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Lake sediments record high intensity shaking that provides insight into the location and rupture length of large earthquakes on the Alpine Fault, New Zealand

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ABSTRACT

Understanding the seismic hazard posed by large earthquakes requires paleoseismic investigation because most faults have not ruptured repeatedly during the period of historic records. However, determining the location and length of fault ruptures using paleoseismic data remains challenging. Our study demonstrates that lake sediments record the high intensity shaking that occurs proximal to fault rupture, allowing the location and length of ruptures to be reconstructed. In two lakes adjacent to the Alpine Fault, New Zealand, seismic shaking is recorded as subaqueous mass-wasting derived turbidites formed by coseismic subaqueous slope failures, which are overlain by sets of hyperpycnites representing elevated fluvial sediment fluxes from earthquake-induced landslides. Precise radiocarbon age models show that shaking events are synchronous between the two lake sites and correlate with the timing of known Alpine Fault earthquakes. Modelled shaking intensities for the last two Alpine Fault earthquakes show that subaqueous mass-wasting occurs when shaking intensities exceed Modified Mercalli scale (MM) VI–VII, and that fluvial sediment fluxes from earthquake-induced landslides occur when shaking intensities exceed MM IX. The data demonstrate that lake records distinguish between strong (MM VI) and violent (MM IX) shaking at a lake site. The ability to map the spatial extent of MM IX shaking provides new insights into the timing and extent of rupture for the last five earthquakes on the Alpine Fault. The study demonstrates that lake deposits constrain the spatial extent of rupture during large earthquakes and may yield long records of the spatial and temporal patterns of fault rupture.

1. Introduction

Destructive earthquakes on continental plate boundary faults, such as the San Andreas Fault in California and the Alpine Fault in New Zealand, are generated by ruptures that can span hundreds of kilometres (De Pascale and Langridge, 2012; Weldon et al., 2005). Ruptures occur infrequently on these faults and therefore their seismic hazard can only be assessed by reconstructing rupture scenarios that include the timing, location and rupture length of sequential prehistoric earthquakes (Weldon et al., 2005). Accurate rupture scenarios require rupture frequency to be reconstructed from multiple sites along a fault, and reliable event correlation between sites (Goldfinger et al., 2007; McCalpin, 2009a; Weldon et al., 2005). The most common method for determining the timing of rupture is by trenching an active fault trace to reveal surface ruptures that can be dated using radiocarbon ages (McCalpin, 2009b). However, fault trenching can fail to identify some earthquakes because the preservation potential of ruptures often varies through time and it can also be difficult to extract reliable targets for radiocarbon dating (e.g. Berryman et al., 2012a; Fumal et al., 2002). As a consequence, the length of fault rupture is often estimated by correlating incomplete and poorly dated event sequences along strike. These characteristics make it difficult to distinguish between a single, long fault rupture and multiple ruptures on adjacent fault segments that are closely spaced in time (e.g. Weldon et al., 2005).

Paleoseismic approaches that make use of continuous records of large earthquakes can make an important contribution to the development of reliable rupture scenarios for plate boundary faults. In marine settings well dated and continuous records of seismoturbidites correlated along the Cascadia subduction margin and the northern San Andreas fault have provided critical insights

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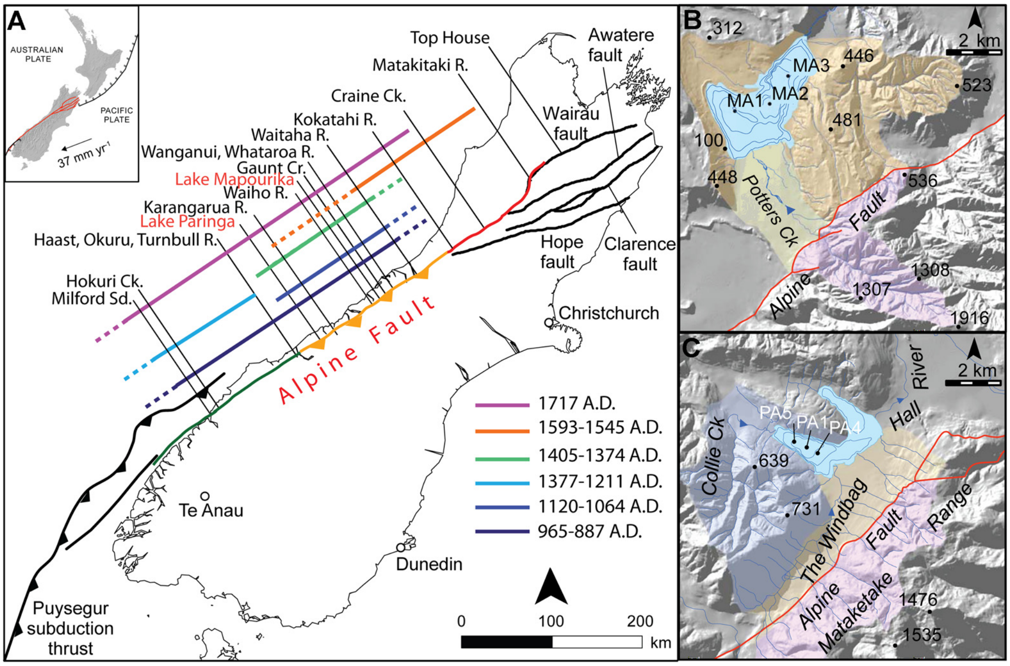

Fig. 1. Map of the Alpine Fault in southern New Zealand and the study locations. (A) shows the Alpine Fault's North Westland (red), Central (yellow) and South Westland (green) sections and earthquake rupture lengths for the last five events (colour coded) (south Westland section of the fault defined according to Barth et al., 2013). Solid coloured lines represent lengths of the fault that ruptured during an event, while dashed lines indicate where the end of rupture is not constrained by available data. The rupture lengths are inferred from published interpretations of the paleoseismic data from sites named on the map (Berryman et al., 2012a; Cullen et al., 2003; Howarth et al., 2012; Sutherland et al., 2007; Wells et al., 1999, 2001). The inset shows the location of the Alpine Fault (red) within the wider context of New Zealand. Maps of lakes Mapourika (B) and Paringa (C) show the lake catchments, their positions relative to the Alpine Fault, and sediment core sites within the basins. Catchment lithology is shown in blue = metasediments, pink = schist, and yellow = Quaternary gravels.

into the location and length of rupture along the plate boundary (Goldfinger et al., 2007, 2008; Goldfinger, 2011). Similar paleoseismic records may be generated from lake basins distributed along continental plate boundary faults because lake sediments provide a continuous record of past earthquakes as subaqueous slope failures form turbidite deposits when shaking intensities exceed Modified Mercalli (MM) VI–VII or equivalent (Inouchi et al., 1996; Monecke et al., 2004; Strasser et al., 2006). However, it is difficult to identify the source fault and rupture length of past earthquakes by correlating such deposits between lake basins because shaking intensities of MM VI–VII can be generated by proximal small earthquakes or by large earthquakes on distant faults. If lacustrine paleoseismic records are to provide information on the source fault and rupture length of earthquakes then they must distinguish between the high intensity shaking (MM IX) that occurs proximal to a ruptured fault plane (Smith, 2002) and lower shaking intensities generated by distal earthquakes.

Lake basins also record deposits formed during periods of elevated postseismic sediment flux driven by extensive earthquake-induced landsliding on catchment hillslopes (Avsar et al., 2014; Howarth et al., 2012). In mountainous regions the density of earthquake-induced landsliding is greatest over and immediately adjacent to a ruptured fault plane, where shaking intensities are highest (Keefer, 2000; Meunier et al., 2007, 2013; Yuan et al., 2013). The density of landsliding decreases significantly as shaking attenuates with distance from the fault rupture (Keefer 1984, 2000; Meunier et al., 2007). The relationship between shaking and landslide density is also preserved in the volume of sediment flux from catchments after an earthquake (Dadson et al., 2004). Consequently, the postseismic flux of material generated by landsliding is partly determined by the proximity of a catchment to fault rupture. If significant increases in post-seismic sediment flux can be linked to shaking intensities that exceed MM IX then mapping variations in postseismic sediment fluxes along major faults may provide first order constraint on the location and spatial extent of fault ruptures.

We hypothesise that deposits formed by large postseismic increases in sediment flux record MM IX shaking intensities that occur proximal to a ruptured fault plane. The hypothesis is tested using the sedimentary records from two lakes adjacent to the Central section of the Alpine Fault, New Zealand (Fig. 1). Deposits in the two continuous and well dated sedimentary records are compared with modelled isoseismals of shaking intensity for the last two earthquakes. This comparison is used to establish thresholds of shaking intensity required to drive the substantial increase in postseismic sediment flux that follows earthquakes on the Alpine Fault. The sedimentary records of paleo-shaking intensity provide new insights into the spatial and temporal rupture history for the Alpine Fault.

2. The Alpine Fault and its paleoseismic record

The Alpine Fault is an ~800 km long transform fault forming the boundary between the Pacific and Australian plates in southern New Zealand (Fig. 1a), and is one of the longest, straightest, and fastest slipping plate boundary transform faults on Earth (Berryman et al., 2012b). The terrestrial portion of the Alpine Fault has a relatively linear trace, differentiated on geomorphic and structural grounds into North Westland, Central and South Westland sections (Fig. 1a; Barth et al., 2013; Berryman et al., 1992). The Central section of the fault has a strike-slip rate of 27 ± 5 mm yr^{-1}, which accommodates ~70–75% of the plate parallel component of inter-plate motion (Norris and Cooper, 2001, 2007). Despite the high slip rate there have been no large earthquakes ($M_W > 7$) on the Alpine Fault during the period of historic records (c. 170 yr).

Paleoseismic studies suggest the South Westland section produces earthquakes with a quasi-periodic return period of 329 ± 68 years (Berryman et al., 2012b). However, rupture length is only