Slip vectors and stretching of the Sumatran fore arc

Robert McCaffrey
Department of Geology, Rensselaer Polytechnic Institute, Troy, New York 12180

ABSTRACT

Slip vectors from thrust earthquakes at the Java Trench southwest of Sumatra demonstrate that the Sumatran fore arc is not a single rigid plate that is translated to the northwest by oblique plate convergence. Instead they indicate arc-parallel stretching of the fore arc at a uniform strain rate of 3–4 × 10^{-8}/yr. The northwestward motion of the fore arc relative to the upper plate (Southeast Asia) increases from near zero at the Sunda Strait to 45–60 mm/yr in northwest Sumatra and should result in variable slip rates on the Sumatran fault.

INTRODUCTION

Fitch (1972) proposed that oblique plate convergence decouples into a component of convergence normal to the plate boundary and a shear component taken up by strike-slip faulting on a transcurrent fault in the interior of the overriding plate. He presented a clear example from Sumatra. Subsequently, Sumatra has been cited as a modern analogue for Mesozoic western North America to explain the rotations and translations of accreted elements there (e.g., Beck, 1986).

Evidence for decoupling in Sumatra is the presence of both the Sumatran fault and subduction earthquakes that show thrusting nearly perpendicular to the arc even though plate convergence becomes quite oblique to it (Fig. 1). If the fore-arc sliver, bounded on the west by the trench, below by the subducting plate, and on the east by the Sumatran fault, behaves as a rigid plate, slip vectors at the Java Trench southwest of Sumatra should be deflected clockwise relative to those south of Java but then should show little variation along the trench northwest of the Sunda Strait. In this paper I use the observed variation in the slip vectors to test whether the Sumatran fore arc behaves as a rigid block. If rigid behavior is indicated, there are two long-term implications: average slip on the Sumatran fault will be constant along its length and, of relevance to the Cenozoic evolution of western North America, the translation of the fore-arc sliver will occur as a single large block, so that internal permanent rotations, of the type observable with paleomagnetism, will be small.

SLIP VECTORS AT THE JAVA TRENCH

Slip vectors for thrust earthquakes at the Java Trench are based on *P*-wave first motions (Kappel, 1980; Fitch, 1972), body waveforms (McCaffrey, 1988), and centroid-moment tensor solutions (e.g., Dziewonski et al., 1981). The fault planes are assumed to be the arcward-

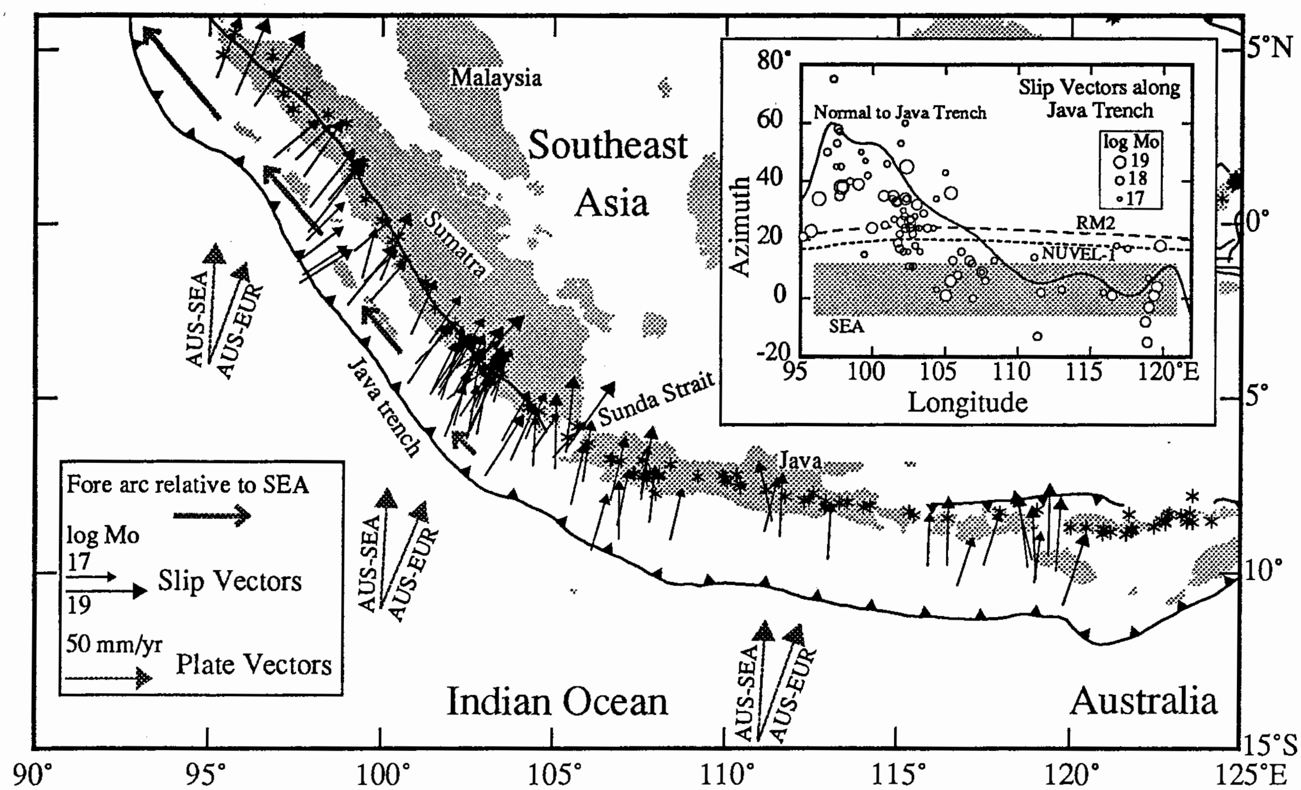

Figure 1. Map of Sunda arc showing tectonic features, slip vectors, and plate-motion vectors. Vectors in Indian Ocean labeled AUS-EUR are from Australia-Eurasia pole of rotation (DeMets et al., 1990) (rate scale in lower left corner), and those labeled AUS-SEA are inferred from slip vectors at Java Trench south of Java. Length of slip vector is scaled to logarithm of seismic moment (Mo) of earthquake (scale at lower left). Heavy line through Sumatra shows trace of right-lateral Sumatran fault. Asterisks indicate positions of volcanoes. Arrows in fore arc show inferred motion relative to Southeast Asia. Inset shows variation in slip-vector azimuths (circles) with longitude along arc. Dashed lines show convergence directions between Australia–Indian Ocean plate and Eurasia predicted by DeMets et al. (1990) pole (labeled NUVEL-1) and Minster and Jordan (1978) pole (labeled RM2). Shaded bar shows convergence direction (N3°E ±9°) inferred from slip vectors east of central Java.

dipping planes, and the slip vector (the pole of the auxiliary plane) shows the direction of motion of the subducting plate relative to the fore arc. The slip-vector azimuth is found by rotating the slip vector into the horizontal plane. Because the auxiliary planes are very steep for these earthquakes (the average dip is 72°), the slip vectors are constrained well. I estimate uncertainties of 15° in azimuth and 5° in plunge for an individual slip vector and expect that the effect of slab structure is included in this amount (e.g., Ekström and Engdahl, 1989; McCaffrey, 1988).

Slip-vector azimuths along the Java Trench are not matched by the motion of Australia relative to Eurasia (Fig. 1). This misfit is due in part to the motion of Southeast Asia relative to Eurasia, which is highly uncertain and so cannot be used to predict the motion of Southeast Asia relative to Australia from vector closure. Large-scale deformation within the Southeast Asian plate along much of its border with Australia renders the slip vectors unreliable indicators of Australia–Southeast Asia motion except east of Sumatra and west of the Banda arc, where little deformation occurs within the island arc or back arc of the Southeast Asian plate. The mean azimuth of 15 slip vectors east of central Java (east of long 110°E; Fig. 1) is N3°E, sample standard deviation 9°, and I take this as the convergence direction of Australia relative to Southeast Asia at the Java Trench. Because the motion of Southeast Asia relative to Eurasia is slow, the Southeast Asia–Eurasia pole of rotation will be close to the Australia-Eurasia pole, which is itself sufficiently far from Indonesia to give little variation in the convergence direction along the Java Trench (Fig. 1). Hence, the motion of Australia relative to Southeast Asia also varies little along the trench.

Because of the curvature of the trench, the obliquity (the angle between the trench normal and the predicted plate-convergence azimuth; Fig. 1) changes by as much as 50° from western Java to northern Sumatra. The Java Trench normal appears to form an upper envelope for the slip vectors that are systematically deflected toward the plate-convergence direction (N3°E). The tendency for slip-vector azimuths to fall between the plate-convergence direction and the normal to the plate boundary is common (DeMets et al., 1990) and indicates that oblique convergence is often not completely decoupled.

KINEMATIC ANALYSIS OF DEFORMATION RATES FROM SLIP-VECTOR AZIMUTHS

The systematic deflection of slip-vector azimuths along the Java Trench southwest of Sumatra relative to the plate-convergence direction can be used to constrain the motion of the fore arc of the upper plate relative to Southeast Asia. To examine the variation along the arc, the analysis is presented in a polar coordinate system in which both the Java Trench and the Sumatran fault roughly form small circles around the origin (at lat 16°N, long 119°E). In this coordinate system, Θ is parallel to the arc and Δ is perpendicular to it (Fig. 2A).

To relate the variation in slip-vector azimuths α to deformation of the fore arc, I impose vector closure on the Australia, Southeast Asia or Eurasia, and fore-arc plates (Fig. 2B). Given V_P, the rate of motion of Southeast Asia relative to Australia, the angle β' that ${}_{SEA}\mathbf{V}_{AUS}$ makes with the vector of motion of the fore arc relative to Southeast Asia (${}_{FA}\mathbf{V}_{SEA}$), and the angle α' that the slip vector makes relative to ${}_{SEA}\mathbf{V}_{AUS}$, the velocity triangle can be solved at any point for V_F, the rate of motion of that point within the fore arc relative to Southeast Asia:

$$V_F = V_P \sin \alpha' / \sin(\alpha' + \beta'). \qquad (1)$$

Using Φ as the azimuth of Australia's motion relative to Southeast Asia and converting angles α' and β' to geographic azimuths α and β (Fig. 2A), both measured clockwise from north, with $\alpha' = \alpha - \Phi$ and $\beta' = \Phi - \beta$, we get

$$V_F = V_P \sin(\alpha - \Phi)/\sin(\alpha - \beta). \qquad (2)$$

V_P, Φ, α, and β can vary along the margin and therefore are functions of Θ. If the fore arc is rigid and the center of the coordinate system is near the pole of rotation of the fore arc relative to Southeast Asia, then $\beta(\Theta)$ is approximately equal to $\Theta - 90°$, as shown in Figure 2A, and implies that the fore arc moves relative to Southeast Asia by strike slip only. β may be varied in other ways; for example, it may be set so that the motion of the fore arc relative to Southeast Asia is locally parallel to the Sumatran fault and can also include across-strike deformation of the fore arc. In the calculations that follow, vectors from the DeMets et al. (1990) Australia-Eurasia Euler pole (labeled NUVEL-1, Fig. 2C) are considered, because this and the Minster and Jordan (1978) Indian Ocean–Eurasia pole give vectors (labeled RM2, Fig. 2C) that are within 1 mm/yr of each other in rate and only a few degrees different in azimuth.

The slip-vector azimuths that I consider are those in the range $0° \leqslant \Theta \leqslant 55°$ (long 119°–96°E). At $\Theta > 55°$ (west of long 96°E), the trench bends to the west and is near both the Ninetyeast Ridge and the diffuse plate boundary between the Indian and Australian plates (DeMets et al., 1990). Because the motion of the Indian Ocean floor relative to Southeast Asia is unconstrained in this region, we can learn little about the deformation of the fore arc. In the calculations, the fore-arc deformation is presumed to lie west of central Java ($\Theta \geqslant 20°$) because the slip-vector azimuths deviate from the Australia–Southeast Asia convergence direction in that area (Fig. 1).

RIGID FORE ARC

First, consider a rigid-fore-arc plate in which all of the shear in the upper plate occurs on an

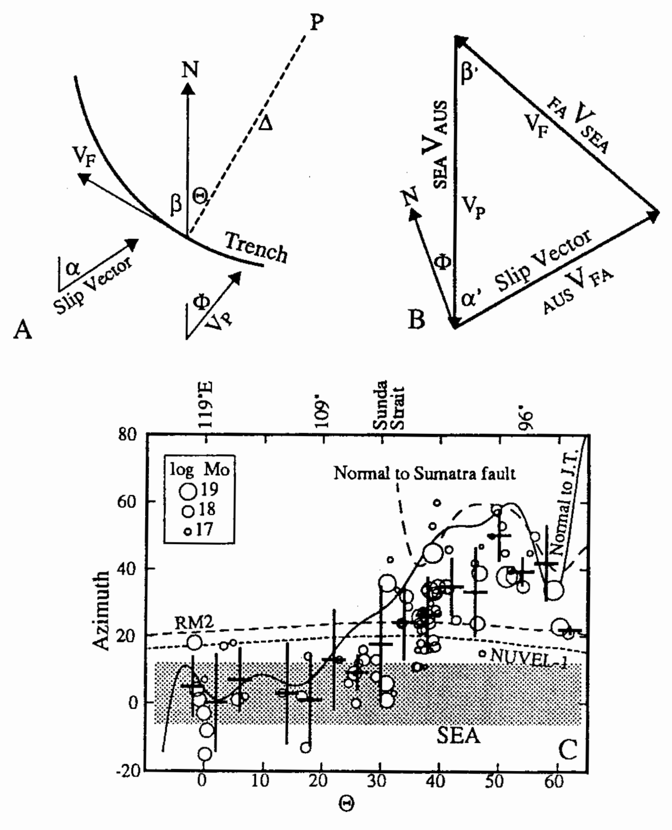

Figure 2. A: Geometry of oblique convergence. P is center of curvature of trench and arc. Points along fore arc are designated by Θ, azimuth to P, and Δ, distance to P. Φ is azimuth of relative plate convergence, and α is slip-vector azimuth, both relative to north. V_P is rate of convergence and V_F is rate of motion of fore arc relative to upper plate. β is direction of V_F relative to north. B: Relation in velocity space of slip-vector azimuth, V_P and V_F. SEA = Southeast Asia; AUS = Australia; FA = fore arc. C: Plot of earthquake slip-vector azimuths vs. position Θ along arc. Vertical bars show average and ±1 (sample) standard deviation for all slip vectors in increments of Θ, 4° wide (1° of Θ ≈ 55 km). J.T. = Java Trench. Other items as in Figure 1.

arc-parallel strike-slip fault. Jarrard (1986) calculated a slip rate of 36 ±5 mm/yr for the Sumatran fault by using (1) the difference between the average of seven slip-vector azimuths at the Java Trench southwest of Sumatra (26.9° ±6.8°), (2) his estimated convergence direction for Australia–Southeast Asia (−1.0° ±6.7° based on five slip vectors south of Java), and (3) a convergence rate of 68 mm/yr derived from the Minster and Jordan (1978) India-Eurasia pole. His calculation is a simplification of equation 2 in which V_P, Φ, α, and β are all averaged along the margin, so his result is an average slip rate.

By using $\beta(\Theta) = \Theta - 90°$ (which implies shear on a vertical plane parallel to the arc), using $V_P(\Theta)$ and $\Phi(\Theta)$ taken from the NUVEL-1 Australia-Eurasia pole of rotation, and setting the left-hand side of equation 2 to a series of slip rates (V_F), the along-arc variations in slip-vector azimuths may be predicted (Fig. 3A). For slip rates of less than about 30 mm/yr, the slip-vector azimuths decrease with increasing Θ (to the northwest). At a rate of 50 mm/yr, the azimuths increase to the northwest but at a much lower rate than the data indicate.

Because Australia-Eurasia is probably not the appropriate plate pair to be using, the presumed motion between Australia and Southeast Asia, subject to the constraints discussed earlier, was tried. Assuming first that the convergence vector between Australia and Southeast Asia is constant along the arc and is described by Φ = N3°E and V_P = 75 mm/yr (roughly the NUVEL-1 convergence rate of Australia-Eurasia in the direction N3°E), the predicted directions again fail to match the data (Fig. 3B). If the Australia–Southeast Asia convergence rate V_P is slowed to 50 mm/yr (in the case of Southeast Asia moving northward relative to Eurasia at ~30 mm/yr) and if Φ = N12°E, a much larger deflection of the slip vector is found for a given value of V_F (Fig. 3C), but the variation in azimuth is not matched. Increasing V_P to 100 mm/yr gives an even poorer match. Motion of the fore arc radially outward from Southeast Asia (i.e., $\beta = \Theta - 180°$), even at the large and implausible rate of 60 mm/yr, is ineffective in deflecting the slip-vector azimuths at $\Theta > 40°$ (Fig. 3D).

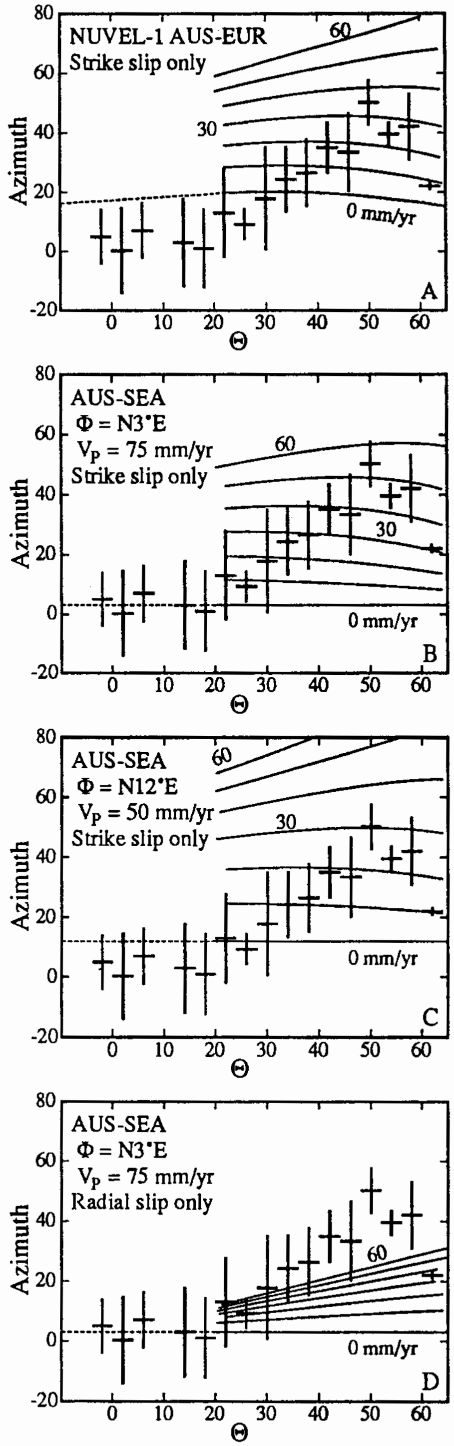

Figure 3. Predicted azimuths of slip vectors vs. Θ for rigid fore arc; different assumed plate-convergence vectors are used (dashed lines). Curves are for constant values of slip rate V_F of fore arc relative to upper plate (Southeast Asia), in mm/yr, starting at 0 for lowest curve and increasing in increments of 10 mm/yr as labeled. Bars characterize mean of observed slip vectors and their standard deviations. A, B, and C assume that slip of fore arc relative to upper plate is parallel to arc (i.e., strike slip); D uses slip of fore arc away from upper plate. Φ and V_P give plate-convergence vector (Fig. 2A). These tests demonstrate that fore arc does not behave as a rigid plate.

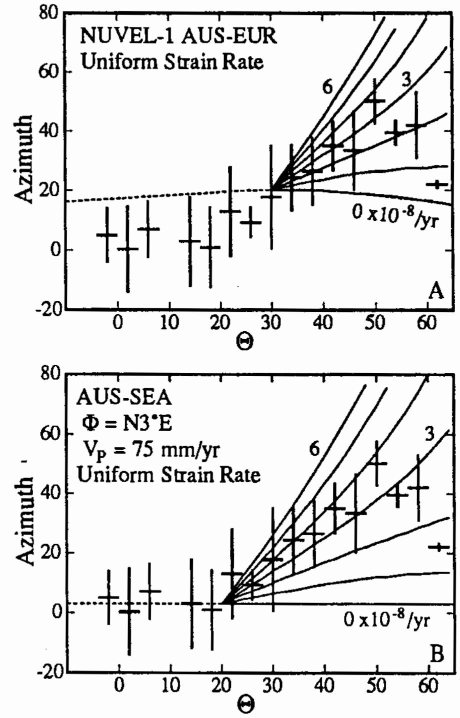

Figure 4. Predicted azimuths of slip vectors for cases in which fore arc expands parallel to arc at uniform strain rate (otherwise plots are similar to Fig. 3). Solid curves show predicted slip directions for assumed uniform strain rates in increments of 10^{-8}/yr, starting at 0 (lowest curve) and increasing to 6. Plate-convergence vectors assumed for A and B are those for Figures 3A and 3B. Slip vectors at Java Trench are matched for strain rate of 3–4 × 10^{-8}/yr; this corresponds to increase in velocity of fore arc relative to Southeast Asia of 45 to 60 mm/yr over distance of 1500 km from Sunda Strait to northwest Sumatra.

UNIFORM STRAIN RATE

Given that rigid plate behavior of the fore arc can be ruled out, suppose the velocity of the fore arc relative to that of Southeast Asia varies linearly with position (i.e., a uniform strain rate). Extension of the fore arc perpendicular to the margin is inefficient in deflecting the subduction slip vectors (Fig. 3D), and compression across the fore arc would rotate them anticlockwise; therefore, these possibilities are not considered further. Horizontal shear on vertical planes parallel to Θ and the arc is unresolvable because it produces a variation in the slip-vector azimuths across the fore arc that is not apparent. Here I present the case of uniform strain rate parallel to Θ and the arc.

Figure 4 shows predicted curves for slip-vector azimuths for different arc-parallel, uniform extensional strain rates. Using the NUVEL-1 Australia-Eurasia pole for Φ and V_P matches the slip directions for $\Theta > 30°$ at strain rates of 2–4 × 10^{-8}/yr (Fig. 4A). The anticlockwise deflection of the slip vectors at Θ < 30° could be explained by left-lateral strike-slip faulting on Java or rapid shortening of the fore arc south of Java, but these are unlikely. It is more likely that the NUVEL-1 Australia-Eurasia pole is not appropriate for the Java Trench. The Minster and Jordan (1978) India-Eurasia pole would do worse in fitting slip directions but would give similar variations in azimuths as the NUVEL-1 pole. Using the Australia–Southeast Asia vector (Φ = N3°E, V_P = 75 mm/yr) fits the slip vectors out to Θ = 55° for strain rates of 3–4 × 10^{-8}/yr (Fig. 4B).

DISCUSSION

The spatial variation in the slip-vector azimuths at the Java Trench southwest of Sumatra suggests that arc-parallel stretching of the fore arc occurs. Rigid plate behavior can be confidently ruled out. Extension of the fore arc across its strike cannot be resolved because it does not contribute much to the rotation of the slip vectors. The scatter in the slip-vector data precludes resolution of the details of the deformation, such as rotations of fore-arc blocks or strain concentrated in a particular place, so that the slip vectors are matched with uniform stretching of the fore arc. The rate of northwestward motion of the fore arc relative to Southeast Asia likely increases from near zero south of central Java to 45–60 mm/yr [$(3\text{–}4 \times 10^{-8}/\text{yr}) \times 1500$ km] in northwest Sumatra. Ekström and Engdahl (1989) and Geist et al. (1988) have suggested that the Aleutian fore arc undergoes similar stretching.

The deformation that acts to stretch the Sumatran fore arc is poorly understood, but from existing evidence it is more likely to occur on strike-slip faults crossing the margin than on arc-perpendicular normal faults that open basins within the fore arc. Only in the south near the Sunda Strait is there evidence for basin-producing extension (Harjono et al., 1991; Huchon and Le Pichon, 1984). Strike-slip faults appear to cut the fore arc and may have many tens of kilometres of displacement (Karig et al., 1980). Lineations in island coastlines, the long, straight western boundary of the fore-arc basin from the equator to about lat 5°S, and earthquake mechanisms (P. Zwick and R. McCaffrey, unpublished results) suggest that strike-slip faults may exist offshore. Shallow strike-slip earthquakes in the fore arc have nodal planes that strike north and east, cutting across the fore arc, rather than parallel to it.

The important consequence of a rigid fore arc—that slip on the Sumatran fault occurs at the same rate all along its length—is not automatically precluded by stretching of the fore arc, but I argue that the slip rate is in fact variable. If the fore arc stretches either by normal faulting that forms basins or by strike-slip faulting, then such faults must cross the fore arc from the trench to a major fault that juxtaposes the fore arc against the Southeast Asia plate. Shallow seismicity beneath the fore arc ends abruptly at the Sumatran fault in the northeast, and large right-lateral strike-slip earthquakes occur on vertical planes parallel to it (Zwick and McCaffrey, 1991). No other clear alignment of fault planes for strike-slip earthquakes is evident. Although it is likely that other undiscovered faults exist offshore, the Sumatran fault is probably the major fault forming the boundary between Southeast Asia and the fore arc. If so, then the rate of slip on the Sumatran fault will increase from southeast to northwest. Information pertaining to the total slip on the Sumatran fault and the current slip rate is sparse and cannot be used to test the hypothesis of a stretching fore arc. Estimates of the offset on the Sumatran fault based on geologic observations range widely, from 20 km (Katili and Hehuwat, 1967) to 100 km (Posavec et al., 1973) to as much as 270 km (Tjia and Posavec, 1972), and timing of the slip is undetermined. Spreading in the Andaman Sea of 460 km in the past 13 m.y. (Curray et al., 1979) and extension in the Sunda Strait of about 100 km in the same time (Huchon and Le Pichon, 1984) are consistent with the idea that deformation increases northwestward along the margin.

Besides the Aleutians and Sumatra, evidence for arc-parallel extension in fore arcs has been presented for the Ryukyu arc (Kuramoto and Konishi, 1989), the Kuril arc (Kimura, 1986), Japan (Toriumi and Noda, 1986), Washington (Brown and Talbot, 1989), and Venezuela (Avé Lallemant and Guth, 1990). Arc-normal extension is felt to be an important mechanism in bringing high-pressure, low-temperature metamorphic rocks to shallow levels in accretionary wedges (e.g., Platt, 1986). Arc-parallel extension is potentially as important because the estimated strain parallel to the Sumatran arc implies thinning of the fore arc at 1–2 mm/yr, which could result in the rapid rise of rocks from deep in the accretionary wedge.

REFERENCES CITED

Avé Lallemant, H.G., and Guth, L.R., 1990, Role of extensional tectonics in exhumation of eclogites and blueschists in an oblique subduction setting, northwest Venezuela: Geology, v. 18, p. 950–953.

Beck, M., 1986, Model for late Mesozoic–early Tertiary tectonics of coastal California and western Mexico and speculations on the origin of the San Andreas fault: Tectonics, v. 5, p. 49–64.

Brown, E.H., and Talbot, J.L., 1989, Orogen-parallel extension in the North Cascades crystalline core, Washington: Tectonics, v. 8, p. 1105–1114.

Curray, J.R., Moore, D.G., Lawver, L.A., Emmel, F.J., Raitt, R.W., Henry, M., and Kieckhefer, R., 1979, Tectonics of the Andaman Sea and Burma, *in* Geological and geophysical investigations of continental slopes and rises: American Association of Petroleum Geologists Memoir 29, p. 189–198.

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 Engdahl, E.R., 1989, Earthquake source parameters and stress distribution in the Adak Island region of the central Aleutian Islands, Alaska: Journal of Geophysical Research, v. 94, p. 15,499–15,519.

Fitch, T.J., 1972, Plate convergence, transcurrent faults and internal deformation adjacent to southeast Asia and the western Pacific: Journal of Geophysical Research, v. 77, p. 4432–4460.

Geist, E.L., Childs, J.R., and Scholl, D.W., 1988, The origin of summit basins of the Aleutian Ridge: Implications for block rotation of an arc massif: Tectonics, v. 7, p. 327–341.

Harjono, H., Diament, M., Dubois, J., and Larue, M., 1991, Seismicity of the Sunda Strait: Evidence for crustal extension and volcanological implications: Tectonics, v. 10, p. 17–30.

Huchon, P., and Le Pichon, X., 1984, Sunda Strait and central Sumatra fault: Geology, v. 12, p. 668–672.

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

Kappel, E.S., 1980, Plate convergence in the Sunda and Banda arcs [B.A. thesis]: Ithaca, New York, Cornell University, 40 p.

Karig, D.E., Lawrence, M.B., Moore, G.F., and Curray, J.R., 1980, Structural framework of the fore-arc basin, NW Sumatra: Geological Society of London Journal, v. 137, p. 77–91.

Katili, J.A., and Hehuwat, F., 1967, On the occurrence of large transcurrent faults in Sumatra, Indonesia: Osaka University Journal of Geoscience, v. 10, p. 5–17.

Kimura, G., 1986, Oblique subduction and collision: Forearc tectonics of the Kuril arc: Geology, v. 14, p. 404–407.

Kuramoto, S., and Konishi, K., 1989, The southwest Ryukyu arc is a migrating microplate (forearc sliver): Tectonophysics, v. 163, p. 75–91.

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

Minster, J.B., and Jordan, T.H., 1978, Present-day plate motions: Journal of Geophysical Research, v. 83, p. 5331–5354.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037–1053.

Posavec, M., Taylor, D., van Leeuwen, T., and Spector, A., 1973, Tectonic control of volcanism and complex movements along the Sumatran fault system: Geological Society of Malaysia Bulletin, v. 6, p. 43–60.

Tjia, H.D., and Posavec, M., 1972, The Sumatra fault zone between Padangpandjang and Muaralabuh: Sains Malaysiana, v. 1, p. 77–105.

Toriumi, M., and Noda, H., 1986, The origin of strain patterns resulting from contemporaneous deformation and metamorphism in the Sumbagawa metamorphic belt: Journal of Metamorphic Geology, v. 4, p. 409–420.

Zwick, P., and McCaffrey, R., 1991, Seismic slip rate and direction of the Great Sumatra Fault based on earthquake fault plane solutions [abs.]: EOS (American Geophysical Union Transactions), v. 72, p. 201.

ACKNOWLEDGMENTS

Supported by National Science Foundation Grants EAR-8903762 and EAR-8908759. I thank Peter Molnar and Yehuda Bock for discussions and Molnar, Hans Avé Lallement, and Muawia Barazangi for helpful reviews.

Manuscript received February 4, 1991
Revised manuscript received May 3, 1991
Manuscript accepted May 10, 1991