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Resolving slip-vector azimuths and plate motion along the southern boundary of the South Bismarck Plate, Papua New Guinea

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The interaction of the Australian, South Bismarck and Solomon Sea Plates in Papua New Guinea is the source of frequent earthquakes that occur as a result of subduction and arc–continent collision. Previous investigators have drawn attention to a discontinuity in the horizontal azimuth of slip vectors along the southern boundary of the South Bismarck Plate, with those to the west of 148°E being systematically rotated ~20–30° clockwise compared to those located east of 148°E. This has led to the suggestion that relative motion may be occurring between the Huon Peninsula and New Britain or that more than two plates are acting south of the South Bismarck Plate. Global positioning system (GPS) measurements since 1991 indicate that there is no internal deformation occurring within the South Bismark Plate and that at least two distinct plates are in contact with the southern edge of the South Bismarck Plate. We show from a study of a recent earthquake dataset that the change in slip-vector azimuth can be modelled by the interaction of the overriding South Bismarck Plate with the underthrusting Australian and Solomon Sea Plates, consistent with the GPS observations, while maintaining the South Bismarck Plate as a rigid entity. We found that a transition zone exists between 147°E and 148°E where the underlying plate changes from the Australian Plate to the Solomon Sea Plate. There are insufficient data at present to indicate whether or not a third plate, the Woodlark Plate, is also interacting directly with the South Bismarck Plate in this transition zone. Slip-vector azimuths were used to estimate an Euler pole (6.74°S, 144.64°E), which describes the relative motion of the South Bismarck and Solomon Sea Plates along the New Britain Trench.

KEY WORDS: global positioning system, New Britain Trench, Papua New Guinea, plate motion, slip vectors, South Bismarck Plate.

INTRODUCTION

Papua New Guinea is a complex tectonic region comprising several microplates trapped between the converging Australian and Pacific Plates (Figure 1). The motions of some of the microplates have been modelled from geophysical and geodetic data, although significant inconsistencies are still to be resolved between all available data and models based on subsets of the data.

Abers and McCaffrey (1994) showed that the horizontal slip-vector azimuths along the New Britain Trench and the Ramu–Markham Fault (Figure 2) appear to be discontinuous at 148°E, with those to the west being systematically rotated by 20–30°. They showed that it was not possible to model all the slip vectors with a rotation about a single relative pole between two plates and that additional deformation of up to 50 mm/y was required in order to resolve this offset in the form of either east–west convergence between the Solomon Sea and New Guinea or east–west extension between the Huon Peninsula and New Britain. Pegler *et al.* (1995) proposed an alternative hypothesis that the slip vectors showed the interaction of the South Bismarck Plate with two plates to the south, the Australian and Solomon Sea Plates. They concluded that it should not be expected that the slip vectors along the Ramu–Markham Fault and New Britain Trench would be able to be modelled by a single relative pole of rotation.

Tregoning *et al.* (1999) showed from global positioning system (GPS) observations that there are no significant changes in baseline lengths between the Huon Peninsula (Madang and Finschaffen) and New Britain (Witu and Jacquinot Bay) (Figure 2). Furthermore, they showed that the absolute velocities of these four sites could be modelled by a rotation about a single Euler pole to within the uncertainties of the GPS velocity estimates. Therefore, they demonstrated that the South Bismarck Plate appears to be a rigid microplate that encompasses both the Huon Peninsula and New Britain with no relative motion occurring across the Vitiaz Strait.

We show that the variation in the azimuths of the slip vectors is caused by the interaction of the South Bismarck Plate with at least two tectonic blocks south of the Ramu–Markham Fault and the New Britain Trench, confirming the hypothesis of Pegler, *et al.* (1995). The slip vectors east of 148°E reflect the interaction of the South Bismarck/Solomon Sea Plates, while those to the west of 147°E reflect interaction of the South Bismarck/Australian Plates. We also used the available slip-vector azimuths to compute a relative pole of rotation for the South Bismarck and Solomon Sea Plates.

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SLIP VECTORS

Slip vectors have been used for many years in tectonic interpretation and have been incorporated into many plate-tectonic models and investigations (Minster & Jordan 1978; McCaffrey 1988; DeMets *et al.* 1990). Long-term average plate directions derived from spreading rates and transform-fault azimuths do not differ significantly from short-term average directions derived from slip vectors (DeMets 1993). The direction of coseismic slip can be represented as a vector in 3-D space (Aki & Richards 1980) and can be defined by three angles: (i) the strike of the fault plane (θ); (ii) the dip of the fault plane from horizontal (δ); and (iii) the rake (or direction of slip) (λ), which is measured in the fault plane anticlockwise from the direction of strike (Aki & Richards 1980). We computed the azimuth of slip vectors in the horizontal plane from the north and east components of a unit vector in the direction of the earthquake slip vector:

$$\text{east} = \cos(\theta)\cos(\delta)\sin(\lambda) + \sin(\theta)\cos(\lambda) \quad (1)$$

$$\text{north} = -\sin(\theta)\cos(\delta)\sin(\lambda) + \cos(\theta)\cos(\lambda) \quad (2)$$

These equations can be used to compute the azimuth of motion of the hanging wall relative to the footwall (the azimuth of the footwall relative to the hanging wall is simply the reverse azimuth). The Harvard Central Moment Tensor (CMT) catalogue contains earthquake source locations (latitude, longitude, depth) along with focal-mechanism solutions (dip, rake and strike for the principal and secondary planes) and estimates of the earthquake magnitude for earthquakes of magnitude >5 that have occurred since 1978 (Dziewonski & Woodhouse 1983). We used information in this catalogue along with the 1966–1992 focal-mechanism solutions listed in table 2 of Abers and McCaffrey (1994) to produce a database of horizontal slip-vector azimuths.

Because the southern boundary of the South Bismarck Plate is a thrust/collision zone (subduction and arc–continental), only the thrust events provide information about the direction of large-scale plate motions. Therefore, we need only be concerned with earthquakes that are related to the thrusting of lithosphere beneath the South Bismarck Plate. To isolate these events from the catalogue, we imposed the conditions that the strike of the fault plane must lie between 230° and 310° (i.e. roughly parallel to the plate boundary) and that the rake must lie between 45° and 135°; that is, the earthquake mechanisms must be predominantly thrust, but may contain some strike-slip component. Allowing a range of acceptable events permits a component of oblique subduction and compensates for possible errors in the focal-mechanism determinations. The earthquakes selected represent 39% of all quakes with magnitude >5.0, account for 54% of the total seismic moment release and form the dataset used in the analysis below. The excluded earthquakes represent strike-slip and normal events related to flexure of the subducting slab and internal readjustment of stresses within the plate boundary zone.

The locations of the horizontal slip-vector azimuths of the footwall relative to the hanging wall are plotted in Figure 2 and the azimuths are plotted against longitude in Figure 3 following Abers and McCaffrey (1994). The predicted direction of convergence is shown using the Euler poles of Abers and McCaffrey (1994) and Tregoning *et al.* (1999) to estimate the relative motion of the South Bismarck and Australian Plates. With an enlarged dataset, including earthquakes since 1994, we show that the step-like offset at 148°E identified by Abers and McCaffrey (1994) is not evident, although it is apparent that there is still a significant swing in azimuth from ~20° on the Huon Peninsula to ~−10° in eastern New Britain that cannot be modelled by a South Bismarck/Australian Plate relative pole alone.

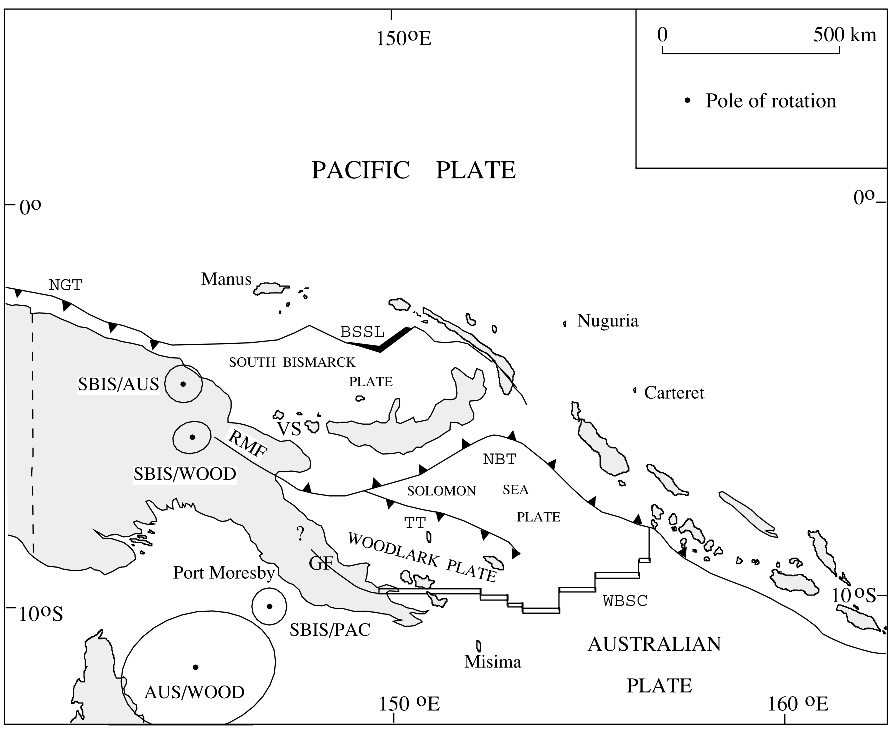

Figure 1 Tectonic setting of Papua New Guinea showing the major plate boundaries. Also plotted are the relative poles of rotation between the Australian (AUS), Woodlark (WOOD), South Bismarck (SBIS) and Pacific (PAC) Plates. GF, Gira Fault; VS, Vitiaz Strait; RMF, Ramu–Markham Fault; NBT, New Britain Trench; TT, Trobriand Trough; BSSL, Bismarck Sea Seismic Lineation; NGT, New Guinea Trench; WBSC, Woodlark Basin Spreading Centre.

AVAILABLE PLATE-MOTION MODELS

The configuration of tectonic elements in the region of the New Britain Trench and the 149°E Embayment (Figure 2) is subject to debate. It is generally accepted that the South Bismarck Plate lies north of the New Britain Trench (Taylor 1979; Cooper & Taylor 1987a; Silver *et al.* 1991; Abers & McCaffrey 1994) and that the Australian Plate lies to the south of the Ramu–Markham Fault (Cooper & Taylor 1987b; Silver *et al.* 1991; Stevens *et al.* 1998). Some authors have suggested that the Huon Peninsula is moving relative to the South Bismarck Plate (Abbott *et al.* 1994; Abers & McCaffrey 1994; Kulig *et al.* 1994), whereas Tregoning *et al.* (1999) showed from GPS site velocities that the rigid South Bismarck Plate includes the Huon Peninsula.

A major uncertainty in the tectonic pattern south of the New Britain Trench is whether the Woodlark and Solomon Sea Plates are also in relative motion or whether they constitute a single Solomon Sea – Woodlark Plate. This cannot be resolved by geodetic observations because of the lack of subaerial exposure on the Solomon Sea Plate on which static GPS measurements could be made. The former scenario requires convergence across the Trobriand Trough, although this is not a region of high seismicity.

Earthquake cross-sections through the Papuan Peninsula reveal a southwest-dipping slab beneath the

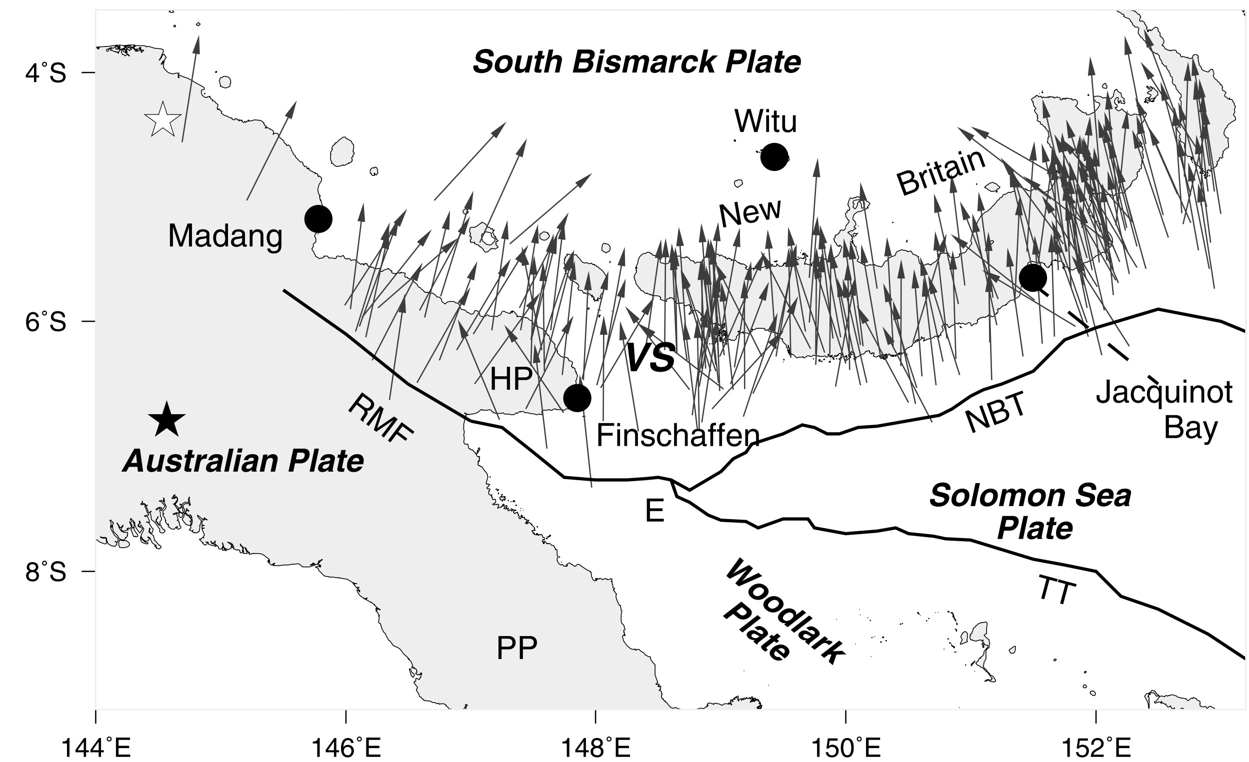

Figure 2 Map of the intersections of the South Bismarck, Solomon Sea, Woodlark and Australian Plates. Horizontal slip-vector azimuths are plotted with lengths scaled by the log of the seismic moment. Locations of sites with global positioning system (GPS)-derived site velocities (●) and the relative Euler poles of the Australian/South Bismarck Plates (☆, Tregoning *et al.* 1999) and South Bismarck/Solomon Sea Plates (★, this study) are plotted. E, 149°E Embayment; HP, Huon Peninsula; NBT, New Britain Trench; PP, Papuan Peninsula; RMF, Ramu–Markham Fault; TT, Trobriand Trough; VS, Vitiaz Strait.

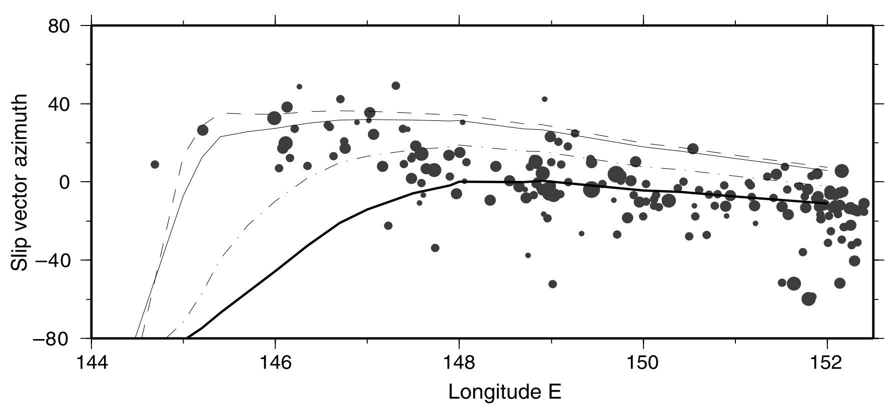

Figure 3 Horizontal slip-vector azimuths of thrust events plotted as a function of longitude. The size of the symbol is proportional to the seismic moment of the event. Predicted azimuths using the relative Euler poles for the South Bismarck/Australian Plates [solid line, Tregoning *et al.* (1999); dashed line, Abers & McCaffrey (1994)], for the South Bismarck/Woodlark Plates [dashed–dotted line, Tregoning *et al.* (1998)] and for the South Bismarck/Solomon Sea Plates (bold solid line, this study) are also plotted. Predicted azimuths are computed 50 km north of the plate boundaries.

peninsula (Davies *et al.* 1984; Cooper & Taylor 1987b). Pegler *et al.* (1995) showed from profiles through the Huon Peninsula that there is a double-dipping slab that has subducted both to the north and south and argued that this was part of the Solomon Sea Plate, which has subducted both at the Trobriand Trough and the New Britain Trench.

Eiichi *et al.* (1986) estimated a rate of convergence across the Trobriand Trough of less than 20 mm/y, whereas Kirchoff-Stein (1992) estimated a convergence of ~6 mm/y from seismic-reflection profiles. Tregoning *et al.* (1998) made no distinction between the Solomon Sea Plate and the Woodlark Plate because they had no geodetic estimate of convergence across the Trobriand Trough. There are no directly observed estimates of subduction across the New Britain Trench, although Johnson (1979) inferred subduction rates of 92–125 mm/y from plate closures and Tregoning *et al.* (1998) estimated convergence rates of 80–150 mm/y on the assumption that there was no relative motion occurring across the Trobriand Trough.

A possible scenario for the interaction of plates near the 149°E Embayment is that the Australian and South Bismarck Plates collide along the Ramu–Markham Fault, the Solomon Sea Plate subducts beneath both the Trobriand Trough and the New Britain Trench, the Woodlark Plate lies between the Trobriand Trough and the Woodlark Basin Spreading Centre (the western boundary with the Australian Plate is not well-defined at this time and hence is not shown on Figure 2), and that the South Bismarck Plate is a rigid entity whose southern boundary runs from the Bismarck Sea Seismic Lineation through to the Huon Peninsula and eastward following the New Britain Trench. Alternatively, there may be no motion across the Trobriand Trough, meaning that the Woodlark Plate [as defined by Tregoning *et al.* (1998) and incorporating the Solomon Sea Plate] is subducting at the New Britain Trench and the Australian Plate collides with the South Bismarck Plate at the Ramu–Markham Fault.

In any event, there are at least three plates (and possibly four) involved in the convergence along the Ramu–Markham Fault and New Britain Trench, thereby confirming the suggestion that the slip vectors cannot be resolved from a single relative Euler vector. Either scenario summarised above is consistent with the GPS observations that there are no changes in baseline lengths between the Huon Peninsula and New Britain.

Tregoning *et al.* (1998, 1999) have computed Euler vectors that model the motions of some of the tectonic blocks in Papua New Guinea. We have used their relative Euler vectors for the Australian, South Bismarck and Woodlark Plates in order to compute expected directions and magnitudes of convergence between the tectonic blocks (Table 1).

DISCUSSION

The predicted azimuths between 145°E and 147°E can be modelled using the Euler poles (Tregoning *et al.* 1999) for the Australian/South Bismarck Plates (Figure 3); however, this Euler pole does not model well the observed slip vectors to the east of 147°E. Also plotted in Figure 3 are the predicted azimuths using the relative Euler vector for the Woodlark/South Bismarck Plates (Tregoning *et al.* 1998). This clearly models the eastern slip vectors more closely, although it still overestimates the azimuths by ~10°. Note that this Euler vector does not model well the vectors to the west of 148°E.

If active subduction is occurring across the Trobriand Trough, the Woodlark/South Bismarck Plate Euler vector (Table 1) will not be valid to represent the convergence of the Solomon Sea/South Bismarck Plates at the New Britain Trench. Consequently, we used the slip vectors east of 148°E to estimate a relative Euler pole for the South Bismarck and Solomon Sea Plates (Table 1), with the motion of the South Bismarck Plate being defined by the GPS site velocities in Tregoning *et al.* (1999). The resulting Euler pole fits the observed slip vectors east of 148°E reasonably well, as one would expect (Figure 3). Thus, we can model the vectors east of 148°E and west of 147°E using two different plates on the southern side of the South Bismarck Plate.

The slip vectors in the transition zone between 147°E and 148°E do not fit the predictions using the relative Euler pole of any plate pair. It has been shown that shallow events in this area relate to the Australian/ South Bismarck collision while deeper events relate to the subducted Solomon Sea Plate (Pegler *et al.* 1995). This was not evident in our dataset, possibly because the depths of events are not well resolved in the CMT catalogue. The vectors in this transition zone lie near an unstable triple junction at the 149°E Embayment, which is propagating southeast at 120–240 km/10^6 y (Silver *et al.* 1991). It may not be reasonable

Table 1 Relative Euler vectors for the South Bismarck/Woodlark Plates (SBP–Wo), South Bismarck/Australian Plates (SBP–Aus) and South Bismarck/Solomon Sea Plates (SBP–SSP).

Euler vector	Latitude (°S)	Longitude (°E)	Rate (°/10^6 y)	Pole error ellipse		
				σ_{maj}	σ_{min}	Azimuth
SBP–Wo (Tregoning *et al.* 1998)	5.7	144.8	9.83 ± 0.02[a]	0.51	0.40	61
SBP–Aus (Tregoning *et al.* 1999)	4.36	144.54	7.91 ± 0.33	0.24	0.16	281
SBP–Aus (Abers & McCaffrey 1994)	4.65	142.75	not specified[b]	–	–	–
SBP–SSP (this study)	6.75	144.57	not calculated[c]	3.1	0.3	84

[a]The rotation rate uncertainties of Tregoning *et al.* (1998) were unrealistically small because of an error in the program used to calculate their relative Euler vectors.
[b]No rate of rotation about the pole or error ellipse of the pole were provided by Abers and McCaffrey (1994).
[c]A rate of rotation cannot be calculated from only slip-vector azimuths.
Motion is described as the movement of the second plate relative to the first with the rotation in a clockwise direction about the pole. The error ellipses of the poles are described by the 1σ semi-major and semi-minor axes of each error ellipse and the clockwise angle from True North of the semi-major axis.

to expect to model thrust events in this transition region using rigid plate theory.

Modelling the convergence using the relative Euler poles of the Australian/South Bismarck Plates and the Solomon Sea/South Bismarck Plates significantly improves the fit to the observed slip vectors, but the predictions do not model the observations to better than ~10°. One additional factor that should be considered is that some of the relative Euler poles are located very close to the actual plate boundaries; hence, small changes in the coordinates of the location in which the prediction is made can significantly affect the resulting predicted azimuth of convergence. For example, the predicted azimuth of convergence between the Australian/South Bismarck Plates at 5°S, 146°E is 15°, whereas the prediction at 5.5°S, 146°E is 30°. Therefore, it can be misleading to plot the slip vectors as a function of longitude because variations in the latitude of the seismic events can also affect the expected azimuth of slip.

Errors in the solution for the earthquake location may introduce errors into the prediction calculation of the slip-vector azimuth because of the demonstrated high sensitivity of predictions to small changes in geographical position of the earthquake. To mitigate these errors we have relocated the earthquake positions using the EHB catalogue (Engdahl *et al.* 1998) when predicting the slip-vector direction. In fact, use of the relocated events caused only minor changes when computing the predicted azimuths.

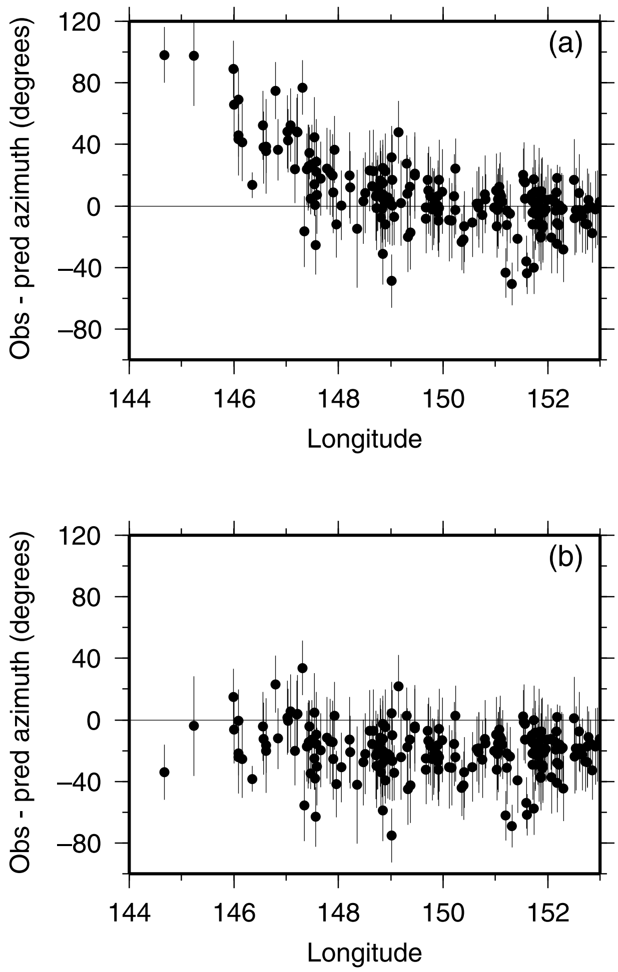

Figure 4 Residual slip-vector azimuths of thrust events after the removal of predicted azimuths using the relative predicted motion of (a) the Solomon Sea/South Bismarck Plates and (b) the Australian/South Bismarck Plates.

To remove the geographical dependence of the predicted azimuths, we computed the predicted azimuth of slip at the geographical location of each earthquake and subtracted this from the observed azimuth. We performed these calculations using the relative Euler poles for the Solomon Sea/South Bismarck Plates (Figure 4a) and for the Australian/South Bismarck Plates (Figure 4b). Uncertainties of the azimuths are calculated using assumed uncertainties of 15° in strike, 10° in dip and 20° in rake (McCaffrey 1988). These residuals can be plotted against longitude without biasing the conclusions because all variations of azimuth as a result of geographical location have been removed. The slip vectors to the east of 148°E have a mean residual of ~0° when the Solomon Sea/South Bismarck Plate predictions are removed (Figure 4a), whereas those to the west differ systematically.

When the Australian/South Bismarck Plate motion is removed (Figure 4b), the mean of the residuals of the vectors east of 148°E are systematically ~–20°. The vectors west of 147°E show considerable scatter and do not have a mean of 0°, suggesting that the South Bismarck/Australian pole is not modelling the convergence direction accurately.

Between 146°E and 147°E (Figure 3), the vector azimuths generally lie between the South Bismarck/Australian and South Bismarck/Woodlark predictions. The Australian/Woodlark boundary is not well defined in this region, although it must lie in the Papuan Peninsula, possibly along the Gira Fault at ~147°E (Davies *et al.* 1984). It is possible that the region south of the Ramu–Markham Fault is undergoing strain accumulation and should not be modelled as rigid Australian–Woodlark – Solomon Sea Plate interaction. There are currently no published site velocities between Port Moresby and the Ramu–Markham Fault estimated from geodetic observations; therefore, it is possible that that the continent south of the Ramu–Markham Fault is deforming and is not moving with Australian Plate velocity.

Without an indication of the convergence rate across the New Britain Trench we cannot estimate the rotation rate about the Euler pole of the Solomon/South Bismarck Plates. If we were able to estimate this parameter we could calculate the relative Euler vector of the Solomon/Woodlark Plates by plate closure between the Solomon/South Bismark and South Bismarck/Woodlark Plates. The rate of rotation about the Solomon/South Bismarck Plates contributes mathematically to the calculation of the geographical location of the Solomon/Woodlark Euler pole when computing the plate closure, thus, at present, this relative Euler pole remains undefined.

If an accurate convergence across the Trobriand Trough were known, one could approach the issue by computing the Solomon Sea/Woodlark Euler vector and, by vector addition, derive the Euler pole and rate of rotation for the Solomon/South Bismarck Plates. However, at the present time there are insufficient data in the CMT catalogue to constrain the azimuth of convergence across the Trobriand Trough using slip-vector azimuths and no direct measurements of convergence rates across the New Britain Trench are currently available. Therefore, it is not yet possible to fully resolve the rate of motion of the Solomon Sea Plate or to estimate relative motion across the Trobriand Trough.

CONCLUSIONS

We have confirmed from earthquake slip-vector azimuths that the relative motion along the Ramu–Markham Fault and New Britain Trench cannot be modelled by a single relative Euler pole representing the collision of two plates. However, unlike Abers and McCaffrey (1994), we have found a smooth transition in azimuth between 147°E and 148°E rather than a step-like offset. We have resolved the variation in azimuth by modelling separately the motion between the South Bismarck and Australian Plates west of 147°E and between the South Bismarck and Solomon Sea Plates east of 148°E, with a transition zone between 147°E and 148°E. There is considerable scatter evident in the vectors west of 147°E and the South Bismarck/Australian relative Euler pole does not model them closely. The region of crustal deformation has a more complex nature than simply two rigid plates colliding, therefore, the observed slip-vector azimuths alone may not reveal the convergence direction of rigid plates.

We have used the horizontal slip-vector azimuths of thrust events east of 148°E to estimate that the Euler pole of rotation for the South Bismarck and Solomon Sea Plates lies at 6.74°S, 144.64°E. However, there are insufficient available data to allow the rate of rotation about this pole to be estimated. This would require a measured estimate of convergence across the New Britain Trench or additional information on the convergence occurring across the Trobriand Trough. We can resolve plate motion and slip-vectors azimuths in this region while still maintaining a rigid South Bismarck Plate from the Huon Peninsula through to New Britain, in agreement with the recent GPS velocity estimates of Tregoning *et al.* (1999), which show that there are no significant changes in baseline lengths across the Vitiaz Strait.

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REFERENCES

Abbott L. D., Silver E. A. & Galewsky J. 1994. Structural evolution of a modern arc–continent collision in Papua New Guinea. *Tectonics* **13**, 1007–1034.

Abers G. & McCaffrey R. 1994. Active arc–continent collision: earthquakes, gravity anomalies, and fault kinematics in the Huon–Finisterre collision zone, Papua New Guinea. *Tectonics* **13**, 227–245.

Aki K. & Richards P. G. 1980. *Quantitative Seismology, Theory and Methods*. W. H. Freeman, New York.

Cooper P. & Taylor B. 1987a. Seismotectonics of New Guinea: a model for arc reversal following arc–continent collision. *Tectonics* **6**, 53–67.

Cooper P. & Taylor B. 1987b. The spatial distribution of earthquakes, focal mechanisms, and subducted lithosphere in the Solomon Islands. *In*: Taylor B. & Exon N. F. eds. *Marine Geology, Geophysics and Geochemistry of the Woodlark Basin—Solomon Islands*, pp. 67–88. Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series **7**.

Davies H. L., Symonds P. A. & Ripper I. 1984. Structure and evolution of the Solomon Sea region. *BMR Journal of Australian Geology & Geophysics* **9**, 49–68.

DeMets C. 1993. Earthquake slip vectors and estimates of present-day plate motions. *Journal of Geophysical Research* **98**, 6703–6714.

DeMets C., Gordon R. G., Argus D. & Stein S. 1990. Current plate motions. *Geophysical Journal International* **101**, 425–478.

Dziewonski A. M. & Woodhouse J. H. 1983. Studies of the seismic source using normal-mode theory. *In*: Kanamori H. & Boschi E. eds. *Earthquakes: Observation, Theory, and Interpretation: Notes from the International School of Physics 'Enrico Fermi' (1982: Varenna, Italy)*, pp. 45–137. North-Holland Publishing Co., Amsterdam.

Eiichi H., Keene J. & Tiffin D. L. 1986. Plate boundaries in Solomon Sea region and subduction at trenches. *American Association of Petroleum Geologists Bulletin* **70**, 927.

Engdahl E. R., Van Der Hilst R. & Biland R. P. 1998. Global teleseismic earthquake relocations with improved travel times and procedures for depth determinations. *Seismological Society of America Bulletin* **88**, 722–743.

Johnson R. W. 1979. Geotectonics and volcanism in Papua New Guinea: a review of the late Cainozoic. *BMR Journal of Australian Geology & Geophysics* **4**, 181–207.

Kirchoff-Stein K. S. 1992. Seismic reflection study of the New Britain and Trobriand subduction systems and their zone of initial contact in the western Solomon Sea. PhD thesis, University of California, Santa Cruz (unpubl.).

Kulig C., McCaffrey R., Abers G. A. & Lets H. 1994. Shallow seismicity of arc–continent collision near Lae, Papua New Guinea. *Tectonophysics* **227**, 81–93.

McCaffrey R. 1988. Active tectonics of the eastern Sunda and Banda arcs. *Journal of Geophysical Research* **93**, 15 163–15 182.

Minster J. B. & Jordan T. H. 1978. Present-day plate motions. *Journal of Geophysical Research* **83**, 5331–5354.

Pegler G., Das S. & Woodhouse J. H. 1995. A seismological study of the eastern New Guinea and the western Solomon Sea regions and its tectonic implications. *Geophysical Journal International* **122**, 961–981.

Silver E. A., Abbott L. D., Kirchoff-Stein K. S., Reed D. L., Bernstein-Taylor B. & Hilyard D. 1991. Collision propagation in Papua New Guinea and the Solomon Sea. *Tectonics* **10**, 863–874.

Stevens C., McCaffrey R., Silver E. A., Sombo Z., English P. & Van Der Kieve J. 1998. Mid-crustal detachment and ramp faulting in the Markham Valley, Papua New Guinea. *Geology* **26**, 847–850.

Taylor B. 1979. Bismarck Sea: evolution of a back-arc basin. *Geology* **7**, 171–174.

Tregoning P., Jackson R. J., McQueen H., Lambeck K., Stevens C., Little R. P., Curley R. & Rosa R. 1999. Motion of the South Bismarck Plate, Papua New Guinea. *Geophysical Research Letters* **26**, 3517–3520.

Tregoning P., Lambeck K., Stolz A., Morgan P., McClusky S. C., Van Der Beek P., McQueen H., Jackson R. J., Little R. P., Laing A. & Murphy B. 1998. Estimation of current plate motions in Papua New Guinea from Global Positioning System observations. *Journal of Geophysical Research* **103**, 12 181–12 203.

Wessel P. & Smith W. F. 1991. Free software helps map and display data. *EOS* **72**, 441.

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