULAWESI, INDONESIA

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Abstract. The island of Sulawesi, Indonesia, has been shaped and deformed as a result of collision with the Sula platform, a sliver of continental material from the northern margin of Australia-New Guinea. The collision has resulted in rotation of the north volcanic arm of Sulawesi and the development of the accretionary wedge of the North Sulawesi trench. The North Sulawesi trench changes laterally from a zone of no active deformation in the eastern part to a wide accretionary wedge in the west. Early stages of thrusting produce a steep frontal slope (8^{o}-16^{o}), indicative of relatively high basal shear stress, whereas the more advanced (western) zone of thrusting produces a gentle (2^{o}) slope, consistent with low basal shear stress. Reported paleomagnetic data suggest post late Eocene counter-clockwise rotation of the North Arm, and the offshore geophysics are explained by a pivot of the North Arm with respect to the Celebes basin about the eastern end of the arc. Convergence between the north Banda basin and Southeast Sulawesi is documented by the presence of the Tolo thrust. Its outcrop is strongly arcuate and its accretionary wedge varies in width from a minimum of a few kilometers at each end to a maximum of 30-40 km in the central part. The northern end transforms to the left-lateral Matano fault, with a reported offset of 20 km. The southern end of the thrust projects toward the deformed rocks of Buton, but the structural relations there are not clear. The Matano fault zone appears to connect westward with the Palu fault, which forms the western transform of the North Sulawesi trench. The Palu-Matano fault system acts as a trench-trench transform between the North Sulawesi trench and the Tolo thrust, and this system is described by the same rotation pole as that for the Sulawesi North Arm.

Introduction

The broad collision zone of eastern Indonesia displays a variety of nonterminal collision events driven primarily by rapid convergence of the Australian plate and continent from the south and the Pacific, Caroline, and Philippine plates from the east against the eastern Sunda, Banda, Sulawesi, and Halmahera arcs (Figure 1). We have proposed [Silver and Smith, 1983] that this complex collision zone can provide a modern example of the processes involved in the accretion of terranes, reported commonly from ancient mountain belts [Coney et al., 1980; Jones et al., 1982; Williams and Hatcher, 1982]. Here we examine the effect on the island of Sulawesi of the middle Miocene collision by the Sula platform.

The primary collision event in the Southeast Asian region was that of Australia colliding with the Indonesian island arcs. Hamilton [1979] interpreted a sequential collision, beginning in western New Guinea (Irian Jaya) in early Miocene time, and progressing eastward to Papua New Guinea in late Miocene time. Rotation of the Banda arc appears to have accompanied the collision.

In addition to rotation of the Banda arc, slices of northern Irian Jaya apparently have been displaced westward to collide with the Sulawesi arc. The largest slice is the Sula platform. The platform includes Paleozoic and early Mesozoic granitic, volcanic, and metamorphic rocks; Jurassic black shale overlying a basal quartz sandstone; Cretaceous clastic sediments and marls; and lower Tertiary sandstone and limestone. A similar geologic section is found in the Bird's Head region of Irian Jaya, providing the basis for the suggested correlation between these areas [Hamilton, 1979]. Hamilton illustrates in his reconstruction that the source terrane for the platform has been moving rapidly northward relative to Southeast Asia during the Neogene.

The major fault systems of Sulawesi at present can be described broadly as conforming to a pole of rotation located at the north tip of the island. These fault systems form an arcuate trench-trench-transform geometry, and we will explore that geometry and its apparent evolution in this paper. The dominant tectonic elements are the North Sulawesi trench, the Palu-Matano transform, and the Tolo thrust (Figure 1). We will examine the system in that order. The deformation appears to have been driven by the collision between Sulawesi and the Sula platform, and we discuss the internal zone of that collision in a separate paper.

Field Program and Data Presentation

Marine geophysical study of the collision zone was carried out during two cruises aboard the R/V Thomas Washington (from Scripps Institution of Oceanography) on Indopac 10 and Mariana 9 expeditions in 1977 and 1979, respectively. Track lines are shown on Figure 2. Supplementary data are from Indopac 7 and 8 and from various other cruises through the area, and some of the latter data are presented by Hamilton [1979]. Data are largely seismic reflection, gravity, magnetics, seismic refraction, and bathymetric surveys. A few profiles are multichannel seismic lines which have received preliminary processing. Seismic profiles are presented largely as line drawing interpretations of original records. Several profiles are shown with free air gravity and magnetic anomaly data. Satellite navigation was used for ship loca-

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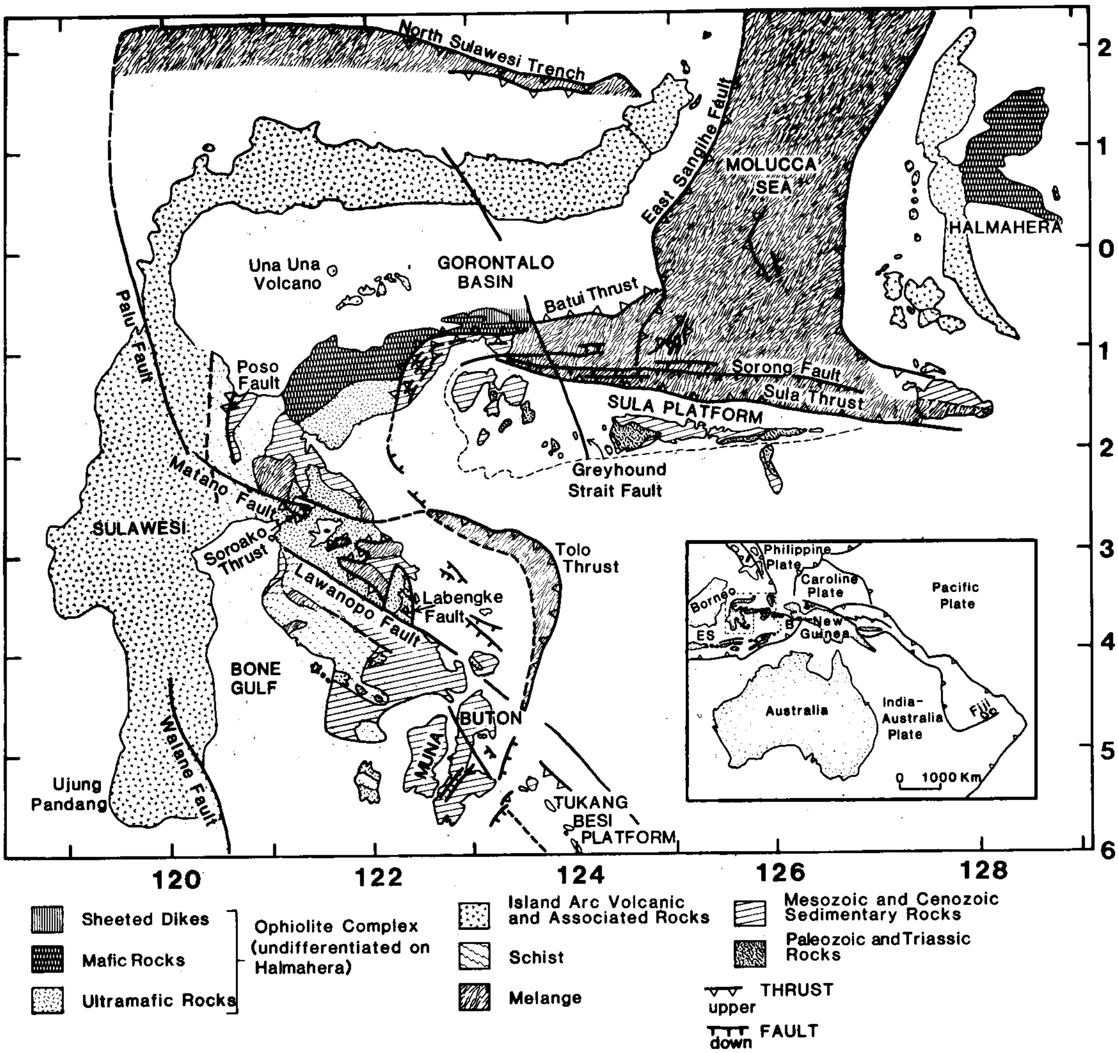

Fig. 1. Generalized tectonic map of Sulawesi and the Molucca Sea region, showing major lithologic sequences and faults. Location map shown as inset (B, Banda arc; ES, Eastern Sunda arc). Bird's Head region of Irian Jaya (New Guinea) is located just north of the symbol "B" on the inset map. Scale along right axis in degrees of latitude, where 1° equals 111 km.

tion. All original data are available through the National Geophysical and Solar-Terrestrial Data Center in Boulder, Colorado.

The North Sulawesi Trench

Hamilton [1979] and Katili [1975] interpreted the North Sulawesi trench as a zone of subduction accommodating convergence between the Celebes basin and Sulawesi North Arm. Katili considered only the western part to be active, but Hamilton [1979] showed the eastern part to be active also. Our more detailed study presented here is in good agreement with Hamilton. Weissel [1980] identified Eocene magnetic anomalies in the Celebes basin which become younger toward the North Sulawesi trench, implying post-Eocene subduction beneath the trench. We surveyed the eastern end in some detail because of the chance to study a zone of convergence showing a rapid change in subduction rate along strike. The five profiles (lines 16 to 25) in Figure 3 display this variation.

These profiles show a westward increase in width of the accretionary prism, a varying structural style in the forearc region, and an independently varying structure of the frontal thrust zone. In the easternmost line (16) the slope basin is deformed, but there is no obvious frontal thrust. Acoustic penetration into the undeformed Celebes basin strata is minimal here, possibly indicating coarse sediment in this corner of the basin. The zone of thrust accretion is 15 km wide in profile 18 and has a broad outer ridge and a narrow forearc basin.

The zone of frontal thrusting is wider in line 21 (over 20 km wide), and the thrusts appear to verge south (landward). Vergence is indicated by the apparent dip of the faults, by the fact that the lowermost fold shows faulting primarily on its south side, and by the level plateau surface (60-80 km) rather than a sloping surface. This structure is comparable to that off central Washington where landward verging thrusts have been well established [Silver, 1972; Carson et al., 1974; Seely, 1977; Barnard, 1978]. The southern part of this plateau (60 km) appears to

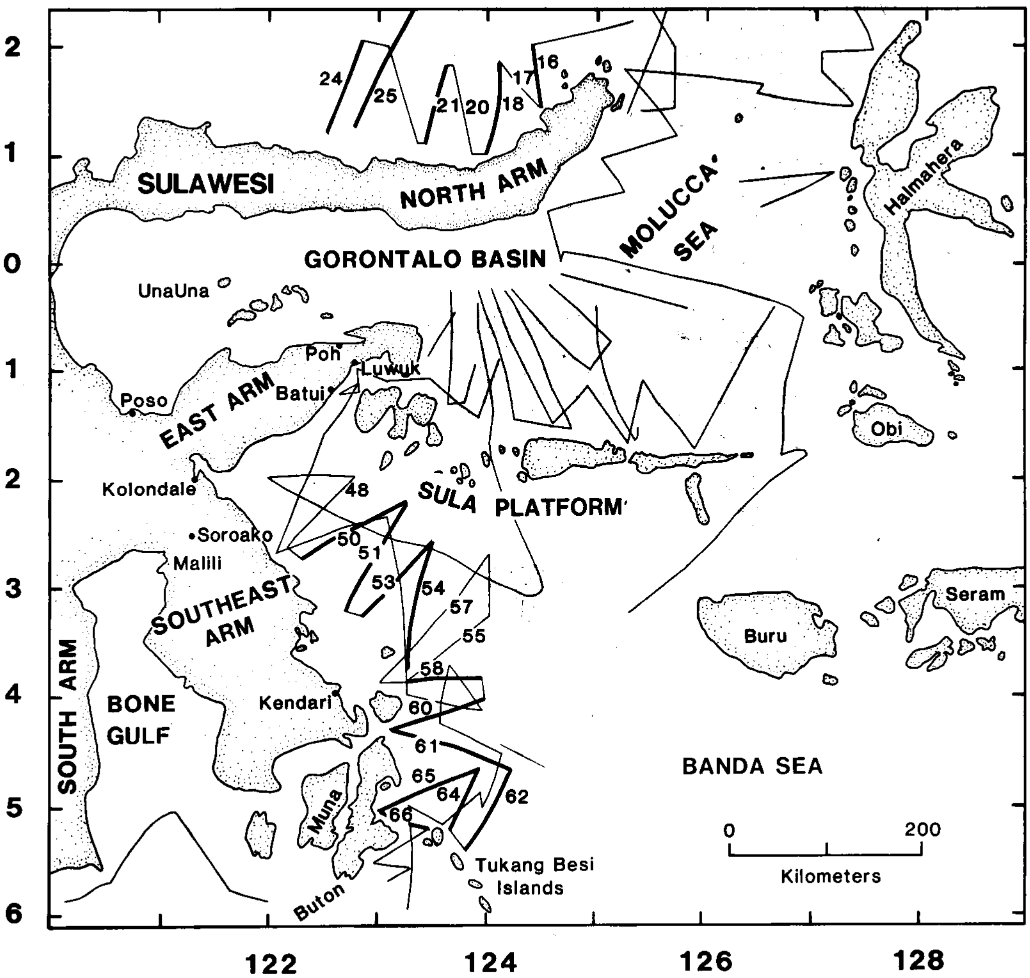

Fig. 2. Track of R/V Thomas Washington on Mariana 9 and Indopac 7 and 10 expeditions. Data along tracks include seismic reflection, gravity, magnetics, and bathymetry. Heavy lines locate profiles shown in this report. Also shown are geographic features discussed in text.

be bounded by several south dipping thrusts.

Lines 24 and 25 show a wide accretionary wedge with seaward verging thrusts, and they follow the surface of oceanic crust below the accretionary zone. They are adjacent profiles, but line 25 is a 21-fold multichannel profile. Note the apparently higher resolution in the single-channel line (24) and the deeper penetration in the nonmigrated multichannel line (Figure 4). The top of the oceanic crust forms a prominent reflector that can be traced beneath the accreting prism for 40 km on line 25. It probably coincides with the main basal thrust a few kilometers south of the frontal thrust. The basal thrust is low angle (less than 6°) except where it cuts through the sedimentary section at the toe of the accretionary wedge. Line 25 allows us to estimate the cross-sectional area of the accretionary wedge because we can trace the basal thrust nearly to where it intersects the front of the constructional arc ediface (40 km, Figures 3 and 4). The accretionary wedge is composed of both accreted thrust slices of Celebes basin strata and of arc derived material deposited directly on the wedge. Although we can estimate and correct for the latter deposits in estimating accretionary volume, we can't distinguish possible sedimentary basin material that may have been first deposited on and later interthrust with the accretionary wedge.

The cross-sectional area of the wedge in profile 25, from 35 to 80 km, excluding the region of slope deposition, is approximately 200 km^2. For a steady state sediment input of 2 km of sediment always about to be accreted at the toe of the wedge and assuming 40% reduction in volume during accretion [Moore and Karig, 1976], the total undeformed area would be 333 km^2, and it implies 120 km of convergence at this location. This figure is a minimum value because of the probability that some of the sedimentary section is not accreted but is removed by subduction. The predicted minimum convergence at the vicinity of Una Una is about 240 km if we assume a pole of rotation at the east end of the North Arm (discussed below) because Una Una is twice as far from this pole of rotation as is line 25. The observed length of the seismic zone here is about 350 km.

The geometry of the accretionary wedge, in which the size of the wedge increases westward, has been explained by Hamilton [1979] as due to rotation of the North Arm about a pivot which is now located near the eastern end of the arm. Hamilton feels that the pivot has migrated eastward with time as the North Sulawesi trench in-

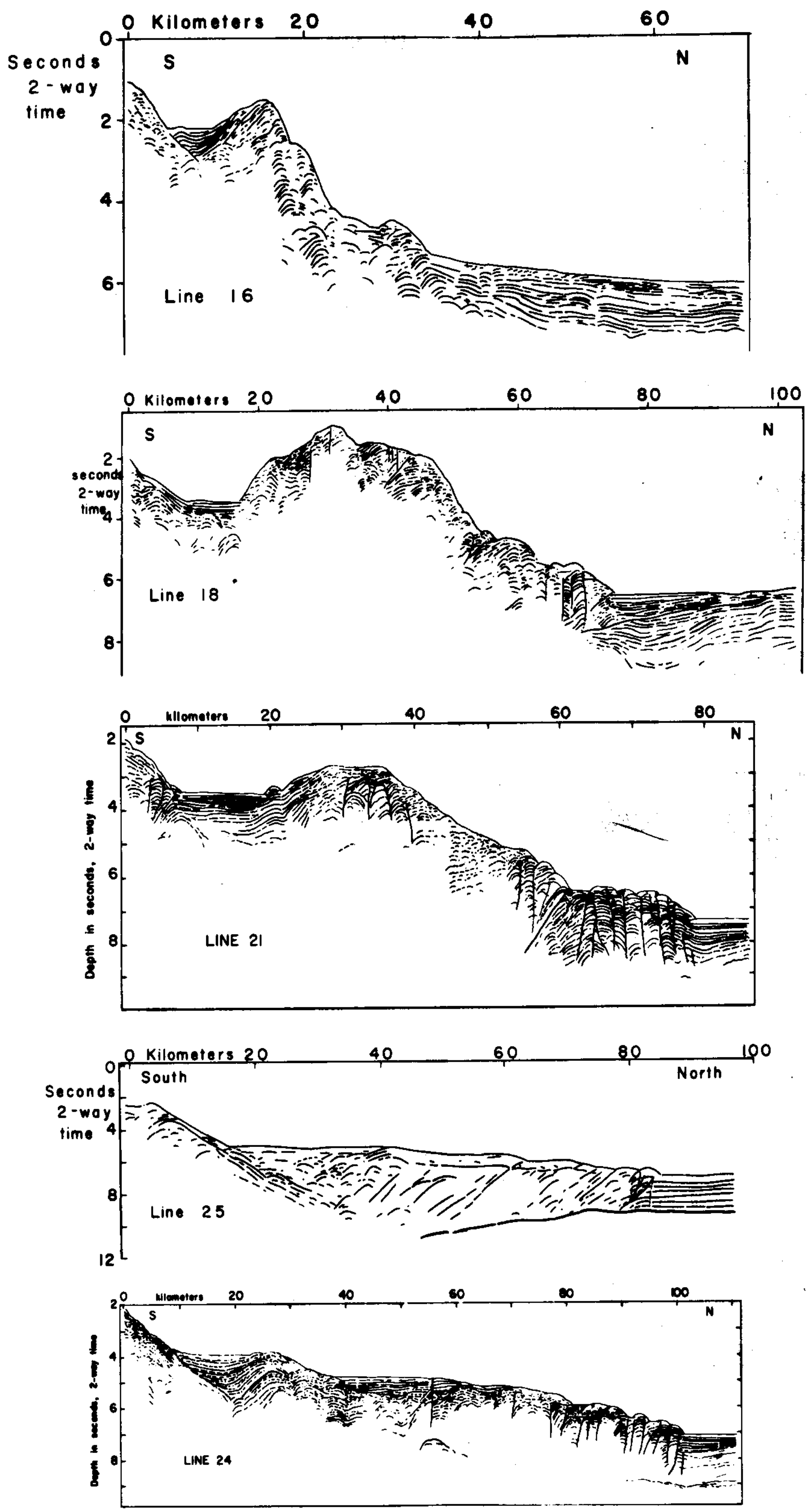

Fig. 3. Line drawing interpretations of profiles crossing the North Sulawesi trench. Lines 16, 18, 21, and 24 are single-channel profiles (Vertical exaggeration = 6.7x). Line 25 is a 21-fold multichannel profile (VE = 3.5x). See Figure 2 for location.

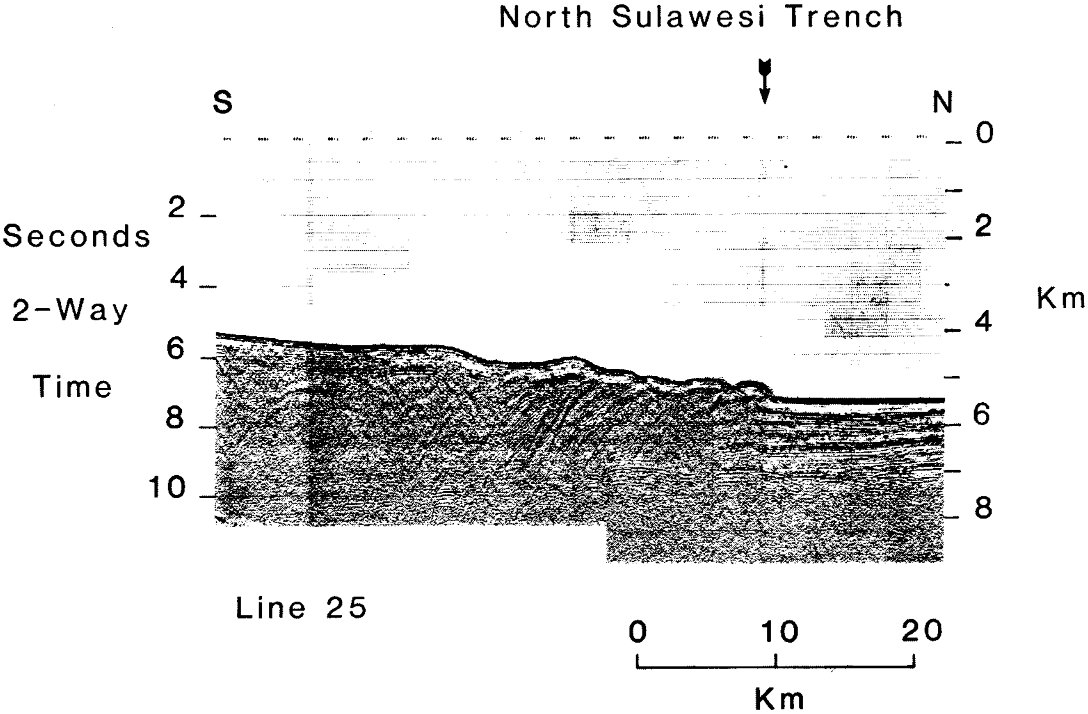

Fig. 4. Detail of multichannel profile 25.

creased in size and the East Sangihe trench decreased. The idea of rotation is supported by paleomagnetic results of Otofuji et al. [1981]. They indicate that more than 90° of clockwise rotation occurred after the Eocene but before the Plio-Pleistocene. These data must be viewed cautiously because of the difficulty in correcting for local tectonic effects.

The variation in structure of the accretionary wedge as seen in Figure 4 may indicate changes in basal shear stress as the thrust develops. Recent work by Davis et al. [1983] and Chapple [1978] shows that the shape (or taper) of the accretionary wedge depends on both the basal shear stress (which is the sum of the stress due to the surface slope and that due to compression on the wedge) and the internal strength of the material. The wedge taper is defined as the sum of the surface slope of the wedge plus the basal slope of the main thrust. It seems unlikely that radical changes in the internal strength of the wedge are occurring over these profiles because the material accreting to the front of the wedge is most likely similar along its length. Thus until we are able to measure the strength of the materials within the wedge, we suggest that it is most likely that significant changes in the shape or taper of the wedge are due largely to differences in the basal shear stress, which, in turn, are critically dependent upon fluid pressures.

The profiles shown in Figure 3 illustrate major changes in the surface slope of the wedge. Measured surface slopes of the wedge in profiles 16, 18, and 21 range from 8° to 16° while the slopes of lines 24 and 25 are 2°. We infer from these observations (and from the assumption of nonsignificant variation in strength of materials along the wedge front) that in the initial stages of thrust development, or where the amount of slip is small, the thrust has a high basal shear stress. As the amount of slip increases (for areas of thick sediment accretion), the basal thrust becomes well established, fluid pressures increase and the thrust surface becomes hydraulically interconnected, and the frictional resistance along the thrust surface decreases sharply. Note the significantly increased flattening of the outer 15 km of the wedge in line 21, compared with line 18 (Figure 3). By line 24 the whole slope region (outer 60 km) is very low angle. This region may prove valuable for future studies of the initiation of thrusting.

A southward dipping seismic zone extends from the North Sulawesi trench to about 300-km depth beneath Una Una volcano, but the zone is observable only in the region from 121.8° to 122.2°E (Figure 5). Several shallow earthquakes are observed north of the North Arm between 120° and 123°E, and these are possibly related to the trench. Two focal plane mechanisms for earthquakes at the trench suggest north-south compression, one at 121.06°E [Cardwell et al., 1980] and the other at 123.28°E [McCaffrey, 1981]. Any connection between the seismic zone and Una Una volcano however, is yet unresolved.

The Palu-Matano Fault System

The Palu fault is the major structure cutting the South Arm (Figure 1). Holocene left slip is established on the fault [Tjia, 1981] and its geomorphic expression is clear. Hamilton [1979] considered this fault to be a bounding transform for the west end of the North Sulawesi trench and that it may connect with the Matano fault. Although such a connection is likely, it has yet to be established.

The Palu fault has had six M>=7.0 earthquakes since 1897 [Duda, 1965; Bath and Duda, 1975]. The seaward extension of the fault is drawn by Hamil-

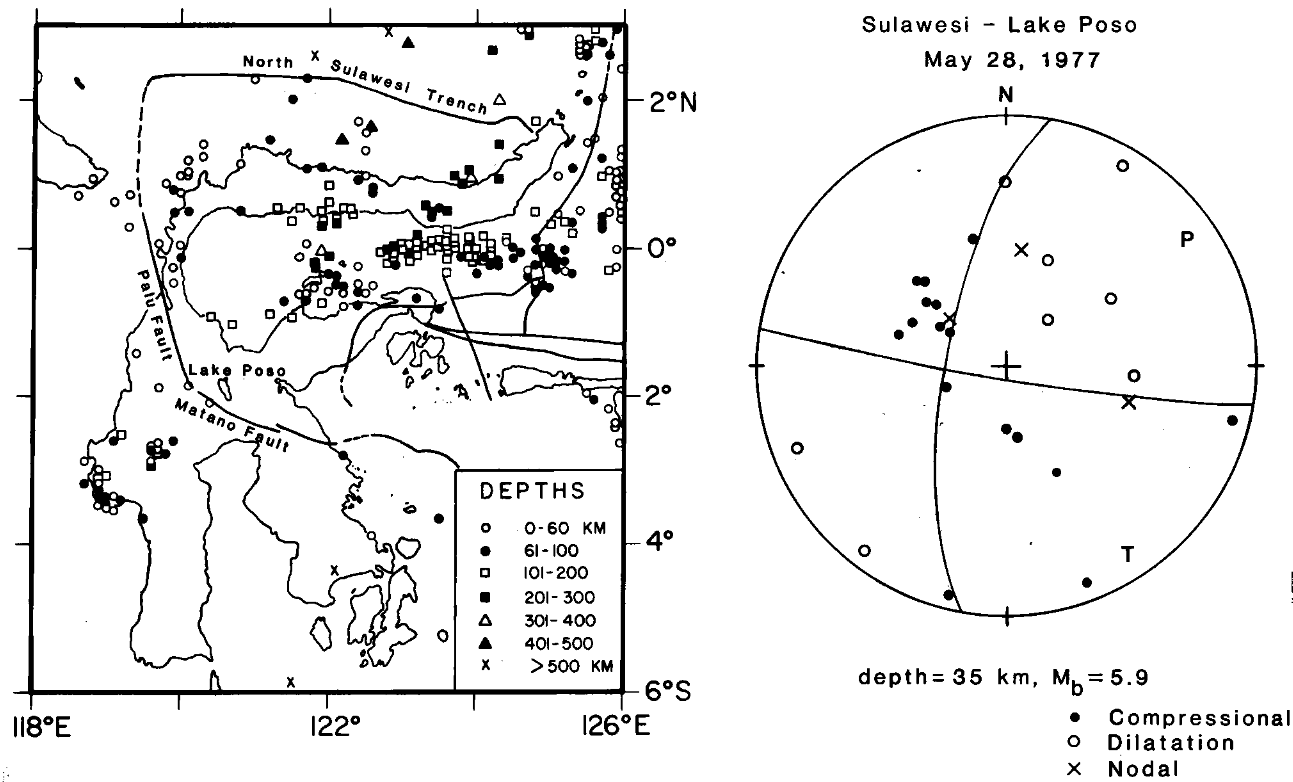

Fig. 5. Map of earthquake epicenters in the Sulawesi region (left) and preliminary fault plane solution for the Lake Poso earthquake of May 28, 1977. Lower hemisphere plot.

ton [1979] to intersect the North Sulawesi trench at about 119.2°E, but the shallow seismic activity aligns in a zone that is more nearly parallel to the sharp bend in the North Arm (Figure 5). These earthquakes may outline a branch of the Palu fault.

In north-central Sulawesi seismic activity is shallow and scattered. Fitch [1970] published a focal plane solution from the Palu fault suggesting left-lateral motion. Figure 5 shows a fault plane solution for the event of May 28, 1977, which had a similar mechanism but probably occurred nearer to Lake Poso than the event reported by Fitch [1970]. This earthquake was near the Poso fault, which bounds the western margin of the lake, and suggests that at least some left-lateral motion is taken up on faults other than the Palu. The area around Lake Poso is a broad zone of deformation [Katili, 1978] and is near the region of probable intersection of the Palu and Matano faults.

Moderate earthquake activity is associated with the Matano fault in east-central Sulawesi. Few earthquakes are reported in International Seismological Center bulletins, but McCaffrey and Sutardjo [1982] reported three which occurred near the lake and had a north striking normal faulting composite fault plane solution. Lake Matano may be a small pull-apart basin offsetting the Matano fault. Only one event has been identified along the seaward extension of the Matano fault near the Tolo thrust (Figure 5).

The Tolo Thrust

The Tolo thrust [Silver, 1981] is a long, arcuate thrust fault that cuts the Tolo Gulf off the east margin of SE Sulawesi. This thrust marks the zone of convergence between southeast Sulawesi and the northwest Banda basin, and it appears to join the Matano fault zone onshore. The location and structure of the Tolo thrust are well controlled by reflection profiles (Figures 6 and 7). The zone of deformation associated with the thrust is greatest in the central part and dies off toward either end. In the south it may splay into a series of faults trending toward and east of Buton Island.

The northernmost profile which shows the thrust is line 50 (Figure 6), where the associated zone of deformation (30 km) is only 5 km wide. Line 48 does not indicate thrusting nor does S17 immediately adjacent. By line 51 the deformation zone is 20 km wide and clearly defined, with a small turbidite basin (40 km) trapped behind the deformed outer ridge. The zone of deformation is over 30 km wide in line 53, is well defined, and has also trapped a small sedimentary basin. The deformed zone maintains a width of 30-40 km around the central part of the thrust, then decreases to 10 km in line 58, less than 10 km in line 60, and about 5 km in line 61 (Figure 7).

Hamilton [1979] suggested that the Matano fault offset the thrust. We find it more reasonable to consider the Matano fault as the inland continuation of the Tolo thrust, intersecting the thrust at its north end, just north of line 50. By this view, a continuous tectonic zone can be followed from Buton northward to the Matano fault, then NW along the Palu fault to the North Sulawesi trench. The Matano-Palu faults would then represent a transform system between the Tolo thrust and the North Sulawesi trench.

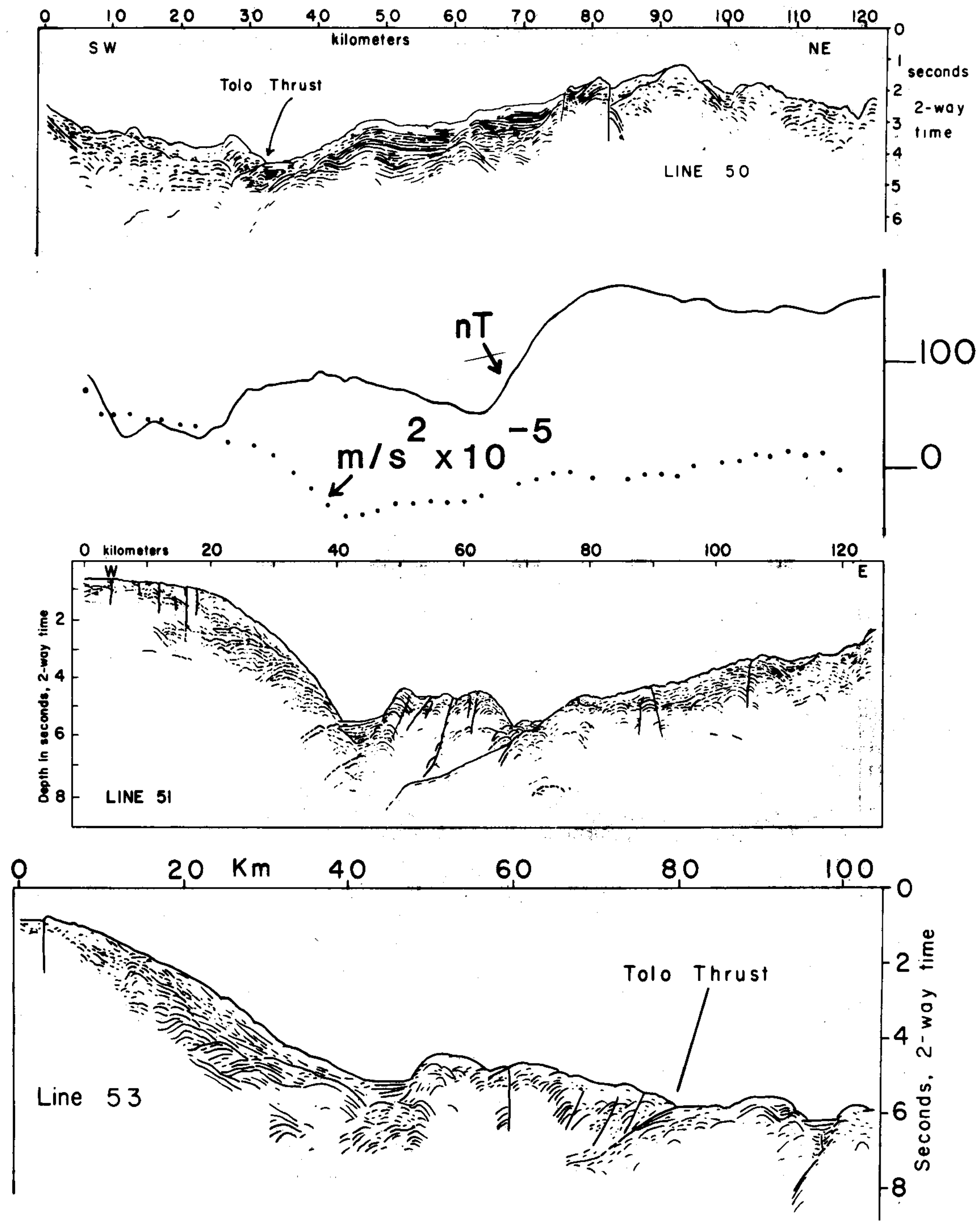

Fig. 6. Line drawing interpretations of profiles 50, 51, and 53 crossing the northern part of the Tolo thrust. (VE = 6.7x.) Free air gravity and magnetic anomaly profiles are shown for profile 51. See Figure 2 for location.

In two areas, local bathymetric highs are colliding with the Tolo thrust. The northern high is best seen in line 54 (Figure 7, 130 km), the southern in lines 60 and 61 (Figure 7). One effect of these collisions appears to be a steepening of the main thrust near the toe, which basically reflects the west slope of these ridges. The southern ridge is associated with a local bend in the mapped outcrop of the thrust. The effect of the northern ridge is less clear. Magnetic anomalies are localized over both ridges, implying volcanic composition.

Faults of large vertical separation cut the north Banda basin east of the Tolo thrust (e.g., line 53, 100 km; line 60, 75 km). Hamilton [1979] mapped one of these faults, which traps an asymmetric sedimentary basin, as an inactive trench. These are not zones of subduction (presumably implied by his use of "trench") because the sediment fill in the small fault basins is not deformed. They may have originated as either normal or reverse faults.

The dramatic decrease in width of the wedge in both directions away from the central part of the thrust appears characteristic of a slide phenomenon, but the geometry of the deformed zone

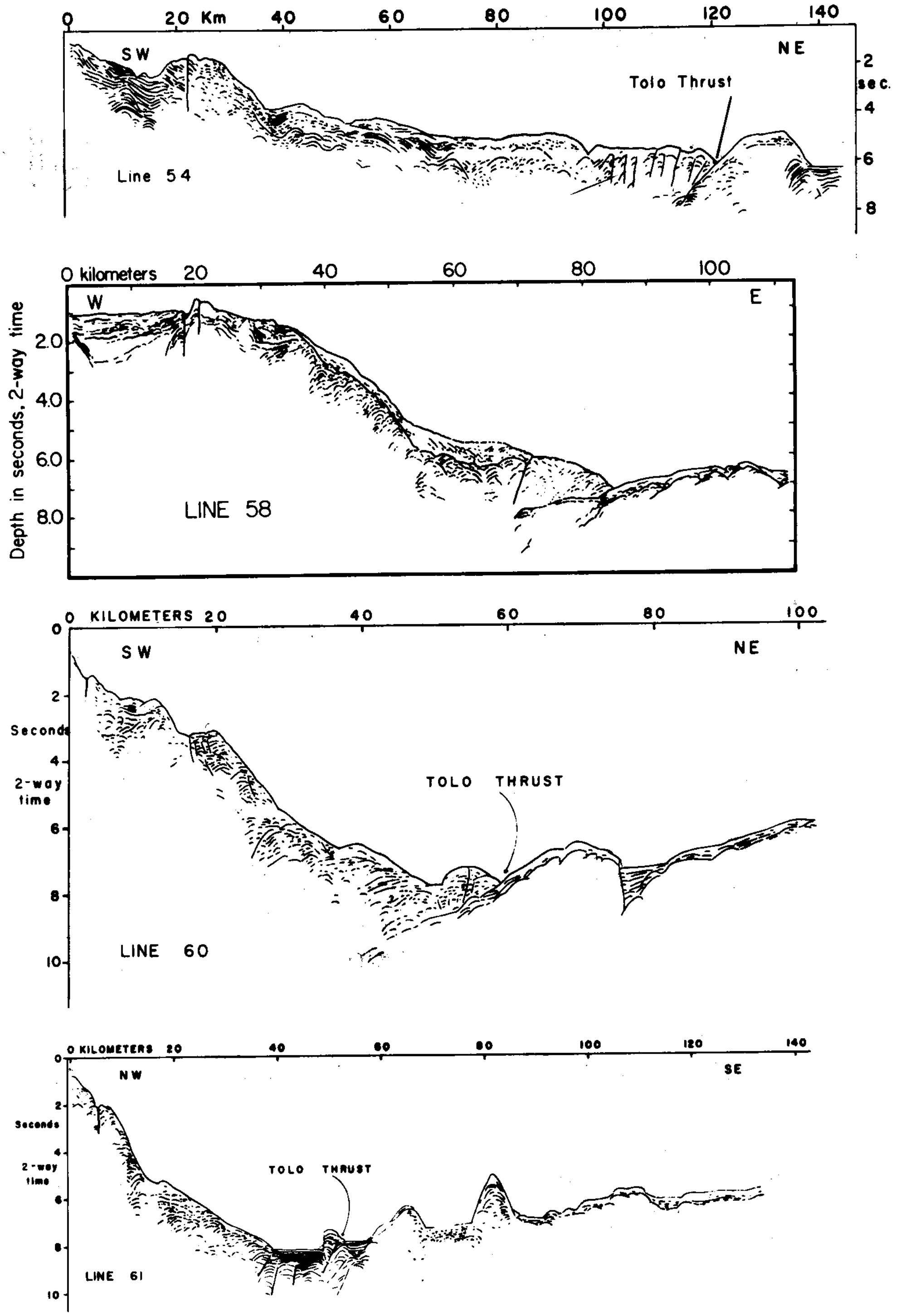

Fig. 7. Line drawing interpretations of profiles 54, 58, 60, and 61 crossing the southern part of the Tolo thrust. (VE = 6.7x.) See Figure 2 for location.

behind the thrust leads us to view its formation as a tectonic thrust. Lines 51 and 53 especially show a distinct difference in the structure of the wedge compared to the slope above it. We see no sign in any profile of an upslope source region for the wedge material. Instead, the wedge appears accreted to the slope, and a small tilted sedimentary basin is trapped in the site of initial accretion. If the convergence direction were that of the Matano fault, then the component of convergence along the north part of the Tolo thrust should decrease progressively as its trend approaches that of the Matano fault, just as observed.

The southern end of the Tolo thrust projects into a transverse, northwest trending slope that lies along the north east boundary of the Tukang Besi platform. This boundary may cut-off the thrust from progressing farther to the south. If, however, we project the trend of the thrust south-

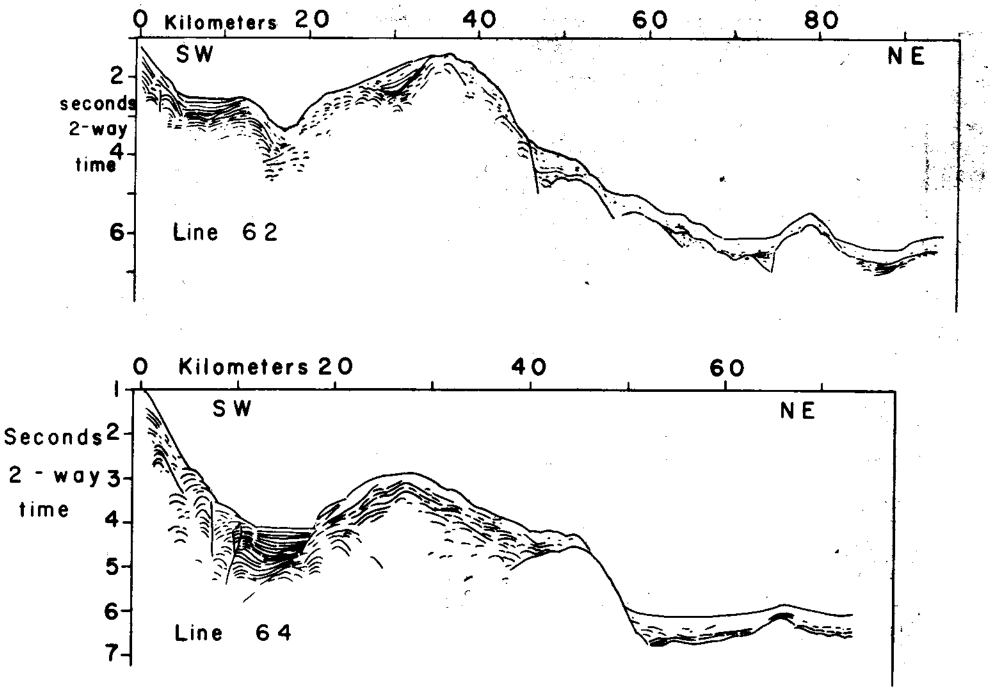

Fig. 8. Line drawing interpretations of profiles 62 and 64, taken over the NE corner of the Tukang Besi platform. (VE = 6.7x.) See Figure 2 for location.

ward to Buton, we encounter a broad zone of folding. Structures mapped on Buton are aligned subparallel to the thrust.

Hamilton [1979] suggested that the northeast margin of the platform might be an inactive trench, but we see no evidence for that on profiles 62 and 64 (Figure 8) or on other profiles in this region. A local zone of minor thrusting is developed on the NE flank of the island ridge in line 64 (10 km), resulting in deformation of sediments in a small turbidite basin, but the thrust has nearly or entirely died out in line 62 (0-20 km). Bedrock has not been reported from the platform, as only coral terrace deposits crop out on the islands. Although the gross structure of the platform is northwest oriented, W. H. Hetzel (unpublished report, 1936) reports northeast striking late Neogene beds on Wangi-Wangi, perpendicular to those of the platform but parallel to those of Buton.

The deformation associated with the Tolo thrust and its northern extensions appears to die out southward. Alternatively, the deformation could be distributed among a series of poorly mapped fault strands that cut the Banda basin, but except for the enigmatic structure bounding the eastern margin of the Tukang Besi platform, such faults have not been identified.

Discussion

The convergence direction between the Sula platform and Sulawesi is difficult to determine by common plate tectonic methods because of uncertainties in major plate motions [e.g. Molnar and Tapponnier, 1975; Hamilton, 1979; Cardwell and Isacks, 1978; Bowin et al., 1980], the abundance of small plates in eastern Indonesia, and the difficulty of determining movement rates between these plates. We can estimate convergence direction from major tectonic features, and although we now have better structural control, we are in general agreement with interpretations of Hamilton [1979]. Based on the dominant direction and sense of slip on thrust and lateral faults, it appears that the Sula platform collided northwestward relative to Sulawesi.

We infer northwesterly motion of the Sula platform relative to South Sulawesi on the basis of several significant observations. One is the arcuate trace of the Batui and related thrust faults on the northwest side of the platform (discussed in a separate paper), implying a leading edge to the moving block. Second, several lines of evidence exist for a clockwise rotation of the North Arm of Sulawesi, that is most easily explained as having been driven by the northwesterly collision of the platform. The accretionary wedge along the north margin of North Arm increases in width westward, and the Matano and Palu strike slip faults transform between the Tolo thrust and the North Sulawesi trench. Both the wedge geometry and the arcuate pattern of transform faulting are consistent with a rotation of the North Arm about a pivot near the east end of the arm. Finally, but with some uncertainty, paleomagnetic data of Otofuji et al. [1981] indicate large clockwise rotation of the westernmost part of North Arm, between Eocene and Pliocene.

While several lines of evidence for rotation of the North Arm seem to fit qualitatively, there are quantitative problems with this interpretation. If 90° of rotation of North Arm were taken up by slip along the Palu-Matano fault system, it implies much more offset than the geological and geometric evidence seemingly allow. Also, while the rotation reported by Otofuji et al. was completed by Pliocene time, seismic and structural data indicate much deformation of the North Sulawesi trench in Plio-Pleistocene time.

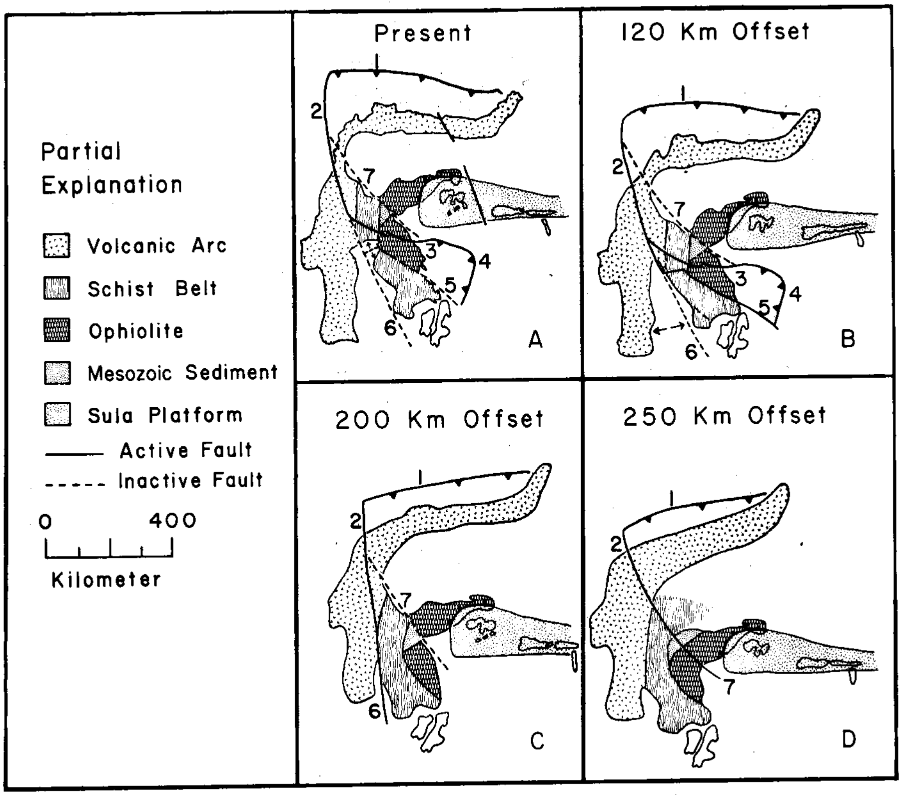

Fig. 9. Hypothetical reconstructions of Sulawesi, based on observed geological relations. (a) Present setting, showing all faults used in the reconstructions. (b) Offset of rocks along the Palu, Lawanopo, and Matano faults, constrained by closing the northern part of the Bone Gulf and by geology along the Matano fault. (c) Offset along the Palu fault and its extension in the Bone Gulf plus closure of the gulf. (d) Slip along the Palu fault and its extension through central Sulawesi, juxtaposing rocks of the ophiolite suite more tightly. Fault names: 1, North Sulawesi; 2, Palu; 3, Matano; 4, Tolo; 5, Lawanopo; 6, Bone Gulf; 7, Kolonodale.

We suggest that the rotation reported by Otofuji et al. may have occurred largely prior to both the deformation we see in the North Sulawesi trench and the offset along the Palu and Matano faults. The trench deformation indicates perhaps 200-300 km of convergence, although these values are approximations and based on a number of untested assumptions. Offset on the Matano fault is perhaps 20 km [Ahmad, 1978] and that along the Palu fault is unknown. Slip of 500-1000 km would drastically disrupt the regional pattern of volcanic, metamorphic, and ophiolitic belts presently observed on Sulawesi, while 150-250 km could be accommodated reasonably, as follows (see Figure 9).

The 20 km of slip on the Matano fault estimated by Ahmad [1978] provides a good measure of the convergence necessary to create the Tolo thrust. This structure is probably young, and the Matano fault is presently active [McCaffrey and Sutardjo, 1982]. We can produce an additional 100 km of slip along the Palu fault by connecting it, via a small spreading center in the northern Bone Gulf [Hamilton, 1979], to the Lawanopo fault [Figure 9]. By connecting the Palu fault with the eastern margin of the Bone Gulf and closing the gulf, as in Figure 9, we can produce an additional 80 km of slip. This offset is not tightly constrained except that much more slip than this would leave an excessive offset along the NW coast of Sulawesi. Finally, we add about 50 km of slip on the Palu-Kolonodale fault, the latter passing through Kolonodale (Figure 9). This movement produces a tighter outcrop pattern for the ophiolite and suggests a tectonic explanation for the apparent sharp cutoff of the schist belt in its north end. The total movement of the North Arm along the Palu fault, according to these reconstructions, is about 250 km.

The difference between this value and the 350-km length of the deep seismic zone may be partly explained by the width of the accretionary prism, which is 50-100 km wide on the west end (see Figure 3, line 24, and Figure 98 of Hamilton [1979]). A large discrepancy is seen, however, between the rotation of the North Arm implied in Figure 9 (20°) and the 90° of rotation indicated by Otofuji et al. [1981]. If we assume that both our constructions and those of Otofuji et al. are valid, the resolution may be in the timing of events. The 250 km of offset that we construct could reasonably have occurred in the past 5 Ma, at a rate of 50 mm/Ma along the Palu fault. The rotations measured by Otofuji et al. could have begun as early as late Eocene time, and the bulk of the rotation resulted from a very different mechanism, such as subduction on the SE side of the North Arm. Alternatively, Otofuji et al. may have observed local rotations of small blocks near major fault zones, not representative of the behavior of the entire North Arm. Such rotations are being discovered increasingly in well-studied tectonic regions [e.g., Beck, 1980]. Interestingly, the study area of Otofuji et al. lies close to a major fault indicated by Katili [1978].

The structural geometry of the North Sulawesi trench is nicely described by a negative rotation (clockwise as viewed from above) about a pole located at the eastern end of the North Arm (as suggested by Hamilton [1979]). The arcuate nature of the Palu fault is nearly, though not quite, a small circle about this pole. The Matano fault deviates by a few degrees from a small circle path but the Lawanopo fault lies close to that path. The Tolo thrust satisfies this geometry as well. The continuation of this system south and east into the Banda Sea is unclear at present. The rather close correspondence of a number of tectonic elements to this nearby rotation pole is more surprising than the deviations because the complex movement history of the Sula platform should have produced varying rotation poles though time.

The development of the complex collision zone as we now observe it in eastern Indonesia involves a variety of processes acting in widely differing directions. Continued slivering of New Guinea, in a manner similar to that of the Sula platform, would result in a complex stack of continental fragments superimposed in the reverse order to their original distributions. The northernmost slice of New Guinea becomes the southernmost sliver in the collision zone. Such slivers, when molded into a linear mountain belt and surrounded by highly strained metamorphic rocks, might be interpreted as "basement core complexes." Grossly misleading interpretations of ancient mountain belts can arise from focusing on a two-dimensional cross-sectional evolution of the belts. Active collision zones cannot provide detailed analogs for ancient moutain belts, but the modern settings can illustrate mechanical processes that may have played important roles in their development.

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