

Rapid rotations about a vertical axis in a collisional setting revealed by the Palu fault, Sulawesi, Indonesia

C. Stevens¹, R. McCaffrey¹, Y. Bock², J. Genrich², Endang³, C. Subarya³, S.S.O. Puntodewo³, Fauzi⁴, and C. Vigny⁵

Abstract. Global Positioning System (GPS) measurements from 1992 to 1995 indicate that the left-lateral Palu fault in central Sulawesi slips at a rate of 38 ± 8 mm/a with a locking depth between 2 and 8 km. From the measured slip rate and the historic seismicity of the fault, we estimate that the Palu fault currently has stored enough strain to produce a $M_w > 7$ earthquake. The Palu and other nearby faults accommodate rapid clockwise rotation of nearly $4^\circ/\text{Ma}$ of E Sulawesi relative to eastern Sunda. The rotation of east Sulawesi transfers E-W shortening between the Pacific and Eurasian plates to N-S subduction of the Celebes Basin beneath Sulawesi.

1. Introduction

Eastern Indonesia is a broad region of tectonic and geologic complexity resulting from the convergence of the Australian, Eurasian, and Pacific plates [Hamilton, 1979] (Fig. 1). The island of Sulawesi forms the western edge of the broad deforming region comprising the triple junction. The Palu fault, a north-trending, left-lateral fault that bisects central Sulawesi, separates the largely rigid Sunda block to the west from the zone of active deformation to the east (Fig. 1).

The Palu fault is visible in aerial photographs as a series of continuous valleys exposed for 200 km south from Palu Bay [Hamilton, 1979]. Stream offsets and hydrothermal activity indicate that it is presently active [Katili, 1970; Hamilton, 1979], but no estimates of slip rates have been derived from the offsets. Few earthquakes have occurred recently on the Palu fault. Katili [1970] reports that earthquakes in 1905, 1907, and 1934 occurred near the known trace of the Palu fault but magnitudes and accurate locations for them are unavailable. A damaging earthquake reportedly occurred on the Palu fault in 1909 [Hamilton, 1979]. A microseismicity study in 1978 recorded little activity from the fault [McCaffrey and Sutardjo, 1982] and few globally recorded epicenters (1964-1995) fall near its trace (Fig. 1).

Of particular tectonic interest is the role the Palu fault plays in the convergence between the Pacific and Eurasian plates in eastern Indonesia. Hamilton [1979] suggested that the Palu and Matano faults reveal a clockwise rotation of the Sulawesi block but was unable to test the idea due to insuffi-

cient data on the continuity of the faults. Fault-bounded blocks that rotate about nearby vertical axes are thought to be an efficient mechanism for shortening in continents [McKenzie and Jackson, 1983]. GPS results presented here and geologic data are consistent with the Palu fault forming one boundary of a block rotating about a nearby vertical axis that accommodates about 1/3 of the shortening in this collisional setting.

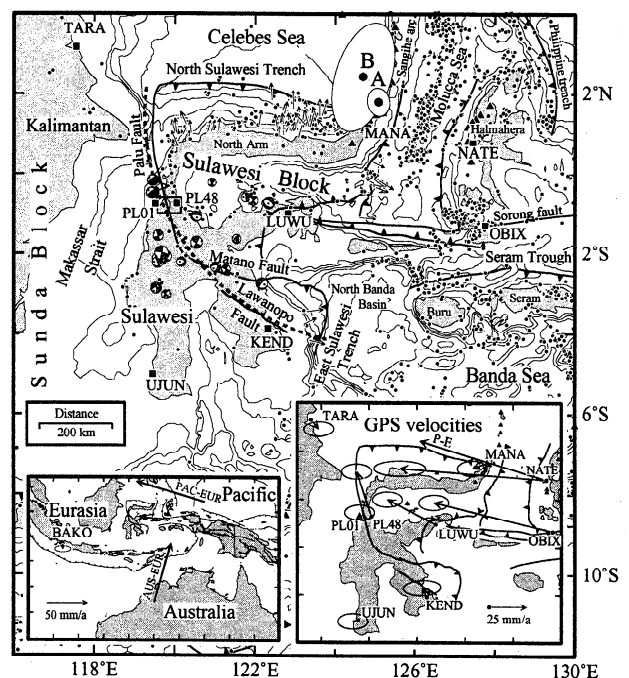


Figure 1: Tectonic map of Sulawesi region, after Hamilton [1979]. Boxed region is Palu study area. Small arrows are slip vectors from thrust earthquakes. Fault plane solutions are from Harvard CMT Catalog (1976-Jan. 1999). Size of focal sphere is proportional to log of seismic moment. Black focal spheres show Oct. 1998 events. Small dots show relocated epicenters at depths < 50 km for earthquakes from 1964-1995 [Engdahl et al., 1998]. Large dots near 2°N with 1-sigma error ellipses show poles of rotation for East Sulawesi block relative to Sunda (pole A based on GPS, fault trace and slip vector data; pole B based on GPS only). Dashed curve is small circle about pole A. Black squares indicate GPS sites, triangles indicate volcanoes, and dark lines show major faults. Bathymetry at 1 km intervals. Lower-left inset: predicted plate motions relative to Eurasia [DeMets et al., 1994]. Lower-right inset: GPS-derived velocities relative to Sunda block. Error ellipses are 95% confidence level. Vector labeled P-E is Pacific-Eurasia velocity from NUVEL-1A.

¹Rensselaer Polytechnic Institute, Troy, NY.

²Scripps Institution of Oceanography, La Jolla, CA.

³National Coordination Agency for Surveying and Mapping, Cibinong, Indonesia

⁴Meteorology and Geophysical Agency, Jakarta, Indonesia

⁵Ecole Normale Supérieure, Paris, France

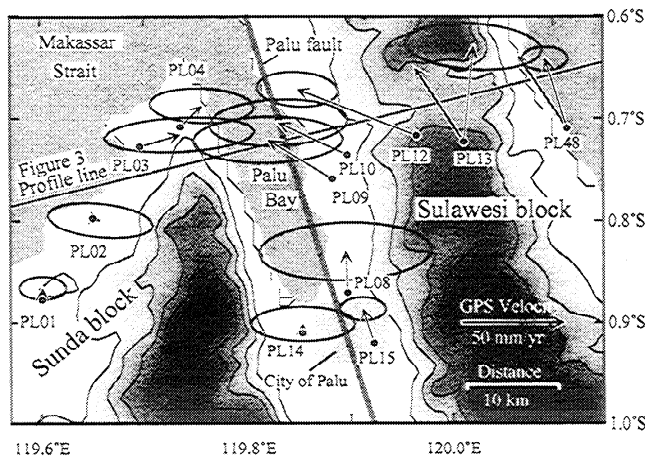


Figure 2: GPS velocities of Palu transect sites relative to Sunda. Error ellipses are 95% confidence level. Gray arrows are predicted velocities of the East Sulawesi block relative to Sunda from Pole A, neglecting elastic strain near the fault. Gray line shows our estimate of the location and trend of the Palu fault based on GPS. Topography at 250 m intervals [Gesch et al., 1999].

2. GPS Measurements, Analysis and Results

In 1992 we established and started observing a 12 station geodetic array extending 30 km both east and west of the Palu fault (Fig. 2). Site PL15 was measured continuously throughout each campaign to anchor the local network relative to regional sites (Fig. 1) that were occupied simultaneously. The remaining Palu array sites were occupied for periods of 1 hour to 2 days each. All measurements were made with dual frequency Ashtech P-12 (1992 and 1993) and Z-12 (1994 and 1995) receivers. Measurements in 1992, 1993, and 1994 were made by Rensselaer Polytechnic Institute (RPI), Scripps Institution of Oceanography (SIO), and National Coordination Agency for Surveying and Mapping (BAKOSURTANAL). In 1995, RPI and BAKOSURTANAL joined Ecole Normale Supérieure (ENS) in remeasuring the sites. ENS and BAKOSURTANAL continued with measurements in 1996, 1997, and 1998. Here we present results from 1992 through 1995 only because a $M_w=7.9$ thrust earthquake located on the N Sulawesi trench about 100 km north of the network in Jan. 1996 may have caused a co-seismic strain across the network that renders unreliable the Palu fault slip rate derived from post-1995 GPS data [Walpersdorf et al. 1998a,b].

GPS data were combined with a subset of the International GPS Service for Geodynamics (IGS) network and improved satellite orbits computed at Scripps Institution of Oceanography [Fang and Bock, 1995] in daily, independent least-squares solutions. Station coordinates, tropospheric zenith delay parameters, and phase ambiguities were estimated from doubly-differenced GPS phase measurements using the GAMIT software [King and Bock, 1995]. Daily solutions were then combined with global IGS solutions to estimate station positions and velocities in the International Terrestrial Reference Frame 1993 (ITRF93) [Boucher et al., 1994] with the GLOBK software [Herring, 1995].

GPS-derived velocities in the ITRF93 reference frame are rotated about a pole that minimizes the velocities at regional sites at Cibinong (BAKO) in west Java, Tarakan (TARA) in

Kalimantan, Ujung Pandang (UJUN) in southwest Sulawesi, and Kendari (KEND) in southeast Sulawesi (Fig. 1; pole at $26.3 \pm 19.4^\circ\text{N}$, $147.8 \pm 24.1^\circ\text{E}$, and angular velocity of $0.47 \pm 0.25^\circ/\text{Ma}$; normalized $\chi^2=1.4$ when weighted by $(4\sigma)^2$, where σ is the formal velocity error). This rotation reduces the 4 regional GPS-derived velocities to less than 7 mm/a and simulates a rigid Sunda reference frame. Applying this same rotation to the ITRF93 velocities for each Palu site puts them into what we call the Sunda reference frame (Fig. 2; Table 1). While this rotation pole is used to define a regional reference frame for our Palu measurements, it is poorly constrained and is not representative of the rotation of Southeast Asia because it was estimated from only four regional sites with limited geographical coverage.

3. The Palu Fault

The relative velocity between the westernmost (PL01) and easternmost (PL48) sites is 26 ± 8 mm/a in the direction $N21^\circ\text{W}$ (Fig. 2). However, this may not be the total far-field slip rate across the Palu fault because the array may lie entirely within the zone of elastic strain due to the fault being locked. Following Savage and Burford [1973], we use an elastic dislocation model for a fault locked at the surface and slipping freely at a rate V below depth D . Using the GPS-derived velocities parallel to the fault, the depth D , the far-field slip rate V , and the location of the fault x_f are estimated by least squares. The fault-parallel velocity of a site at a perpendicular distance x from the fault is

$$v(x) = V \pi^{-1} \tan^{-1} \{ (x - x_f) / D \} + V / 2 \quad (1)$$

where the reference frame is the Sunda block (at large negative x) and $x=0$ at the fault (Fig. 3). The orientation and location of the Palu fault are not well known. Hence, we vary the fault strike between the orientations of the west and east boundaries of the Palu valley ($N16^\circ\text{W}$ to $N5^\circ\text{W}$) and solve for its position. Because the sites east of the Palu fault vary in distance from the E Sulawesi pole of rotation, a velocity gra-

Table 1: GPS-derived north (V_n) and east (V_e) velocities, one standard deviation errors (σ) and correlation coefficients (σ_{ne}) for GPS sites in the ITRF93 reference frame. Also given are velocities relative to the Sunda block. All velocities in mm/a.

Site	Lat., °N	Long., °E	ITRF93 Velocity				Sunda Velocity			
			V_n	V_e	σ_n	σ_e	σ_{ne}	V_n	V_e	σ_{ne}
KEND	-4.088	122.407	-14	23	2	5	0.04	6	-3	
UJUN	-5.060	119.549	-23	23	2	4	0.01	-1	-4	
TARA	3.327	117.570	-30	26	2	4	0.01	-7	5	
BAKO	-6.491	106.849	-29	27	2	4	-0.08	2	0	
MANA	1.547	124.925	-22	12	2	4	0.03	-4	-10	
LUWU	-1.040	122.772	-3	-8	2	4	0.00	17	-32	
NATE	0.825	127.380	-9	-75	2	7	0.00	7	-97	
OBIX	-1.341	127.644	3	-55	2	4	0.03	19	-79	
PL48	-0.709	120.095	8	14	2	4	0.00	30	-10	
PL13	-0.722	119.994	19	28	4	12	-0.16	41	4	
PL12	-0.716	119.948	-2	-28	3	7	-0.12	20	-52	
PL15	-0.916	119.906	-7	19	2	4	-0.01	15	-5	
PL08	-0.867	119.880	-4	23	5	15	0.07	18	-1	
PL10	-0.735	119.880	-8	-6	4	12	0.11	14	-30	
PL09	-0.758	119.866	-5	-4	4	13	0.05	17	-28	
PL14	-0.906	119.837	-18	24	3	9	-0.01	4	0	
PL04	-0.708	119.720	-13	33	3	9	-0.11	9	10	
PL03	-0.727	119.681	-17	41	3	13	0.19	5	17	
PL02	-0.795	119.635	-23	27	3	9	-0.28	-1	3	
PL01	-0.874	119.587	-17	24	2	4	-0.01	5	0	

dient of about 1 mm/a per 10 km across the eastern half of the array should be present – we neglect this small gradient while fitting the profile. The best fit between the fault parallel observed and predicted velocities are obtained for a fault with a strike of N13°W (passing near PL08) a locking depth of 5 ± 3 km, and a slip rate of 38 ± 8 mm/a (Fig. 3).

The last large earthquake ($M > 5$) near the trace of the Palu fault may have occurred in 1934. Using our minimum estimated slip rate of 30 mm/a, at least 2.0 m of slip is necessary to alleviate the accumulated strain over the ensuing 65 year period. Assuming a crustal rigidity of 4×10^{10} N/m², a rupture length of 100 km and depth of 5 km, this missing slip gives a moment deficit of 4×10^{19} Nm, or equivalent to a $M_w = 7.0$ earthquake. The Harvard CMT catalog reports only two earthquakes near the fault trace since our measurements in 1995. The $M_w = 5.9$ and $M_w = 6.0$ Oct. 10, 1998, earthquakes occurred approximately 50 km north of the GPS network (Fig. 1) and had a combined seismic moment of 2.0×10^{18} Nm, a factor of 20 too small to release the accumulated strain. Moreover, these earthquakes do not have the correct mechanisms for slip on the Palu fault and more likely occurred on the N. Sulawesi thrust. Hence, the Palu fault continues to pose a seismic risk for surrounding regions.

4. Block Rotations and Regional Tectonics

Using the horizontal GPS velocities in the Sunda reference frame at sites PL48 (the easternmost transect site), LUWU, and MANA, earthquake slip vectors at the N Sulawesi trench, and the onland traces of the Matano and Palu faults (Fig. 1), we compute a pole for the rotation of the region east of the Palu fault (East Sulawesi block) relative to the Sunda region. The pole (pole A in Fig. 1), at $1.5 \pm 0.4^\circ$ N, $125.0 \pm 0.3^\circ$ E and angular velocity of $-3.8 \pm 0.4^\circ$ /Ma, matches the GPS vectors with a normalized $\chi^2 = 2.2$ when velocities are weighted by $(4\sigma)^{-2}$. The match of the Matano and Palu faults to a small circle about Pole A is shown in Fig. 1 and the agreement with N Sulawesi trench earthquake slip vector azimuths is shown in Fig. 4. Using the GPS vectors alone results in a pole of rotation (Pole B at $2.5 \pm 1.6^\circ$ N, $124.7 \pm 1.0^\circ$ E, angular velocity -

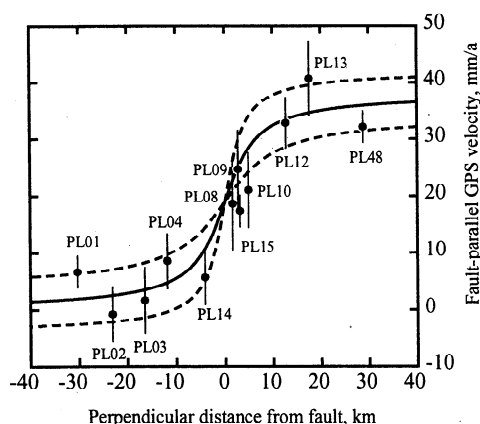


Figure 3: Fault-parallel GPS velocities (one standard deviation error bars) plotted with distance from Palu fault. Solid and dashed lines show best-fit and one-standard deviation for a locked vertical fault in a half-space; locking depth = 5 ± 3 km; far-field slip rate = 38 ± 8 mm/a; fault azimuth = N13°W; fault position at 2 ± 2 km.

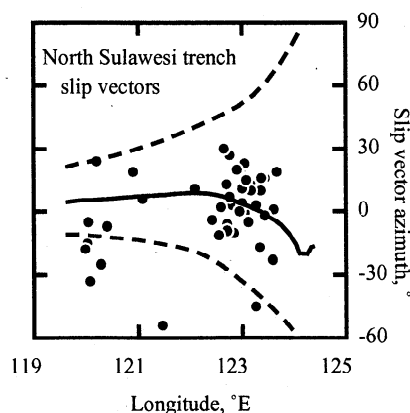


Figure 4: North Sulawesi trench slip vector azimuths. Solid and dashed lines show predicted and one standard deviation computed from E Sulawesi-Sunda rotation pole.

$3.5 \pm 1.2^\circ$ /Ma, normalized $\chi^2 = 1.2$ when weighted by $(4\sigma)^{-2}$ that is similar to that determined with the combined data (Fig. 1). Hence, the GPS vectors are consistent with the fault trace and slip vector data and are sensitive to the pole location.

The more northerly trace of the left-lateral Palu fault near Palu relative to the best-fit small circle (Fig. 1) indicates a small component of shortening across the fault. Using pole A, the predicted slip rate at the Palu transect is 43 ± 4 mm/a at an azimuth of N24°W (Fig. 2). The least-squares estimate of the fault strike from the GPS observations is N13°W, hence we expect about 8 mm/a of convergence and 42 mm/a of strike-slip across the Palu array, well within the bounds of our estimate from the fault model. Sites PL12, PL10, and PL09 have fault-normal velocities of 49 ± 7 , 29 ± 13 , and 27 ± 14 mm/a, respectively (Fig. 2), much faster than expected. Even small amounts of convergence on strike-slip faults can greatly increase their seismic hazards (for example, the San Andreas system in California produced several recent destructive thrust earthquakes). The eastern two sites do not show fast fault-normal motion suggesting that there may be other faults east of the main strand of the Palu fault and that there may be smaller-scale block rotations.

South of 2°S, the orientation of the Matano fault relative to a small circle indicates that both strike-slip and extension occurs on it (Fig. 1). Stream offsets show left-lateral slip and earthquakes show both strike-slip motion and normal faulting (Fig. 1) [Hamilton, 1979; McCaffrey, 1981]. Slip on the Matano fault predicted by the estimated pole ranges from 45 mm/a at N37°W near 120.3°E (44 mm/a of strike-slip motion and 10 mm/a of extension) to 37 mm/a at N57°W azimuth near 122.5°E (23 mm/a of strike-slip motion and 29 mm/a of extension).

The Lawanopo fault, south of the Matano fault, falls on a small circle about the rotation pole (Fig. 1). However, there is little geologic or seismologic evidence to suggest that this fault is presently active. It is more likely that the Matano fault and E Sulawesi trench, which both produce earthquakes, form the active plate boundary yet an active Lawanopo fault cannot be ruled out.

N-trending earthquake slip vectors at the N Sulawesi trench are matched well by a rotation pole at its eastern end (Fig. 4). The predicted convergence rate decreases from 41 mm/a at the western end of the N Sulawesi trench to 10 mm/a at the eastern end.

The difference in the GPS-derived velocities at NATE and MANA in the Sunda reference frame (Fig. 1; Table 1) is close to the predicted NUVEL-1A Pacific-Eurasia velocity [DeMets *et al.*, 1994]. Apparently, Pacific-Eurasian plate convergence is fully accommodated across the narrow Molucca Sea near 1°N by shallow, high-angle thrust faulting [McCaffrey, 1991]. South of the Molucca Sea, near 1.5°S, the left-lateral Sorong fault, that extends eastward to Irian Jaya, separates the Molucca Sea and Pacific plates from the deforming Banda Sea region (Fig. 1). The difference in GPS velocities at sites NATE and OBI (Table 1) across the Sorong fault at 126°E indicate a slip rate of 20 ± 11 mm/a.

In contrast to the Molucca Sea, where crustal shortening takes up all plate motion, south of the Sorong fault about 1/3 or more of the shortening occurs by block rotation. Our estimated rotation pole and the GPS velocity at LUWU indicate that rotation of E Sulawesi takes up 30 to 40 mm/a of the predicted 88 mm/a of Pacific-Eurasian convergence. It is not clear where the remaining 2/3 of the convergence occurs but one possibility is that we have underestimated the slip rate on the Sorong fault (GPS site OBI is close to the fault and may not show the full motion). A higher Sorong fault slip rate would decrease the required convergence rate south of it. In any case, block rotation transfers a large fraction of the E-W plate convergence to N-S shortening between Sulawesi and the Celebes Basin at the N Sulawesi trench. Clearly, block-rotation is an important mechanism for accommodating shortening in this region.

5. Conclusions

We observe a typical elastic strain profile in GPS-derived velocities across the Palu fault, suggesting that it is currently locked and storing elastic strain in surrounding rocks. Our estimates of the locking depth is 5 ± 3 km and of the slip rate is 38 ± 8 mm/a. From these estimates and the lack of seismicity on the fault over the past several decades, we infer that it will take the equivalent of a $M_w \sim 7$ or larger earthquake to release the accumulated strain. Thus, the Palu fault poses a seismic hazard for regions surrounding it.

We compute a pole of rotation for East Sulawesi relative to Eastern Sunda based on GPS-derived velocities, earthquake slip vectors, and fault traces. The pole location agrees with that suggested by Hamilton [1979] and Silver *et al.* [1983] but GPS allows an estimate the angular velocity. Our estimated rotation rate of $4^\circ/\text{Ma}$ is consistent with paleomagnetic evidence for post-Miocene clockwise rotations of $20\text{--}25^\circ$ for the western part of the North Arm of Sulawesi [Surmont *et al.*, 1994], and suggests that such rotations continue today. The Palu and Matano fault, by accommodating rapid rotation of east Sulawesi relative to Sunda, act to transfer E-W shortening between the Pacific and Eurasian plates to N-S shortening between Sulawesi and the Celebes Basin.

Acknowledgments. We thank surveyors at BAKOSURTANAL for collecting data and Linette Prawirodirdjo, Bob King, and Tom Herring for discussions on GPS processing. Scripps Orbit and Permanent Array Center provided precise satellite orbits and global GPS solutions. Supported at RPI by NSF grant EAR-9114349, at SIO by NSF grant EAR-9114864, and by Ecole Normale Supérieure.

References

- Boucher, C., Z. Altamimi, and L. Duhem, Results and analysis of the ITRF93, IERS Tech. Note 18, Int. Earth Rotation Serv., Observatoire de Paris, Paris, France, 1994.
- DeMets, C., R. G. Gordon, D. Argus and S. Stein, Effects of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, 21, 2191-2194, 1994.
- Engdahl, E.R., R.D. Van der Hilst, and R.P. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seismol. Soc. Amer.* 88, 722-743, 1998.
- Fang, P., and Y. Bock, Scripps Orbit and Permanent Array Center report to the IGS, in *1994 Annual Report, International GPS Service for Geodynamics*, edited by J.F. Zumberge, R. Liu, and R.E. Neilan, 213-233, IGS Cent. Bur., Jet Propul. Lab., Pasadena, Calif., 1995.
- Gesch, D.B., K.L. Verdin, and S.K. Greenlee, New land surface digital elevation model covers the Earth, *EOS*, 80, 6, 69-70, 1999.
- Hamilton, W., Tectonics of the Indonesian region, *U.S. Geol. Surv. Prof. Paper* 1078, pp. 345, 1979.
- Herring, T.A., Documentation of the GLOBK software version 3.3, Mass. Inst. of Technol., Cambridge, MA, 1995.
- Katili, J.A., Large transcurrent faults in southeast Asia with special reference to Indonesia, *Geol. Rundsch.*, 59, 581-600, 1970.
- King, R.W. and Y. Bock, Documentation for the GAMIT GPS software analysis version 9.3, Mass. Inst. of Technol., Cambridge, 1995.
- McCaffrey, R., Crustal structure and tectonics of the Molucca Sea collision zone, Indonesia, Ph.D. Thesis, Univ. of Calif., Santa Cruz, 157 pp., 1981.
- McCaffrey, R. and R. Sutardjo, Reconnaissance microearthquake survey of Sulawesi, Indonesia, *Geophys. Res. Lett.* 9, 793-796, 1982.
- McCaffrey, R., Earthquakes and ophiolite emplacement in the Molucca Sea, Indonesia, *Tectonics* 10, 433-453, 1991.
- McKenzie, D.P., and J.A. Jackson, The relationship between strain rates, crustal thickening, paleomagnetism, finite strain and fault movements, *Earth Planet. Sci. Lett.*, 65, 1822-202, 1983.
- Savage, J.C., and R.O. Burford, Geodetic determination of relative plate motion in central California, *J. Geophys. Res.*, 78, 832-845, 1973.
- Silver, E.A., R. McCaffrey, and R.B. Smith, Collision, rotation, and the initiation of subduction in the evolution of Sulawesi, Indonesia, *J. Geophys. Res.*, 88, 9407-9418, 1983.
- Surmont, J., C. Laj, C. Kissel, C. Rangin, H. Bellon and B. Priadi, New paleomagnetic constraints on the Cenozoic tectonic evolution of the North Arm of Sulawesi, Indonesia, *Earth Planet. Sci. Lett.*, 121, 629-638, 1994.
- Walpersdorf, A., Vigny, C., Subarya, C., and . Manurung, Monitoring the Palu-Koro fault (Sulawesi) by GPS, *Geophys. Research Lett.*, 25, 2313-2316, 1998a.
- Walpersdorf, A., C. Rangin, and C. Vigny, GPS compared to long-term geologic motion of the north arm of Sulawesi, *Earth Planet. Sci. Lett.* 159, 47-55, 1998b.

C. Stevens and R. McCaffrey, Rensselaer Polytechnic Institute, Troy, NY 12180. (e-mail: mccafr@rpi.edu)

Y. Bock and J. Genrich, Scripps Institution of Oceanography, La Jolla, CA.

Endang, C. Subarya, and S.S.O. Puntodewo, National Coordination Agency for Surveying and Mapping, Cibinong, Indonesia
Fauzi, Meteorology and Geophysical Agency, Jakarta, Indonesia
C. Vigny, Ecole Normale Supérieure, Paris, France.

(Received April 6, 1999; revised July 2, 1999;
accepted July 19, 1999.)