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Accretion of the southern Banda arc to the Australian plate margin determined by Global Positioning System measurements

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Abstract. Global Positioning System geodetic measurements at thirteen locations in Indonesia and four in Australia reveal that the Australian continent has accreted the Banda island arc to its margin. Small relative velocities of five sites on west Java, south Kalimantan, Bali, and south Sulawesi define a rigid Sunda shelf that moves relative to northern Australia in a manner consistent with pole locations from NUVEL-1 Australia-Eurasia but at a rate that is about 7% slower. Block-like northward motion of the southern Banda arc toward the Sunda shelf at nearly the same rate as Australia suggests that the Timor trough is now inactive as a thrust. Little of the convergence of Australia with Eurasia is accommodated by strain within the Banda arc structure. Most of the convergence appears to occur as northward translation of the rigid arc with shortening on the Flores and Wetar thrusts and possibly on faults within the back arc basin.

Introduction

The Indonesian island chain (Figure 1) from Sumatra in the west to the Aru islands in the east forms volcanic and nonvolcanic arcs associated with the convergence of the Australian and Eurasian plates. Along the Java trench, old lithosphere of the Indian ocean plate descends beneath the continental margin of the Sunda shelf. East of the Sunda arc, along the southern Banda arc from Timor to the east, however, collision of continental lithosphere with an island arc occurs. The thickness of the low-density continental crust is thought to prevent it from being subducted to great depths, so subduction is expected to cease with plate convergence being transferred to other faults, possibly in a distributed fashion. Contemporary structures accommodating collision of Australia with the Banda arc include northward verging thrusts at the south margins of the Flores and Banda back arc basins [*Silver et al.*, 1983; *McCaffrey and Nabelek*, 1984] and strike-slip and thrust faults within the back arc basin lithosphere [*McCaffrey*, 1988]. The relative importance of these structures is unknown and with it the question of whether or not active subduction of continental lithosphere continues.

Convergence between Australia and Eurasia at the Timor trough is expected to occur at a rate of 74±2 mm/yr at N17°E±3° azimuth according to the NUVEL-1A global velocity model of rigid plate motion [*DeMets et al.*, 1994]. *Tregoning et al.* [1994] estimate a convergence rate of 67±7 mm/yr at N11°E±9° from 4 years of Global Positioning System (GPS) measurements across the Java trench between Christmas Island and west Java, suggesting that the NUVEL-1 Australia-Eurasia pole can be applied to the Java trench. Historically, the Timor trough has produced no large thrust earthquakes that commonly characterize fast subduction zones. Such seismic quiescence may indicate either aseismic slip, implying low risk for large earthquakes, or a locked fault, implying an impending major earthquake, but tells us little about the slip rate at the Timor trough. Geologic arguments for the modern slip rate at the Timor trough have lead to conflicting views [*Johnston and Bowin*, 1981; *Karig et al.*, 1987; *Snyder et al.*, 1996]. Here we present the first geodetic measurements of present-day slip across the Timor trough; these indicate a very low convergence rate but possibly left-lateral shearing across the margin.

Although GPS measurements have been available for more than a decade, the recent completion of the satellite constellation, the expansion of the global tracking network, and innovations in receiver hardware and data analysis software have advanced the technology to a mature operational stage. GPS geodesy is now able to yield accurate estimates of regional contemporary crustal deformation from a few periods of multiday observations spaced several months apart. We have taken advantage of these developments to determine velocities of several sites along the Sunda and Banda arcs, Indonesia, from GPS measurements taken in 1992-1994.

GPS Measurements

Four GPS geodetic surveys along the eastern Indonesian island arc were conducted at 13 sites (Table 1) over a 2-year interval from 1992 to 1994. After the initial survey in August 1992, the December 12, 1992, M_W=7.8 Flores Sea earthquake prompted a resurvey of 10 sites. Eight sites were surveyed again in August 1993, and all except RUTE were reoccupied in August 1994. GPS data from four northern Australia stations (Table 1) are also available during many survey days.

Each day's observations are analyzed independently with concurrent data from a Pacific Rim subset of the *International GPS Service for Geodynamics* (IGS) [1995] network. Weighted least squares estimates of daily station positions, satellite state vectors, tropospheric zenith delay parameters, and phase

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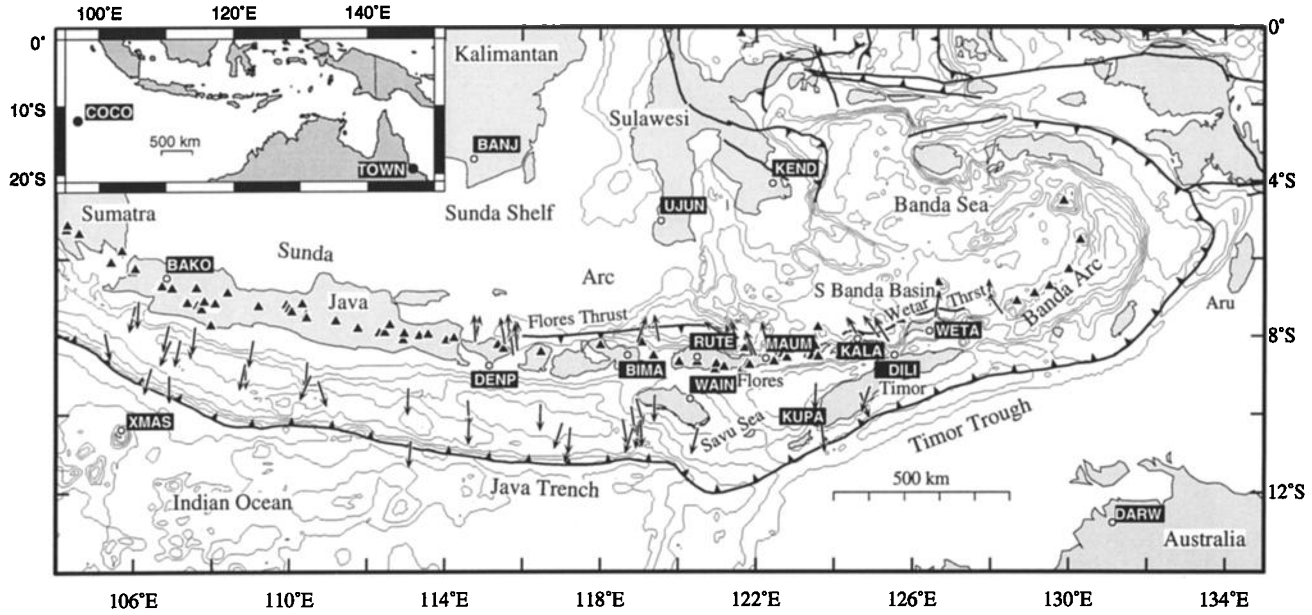


Figure 1. Eastern Indonesian island arc region with major geographic and tectonic features. Bold solid lines refer to major faults, thrust faults are identified by barbs on the overriding plate. Arrows are earthquake slip vectors (1964-1994) [*Dziewonski et al.*, 1995; *McCaffrey*, 1988] pointing in the direction of motion of hanging wall relative to footwall. Triangles denote locations of volcanoes. Bathymetry is contoured at 1-km intervals. Open circles labeled with four capital letters indicate GPS site locations and corresponding site codes. Map insert shows location of northern Australia sites COCO and TOWN.

Table 1. Horizontal Site Velocities With One Standard Deviation Errors and North to East Correlation Coefficients Derived From Four GPS Surveys in 1992-1994

Site Code	Site Location	Latitude °S	Longitude °E	Velocity[a] mm/yr		N-E Correlation	Velocity[b] mm/yr	
				North	East		North	East
BAKO	Cibinong, west Java	6.4911	106.8489	1±2	5± 6	-0.04	-56±2	-16± 6
BANJ	Banjarmasin, Kalimantan	3.4468	114.7548	-2±3	-14± 9	-0.05	-64±3	-32± 9
DENP	Denpasar, south Bali	8.8182	115.1457	-1±2	-5± 7	0.01	-63±2	-26± 7
KEND	Kendari, SE Sulawesi	4.0877	122.4075	3±2	-2± 7	-0.00	-62±2	-19± 7
UJUN	Ujungpandang, SW Sulawesi	5.0599	119.5488	-1±2	0± 5	-0.06	-66±2	-18± 5
BIMA	Bima, Sumbawa	8.5434	118.6928	9±2	14± 7	-0.02	-55±2	-34± 7
RUTE	Ruteng, west Flores	8.5970	120.4784	21±3	-41±13	-0.05	-44±3	-61±13
WAIN	Waingapu, Sumba	9.6696	120.3016	19±2	2± 7	-0.00	-46±2	-18± 7
DILI	Dili, east Timor	8.5478	125.5281	55±2	10± 6	-0.03	1±2	7± 6
KALA	Kalabahi, north Alor	8.1355	124.5955	44±2	4± 6	0.02	-12±2	0± 6
KUPA	Kupang, west Timor	10.1771	123.6631	60±2	-3± 5	-0.00	3±2	-4± 5
MAUM	Maumere, central Flores	8.6385	122.2371	58±3	3±10	0.03	-1±3	0±10
WETA	Wetar, Wetar	7.9348	126.4286	58±3	6± 8	0.16	6±3	2± 8
COCO	Cocos Islands, Australia	12.1884	96.8340	47±4	33±12	-0.09	-2±4	7±12
DARW	Darwin, north Australia	12.8437	131.1327	70±2	21± 8	-0.01	1±2	3± 8
TOWN	Townsville, north Australia	19.2598	146.8141	66±3	-3± 9	0.23	-3±3	-16± 9
XMAS	Christmas Island, Australia	10.4496	105.6896	56±3	33±10	-0.00	-1±3	10±10

Standard deviations are twice the formal values but do not include the uncertainty in relative motion of the reference kinematic block with respect to ITRF93. The velocity estimates for MAUM have been adjusted to exclude coseismic displacements caused by the December 12, 1992, Flores Sea earthquake.

[a] Velocity components are relative to the Sunda shelf reference frame (SSH) defined as a rigid block by BAKO, BANJ, UJUN, KEND, and DENP.

[b] Velocity components are relative to the northern Australia block (NAB, defined by COCO, DARW, TOWN, and XMAS), except for DILI, KALA, KUPA, MAUM, and WETA that define a southern Banda block (SBB). Velocity components listed for these five sites are residuals relative to SBB.

ambiguities are computed from doubly differenced GPS phase measurements [*Dong and Bock*, 1989]. Site positions and velocities in the International Terrestrial Reference Frame 1993 (ITRF 93) [*Boucher et al.*, 1994] are then estimated from the daily regional and global solutions [*Feigl et al.*, 1993; *Bock et al.*, 1993].

To assess the precision of relative site positions and velocities, we examine baselines between regional sites located far from the influence of the Flores Sea earthquake. The 653-km line between the sites UJUN in southwest Sulawesi and KALA on the island of Alor is one of the most surveyed and among the longest in our network. Daily root mean square (RMS) repeatabilities of relative positions for all four surveys are about 4-5 mm for the north, 10-15 mm for the east, and 20-25 mm for the vertical components (Figure 2). Velocity estimates for sites observed during all four surveys have formal standard deviations of about 1-2 mm/yr in the north and 3-5 mm/yr in the east components. Our measurements cover only 24 months, but we note that our velocity estimates at three sites (BAKO, UJUN, and TOWN) agree at two standard deviations with those derived from two sets of GPS observations that either span a larger time interval [*Tregoning et al.*, 1994] or include more Indonesian sites [*Bock et al.*, 1994].

Motion within the local horizontal plane at all but three sites fits well with a uniform rate. Weighted RMS misfits of site positions to a straight line are typically 6 mm for the north component and 10 mm for the east component. These misfits, in connection with the repeatabilities and standard errors in velocities above, indicate that realistic uncertainties in regional site velocities are about twice the formal errors, that is, about 4 mm/yr for northward motion and 12 mm/yr for eastward motion. The relatively large scale of the network combined with the more intense ionospheric refraction of the GPS radio signals in equatorial regions precludes robust integer-cycle phase ambiguity resolution [*Dong and Bock*, 1989]. This deficiency leads to a substantial loss in precision by a factor of approximately 3 for the east component because of the high GPS orbital inclination. A more favorable ratio of about 2 can be achieved in higher

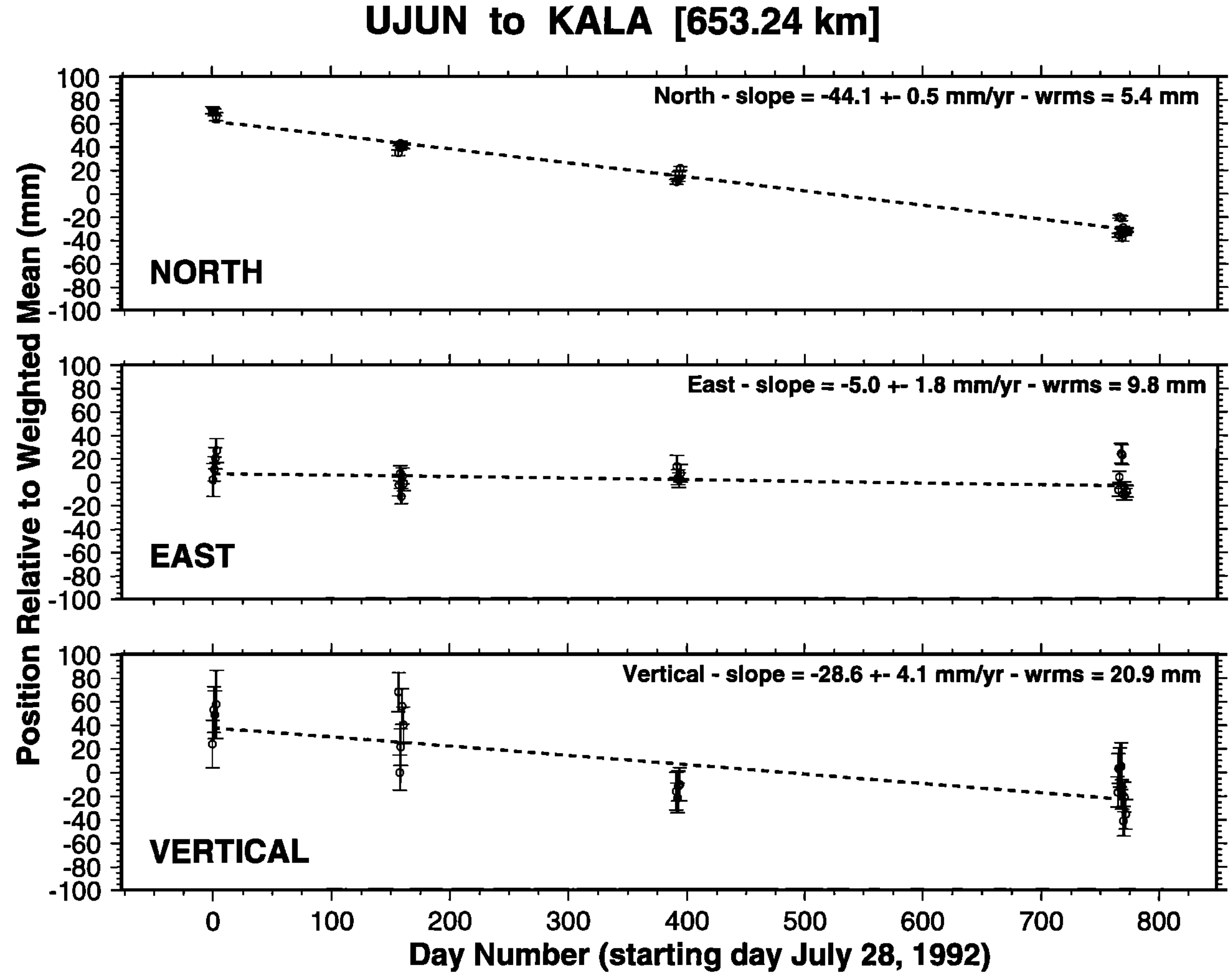
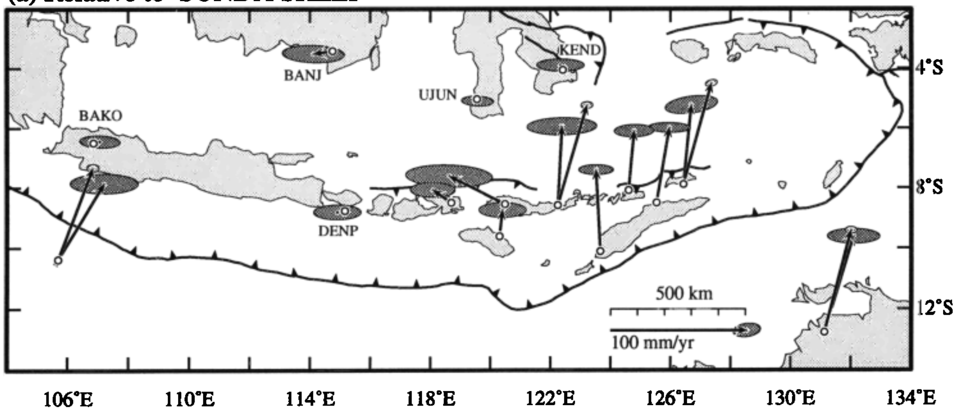
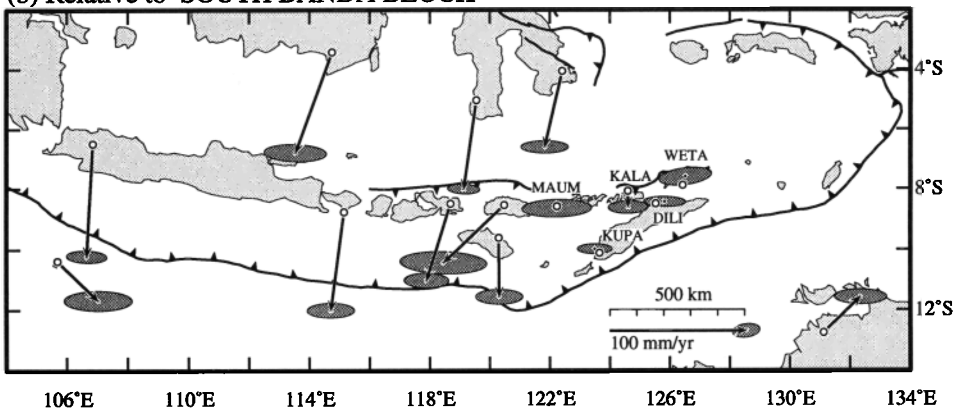


Figure 2. North, east, and vertical components of daily geodetic solutions for the Ujungpandang (southwest Sulawesi) to Kalabahi (north Alor) baseline. Horizontal axes are labeled in number of days counted from the initial day of observations (July 28, 1992). Dashed lines indicate weighted least squares solutions for a linear fit; statistical parameters of the corresponding slopes are shown within each panel. Error bars are one standard deviation.

(a) Relative to SUNDA SHELF



(b) Relative to SOUTH BANDA BLOCK



(c) Relative to NORTHERN AUSTRALIA BLOCK

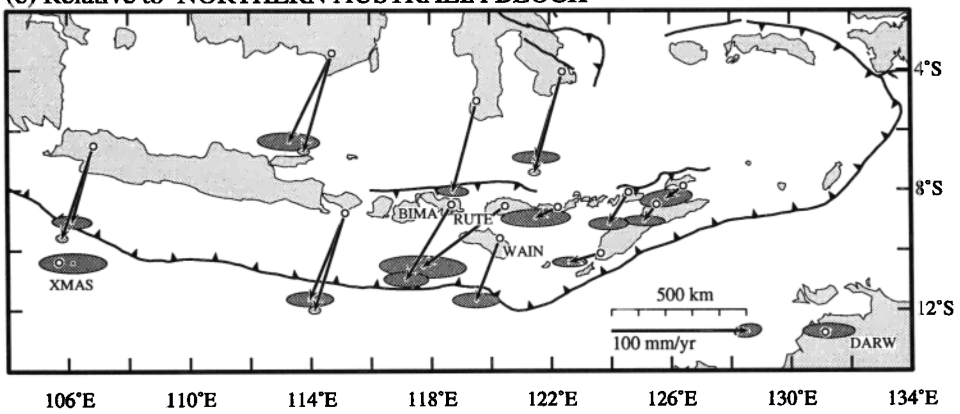


Figure 3. GPS site velocities relative to three reference frames. GPS-determined velocity vectors are drawn as arrows with dark shaded error ellipses. Arrows with light shaded error ellipses represent Australia-Eurasia (AUS-EUR) vectors based on NUVEL-1A [*DeMets et al.*, 1990, 1994]. Arrow length is proportional to the corresponding velocity vector, the ellipses indicate a 95% confidence level. Bold solid lines refer to major faults, thrust faults are identified by barbs on the overriding plate. (a) Velocities relative to the Sunda shelf reference frame (SSH) defined by minimizing relative motion at sites BAKO, BANJ, DENP, KEND, and UJUN; (b) velocities relative to the southern Banda block (SBB) defined by minimizing relative motion at sites DILI, KALA, KUPA, MAUM, and WETA; (c) velocities relative to the northern Australia block (NAB) defined by minimizing relative velocities at sites COCO (see Figure 1), DARW, TOWN (see Figure 1), and XMAS.

Table 2. Poles of Rotation Parameters for Pairs of Tectonic Blocks

Block Pair	Latitude, °N	Longitude, °E	Rate, deg/Myr	Number of Sites	RMS, mm/yr	Minor, deg	Major, deg	Azimuth, deg
AUS-EUR[a]	15.1±1.7	40.5± 1.7	0.69±0.01			1.1	2.1	-45
NAB-SSH	13.0±8.6	51.7± 2.7	0.64±0.02	4	3.7	2.4	8.9	13
SBB-SSH	9.0±8.6	-26.6±17.9	1.04±0.60	5	5.9	7.3	19.1	71
NAB-SBB	-0.9±3.9	119.1± 0.4	1.10±0.03	4	3.7	0.4	3.9	4

Tectonic block pair, location of rotation pole (latitude and longitude), rate of rotation, number of GPS sites used to determine pole of rotation, RMS error, and error ellipse parameters (minor and major axes, orientation) are given. Blocks are abbreviated as SSH for Sunda shelf, NAB for northern Australia, and SBB for southern Banda.

[a]AUS and EUR denote the Australian and Eurasian plates, respectively. Pole parameters for AUS-EUR are those of NUVEL-1A [*DeMets et al.*, 1990, 1994].

latitudes without phase ambiguity resolution, even under incomplete satellite configuration [*Dong and Bock*, 1989]. The predominately north-south oriented Australia-Eurasia convergence is fortuitously parallel to a direction of high GPS geodetic resolution.

Displacement rates at three sites are not uniform. The December 1992 measurements at BIMA on Sumbawa show a large northward displacement, whereas the 1993 northern Australia (DARW) data show excessive eastward motion. Both data sets are excluded from our velocity estimates. Nonuniform displacement at the site in east Flores (MAUM) is due to the effects of the December 1992 Flores Sea earthquake. Dislocation models [*Mansinha and Smylie*, 1971; *Okada*, 1985] based on the source mechanism and seismic moment of this event (Harvard Centroid Moment Tensor solution M121292B) suggest that MAUM is the only site predicted to be measurably displaced during the earthquake. This prediction is consistent with our geodetic measurements at MAUM that reveal a 966±7 mm seismic horizontal displacement at azimuth N18°E and a subsidence of 227±15 mm relative to sites outside the region of seismic deformation. Our velocity estimate for MAUM is therefore based only on the three postearthquake measurements.

GPS Velocity Field and Strain Resolution

We can identify four distinct tectonic blocks from the GPS velocity field. Sites in west Java (BAKO), Bali (DENP), southwest Sulawesi (UJUN), and southeast Sulawesi (KEND) do not move horizontally relative to one another (at one standard deviation), and south Kalimantan (BANJ) is fixed relative to the other four at two standard deviations. These sites define a Sunda shelf (SSH) reference frame in which all five velocity vectors are minimized, with a weighted RMS residual of 2.5 mm/yr. Velocities for all sites relative to this reference frame are listed in Table 1 and shown on Figure 3a.

The north component of the velocity at BIMA (9±2 mm/yr) in eastern Sumbawa is attributed to active back arc thrusting in the Bali basin [*McCaffrey and Nabelek*, 1987]. Farther eastward along the Sunda arc the rate of thrusting at the back arc increases. At RUTE on western Flores and WAIN on Sumba we observe about 20±3 mm/yr of northward motion relative to the Sunda shelf, and at MAUM on eastern Flores it increases to 58±3 mm/yr.

GPS velocities of all four Australian sites define a rigid northern Australia block (NAB) (Figure 3c) at a weighted RMS of 3.7 mm/yr. Its pole of rotation relative to the Sunda shelf is 10° closer to Indonesia than the NUVEL-1 pole for Australia-Eurasia [*DeMets et al.*, 1990], and the rate of rotation is about 7% lower than the corresponding NUVEL-1A rate [*DeMets et al.*, 1994]. Accordingly, the observed convergence along the southeastern Indonesian island arc section of the plate margin is about 12 mm/yr less than the NUVEL-1A prediction based on rigid Eurasia and Australia.

Velocities of five sites along the southern Banda arc (KUPA, KALA, DILI, and WETA) and on eastern Flores are all similar to one another in direction and magnitude (Figure 3a). This area acts as a rigid block (southern Banda block (SBB) in Figure 3b and in Table 1) with a maximum deviation of 12 mm/yr at KALA. KUPA on western Timor, north of the trough, moves relative to the Sunda shelf at about the same rate (60±3 mm/yr at N3°W±6°) as Australia (69±3 mm/yr at N3°E±8°) based on the northern Australia-Sunda shelf pole of rotation (Table 2). Relative motion between KUPA and DARW is 27±10 mm/yr at N107°W±16° as computed from the corresponding baseline observations or -26±8 mm/yr in the direction of approximate trough orientation (N60°E). Deformation across the Timor trough is almost entirely left-lateral shear parallel to the trough (Figure 3c).

Uniform deformation rates within the southern Banda block are estimated by calculating the two-dimensional (east/north) Cartesian velocity gradient tensor L [*Malvern*, 1969] using the five sites MAUM, KUPA, KALA, DILI, and WETA. A single tensor L fits the site velocity components with a RMS error of 7 mm/yr, comparable to our estimates of relative site velocity resolution. The actual tensor components ($L_{EE} = 1.9 \pm 22.0$, $L_{EN} = 2.7 \pm 22.8$, $L_{NE} = 1.9 \pm 2.8$, $L_{NN} = -5.6 \pm 3.2$) $\times 10^{-8}$ yr^{-1} reveal a 6.3×10^{-8} yr^{-1} shortening in a NNE direction and a poorly resolved 3×10^{-8} yr^{-1} extension parallel to the arc.

Discussion

Earthquake slip vectors and GPS-derived velocity vectors along the eastern Sunda arc are essentially perpendicular to the trench (Figure 4). Significant exceptions are the velocities for BIMA and RUTE. Although both estimates are determined from only two measurement epochs with a large uncertainty in the east

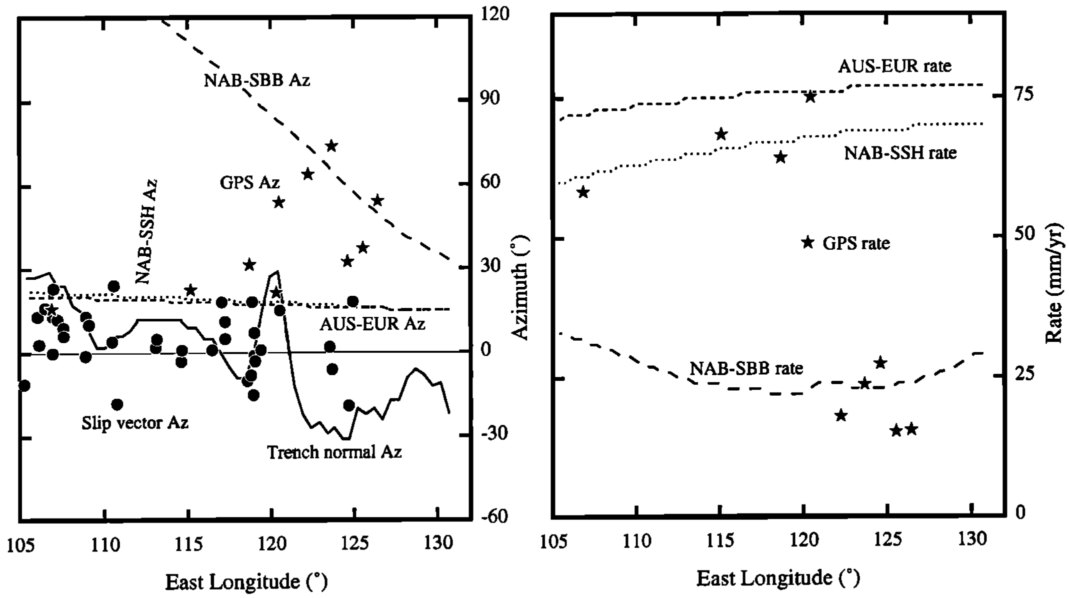


Figure 4. Convergence along the eastern Java-southern Banda trench. (Left) azimuth and (right) rates of vectors are shown as a function of longitude. Also included are the azimuth of the trench normal and rates and azimuths of convergence vectors for the northern Australia block (NAB) relative to the Sunda shelf (SSH) and the southern Banda block (SSB) (see Table 2 and Figure 3 for their definitions) and for AUS-EUR, based on NUVEL-1A [*DeMets et al.*, 1990, 1994]). GPS vector components are relative to NAB. West of the transition zone around E121° longitude, GPS vectors follow NAB-SSH, east of E121° they fall on NAB-SBB. NAB-SSH is close to AUS-EUR in azimuth but lower in rate.

component for RUTE, they tend to support the notion of anticlockwise rotation of the eastern end of the inner Sunda arc island chain relative to the Sunda shelf [*McCaffrey*, 1988].

Slip vectors of the few thrust earthquakes along the southern Banda arc range in azimuth from a trough-normal orientation to the direction of convergence, which is considerably oblique along this part of the trough (Figure 4). In connection with shallow strike-slip events observed near Timor this deflection of thrust vectors points to a possible partitioning of slip [*McCaffrey*, 1992]. Azimuths of GPS-based velocity vectors from sites in this area fall outside this range and are, as a group (Figure 3c), consistent with a close pole of rotation located toward the northwest (Table 2).

The homogeneous velocity field for the southern Banda arc, with a slightly lower northward component of KALA as the only exception, indicates that the present northward motion of Australia results in little internal compression of the arc structure. This observation and the relatively aseismic nature of the upper plate in the Timor region suggest that this segment of the island arc, bounded by the Timor trough and the back arc Wetar thrust, is thrusting over the back arc basin as a rigid block (Figure 3a). The slight compression of this southern Banda block in the direction of plate convergence cannot be attributed to elastic strain associated with locking at a potentially still active Timor trough. Velocities relative to northern Australia in the direction of convergence (N17°E) are essentially constant (-13±3 for KUPA, -14±3 for DILI, and -12±4 mm/yr for WETA and MAUM) for all four sites away from the Wetar thrust. These velocities are consistent with profiles derived by elastic dislocation modeling for an inactive Timor through (Figure 5). Modeling also suggests that the significant southward motion of northern Alor (KALA) relative to the southern Banda block (12±2 mm/yr, Figure 3b) indicates locking at the Wetar thrust. Elastic strain distribution across the block as inferred from GPS site velocities is thus in agreement with recent seismic history. Thrust events are absent at the trough but frequent at the Wetar thrust [*McCaffrey and Nabelek*, 1986].

The degree to which deformation within the lithosphere of the Banda Basin accommodates Australia's northward path is undetermined by the present measurements, but seismicity suggests that it might be important [*McCaffrey*, 1988]. In any case, the southeastern Indonesian island arc shows a transition from normal subduction of oceanic lithosphere south of Java to a completed accretion of an island arc terrain to a continental margin at Timor. In the process, convergence has jumped from the forearc trench to the back arc thrust (Figure 4). Convergence normal to the Timor trough is less than 10 mm/yr, confirming that subduction at the trough has essentially ceased, as suggested by *Johnston and Bowin* [1981]. Seismic reflection profiles (BIRPS) in the Timor region have been interpreted similarly by *Snyder et al.* [1996], but they suggest a northward translation of crustal thrusts accompanied by a broad zone of deformation within the Banda island arc structure.

The velocity estimate for WAIN on Sumba (19±8 mm/yr at N7°E±27° relative to the Sunda shelf) demonstrates that subduction at the eastern end of the Java trench accommodates at least 70% of the total convergence and is essentially parallel to the direction of plate convergence (Figure 3a). Part of the observed velocity may be due to elastic strain. The transfer of convergence to the back arc is therefore rather abrupt (Figure 4)

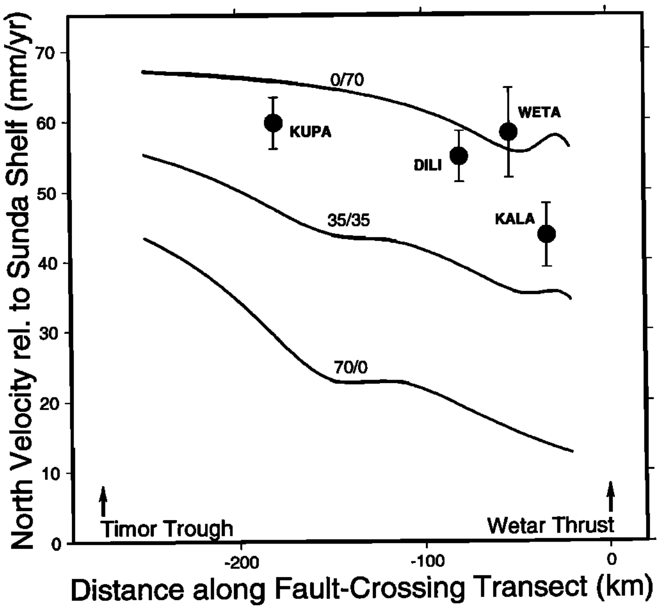


Figure 5. Elastic deformation of the southern Banda block for different slip scenarios at the Timor trough and Wetar thrust. North components of slip rates as inferred from elastic dislocation modeling are shown as a function of distance from the Wetar thrust along a fault-crossing line of N25°W azimuth. Profiles are labeled by a pair of numbers that indicate the corresponding slip deficits in millimeters per year at both the Timor trough (first number) and the Wetar thrust (second number). GPS-derived velocity north components (relative to the Sunda shelf, shown as solid circles that are labeled with the site code) and corresponding one standard deviations are included for the four applicable sites of the southern Banda block. Dip-slip dislocation is assumed to be uniform along planar thrust fault surfaces striking N65°E at 20° dip (Timor) and N100°W at 40° dip (Wetar).

and has to be accommodated by significant left-lateral shear trending north-south in the Savu Sea and across central Flores. *Audley-Charles* [1975] identifies the left-lateral Sumba fracture as a major discontinuity between eastern and western Indonesia. This trend traverses the Savu sea in a NNW direction and probably marks the limit of continental crust beneath the forearc. The contemporary shear zone across the Savu sea may thus be located above the edge of the subducted continental shelf.

Current kinematics of the southern Banda arc reflect a very recent development of the collision zone. At a convergence rate of 55±5 mm/yr, as suggested by our GPS measurements, 10 km of crustal shortening on the Wetar thrust, as estimated by *McCaffrey and Nabelek* [1986], takes less than 200,000 years. Since the onset of high-rate back arc thrusting should coincide with the cessation of subduction under the forearc, we can estimate that the Timor trough became inactive as a subduction zone within the last 160,000-200,000 years.

This time interval is similar to geological estimates. On the basis of sedimentation rates in the Timor trough obtained from deep-sea drilling cores, *Charlton* [1986] concluded that subduction ceased about 500,000 years ago. Both estimates can be reconciled if the transition of convergence from the trough to the back arc thrust was rather gradual and resulted in an average back arc convergence rate that is only about half of the present-day velocity. Other geological data tend to support an average velocity that is much closer to the GPS-determined current rate. Australian continental material arrived at the trough in middle Pliocene or even earlier, and cumulative continental underthrusting is estimated at several hundred kilometers [*McCaffrey*, 1989]. The recent transfer of plate convergence to the back arc may have resulted from Quaternary uplifting and crustal thickening within the Timor accretionary wedge [*Silver et al.*, 1983]. Sediments and their microfossils in west Timor indicate that a phase of rapid uplift of the island commenced about 200,000 years ago [*DeSmet et al.*, 1990].

Conclusions

On the basis of GPS geodetic measurements and earthquake slip vectors, we identify four tectonic regions along the southeastern Indonesian part of the Australian-Eurasian plate margin: (1) northern Australia, a rigid block south of the Java trench/Timor trough; (2) Sunda shelf (Java, Bali, Kalimantan, and Sulawesi) converging with northern Australia in a direction similar to NUVEL-1 Australia-Eurasia but at a slower rate (Figure 4); (3) inner eastern Sunda volcanic arc (Sumbawa to Flores) rotating anticlockwise relative to the Sunda shelf, resulting in convergence at the Flores thrust; and (4) southern Banda volcanic and outer arc (Timor to Wetar) closing the Banda sea in a north-south direction at nearly the full plate convergence rate and much faster than the rotation of the inner eastern Sunda arc. Islands of the outer eastern Sunda arc (Sumba) act as a transition zone between the inner eastern Sunda and the southern Banda arcs. This zone separates subduction at the Java trench from left-lateral shear orthogonal to the direction of plate convergence farther east.

The plate margin along the eastern Indonesian island arc has developed from subduction at the Java trench and Timor trough into a complex zone of deformation. Its western end shows subduction along the forearc, while to the east the major thrust components are shifted to the back arc region. Rather than the locus of subduction, the Timor trough forearc has now become an area of significant shear strain.

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