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Is the Australian Plate deforming? A space geodetic perspective

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Measurements at discrete points spanning the Australian Plate have been made for over a decade using the Global Positioning System (GPS) space geodetic technique. These measurements show that, to within the resolution of the technique (~2 mm/y at 95% confidence level), there are no significant changes in the dimensions of the Australian Plate across the Australian continent. That is, no changes in baseline lengths are evident between any sites located in Australia when taking into account the measurement and modelling errors. However, during the past two decades, several significant earthquakes have occurred within the Australian Plate indicating that at times stress failure levels are reached, resulting in failure within the crust. Therefore, the rate at which stress accumulates must be slower than is visible in the geodetic measurements. With the exception of two sites affected by earthquake co-seismic displacement and equipment failure, all time series of sites in the interior of the Australian Plate are linear and site velocities are not significantly different from the predicted motion of the 'rigid' Australian Plate. However, the northern margin of the plate in Papua New Guinea is undergoing regional deformation. This is probably a result of the interaction with neighbouring plates and the proximity of the GPS site to nearby plate-boundary zones.

KEY WORDS: Australian Plate, GPS, intraplate deformation.

INTRODUCTION

The Australian Plate is one of 14 major tectonic plates covering the surface of the Earth (DeMets *et al.* 1990) and shares tectonic boundaries with seven other macro- and micro-plates (Figure 1). An active spreading centre separates the southern margin of the Australian Plate from the Antarctic Plate, while along the eastern margin subduction of the Pacific Plate occurs on several active subduction trenches (Figure 1). The Australian Plate subducts beneath the Solomon Islands at the San Cristobal Trench, separates from the Woodlark Plate along the Woodlark Basin Spreading Centre and collides with the South Bismarck Plate along the Ramu–Markham Fault in Papua New Guinea (Figure 1). The northwestern margin of the Australian Plate subducts beneath the Sundaland Block along the Java Trench while convergence is partitioned between oblique subduction beneath Sumatra and right-lateral slip on the Great Sumatra Fault.

The western boundary of the Australian Plate is much more poorly defined. Early global plate-motion models (Le Pichon 1968; Minster *et al.* 1974) postulated that the Indo-Australian Plate was one rigid entity that stretched west to the boundary with the African Plate. Minster and Jordan (1978) showed that the geophysical data of transform fault azimuths, spreading rates etc. were better fitted if the Indian and Australian Plates were considered to be separate entities. Subsequent global plate models (DeMets *et al.* 1990, 1994a; Argus & Gordon 1991) considered the two plates as separate, rigid plates although did not define a discrete boundary between them. More recent analyses of gravity data and spreading rates from aeromagnetic surveys suggest that the relative motion between the Indian and Australian Plates is taken up on many fracture zones and large regions of distributed deformation have been identified (DeMets *et al.* 1994b; Royer *et al.* 1997; Gordon *et al.* 1998) (see Figure 1).

Since 1976, 19 earthquakes with magnitude $M_w > 5.0$ have occurred within the interior of the Australian Plate and may be considered to be 'intraplate' earthquakes (Figure 1). This indicates that stresses do accumulate within the Australian Plate and, from time to time, large readjustments of the stress field occur (Wdowinski 1998; Hillis & Reynolds 2000)

Since the 1970s space geodetic techniques have been used to measure the precise coordinates of discrete sites spanning the Australian Plate. Very Long Baseline Interferometry (VLBI) observations of baselines in Australia began in 1982 (Harvey 1985), while Satellite Laser Ranging (SLR) measurements commenced in Canberra and Yaragadee in the 1970s. Monitoring of the Australian continent using GPS began in the early 1990s and the network of permanently operating sites continues to increase in density.

In this paper the motion of 12 sites estimated from GPS observations are presented. The data span at least three years and in some cases 10 years and the GPS sites cover the entire Australian Plate. The other two space geodetic techniques are limited in their spatial distribution, with SLR observations at only Yaragadee and Canberra and VLBI observations at Hobart, Canberra and some at Parkes and Narrabri. Therefore, the spatial resolution is considerably better from the GPS network and only GPS velocity estimates will be considered below. With only a couple of exceptions, the estimated site velocities are consistent with a rigid Australian Plate.

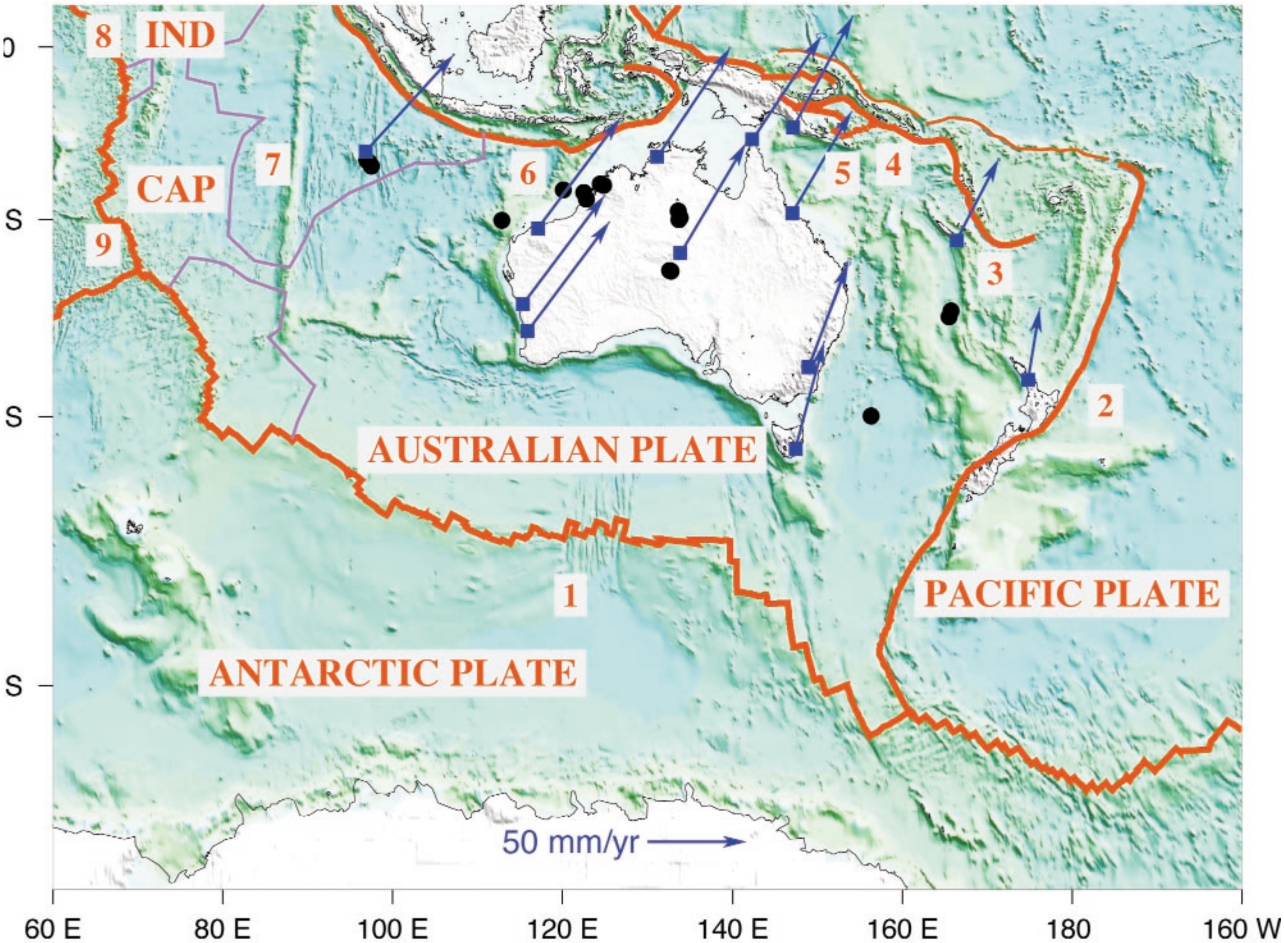

Figure 1 Tectonic map showing the boundaries of the Australian Plate. Bathymetry and topography is taken from the ETOPO5 dataset (ETOPO5 1986). GPS sites on the Australian Plate and their ITRF97 velocities are plotted along with the locations of 'intraplate' earthquakes (black circles) which have occurred since 1976 within the geographical coverage of the GPS network. The areas bounded in pink are diffuse plate boundaries between the Australian, Indian (IND) and Capricorn Plates (CAP) (Gordon *et al.* 1998). 1, Southeast Indian Ridge; 2, Kermadec Trench; 3, New Hebrides Trench; 4, San Cristobal Trench; 5, Woodlark Basin Spreading Centre; 6, Java Trench; 7, Ninety East Ridge; 8, Carlsberg Ridge; 9, Central Indian Ridge.

GPS NETWORK AND DATA ANALYSIS

The Australian Surveying and Land Information Group (AUSLIG) has established a permanent network of continuously operating GPS stations across Australia (Figures 1, 2) and data from this network forms the basis of this analysis. Observations made at these sites prior to their continuous operation (Tregoning 1996) have also been included. In addition, campaign-style observations have been made in Cape York in 1996 and 1999 and data were used from two sites located in Auckland and Noumea, which are freely available from the International GPS Service (IGS) (Beutler *et al.* 1993) and one site in Port Moresby (operated by the Papua New Guinea National Mapping Bureau), to extend the span of the network out to the most northern and eastern extremities of the Australian Plate.

The GPS data have been analysed using the GAMIT/GLOBK software (King & Bock 2000; Herring 2000) following the procedures explained in detail in Feigl *et al.* (1993) and Dong *et al.* (1998). In brief, data from sites in the Australasian region were combined with up to 70 sites from the global IGS network to derive daily estimates of the site positions. Satellite orbits, earth orientation parameters, tropospheric delay parameters and site positions are all estimated simultaneously using a least-squares process.

Two different solutions were generated for the analysis presented below. In the first solution the coordinates and velocities of 45 core IGS sites were constrained to their values in the International Terrestrial Reference Frame 1997 (ITRF97) (Boucher *et al.* 1999) (but did not constrain any sites located on the Australian Plate). A Kalman back-filter solution was performed with stochastic variation permitted on the sites located on the Australian Plate to generate daily estimates of the positions of all such sites.

In the second solution a 7-parameter Helmert transformation of the velocities of the 12 sites located on the Australian Plate was performed with respect to a stationary reference frame (i.e. relative to the Australian Plate itself as defined by the velocities of these sites) (Table 1). Any sites with velocities which are significantly different from zero (all statistical tests are two-tailed, 2σ confidence interval, normal distribution tests unless otherwise specified) in

Table 1 Site velocities (and 1σ uncertainties) with respect to a rigid Australian Plate defined by a best-fitting Euler vector using the velocities of the sites listed below (except MORE).

Site	Code	Velocity with respect to Australian Plate (mm/y)			
		V_n	σ_n	V_e	σ_e
Alice Springs	ALIC	0.1	0.6	0.0	0.6
Auckland	AUCK	–0.9	0.5	–0.9	0.5
Cocos Islands[a]	COCO	–0.0	0.6	–0.7	0.6
Darwin	DARW	–0.6	0.5	–0.3	0.6
Hobart	HOB2	0.1	0.5	–0.5	0.5
Karratha	KARR	0.2	0.5	0.6	0.5
Noumea	NOUM	0.2	0.7	–0.6	0.7
Perth	PERT	0.5	0.4	0.7	0.5
Tidbinbilla	TIDB	0.5	0.5	0.2	0.5
Townsville	TOW2	–0.7	0.6	–0.2	0.5
Yaragadee	YAR1	–0.7	0.4	0.6	0.5
Port Moresby	MORE	0.3	0.5	–3.8	0.5
Mt Stromlo	STR1	1.2	0.7	0.6	0.8

[a] Velocity estimate for the Cocos Islands excludes data subsequent to the 16 June 2000 earthquake.

such a reference frame indicate that these sites are moving relative to the Australian Plate. With the exception of Port Moresby (see discussion below), none of the residuals is significantly different from zero at even the 1σ level (66% confidence interval) (Figure 2; Table 1), indicating that the GPS analysis is not able to detect any significant shortening or extension across the Australian Plate from Cocos Island in the west to Noumea and Auckland in the east.

Morgan *et al.* (1996) suggested that GPS velocities relative to the 'NUVEL model' [I presume here that this referred to the No-Net-Rotation NUVEL-1 model (DeMets *et al.* 1990; Argus & Gordon 1991)] showed evidence for east–west compression of the Australian Plate. Using a more comprehensive dataset, I find no such evidence at the sub-2 mm level. These results confirm the earlier analyses of Tregoning (1996) who concluded that no significant deformation could be detected within the Australian Plate.

The site at Port Moresby (MORE) shows relative motion with respect to the Australian Plate of ~4 ±1 mm/y with an azimuth of 274 ±15° (Figure 2). Previous estimates of the velocity of MORE have found no significant motion relative to the Australian Plate (Tregoning *et al.* 1998). The estimate here is derived from data with a considerably longer temporal scale (~11 years rather than ~6 years), with most of the observations occurring after the establishment of the IGS global tracking network. The enhanced tracking network after this time improves the accuracy of the the orbit estimations; hence the site coordinates and velocity estimates are more accurate. The uncertainties in these velocity estimate are considerably smaller than those of Tregoning *et al.* (1998), making the motion relative to the Australian Plate statistically significant.

TEMPORAL ANALYSIS

Figure 3 shows the time series of daily coordinates estimates for the sites at Alice Springs (ALIC), Auckland (AUCK), Karratha (KARR) and Townsville (TOW2). These time series are indicative of the eight other sites estimated but not shown here and show clearly that, to within the level of uncertainty of the GPS measurements (~5 mm for each individual daily estimate), each site is moving with linear horizontal motion.

There are two sites which do not show consistent linear motion: Cocos Islands (COCO) and Mt Stromlo (STR1). The time series of COCO has a discontinuity on 16 June 2000 (Figure 4) that corresponds to the timing of a M_w =7.8 earthquake which occurred ~150 km to the southeast of the GPS site (Robinson *et al.* 2001). The offsets of ~–7 mm in north and ~+34 mm in east are a measure of the co-seismic displacement which occurred at the Cocos Islands as a result of the seismic event. This event has been interpreted as an intraplate earthquake, and Robinson *et al.* (2001) suggested that the diffuse boundary between the Australian

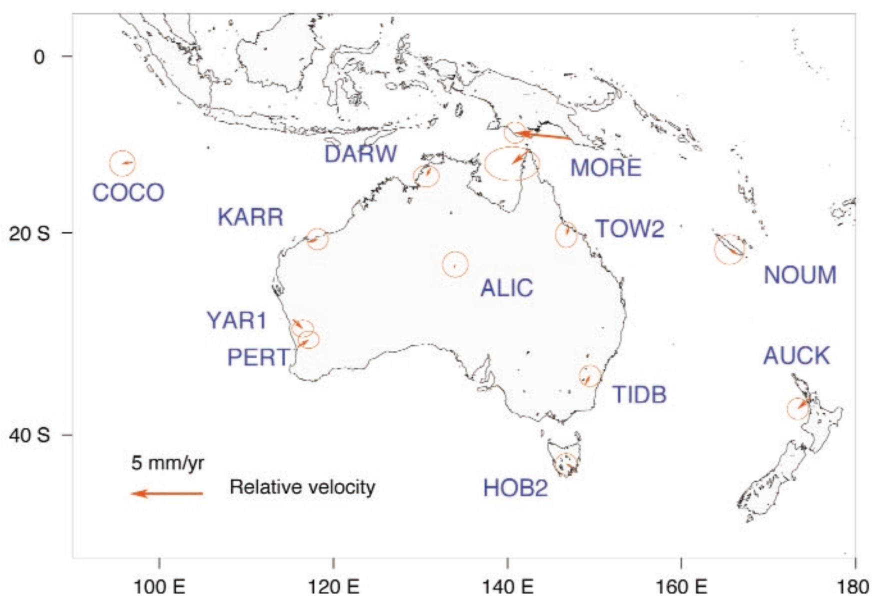

Figure 2 Site velocities (and 1σ error ellipses) with respect to a rigid Australian Plate. Most of the vectors are so small they are barely visible. Relative motion at MORE is clearly evident.

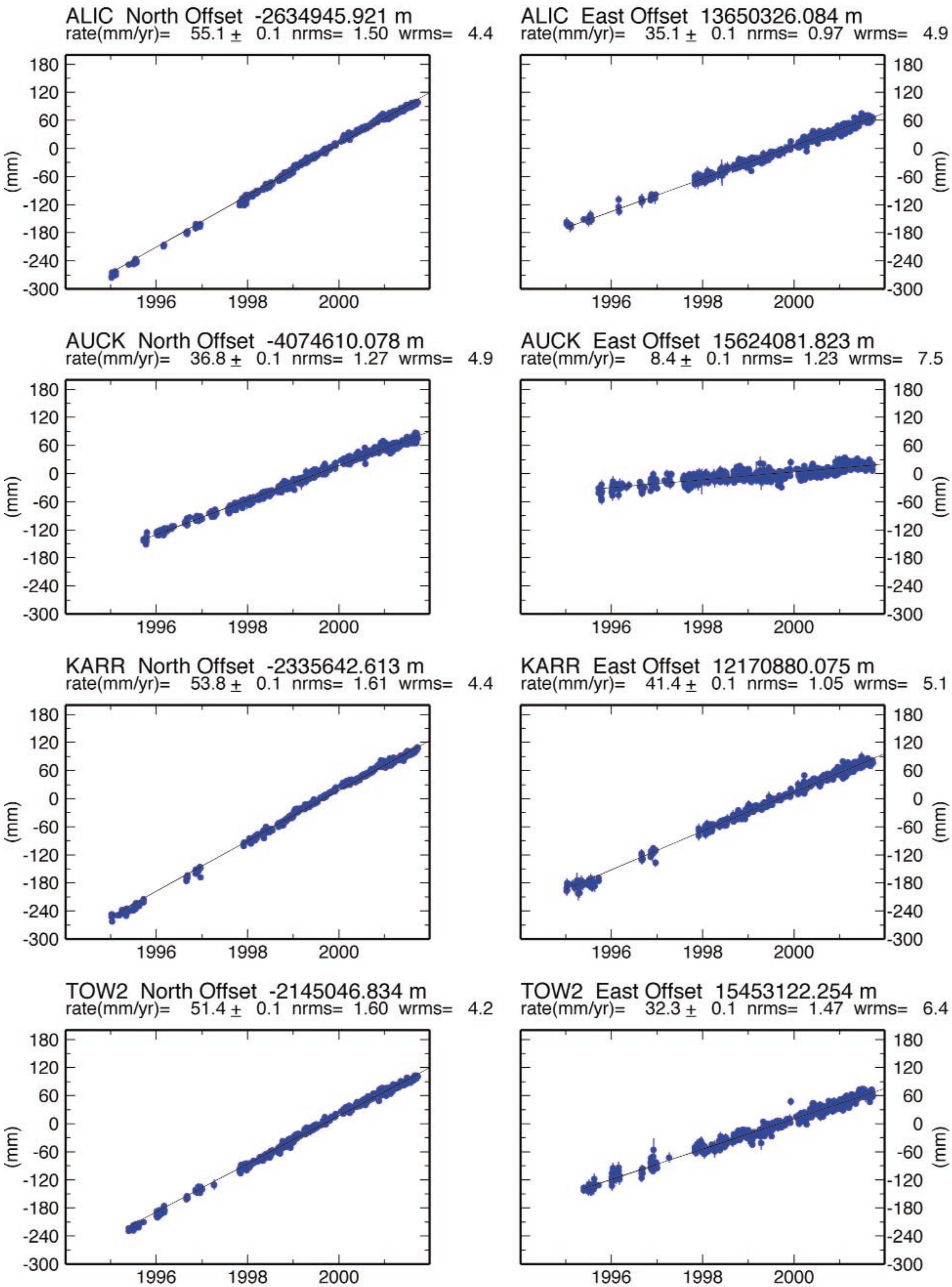

Figure 3 GPS time series from 1994 to 2001 for four typical GPS sites: Alice Springs (ALIC), Auckland (AUCK), Karratha (KARR) and Townsville (TOW2). nrms, normalised root mean square; wrms, weighted root mean square using the daily formal GPS position uncertainties.

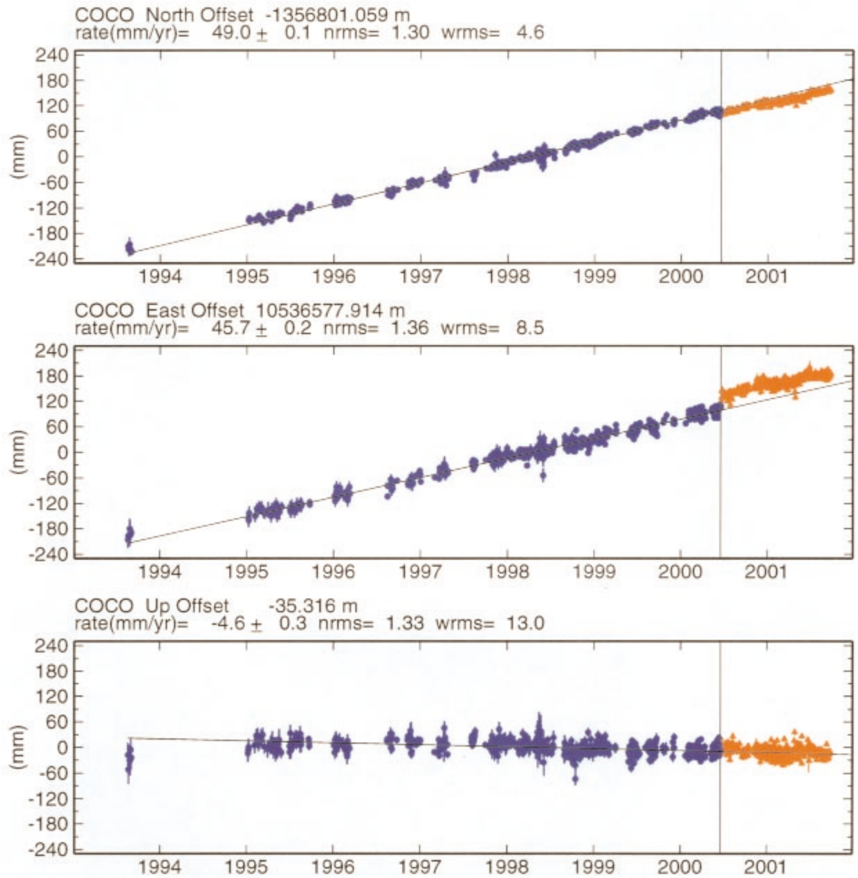

Figure 4 GPS time series at Cocos Islands (COCO). The time of the M_w =7.8 earthquake is indicated by a vertical line, with subsequent site estimates plotted in red. The pre-earthquake linear velocities are shown for each component.

and Indian Plate may be localising with time into a narrower north–south region of deformation.

The correlation between the timing of the discontinuity in the time series at COCO and the physical occurrence of the earthquake shows the small levels of discontinuous motion which can be detected with GPS. It also adds strength to the arguments that, where no motion is detected between other sites, no significant motion has occurred.

The second non-linear site, Mt Stromlo, is more difficult to explain. The site has been observing continuously since May 1998, although there are discontinuities of up to 100 mm evident during 1998/99 (Figure 5). Some of these jumps coincide with changes of equipment hardware, but not all. The GPS receiver is co-located with the Satellite Laser Ranging (SLR) system in Canberra. The SLR time series at Mt Stromlo does not show the discontinuities visible in the GPS time series (Figure 5).

Between September 1998 and May 1999 the GPS antenna used at STR1 was an Ashtech GPS/GLONASS model (IGS code ASH701073.1), whereas before and after this period the antenna was a Turborogue Dorne Margolin (IGS code AOAD/M_T). Since September 1998, the same GPS receiver has been used (Turborogue: IGS code AOA ICS-4000z); thus, the anomalous record cannot be considered to be caused by receiver malfunctions. It is clear in the time series that the observations before September 1998 and after May 1999 show linear motion of the site, while all observations between these times are not part of the same population. I suspect that there was either incompatibility between the Turborogue receiver and Ashtech antenna or that the Ashtech antenna failed slowly, causing a horizontal drift in the position estimates. Once this antenna was removed, the position estimates appear to once more fit a pattern of linear motion. This effectively rules out electrical interference from other equipment at the Mt Stromlo site as the cause of the anomalous motion.

The antenna which may have been faulty has since been returned to the manufacturer and replaced (R. Govind pers. comm. 2001) and hence it is not possible to perform specific tests to demonstrate conclusively that the explanation above is correct. However, given that since May 1999 the time series at STR1 is essentially linear and that the SLR time series of the co-located SLR tracking station shows no such discontinuities during 1998 and 1999, it is reasonable to assume that the non-linear motion at Mt Stromlo is not related to tectonic movement within the Australian Plate.

DEFORMATION IN PAPUA NEW GUINEA

The GPS site at Port Moresby located on the southwestern coast of the Papuan Peninsula is the only site which shows systematic, significant relative motion with respect to the Australian Plate. Previous authors have assumed that it lies

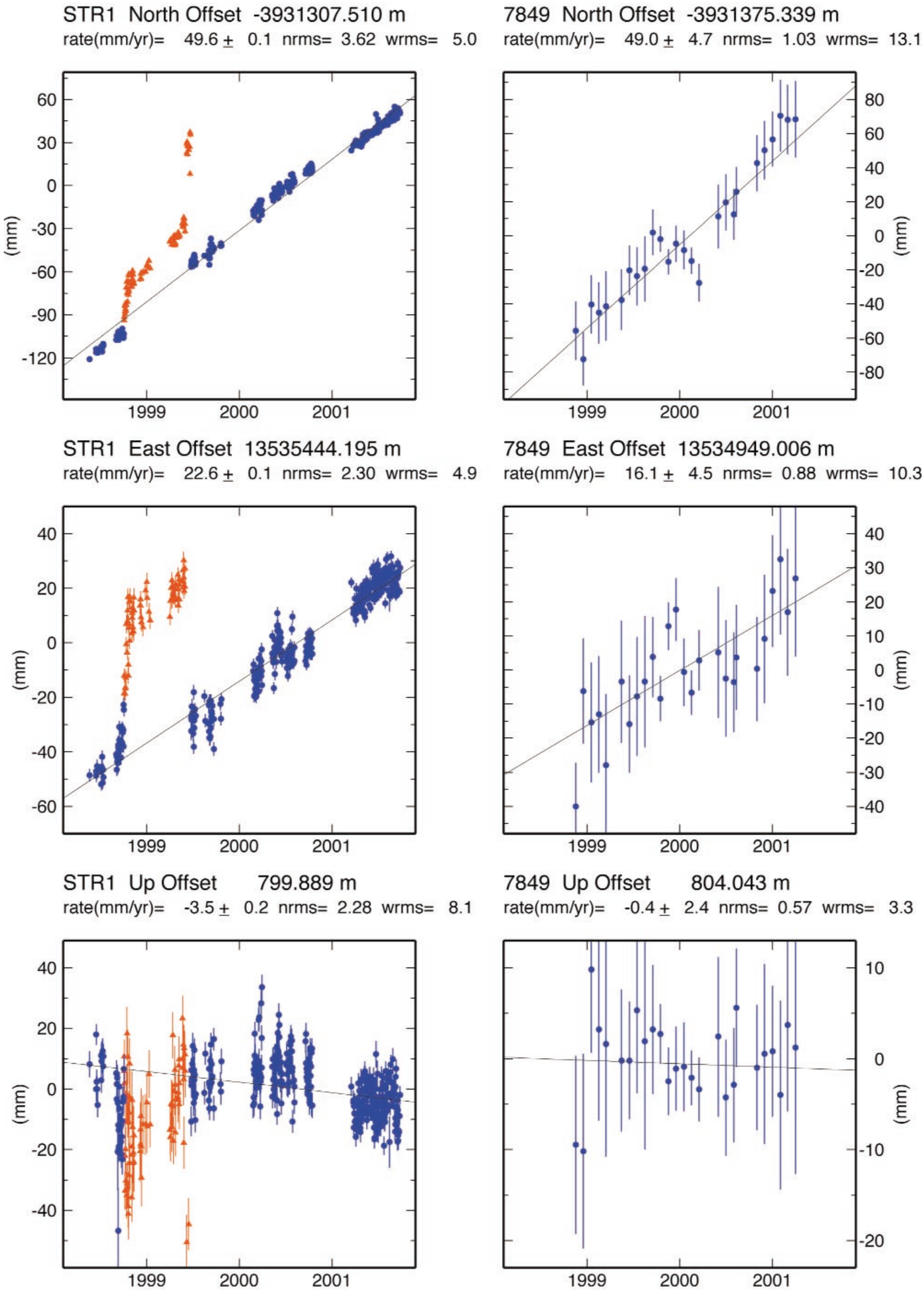

Figure 5 Time series of position estimates at Mt Stromlo (STR1) from GPS and SLR observations. The GPS observations that occurred during the time of suspected faulty equipment are shown in red. These data were excluded from the calculation of the linear velocity plotted in the figure. SLR estimates are derived from SINEX files provided by AUSLIG.

on the rigid Australian Plate (Tregoning *et al.* 1998). This site lies ~100 km west of the likely boundary between the Australian and Woodlark Plates where the predicted relative motion between these two plates is ~10 mm/y (Tregoning *et al.* 1998).

Assuming that the plate boundary here is locked, one could expect to see interseismic strain accumulation in regions close to the locked boundary. The actual location of the boundary is not known (Tregoning *et al.* 1998). Modelling the interseismic strain [using a screw dislocation (Okada 1985) and assuming that the plate boundary runs through the middle of the Papuan Peninsula and is locked to 20 km depth] results in predicted relative motion at MORE of <1 mm/y. This is significantly smaller than the observed 4 ±1 mm/y relative motion, suggesting that either the plate boundary is considerably closer to MORE or that there is another cause for the observed relative motion (e.g. local site instability).

CONCLUSIONS

GPS data spanning up to 10 years at 12 sites across the Australian Plate do not reveal intraplate deformation at the 2 mm/y level. With the exception of one site located near an active plate boundary, one site affected by co-seismic motion and one site with suspected instrumental problems, all temporal estimates of positions are essentially linear with velocities which match that of the motion of a single, rigid Australian Plate. While the occurrence of intraplate earthquakes indicates that intraplate stress accumulates and releases, the geodetic observations across the Australian Plate do not reflect this cycle—at least not on a time scale of a decade or less. If deviations from rigid plate motion within the Australian Plate do occur they are below the noise level of the GPS analysis (~2 mm/y).

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