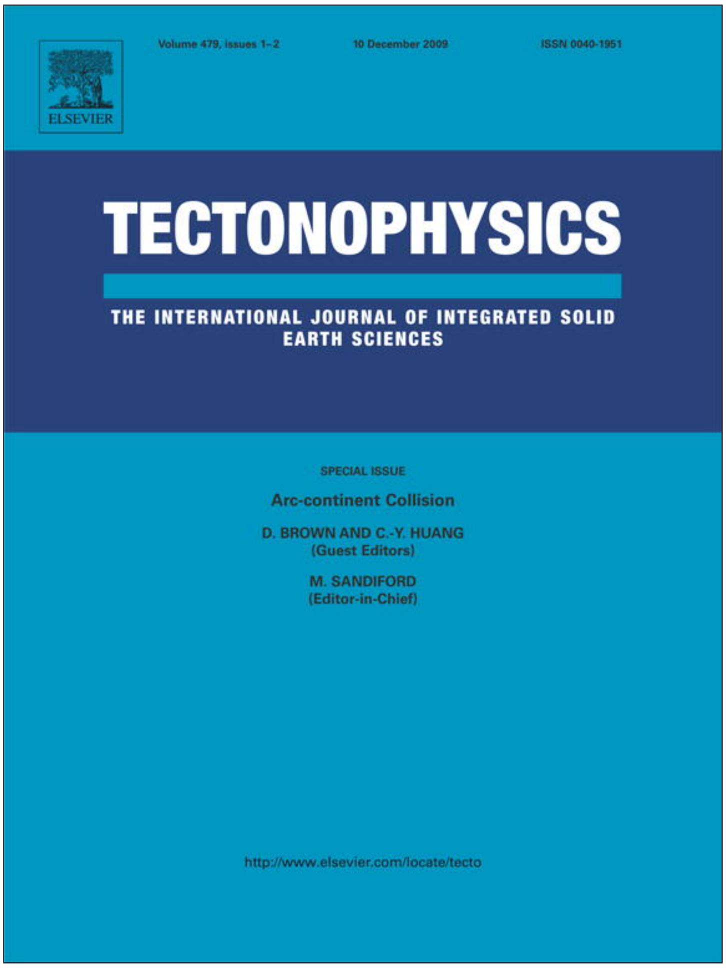
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Plate boundary reorganization in the active Banda Arc–continent collision: Insights from new GPS measurements

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A B S T R A C T

New GPS measurements reveal that large sections of the SE Asian Plate are progressively accreting to the edge of the Australian continent by distribution of strain away from the deformation front to forearc and backarc plate boundary segments. The study was designed to investigate relative motions across suspected plate boundary segments in the transition from subduction to collision. The oblique nature of the collision provides a way to quantify the spatial and temporal distribution of strain from the deformation front to the back arc. The 12 sites we measured from Bali to Timor included some from an earlier study and 7 additional stations, which extended the epoch of observation to ten years at many sites.

The resulting GPS velocity field delineates at least three Sunda Arc–forearc regions around 500 km in strike-length that shows different amounts of coupling to the Australian Plate. Movement of these regions relative to SE Asia increases from 21% to 41% to 63% eastward toward the most advanced stages of collision. The regions are bounded by the deformation front to the south, the Flores–Wetar backarc thrust system to the north, and poorly defined structures on the sides. The suture zone between the NW Australian continental margin and the Sunda–Banda Arcs is still evolving with more than 20 mm/yr of movement measured across the Timor Trough deformation front between Timor and Australia.

1. Introduction

The Sunda Arc–trench system accommodates up to 7 cm/yr of convergence between the large Indo-Australian and Asian plates (Tregoning et al., 1994). Most plate convergence (90%) in the western Sunda Arc Region is localized in a narrow zone near the deformation front (Stockmal, 1983; Sieh et al., 1999). The Eastern Sunda Arc is transitional into the Banda Arc, where the nature of both the Indo-Australian lower plate and the Asian upper plate progressively change (Fig. 1). The upper plate has been modified by marginal basin development and changes from the continental Sunda shelf to a series of composite oceanic basins eastward. The lower subducting plate changes from old oceanic seafloor that is subducting beneath the Sunda Continent at the Java Trench to the Australian passive continental margin. These changes transform the subduction system into a collision between the Banda oceanic arc and the Australian passive continental margin, known as the Banda Orogen.

The increase in crustal shortening from the Java Trench to Banda Orogen is generally driven by increased coupling with the underthrust Australian plate, which progressively changes from oceanic to continental (Harris, 1991). Along strike variations in the distribution of strain from the Java Trench to the Banda Orogen are demonstrated by structural field studies of the region (Carter et al., 1976; Harris, 1991), age of synorogenic sedimentary units (Roosmawati and Harris, this issue), the distribution of earthquakes (McCaffrey, 1988; McCaffrey and Albers, 1991) and regional GPS measurements (Genrich et al., 1996). These data reveal that a reorganization of the plate boundary is in progress. Some of the questions we investigate in this paper about this process are: What drives plate boundary reorganization? How is strain distributed throughout the process? What is the nature and present location of the plate boundary? How does it evolve through time? To address these questions, a new grid of GPS stations was established during the summers of 2001 and 2003 to measure baselines throughout the regions and across several potential plate boundary segments identified from earlier studies (Fig. 2).

2. Shortening estimates and the temporal distribution of strain

Obliquity between the continental margin of Australia and the Java Trench provides a way to track the plate boundary reorganization through the transition from subduction to collision in time and space. Plate kinematics predicts that the collision propagates westward from Timor to Rote at a rate of 110 km/Ma (Harris, 1991). The

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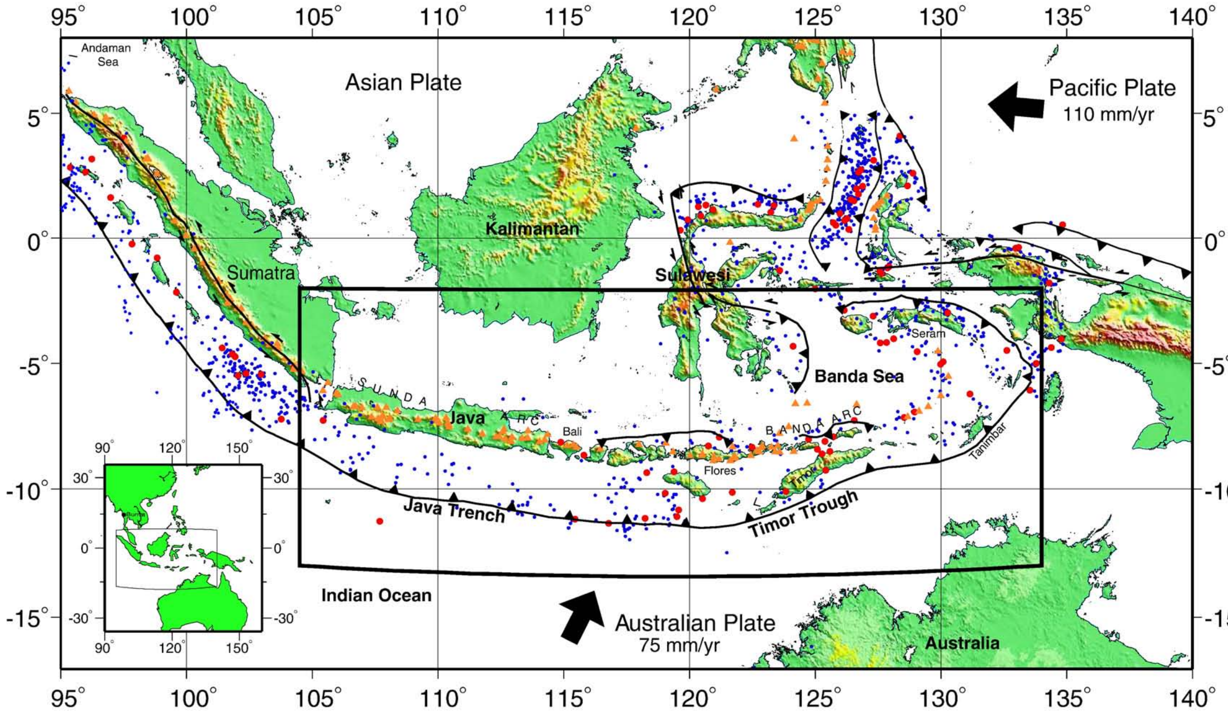

Fig. 1. Tectonic map of the Indonesia region with epicentral locations from 01/01/1976 to 28/03/2005 (<50 km, red dots) with magnitudes greater than six (Mw>6.0); blue dots are earthquakes with magnitudes ≤6. Orange triangles show active volcanoes. Box encloses area of study (Fig. 2). Black arrows represent plate movements based on NUVEL-IA.

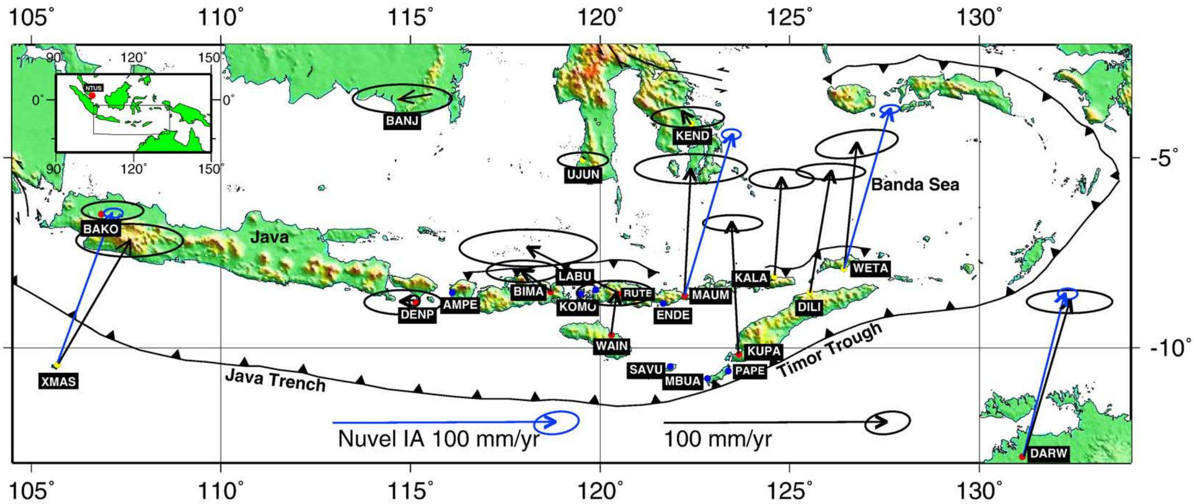

Fig. 2. Several GPS stations in the Indonesia region. GPS velocity vectors show relative motion to the Sunda shelf reference frame by minimizing relative motion at sites BAKO, BANJ, DENP, KEND, and UJUN (Genrich et al., 1996).

breadth over which the subduction to collision transition takes place (600 km) provides a unique display of collision zone development over a space–time equivalence of 5.5 to 7 m.y. (Fig. 2).

Area balanced serial sections at 100 km intervals through the transition from Subduction to collision (Fig. 3) provide estimates of total shortening that we can compare with decadal strain. The western-most cross-sections through Sumba and Savu represent the initial stages of collision and only correspond to around 20% shortening. Between the two sections is a dramatic reduction in wedge taper that extends the accretionary slope over 100 km south of its position on either side of the Savu region (Fig. 1). Geological relations exposed in Savu and interpreted from seismic lines offshore show the development of an arc-ward thrust system that moves the accretionary wedge over the Savu forearc basin and uplifts Pleistocene deep sea deposits and coral terraces (Harris et al., 2009). Most of the material incorporated into the emerging accretionary wedge was transferred from underthrust units of the continental Scott Plateau. Many of these units consist of over-pressured, clay-rich successions that reduce the basal coefficient of friction, causing extensional collapse and massive shale diapirism (Harris et al., 1998).

The arrival of the Australian shelf at the deformation front initiates a phase of rapid uplift associated with dewatering, wedge contraction and increased arcward movement along back-thrusts (Prasetyadi and Harris, 1996). Retro-wedge motion eventually consumes the forearc basin as the orogenic wedge, and later the volcanic arc, becomes partially accreted to the lower plate. Estimates of shortening in the Timor part of the orogenic wedge predict that up to 70% of the plate convergence is partitioned away from the deformation front and contributes to continued northward motion and internal shortening of the orogenic wedge (Harris, 1991). At this stage of collision, seismic data (Snyder et al., 1996) and neotectonic features (Cox et al., 2006) indicate that nearly all plate convergence is taken-up away from the deformation front.

3. Geodetic studies

GPS studies of the Eastern Sunda Arc and Banda Orogen provide another way to investigate the distribution of strain in zones of oblique convergence on the western and eastern edge of the 'Sunda' Block (Genrich et al., 1996; McCaffrey et al., 2000; Prawirodirdjo et al., 2000). The Sunda Block includes the Sunda shelf region of Borneo, the Malay Peninsula and Indochina-excluding South China (Simons et al., 1999; Michel et al., 2001; Simons et al., 2007), which together comprise the relatively stable continental nucleus of the Indonesian region defined by little to no internal deformation and low seismicity. Relative to Eurasia, the Sunda block moves 6 ± 1 to 10 ± 1 mm/yr eastward (Chamot-Rooke and Pichon, 1999; Michel et al., 2001; Simons et al., 2007). The Sunda Block is surrounded by the actively deforming regions of Sumatra on the west, Sulawesi on the east, and the Sunda–Banda Arcs to the south (Fig. 1).

The eastern edge of the Sunda block is influenced mostly by the westward movement of the Philippine Sea plate, continental fragments it has torn from the northern edge of Australia (Walpersdorf et al., 1998), and some effect of northward movement of the Australian plate. These tectonics instabilities create problems for establishing GPS reference frames in the Banda Orogen. However, the Australian Plate reference frame, which is computed using the ITRF 2000 solution (Altamimi et al., 2002) uses several permanent stations and is much more reliable for tracking movements in the Banda Orogen.

Beginning in the early 90s Tregoning et al. (1994) used GPS data to establish a rate of convergence across the Java trench. Three individual stations were measured including Christmas Islands, Cocos Islands, and West Java. The velocity vectors of Christmas and Cocos Island agree with the NNR NUVEL-1 model in azimuth, but the magnitudes were less by 18 mm/yr and 26 mm/yr, respectively. These differences were interpreted as a function of either SE-Asia movement or local deformation (Tregoning et al., 1994).

In 1991 to 1993, GPS measurements were used to estimate the slip distribution between the Australia–Pacific Plate boundary in Irian Jaya (now West Papua) Indonesia (Puntodewo et al., 1994). Similar studies were also conducted in Sulawesi (Walpersdorf et al., 1998; Socquet et al., 2006), Sumatra and the Sunda Block (Baroux et al., 1998; Prawirodirdjo et al., 2000). Global studies that include parts of Indonesia were also conducted as part of the GEODYSSEA project (Chamot-Rooke and Pichon, 1999; Simons et al., 1999; Michel et al., 2000, 2001; Simons et al., 2007) and other global plate studies (Kreemer et al., 2000; Bock et al., 2003).

The first GPS study that focused on resolving regional deformation in the Eastern Sunda and Banda Arcs was conducted by Genrich et al. (1996). Their GPS campaign identified what they called four distinct tectonic 'blocks' with different GPS velocity fields within the arc–continent collision zone. Sites in West Java (BAKO), Bali (DENP), southwest Sulawesi (UJUN), southeast Sulawesi (KEND) and Kalimantan (BANJ) showed no movement relative to one another, which they called the Sunda or SE Asian block (Fig. 2). Newer GPS results confirm these inferences (Walpersdorf et al., 1998). Arc and forearc islands to the east and south of these sites show various amounts of movement relative to the Sunda block. Sites at Bima (BIMA), Waingapu (WAIN), Ruteng (RUTE), and Maumere (MAUM) have different horizontal movement rates attributed to active back arc thrusting in the Bali basin (McCaffrey and Nabelek, 1987). On eastern Flores and Timor, four stations, Kupang (KUPA), Kalabahi (KALA), Wetar (WETA) and Dili (DILI) are similar to one another in direction and magnitude, and nearly the same as Darwin (DARW) in Australia. This implies that these stations act as one rigid block and that the Eastern Sunda and Banda Arcs have accreted to the Australian continental margin. What could not be resolved from these studies were the nature and extent of the block boundaries, the relative motions between various parts of the forearc ridge region, and the relations between the GPS velocity field and other studies of strain distribution in the Banda Orogen.

4. GPS measurement and analysis

We occupied 14 sites in the Eastern Sunda Arc during the 2001 and 2003 GPS campaigns with the assistance of personnel from Brigham Young University and Bakosurtanal (National Survey Agency of Indonesia). Eight of these sites were also used in the Genrich et al. (1996) study (Fig. 2). The other six sites, including two that were newly installed, Ampenan [AMPE], Ende [ENDE], Labuhanbajo [LABU], Savu [SAVU], Mbuain [MBUA] and Papela [PAPE] (blue dots in Fig. 2), were included to provide new baselines across the Savu sea, to measure possible lateral (east–west) variations in lower plate coupling. Five permanent stations in the region (Bakosurtanal [BAKO], Darwin [DARW], Kupang [KUPA], Cocos Island [COCO] and Singapore [NTUS]) were also used (Fig. 2) along with other IGS global permanent stations. Several of the Genrich et al. (1996) stations could not be reoccupied, such as Christmas Island (XMAS), Banjarmasin (BANJ), Ujungpandang (UJUN), Kendari (KEND), Kalabahi (KALA), Wetar (WETA) and Dili (DILI) (cyan dots in Fig. 2).

New GPS sites on the island of Savu (SAVU) and Rote (MBUA and PAPE) were occupied to constrain the width of the plate boundary reorganization zone between the Java Trench and the Timor trough. Baselines between these stations and Sumba (Waingapu [WAIN]) and the arc islands to the north (Ende [ENDE], Ruteng [RUTE], Labuhanbajo [LABU], and Komodo Island [KOMO]) also provide a way to test for movement along faults between the arc and forearc islands, such as the Savu thrust. In eastern and western Rote, two stations (MBUA and PAPE) were occupied in order to test for movement across the island, which lies along a major structural discontinuity in the collision zone.

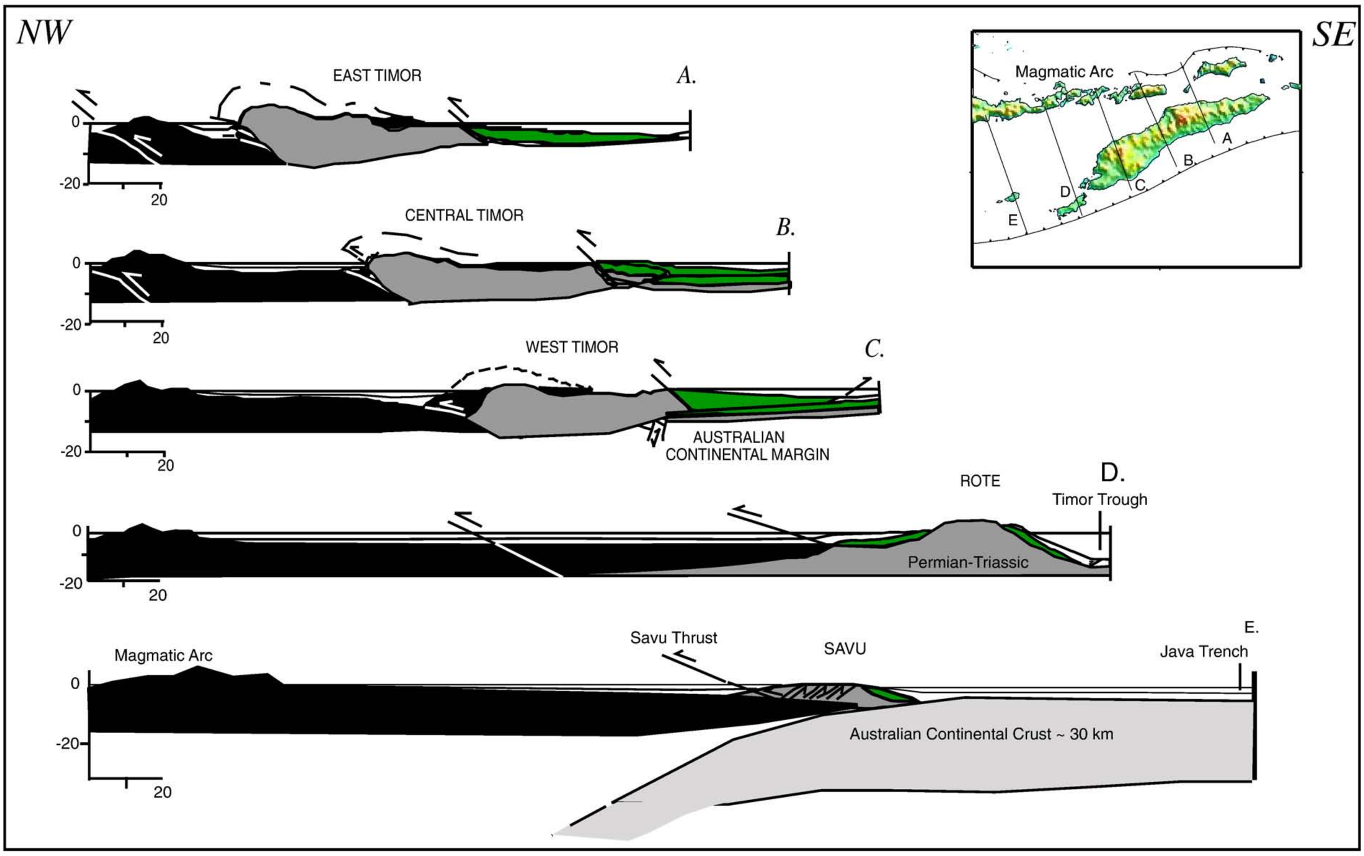

Fig. 3. Serial sections through Timor, Rote, and Savu Islands. The sections relate to a time–space continuum along orogenic strike, where Savu represents the initial stage of collision and East Timor the most advanced stage. Lithotectonic units explanation: Black — forearc basement; Dark grey — Gondwana Sequence sedimentary basement and melange; Green — Australian Continental Margin Sequence (Kolbano Sequence); White — synorogenic deposits. Redrawn from Harris (1991) and Harris et al. (1998).

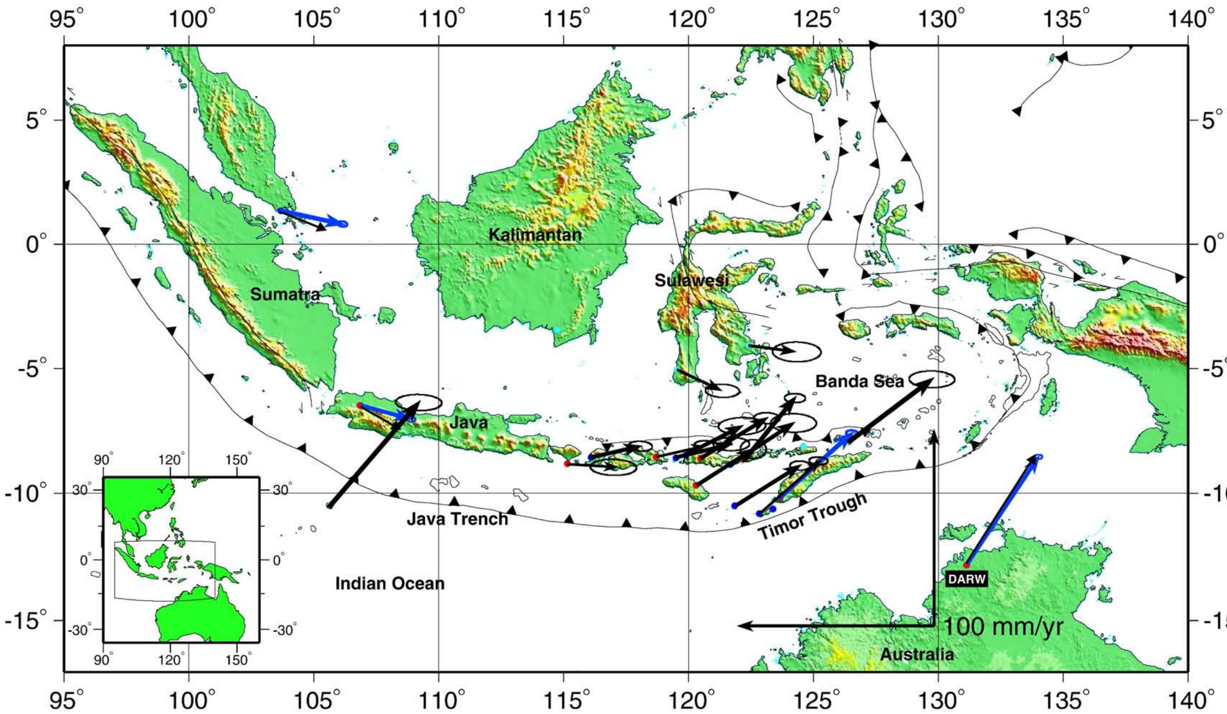

Fig. 4. Global GPS velocities: thick arrows are measured GPS velocity vectors; thin arrows are GPS velocity vectors based on NNR-NUVEL-1A (DeMets et al., 1994). The NNR-NUVEL-1A velocity field for Asia is shown at NTUS and BAKO and for Australia at DARW and KUPA.

Table 1
GPS Velocity of Eastern Sunda Arc Region relative to the ITRF00 reference frame.

Site	Longitude (°)	Latitude (°)	Vector length (mm/yr)	E & N rate (mm/yr)		E & N adj. (mm/yr)		E & N +− (mm/yr)		Rho	H rate (mm/yr)	Epoch (yr)
PAPE	123.385	−10.614	Outliers	61.66	16.52	−1.12	−0.01	3.79	1.37	−0.049	−20.48	3
COCO	96.834	−12.188	Not plotted	41.73	49.06	−0.73	−0.32	0.55	0.26	−0.092	7.47	10
BIMA	118.693	−8.543	24.2	26.81	4.75	38.17	57.42	0.76	0.36	−0.042	2.64	10
KEND	122.408	−4.088	24.6	22.13	−2.89	22.13	−2.89	4.53	1.85	−0.031	56.53	3
UJUN	119.549	−5.06	25.6	20.83	−9.82	20.83	−9.82	3.18	1.24	−0.063	−35.15	3
AMPE	116.101	−8.561	26.7	22.38	5.7	−2.31	−0.34	2.37	0.95	−0.113	−9.19	3
DENP	115.146	−8.818	26.7	11.01	−18.03	41.25	56.44	5.57	2.14	−0.137	−32.17	10
BAKO	106.849	−6.491	27.3	21.54	−7.68	−2.38	−1.9	0.3	0.17	−0.105	−4.45	10
KOMO	119.492	−8.589	29.8	26.1	7.1	−1.53	0	3.72	1.34	0.012	191.46	3
LABU	119.88	−8.489	33.5	27.11	14.96	−1.34	−0.25	4.87	1.74	0.054	16.8	3
NTUS	103.68	1.346	33.5	31.43	−6.9	0.94	−2.47	0.97	0.55	−0.165	5.08	3
WAIN	120.301	−9.669	33.9	29.88	17.64	1.79	−1.02	0.39	0.19	−0.032	6.47	10
SAVU	121.846	−10.493	38.6	30.25	20.19	−1.34	−0.21	2.02	0.87	−0.039	5.7	3
ENDE	121.663	−8.848	39.1	26.47	20.75	−5.03	−0.77	4.66	1.89	−0.021	−10	3
RUTE	120.478	−8.597	40.2	27.49	13.29	−5.72	−7.51	0.56	0.26	−0.058	35.66	10
MAUM	122.237	−8.639	42.3	26.92	32.85	1.66	0.82	0.35	0.18	−0.034	−11	10
MBUA	122.829	−10.807	42.4	30.04	27.71	−1.27	−0.52	1.88	0.74	−0.069	−3.04	3
KUPA	123.663	−10.177	49.4	35.39	32.98	−0.93	−0.3	1.04	0.46	−0.041	−4.17	3/3
KALA	124.596	−8.136	55.5	38.16	28.82	38.16	28.82	4.26	1.56	−0.043	−8.51	3
DARW	131.133	−12.844	66.1	35.08	55.12	35.08	55.12	0.49	0.23	−0.022	0.16	3/3
XMAS	105.69	−10.45	71.1	40.93	47.74	40.93	47.74	4.32	1.51	−0.062	2.52	3

Data was processed using GAMIT/GLOBK (King and Bock, 2002) and its consistency of analyses can be seen through the velocities with respect to a no-net-rotation (NNR) frame. The statistics of the solution shows low RMS, which is 1.7 mm/year compared to 2–3 mm/year as found by Simons et al. (1999). Detailed horizontal movement of each station can be seen in Fig. 4 and Table 1.

A rotation vector of ITRF00 to the Australian plate estimated by Altamimi et al. (2002) was used to calculate the velocities from GPS data in Eastern Indonesia relative to the Australian Plate. The result can be seen in Table 2. With velocities of stations in Singapore (NTUS) and Bakosurtanal (BAKO) set to zero, the velocities of other stations relative to the Sunda Block were computed (Fig. 5; Table 3).

5. Plate boundary location

Several plate boundary zones have been proposed for the Banda Arc–continent collision. The Sumba fracture zone was proposed by Audley-Charles (1975, 1985) as the boundary between subduction in the Sunda Arc to the west and collision in the Banda Arc (Fig. 6). However, there is little seismic or sea floor mapping evidence for the Sumba fracture (van der Werff, 1995). Other plate boundaries have been proposed based on various regional GPS investigations. Several micro-plates in the active deformation zone of Eastern Indonesia are proposed (Genrich et al., 1996; Walpersdorf et al 1998; Bock et al., 2003). The GEODYSSEA project defined a plate boundary that delineates the Sunda Block from the rest of the Banda Arc. The boundary curves north of eastern Sumba Island, across Flores, and continues eastward parallel to the inner volcanic chain (Fig. 6). Our investigation shows that this boundary is most likely near the western edge of Timor, which is supported by field evidence from Rote Island (Roosmawati and Harris, this issue).

Genrich et al. (1996) and Bock et al. (2003) show a N–S boundary to the west of Sumba to mark the Sunda Block (Fig. 6). The boundary turns northward at about 116°E to the east of Lombok Island and joins with the Flores thrust. At the end of the thrust, it turns northward again, separating the two southern arms of Sulawesi and connects with the Palu Fault.

The only boundaries where there is geological and geophysical evidence for active faulting are the Flores and Wetar thrusts (Silver et al., 1983), and a poorly constrained structural and bathymetric discontinuity that bounds the west coast of west Timor near 123° longitude (Harris, 1991). Faults that may be associated with the 123° discontinuity are seen in seismic reflection profiles (Karig et al., 1987) as well as a linear zone of mud diapirs with active mud volcanoes (Barber et al., 1986; Harris et al., 1998). There is also a diffuse zone of seismicity with

Table 2
GPS velocity of Eastern Sunda Arc Region relative to Australia reference frame.

Site	Longitude (°)	Latitude (°)	Vector length (mm/yr)	E & N rate (mm/yr)		E & N adj. (mm/yr)		E & N +− (mm/yr)		Rho	H rate (mm/yr)	Epoch (yr)
PAPE	123.385	−10.614	Outliers	25.28	−41.89	25.28	−41.89	4.08	2.02	−0.032	−23.16	3
COCO	96.834	−12.188	Not plotted	2.37	−0.94	2.17	−1.67	3.94	3.86	−0.003	0.29	10
DARW	131.133	−12.844	3.9	0.19	−2.98	0.19	−2.98	2.02	1.95	0.002	−3.77	3/3
XMAS	105.69	−10.45	6.9	−3.45	−6.65	−3.45	−6.65	9.27	4.46	−0.051	2.84	3
KUPA	123.663	−10.177	25.2	−1.14	−25.24	−1.14	−25.24	1.83	1.55	−0.009	−6.36	3/3
MAUM	122.237	−8.639	26.2	−10.84	−24.19	−10.84	−24.19	0.49	0.37	−0.007	−11.98	10
KALA	124.596	−8.136	28.5	−7.68	−27.66	−7.68	−27.66	9.63	4.55	−0.024	−2.98	3
MBUA	122.829	−10.807	30.8	−6.55	−30.32	−6.55	−30.32	2.41	1.66	−0.026	−5.89	3
ENDE	121.663	−8.848	37.9	−9.36	−36.7	−9.36	−36.7	4.91	2.4	−0.016	−10.65	3
SAVU	121.846	−10.493	38.5	−6.4	−37.93	−6.4	−37.93	2.53	1.72	−0.018	1.46	3
WAIN	120.301	−9.669	39.9	−8.05	−39.41	−8.05	−39.41	0.53	0.41	−0.007	5.49	10
LABU	119.88	−8.489	43.8	−9.9	−42.7	−9.9	−42.7	5.1	2.29	0.039	12.56	10
RUTE	120.478	−8.597	44.4	−10.35	−43.47	−10.35	−43.47	1.06	0.56	−0.045	42.63	3
KOMO	119.492	−8.589	51.9	−10.83	−50.67	−10.83	−50.67	4.01	2	0.007	187.68	3
AMPE	116.101	−8.561	53.1	−14.95	−50.96	−14.95	−50.96	2.81	1.76	−0.053	−10.03	3
BIMA	118.693	−8.543	53.7	−11.36	−52.67	−11.36	−52.67	0.86	0.56	−0.015	2.29	10
NTUS	103.68	1.346	60.8	−8.11	−60.26	−2.65	−3.81	1.1	0.86	−0.011	0.18	3
UJUN	119.549	−5.06	63.1	−23.88	−65.92	−23.88	−65.92	7.48	4.12	−0.025	−30.81	3
BAKO	106.849	−6.491	63.3	−17.82	−60.81	−2.93	−1.71	0.49	0.39	−0.057	−5.45	10
KEND	122.408	−4.088	70.1	−23.78	−58.53	−23.78	−58.53	10.05	5.05	−0.018	56.94	3
DENP	115.146	−8.818	80.5	−30.24	−74.47	−30.24	−74.47	12.34	5.57	−0.116	−22.43	10

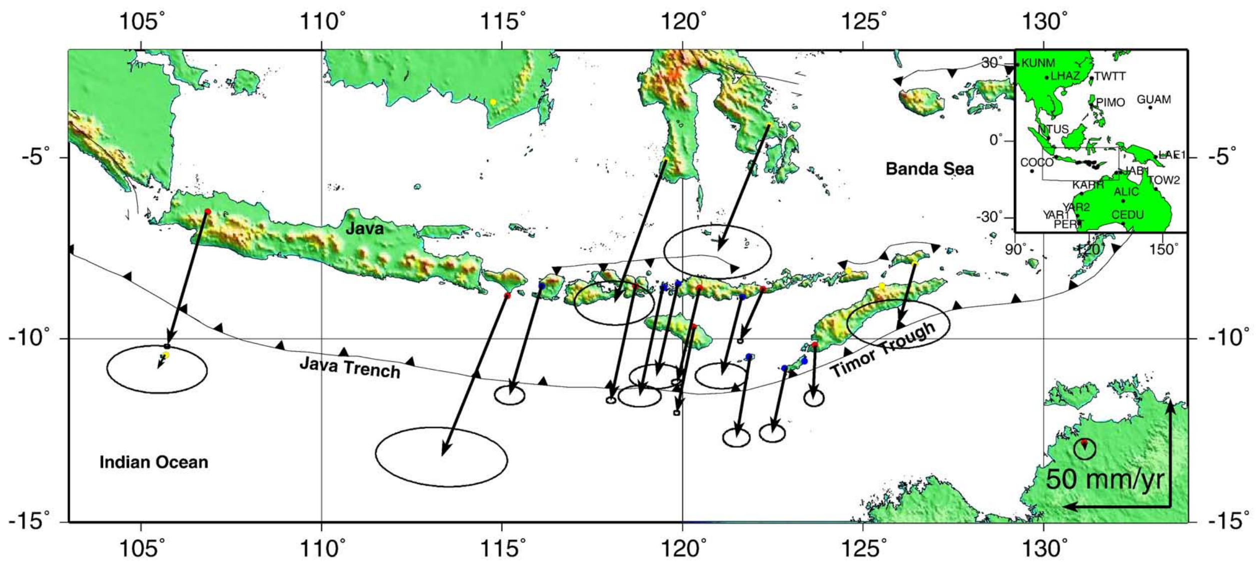

Fig. 5. GPS velocities of Sunda and Banda Arc regions relative to Australia.

Table 3
GPS velocity of Eastern Sunda Arc Region relative to Asian reference frame.

Site	Longitude (°)	Latitude (°)	Vector length (mm/yr)	E & N rate (mm/yr)		E & N adj. (mm/yr)		E & N +− (mm/yr)		Rho	H rate (mm/yr)	Epoch (yr)
PAPE	123.385	−10.614	Outliers	39.59	26.95	−23.18	10.41	3.79	1.37	−0.049	−20.46	3
COCO	96.834	−12.188	Not plotted	20.81	53.35	−21.64	3.97	0.57	0.27	−0.09	7.53	10
BAKO	106.849	−6.491	3.4	−1.31	−0.89	−2.4	−1.9	0.31	0.18	−0.107	−4.40	10
KEND	122.408	−4.088	3.4	−1.54	7.34	−1.54	7.34	4.53	1.85	−0.031	56.57	3
NTUS	103.68	1.346	4.4	3.4	−1.27	−2.24	−2.85	0.65	0.31	−0.07	4.34	3
UJUN	119.549	−5.06	6.9	−2.57	−0.17	−2.57	−0.17	3.18	1.25	−0.062	−35.11	3
DENP	115.146	−8.818	7.4	−11.41	−9.30	18.83	65.57	5.57	2.14	−0.136	−32.09	10
BIMA	118.693	−8.543	14.6	4.20	14.24	15.56	66.91	0.77	0.37	−0.044	2.71	10
AMPE	116.101	−8.561	14.6	−0.06	14.61	−24.74	8.57	2.37	0.95	−0.113	−9.15	3
KOMO	119.492	−8.589	17.1	3.59	16.74	−24.04	9.64	3.72	1.34	0.012	191.49	3
RUTE	120.478	−8.597	23.4	4.95	23.14	−28.26	2.33	0.56	0.26	−0.058	35.70	10
LABU	119.88	−8.489	25.2	4.57	24.67	−23.87	9.47	4.88	1.74	0.054	16.83	3
WAIN	120.301	−9.669	28.6	7.64	27.45	−20.45	8.79	0.39	0.2	−0.034	6.51	10
SAVU	121.846	−10.493	31.3	8.19	30.31	−23.4	9.91	2.02	0.87	−0.039	5.73	3
ENDE	121.663	−8.848	32.1	3.98	30.83	−27.52	9.31	4.67	1.89	−0.021	−9.97	3
MBUA	122.829	−10.807	39.9	8.04	38.03	−23.28	9.8	1.88	0.74	−0.069	−3.01	3
KALA	124.596	−8.136	43.6	15.41	39.48	15.41	39.48	4.26	1.56	−0.043	−8.47	3
MAUM	122.237	−8.639	44.0	4.35	43.05	−20.91	11.02	0.35	0.19	−0.036	−10.97	10
KUPA	123.663	−10.177	46.9	13.18	43.46	−23.13	10.18	1.04	0.47	−0.041	−4.14	3/3
XMAS	105.69	−10.45	59.1	19.3	54.24	19.3	54.24	4.32	1.51	−0.062	2.57	3
DARW	131.133	−12.844	69.2	13.29	66.97	13.29	66.97	0.49	0.24	−0.023	0.18	3/3

similar left-lateral fault plane solutions. Based on the occurrence of mud volcanoes along Rote Island, Semau Island, Kupang bay and the northern part of Timor Island, we suspect that the western end of the fault system crosses Rote Island and trends NE connecting with the Wetar thrust near western Alor. The fault zone is most likely a relatively young plate boundary segment (Fig. 6). No other discrete plate boundary segments are recognized throughout the region.

6. Fault bounded tectonic blocks or a deformation continuum?

If the velocity field from 2001–2003 GPS campaign is interpreted in the same way as the previous study by Genrich et al. (1996), it shows at least five tectonic blocks (Fig. 8). According to this interpretation, each of the blocks moves in the same direction as the Indo-Australian Plate, but at different velocities relative to the stable Sunda Continent, which is defined by nearly zero motion between stations in Singapore (NTUS), Banjar, Kalimantan (BANJ), Bakosurtanal, West Java (BAKO), Denpasar, Bali (DENP) and Ujungpandang (UJUN) and Kendari (KEND) in Sulawesi (Fig. 8). With respect to these stations, GPS velocities increase in magnitude from Lombok to sites in Timor. However, with little to no evidence for active faults between sections of the Sunda–Banda Arc with similar velocities (blocks), and evidence for transitions across these zones (between Sumbawa and Flores, and Savu and Timor), distributed deformation over regions as wide as 200 km may be a more viable model than assuming blocks are rigid or bounded by discrete zones of shear. For this reason we refer to sections of arc–forearc with similar velocities as 'segments' to avoid the untested assumption of internal rigidity and discrete, fault bounded boundaries.

Although some of the zones of transitional velocity also have linear tracks of earthquakes with similar strike-slip fault plane solutions (Figs. 6 and 7) the faults themselves may not be well enough developed to localize the deformation between the mostly 400 km long arc and forearc segments with similar velocities. Stations on Lombok and Sumbawa have very similar velocities and directions of motion that account for approximately 21% of the rate of the Australian plate relative to the stable Sunda Block (Fig. 8). However, the motion of Komodo Island is transitional with the Flores–Sumba–Savu arc–forearc segment. It is more similar in velocity to the Lombak–Sumbawa arc–forearc segment, but more similar in direction to the Flores–Sumba–Savu segment.

The Flores–Sumba–Savu arc–forearc segment, which includes Labuhanbajo, Ruteng, and Ende of Flores; Waingapu, Sumba and Savu Island moves at 41% of the Australia plate velocity (Fig. 8). Directly to the east of these stations Maumere, Flores and Mbuain, Rote are transitional to the Timor–Wetar segment. However, the motion of Maumere may be influenced by transient affects of December 1992 Mw = 7.8 earthquake in the region (Genrich et al., 1996) at least 7 ± 1 mm/yr of convergence is measured across the Savu Thrust between Savu and western Flores, and another 22 mm/yr across the Flores Thrust between Flores and the Sunda Shelf.

The transition from the Flores–Sumba–Savu segment to the Timor–Wetar segment lies near the poorly constrained 123° structural discontinuity that separates parts of the Banda Orogen with very different amounts of shortening. The discontinuity essentially acts as a lateral ramp for the evolving orogen. The Timor–Wetar segment to the east of the discontinuity includes both campaign and permanent GPS data from Kupang, Timor, and campaign data of Genrich et al. (1996) from Kalabahi, Alor, Wetar, and Dili, East Timor. Up to 63% of the motion of the Australian Plate is accounted for by this segment (Fig. 8), which is close to the 70% predicted from total shortening based on structural studies conducted on the island (Harris, 1991).

Although the Timor–Wetar segment is interpreted as accreted to the Australian continent (Genrich et al., 1996), over 20 mm/yr of Australian Plate motion remains unaccounted for between Timor and Darwin, Australia. The only possibly active fault recognized between the two velocity domains is the deformation front near the Timor Trough. Although many rival hypotheses exist about how active the deformation front is, GPS data indicate that it or some other unrecognized structure is accumulating strain at a rate that could produce a large earthquake in the region. If all of the strain is accumulating on the deformation front in the Timor Trough, a mega-thrust earthquake may result that produces a large tsunami.

7. Lower plate heterogeneity

A progressive eastward increase in velocity of Sunda–Banda Arc tectonic segments requires increased slip along the Flores and Wetar backarc thrust systems. Magmatism has been extinguished in the stretch of the Banda Arc from Alor to east of Wetar, with a new volcanic zone forming over 100 km to the north (Fig. 1). Silver et al. (1983) document strike-slip faults that offset the Banda Arc near Wetar 60 km to the north of the line of active volcanoes to the west. These adjustments to the collision of the Australian Shelf with the deformation front indicate further evidence for active accretion of the Banda Arc to the Indo-Australian Plate, disruption or displacement of the asthenospheric wedge beneath the Arc and southward directed underthrusting of South Banda Sea oceanic lithosphere beneath the Banda Arc (incipient subduction polarity reversal?).

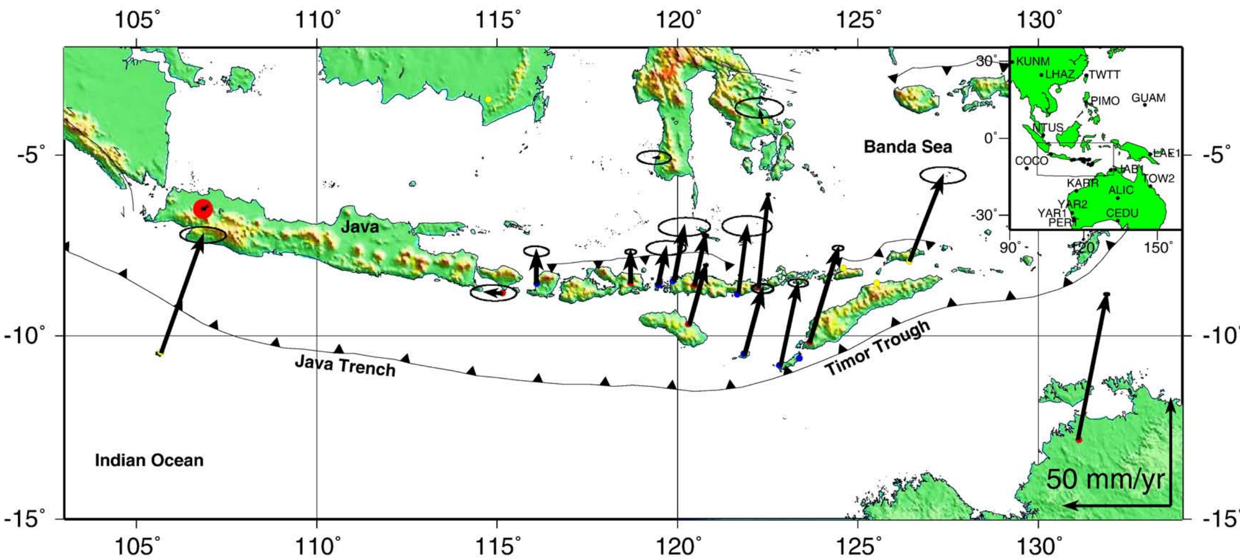

Fig. 6. GPS velocities of Sunda and Banda Arc region relative to Asia.

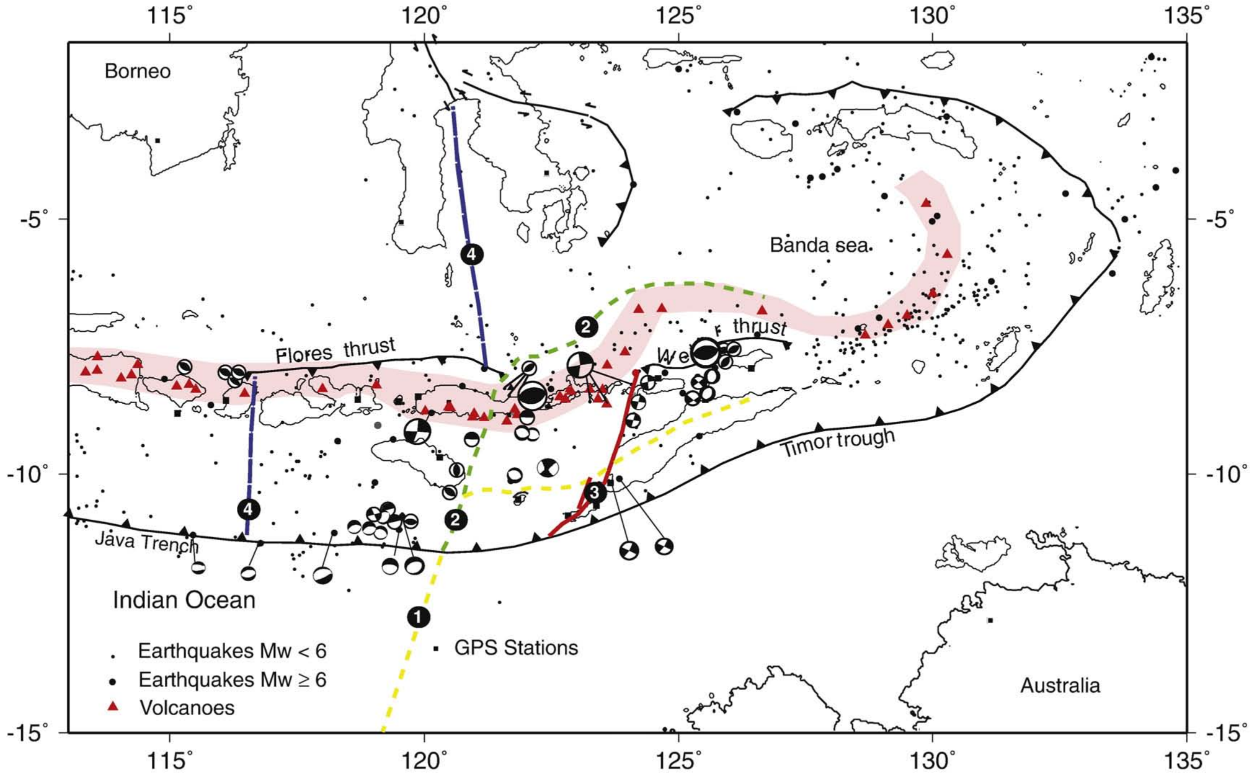

Fig. 7. Plate boundary positions proposed in the Banda Arc region. Numbers inside filled circles relate to previous plate boundary interpretations. Fault plane solutions compiled from Harvard CMT and McCaffrey and Albers (1991).

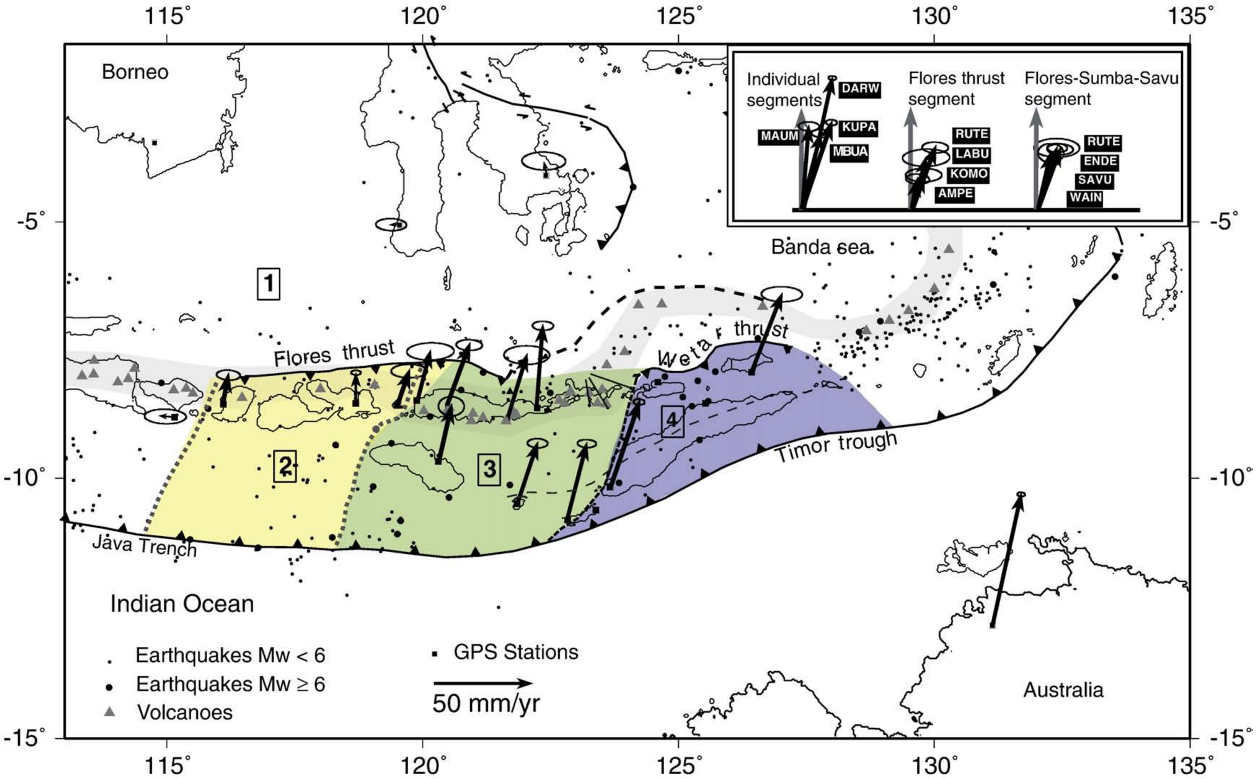

Fig. 8. Plate boundary segments in the Banda Arc region. Numbers inside rectangles show possible micro-plate blocks based on GPS velocities.

Along-strike changes in velocity of tectonic segments in the Sunda–Banda Arc can mostly be attributed to changes in the nature of the upper and lower plates in the plate boundary reorganization zone. For example, the negative buoyancy of oceanic lithosphere in the backarc region most likely controls the extent of westward propagation of the Flores Thrust, which accommodates northward movement of the Sunda–Banda Arc system relative to stable Sundaland. The abrupt increase in northward motion of the Sunda Arc east of Komodo Island corresponds to where the Indo-Australian lower plate changes from oceanic to stretched continental lithosphere. The positive buoyancy of the underthrust Scott Plateau translates into an abrupt increase in coupling of the Sunda Arc with the lower plate, and therefore an abrupt increase in northward velocity and internal deformation of the Flores–Sumba–Savu segment. Initiation of the northward verging Savu Thrust within this segment accommodates northward motion of the accretionary wedge over the forearc basin (Harris et al., 2009). Further east, in the Timor–Wetar segment the forearc basin has been completely overridden by the northward-verging retro-wedge of the Timor fold and thrust belt. Increased internal shortening, uplift and northward translation of the Banda Arc in the Timor–Wetar segment corresponds to where the Australian Shelf has collided with the deformation front and driven it over 100 km northward (Fig. 1).

8. Discussion

There were four major questions about plate boundary reorganization that we pose in this investigation. First, what is the driving mechanism? The alignment of the GPS velocity field with the direction of Indo-Australian Plate motion indicates that the lower plate of the collision is the driving force behind deformation of the Sunda–Banda Arc system. The progressive increase of GPS velocity to the east of each velocity segment we attribute to increased coupling with the lower plate as its positive buoyancy increases.

How is strain distributed throughout the reorganization process? The GPS velocity field demonstrates that strain is distributed away from the deformation front into the forearc and backarc region. Although there are geological and geophysical evidence for large amounts of internal shortening in the forearc, the current zones of greatest shortening are near seismically active regions of the forearc and backarc plate boundary segments. The baselines we measured across the orogen do show that forearc islands move 2–5 mm/yr faster than arc islands to the north (Table 3). The areas across which these baselines were measured are some of the least shortened parts of the forearc, such as the Savu Basin. However, flights of uplifted coral terraces on the north coasts of Sumba, Savu and East Timor, with surface uplift rates of 0.5–1.5 mm/yr, demonstrate that there is active shortening within N–S baselines across the Banda Orogen (Merritts et al., 1998; Cox et al., 2006; Harris et al., 2009).

What is the nature and present location of the plate boundary? The boundary between the Indo-Australian and SE Asian Plates is well defined south of Java where up to 90% of the convergence is accounted for near the trench. However, the data presented here indicates that east of Java the plate boundary widens to include the entire arc–trench region of the Eastern Sunda Arc. Although the amount of convergence distributed between the forearc and backarc increases segment by segment to the east, it is not until the 123° E structural discontinuity that the majority of plate convergence is taken up in the backarc. It is at Rote Island, along the west coast of Timor and through Alor where most of the plate convergence is transferred to the backarc Wetar Thrust system. Geologic evidence supports the progressive south to north stepping of the plate boundary from the southern deformation front to backthrusts such as the Savu Thrust, Wetar Strait Thrust and the Wetar Thrust (Price and Audley-Charles, 1987, Harris, 1991).

How does the plate boundary evolve through time? The obliquity of the Banda Arc–Australian continental margin collision provides a time–space continuum along orogenic strike for evaluating the distribution of strain through time. Variations in GPS velocities along orogenic strike provide snap shots of the likely distribution of strain during different stages of collision separated by millions of years. In this case, the GPS velocity field need not be limited to only decadal temporal scales. When the NW Australian Shelf arrives at the deformation front south of the Flores–Sumba–Savu segment it is highly likely that its velocity field will look more like that of the current Timor–Wetar segment. The continued northward motion will likely meet resistance as the collisional complex begins to converge with continental fragments south of Sulawesi. Assuming no major changes in plate motions and continued development of the Flores and Wetar Thrust into a plate boundary, within 10 m.y. NW Australia will begin colliding with collapsed arc terranes and continental fragments of the Sunda Shelf region, which could result in a full-scale continent–continent collision. An intermediate stage of this scenario is observed in New Guinea, which is directly adjacent to the Banda Arc to the east (Harris, 2003). Back arc thrust systems in this arc–continent collision evolved into a subduction polarity reversal. The Himalaya to the west of the Sunda Arc offers a possible modern analog of the continent–continent collisional stage that follows subduction polarity reversal.

9. Conclusion

New GPS measurements for the active Banda Arc–continent collision reveals:

1. Several arc–forearc sections around 400 km in length with similar velocities in the plate boundary reorganization zone.
2. Relative to a SE Asian Plate reference frame, most of these sections move in the same direction as the Australian lower plate, but at different rates.
3. Transitional velocities are found between changes in velocity from one arc–forearc section to another. The transitional zones are mostly diffuse and transfer slip from the deformation front to forearc and backarc thrust systems.
4. The deformation front in the Timor Trough may account for at least 20 mm/yr of motion between Timor and Darwin, and may be currently accumulating elastic strain energy.
5. The origin of the upper plate segments of similar velocity may be associated with crustal heterogeneities in the Indo-Australian lower plate, which abruptly changes eastward from old oceanic to stretched continental to continental shelf crust. Velocity segments closely align with these lower plate transitions.
6. Northward motion of the Sunda–Banda Arc system relative to the Sunda Shelf is attributed to westward propagation and development of the Flores–Wetar backarc thrust system.

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