PNG ON THE MOVE - GPS MONITORING OF PLATE TECTONICS AND EARTHQUAKES

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Abstract
PNG is one of the most tectonically active countries in the world. Major earthquakes and volcanic eruptions resulting from this tectonic activity pose significant threats to PNG's population and fragile infrastructure. Modern surveying techniques such as GPS can measure movement of tectonic plates to within a centimetre anywhere in PNG. These measurements have provided a much better understanding of PNG's tectonic setting and also have the potential to significantly improve the accuracy of PNG's geodetic datum. This paper highlights contributions made by The Australian National University, the National Mapping Bureau, RVO and UniTech's Department of Surveying and Land Studies showing some startling results from these surveys.

Introduction

Papua New Guinea lies in one of the most tectonically and volcanically active regions in the world, a region where the Pacific and Australian Plates collide. Within Papua New Guinea there are also several smaller crustal fragments or “microplates” and many regions that are undergoing active crustal deformation. Seismic activity is often associated with this deformation, usually where strain accumulates over many years on locked faults in plate boundary zones. Since 1994 there have been nearly 1500 earthquakes in PNG greater than M_w 5, including 20 above M_w 7 (NEIC database). On the 17th July 1998 an undersea earthquake of M_w 7.1 along the New Guinea Trench near Aitape causing a devastating tsunami killing over 2,000 people in coastal villages nearby. On the 16th November 2000, severe earthquakes of M_w 7.9 and 8.0 were associated with a major rupturing of the Weitin Fault in Southern New Ireland over hundreds of kilometres. The earthquakes resulted in massive horizontal land movements of up to several metres (Figure 1), landslides and some minor tsunami activity. Two years later, on the 8th September 2002, a M_w 7.8 earthquake struck off the Wewak coast, causing significant surface ruptures and minor tsunamis in the region. Subduction of oceanic plates and continental rifting result in the significant volcanic activity in PNG, especially in New Britain, Bougainville, along the Sepik Coast and in Oro Province. The twin volcanic eruptions of Tavurvur and Vulcan near Rabaul on 19th September 1994 destroyed much of the city and many other communities in PNG face the constant threat of renewed or nascent volcanic activity (e.g. Ulawun, Pago, Manam, Karkar, Bagana and Lamington). This paper highlights the role played by surveyors and surveying organisations in monitoring tectonic motion in PNG and associated geological hazards.

Fig 1. 5 m earthquake rupture offset of a track crossing the Weitin Fault, November 2000

The role of surveyors in geological hazard monitoring

The role of surveyors in monitoring of geological hazards in PNG is very much understated but of critical importance, especially in high risk and densely populated areas such as the Gazelle Peninsula, Lae and Wewak. While earthquake prediction using geodetic measurements is still inexact, measurement of inter-seismic strain, co-seismic displacement and post-seismic relaxation allows for better forecasting and hazard assessment in these areas. The USA (Southern California), Japan and New Zealand are some of the seismically active countries and regions where extensive geodetic monitoring networks have been established for this purpose. Slope and uplift monitoring of active or potentially active volcanoes allows volcano observers to better predict when a full-scale eruption is imminent.

Many low-lying coastal regions and islands in PNG are not only threatened by potential tsunamis, but are also potentially subject to an increase in sea level as a result of climate change. The risk is magnified if tectonic subsidence is also occurring. The South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) (http://www.pacificsealevel.org/index.htm) has been operational since 2002. Continuous GPS measurements are made in close proximity to SEAFRAME tide gauges operated by the National Tidal Facility (NTF). Comparison of the vertical displacement of the tide-gauge with the actual tide data allows estimation of absolute sea-level change in the region without systematic bias resulting from tectonic uplift or subsidence at the monitoring site from.

Volcano slope monitoring by geodetic methods can be achieved by accurate measurements from a nearby stable network; however inter-seismic strain which often occurs over broad areas can really only be effectively monitored from a geophysically stable network such as the International Terrestrial Reference Frame (ITRF). A network of four Continuous GPS (CGPS) stations has been established around the Rabaul Caldera by the Rabaul Volcanological Observatory (RVO) to monitor volcanically related deformation, particularly uplift resulting from magma movement close to the surface.

What's happening to PNG's plates?

PNG is located in one of the most complex tectonic regions in the world. Over periods of millions of years, ancient islands, land masses and continents moving at up to several centimetres a year have collided, to raise great mountain ranges, or rifted apart, opening up great seas and wide valleys. Whole ocean floors have subducted beneath island arcs creating very deep ocean trenches, spawning destructive volcanoes. All of these forces have created the dramatic topography that characterises Papua New Guinea and contnues to this day. 7 centimetres a year may not seem to be very significant, but when viewed through the telescopic lens of time it does add up. The first human settlers in New Guinea some 50,000 years ago would have seen the Markham Valley 2 km wider than it is now. During this same period of time the Australian Plate has rammed 1 km further into New Guinea like a continental scale bulldozer, raising the Highland Ranges and ridges on the Papuan Fold and Thrust Belt by as much as 100 metres. PNG is caught in a massive continental scale jaw-like vice where the Australian and Pacific plates are closing together on the smaller microplates which form a large part of PNG (Figure 2).

What follows is a synopsis of recent research conducted by ANU and UCSC (Tregoning *et al.*, 1998, 1999, 2000; Stanaway, 2004; Wallace *et al.*, 2004)

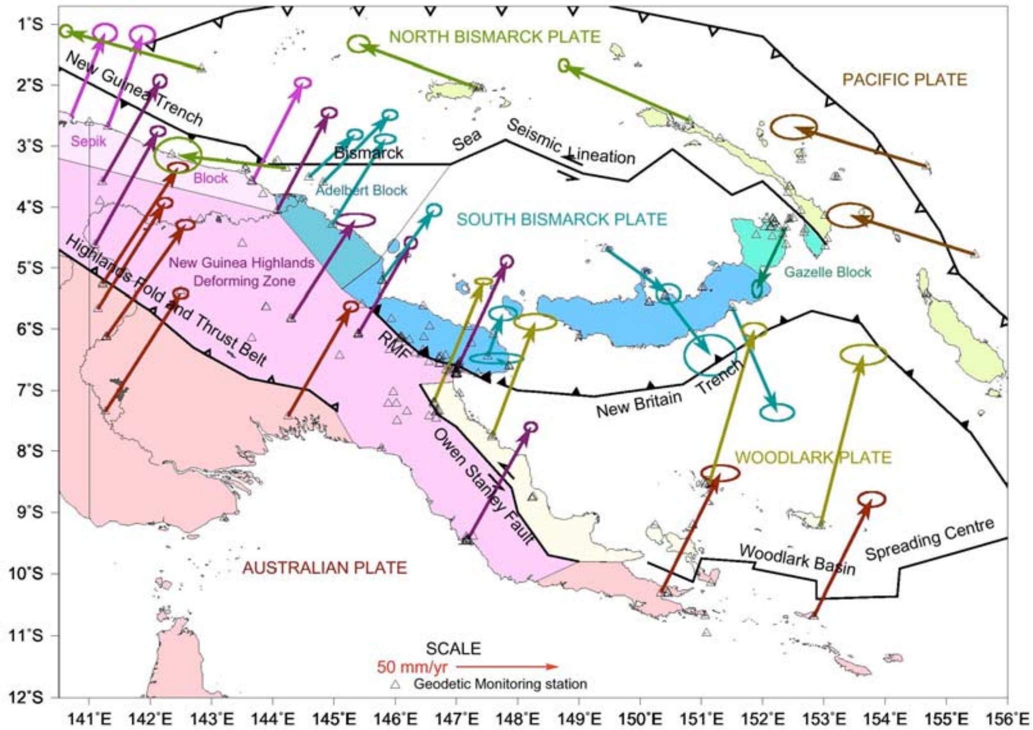

Fig 2. The Papua New Guinea tectonic setting

All types of plate boundary are represented in PNG, with relative motions between distinct microplates some of the most rapid anywhere on the Earth.

The Australian plate is moving in a north-northeasterly direction at about 60 mm/yr, colliding with the New Guinea Highlands (NGH) along the Highlands Fold and Thrust Belt where the main PNG Oilfields are located. The North Bismarck Plate (Manus Island and most of New Ireland) is being subducted obliquely beneath the Sepik Block along the New Guinea Trench (the source of the Aitape tsunami). Further to the east, the NGH are colliding with the Adelbert block and South Bismarck Plate along the Ramu-Markham Fault Zone (RMFZ). Here, the western part of the South Bismarck Plate (SBIS) is currently overthrusting the NGH. The collision is propagating towards the east-southeast along the RMFZ as the SBIS rotates clockwise and generates large earthquakes in the Lae area. This rotation is also opening up the Manus Basin with spreading and strike-slip motion along the Bismarck Sea Sesimic Lineation (BSSL) to the north, and northwesterly subduction of the Solomon Sea Plate along the New Britain Trench (NBT) to the south. This very rapid subduction gives rise to the string of destructive volcanoes in New Britain. Southward subduction of the Solomon Sea Plate beneath the Woodlark Plate along the Trobriand trough is believed to be inactive, or very slow, and the two plates can be considered to be a single entity. The Woodlark Plate is rifting anti-clockwise away from the Australian Plate along the WBSC with continental rifting occurring at the eastern end of the Papuan Peninsula. To the northeast, the Woodlark Plate is subducting northeasterly beneath the Pacific plate along the NBT and San Cristobal Trench south of the Solomon Island arc. To the west, the Woodlark Plate is moving northwest relative to the Australian Plate through strike-slip motion along the Owen Stanley Fault Zone (OFSZ), becoming transpressional closer to the RMFZ. The Pacific Plate is moving rapidly (at between 80 and 90 mm/yr) west-northwestwards across the northern margin of PNG, with a major left-lateral strike slip boundary with the SBIS along the Weitin Fault, and slow oblique subduction beneath the North Bismarck Plate along the Kilinailau and Manus Trenches. The Weitin Fault is probably the fastest strike-slip boundary in the world and is associated with frequent and very significant earthquakes.

What causes earthquakes and what affect do they have on the ground?

As crustal rocks deform elastically on geological timescales, strain accumulates across locked faults during the inter-seismic period. Once the strain exceeds the elastic limit, a rupture occurs resulting in an earthquake and associated co-seismic deformation. Crustal rocks may deform aseismically or anelastically if the block material is relatively unconsolidated (alluvium etc.) or the frictional coefficient is very small along the fault.

An anelastic post-seismic relaxation phase is often evident where movement across the fault stabilises after an episode of major co-seismic displacement. The time series for Rabaul in PNG before and after the M_w 8.0 New Ireland earthquake on 16th November 2000 clearly shows the three stages of the earthquake cycle, (Figure 3). The plot shows linear inter-seismic motion up until the time of rupture, an abrupt co-seismic offset followed by an exponential post-seismic relaxation phase as the velocity stabilises to inter-seismic levels.

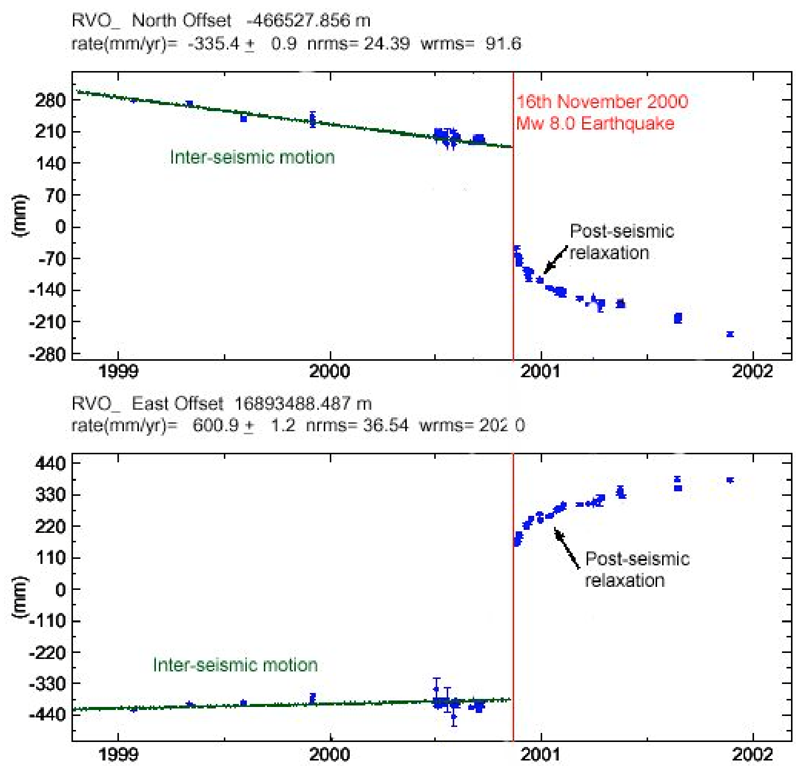

Figure 3. Time series for RVO_ (Rabaul Volcanological Observatory, PNG) site showing co-seismic offset (~0.21m N and ~0.55m E) and post-seismic relaxation as a result of the 16th November 2000 Mw 8.0 earthquake near New Ireland. The earthquake epicentre was *c.* 33 km from the site.

Who is measuring tectonic deformation in PNG?

PNG has been the subject of a number of crustal deformation surveys. In the 1970s, two trilateration networks were established by the Australian National Mapping Division to measure tectonic movement in two areas in PNG suspected to be undergoing rapid deformation (Sloane & Steed, 1976). The first network was established across the Markham Valley near Kaiapit, west of Lae and the second across the St. Georges Channel between the Gazelle Peninsula and southern New Ireland. Massive pillars were constructed for these monitoring surveys but results were inconclusive, due largely to the short observation span of the surveys.

In 1981, a network of stations around PNG was surveyed using the Transit Doppler satellite navigation system (Angus-Leppan *et al.*, 1983), and remeasured by GPS in 1990 by a team of geodesists from the University of New South Wales (UNSW) (Stolz, 1989). The first geodetic measurements of the rapid convergence across the New Britain Trench were made with this study. The network was extended and resurveyed in 1991 and 1992 by UNSW funded by ANU (McClusky *et al.*, 1994; Mobbs, 1997).

From 1993 onwards, research groups from the University of California, Santa Cruz (UCSC) and the Research School of Earth Sciences (RSES), Australian National University have undertaken extensive GPS monitoring campaigns in PNG in collaboration with local institutions. These surveys were designed to observe and densify the geodetic monitoring network, in order to define the large-scale tectonic framework and to investigate deformation in plate boundary zones in PNG. Local institutions involved in these campaigns have included the PNG National Mapping Bureau (NMB), Department of Surveying and Land Studies, Papua New Guinea University of Technology (UniTech), RVO and the PNG Geological Survey.

Since 1996, eight permanent geodetic tracking stations have been established by different geodetic agencies in PNG (Table 1). The four GPS stations in the Rabaul Network provide real time monitoring of the main active caldera. The Manus SPSLCMP site was installed by the National Mapping Division of Geoscience Australia in 2002 to monitor vertical motion of the NTF SEAFRAME tide gauge site on Manus. The SPSLCMP is an AusAID project.

A substantial archive has been formed of dual-frequency GPS observations since 1990 from an extensive network of sites around PNG. This archive is ideal for the geodetic estimation of the PNG velocity field and the computation of a new geodetic datum. The data quality and quantity vary significantly but approximately 110 sites in PNG have sufficient quality data to define their ITRF position with an accuracy of < 20mm.

SITE	Network	Method	Installed	Location	Responsible Agencies
LAE1	IGS	GPS	1996	Sandover Building, Papua New Guinea University of Technology, Lae	RSES, ANU UNITECH, PNG
MORE	WING W. Pacific Integrated Network	GPS	1993	NMB Tower at Waigani, Port Moresby	ERI (Earthquake Research Institute), University of Tokyo NMB
MORB	DORIS	DORIS	2002	NMB, Waigani, Port Moresby	Institut Geographique National, France / NMB
RVO_	Rabaul Caldera Network	GPS	1998	Rabaul Volcanological Observatory	PNG Department of Minerals & Energy
SPT_	Rabaul Caldera Network	GPS	1998	Sulphur Point, Rabaul	PNG Department of Minerals & Energy
SDA_	Rabaul Caldera Network	GPS	1998	Matupit SDA Church, Rabaul	PNG Department of Minerals & Energy
VIS_	Rabaul Caldera Network	GPS	1998	Vulcan Island, Rabaul	PNG Department of Minerals & Energy
PNGM	SPSLCMP S. Pacific Sea Level & Climate Monitoring Project	GPS	2002	Lombrum Naval Base, Manus	AusAID NMD, GA

Table 1 Continuous GPS/DORIS sites in PNG in 2008

GPS has been used extensively in PNG for geodynamics studies and regional geodetic datum development. The aim of the earlier GPS campaigns was to obtain the first geodetic measurements across the larger plate boundaries in PNG, between the South Bismarck, Woodlark, Pacific and Australian Plates and also to realise the PNG94 Datum. Subsequent campaigns have increasingly focused on identifying smaller microplates, rigid blocks and measuring strain rates in deforming zones near plate boundaries. The campaigns have necessarily been collaborative in nature, due to the logistical difficulties operating in PNG and the mutual interests of many of the participating institutions. Many of the GPS data collected by campaigns conducted by NMB for mapping and land development purposes have also been useful for geodynamics studies. The GPS base station at the Department of Surveying and Land Studies at UNITECH, Lae has been part of the IGS tracking network since 2002, and is an important contribution by PNG to global geodynamic and geodetic studies. In addition to these major survey campaigns, a significant amount of GPS data have also been obtained from private survey firms, exploration and mining companies operating in PNG. For example, Oil Search has recently funded an extensive resurvey of their geodetic network to resolve issues with their datum and spatial infrastructure.

These studies, together with other seismological and geological studies, have collectively formed the basis for the current understanding of plate kinematics and crustal deformation in PNG (Tregoning *et al*., 1998; Wallace *et al.*, 2004; Stanaway, 2004). Continued re-observation and densification of the monitoring network is now drawing to a close due to lack of funding, however the results of these studies have improved the resolution of the velocity field and strain estimates in PNG.

How is tectonic displacement measured ?

1-5 days of continuous GPS dual-frequency carrier-phase observations are typically collected at a widespread network of monitoring marks (usually PSMs or Pillars) spanning known tectonic plate boundaries. One day of observations typically achieves an accuracy of 10 mm, while five days of observations improves the accuracy to 5 mm. Software packages such as GAMIT/GLOBK, Bernese, Gipsy and online processing services such as AUSPOS derive mm-cm accurate positions using precise orbit models determined from the global IGS (International GPS Service) tracking network. The same site is observed over several epochs and a time-series is plotted, showing any station movement between epochs (and therefore site velocities) within ITRF. Vertical movement of sites is inherently more difficult to measure due to much lower magnitudes in this direction. The precision of the vertical component of a position solution is an order of 2-3 times weaker than the horizontal component due to poorer satellite geometry, phase centre variations in GPS antennas and temporal variation due to unmodelled tidal loading and groundwater changes. Vertical motion is difficult to model with any level of confidence for epoch intervals of less than 10 years.

Implications for Geodetic Datums in PNG (PNG94)

Major earthquakes generally occur every few decades in PNG. The dislocation resulting from these events introduces major discontinuities into the geodetic datum where relative movement of several metres can occur within the seismic area.

PNG94 was realised as a static datum. With increasingly widespread adoption of GPS by surveyors, where baselines can be measured over long distances to mm accuracy, it is now apparent that a static PNG94 datum cannot be used as a basis to conduct GPS surveys which span plate boundaries. Furthermore, use of precise point positioning systems such as AUSPOS and OmniSTAR-HP will produce coordinates that will change by several centimetres a year for any given station in PNG. This has important implications for surveyors and other spatial professionals who require coordinates of features to remain static in an otherwise dynamic environment.

References

Allman, J., *Geodetic Datum & Geodetic Adjustment for Papua New Guinea (PNG94)*, ACLMP report, 1996.

Angus-Leppan, P., Allman J., and Sloane, B., Crustal Movement from Satellite Observations in the Australian Region, *Tectonophysics*, 97, 87-93, 1983.

Blick, G., Crook, C., Grant, D., and Beavan, J., Implementation of a Semi-Dynamic Datum for New Zealand, *IAG Proceedings*, 2003.

McClusky, S., Mobbs, K., Stolz, A., Barsby, D., Loratung, W., Lambeck, K., and Morgan, P., The Papua New Guinea satellite crustal motion surveys, *The Australian Surveyor*, 39, 194-214, 1994.

Mobbs, K., *Tectonic interpretation of the Papua New Guinea region from repeat satellite measurements*, Unisurv Report S-48, University if New South Wales, 1997.

Sloane, B., and Steed, J., *Crustal Movement survey, Markham Valley – Papua New Guinea, Technical Report 23,* Department of Natural Resources, Division of National Mapping, Australia, 1976a.

Sloane, B., and Steed, J., *Crustal Movement survey, St. Georges Channel – Papua New Guinea, Technical Report 24,* Department of Natural Resources, Division of National Mapping, Australia, 1976b.

Stanaway, R., *Implementation of a Dynamic Geodetic Datum in Papua New Guinea: A case study*, MPhil thesis, The Australian National University, 2004

Stolz, A., *Monitoring crustal motion in Papua New Guinea using the Global Positioning System*, Association of Surveyors, Papua New Guinea, 24th Survey Congress, Port Moresby, 26th-28th June 1989.

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

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

Tregoning, P., McQueen, H., Lambeck, K., Jackson, R., Little. R, Saunders, S. and Rosa, R., Present-day crustal motion in Papua New Guinea, *Earth Planets Space*, 52, 727-730, 2000.

Wallace, L., Stevens, C., Silver, E., McCaffrey, R., Stanaway, R., Loratung, W., Hasiata, S., Curley, R., Rosa, R., and Taugaloidi, J., GPS constraints on active tectonics and arc-continent collision in Papua New Guinea: implications for mechanics of microplate rotations in a plate boundary zone, *Journal of Geophysical Research*, 2004.