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Silent triggering: Aseismic crustal faulting induced by a subduction slow slip event

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ABSTRACT

Slow Slip Events (SSEs) are a form of fault slip behaviour whose importance has only been recognised in the last decade at subduction zone plate boundaries worldwide. Here, we show one of the first examples of the use of Interferometric Synthetic Aperture Radar (InSAR) data to document deformation during an SSE on the Hikurangi subduction interface in New Zealand. Although much of the deformation that we observe is attributable to slow slip on the subduction interface, the InSAR data also reveals surface offsets of up to 1–2 cm across a major crustal fault during the period of the slow slip event. In order to fit the observations, we find that reverse aseismic slip is required along a portion of the Wellington fault where the Coulomb Failure Stress changes (ΔCFS), due to the SSE, are in excess of 0.01 MPa. This is the first-ever documented example of a subduction interface SSE triggering a transient slip event on a major upper plate fault, and it has wide-ranging implications for the role that SSEs can play in time-dependent seismic hazard.

1. Introduction

Slow Slip Events (SSEs) involve transient aseismic slip across a fault at rates intermediate between plate boundary slip rates and those required to generate seismic waves. SSEs have been observed at subduction margins around the globe with equivalent seismic moment magnitudes ranging from Mw ∼6 up to ∼7 and fault slip of a few to tens of centimetres (Dragert et al., 2001; Miyazaki et al., 2006; Wallace and Beavan, 2010). Typically, land based GPS measurements are used to detect SSEs and determine the slip distribution along the plate interface. However, the coarse spacing of GPS sites can inhibit the precise determination of the slip distribution and potential interactions with neighbouring crustal faults. InSAR, unlike GPS, provides a high spatial density giving a more complete view of deformation at the Earth's surface. SSEs at most well-studied locales such as Cascadia and southwest Japan produce surface deformation that is too small (<5–10 mm) to detect with InSAR techniques. However, large SSEs in Mexico (Hooper et al., 2012; Cavalié et al., 2013; Bekaert et al., 2015) and New Zealand (Wallace and Beavan, 2006; Wallace et al., 2012) provide a unique opportunity to develop the use of InSAR as a new tool to contribute to investigations of this intriguing form of fault slip.

Numerous studies have shown that SSEs play a fundamental role in the accommodation of plate motion budget at subduction plate boundaries (Wallace and Beavan, 2010; Melbourne et al., 2005). Modelling studies have also suggested that SSEs can induce stress changes that may help to trigger large, megathrust earthquakes (Segall and Bradley, 2012). Seismological observations and data from seafloor pressure sensors suggest that the Mw 9.0 Tohoku earthquake in 2011 was actually preceded by a large SSE (Kato et al., 2012; Ito et al., 2013). It has long been recognised that earthquakes can be triggered by stress changes due to other earthquakes (King et al., 1994), but whether or not stress changes in the crust during SSEs can actually lead to slip on nearby crustal faults (e.g., not just on the subduction thrust) is still unknown. Upper crustal faults have been shown to exhibit creep following megathrust events (Shirzaei et al., 2012) and have been implicated in limiting the updip limit of slip during such events (Moreno et al., 2012). Better understanding of these issues has major implications for our understanding of time-varying seismic hazard, and our knowledge of the effective stress on faults. Here, we take advantage of the high spatial resolution offered by InSAR to document for the first time that aseismic slip on a crustal fault was triggered by slow slip on the subduction interface.

Subduction of the Pacific plate beneath the North Island of New Zealand occurs along the Hikurangi trench located less than

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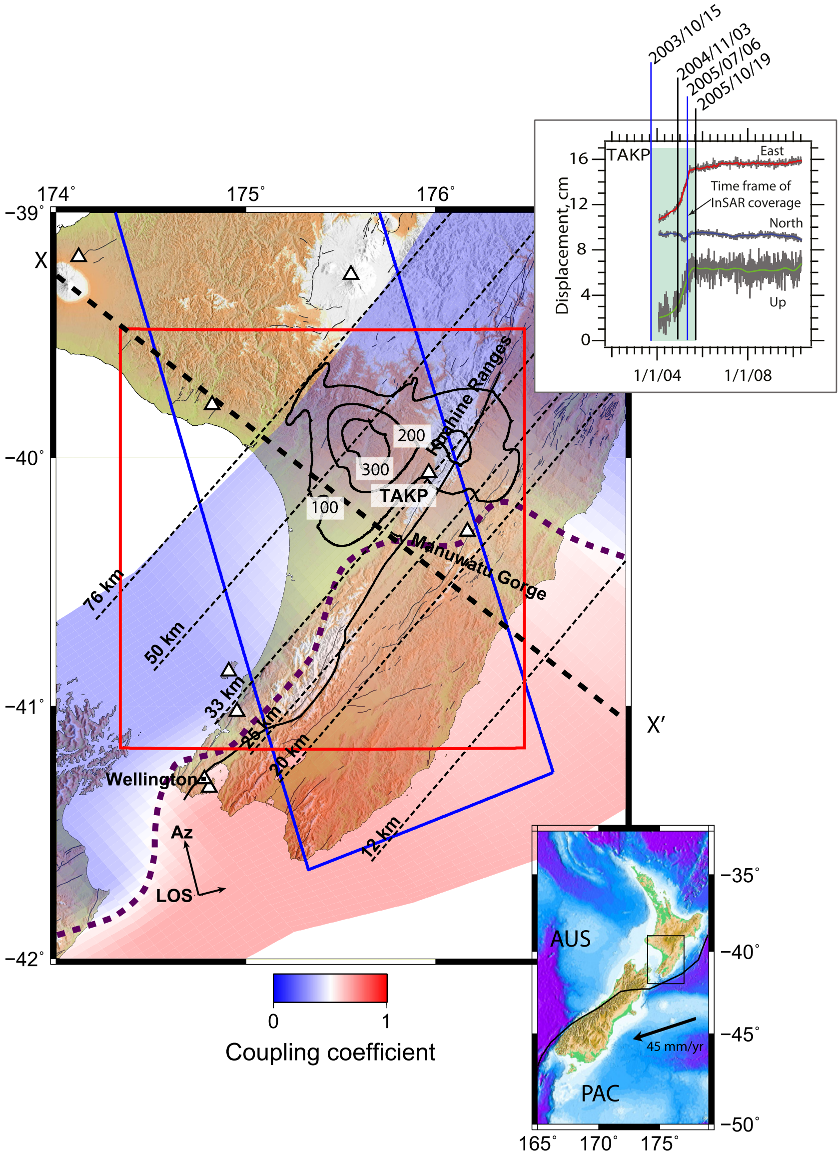

Fig. 1. Colour shaded relief map of the southern North Island, New Zealand. The lower right inset shows the location of the plate boundary between the Pacific (PAC) and Australian (AUS) plates with the relative motion between the two shown by the arrow. In the main figure, the red box shows the study area shown in Fig. 2; the blue rectangle shows the outline of InSAR track 423. The white triangles are the location of the continuous GPS sites used in the joint inversion; the solid black lines show the location of the Wellington/Mohaka fault. Dashed black lines show the depth contours of the modelled subduction interface. The black contours show the inferred slip distribution from the inversion of GPS data from Wallace and Beavan (2006). The overlay shows the slip rate deficit on the subduction interface (Wallace et al., 2012), the red regions indicate the locked zone. The graph to the upper right of the main figure shows the timeseries recorded at cGPS site TAKP during the slow slip with the period covered by the InSAR data highlighted. The profile along X–X′ is shown in Fig. 3 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

100 km offshore (Fig. 1). In the North Island, where Australia-Pacific convergence is oblique, margin normal relative plate motion is accommodated by a combination of shortening within the overriding plate (Nicol and Beavan, 2003) and slip along the shallow subduction thrust (Fig. 1), while the margin parallel component is accommodated via a combination of strike slip faulting (including the Wellington/Mohaka faults) and rotation of the forearc (Wallace et al., 2004). Since 2002, more than 20 SSEs have been detected by a network of continuous GPS (cGPS) instruments in a number of regions around the North Island (Wallace and Beavan, 2010, 2006; Wallace et al., 2012). SSEs at the northern Hikurangi margin largely occur along the offshore portion of the plate boundary making InSAR observations of surface deformation difficult. However, SSEs at southern and central Hikurangi margin are deeper. One of the largest SSEs at central Hikurangi began in January 2004 beneath the Manawatu region of the central North Island (Fig. 1). This event is ideally situated for investigation with InSAR as it occurs on a portion of the interface that completely underlies the land. The event can be separated into three sub events characterised by a migration in the slip location (Wallace et al., 2012); January–December 2004, December 2004–March 2005 and March–June 2005. The inversion of GPS data suggests slip of up to 350 mm over an area of ~75 km by 100 km with an equivalent Mw of ~7.0 (Wallace and Beavan, 2006). The 2004 Manawatu event occurred during a time when the cGPS network was relatively sparse, and only 11 cGPS sites were available to record deformation in the region during the event (Fig. 1). Analysis of two InSAR datasets from November 2004 to October 2005 and from October 2003 to July 2005 show clear deformation signals consistent with the observed cGPS displacements, allowing for a dramatic improvement in the spatial resolution of slip in the 2004 Manawatu SSE (Fig. 2). To fit the observations, we find that reverse aseismic slip is also re-