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Shallow fault segmentation of the Alpine fault zone, New Zealand revealed from 2- and 3-D GPR surveying

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ABSTRACT

Where they are preserved, landforms that have been truncated and offset by past fault movements provide potentially valuable quantitative data that can be used to estimate slip rates. At such locations, it is important to investigate the fault zone in sufficient detail to understand how displacements are accommodated on individual fault strands. At a site along a northern section of the Alpine fault zone on the South Island of New Zealand, surface mapping of a series of faulted river terraces and channels has revealed a complicated and poorly understood paleoearthquake history. We have acquired high-resolution 2- and 3-D ground-penetrating radar (GPR) data over a large area (~500 × 500 m) of the terraces to map along-strike changes in shallow (<20 m) fault zone morphology. By identifying distinct reflection patterns within the topographically migrated 3-D GPR volumes and extrapolating them to the longer and more widely spaced GPR profiles, we determined the subsurface extent of two main structural/depositional facies that were juxtaposed by three left-stepping en-echelon fault strands. Two regions of warped strata are interpreted to result from transpressive folding between the overlapping strands, where displacement is transferred from one fault to the next. We suggest that diffuse deformation between the overlapping fault tips results in anomalously low estimates for horizontal and vertical fault displacements of some geomorphic features.

1. Introduction

By mapping landforms displaced by pre-historic earthquakes, important physical parameters associated with active faults can be estimated. In the case of strike-slip faulting, slip rates can be derived from offsets of dated geomorphic markers like fluvial terraces, alluvial fans, and moraines (e.g. Van Dissen and Berryman, 1996; Brown et al., 2002; Cowgill, 2007). Unfortunately, modifications by burial and erosion may mean that the surface expression of more subtle deformational structures (e.g. stepovers and folding) may not be preserved. Such structures are potentially important indicators of how fault rupture at depth is manifest at the surface. For example, detailed surface mapping of deformation produced by recent strike-slip dominated earthquakes has revealed evidence for distributed slip on multiple principal and minor fault strands (e.g. 1992 Landers (Sieh et al., 1993), 1999 İzmit (Barka et al., 2002) and 1999 Düzce (Pucci et al., 2006) earthquakes). High-resolution ground-penetrating radar (GPR) surveying provides a means to image shallow complex structures not evident at the surface (e.g. Smith and Jol, 1995; Yetton and Nobes, 1998; Green et al., 2003; Liberty et al., 2003; Gross et al., 2004; Tronicke et al., 2006; McClymont et al., 2008a, 2008b).

The Alpine fault zone is a major continental transform fault zone on the South Island of New Zealand (Fig. 1a). Since the fault has not ruptured during the past ~200 years of European settlement in New Zealand, most of our present understanding of the probable recurrence time and damaging effects of future major ruptures (>magnitudes 7.5) is based on paleoseismic investigations (Cooper and Norris, 1995; Wells et al., 1999; Sutherland et al., 2006).

At a few locations along the Alpine fault zone, flights of offset fluvial terraces provide potentially useful late Pleistocene and Holocene chronologies of fault movement. One such location is at Calf Paddock, where northeastward migration of a section of the Maruia River has left behind a sequence of at least four terraces that have been offset horizontally and vertically by transpressive movement along the fault (Figs. 1b and 2a; Wellman, 1952; Berryman, 1975). Unfortunately, the pattern of progressively offset terrace risers and paleochannels is not well understood; some displacement may have been transferred to one or more overlapping fault strands (Berryman, 1975; Yetton, 2002). Because the geometries of the youngest fault strands are not well

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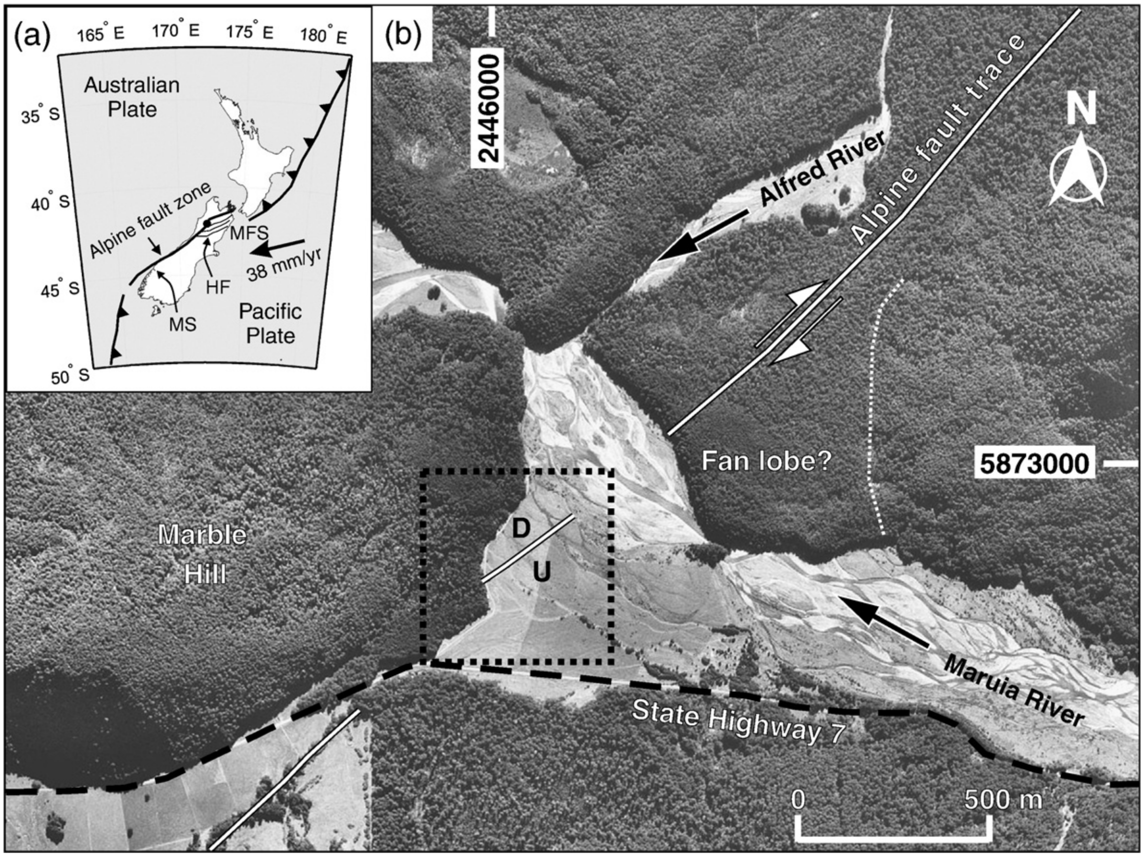

Fig. 1. (a) New Zealand plate-boundary setting showing locations of the Alpine fault zone (bold line), Marlborough Fault System (MFS; thin lines), Milford Sound (MS), Hope fault (HF) and survey location (black dot). (b) Aerial photo showing location of Alpine fault trace across abandoned river terraces on the southwest side of the Maruia River. Black arrows—river flow directions; white arrows—sense of slip; D and U—locally downthrown and upthrown sides of the fault, respectively; dashed line—State Highway 7; dotted square—region shown in Fig. 2a. Coordinates are New Zealand Map Grid (NZMG).

known, no attempt has been made to date systematically the terraces to determine a representative slip rate.

An early seismic refraction, gravity and drilling investigation determined that the Alpine fault zone at Calf Paddock dips steeply (>65°) to depths >83 m, but did not elucidate the geometry of shallow strands responsible for the pattern of displacements at the surface (Garrick and Hatherton, 1974). A 3-D GPR data set acquired in 2003 using 100 MHz antennas over an ~30 × 115 m area across the principal fault strand (3D1; Figs. 1a and 2b) imaged a steeply dipping fault plane (~80°) in the near surface (<15 m) and revealed evidence for off-fault folding and tilting within a broad ~50-m-wide zone of deformation (McClymont et al., 2008a). From interpretations of a recently acquired ultra-high-resolution reflection seismic profile over the same area, Kaiser et al. (2009) have demonstrated that the fault dips at 75–80° to the southeast and offsets vertically the dipping surface of underlying Triassic and Paleozoic basement units by ~35 m.

In 2006, additional 2- and 3-D GPR data were collected using 100 and 200 MHz antennas over a much larger (~500 × 500 m) section of the fault zone at Calf Paddock to investigate along-strike variations in fault zone structure and to image the postulated overlapping fault strands (e.g., A–A′–K–K′; 3D2; Fig. 2). Here, we combine interpretations from all of the 2003 and 2006 GPR data in an attempt to map in detail the shallow fault zone structures that have affected the river terraces.

We begin by reviewing the tectonic setting of the Alpine fault zone and geology at the Calf Paddock study site. After outlining details of the acquisition and processing of the GPR data, we present an interpretation of fault zone structures imaged by our two 3-D datasets. Our structural and depositional model is then used as a basis for interpreting features imaged by our 2-D profiles, which cover much longer sections of the fault zone. Using interpretations of these data we develop a detailed structural model of the fault zone at Calf Paddock. Finally, we reconcile our structural model with geomorphic observations to explain the pattern of fault offsets observed at the surface.

2. Tectonic setting

2.1. Paleoseismicity of the Alpine fault zone

The Alpine fault zone is a major right-lateral transpressive structure that transects the South Island of New Zealand (Fig. 1a). It extends for at least 800 km and accommodates around two thirds of the 30–40 mm/year of relative convergence between the Pacific and Australian Plates (Sutherland et al., 2007). Although the fault zone appears to be remarkably straight on aerial photographs, detailed mapping shows that in places it exhibits recent short en-echelon strands and stepovers, typical of a strike-slip fault (Berryman et al., 1992; Sutherland and Norris, 1995; Norris and Cooper, 2007).

Late Quaternary geological data indicate that strike-slip and dip-slip rates reach maxima of 27 ± 5 mm/year and 8 ± 3 mm/year, respectively, along a well defined central segment of the Alpine fault zone between Milford Sound (MS) and its intersection with the Hope fault (HF in Fig. 1a; Norris and Cooper, 2001). Displacement rates along the Alpine fault zone decrease north of the confluence with the Hope fault, where the Pacific–Australia plate-boundary