Orogeny in arc-continent collision: The Banda arc and western New Guinea

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ABSTRACT

Eastern Indonesia contains a modern continent–island-arc collision that demonstrates how a complex juxtaposition of continental and oceanic elements can occur in an orogenic belt. Shallow earthquakes show that strike-slip faulting transports large crustal blocks into, out of, and along the collision zone while crustal shortening and thickening occur by steep-angle thrust faulting near the strike-slip faulting. Whereas strike-slip faulting is paramount in positioning Australian continental rocks so as to enclose the oceanic and island-arc rocks of eastern Indonesia, its role may be overshadowed by the contemporaneous thrusting and may confuse geologic interpretations of the resulting orogenic belt.

INTRODUCTION

The Indonesian region is a likely site for the development of a complex orogenic belt that has older analogs in various parts of the world (e.g., Davis et al., 1978; Trümpy, 1983). Thus, understanding the processes active there can provide valuable insights for geologists working in orogenic belts. Of interest here is the collision between the Australian continent and oceanic elements of eastern Indonesia. We present new evidence on the deformations accompanying the collision and discuss some implications for orogenic belts.

Australian continental crust thrusts beneath the Banda island arc along a horseshoe-shaped set of trenches; the Timor, Aru, and Seram troughs (Fig. 1). The Bird's Head in the north is stratigraphically and paleomagnetically similar to Australia and, because the motion of Australia relative to Southeast Asia is northerly, its present geographic position north of the Banda arc presents a geometrical problem. Such a geometry requires either that the overriding plate expands to allow the arcs to migrate outward over a single subducting plate (Hamilton, 1979), or that the Australian plate is split into two or more separate plates in relative motion (Cardwell and Isacks, 1978; Bowin et al., 1980). The two hypotheses predict quite different evolutionary scenarios.

The history and active deformation of the upper plate can be diagnostic of the region's evolution. Parts of the back-arc Banda basin are underlain by oceanic crust (Bowin et al., 1980) of unknown age; it could be older trapped crust or could have formed in place in the Neogene. Other parts of the basin, the Banda ridges in particular, have lithologic similarities to the continental Bird's Head and are thought to be slices of it faulted into position during the middle to late Miocene (Silver et al., 1985). Stratigraphic correlations of northern Australia, southern New Guinea, and the Bird's Head to several islands in eastern Indonesia suggest that they have a similar origin (Hamilton, 1979; Visser and Hermes, 1962).

Here we use focal mechanisms of large ($m_b \geq 5.5$), shallow earthquakes to understand the style of deformation within the region (Fig. 1).

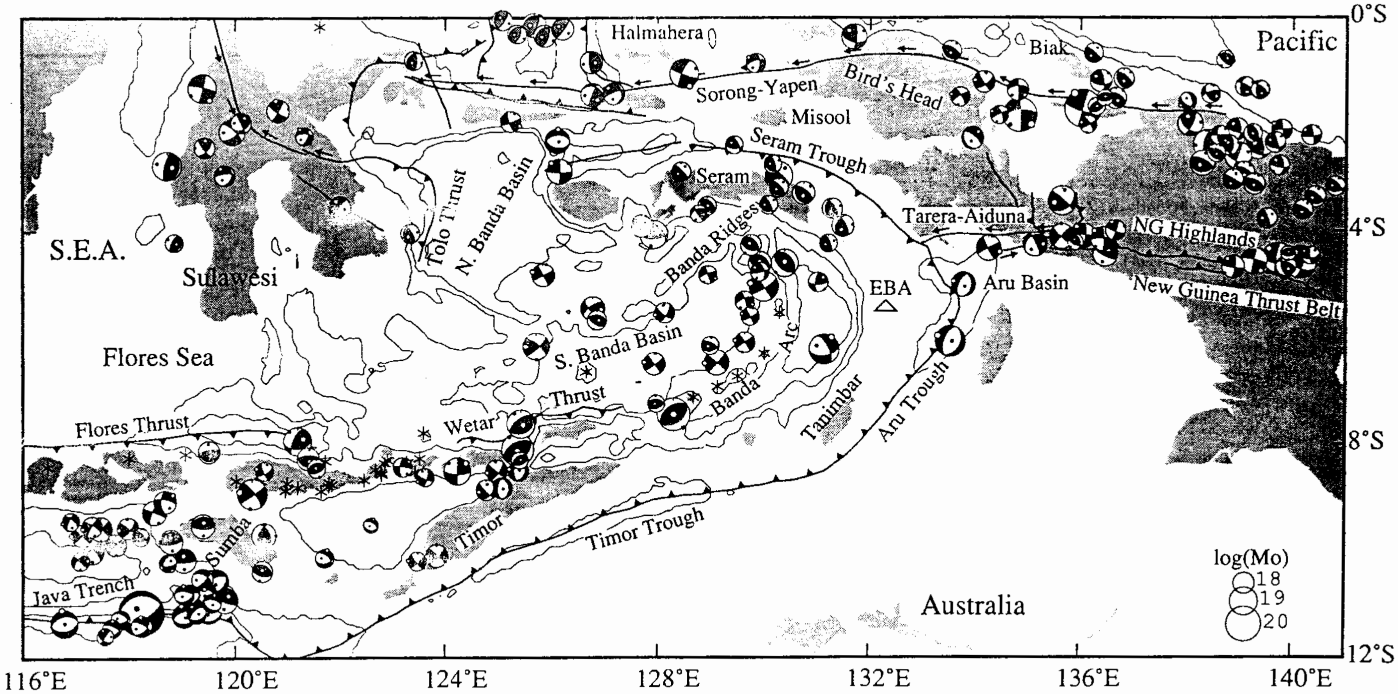

Figure 1. Fault-plane solutions for shallow earthquakes from Banda arc and western New Guinea. Lower-hemisphere, equal-area projections are shown and compressional quadrants are shaded. Shown are all waveform solutions shallower than 35 km (those with black quadrants) and centroid-moment tensor (CMT) solutions with depths given as shallower than 50 km but with seismic moment of greater than 3×10^{17} Nm (gray quadrants). Diameter of each focal sphere is proportional to logarithm of earthquake's seismic moment; scale is shown in lower right of map. Smaller events are in some cases shifted from their epicenters to avoid obliteration of other events. Dots and circles within focal spheres are P and T axes. Heavy lines show active faults; asterisks show positions of active volcanoes. Bathymetric contours are every 2000 m. Triangle labeled EBA is marker for eastern Banda arc. S.E.A. = Southeast Asian plate; NG = New Guinea.

Many of the solutions are from analyses of teleseismic, long-period body-wave seismograms (Abers, 1989; Abers and McCaffrey, 1988; McCaffrey, 1988) and others are from centroid-moment tensor (CMT) solutions (e.g., Dziewonski et al., 1981). For both types of solutions, typical uncertainties are ±20° in strike and ±10° in dip of the nodal planes. The uncertainties in depth are about ±5 km for the wave-form solutions and ±20 km for the CMT solutions. The errors in depths using wave forms are much less than those based on teleseismic arrival-time data (the latter can be many tens of kilometres for this part of the world; McCaffrey, 1988), so we can distinguish deformation in the upper plate from that in the subducting plate.

DEFORMATION OF THE BANDA ARC AND BANDA BASIN

Shallow earthquakes show that crustal deformation in the Banda arc and western New Guinea is dominated by thrust and strike-slip faulting, commonly in close association. Azimuths of P axes and slip vectors, inferred from the fault-plane solutions, beneath the Banda fore arc change from north near Sumba to southwest at the Seram trough (Fig. 2A). Because no single pole of rotation can be found to satisfy the slip vectors at both the Java trench and Seram trough, we can rule out a system of two rigid plates. Thus, deformation must occur in either or both of the plates.

Earthquakes show that the back-arc basin deforms internally. Horizontal projections of the P axes for both strike-slip and thrust earthquakes throughout the back-arc basin are aligned north to north-northeast (Fig. 2A), indicating shortening in that direction. The consistency of the T axes suggests that the Banda basin grows eastward (Fig. 2B), but the lack of normal-faulting earthquakes and the presence of thrust faulting show that the area of the Banda basin decreases in the process. (Normal faulting in the Aru basin occurs within the Australian lithosphere, so it does not contribute to elongation of the Banda fore arc.) In response to the collision, the lithosphere of the Banda basin is being extruded laterally as it contracts north-south.

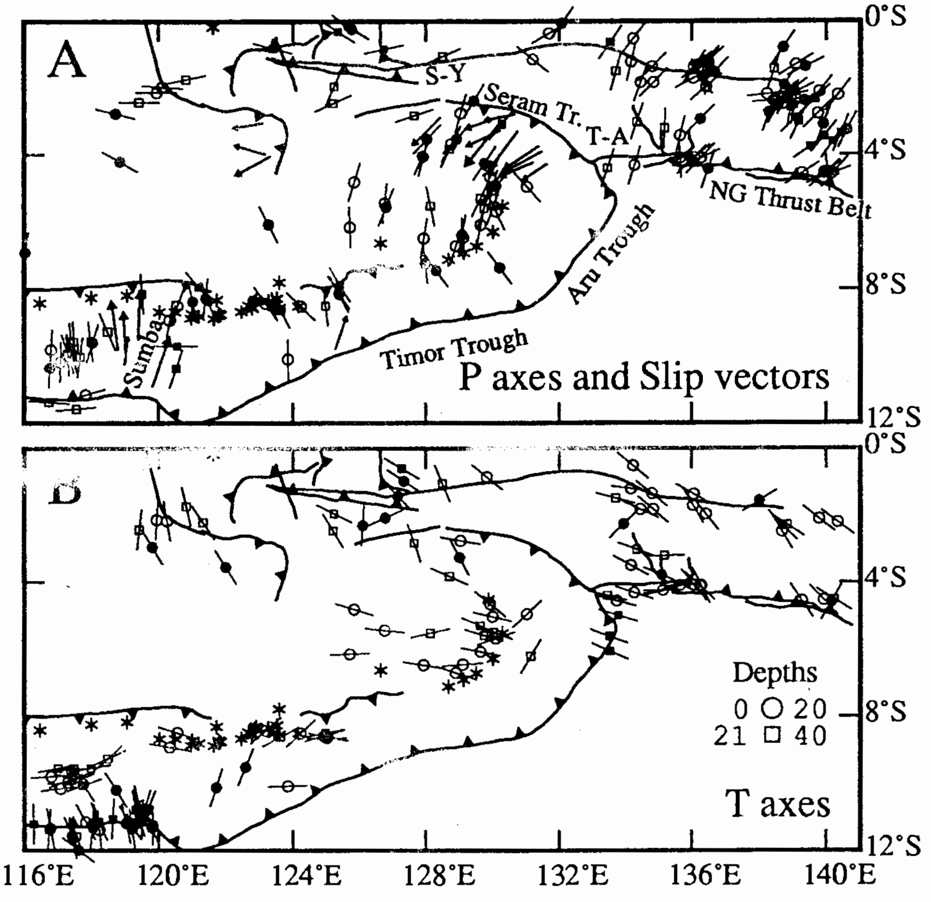

Figure 2. Horizontal projections of P and T axes (short lines through symbols) and slip vectors (arrows in A) inferred from earthquake waveform solutions and CMT solutions with moments greater than 10^{17} Nm; some events not shown in Figure 1 are included here. Only those P and T axes whose plunge is less than 35° are shown. Open symbols represent strike-slip earthquakes (defined by plunge of both P and T axes less than 45°); closed symbols indicate dip-slip earthquakes (thrust in top figure and normal in bottom). Slip vectors are shown only for underthrusting earthquakes at trenches; tail of arrow is at epicenter, and length is scaled to logarithm of seismic moment. Legend in lower right gives symbols for earthquake depth ranges in kilometres. Tr. = trough; T-A = Tarera-Aiduna fault; S-Y = Sorong-Yapen fault; NG = New Guinea.

The style of deformation in the Banda basin inferred from earthquake mechanisms precludes subduction of a rigid Australian plate at the Timor, Aru, and Seram troughs, by the following reasoning. If the Bird's Head is rigidly attached to Australia, then in order for Timor to move southward relative to Australia (at the Timor trough) and for Seram to move east-northeast relative to the Bird's Head (indicated by slip vectors at the Seram trough), Timor and Seram would have to be diverging in a north to northeast direction. However, the contraction of the Banda basin in the north-northeast to northeast direction results in convergence between Timor and Seram, so deformation must occur somewhere south or east of the Bird's Head to allow relative motion between it and Australia.

TARERA-AIDUNA FAULT ZONE OF WESTERN NEW GUINEA

We suggest, on the basis of earthquakes and geologic observations, that the Tarera-Aiduna fault zone and New Guinea thrust belt in western New Guinea (Fig. 1) accommodate west-southwest motion of the Bird's Head with respect to Australia. Earthquakes in western New Guinea (Fig. 1) fall on two east-west trends and their fault-plane solutions are consistent with left-lateral strike-slip and thrust motion along such trends. The southwestern edge of the seismic activity coincides with the Tarera-Aiduna fault zone, which is clearly visible in a side-looking airborne radar image (Hamilton, 1979), and forms the structural northern boundary of the Aru basin (Jongsma et al., 1989). The fault is not obvious in radar images or in surface geology east of about 135.5°E, where extreme topography and landslides may hide any traces. However, left-lateral strike-slip earthquake mechanisms suggest that the Tarera-Aiduna fault zone continues east to at least 140°E, north of range-bounding faults in the New Guinea Highlands (Fig. 1). Thrust earthquakes along with high topography indicate that crustal shortening occurs in the Highlands (Abers and McCaffrey, 1988) and suggest a significant convergent component between western New Guinea and Australia.

Hamilton (1979) referred to an estimate of lateral offset on one part of the Tarera-Aiduna fault system of 50 km since middle Pliocene time, giving an average slip rate of about 15 mm/yr. From the linear relation between seismic slip rate and earthquake moment rate, Abers and McCaffrey (1988) calculated a slip rate of 5–25 mm/yr for the Tarera-Aiduna fault zone over 22 yr (1964–1985). Richter (1958) listed three shallow earthquakes (in 1900, 1916, and 1926) of M 7.8–8.1 within 100 km of the Tarera-Aiduna fault zone. Everingham (1974) reported events of M 7.3 (in 1936) and M 7.1 (in 1942) from the western end of the fault zone and one of M 7.0 (in 1954) from the eastern end near 6°S, 142°E. If any one of the larger earthquakes was strike slip, then the seismic slip rate for the period 1900–1985 could be double the estimate of Abers and McCaffrey (1988) for 1964–1985 (i.e., about ten times the total seismic moment in four times the time).

To compare the Tarera-Aiduna fault to a more familiar fault, we calculated the rate of seismic moment generation for the San Andreas fault system for the years 1977 through 1988 from the published CMT solutions (see also Ekström and England, 1989). To correct for the differing lengths and depths of the faults (1100 × 15 km in California vs. 800 × 25 km for the Tarera-Aiduna), we normalized the earthquake moment rates by fault area. Taking all events between 32°N and 40°N that occurred in western California (excluding the Mammoth Lakes region) and offshore, we find that the rate of seismic moment generation for horizontal shear parallel to the San Andreas fault is only 70% that for the Tarera-Aiduna fault. We do not propose that the slip rate on the Tarera-Aiduna fault system is greater than that on the San Andreas system, but we suggest that the comparable rate of activity on the Tarera-Aiduna fault system indicates that it is accommodating tectonically significant motion.

The northern group of earthquakes in New Guinea corresponds to the left-lateral Sorong-Yapen fault zone bordering the Pacific plate (Fig. 1). The Sorong-Yapen fault produces frequent large earthquakes, and its rate of seismic moment/fault area for left-lateral faulting in western New Guinea (128° to 137.5°E) for the past 25 years is about four times that for the Tarera-Aiduna fault. Partitioning the component of Australia-Pacific relative motion rate parallel to the faults (~100 mm/yr) according to the relative values for left-lateral shear implies ~80 mm/yr slip on the Sorong fault and ~20 mm/yr on the Tarera-Aiduna fault. These numbers are within the bounds of the estimated seismic slip rates (Abers, 1989) and are consistent with the idea that the east-west shear component of Australia-Pacific relative motion is taken up completely by slip along the Sorong-Yapen and Tarera-Aiduna fault zones. The mechanism for accommodating the large amount of convergence across New Guinea is not clear, although large thrust earthquakes beneath the basin north of the Highlands suggest that part of it may occur there (Fig. 1).

RATE OF EASTWARD EXTRUSION OF THE BANDA ARC

Two lines of evidence suggest that the eastward motion of the eastern Banda arc relative to Southeast Asia and Australia may be as fast as 40 mm/yr. First, the motion of west New Guinea relative to the eastern Banda arc results in subduction at the Seram trough. This subduction is likely faster than the shear component of the west New Guinea–Australia slip at the Tarera-Aiduna fault, because the eastern Banda arc must have an eastward component of motion relative to Australia to produce subduction at the eastern Aru trough. The length of the seismic zone beneath Seram measured in the direction of modern convergence is at least 600 km (McCaffrey, 1989) and, allowing for aseismic extension of the slab to greater depth, places a lower bound on the total convergence (subduction) between the Banda arc and the Bird's Head. Furthermore, the island of Misool, which is stratigraphically similar to the Bird's Head and does not appear to be separated from the Bird's Head by any fault, now sits 500 km west of the eastern end of the subduction zone, attesting to this amount of longitudinal motion between west New Guinea and the Banda arc. It is unknown when subduction started at the Seram trough, but it was probably no earlier than 10 Ma (Silver et al., 1985), so the average subduction rate is at least 60 mm/yr. The rate of subduction at the Seram trough is the sum of the rates of motion of the northeastern Banda arc eastward relative to Southeast Asia plus west New Guinea westward relative to Australia (because Southeast Asia–Australia motion has little or no east component). If the west New Guinea–Australia motion is ~20 mm/yr on the Tarera-Aiduna fault, then another 40 mm/yr or more occurs by eastward elongation of the Banda arc.

The second observation that can be used to place bounds on the rate of east-west elongation in the Banda arc is the direction of convergence at the Aru trough; although the direction is not shown by earthquake slip vectors at the plate interface, it can be inferred to be oriented northwest, perpendicular to the local trend of the trench, from the P axes of two earthquakes that occurred in the upper plate (Figs. 1 and 2A). If the convergence direction remains roughly normal to the trench, as often occurs in oblique subduction zones (Jarrard, 1986), then the 40° bend in the eastern end of the trench (near 8°S, 132°E) indicates a 40° counterclockwise rotation of the local convergence direction. The relative rotation pole between Australia and Eurasia from the NUVEL-1 plate-motion solution (DeMets et al., 1990) predicts only 2° variation in the subduction direction east of Timor. Less than 10° in the variation of the convergence direction would arise from a rigid-body rotation of the Banda basin relative to Australia, considering that the pole of rotation for such motion would have to be west of Sumba to produce northward convergence near Sumba (Fig. 1) and west of north convergence at the Aru trough.

Earthquake slip vector azimuths at the Java trench south of Java and near Sumba (Fig. 1) trend north and probably represent motion of Australia relative to the Southeast Asian plate rather than to the Eurasian plate (McCaffrey et al., 1990). If convergence between Australia and Southeast Asia is northerly at velocity V, then by trigonometry the velocity of easterly motion, V_e, of the east Banda arc relative to Southeast Asia needed to rotate the convergence direction (representing east Banda arc–Australia motion) at the Aru trough counterclockwise by an angle Θ is $V_e = (V - V_n) \tan \Theta$, where V_n is the north component of east Banda arc–Southeast Asia motion. The rate assumed for V (77 mm/yr) is the north component of the NUVEL-1 Australia-Eurasia vector at 9°S, 130°E (80 mm/yr at azimuth of 15°). For $V_n = 0$ and $\Theta =$ 30° to 40°, the eastward motion of the east Banda arc relative to Southeast Asia is ~45 to 65 mm/yr. If the motion of the east Banda arc relative to Southeast Asia includes a north component, then the eastward component can be reduced, but not indiscriminately, because $V - V_n$ is the rate of subduction at the Timor trough.

IMPLICATIONS FOR THE STRUCTURE OF OROGENIC BELTS

The motion of the Australian continent relative to Southeast Asia and the Pacific will result in the emplacement of a large number of fault-bounded allochthonous blocks of different histories onto the Australian and Southeast Asian continental margins in a complex mountain belt. In western New Guinea (Pigram and Davies, 1987), pieces of the Bird's Head that were previously attached to Australia are now moving southwestward relative to Australia and will likely be reattached to it in the core of the collision zone. In this manner, rocks from a single continental source are enclosing the ocean basins and island arcs of eastern Indonesia.

To explore the geologic evolution of the mountain belt we approximate the internal deformation of the region with the motions of west New Guinea, Timor, Seram, and the east Banda arc relative to Southeast Asia. The motions are shown in a velocity space diagram that satisfies slip vectors, P and T axes, the relative velocity vectors of the major plates (Pacific-Australia and Pacific-Eurasia relative motion vectors are calculated at 6°S, 132°E using the NUVEL-1 poles), and the Australia–Southeast Asia motion discussed above (Fig. 3, inset). We presume that the poles of rotation for the major and minor plates are sufficiently distant so that variations in the velocity vectors across the Indonesian region are negligible. In support of this presumption, paleomagnetic measurements from the Bird's Head show little evidence for Neogene rotations with respect to Australia (Klootwijk et al., 1986). The presence of long, approximately linear faults such as the Sorong-Yapen and Tarera-Aiduna are evidence that the poles of rotations for the juxtaposed plates are far away. Rotations of the smaller blocks probably occur, but these rotations have little consequence for the large-scale evolution of the collision zone.

Using the constant velocity vectors, we project the Banda arc–New Guinea collision forward in time 10 m.y. until the south Banda basin

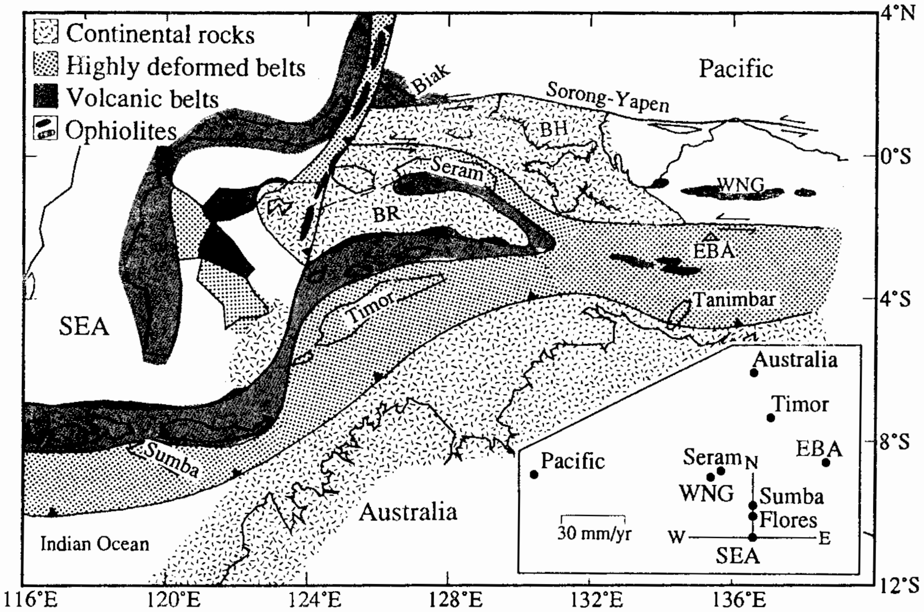

Figure 3. Hypothetical geologic map of Banda arc–western New Guinea collision zone in 10 m.y. All motions have been calculated relative to geographically fixed Southeast Asian (SEA) plate. Inset is velocity space diagram used to generate geologic map. BH = Bird's Head; BR = Banda ridges; EBA = east Banda arc; WNG = west New Guinea.

is closed. In addition to the motions discussed above, we have included 10 mm/yr of underthrusting at the Flores thrust and shortened the fore arc between the Java trench and the Flores thrust at 5 mm/yr (McCaffrey, 1988). We also use a low average velocity between Seram and west New Guinea, even though the past rate has been much higher, because these continental blocks will soon collide; following this collision, the westward motion of west New Guinea (and Seram) relative to Southeast Asia may occur by closing of the north Banda basin.

The closing of the south Banda basin and other plate motions over 10 m.y. will result in a geologically complex orogenic belt comprising various lithologic belts (Fig. 3). In a south to north section at about 128°E, the main elements include the Australian continent, a melange belt underlain by and including Australian basement rocks (Timor), a south-facing island arc (southern Banda arc), possibly an ophiolite belt (south Banda basin), more Australian rocks (the Banda ridges), a north-facing island arc (northern Banda arc), a second melange belt including Australian rocks (Seram), and then Misool and the Bird's Head, pieces of Australia comprising blocks of continental and oceanic rocks (Pigram and Davies, 1987).

Although the large uncertainties in times and velocity vectors lead to uncertainties in the final spatial relations among the geologic elements, we feel that this particular scenario illustrates the possible outcomes. The paradox in the tectonic development of the eastern Indonesian collision zone is that the final positions of the crustal blocks are dictated largely by their translations along great distances by strike-slip faulting, yet geologic structures will likely be dominated by smaller amounts of thrust faulting. The Tarera-Aiduna fault zone is the site of important horizontal shear in western New Guinea; that it is so difficult to identify as strike slip while it is active suggests that it may be overlooked easily in the geologic record after activity has ceased. If it cannot be identified as a strike-slip zone, then a reasonable but wrong interpretation of the geologic structure shown in Figure 3 may be that a small ocean basin opened between Australia and the Bird's Head and was subsequently closed. Examples of such basins are numerous in interpretations of the tectonic evolution of Tethyan margins; a modern example (149°–156°E) is the Woodlark rift, which is propagating westward and splitting continental eastern New Guinea.

REFERENCES CITED

Abers, G.A., 1989, Active tectonics and seismicity of New Guinea [Ph.D. thesis]: Cambridge, Massachusetts Institute of Technology, 255 p.

Abers, G.A., and McCaffrey, R., 1988, Active deformation in the New Guinea fold-and-thrust belt: Seismological evidence for strike-slip faulting and basement-involved thrusting: Journal of Geophysical Research, v. 93, p. 13,332–13,354.

Bowin, C., Purdy, G.M., Johnston, C., Shor, G.G., Lawver, L., Hartono, H.M.S., and Jezek, P., 1980, Arc-continent collision in the Banda Sea region: American Association of Petroleum Geologists Bulletin, v. 64, p. 868–915.

Cardwell, R.K., and Isacks, B.L., 1978, Geometry of the subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions: Journal of Geophysical Research, v. 87, p. 2825–2838.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, *in* Howell, D.C., and McDougall, K.A., eds., Mesozoic paleogeography of the United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 1–32.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425–478.

Dziewonski, A.M., Chou, T.-A., and Woodhouse, J.H., 1981, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity: Journal of Geophysical Research, v. 86, p. 2825–2852.

Ekström, G., and England, P., 1989, Seismic strain rates in regions of distributed continental deformation: Journal of Geophysical Research, v. 94, p. 10,231–10,257.

Everingham, I.B., 1974, Large earthquakes in the New Guinea–Solomon islands area, 1873–1972: Tectonophysics, v. 23, p. 323–338.

Hamilton, W., 1979, Tectonics of the Indonesian region: U.S. Geological Survey Professional Paper 1078, 345 p.

Jarrard, R.D., 1986, Relations among subduction parameters: Reviews of Geophysics, v. 24, p. 217–284.

Jongsma, D., Huson, W., Woodside, J.M. Suparka, S., Sumantri, T., and Barber, A.J., 1989, Bathymetry and geophysics of the Snellius-II triple junction and tentative seismic stratigraphy and neotectonics of the northern Aru trough: Netherlands Journal of Sea Research, v. 24, p. 231–255.

Klootwijk, C., Pigram, C., and Giddings, J., 1986, Pilot paleomagnetic results from the Bird's Head, Irian Jaya, *in* IOC Symposium on Marine Science in the Western Pacific: The Indo-Pacific convergence: Townsville, Intergovernmental Oceanographic Commission, p. 21.

McCaffrey, R., 1988, Active tectonics of the eastern Sunda and Banda arcs: Journal of Geophysical Research, v. 93, p. 15,163–15,182.

——1989, Seismological constraints and speculations on Banda arc tectonics: Netherlands Journal of Sea Research, v. 24, p. 141–152.

McCaffrey, R., Bock, Y., and Rais, J., 1990, Crustal deformation and oblique plate convergence in Sumatra [abs.]: Eos (Transactions, American Geophysical Union), v. 71, p. 637.

Pigram, C.J., and Davies, H.L., 1987, Terranes and the accretion history of the New Guinea orogen: Bureau of Mineral Resources Journal of Australian Geology and Geophysics, v. 10, p. 193–211.

Richter, C.F., 1958, Elementary seismology: San Francisco, W.H. Freeman and Co., 768 p.

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

Trümpy, R., 1983, Alpine paleogeography: A reappraisal, *in* Hsü, K.J., ed., Mountain building processes: London, Academic Press, p. 149–156.

Visser, W.A., and Hermes, J.J., 1962, Geological results of the exploration for oil in the Netherlands New Guinea: Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap, Verhandelingen, Geologische Series, v. 20, p. 1–265.

ACKNOWLEDGMENTS

Supported by National Science Foundation Grants EAR-8319250, EAR-8608405, and EAR-8720773 (McCaffrey). We thank Frank Spear for suggestions.

Manuscript received August 17, 1990
Revised manuscript received December 24, 1990
Manuscript accepted January 8, 1991