Evidence for Block Rotations and Basal Shear in the World's Fastest Slipping Continental Shear Zone in NW New Guinea

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Global Positioning System measurements from 1991 to 1997 reveal that the Bird's Head region of eastern Indonesia moves at 75 to 80 mm/a relative to northern Australia along a continental shear zone that may be as wide as 300 kilometers. The estimated slip rate across the shear zone is twice as fast as any other found in a continent yet the shear zone contributes little to the seismic moment release in the region. Movements of points outside the deforming zone suggest simple shear across the zone while some points within the shear zone show significant velocities normal to the edges, consistent with deformation accommodated at least in part by rotating blocks rather than solely by sub-parallel strike-slip faults. A simple analysis of the possible forces acting on the Bird's Head continental block suggests that it may be driven by basal drag from the Pacific plate sliding beneath it.

INTRODUCTION

The island of New Guinea forms the northern edge of the Australian continental plate that moves to the ENE at about 110 mm/a relative to the Pacific plate (Fig. 1a) [*DeMets et al*. 1994]. Attempts to unravel the deformation within this complex plate boundary using both geological and seismological data [*Hamilton*, 1979; *Dow and Sukamto*, 1984; *Abers*, 1989; *Ekström and England*, 1989; *McCaffrey and Abers*, 1991] largely concluded that convergence was almost completely partitioned between strike-slip on the Sorong and Yapen faults and on E-trending faults in the Highlands Range and shortening across the fold-thrust belt at the flanks of the Highlands and at the New Guinea trench (NGT). This view of the normal and parallel components of relative plate motion occurring on separate faults was one of classical slip partitioning as first recognized in Sumatra by *Fitch* [1972]. However, fault slip rates inferred from earthquakes were considerably lower than expected from relative plate motions. Nevertheless, the earthquakes were still considered to be revealing the correct faulting geometry [*Ekström and England*, 1989; *McCaffrey and Abers*, 1991]. Initial GPS measurements [*Puntodewo et al.*, 1994] showed that the Sorong fault zone where it came on land on the Bird's Head was not slipping rapidly, if at all, casting doubt on our understanding of the large-scale geometry of the faulting. Additional GPS measurements at the original sites and an expanded network presented here now show that the Pacific - Australia plate boundary cuts through the island of New Guinea in a broad fault zone that is oriented and slipping nearly parallel to the Pacific – Australian motion, largely transferring the Bird's Head continental region to the Pacific plate. The boundary between the Bird's Head and the Australian plate is identified as a shear zone approximately 300 km wide slipping at about 75 to 80 mm/yr. In this paper we present the evidence for the rapid slip rate, show that deformation within the shear zone may comprise large, rotating blocks, and speculate on the forces that drive such rapid motion of the Bird's Head.

GLOBAL POSITIONING SYSTEM MEASUREMENTS AND ANALYSIS

The six geodetic sites AUKE, BIAK, SENT, SORO, TIMI, and WAME were established and first occupied with the Global Positioning System (GPS) in 1991 in the Irian Jaya province of Indonesia [*Puntodewo et al.*, 1994]. (The Irian Jaya province is now referred to as West Papua, as we will do here.) GPS observations at the remaining sites shown in Figure 1b began in 1992 as part of a larger network spanning eastern Indonesia [*Stevens*, 1999]. The core network of nine sites in West Papua was occupied yearly through 1997 except in 1995. Dual-frequency GPS data were collected at each site for several days during each campaign. The positions of each site during each campaign were first estimated in the global ITRF96 reference frame [*Sillard et al.*, 1998] using the GAMIT/GLOBK analysis package [*King and Bock*, 1999; *Herring*, 1999]. Velocities and their covariances were estimated by linear regression to the time series of positions in that reference frame (Table 1; Fig. 2). Velocities were transformed to a north Australia (NAUS) reference frame by a rotation that minimizes in a least-squares sense the velocities of 10 sites in SE West Papua, Papua New Guinea, and northern Australia (Tables 1 and 2). The fit to the NAUS pole results in a reduced chi-square of $\div_n^2 = 1.21$ indicating that a rigid plate is an adequate approximation given the uncertainties in the GPS velocities.

Two sites, BIAK and YAPE, were measurably displaced during the February 17, 1996, $M_w = 8$ earthquake on the New Guinea trench NE of Biak Island [*Masturyono*, 2000]. The time series for both sites show differences in the velocities before and after the earthquake (Fig. 2). The post-quake velocities are consistent with post-seismic relaxation but our measurements are too few to characterize its nature. For these two sites, we use the pre-quake measurements only (1991-1994) to estimate the interseismic velocities. Co-seismic displacements are estimated by extrapolating the pre-quake position time series to the time of the 1996 measurements that were made 1 month after the earthquake. Estimated offsets are 817 mm N, 620 mm E, and 50 mm down for BIAK and 190 mm N, 25 mm W, and 111 mm up for YAPE. Because similar large thrust events are unknown on the western New Guinea trench in recorded earthquake history and local Biak history makes no reference to large earthquakes, we suspect the interseismic period must last at least a century. Therefore, the velocities due to interseismic elastic strain accumulation at the BIAK and YAPE sites are likely less than 10 and 2 mm/a, respectively. Co-seismic offsets were not measurable at the other sites (Fig. 2).

PACIFIC – AUSTRALIA CONVERGENCE ACROSS EASTERN INDONESIA

In the North Australia (NAUS) reference frame we observe rapid rotation of the Bird's Head (BH) and the region to the west as far as site OBIX (Fig. 1b; we will refer to this larger region as the Bird's Head block). Six GPS vectors on the Bird's Head block match a rigid rotation (Tables 1 and 2) with a misfit of $\div_n^2 = 10.7$ ($\div_n^2$ of the GPS data in the NAUS frame is 148.0; we multiply the uncertainties listed in Table 1 by a factor of 3 in calculating the chi-square misfit). Fitting both a rigid rotation and uniform strain rates within the Bird's Head results in a significantly better match, $\div_n^2 = 2.6$. Principal strain rates are extension of 19 ±12 nanostrain/a at an azimuth of 115° ±5° and contraction of –84 ±11 nanostrain/a at 25° ±5° azimuth. Hence, most of the motion of these 6 sites relative to North Australia is attributed to a rigid body rotation while the smaller part of the measured motion is due to internal strain or noise or both.

Relative to Australia, the Bird's Head is moving nearly as fast as the Pacific plate and in almost the same direction. Calculated at 1°S, 133°E, the Pacific plate moves at 112 ±2 mm/a at an azimuth of 246 ±1° while the Bird's Head moves at 86 ±9 mm/a at 252 ±1° azimuth. Accordingly, assuming rigid blocks, there could be 26 ±10 mm/a of subduction of the Pacific plate beneath the Bird's Head. Site NATE appears to move faster than the Bird's Head and within 1 cm/a of the Pacific rate.

Clearly the majority of the Pacific – Australia convergence across eastern Indonesia is accommodated by deformation within the lithosphere of the overriding continental plate. To elucidate the distribution of slip across the PAC-AUS boundary west of the shear zone, we estimate a horizontal velocity profile across the Bird's Head, Seram trough, Banda Basin, and the Timor trough (Fig. 1c) constrained by GPS, with the assumption of uniform strain rates in the Banda Basin and the Bird's Head. From south to north, GPS results from the southern Banda arc [*Genrich et al.*, 1996] reveal slow convergence across the Timor trough and Wetar thrust. The site BAPI, about 200 km south of the Seram trough, moves at 33±6 mm/a relative to

NAUS. This rate requires some strain south of BAPI, consistent with earthquake mechanisms, although earthquakes account for only 1/3 of the GPS-estimated rate of shortening between the Seram trough and Australia [*McCaffrey*, 1988]. From the Wetar thrust to the Seram trough we assume uniform strain and also satisfying the BAPI site velocity (the strain rate indicated by the slope of this line is 36 nanostrain/a). North of the Seram trough, we draw a linear velocity profile between FAFK, that moves at 65±3 mm/a relative to NAUS, and BIAK, which is about 150 km south of the NG trench. The strain rate for this line is 62 nanostrain/a which is ¾ the overall contractional strain rate estimated from all the GPS sites on the Bird's Head. This analysis yields estimates of slip rates of 20 mm/a at the Seram trough and 10 mm/a at the NG trench. Overall, west of the shear zone, about 2/3 of the Pacific – Australia motion is accommodated by deformation within continental lithosphere north of Seram and about 1/3 within the oceanic Banda Basin and Banda arc.

THE SHEAR ZONE

The geodetic array grossly brackets the location of the most rapid left-lateral shear between the Bird's Head (BH) and New Guinea to fall within a region about 300 km wide (shown by the dashed curves in Fig. 1b, which are small circles about the BH-NAUS rotation pole). Assuming that all the slip occurs in this region, a slip rate between 75 and 80 mm/a is estimated from the BH-NAUS rotation pole (Table 2). This rate is about twice that of the previously known fastest strike-slip fault in a continental setting - the San Andreas fault (Table 3).

It is not obvious from direct examination of the GPS results whether the rapid slip occurs on a single fault, as in most continental shear zones, or is widely distributed over more than one fault, as in parts of New Zealand and California. The deforming zone is too wide to be explained by elastic strain surrounding a single locked strike-slip fault [*Savage and Burford*, 1970] unless the locking depth is several tens of kilometers or more (Fig. 3a). Such deep locking is unlikely in continental crust where rock elasticity decrease rapidly below about 15 km depth.

Within the deforming zone outlined by the velocity field, only the Tarera Fault (TFZ in Fig. 1a) has been described in any detail and clearly displays left-lateral offsets [*Hamilton*, 1979; *Pubellier et al.*, 1999]. Shallow earthquake hypocenters (Fig. 4) are generally scattered but one lineation extends NE from the Aru trough, where active extension occurs (indicated by the relative motion of sites ARUX and TUAL – Fig. 1b), to the Tarera Fault and then continues halfway up the eastern margin of Cenderawasih Bay (CB in Fig. 4). Geologic mapping [*Pubellier et al.*, 1999] reveals two large NE-trending faults in this region, the Lowlands Fault Zone (LFZ) and the Paniai Fault Zone (PFZ), that truncate the western end of the Highlands mountain range. The LFZ, the longer segment, coincides with thrust and strike-slip earthquakes (Fig. 4). East of 136°E, it can be followed along the northwestern edge of a NE-trending mountain range by river drainage offsets. To the north, it splays in the Mamberambo thrust belt (MTB; Fig. 4) and may connect to the Yapen Fault. To the south, the LFZ intersects the Weyland Thrust (WT; Fig. 4) obliquely and connects to the Tarera Fault, the major active fault west of 136°E. The Paniai Fault Zone (PFZ; Fig. 4), mapped using Spot Pan and XS, as well as ERS-1 and JERS-1 images, forms a 1300-m scarp on which both dip slip and strike slip are observed [*Pubellier et al.*, 1999]. Hence, at the present time these two faults are the most likely candidates for through-going faults that could take up several cm/a of motion. Accordingly, we tentatively refer to the shear zone identified with GPS as the “Paniai shear zone”.

Motion of the Bird’s Head block relative to Australia may have started around 5 Ma [*Ego and Pubellier,* 2001]. Dioritic intrusives (porphyry coppers) dated between 5 and 2 Ma were injected in some of the NE-trending faults near the Paniai fault zone. Pliocene diorites and andesites of the Highlands range are offset by about 200 km left laterally [*Ego and Pubellier,* 2001]. West of 136°E, plutons with similar petrological and geochemical properties are found at 4°S at the front of the Weyland Thrust. A metamorphic belt in the northern part of the Highlands Range is offset by a similar amount [*Ego and Pubellier,* 2001]. If the slip rates inferred from GPS were active since 5 Ma, the total offset would be 400 km, twice that indicated by geology. This discrepancy may be explained either by acceleration of the slip rate in recent times (after 2 Ma), when the tectonic regime became transtensional [*Pubellier et al.*, 1996] or by slip on other faults.

EVIDENCE FOR BLOCK ROTATIONS

Evidence for a wide, rather than narrow, shear zone is found in the large radial GPS velocity components that point toward and away from the BH-NAUS rotation pole (Fig. 3b). We consider these to signal the presence of large rotating blocks within a broad shear zone. In the case of simple shear, all radial velocities (*i.e.*, those that point toward or away from the rotation pole) are expected to be zero. In California, for example, where the overall slip rate is about 50 mm/a, the standard deviation of the GPS-derived velocities pointing toward or away from the Pacific – North America pole of rotation (Fig. 5) is a mere 2 mm/a [CDWG, 1998]. The projection we use in Fig. 3 is designed to minimize radial velocities and outside the deforming region they are appropriately zero.

The large radial velocities within the shear zone are best explained by rotations of blocks about nearby vertical axes. The deforming zone is the region between the large, relatively rigid blocks (SE West Papua and the Bird’s Head) whose relative motion is defined by the BH-NAUS pole of rotation. The boundaries of the deforming zone are taken as the two small circles (about the BH-NAUS pole of rotation) that bracket the GPS sites having velocities inconsistent with either rigid block (Figs. 1b and 3). If the velocity differential across the deforming zone of width a is U (Fig. 6), then the average shear strain rate parallel to the boundaries is $\partial u/\partial y = U/a$. The angular velocity ω of a block within the shear zone rotating about a nearby vertical axis and floating in a uniformly shearing substrate will be $U/2a$. If the rotating blocks, like roller-bearings, are driven by shear along their edges the angular velocity is twice as high [*McKenzie and Jackson*, 1983; *Lamb*, 1994]. The rotating blocks need not be circular or bounded by vertical faults.

The local geology is not known well enough to identify individual blocks or the faults separating them. Nevertheless, the magnitudes of the radial velocities statistically constrain the block sizes as follows. A point at (x, y) on a block rotating about an axis at (X_o, Y_o), will have a radial (y-component in Fig. 6) velocity of $\omega\,(x\text{-}X_o)$. A block driven by simple shear will have a net radial velocity of zero because the deforming substrate has no radial velocity component and therefore must rotate about a vertical axis near its centroid.

Because the radial velocity depends only on the distance to the pole in the along strike (x) direction and not on the across-strike (y) distance, the spread in GPS radial velocities depends on the size of the rotating block because the block size limits the magnitude of $x\text{-}X_o$. If the GPS sites are randomly distributed on the rotating blocks, the radial velocities will have a mean of zero and standard deviation of $0.57\ \omega\, r$, where r is the average radius of the blocks (Fig. 6). If a single block spans the width of the Paniai deforming region (*i.e.*, $r = a/2$ with $U = 80$ mm/a and $a = 300$ km), the standard deviation of the radial velocities should be approximately 11 mm/a if driven by shear from below or 22 mm/a if driven by shear from the side. While we have too few measurements to allow robust statistics, the standard deviation of 10 mm/a of the radial velocities within the deforming zone (Fig. 3b) argues for rotating blocks with diameters at least half as wide as the deforming region. For comparison, the standard deviation of the radial vector components in California, with a similar deforming region width, is 1/25th of the strike-slip rate (Fig. 5); in the Paniai shear zone it is 1/7th of the slip rate.

SEISMIC SLIP RATES

Earthquake focal mechanisms (Fig. 4) have led many authors to infer that left-lateral shear on E-W trending planes is the major type of strain across western New Guinea. However, all such studies found slip rates inferred from seismic moments of earthquakes to be considerably less than expected from plate motion rates. Only the contractional Mamberambo thrust belt (Fig. 4) produces a seismic moment rate that is comparable to the rate expected from GPS – derived estimates [*Puntodewo et al.*, 1994]. Indications of NNE oriented strike-slip in earthquake focal mechanisms are few. Most earthquakes near the Paniai fault zone show predominantly N-S thrusting.

The expected rate of seismic moment production on a fault is the product of the long-term slip rate, the area of the fault, and the rigidity of the rocks on either side of the fault [*Brune*, 1968]. If the seismogenic part of the Paniai shear zone is 900 km long, 10 km deep, and has a slip rate of 80 mm/a, and assuming a crustal rigidity is 40 GPa, the expected moment rate is about 3 x 10^{19} Nm/a. From 1963, when seismological observations first began to provide reliable moment estimates, to the present the expected moment release from this fault is about 10^{21} Nm, about the moment released by a single $M_w = 8$ earthquake.

Oblique-slip events of moments M_o = 1.4 x10^{19} in 1970 [*Abers*, 1989] and M_o = 5.8 x10^{18} Nm in 1994 (Fig. 4) are the largest earthquakes since 1963 consistent with left-lateral strike-slip on a NNE trend in the Paniai shear zone. Together they account for only 2% of the moment expected from the slip rate inferred from GPS measurements. Either this shear zone slips steadily without earthquakes or a large amount of earthquake moment is yet to come. In either case, this region reveals a large disagreement between seismologic and geodetic estimates of deformation rates and patterns. It is sobering that the world's fastest slipping continental shear zone is nearly invisible seismically.

SPECULATIONS ON THE EXISTENCE OF BASAL DRIVING FORCE BELOW THE BIRD'S HEAD

The tectonic setting and rapid motion of the Bird's Head together present a tectonic paradox. It appears that subduction of continental lithosphere (the Bird's Head) at the Seram trough is favored over subduction of oceanic lithosphere (the Pacific plate) at the New Guinea trench. Because there is likely more resistance to subduction of buoyant continental lithosphere than there is to subduction of gravitationally unstable oceanic lithosphere [*Molnar and Gray*, 1979], it is odd that subduction of the Bird's Head at the Seram trough is currently faster than subduction of Pacific lithosphere at the New Guinea trench. The seafloor subducting at the New Guinea trench is deeper than 4 km and older than 35 Ma [*Weissel and Anderson*, 1978], arguing against buoyancy driven deformation (younger oceanic lithosphere subducts in other parts of the world without causing major deformation of the overriding plate).

Deformation across the Pacific – Australia plate boundary in eastern Indonesia is distributed over 1500 km (Fig. 1c), more resembling a continental collision than subduction. Over 70% of the convergence occurs in the northern half of the region (north of site BAPI) where the major faults are the Seram trough and the New Guinea trench. While *Audley-Charles et al*. [1979] argue that the Seram trough is an intracontinental thrust belt, an intermediate depth seismic zone SW of Seram, typical subduction earthquakes SW of the Seram trough, and the rapid convergence rate all favor subduction. Even if the Seram trough is a backarc thrust, it is still unusual in that it's vergence is opposite what one would expect from buoyancy arguments and its shortening rate is faster than that of the subduction zone that presumably drives it. Most backarc thrusts, such as in the Andes, other parts of Indonesia, and Japan, slip at a small fraction of the subduction rate.

To explain this apparent subduction paradox, we present a simple and speculative but nonetheless plausible calculation of forces acting on the Bird's Head that suggests that basal traction arising from the Pacific plate sliding below it may currently help to drive it. The perimeter of the Bird's Head comprises trenches in the NE and SW, the Paniai shear zone, the Tarera – Aiduna fault zone, and the Sorong Fault west of the Manokwari trough [*Milsom et al.*, 1992] that connects to the Molucca Sea (Fig. 7a). (Our GPS results suggest that the Sorong and Yapen faults east of 131°E are not slipping and west of 131°E the Sorong fault moves at about 20 mm/a.) We note again that the motion of the Bird's Head block is nearly parallel to the Pacific motion suggesting that the Pacific plate is providing the driving force. Hence, we calculate the driving force only in the direction of Pacific plate motion. Assuming that (1) the force across the New Guinea trench is limited by the shear stress on the thrust fault, (2) resistance to subduction of continental crust can be calculated from buoyancy [*Molnar and Gray*, 1979], and (3) the resistance along the Paniai fault and the Seram trough is negligible, we estimate whether or not the force across the New Guinea trench alone is sufficient to drive subduction of continental lithosphere at the Seram trough.

The northern boundary of the BH block is 1400 km long from point B to E in Fig. 7a and is oriented such that its normal is at an azimuth of 0°. The Pacific – Australia motion across this boundary is at an azimuth of 67° so the length of the northern boundary that is perpendicular to the convergence direction is $1400 \text{ km} \times \cos(67°-0°) \approx 550$ km. We assume that the mechanical properties of this entire boundary are similar to the New Guinea trench (NGT). For the maximum average stress on the NGT we adopt a value of 20 Mpa. This value is based on thermal arguments of *Peacock* [1996], on stress drops of subduction zone earthquakes that are typically less than 10 MPa [*Kanamori and Anderson* 1975], and the stress drop of the 1996 $M_w = 8$ earthquake on the NGT which was only 2 MPa [*Masturyono*, 2000]. The area of the thrust fault is about 100 km downdip [*Tichelaar and Ruff*, 1993; *Masturyono*, 2000] by 550 km along strike, giving a total driving force of $F_s \approx 1.1 \times 10^{18}$ N.

Ignoring all other forces that resist motion of the Bird's Head, we estimate the resistance to subduction of continental crust of the Bird's Head at the Seram trough (Fig. 7b). The buoyancy force of continental crust in the mantle is given by

$$F_c = (r_m - r_c)\, g\, h_c\, d\, L$$

where r_m is the mantle density, r_c is the crustal density, g is the acceleration of gravity, h_c is continental crust thickness, d is the length of the subducted crust, and L is the along-strike length of the subduction zone [*Molnar and Gray*, 1979]. Assuming $r_m = 3300$ kg/m^3, $r_c = 2800$ kg/m^3, $g = 10$ m/s^2, $h_c = 30$ km, and $L = 510$ km (the distance from C to D in Fig. 7), the force resisting subduction of continental crust is $F_c \approx 8 \times 10^{16}$ N per kilometer of subducted crust.

Hence, the force across the NGT subduction zone alone could cause subduction of only about $F_s/F_c \approx 15$ km of intact continental crust or 30 km if half of the crust was detached and remained at the surface. In contrast, evidence suggests, but does not prove, that as much as a couple hundred kilometers of continental lithosphere could have been subducted at the Seram trough. The mantle seismic zone beneath Seram extends to a depth of about 300 km (a slab length of 400 km, [*McCaffrey*, 1989]) and deformation of Australian rocks on Seram began around 5 Ma [*Audley-Charles et al.*, 1979] to 8 Ma [*Linthout et al.*, 1996]. GPS velocities indicates a modern convergence rate of 20 to 30 mm/a across the central Seram trough. If the slab beneath Seram was subducted at today's rate and if continental rocks entered the subduction zone at 5 to 8 Ma, a large fraction (100 to 200 km) of the subducted slab could be continental lithosphere. If so, an additional force beyond push of the Pacific plate across the NGT is needed to force the BH continental crust into the mantle. In addition, forces are needed to account for resistance on the boundary faults that we ignored in the analysis.

At the eastern end of the Paniai shear zone and to the east [*Pegler et al.*, 1995], a mantle seismic zone suggests that the Pacific plate thrusts beneath New Guinea (Fig. 8a). Despite the lack of similar seismicity beneath the Bird's Head (Fig. 8b), differences between expected Pacific and observed BH velocities discussed earlier indicate that the convergence rate at the New Guinea and Manokwari trenches west of the shear zone is 10 to 20 mm/a. Hence, lithosphere of the Pacific plate probably continues to thrust, though relatively slowly, beneath the Bird's Head (Fig. 7b). The area of the Bird's Head block (Fig. 7a) is about 4×10^5 km^2, so the total basal drag force is 4×10^{17} N per MPa of basal shear stress. If so, about 3 MPa of basal stress would result in a force equivalent to that acting at the NGT subduction zone. *Molnar* [1992] argues that stress across horizontal planes in the mantle below the San Andreas fault could be as high as 100 MPa. If such stress exists in the mantle beneath the Bird's Head it could drive subduction of BH continental crust under the Seram trough.

CONCLUSIONS

GPS measurements from eastern Indonesia show that the Bird's Head continental block moves SW at about 80 mm/a relative to Australia along a shear zone that may be up to 300 km wide. Velocities of a few sites within the shear zone are not parallel to the edges of the shear zone indicating the presence of large, rotating blocks. The presence of basal shear acting on the Bird's Head can explain the unusual case of subduction of the Bird's Head continental block being favored over subduction of the oceanic Pacific lithosphere at the New Guinea trench.

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Table 1. Horizontal components of site velocities derived from GPS measurements

Site			ITRF96					NAUS		BH (rot)		BH (rot+strain)	
	Lat., °N	Long., °E	V_N, mm/a	s_N, mm/a	V_E, mm/a	s_E, mm/a	r_{NE}	V_N, mm/a	V_E, mm/a	V_N, mm/a	V_E, mm/a	V_N, mm/a	V_E, mm/a
AMBG	-3.68	128.09	13.3	0.4	16.5	1.2	-0.0585	-40.5	-27.9				
ARUX	-5.99	134.31	57.2	0.6	47.4	2.5	0.0961	**4.3**	**4.0**				
AUKE	-8.47	140.41	51.3	0.4	43.9	1.5	-0.0060	**-0.4**	**2.0**				
BAPI	-4.49	129.77	27.6	2.2	24.4	5.2	0.0000	-26.1	-19.8				
BIAK	-1.16	136.09	26.9	0.7	-44.7	2.2	0.0334	-25.9	-89.2	**-9.2**	**-9.5**	**-3.5**	**-3.5**
COCO	-12.11	96.83	48.6	1.0	47.3	2.8	-0.0988	**1.0**	**-1.6**				
DARW	-12.76	131.13	47.3	0.9	41.1	2.5	0.0859	**-6.1**	**-1.0**				
DILI	-8.49	125.53	37.1	1.2	44.2	4.0	0.0351	-16.8	0.1				
FAKF	-2.9	132.26	27.6	0.9	-15.2	2.9	0.0343	-25.8	-59.5	**3.0**	**14.7**	**-5.6**	**6.2**
KAIM	-3.62	133.69	45.6	0.7	-14.7	2.1	0.0172	-7.6	-58.8	**16.7**	**13.1**	**3.5**	**-1.5**
KALA	-8.08	124.6	29.2	1.0	44.1	3.5	-0.0174	-24.7	-0.2				
MANO	-0.89	134.05	25.0	0.7	-40.5	2.8	0.0301	-28.2	-85.1	**-5.0**	**-4.5**	**1.8**	**3.8**
NATE	0.82	127.38	-3.9	1.5	-66.3	5.0	-0.0243	-57.7	-111.1				
OBIX	-1.33	127.64	7.9	0.7	-44.0	2.6	0.0113	-45.9	-88.7	**-2.7**	**-9.4**	**-1.9**	**-4.4**
SAUM	-7.94	131.31	47.6	0.9	48.8	2.6	0.0340	**-5.8**	**5.5**				
SENT	-2.56	140.52	37.9	0.6	25.9	1.6	0.0188	-13.9	-18.1				
SORO	-0.87	131.25	19.8	0.7	-41.6	2.5	0.0121	-33.7	-86.3	**-1.8**	**-5.6**	**3.9**	**3.1**
TIMI	-4.5	136.9	55.9	0.4	46.4	1.5	-0.0101	**3.4**	**2.8**				
TOWN	-19.14	146.81	45.8	1.3	40.0	3.2	0.0648	**-3.9**	**4.5**				
TUAL	-5.25	133.13	56.4	0.6	24.9	1.8	0.0225	3.1	-18.9				
WAME	-4.07	138.95	49.8	0.4	34.3	1.6	-0.0112	**-2.2**	**-9.2**				
WETA	-7.88	126.43	43.3	1.3	48.2	4.3	0.0429	-10.6	4.1				
XMAS	-10.38	105.69	43.4	1.3	56.6	4.6	-0.0853	**-7.5**	**9.6**				
YAPE	-1.86	136.24	18.1	0.9	9.7	2.8	0.0376	-34.7	-34.7				
YAR1	-28.88	115.35	54.6	0.6	42.5	1.0	-0.0318	**1.6**	**-0.7**				

Velocities in bold identify sites used to estimate NAUS-ITRF96 rotation pole and the BH-NAUS pole. BH (rotation) shows fits for rotation only; (rot + strain) shows residuals when rotation and uniform strain are calculated for the BH.

Table 2. Poles of rotation derived from GPS velocities

Pole	No. Sites	c_n^2	Latitude, °N	Longitude, °E	Angular vel., °/Ma	Semi-major axis, °	Semi-minor axis, °	Azimuth, °
NAUS-ITRF96	10	1.2	39.7	34.5	0.63 ± 0.02	4.2	1.6	274
BH-NAUS	6	10.7	-24.6	141.3	1.80 ± 0.16	2.4	0.4	338
PAC-AUS*	--	--	-60.1	181.7	1.07 ± 0.02	1.0	0.9	302

NAUS = North Australia; BH = Bird's Head; PAC = Pacific plate; AUS = Australian plate; χ_n^2 = reduced chi-square. Errors are based on using 3σ uncertainties for GPS velocities. *Pole from *DeMets et al*. [1994].

Table 3. Slip rates and widths of major continental strike-slip faults

Fault System	**Position of obs.**	**Width, km***	**Slip Rate, mm/a**	**Source**
San Andreas	37.5°N	120	40	USGS, 1999
San Andreas	35.5°N	350	40	CDWG, 1998
San Andreas	34°N	240	50	CDWG, 1998
San Andreas	33°N	80	45	CDWG, 1998
Philippine	11°N	?	26±10	Dusquenoy et al., 1994
Altyn-Tagh	90°E	50	9±6	Bendick et al., 2000
Alpine, N.Z.	43.5°S	70	30±2	Beavan et al., 1999
Marlboro, N.Z.	42°S	160	39	Bourne et al., 1998
Palu, Sulawesi	0.8°S	40	38±8	Stevens et al., 1999
Sumatra	0.8°S	100	23±5	Genrich et al., 2000
Sumatra	2.7°N	50	26±2	Genrich et al., 2000
N. Anatolian	40°N	?	24±1	McCluskey et al., 2000
E. Anatolian	38°N	?	9±1	McCluskey et al., 2000

Width is defined as the fault-normal distance over which most of the shear strain is evident in geodetic measurements.

Figure 1. (a) Tectonic map of Eastern Indonesia. Large arrow represents the motion of the Pacific plate relative to the Australian plate [*DeMets et al*., 1994]. Dashed line shows the circuit for which velocities are estimated in Fig. 1c. Topography contoured every 1500 m. (b) GPS vectors in North Australia reference frame (large arrows) with 95% confidence ellipses and site names. Dashed curves trace small circles about Bird's Head - North Australia rotation pole and roughly bound deforming region. Triangles indicate locations of active volcanoes. BH = Bird's Head, MR = Mapia Ridge, CB = Cenderwasih Bay, LFZ = Lowlands fault zone, PFZ = Paniai fault zone, MTB = Mamberambo thrust belt, AB = Aru Basin, TFZ = Tarera fault zone, MT = Manokwari trough, WT = Weyland thrust. (c) Profile of slip distribution between the Pacific and Australian plates inferred from GPS measurements. The profile location is given by the dashed line in Fig. 1a.

Figure 2. Time series of horizontal components of site positions. Linear trends have been removed to show scatter. Each point represents the position estimated from an entire campaign. Error bars are 1-standard deviation. Horizontal tics represent 1 year starting in 1991. Position axes are ±50 mm. The lines connecting positions at BIAK and YAPE show the deviations from the linear trends following the January 1996 $M_w = 8$ Biak earthquake (shown by arrows on the time axes). These two time series have been corrected for the co-seismic offsets.

Figure 3. (a) Components of GPS vectors (Fig. 1b) parallel to small circles about rotation pole plotted along a profile radial to pole. Reference frame is the North Australia block. Curves are predicted surface slip rates for single locked fault with a slip rate of 80 mm/a and locking depths of 1, 15, 30, and 50 km as labeled. Slope in velocities on Bird's Head side is due to rotation of the Bird's Head block. (b**)** Component of GPS vectors that point toward (negative values) and away from BH-NAUS pole of rotation. Sites outside deforming zone (shaded area) show no convergence across it. Large radial velocities within deforming zone are likely due to block rotations.

Figure 4. Recent seismicity of western New Guinea region. Small dots show locations of earthquakes shallower than 40 km [*Engdahl et al*., 1988]. Focal mechanisms are from Harvard moment-tensor catalog (1/1976-10/1999), scaled by seismic moment. Vectors with error ellipses are GPS velocities relative to North Australia and vector labeled PAC-AUS shows Pacific plate motion relative to Australia. Dashed arcs outline inferred shear zone. Topography is contoured at 1 km. CB = Cenderwasih Bay, LFZ = Lowlands fault zone, PFZ = Paniai fault zone, MTB = Mamberambo thrust belt, TAFZ = Tarera fault zone, WT = Weyland thrust.

Figure 5. Plots of horizontal components of GPS vectors in California relative to the Pacific – North America direction of motion. The map at top shows the GPS site distribution in California divided into four regions. The dashed arcs are small circles about the Pacific – North America pole of *DeMets et al*. [1994]. Lower panels show the GPS components parallel to (open circles) and perpendicular to (dots) the small circles for the four regions plotted vs. radial distance from the pole (with arbitrary origin). These plots demonstrate that despite the complexity of faulting in parts of California the GPS vectors generally remain parallel to the expected direction of relative plate motion.

Figure 6. Diagram depicting how rotating blocks within a deforming zone produce radial (y-direction in this case) components in site velocities. a is the width of the deforming region; U is the total slip across the zone; and ω is the angular velocity.

Figure 7. (a) Inferred boundaries of the Bird's Head block drawn as heavy, dashed lines. Tics labeled A through E identify reference points for calculated distances. Opposing arrows show the principal strain rates for the Bird's Head block estimated from GPS vectors. NNE-oriented contraction is -84±11 nanostrain/a and the ESE-oriented extension is 19±12 nanostrain/a. CB = Cenderwasih Bay, LFZ = Lowlands fault zone, PFZ = Paniai fault zone, TAFZ = Tarera fault zone, BH = Bird's Head, MT = Manokwari trough. (b) Cartoon cross-section showing the forces acting on the Bird's Head block. We argue that the frictional coupling across the New Guinea trench is insufficient to overcome the buoyancy of the continental crust subducting at the Seram trough and that some type of viscous coupling (basal drag) below the Bird's Head helps drive it.

Figure. 8. N30°E cross-sections of earthquake hypocenters [*Engdahl et al*., 1988] across the Bird's Head and western New Guinea. Mid-points of the two cross-sections are near 1.5°S, 132°E and 3.5°S, 139°E, respectively. Hypocenter cross-sections are to scale but topography is exaggerated 10x.