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Vertical tectonics at an active continental margin

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ABSTRACT

Direct observations of vertical movements of the earth's surface are now possible with space-based GPS networks, and have applications to resources, hazards and tectonics. Here we present data on vertical movements of the Earth's surface in New Zealand, computed from the processing of GPS data collected between 2000 and 2015 by 189 permanent GPS stations. We map the geographical variation in vertical rates and show how these variations are explicable within a tectonic framework of subduction, volcanic activity and slow slip earthquakes. Subsidence of >3 mm/yr is observed along southeastern North Island and is interpreted to be due to the locked segment of the Hikurangi subduction zone. Uplift of 1–3 mm/yr further north along the margin of the eastern North Island is interpreted as being due to the plate interface being unlocked and underplating of sediment on the subduction thrust. The Volcanic Plateau of the central North Island is being uplifted at about 1 mm/yr, which can be explained by basaltic melts being injected in the active mantle-wedge at a rate of ~6 mm/yr. Within the Central Volcanic Region there is a 250 km^2 area that subsided between 2005 and 2012 at a rate of up to 14 mm/yr. Time series from the stations located within and near the zone of subsidence show a strong link between subsidence, adjacent uplift and local earthquake swarms.

1. Introduction

Most tectonic studies based on GPS have focused on the horizontal components of velocity (Thatcher, 2003), as these are more accurately determined than the vertical rate. The reason for this is that tropospheric changes and satellite constellation geometry issues compromise the estimates of vertical velocities more than that of the horizontal ones (Houlié et al., 2016). Arrays of continuous GPS instruments (C-GPS) that were installed more than a decade ago are now providing surface vertical rates that could be compared to long-term estimates (Beavan et al., 2010).

Vertical velocities are important because they provide different constraints, compared to horizontal velocities, on processes in the Earth such as dynamics of the upper mantle (Gurnis et al., 1998; Molnar, 2015), glacial isostatic adjustment (Bradley et al., 2009; Sella et al., 2007; Teferle et al., 2009), erosion rates (Cox et al., 2012; Herman et al., 2010; Nibourel et al., 2015), stability of mountains belts (Ching et al., 2011; Hammond et al., 2012; Houlié et al., submitted for publication; Koons, 1990; Liang et al., 2013; Serpelloni et al., 2013), spatial variations in the coupling of a subduction thrust (Kaneko et al., 2010; Savage, 1983) or crustal thinning (Steckler, 1985). There are also evolving practical applications for C-GPS data to monitoring water tables (Amos et al., 2014) and detecting locked faults (Howell et al., 2016; Lamb and Smith, 2013). Plate boundary settings are particularly favorable locations for these studies because the rates of vertical movement tend to be relatively large (>2 mm/yr).

Both GPS and geodetic solutions of vertical and horizontal velocities within plate boundary zones result from short- (year to decades) and long-term (million years) processes. For example, in New-Zealand, vertical rates have been used to constrain shortening rates across the Alpine fault (Beavan et al., 2010, 2004), and to provide insight to both the level of incompressibility of the lithosphere (Houlié and Stern, 2012), and the extent of the locked segments of the subducted Pacific plate slab along the Hikurangi margin (Lamb and Smith, 2013). In this study we present the first surface uplift map for New Zealand based on GPS and discuss its implications for tectonic processes.

2. Data

We processed GPS data collected by the GEONET-NZ network (Fig. 1) for the period spanning from January 2000 to March

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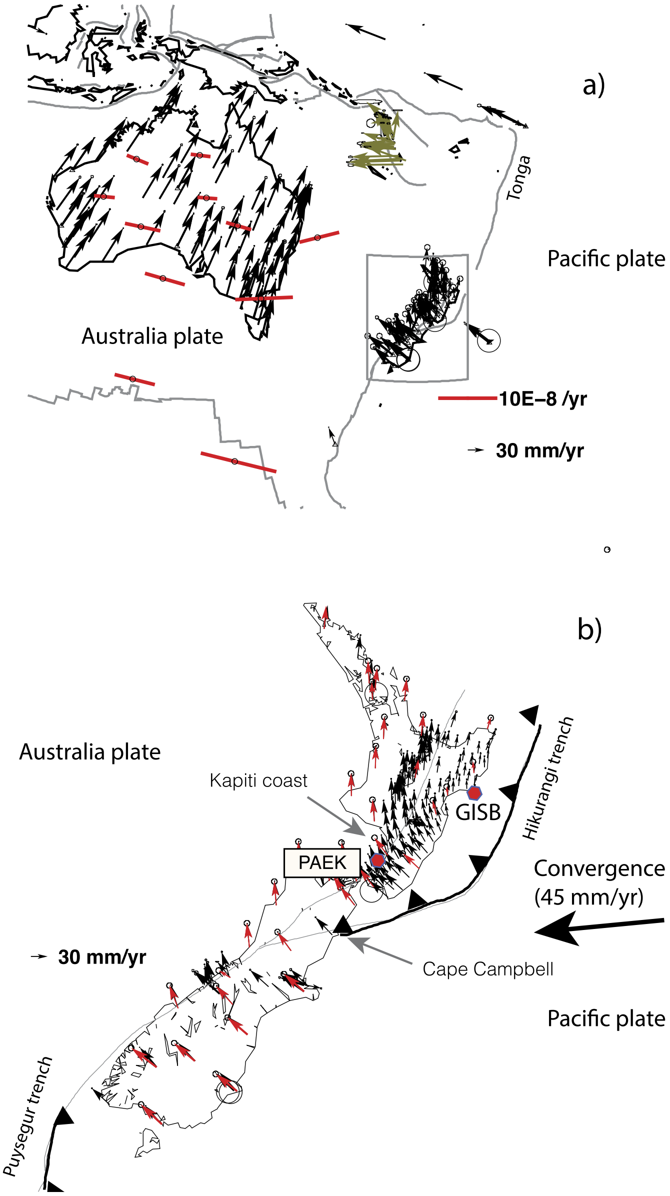

Fig. 1. a) Surface motions in the surroundings of East Australia plate and New Zealand. b) Velocities of New Zealand GEONET cGPS stations (www.geonet.org.nz) obtained by Houlié and Stern (2012) are compared with those presented in this study (black). All velocities are shown in the ITRF08 (Altamimi et al., 2012). Green and red vectors are from Bergeot et al. (2009) and Houlié and Stern (2012), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2015 using GAMIT (King and Bock, 2012). As the complete dataset was too big to be processed as one, we divided it into five sub-networks; each of them including the same reference sites (AUCK, CHAT, CHTI, GUAM, OUS2 and WGTN, see Fig. A1 of Supplementary materials) for which we know positions and velocities with high accuracy from the ITRF2008 (Altamimi et al., 2012). Using this backbone network, daily solutions were combined using GLOBK/GLORG (Herring, 2003) by minimizing the shift between the ITRF2008 solutions (Altamimi et al., 2012) and ours. All rates were computed using a linear regression assuming uncertainties of east, north and vertical components were equal to 2.0, 2.0 and 5.0 mm, respectively.

We took into account the disruption of trends generated by large seismic events. During the last decade, five major seismic events have occurred in the South Island of New Zealand in this period: Dusky Sound (Mw 7.8, 2009/07/15), Canterbury (Mw 7.1, 2010/09/04), Christchurch (Mw 6.3, 2011/02/22), Cook Strait (Mw 6.3, 2012/07/03) and Seddon (Mw = 6.5, 2013/07/21). These seismic events induced sharp discontinuities (coseismic) and smoother non-linear (post-seismic) motions of the closest sites. For those that have been affected, we introduce offsets in the time-series at the times of the earthquakes to minimize the impact of the co- and post-seismic deformation on interseismic rates. We did not remove data of the time-series. Another perturbation effect on the vertical uplift field is the occurrence, along the east of North Island, of slow slip events associated with the subducted Pacific plate (Delahaye et al., 2009; Wallace and Beavan, 2006, 2010). These events typically occur over periods of months to 5 yr and do not necessarily produce consistent patterns across the network, suggesting that regional filtering (Wdowinski et al., 1997) cannot be applied here without changing the overall pattern of the surface deformation. For these sites, rates ($\vec{v}$) should be described as "apparent" and decomposed as follows:

$$\vec{v} = \vec{V}_{int.} + \sum_{n=1}^{i} \frac{\vec{d}_{slow}}{\partial t}$$

where ∂t is the duration of each slow slip event and $\vec{d}_{slow}$ is the amount of vertical movement during a slow slip event. As $\vec{V}_{int.}$ and $\sum_{n=1}^{i}(\vec{d}_{slow})$ are of opposite signs they have opposite effects regarding the consequences of the global sea level rise occurring in the area. In this first study of cGPS for vertical uplift rates in New Zealand we have not tried to isolate the effect of slow slip as the cGPS time-series are still too short and corrections would require subjective judgments. Instead we note that, in the area where slow-slip events have occurred in the past 15 yr, computed rates are not truly representative of the interseismic deformation, but are only short-term apparent rates (Fig. 2). The equality between long-term inter-seismic rates and apparent ones depend on a complex function of both the number of slow slip events, and of their amplitudes. At the end of the process, horizontal velocities were available for 189 sites.

3. Results

3.1. Uncertainties

For 161 sites located in New Zealand, vertical rates were constrained with a formal accuracy of less than 2.0 mm/yr (Fig. 3). The vertical rate uncertainties depend on the number of operational days for each site in the network (Fig. 3). For 53 sites that are the oldest, with records >6 yr, an accuracy of <1 mm/yr was reached. In order to assess the quality of the GPS vertical rates, uncertainties reached after the combination of each sub-networks are plotted against the number of processed days for each station (Fig. 3c). Two parallel trends are visible in the station uncertainties pool: the stations with the lowest vertical uncertainties being those of the "LINZ" backbone array (www.geonet.org.nz). For those, uncertainty drops to less than 1 mm/yr after about 2000 days (~6 yr). Monuments quality, troposphere conditions and ground transients visible at the local scale are likely to be the main causes to explain why we observe two groups within the uncertainties data cloud.

3.2. The choice of level of reference for the vertical rates

In New Zealand, horizontal velocities are often referenced to a stable Australia plate although small strain rates ($<4.0 \times 10^{-8}$/yr) between Australia, Samoa and New Zealand can be inferred from regional GPS data analysis (Fig. 1). Choosing a reference for vertical rates is however less trivial. Geological estimates of uplift are

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