Lae, a City caught between two plates - 15 years of Deformation Measurements with GPS

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Abstract

Lae is located in the Ramu-Markham Fault Zone where the New Guinea Highlands and South Bismarck tectonic plates are converging at up to 50 mm/yr. The city is caught in a giant geological vice and the seismic hazard is significant. More than 15 years of GPS measurements collected by staff and students of The Department of Surveying and Land Studies at Unitech, as well as researchers from the USA and Australia, have been analysed. The results show how rapidly Lae city and its survey network is deforming. The paper explains how these measurements tie in with the regional geological setting and also highlights some of the potential seismic hazards that the city faces.

Introduction

Lae, the second largest city in Papua New Guinea and its major industrial centre, is located on the boundary between two converging tectonic plates, the New Guinea Highlands Deforming Zone (NGHDZ) north of the Australian Plate and the South Bismarck Plate (SBP). The Ramu-Markham Fault Zone (RMFZ), which follows the northern edge of the Markham Valley, is the active plate boundary between the SBP and Terranes within the NGHDZ. The RMFZ has generated large thrust earthquakes (e.g. the 6th April 1999 Mw 6.4, 16 km North of Lae, near Hobu, and the 22nd November 2007 Mw 6.8, 110 km North of Lae). Geological evidence suggests that major earthquakes in pre-historic times have occured in the Lae area (Crook, 1989), and that there is the potential for another large earthquake to occur anytime within the next 100 years (Crook, 1989; Ripper and Anton, 1995).

Since the early 1990s, researchers from the University of California, Santa Cruz (UCSC), and the Australian National University's Research School of Earth Sciences (RSES, ANU) have worked in close collaboration with the Department of Surveying and Land Studies at the PNG University of Technology (DSLS, Unitech) and the Geodetic Section of the PNG National Mapping Bureau (NMB) to study tectonics in the Lae area using GPS.

A geodetic network of Permanent Survey Marks (PSMs) and geodetic monitoring stations has been established around the Lae area and a continuously operating GPS reference station (CORS) provided by UCSC has been set up at Unitech (LAE1) to provide a time-series of its position within the International Terrestrial Reference Frame (ITRF). Repeat measurements of the network have enabled deformation within the Lae area to measured with centimetre accuracy over the last 15 years.

This paper describes the tectonic setting of the Lae region and discusses additional insights from GPS measurements of the geodetic network. Seismic hazards are also described.

Tectonic Setting of the Lae region

Over the last four million years the Finisterre Ranges and Huon Pensinsula, which constitute the Finisterre arc terrane, have been colliding with mainland New Guinea along the Ramu-Markham Fault (Jaques and Robinson, 1977; Abbott *et al*., 1994a). New Britain, the Finisterre Terrane and the Southern Bismarck sea together constitute a stable tectonic microplate, the South Bismarck Plate (SBP) (Tregoning *et al.*, 1998, 1999; Weiler and Coe, 2000). As the Australian Plate has moved northwards over the last 60 million years, it has collided with sequences of volcanic island arcs and terranes in the ancient Pacific Ocean. These island arcs and terranes have accreted to form the island of New Guinea as we see it today. The convergence process is ongoing. The New Guinea Highlands form the northern margin of the Australian Plate and are thought to be part of a smaller tectonic plate, the New Guinea Highlands block (NGH). Several million years into the future, the island of New Britain will have also been emplaced onto the New Guinea mainland as the Australian continental bulldozer continues driving northward. Only four million years ago the Huon Peninsula and Finisterre Range unit was an island to the North of New Guinea, like New Britain is today.

The collision between the Finisterre terrane and the northern margin of the Australian Plate started in the North-West (near Usino) and has propagated South-East over the last few million years (Cooper and Taylor, 1987; Silver *et al.*, 1991). The collision appears to be driving clockwise rotation of the SBP due to the resistance of the buoyant continental lithosphere of the New Guinea Highlands to underthrusting (Wallace *et al.*, 2004). The collision is closing the Markham Valley in a manner similar to a closing jaw (Figure 1).

Uplift rates are estimated to be 0.8 – 2.1 mm/yr along the southern flanks of the Finisterre Range as indicated by uplifted fluvial terraces; and increasing to *c.* 7 mm/yr in the Lae area (Abbott *et al*., 1997; Crook, 1989). Uplift rates increase towards the southeast of the RMFZ commensurate with the rate of horizontal convergence.

The Ramu-Markham Fault (RMF) is a shallow (15°) north-northeasterly dipping mid-crustal detachment ramp connecting to a steeply dipping ramp at *c.* 20km depth beneath the Markham River (Kulig *et al.*, 1993; Abbott *et al.*, 1994b; Stevens *et al.*, 1998). The collision between the highlands and the Finisterre terrane along the Markham Valley has resulted in some convergence being accommodated along additional “out-of-sequence” thrust faults (OOSTs) along the southern face of the Finisterre ranges to the north of the RMF (Abbott *et al.*, 1994b). An OOST is conceptually like the custard in a vanilla slice.

Biting one end (the plate collision) causes the custard (OOST) to rapidly escape out the other end.

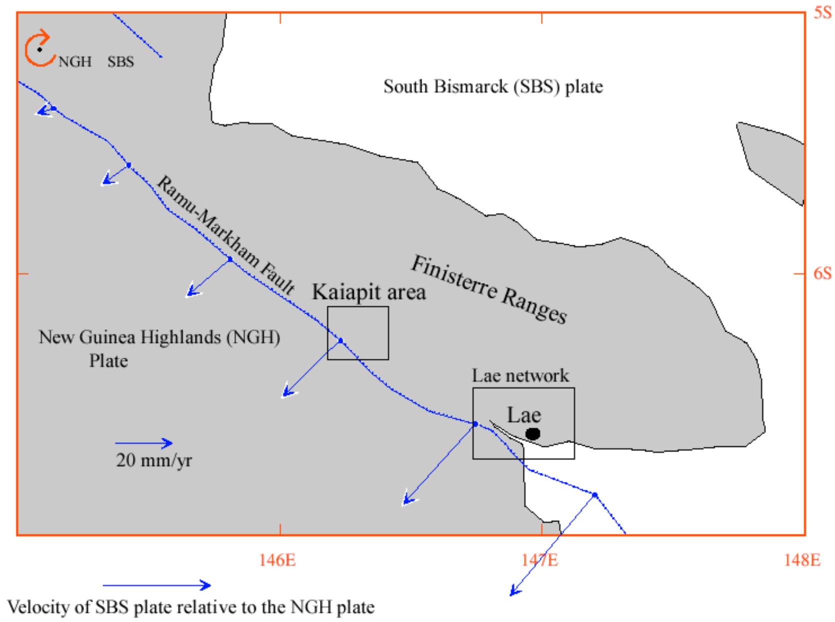


Figure 1. Predicted rigid plate motion between the South Bismarck Plate and the New Guinea Highlands along the Ramu-Markham Fault (from Wallace, 2002)

The Lae urban area appears to be located on the South Bismarck Plate, the upper plate in the collisional geometry and the RMF projects to the south of Lae (Kulig *et al.*,1993; Wallace *et al.*, 2004). This hypothesis is supported by strain dislocation modelling using realistic local fault geometries that fit GPS velocities in Lae, assuming that Lae is on the South Bismarck Plate above an interseismically locked Ramu Markham Fault (Wallace, *et al.*, 2004). Anticlines in the vicinity of Lae, such as the Atzera Range and hills near Situm, appear to indicate that the RMF changes dip close to the surface from a steep ramp to a shallow fault, breaching the surface south of Lae. If the RMF is a steep ramp between 20km and 1 km depth and a shallow detachment in the uppermost 1 km, site velocities in the Lae region and the rapid uplift between Situm and Hobu can be reproduced provided that the RMF is locked between earthquakes.

The Seismic Hazard in Lae

Previous studies have highlighted the seismic hazards posed to Lae city due to its location in the active plate boundary zone (Ripper and Anton, 1995; Buleka *et al.*,1999). A seismic zone has been identified (The Lae Seismic Zone) (Kulig *et al.*, 1993), located between the Atzera Range and Situm, which has the potential to generate shallow Mw ~7.0 earthquakes. It is believed that such earthquakes in the Lae region have a return period of 100-110 years and are likely to result in ~1 metre vertical coseismic displacements, as evidenced by mapping and dating of Quaternary sediment profiles in the Lae area (Crook, 1989). Such an event would cause significant damage, not only as a direct result of ground motion from the earthquake, but also from landslides on steep land around the city (e.g. the Atzera Range). A submarine landslide off the Lae coast triggered by seismic energy could also generate a tsunami that would endanger coastal areas and port facilities. This risk is not understated, as there is a steep coastal gradient of unconsolidated alluvium along the Lae coast due to the close proximity of the deep New Britain trench.

The seismic hazard in Lae is further amplified by the very thick alluvial deposits that the city and many of its suburbs are built on. Sedimentary basins amplify seismic energy and the damage from even smaller magnitude earthquakes can be significant.

How Space Geodetic Methods can be used to measure deformation

Advances in space geodetic techniques in the last twenty years have enabled millimetre accurate measurements of Earth deformation to be measured on a global scale. Conventionally, the US Global Positioning System (GPS) has been used for most regional scale geodetic studies, but other related systems such as the Russian GLONASS, the forthcoming European Space Agency's GALILEO, Chinese, Japanese and Indian systems have been integrated to form a Global Navigation and Surveying System (GNSS). Many receivers now observe data from different systems and are termed GNSS receivers.

By measuring positions at different times (epochs) the movement of a geodetic station can be measured and the motion defined as a site velocity (rate of change of position) within a reference frame or datum. Inversion of these site velocities enables the motion of rigid tectonic plates, localised deformation and strain rates to be modelled.

In tectonically active areas such as PNG, GNSS techniques are vital for monitoring of geological hazards such as locked faults, volcanic activity, landslides and relative sea level changes.

The Lae Geodetic Network

In 1993, researchers from the University of California, Santa Cruz (UCSC) led by Colleen Stevens, constructed a network of geodetic stations in the region as the basis for a longer term study of regional tectonics (Figure 2). GPS observations of this network were collected at regular intervals in collaboration with staff and students from DSLS, Unitech and surveyors from NMB. Around this time, the NMB also collected GPS observations at PSM 9799 (BM 38) at the Unitech Sports Field as part of a regional GPS campaign that resulted in the realisation of the PNG94 and GDA94 datums (Morgan *et al.*,1996).

This UCSC research was continued by Laura Wallace until 2001 (Wallace, 2002). UCSC provided an Ashtech Z12 receiver and choke-ring antenna for use as a GPS base station at the DSLS Sandover Building at Unitech (Figure 3). The receiver continues to operate today and is an important reference frame station for the International GNSS Service (IGS) and is also a datum station for the International Terrestrial Reference Frame (ITRF) (Altamimi *et al.*, 2007).

Researchers from the Research School of Earth Sciences at the Australian National University (RSES, ANU) led by Paul Tregoning became involved with the regional study in 1996 and RSES donated two Ashtech Z12 GPS receivers and chokering antennas to the DSLS for use in GPS campaigns. Richard Stanaway, a Masters student at ANU continued studies of deformation in the Lae area until 2003 and during this time established several more stations to augment the network in 2002 (Figure 2), particularly north of Lae city where baseline changes were more evident.

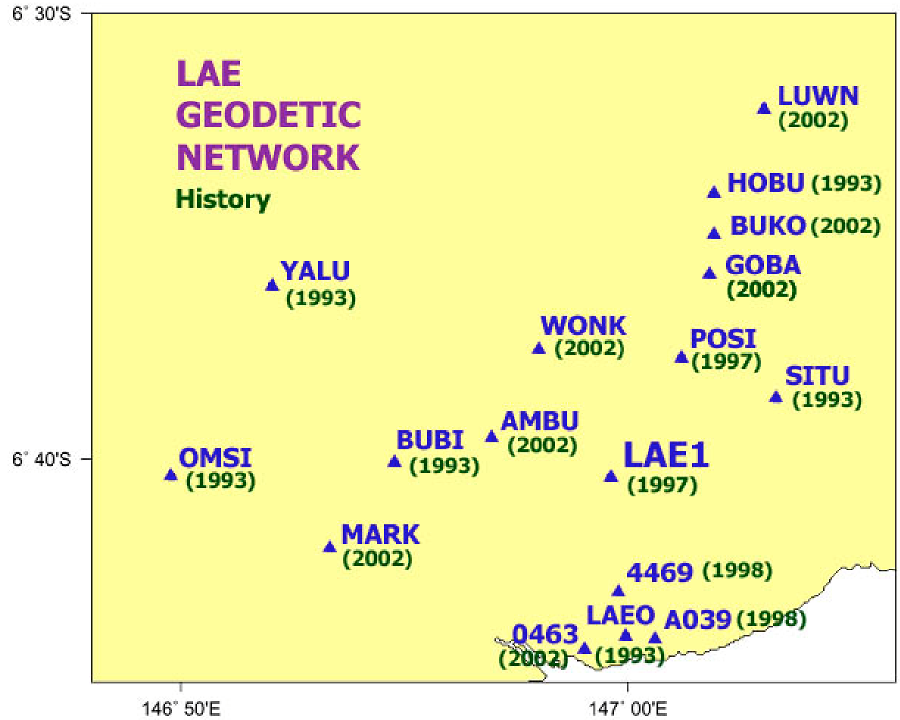


Figure 2. Lae geodetic network, with dates of first GPS observations

Figure 3. LAE1 IGS Reference Station on the roof of the Sandover Building, DSLS, UniTech

In 1998, the NMB undertook an extensive Digital Cadastral Database (DCDB) survey of the Lae area to connect the Lae cadastre to PNG94. Base stations used for the 1998 survey were reobserved in 2002 and 2003 by Richard Stanaway and final year surveying students from Unitech. In July 2009, Zebedee Sombo led a group of staff and students from DSLS, reobserving important stations to update the monitoring of the network.

Analysis

All available GPS data were reanalysed including the dataset collected by Unitech in July 2009. Available LAE1 data were uploaded to the Natural Resources Canada (NRCan) online post-processing service which uses precise IGS Final GPS orbits to compute positions for the submitted data in compressed RINEX format. The NRCan solutions for LAE1 were compared with the ITRF2005 GPS SSC (Set of Station Coordinates) solution (position and site velocity) (Altamimi *et al.*, 2007; http://itrf.ensg.ign.fr/ITRF_solutions/2005/doc/ITRF2005_GPS.SSC.txt) and the results showed agreement at 10-20mm for Northing and 12-30mm in Eastings over most epochs, with a minor corrections between different realisations of ITRF. Coordinates of LAE1 at Epoch 1994.0 (concurrent with PNG94) were computed by linear regression of the NRCan solution (Table 1). The ITRF2005 Epoch 1994.0 solution is very close to the computed PNG94 solution which is:

LAE1 PNGMG94 Zone 55 E 499246.669 N 9262320.808 Ellipsoid Ht. 130.397

Selected GPS observations within the Lae network were processed using Trimble Geomatics Office and Sokkia Spectrum software packages between 1997 and 2009 to compute topocentric components of baseline changes (ΔEast, ΔNorth and ΔUp per year) with respect to LAE1 during this period of time (Table 1).

		PNGMG94 (PNG94) Zone 55 (updated)				Positional Uncertainty (1σ)		
Site ID	**Location**	**No**	**E**	**N**	**Ell. Ht.**	**E**	**N**	**ht**
0463	Lae Wharf	PSM 20463	498296.713	9255179.742	76.120	0.014	0.007	0.024
9799	Unitech	PSM 9799	499765.887	9262578.623	130.332	0.004	0.004	0.010
BUBI	Bubia	ST 31021	490374.510	9262915.834	106.932	0.008	0.006	0.015
GOBA	Gobari	n/a	503379.197	9270724.151	370.403	0.014	0.009	0.018
HOBU	Hobu	ST 31028	503520.544	9274039.099	528.021	0.008	0.004	0.018
LAE1	Unitech	PSM 31107	499246.770	9262320.802	140.340	0.006	0.003	0.012
LAEO	Old Airport	ST 31022	499918.240	9255768.942	84.372	0.014	0.007	0.024
OMSI	Omsis	ST 31025	481219.098	9262352.515	97.525	0.014	0.004	0.017
POSI	Posie	n/a	502219.091	9267253.886	242.971	0.017	0.009	0.019
SITU	Situm	ST 31029	506134.357	9265567.214	169.843	0.004	0.006	0.012
			Velocity relative to LAE1			**Uncertainty (1σ)**		
Site ID	**Location**	**No**	**E m/yr**	**N m/yr**	**U m/yr**	**E**	**N**	**ht**
0463	Lae Wharf	PSM 20463	0.001	-0.002	0.006	0.001	0.001	0.004
9799	Unitech	PSM 9799	0.000	0.000	0.000	0.001	0.001	0.003
BUBI	Bubia	ST 31021	0.003	0.000	-0.008	0.002	0.001	0.004
GOBA	Gobari	n/a	-0.004	-0.004	0.008	0.002	0.002	0.003
HOBU	Hobu	ST 31028	-0.022	-0.019	0.028	0.002	0.001	0.003
LAE1	Unitech	PSM 31107	0.000	0.000	0.000	0.000	0.000	0.000
LAEO	Old Airport	ST 31022	0.001	0.000	0.004	0.001	0.001	0.004
OMSI	Omsis	ST 31025	0.006	0.001	-0.003	0.002	0.001	0.004
POSI	Posie	n/a	-0.001	0.001	0.003	0.002	0.001	0.003
SITU	Situm	ST 31029	-0.001	0.003	0.003	0.001	0.001	0.002

Table 1. PNGMG94 coordinates and deformation rates w.r.t. LAE1 for the Lae Geodetic Network

Baseline changes between LAE1 and stations within the Lae city network were insignificant at a level of less than 15 mm over the observation period, however significant baseline changes were observed to the north of Lae within the RMFZ (Figure 4).

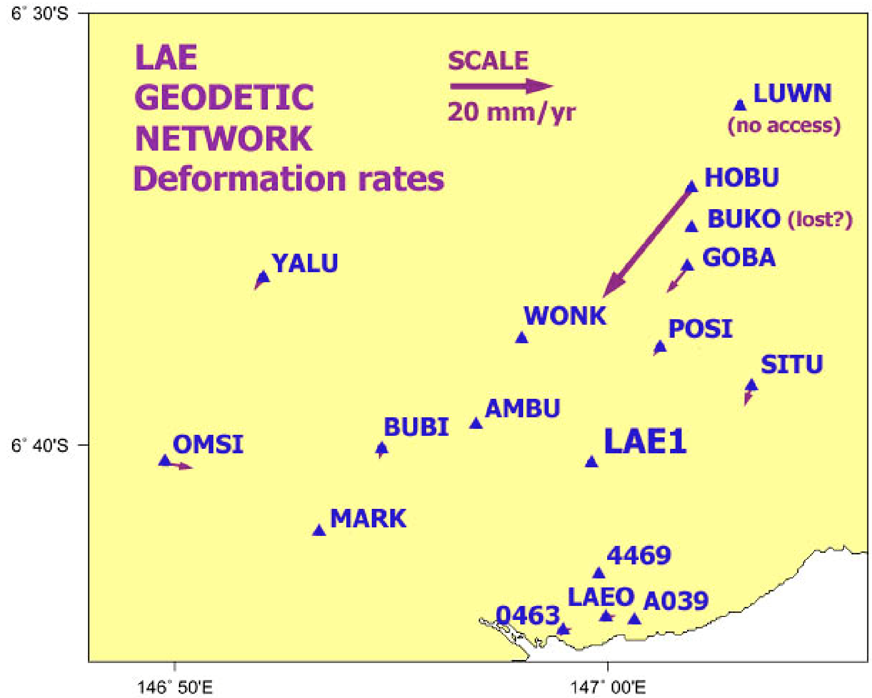


Figure 4. Deformation rates of the Lae network with respect to LAE1, estimated from 15 years of GPS observations.

The rapid shortening between HOBU and LAE1 (29 mm/yr) is evident and concurs with earlier GPS analyses (Wallace *et al.*, 2004; Stanaway, 2004). The latest analysis shows that most of the convergence is taken up between GOBA (Gobari) and HOBU, with shortening of 23 mm/yr on a line of only 3300 m between the two stations! Unfortunately further constraints on the shortening could not be made as the BUKO monument could not be found in 2009. The very low rate of shortening between OMSI (Omsis), south of the RMFZ and LAE1 suggests that LAE1 and most of the Lae network are moving with the New Guinea Highlands Block.

The 2009 analysis has also confirmed rapid uplift of sites to the north of Lae (Table 1). The long term ITRF vertical timeseries for LAE1 indicates subsidence of 2 mm/yr +/- 0.5. The stability of LAE1 (mounted on the roof of three storey concrete structure) has been verified by static GNSS baselines measured from PSM 9799 (a nearby ground station set in concrete).

Discussion

The latest GNSS results are consistent with the previous suggestion of Wallace *et al.* (2004) that the Lae region lies above a locked Ramu-Markham fault which dips at a very low angle beneath the Lae area, and steepens to a higher-angle ramp fault somewhere beneath Hobu. The data are also consistent with an alternative hypothesis that significant activity is occurring on an out of sequence thrust fault (OOST) north of Lae. Alternatively, a combination of the two hypotheses could also fit the data well.

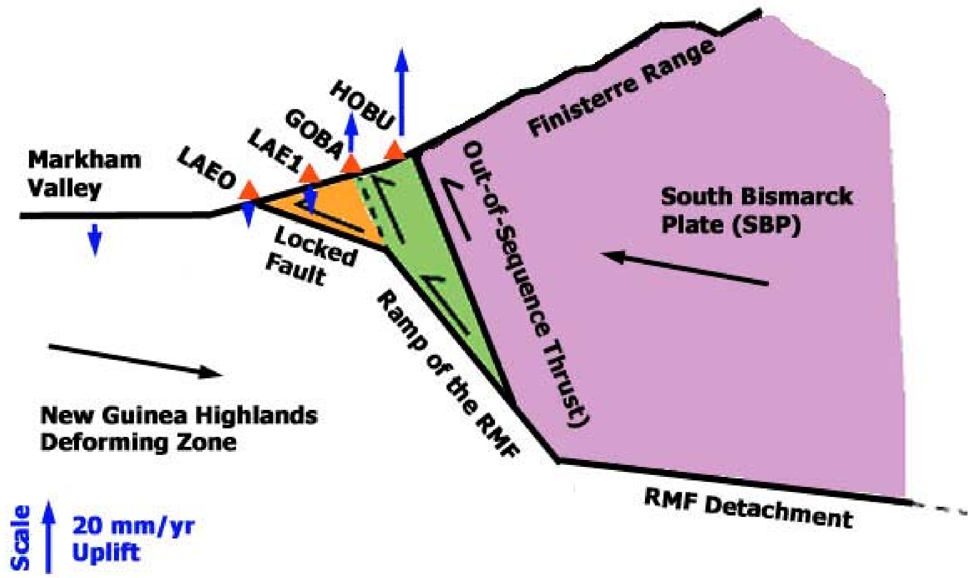
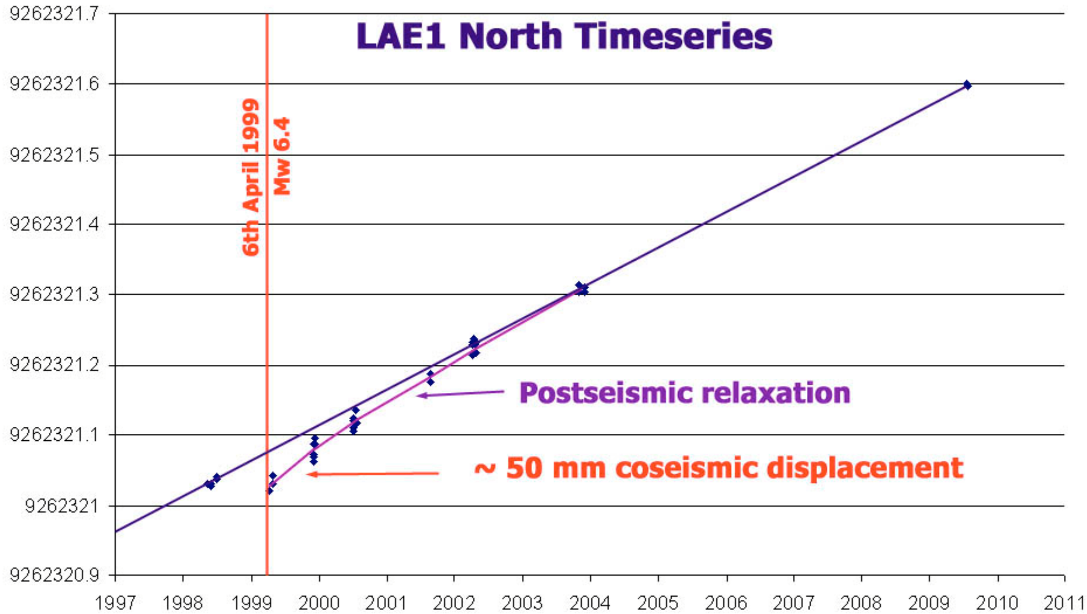


Figure 5. Ramp detachment geometry across the RMFZ near Lae (adapted from Wallace, 2002); The Lae commercial area, wharf and residential areas are located around the LAE1 site, above the low-angle fault. The Finisterre Range is on the SBP overriding the New Guinea Highlands block along the ramp of the RMF.

The lack of significant relative deformation between the Lae network and the NGH suggests that the Lae region is either (1) part of the New Guinea Highland plate, or (2) on the South Bismarck plate but lies above a "locked" Ramu-Markham fault that causes the Lae region sites to mimic New Guinea Highlands block movement in the time period between major earthquakes on the Ramu-Markham fault. Knowing which of the two hypotheses is correct has major implications for seismic hazard in the Lae region. Measured subsidence of LAE1 supports both hypotheses. The sedimentary record indicates longterm uplift rates of 7 mm/yr in the Lae area (Crook, 1989) and so it is possible that much of this uplift can be attributed to episodic cosesimic deformation.

Deformation arising from the 6th April 1999 Earthquake

Analysis of timeseries for LAE1 and HOBU clearly show coseismic deformation and postseismic relaxation arising from the April 1999 earthquake north of Hobu (Figure 6).



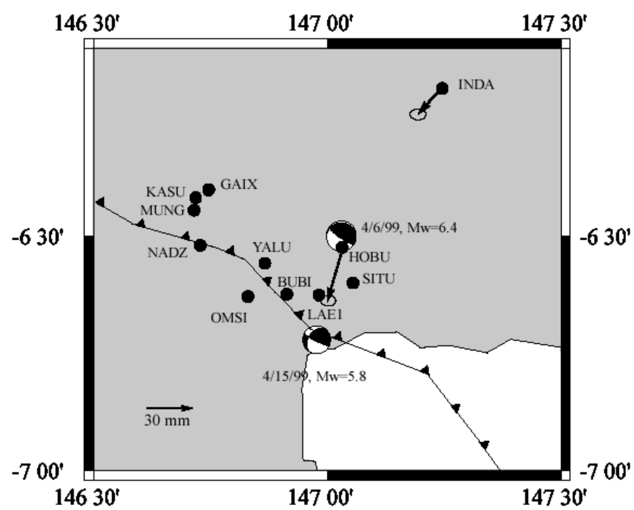


Figure 6 (above) Time series North component for LAE1. Co-seismic deformation is evident after the 6th April 1999 Mw 6.4 earthquake. **(below)** Earthquake locations and HOBU displacement (from Wallace, 2002).

Conclusions

The latest GNSS survey has significantly improved the monitoring of deformation in the Lae area resulting from the ongoing convergence between the South Bismarck Plate and the New Guinea Highlands Plate on the northern margin of the Australian Plate. Lae is located on the Ramu-Markham Fault Zone which represents the boundary zone berween the two plates. In the Lae area the New Guinea Highlands and South Bismarck plates are converging at a rate of 50 mm/yr and most of this convergence is currently seen as rapid deformation north of Lae near Hobu. GNSS measurements of the Lae geodetic network have confirmed that most of Lae city is currently moving with velocities similar to the New Guinea Highlands Block and that subsidence of 2 mm/yr is also occurring. Geological and seismological studies have however shown that Quaternary uplift rates have been 7 mm/yr in the Lae area, mostly represented by episodic ~1 metre coseismic displacements. The implication of these studies and the lack of any major earthquake within Lae city in the last 80 years suggests that Lae city is actually on the South Bismarck Plate and overlies the Ramu-Markham fault which appears to be "locked" between earthquakes. Such a scenario has implications for seismic hazards in Lae. As Lae city is mostly constructed on thick alluvial deposits, any seismic hazard is magnified. It is essential that monitoring of the Lae geodetic network continue.

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References

Abbott, L.D., Silver, E.A., Thompson, P.R., Filewicz, M.V., Schneider, C., and Abdoerrias, Stratigraphic constraints on the development and timing of arc-continent collision in northern Papua New Guinea: *J. of Sedimentary Res., v. B64*, p. 169-183., 1994a

Abbott, L., Silver, E., and Galewsky, J., Structual evolution of a modern arc-continent collision in Papua New Guinea, *Tectonics*, 13, 1007-1034, 1994b.

Abbott, L., Silver, E., Anderson, R., Smith, R., Ingles, J., Kling, S., Haig, D., Small, E., Galewsky, J., and Sliter, W., Measurement of tectonic surface uplift in a young collisional mountain belt, *Natur*e, 385, 501–507, 1997.

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

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

Altamimi Z., Collileux J., Legrand J., Garayt B., and Boucher, C.; ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, *Journal of Geophysical Research*, Vol. 112, B09401, doi:10.1029/2007JB004949, 2007

Buleka, J., Prior, D., and Van der Spek, A., *COASTPLAN geology and natural hazards of Lae City and surroundings, Papua New Guinea*. CCOP COASTPLAN Case Study Report No. 3, Geological Survey Division, Department of Mineral Resources, Papua New Guinea and Committee for Coordinating Geoscience Programmes in East and Southeast Asia, 1999.

Chappell, J., Ota, Y. and Berryman, K., Late Quaternary Co-seismic Uplift History of Huon Peninsula, Papua New Guinea, *Quaternary Science Reviews*, 15, 7-22, 1996.

Cooper, P. and Taylor, B., Seismotectonics of New Guinea; A model for arc reversal following arc-continent collision, *Tectonics*, 6, 53-67, 1987.

Crook, K., Quaternary uplift rates at a plate boundary, Lae urban area, Papua New Guinea, *Tectonophysics*, 163, 105-118, 1989.

Davies, H., Lock, J., Tiffin, D., Honza, E., Okuda, Y., Murakami, F., and Kisimoto, K., Convergent tectonics in the Huon Peninsula region, Papua New Guinea, *Geo-Marine Letters*, 7, 143-152, 1987.

Jaques, A., and Robinson, G., The continent/island-arc collision in northern Papua New Guinea, *BMR Journal of Australian Geology & Geophysics*, 2, 289-303, 1977.

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

Kulig, C., McCaffrey, R., Abers, G., and Letz, H., Shallow seismicity of arc-continent collision near Lae, Papua New Guinea, *Tectonophysics*, 227, 81-93, 1993.

Morgan P., Bock, Y., Coleman, R., Feng, P., Garrard, D., Johnston, G., Luton, G., McDowall, B., Pearse, M., Rizos, C., and Tiesler, R., *A Zero Order GPS Network for the Australian Region*, University of Canberra, 1996 (also printed as University of New South Wales, School of Geomatic Engineering, Unisurv S-46, 1996)

Ripper, I.D., and Anton, L.,*Seismic hazard, Lae*. Papua New Guinea Geological Survey Report 95/2, 1987.

Pigram, C. and Davies, H., Terranes and the accretion history of the New Guinea orogen*, BMR Journal of Australian Geology & Geophysics*, 10, 193-211, 1987.

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

Stanaway, R., *Implementation of a Dynamic Geodetic Datum in Papua New Guinea: A case study*, MPhil thesis, The Australian National University, Canberra, Australia, 2004 (http://dspace.anu.edu.au/bitstream/1885/42082/1/stanaway2004.pdf)

Stevens, C., McCaffrey, R., Silver, E., Sombo, Z., English, P., and Van der Keive, J., Mid-crustal detachment and ramp faulting in the Markham Valley, Papua New Guinea, *Geolog*y, 26, 847–850, 1998.

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.

Tregoning, P., H. McQueen, Resolving slip-vector azimuths and plate motion along the southern boundary of the South Bismarck Plate, Papua New Guinea, *Australian Journal of Earth Sciences*, **48**, 745-750, 2001.

Wallace, L., Tectonics and arc-continent collision in Papua New Guinea: Insights from geodetic, geophysical and geologic data. 244 pp., *PhD Thesis*, University of California, Santa Cruz, 2002.

Wallace, L.M., Stevens, C., Silver, E., McCaffrey, R., Loratung, W., Hasiata, S., Stanaway, R., Curley, R., Rosa, R., and Taugaloidi, J., GPS and Seismological Constraints on Active Tectonics and Arc-Continent Collision in Papua New Guinea: implications for mechanics of microplate rotations in a plate boundary zone: J. of Geophys. Res., v. 109, doi: 10.1029/2003JB002481., 2004

Weiler,P. and Coe, R., Rotations in the actively colliding Finisterre Arc Terrane: paleomagnetic constraints on Plio-Pleistocene evolution of the South Bismarck microplate, northeastern Papua New Guinea, *Tectonophysics*, 316, 297-325, 2000