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Present-day crustal motion in Papua New Guinea

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Papua New Guinea is one of the most active tectonic regions in the world. It comprises several microplates and deforming zones trapped in the collision of the Australian and Pacific Plates. GPS observations have been used to estimate plate velocities across a network of sites spanning most of the country. We present new velocites in the northwestern region of New Guinea, and look in detail at the strain accumulation region between the South Bismarck and Pacific Plates in the New Ireland/New Britain region.

1. Introduction

Papua New Guinea lies in a complex and active tectonic region. There are numerous plate boundaries within this region, several microplates and many areas undergoing active deformation. In 1999 alone there have been 37 earthquakes in Papua New Guinea with $M_w > 5$.

The Australian Plate is colliding with the Pacific Plate, providing the dominant tectonic forces in the region. Between these two plates lie the Woodlark, South Bismarck and Solomon Sea Plates. Active spreading is occurring between the Woodlark and Australian Plates at the Woodlark Basin Spreading Centre, subduction of the Solomon Sea Plate is occurring at the New Britain Trench, the Australian and South Bismarck Plates are colliding along the Ramu-Markham Fault and the South Bismarck and Pacific Plates share a long boundary whose relative motion includes left-lateral strike slip in New Ireland/New Britain and along the Bismarck Sea Seismic Lineation and regions of active spreading in the South Bismark Sea (see e.g. Tregoning *et al.*, 1998 and references therein) (Fig. 1). Every possible type of plate boundary can be found in Papua New Guinea.

Since 1990 GPS has been used in Papua New Guinea as a tool for monitoring tectonic motion. An extensive database of geodetic observations now exists (Fig. 2) and large-scale tectonic motion has been modelled from the geodetic data (McClusky *et al.*, 1994; Stevens *et al.*, 1998; Tregoning *et al.*, 1998, 1999). The focus of continuing research in Papua New Guinea is to identify the locations of plate boundaries and areas of distributed deformation and to monitor the regional inter-seismic strain accumulation.

The GPS data have been analysed using the GAMIT/-GLOBK software in a two-step, global procedure described in detail in, for example (Feigl *et al.*, 1993; Dong *et al.*, 1998; Tregoning *et al.*, 1998). The regional data are analysed in conjunction with data from up to 70 IGS tracking sites to compute a global, free-network of site positions and velocities. We then align this network with the ITRF97 by computing 6-parameter transformations on the coordinates and velocities of 47 core IGS sites.

In this paper we present velocities of sites along the northern coastline of New Guinea, around the Ramu-Markham Fault and in the eastern New Britain/New Ireland region and we provide preliminary interpretations of the active tectonic forces. We compare observed site velocities to velocities predicted by the Euler vectors for the Australian Plate (31.6°N, 41.3°E, 0.62°/My) (Tregoning *et al.*, 1998), Pacific Plate (61.4°S, 105.0°E, 0.63°/My) (Tregoning *et al.*, 1998) and South Bismarck Plate (6.75°N, 32.02°W, 8.11°/My) (Tregoning *et al.*, 1999).

2. Northern New Guinea

The Australian and South Bismarck Plates are colliding along the Ramu-Markham Fault (RMF), resulting in the uplift of the Finisterre Range and the Huon Peninsula (Abbott *et al.*, 1997). Further west, there is no clearly defined boundary of the South Bismarck Plate; instead, there may be a gentle transition from the South Bismarck Plate to the Australian Plate in the region of the relative pole of the two plates—a region of low-rate strain accumulation because here both rigid plates would move with nearly the same velocity.

GPS velocities estimated at Madang (MAD1, S6°13’, E145°47’) and Finschhafen (FINS, S6°37’, E147°51’) agree with the rigid plate motion of the South Bismarck Plate (Tregoning *et al.*, 1999) (Fig. 3). Tregoning *et al.* (1998) concluded from two observations at a site at Lae (LAE1, S6°40’, E146°59’) that the site moved as part of the Woodlark Plate. We show here from continuous data since July 1997 that, although close to the predicted motion of the Australian Plate, the Lae site velocity is significantly different to the predicted motions of the Australian, South Bismarck or Woodlark Plates at 95% confidence level. We infer that it

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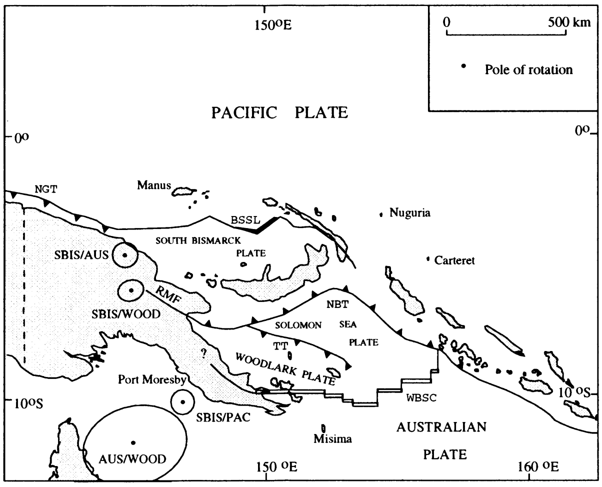

Fig. 1. Tectonic features in the Papua New Guinea region. Relative Euler poles of rotation of the plates are plotted, along with 95% error ellipses. NGT: New Guinea Trench; BSSL: Bismarck Sea Seismic Lineation; RMF: Ramu-Markham Fault; NBT: New Britain Trench; TT: Trobriand Trough; WBSC: Woodlark Basin Spreading Centre AUS: Australian Plate; SBIS: South Bismarck Plate; WOOD: Woodlark Plate; PAC: Pacific Plate.

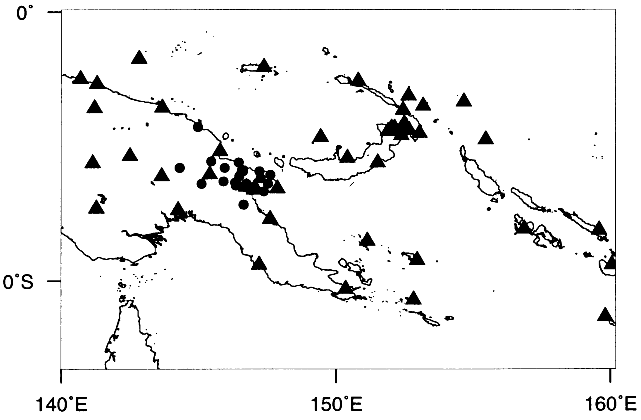

Fig. 2. Sites observed in Papua New Guinea with GPS since 1990. Not all sites have repeat observations. Sites indicated with circles are part of the GPS network of the University of California, Santa Cruz.

is located in a deforming zone associated with the collision occurring on the RMF (Fig. 3).

Further north, the Pacific Plate is moving at an azimuth of 280° at ~68 mm/yr. The relative motion between the Australian and Pacific Plates is ~103 mm/yr at an azimuth of 70°. If all this relative motion is accommodated at the New Guinea Trench, one would see convergence of 67 mm/yr and a left-lateral strike-slip component of 78 mm/yr. From summation of earthquake seismic moments, crustal thickening estimates and from geodetic measurements, less than 20% of the convergence is accommodated within the western Highland thrust belt, requiring that the remainder of the convergence occurs at the New Guinea Trench (Abers and McCaffrey, 1988; Puntodewo *et al.*, 1994).

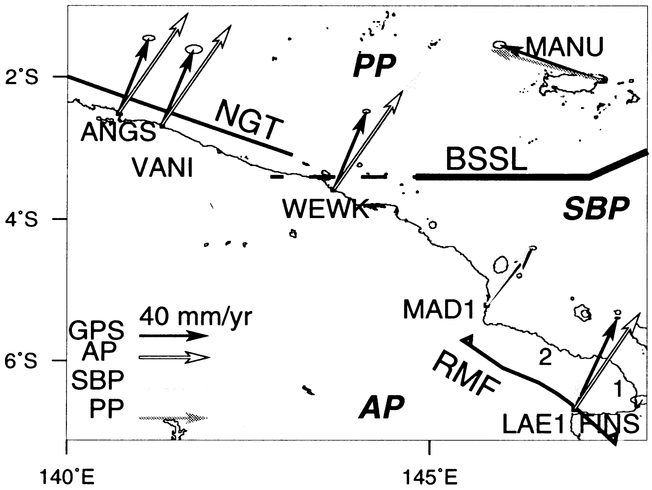

Fig. 3. Tectonic features and GPS velocities in the northern New Guinea region. The velocity of FINS is <5 mm/yr because it is located ~25 km from the pole of rotation of the plate. The vector can barely be seen in the figure. PP: Pacific Plate; AP: Australian Plate; SBP: South Bismarck Plate; RMF: Ramu-Markham Fault; NGT: New Guinea Trench.

The estimated motion of Manus Island (MANU) is not significantly different to the predicted motion of the Pacific Plate at this location (Tregoning *et al.*, 1998) and we conclude that the oceanic lithosphere to the north of the coastline is moving with the Pacific Plate. While Weissel and Anderson (1978) postulated the existence of the Caroline Plate to the north of Papua New Guinea, the available geodetic and geological data is unable to unambiguously detect relative motion between it and the Pacific Plate. Whether this plate is the Caroline or Pacific has little bearing on the results herein, so we refer to it as the Pacific Plate.

GPS data observed in several campaigns at Vanimo (VANI) and Wewak (WEWK), along with data from a site in the WING Network at Jayapura (ANGS) (Kato *et al.*, 1998) provide the only estimates of motion along the northern coastline. The motions of these three sites are consistent, with each site velocity being ~30% slower than the Australian Plate prediction and with ~10° anti-clockwise rotation in azimuth.

The variations of these site velocities from the rigid Australian Plate motion suggest that the northern coastline to the west of Madang is either moving as a separate block or that the boundary with the Pacific Plate is locked and the region is undergoing inter-seismic strain. We currently have no velocity estimates to the south of the coastal sites; a transect of velocities southward into the Highlands would indicate which of the above scenarios are correct and would allow us to model the tectonic motion of this region. This research is ongoing, with future plans to densify the geodetic network southward into the Highlands and to reobserve sites which have been occupied only once (see Fig. 2).

3. Eastern South Bismarck/Pacific Plate Boundary

In eastern Papua New Guinea the South Bismarck and Pacific Plates share a common boundary that includes spreading segments and NW-SE trending transform faults (Taylor, 1979). The boundary runs from the Bismarck Sea Seismic Lineation (BSSL) in the South Bismarck Sea southeast through the Gazelle Peninsula and southern New Ireland regions (Figs. 4 and 5). The most prominent tectonic feature through southern New Ireland is the Weitin Fault, a large steep-sided valley running NW-SE from the west coast through to the southeastern coast. It has been suggested (e.g. Taylor, 1979; Mori, 1989) that the Weitin Fault is a major strike-slip fault which is the extension of the BSSL. Hohnen (1978) did not find conclusive evidence of left-lateral transcurrent movement on this fault, although acknowledged that it was most likely. Assuming that all the relative motion between the South Bismarck and Pacific Plates was accommodated along the Weitin Fault, there would be ~130 mm/yr strike-slip and ~17 mm/yr convergence on the fault (Tregoning *et al.*, 1999).

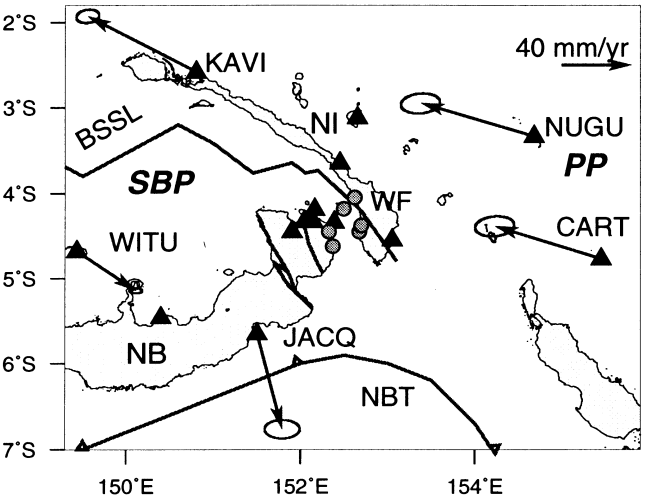

Fig. 4. Tectonic setting in the New Britain/New Ireland region. Far-field GPS velocities which have been estimated in this area are plotted. GPS sites in the deformation area are also plotted. Sites observed with Geodimeter in 1975 are indicated with circles. NI: New Ireland; NB: New Britain; BSSL: Bismarck Sea Seismic Lineation; WF: Weitin Fault; *PP*: Pacific Plate; *SBP*: South Bismarck Plate.

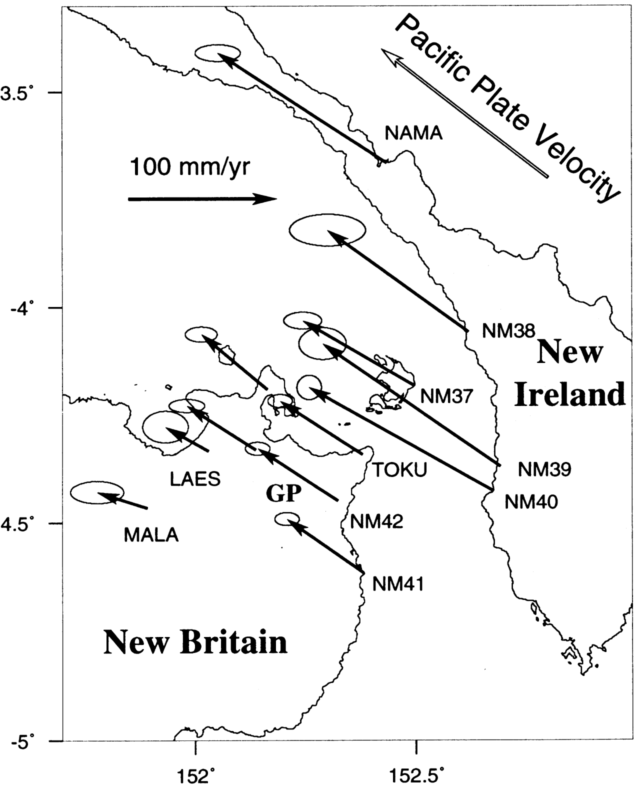

Fig. 5. Velocities (and 95% error ellipses) relative to the South Bismarck Plate. The motion of the rigid Pacific Plate is plotted in the top right corner. GP: Gazelle Peninsula.

3.1 Geodetic data

Tregoning *et al.* (1998, 1999) have estimated GPS site velocities at several sites surrounding the probable boundary of the South Bismarck and Pacific Plates in New Ireland. Witu (WITU) and Jacquinot Bay (JACQ) are moving with the rigid South Bismarck Plate (Tregoning *et al.*, 1999), while Kavieng (KAVI), Carteret (CART) and Nuguria (NUGU) are moving with the Pacific Plate (although there may be some northward deviation from rigid Pacific Plate motion at KAVI) (Tregoning *et al.*, 1998). Figure 4 shows the location of GPS sites observed on the Gazelle Peninsula and southern New Ireland.

In 1975, the Australian Division of National Mapping conducted a Model-8 Geodimeter survey of 7 sites spanning the St Georges Channel between New Britain and New Ireland. Each baseline was observed for 2–3 days over a period of 6 weeks and has an expected precision of better than 20 mm (Sloane and Steed, 1976). Six of these sites have been re-observed with GPS, although most of the observing sessions were less than 4 hours at some time between 1994 and 1998 and the GPS observations are not simultaneous at all sites. Nonetheless, sufficient data are available to estimate changes in site positions between the Geodimeter and GPS surveys (see below).

3.2 Combining terrestrial and GPS data

There are several issues to overcome when combining terrestrial and space-geodetic data. Our objective was to estimate a coherent set of site velocities across the whole deformation zone. The two types of measurements need to be brought into a common reference frame, with each type having different rank deficiencies. In our case, we removed the rank deficiencies of the GPS solutions by transforming the coordinates and velocities of a free-network onto the coordinates of selected IGS sites. This ‘global’ approach requires no *a priori* tectonic knowledge about the region of interest.

One can remove rank defects in terrestrial networks by linking velocity estimates of co-located sites and by imposing local ties between sites and removing any scale factors between the networks (Dong *et al.*, 1998). Unfortunately, we do not have repeat Geodimeter measurements; hence, do not have velocity estimates based on terrestrial data. Furthermore, we do not yet have enough GPS data on any of the Geodimeter sites to estimate a reliable GPS velocity. We don’t require local ties since the same survey marks were used for Geodimeter and GPS observations.

We removed the rank deficiencies of the terrestrial network by linking the velocity estimates of two sites located on the east coast of New Britain (NM42 and NM41) with the velocity estimate of the closest site with a well-determined GPS velocity (TOKU—about 20 km away) (see Fig. 5). Since we cannot assume that any of the baseline lengths have remained constant, we have no way of ensuring that there is no scale factor between the GPS and terrestrial networks; however, Stevens *et al.* (1998) reported no scale factor between GPS and Geodimeter data using the same Geodimeter to measure across the Markham Valley in 1975.

Since the GPS and terrestrial networks lie in a deforming zone, it may not be reasonable to assume that the velocities of NM41 and NM42 are the same as TOKU; however, at this stage, we have no further infomation available which can be used to remove the rank deficiencies of the terrestrial network. Therefore, we acknowledge that there may still be some errors in our combined velocity field caused by our definition of the reference frames.

3.3 Velocity field

The velocity field resulting from the above procedure is shown in Fig. 5 relative to the South Bismarck Plate. The sizes of the error ellipses vary considerably corresponding to the amount of geodetic data used in estimating the site velocities. The estimates based on only Geodimeter data and one short (i.e. ∼4 hour) occupation with GPS have the largest error ellipses. All velocities relative to the South Bismarck Plate are nearly parallel to the expected motion of the Pacific Plate relative to the South Bismarck Plate and increase in magnitude from southwest to northeast.

There appears to be a velocity gradient of ∼1 mm/km across the region. This suggests that the plate boundary is locked and that the inter-seismic strain accumulation region extends a further 25 km to the southwest of Malasait (MALA, see Fig. 5). The along-strike component of the relative velocity of Namatanai (NAMA) is 98% of the rigid Pacific Plate velocity relative to the South Bismarck Plate.

The magnitudes of the relative velocity vectors at two sites in southern New Ireland (NM39 and NM40—see Fig. 5) appear to be higher than the nearby vectors by a factor of 2. We suspect that these estimates may contain some co- and/or post-seismic displacement caused by a $M_s = 7.2$ earthquake which occurred in the vicinity of the Weitin Fault in 1985 (Mori, 1989). One would expect that an interplate earthquake would weaken the coupling of the plates at the boundary, thereby decreasing the magnitude of the northwest relative motion of sites located near the boundary. In fact, the opposite appears to have occurred. At this stage we do not have sufficient geodetic data to understand this anomaly nor to separate the interseismic motion from any deformation caused by seismic events. Work is continuing to resolve the characteristics of the tectonic features in this region with the geodetic velocity field.

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