[EA]Neotectonics of the Papuan Fold and Thrust Belt – Insights from Space Geodetic Analysis*

Richard Stanaway[1], Luke Mahoney[2], John Noonan[2], and Sandra McLaren[3]

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[1]Quickclose Pty Ltd, Melbourne, Australia (richard.stanaway@quickclose.com.au)
[2]Oil Search Ltd, Sydney, Australia
[3]The University of Melbourne, Melbourne, Australia

Introduction

Space geodetic and remote sensing techniques including GNSS/GPS, InSAR, and sub-pixel offset tracking (SPOT) now routinely provide high resolution measurements of crustal displacement. These techniques are especially suited to monitoring deformation across the Papuan Fold and Thrust Belt (PFTB) which forms the convergent margin between the Australian and Papua New Guinea Highlands tectonic plates. A dense network of geodetic survey control stations has been developed across the PFTB since the 1970s to support surveying and positioning for petroleum exploration and development. Quickclose has maintained and analysed a database of static GPS observations on approximately 700 of these stations since 2005 on behalf of the PNG oil and gas producers.

Geodetic analysis of this static GPS observation database has provided detailed insight into current crustal deformation processes across the PFTB. The geodetic network was re-observed by GPS between 2018 and 2020 to directly measure the surface displacements which have resulted from the destructive earthquake sequence initiated by the 26th February 2018 M_w 7.5 mainshock near the Hides gas field. Significant sections of the PFTB, including producing oilfields and LNG facilities were uplifted by up to 1.2 metres during the earthquake sequence with horizontal displacements of up to 50 cm. Footwall subsidence was also observed in the Usano Field and as far away as Gobe. The network density enabled high resolution definition of the displacement field resulting from the earthquake sequence which also correlates well with InSAR and SPOT analyses.

Longer period observations for GPS base station data have also been processed in the International Terrestrial Reference Frame 2014 (ITRF2014) to form an interseismic time series of displacement due to secular tectonic processes. Analysis of the time series enables a site velocity to be estimated for each site. Kinematic plate models and plate boundary strain rates can then be estimated by inversion of these site velocities. These kinematic models can be correlated with *insitu* stress measurements and from borehole breakouts, earthquake source mechanisms and structural geological analysis to provide a detailed insight into neotectonic processes active within the PFTB.

This paper provides an overview of plate boundary kinematics within the PFTB, including the deformation arising from the 2018 earthquakes. Practical implications of the deformation on other modelling are also discussed.

Discussion

The PFTB forms the plate boundary between the Australian and PNG Highlands tectonic plates. While the convergence between these two plates is slow (typically less than 5 $mmyr^{-1}$) (Koulali et al., 2015; Stanaway and Noonan, 2015), large earthquakes such as the damaging 2018 sequence do occur periodically once a stress threshold is attained due to ongoing strain accumulation within the convergent plate boundary zone.

Most well heads and production facilities in the PNG oilfields have two or more geodetic control stations, many of which are classified as Permanent Survey Marks (PSMs) registered by the Office of the Surveyor-General (OSG), a branch of the PNG Department of Lands and Physical Planning (DLPP). Civil works and built infrastructure also have many associated geodetic stations to support construction and maintenance. Since 2005 approximately 700 stations in the PFTB region have been surveyed by static GPS to achieve a 3D positional uncertainty of better than 50 mm (95% CI). The periodic nature of surveying activities in the PFTB has enabled many of the primary control stations to be reoccupied as GPS reference stations over a 15-year observation period enabling monitoring of tectonic and localised deformation within the oil fields and also estimation of interseismic site velocities. GPS observations have been made by a diverse array of contractors including seismic surveyors, Arman Larmer Surveys, Asia Pacific Surveys, Exxon-Mobil survey contractors, and others. Quickclose has managed this extensive archive of geodetic observations on behalf of operators and the PNG government to enable improvement and maintenance of the geodetic network and geodetic datum modernisation within PNG.

Static dual-frequency GPS carrier phase observations over a 15 year period between 2005 and 2020 have been processed in a global reference frame (currently ITRF2014) to estimate coordinates and uncertainties for each epoch of observations. These coordinates were then stacked to form a time series of station movement within ITRF2014 due to interseismic movement of the station (largely due to plate motion). Cartesian ITRF2014 site velocities were estimated for each site by linear regression of the time series using a weighting strategy related to the positional uncertainty of each of the ITRF2014 measurements scaled by 2 to improve the robustness of the estimation by minimising the effect of unmodelled seasonal signals.

The cartesian time series were then converted to topocentric East, North, and Up velocity components. Outlier measurements were identified (by visual inspection of the time series) and eliminated from the time series and the velocities re-estimated. Observations made after the 2018 earthquake sequence have been isolated from the time series analysis in order to estimate the coseismic and ongoing postseismic displacements arising from the sequence. The ITRF2014 interseismic site velocities were then transformed into the ITRF2014 Australian plate frame (Altamimi et al., 2017) by subtracting the Euler pole rotation of the Australian plate from the ITRF2014 NNR site velocity. Pre-2018 earthquake site velocities in both ITRF and stable Australian Plate reference frames for the primary monitoring network were then estimated (Figure 1 and Table 1).

Geodetic estimates of the magnitude and orientation of shortening across the PFTB correlate well with lateral variations, structural trends, and borehole breakout orientation measurements (Stanaway and Noonan, 2015).

Deformation from the 2018 Earthquake Sequence

At 03:44 PNG Time on 26th February 2018, a M_w 7.5 earthquake occurred in the PFTB (USGS, 2018). The USGS estimated epicentre was located 27 km SW of Tari (Figure 1), only 8 km SW of the Hides Gas Conditioning Plant (HGCP). The estimated focal depth has since been revised to 25 km. The main shock was followed by a number of large aftershocks across the central PFTB over the next few months. The earthquake sequence triggered several catastrophic scale landslides throughout the region, particularly prominent within the unstable volcanoclastic sediments in the flanks of Mt Sisa and Mt Kerewa. The Japan Aerospace Exploration Agency (JAXA) ALOS-2 satellite provided the first measurements of the deformation using InSAR (GSIA, 2018). These remote sensing measurements indicated ~1 m surface displacements between Lake Kutubu and Hides, predominantly as uplift together with a smaller SW displacement as inferred by the USGS moment tensor solutions.

GPS surveys recommenced within weeks of the mainshock. Quickclose Pty Ltd and Arman Larmer Surveys were called out by Oil Search in May 2018 to undertake an extensive resurvey of regional geodetic network between Hides and Kikori. The primary purpose of the survey was to measure the coordinate and elevation changes of Oil Search's primary geodetic network due to the earthquake sequence. The geodetic network is also utilised by Exxon-Mobil and other operators and underpins spatial referencing within the PNG oilfields. The secondary purpose of the survey was to provide ground control point (GCP) control for extensive UAV surveys over production facilities, well pads, and other infrastructure damaged by the earthquakes. Arman Larmer Surveys and Wood Group then completed LiDAR ground validation GPS surveys between Hides and Moro. Ongoing GPS surveys of well heads and seismic surveys have contributed to the overall ongoing analysis.

The estimated interseismic velocities for each station were then used to predict the ITRF2014 position of the station at the epoch of the post-earthquake measurement. This actual post-earthquake ITRF2014 measurement was differenced from the prediction to estimate the coseismic displacement caused by the earthquake sequence. All the post-earthquake measurements have some latency between the mainshock and the measurement and consequently these measurements also include some postseismic deformation (afterslip) and additional coseismic deformation from larger aftershocks. Regular reoccupation of Pillar 11 at HGCP (PL11) clearly shows postseismic afterslip and aftershock deformation in the North component (Figure 2). In some instances (e.g. Gobe network) there has been some time lag between the previous observation (pre-earthquake) and the 2018 observations. The Gobe network was near the epicentre of a M_w 5.8 earthquake on 29th July 2014, however there were insufficient resources to measure the coseismic deformation caused by this earthquake at the time and so the current analysis conflates the deformation from both the 2014 and 2018 earthquakes at Gobe.

The most notable aspect of the observed deformation is its spatial extent (Figure 3). Approximately 170 km of the PNG Highlands Plate uplifted by up to 1.3 metres between Lake Kutubu and Koroba during the mainshock, most likely as a rapid propagation of failure along a series of separate locked faults within the PFTB. SW deformation of up to 0.4 m is also evident which correlates with USGS moment tensor diagram for the main shock. The deformation is commensurate with a release of ~80 years of strain accumulation in the earthquake zone where

~5-10 mm yr^{-1} convergence has been evident during the interseismic period. Immediately to the south of the uplifted zone (e.g. Iagifu Ridge Camp), subsidence and NE motion of up to 0.2 m was evident. For each of the main fields and operational locations, deformation maps have been created using the observed or derived deformation data for each measured station. These have been used for post-earthquake remediation surveys and ongoing deformation monitoring.

References Cited

Altamimi, Z., L. Métivier, P. Rebischung, H. Rouby, and X. Collilieux, 2017, ITRF2014 Plate Motion Model: Geophysical Journal International, v 209/3, p. 1906.1912. doi.org/10.1093/gji/ggx136

GSIA, 2018, The 2018 Papua New Guinea Earthquake: Crustal Deformation Detected by ALOS-2 Data: Geospatial Information Authority of Japan (GSIA), August 2018. https://www.gsi.go.jp/cais/topic180301-index-e.html. Website accessed August 2020.

Koulali, A., P. Tregoning, S. McClusky, R. Stanaway, L. Wallace, and G. Lister, 2015, New Insights into the Present-Day Kinematics of the Central and Western Papua New Guinea from GPS: Geophysical Journal International, v. 202/2, p. 993-1004. doi.org/10.1093/gji/ggv200

Stanaway, R., and J.W. Noonan, 2015, Geodetic Measurement of Deformation Within the Papuan Fold and Thrust Belt: SEG Global Meeting Abstracts, p. 114-114. doi.org/10.1190/ice2015-2210749

USGS, 2018, M 7.5 - 83km SW of Porgera, Papua New Guinea. https://earthquake.usgs.gov/earthquakes/eventpage/us2000d7q6/executive. Website accessed August 2020.

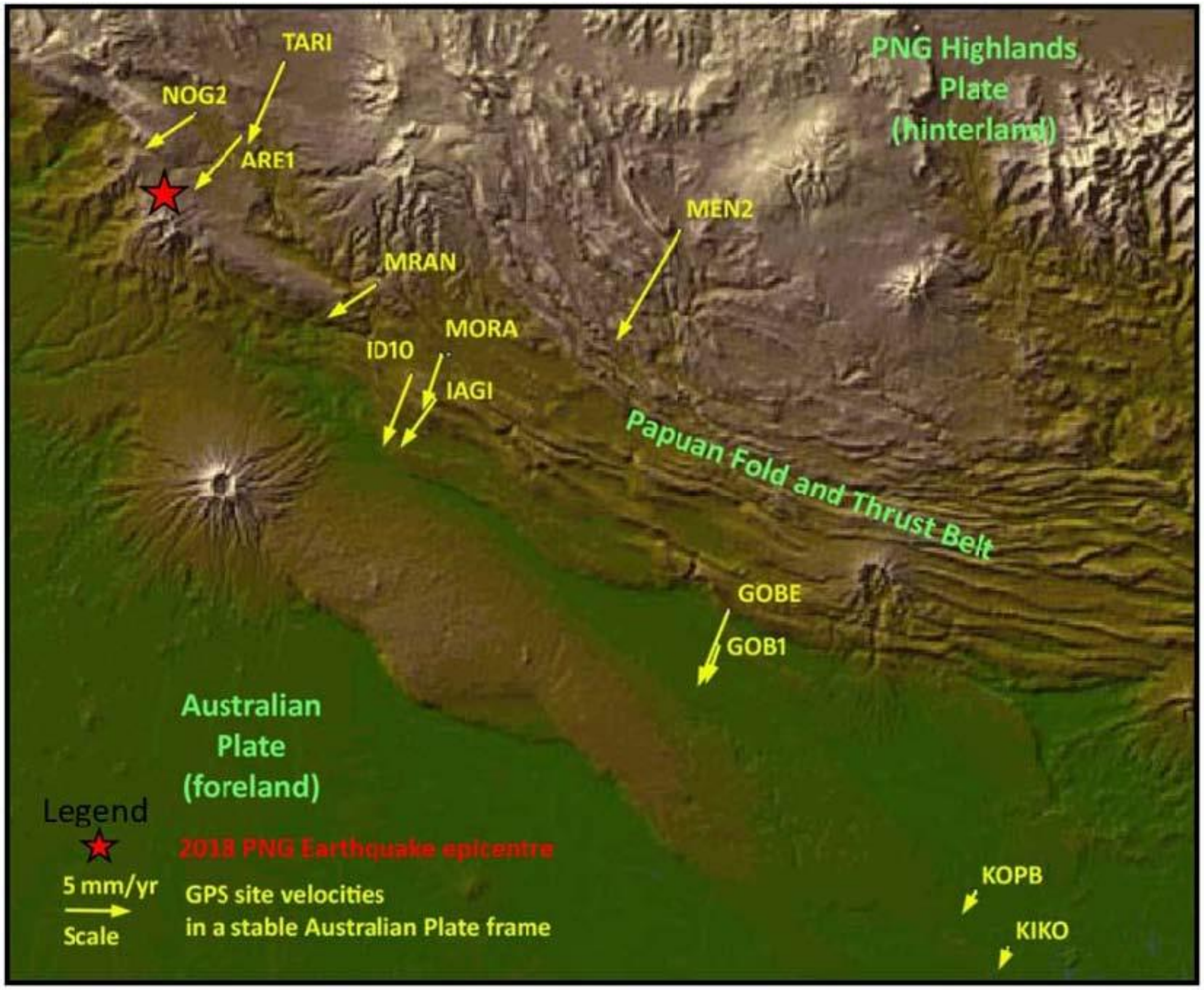

Figure 1. Observed interseismic site velocities relative to the stable Australian plate, showing strain accumulation across the PFTB before the 2018 earthquake sequence.

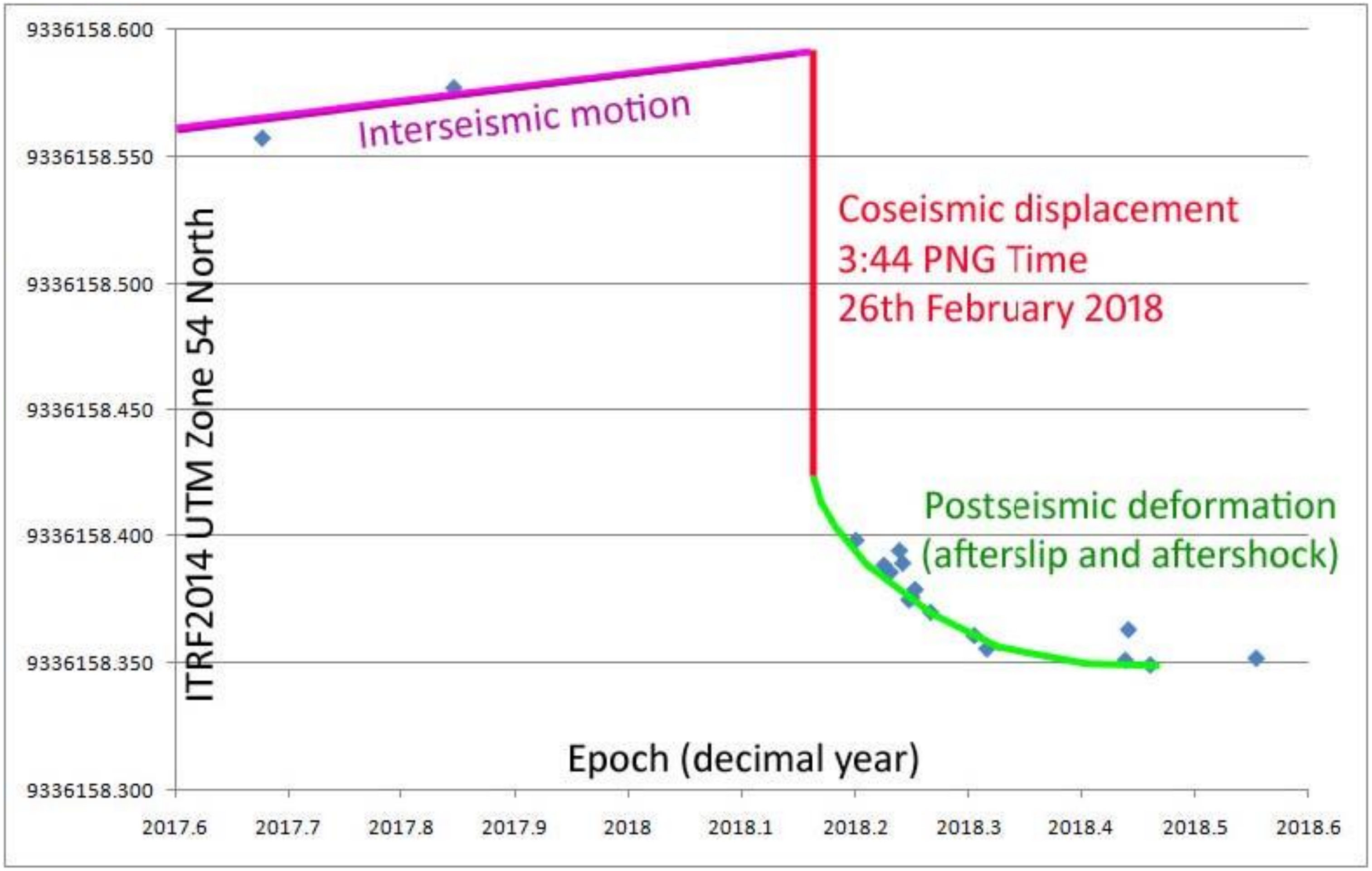

Figure 2. North time series for Pillar 11 HGCP showing coseismic and postseismic deformation.

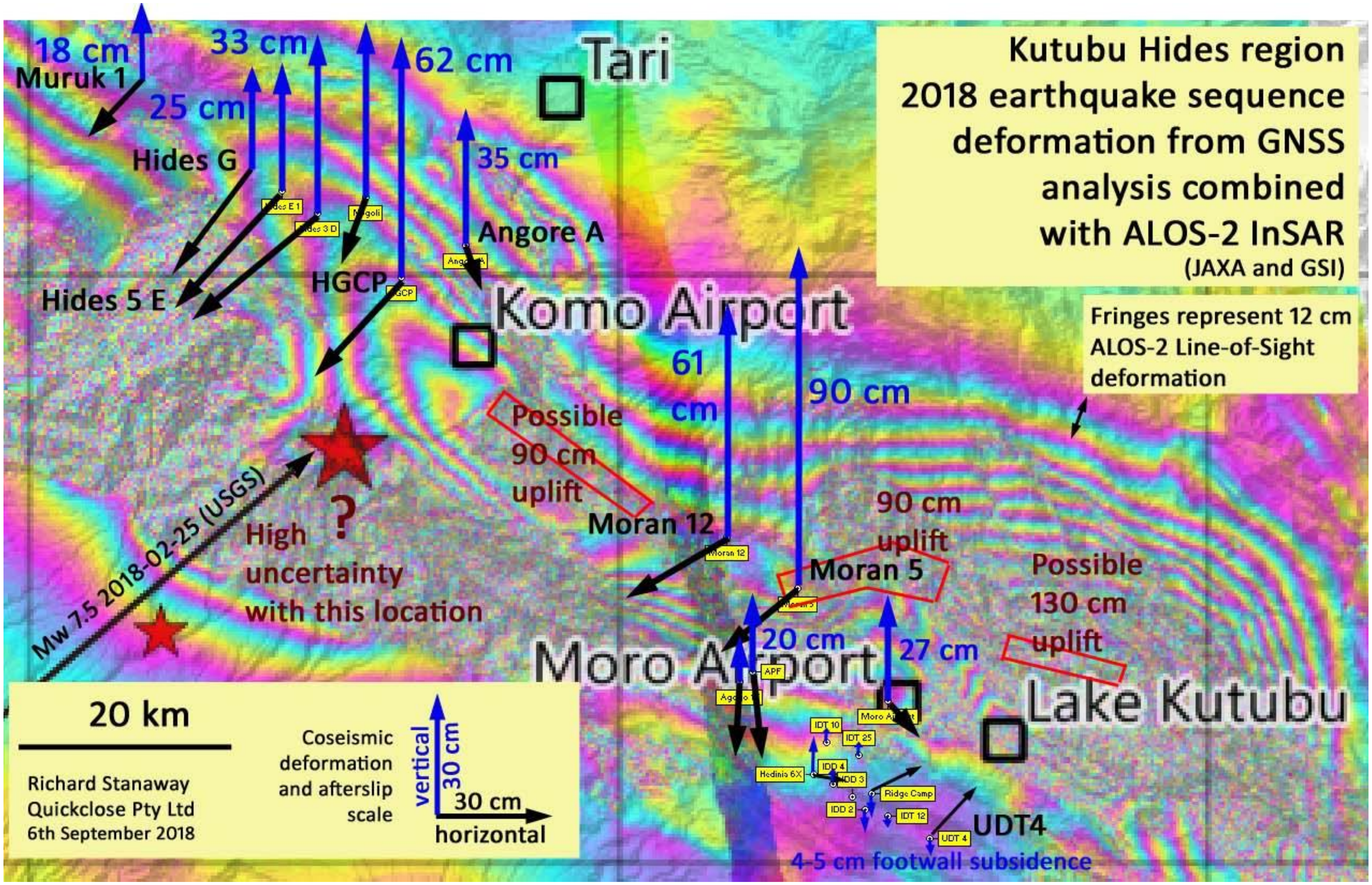

Figure 3. GNSS observed deformation with the PFTB overlain on the ALOS-2 interferogram.

Station	ITRF2014 site velocity (mm yr^{-1})		Stable Australian Plate velocity (mm yr^{-1})		
	East	North	East	North	Magnitude
ARE1 PSM 33178	29.7	52.3	-6.0	-5.0	7.8
GOB1 PSM 15262	33.1	56.6	-2.3	-0.4	2.3
GOBE PSM 32563	33.2	51.3	-2.2	-5.8	6.2
IAG2 PSM 17743	33.3	53.7	-2.3	-3.5	4.2
IAGI PSM 32567	33.3	53.7	-2.3	-3.5	4.2
ID10 PSM 32835	33.6	52.3	-2.0	-4.9	5.3
KIKO PSM 5583	34.5	55.1	-0.6	-1.8	1.9
KOPB PSM 30040	34.2	56.2	-1.0	-0.8	1.2
MEN2 PSM 9830	31.1	48.9	-4.5	-8.2	9.3
MORA PSM 17742	34.5	53.3	-1.1	-3.9	4.0
MORB PSM 32566	34.6	54.4	-1.0	-2.8	3.0
MRAN PSM 32838	32.0	54.9	-3.7	-2.3	4.3
NOG2 PSM 33978	32.8	54.8	-3.0	-2.5	3.9
TARI T630	33.5	51.5	-2.3	-5.8	6.2

Table 1. PFTB monitoring network ITRF2014 and stable Australian plate site velocities.