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First geodetic measurement of convergence across the Java Trench

P. Tregoning[1], F. K. Brunner[1], Y. Bock[2], S. S. O. Puntodewo[3], R. McCaffrey[4], J. F. Genrich[2], E. Calais[2], J. Rais[3] and C. Subarya[3]

Abstract. Convergence across the Java Trench has been estimated for the first time, from annual Global Positioning System (GPS) measurements commencing in 1989. The directions of motion of Christmas and Cocos Islands are within 1° of that predicted by the No-Net Rotation (NNR) NUVEL-1 plate motion model for the Australian plate although their rates are 25% and 37% less than predicted, respectively. The motion of West Java differs significantly from the NNR NUVEL-1 prediction for the Eurasian plate with a 21° difference in direction and a 40% increase in rate. We infer that either West Java moves with a distinct Southeast Asian plate or this region experiences plate margin deformation. The convergence of Christmas Island with respect to West Java is 67±7 mm/yr in a direction N11°E ± 4° which is orthogonal to the trench. The magnitude of convergence agrees with the rescaled NUVEL-1 relative plate model which predicts a value of 71 mm/yr between Australia and Eurasia. The direction of motion matches the direction inferred from earthquake slip vectors at the trench but may be more northerly than the N20°E±3° predicted by NUVEL-1. On June 2, 1994, almost a year after the last GPS survey, an M_W=7.5 earthquake with slip vector direction N5°E occurred south of central Java.

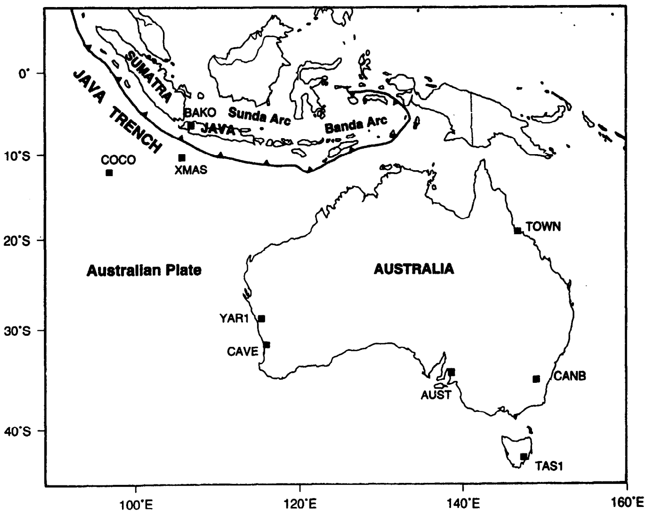

Figure 1. Tectonic setting of the Java Trench convergence zone between the Australian plate and the Indonesian archipelago and the location of GPS sites.

Introduction

The Java Trench at the north-eastern edge of the Indian Ocean and south of Java, Indonesia, is part of the Sunda Arc, an island arc which stretches from the Eastern Himalaya syntaxis, through Western Burma, the Andaman Sea, Sumatra and Java eastward to the Banda Arc in Eastern Indonesia. It is the site of convergence of the Australian and Eurasian (or Southeast Asian) plates, a manifestation of continental arc collision and subduction. The subduction zone varies from oblique subduction in the Andaman sea region and southwest of Sumatra to frontal subduction south of Java. The outer-arc ridge, fore-arc basin and trench are well defined in the Java-Sumatra area [Hamilton, 1979]. The angle of dip of the oceanic slab increases from Sumatra to Java, as does the depth of seismicity. The age of the subducting lithosphere also increases from the Sumatra Trench to the Java Trench. Seismicity along the arc displays a distinct Benioff zone and active andesitic volcanism occurs along most of its length [Curray, 1989]. Historic seismic activity near West Java has not been enough to account for the rate of subduction leading Newcomb and McCann [1987] to suggest that the majority of slip occurs aseismically and that the plate interface near Java has low seismic potential. An M_W=7.5 earthquake which occurred south of central Java in June 1994 causing a tsunami on Java puts this interpretation into question.

The plate convergence near West Java is particularly amenable to geodetic study as Christmas Island is on the subducting oceanic plate about 150 km south of the trench (Figure 1). From annual GPS surveys (1989-1993) on Christmas Island and Cibinong, West Java, we have obtained the first estimates of the velocity vector across this subduction zone. South-west of Christmas Island are the Cocos Islands, also on the Australian plate. GPS measurements were conducted simultaneously at Cocos Islands, Christmas Island and West Java (1992-1993) from which we derive site velocities in the International Terrestrial Reference Frame 1992 (ITRF92) [Boucher et al., 1993].

Geological Framework

The kinematics of Southeast Asia is not well determined by global plate motion models. The NUVEL-1 model [DeMets et al., 1990] uses no data from the Sunda Arc. Southeast Asia is probably moving independently of the Eurasian plate [Curray, 1989] although it is nominally considered to be part of this plate. NUVEL-1 predicts convergence between West Java (Eurasian plate) and Christmas Island (Australian plate) of

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[1] School of Surveying, The University of New South Wales, Sydney, Australia

[2] Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, UCSD, La Jolla, CA, U.S.A.

[3] National Coordination Agency for Surveying and Mapping, Cibinong, West Java, Indonesia

[4] Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY, U.S.A.

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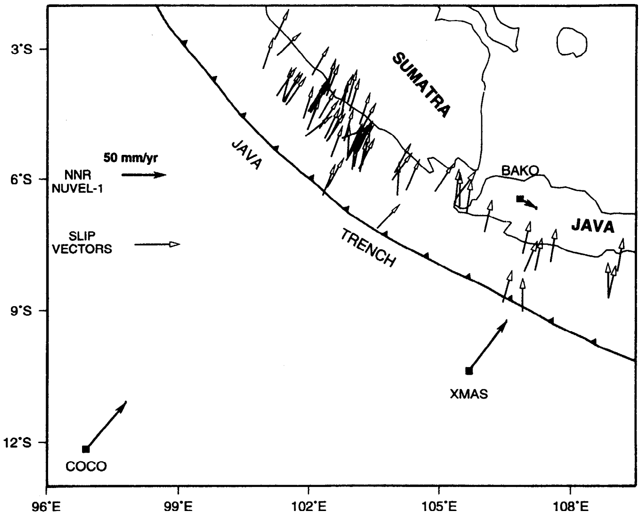

Figure 2. Map of the convergence zone near West Java showing NNR NUVEL-1 plate motion vectors for BAKO, COCO and XMAS and the direction of slip vectors from earthquake solutions between 100°E and 110°E.

71±2 mm/yr in the direction N20°E±3°, after applying a rescaling factor of 0.959 to the rate due to revisions in the magnetic polarity time scale [DeMets et al., 1994]. Newcomb and McCann [1987] calculate from 4 slip vector azimuths of thrust earthquakes that the convergence by Java is N0.2°W. McCaffrey [1991] uses the mean azimuth of 15 slip vectors east of central Java to compute a direction of N3°E±9° for the convergence of the Australian plate relative to Southeast Asia. Using the mean azimuth of 14 slip vectors between 105°E and 110°E [McCaffrey, 1994], we compute a convergence direction of N11°E±9° (Figure 2). Jarrard [1986] indicates that it is unlikely that the direction of convergence is biased near Java, as there are no obvious strike-slip faults accommodating a significant portion of the slip between the two plates, although such faults beneath the fore-arc cannot be ruled out.

The No-Net-Rotation (NNR) NUVEL-1 model of Argus and Gordon [1991] predicts absolute plate motions with respect to an arbitrary reference frame by imposing the condition that there is no net torque acting on the lithosphere. Using the rescaled NUVEL-1 rates, it predicts that Christmas Island will move 71mm/yr in a direction of N37°E, Cocos Island 70mm/yr in a direction of N39°E and West Java (Eurasian plate) 21mm/yr in a direction of N119°E (Figure 2).

GPS Surveys and Analysis

The five annual surveys of the BAKO to XMAS baseline are summarized in Table 1. Years 1989 to 1991 suffered from few global and regional GPS stations. Figure 1 shows the regional sites used in this analysis, namely BAKOSURTANAL (BAKO) located in West Java, Christmas Island (XMAS) and Cocos Islands (COCO) in the Indian Ocean, and Yaragadee (YAR1), Caversham (CAVE), Smithfield (AUST), Hobart (TAS1), Canberra (CANB) and Townsville (TOWN) in Australia. The BAKO data are part of a network spanning the Indonesian archipelago from Irian Jaya to Sumatra [e.g., Puntodewo et al., 1994]. In 1989, TI 4100 geodetic receivers were used at BAKO and XMAS. Trimble 4000 SST receivers were used in all subsequent surveys at BAKO, XMAS and COCO.

Table 1. Christmas Is., Cocos Is., and West Java Surveys.

Survey	Days of Year	Global	Regional Tracking Stations
1989	254-263	9	BAKO, XMAS, AUST, CAVE
1990	200-233	13	BAKO, XMAS, AUST, TAS1, WELL
1991	030-039	18	BAKO, CANB, TAS1, WELL, YAR1
1991	175-181	14	BAKO, XMAS, CANB, TAS1, TOWN, WELL,
1992	207-233	26	BAKO, COCO, XMAS, CANB, MCMU, TAS1, TOWN, YAR1
1993	227-239	29	BAKO, COCO, XMAS, CANB, MCMU, TAS1, TOWN, YAR1

The total number of global tracking stations and the indivdual regional tracking stations are shown. Also included are sites in Wellington, New Zealand (WELL), and Antarctica (MCMU).

Accurate geodetic positions of field receivers require precise satellite orbits estimated from global tracking data. The number and worldwide distribution of tracking sites steadily improved over the period of this study, culminating in 1992 with the establishment of the International GPS Service for Geodynamics (IGS) [Beutler and Brockmann, 1993]. Furthermore, the GPS constellation nearly approached its full operational configuration with 25 satellites available during the 1993 survey compared to only 8 satellites in 1989.

The GPS measurements were analyzed in two steps [e.g., Feigl et al., 1993]. In the first step, daily solutions were obtained with the GAMIT software [King and Bock, 1993]. Loose constraints were applied to the estimated parameters including station coordinates, satellite initial conditions, a zenith delay parameter per site and integer-cycle phase ambiguities. A "solution" file output for each day contains estimates of station coordinates and orbital elements and their corresponding full variance-covariance matrices.

In the second step, the complete set of GAMIT solution files were analyzed with the GLOBK Kalman filter program [Herring, 1992] to estimate a consistent set of station coordinates and velocities. The corresponding global GAMIT solution files for 1992 and 1993 produced daily at Scripps Institution of Oceanography were included to provide better determination of the satellite orbits and the tie to the ITRF92 [Bock et al., 1993]. We constrained the coordinates (5 mm in the

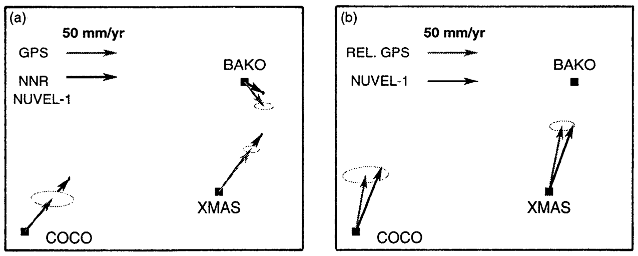

Figure 3. a) ITRF92 site vectors for BAKO, XMAS and COCO compared with predicted NNR NUVEL-1 velocities. b) Relative vectors between XMAS-BAKO and COCO-BAKO compared with NUVEL-1 velocities. Site positions are not to scale. Plotted on the GPS determined vectors are 95% error ellipses.

horizontal and 10 mm in the vertical) and fixed the velocities of the primary IGS stations to their ITRF92 values, including YAR1 and CANB on the Australian plate (Figure 1). The ITRF92 adopts a combination of the NNR NUVEL-1 model and solutions from very long baseline interferometry, satellite laser ranging and global GPS for the velocities of sites in stable plate interiors. Hence, the inherent reference frames in ITRF92 and NNR NUVEL-1 are compatible.

Results

Figure 3a shows the computed ITRF92 velocities of BAKO, XMAS and COCO and the predicted NNR NUVEL-1 velocities. Magnitudes and directions of motion are given in Table 2.

Figure 3b shows the velocity vectors of XMAS and COCO relative to BAKO computed from the GAMIT/GLOBK analysis, compared with the relative plate motion predicted by NUVEL-1. Magnitudes and directions of motion are given in Table 3.

Since the relative velocity vector of XMAS to BAKO is nearly parallel to its relative position vector, we computed as a comparison the rate of change of baseline length of XMAS to BAKO from a weighted least squares slope through all daily GLOBK back filter estimates (Figure 4). The weighted least squares solution yields a slope of 62±3 mm/yr which agrees with the magnitude of velocity of 67±7 mm/yr obtained from a deterministic GLOBK forward filter solution.

The steady improvement in the quality of relative position determination is clearly seen in the scatter of individual length determinations (Figure 4). The multiple measurements made over several week observation periods in 1989 and 1990 were critical in obtaining averaged relative positions of similar precision to the later surveys of shorter duration. Without the 1989 and 1990 surveys, the slope of the line would be less steep, thereby increasing the discrepancy with NUVEL-1. The BAKO station was observed for 10 days during the GIG'91 experiment [Blewitt, 1993], a 22 day period in January to February 1991 where a tracking network similar to the 1992 IGS network was operational, including the Australian site of YAR1. Many of these sites later became a permanent part of the IGS network, and thus provide the earliest link to the ITRF92 reference frame.

Discussion and Conclusions

Individual site velocities of Christmas Island, Cocos Islands and West Java have been estimated with respect to the ITRF92 reference frame. The velocity vector derived for Christmas Island agrees with the NNR NUVEL-1 model in azimuth, although the magnitude is 18 mm/yr less than predicted. Similarly, the azimuth of the velocity vector at Cocos Islands agrees with NNR NUVEL-1 prediction but the rate is 26 mm/yr slower. This could be due to intraplate deformation occurring on the oceanic plate close to the convergence zone. However, the Cocos Islands are approximately 800 km from the Java Trench, making this unlikely. The West Java vector differs significantly in azimuth from NNR NUVEL-1 for the Eurasian plate at a 95% confidence level. This appears to support the suggestion of Molnar and Tapponier [1977] that there is a block movement of the Southeast Asian region, but these results could also be due to local deformation in West Java. Alternatively, there may be some other discrepancy between the ITRF92 and NNR NUVEL-1 reference frames which would be apparent in the site vectors but would be removed in the relative vectors. Similar discrepancies have been noted in Europe between satellite laser ranging determined vectors and NNR NUVEL-1 [Robbins et al., 1993].

Table 2. ITRF92 velocities of BAKO, XMAS and COCO compared with NNR NUVEL-1 predicted velocities.

Site	Magnitude (mm/yr)		Direction	
	Observed	NNR	Observed	NNR
BAKO	30±2	21	N140°E±4°	N119°E
XMAS	53±2	71	N037°E±2°	N037°E
COCO	44±4	70	N041°E±5°	N039°E

Table 3. Relative velocities of XMAS and COCO relative to BAKO compared with NUVEL-1 predicted values.

Baseline Vector	Magnitude (mm/yr)		Direction	
	Observed	NUVEL	Observed	NUVEL
XMAS-BAKO	67±7	71	N011°E±4°	N020°E
COCO-BAKO	58±4	70	N010°E±9°	N022°E

Convergence of 67±7 mm/yr is measured between Christmas Island and West Java in a direction of N11°E±4°. The magnitude is not significantly different from the NUVEL-1 plate motion model rate of 71±2 mm/yr between the Australian and Eurasian plates. The convergence measured is the sum of the plate convergence plus any elastic strain that may be present should the plate boundary be locked. Local effects at the plate interface will reduce with increasing distance from the plate boundary and we estimate that the elastic strain rate due to a locked interface (if present) would be less than 10 mm/year on the Christmas Island to West Java baseline.

The GPS estimated direction of motion is more northerly than the N20°E predicted by NUVEL-1 but is not significantly different at a 95% confidence level. It agrees with the estimated N11°E±9° direction from earthquake slip vectors on this section of the Java Trench.

There has not been any significant seismic activity on the West Java section of the Sunda Arc in the five year period spanned by our surveys, yet Figure 4 clearly shows a steady subduction rate. A locked plate boundary would explain why

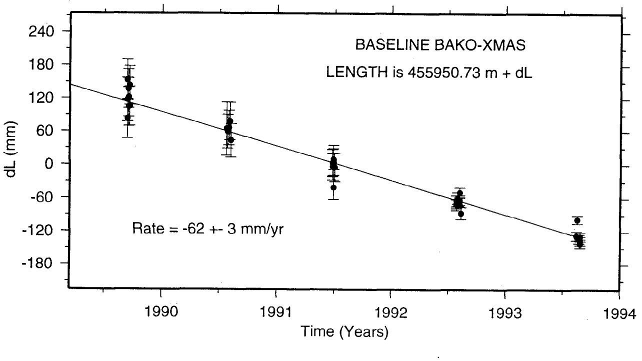

Figure 4. Daily estimates of the distance between XMAS and BAKO from the Kalman filter back solution. Formal one sigma error bars are shown. Weighted least squares line of best fit yields a rate of change of distance of -62±3 mm/yr.

our magnitude of convergence is slightly slower than that predicted by NUVEL-1, and why there is little seismic activity on this section of the trench. Alternatively, subduction could be occurring aseismically as suggested by Newcomb and McCann [1987]. However, a large thrust earthquake (M_W=7.5) occurred south of central Java on June 2, 1994 with a slip vector direction of N5°E, several hundred kilometers east of the Christmas Island to West Java baseline. Our next GPS measurement of this baseline scheduled for August 1994 will determine the magnitude of coseismic deformation and may reveal the extent to which our earlier measurements were influenced by elastic strain. Although not conclusive in itself, our measurement of convergence between Christmas Island and Cocos Island and West Java provides a constraint on possible mechanisms of subduction occurring on this section of the Java Trench.

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P. Tregoning and F. K. Brunner, School of Surveying, The University of New South Wales, Sydney, N.S.W., 2052, Australia. (e-mail: paul@wally.gas.unsw.edu.au)

Y. Bock, E. Calais and J. Genrich, IGPP, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA, 92093, U.S.A. (e-mail: bock@pgga.ucsd.edu)

S.S.O. Puntodewo, J. Rais, and C. Subarya, National Coordination Agency for Surveying and Mapping, Cibinong, West Java, Indonesia.

R. McCaffrey, Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY, 12180, U.S.A (e-mail: robmcc@harold.geo.rpi.edu)

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