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Recent deformation of Quaternary sediments as inferred from GPR images and shallow P-wave velocity tomograms: Northwest Canterbury Plains, New Zealand

S.F.A. Carpentier [a,*], A.G. Green [a], J. Doetsch [a], C. Dorn [a,1], A.E. Kaiser [a], F. Campbell [a], H. Horstmeyer [a], M. Finnemore [b]

[a] ETH Zürich, Institute of Geophysics, Zürich, Switzerland
[b] Southern Geophysical Ltd, 28/3 Tanya Street, Bromley, Christchurch, New Zealand

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ABSTRACT

Prior to the recent highly damaging M 7.1 earthquake near the city of Christchurch on the South Island of New Zealand, we recorded coincident high-resolution seismic and ground-penetrating radar (GPR) data across parts of the northwest Canterbury Plains. The seismic reflection images reveal a vast network of interconnected faults and folds below a seemingly undisturbed flat surface. To complement the seismic images, which only provide limited information on the very shallow subsurface (i.e., <20 m), we have now processed and analysed the GPR data. The migrated GPR images are dominated by complex reflection patterns characteristic of glaciofluvial sediments. Such sediments eroded from the Southern Alps are observed at the surface throughout our study site. Although it is difficult to distinguish between complexities associated with complicated sedimentation processes and disruptions and offsets of GPR reflections associated with recent movements on faults and folds, we identify a number of regions where the GPR data are consistent with tectonic deformation of Holocene sediments. Two of these regions straddle an interpolated connection between active faults mapped at the surface. In a third region, the development of river terraces imaged in the GPR data may have been affected by slip on newly discovered underlying faults. The most significant near-surface deformation, which is apparent on a coincident seismic reflection image, P-wave tomogram and GPR image, is observed on the flank of a major anticline that appears to have been thrust close to the surface along a reverse fault. Some of the faults and folds resolved in our seismic and GPR data may have been reactivated during the recent period of intense seismicity.

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1. Introduction

Buried or blind faults that have the potential to rupture as large earthquakes make the construction of reliable seismic hazard and risk maps extremely difficult in numerous regions worldwide (Ambraseys, 1981; Calais et al., 2010; Dolan et al., 2003; Feng et al., 2010; Guzofski et al., 2007; Jackson, 2006; Leon et al., 2009; Lettis et al., 1997; MonaLisa et al., 2007; Shyu et al., 2005; Talebian et al., 2004). Since ruptures on such faults may cause dislocation or folding of the overlying strata, their presence at some locations may be deduced from detailed geomorphological studies and/or paleoseismological and geophysical investigations of the shallow sedimentary units. In this contribution, we image faults and folds using a combination of high-resolution seismic reflection and ground-penetrating (GPR) profiling.

The geology between the Pacific Ocean and the Southern Alps of New Zealand (Fig. 1) is largely hidden beneath a variably thick veneer of relatively young (<24 ka) Quaternary glaciofluvial sediments that creates the remarkably flat and even landscape of the Canterbury Plains (Fig. 2). Extensive exposures in the foothills of the Southern Alps and the Malvern Hills together with isolated outcrops along the banks of the Waimakariri River and adjacent uplifted hills suggest that the geology underlying the northwest Canterbury Plains (Forsyth et al., 2008) is extremely complex. These exposures and small outcrops reveal Permian–Triassic Torlesse Group basement rocks overlain by Late Cretaceous–Tertiary interbedded sedimentary and volcanic layers, all of which are highly faulted and folded. Relatively old (>59 ka) Quaternary glaciofluvial sediments that are less faulted and folded are observed at a number of locations.

Because several of the exposed faults and folds offset or disrupt Holocene sediments, they have been classified as active (Campbell et al., 2000; Dorn et al., 2010; Estrada, 2003; Forsyth et al., 2008; May, 2004; McLennan, 1981). Low levels of seismicity recorded prior to 2010 (e.g., two M 5+ events since 1974 and two M 4+ events in 2009) appeared to support the hypothesis that this region of the South Island is tectonically unstable (Dorn et al., 2010). In September and October 2010, a highly damaging M 7.1 earthquake and a large number of aftershocks (e.g., twelve M 5.0–5.9 and one hundred and thirty three M 4.0–

* Corresponding author at: Institute of Geophysics, Dep. of Earth Sciences, ETH, Sonneggstr. 5, CH-8092, Zurich, Switzerland. Tel.: +41 44 6332659.
E-mail address: carpentier@aug.ig.erdw.ethz.ch (S.F.A. Carpentier).
[1] Now at the Institute of Geophysics, University Lausanne, Lausanne, Switzerland

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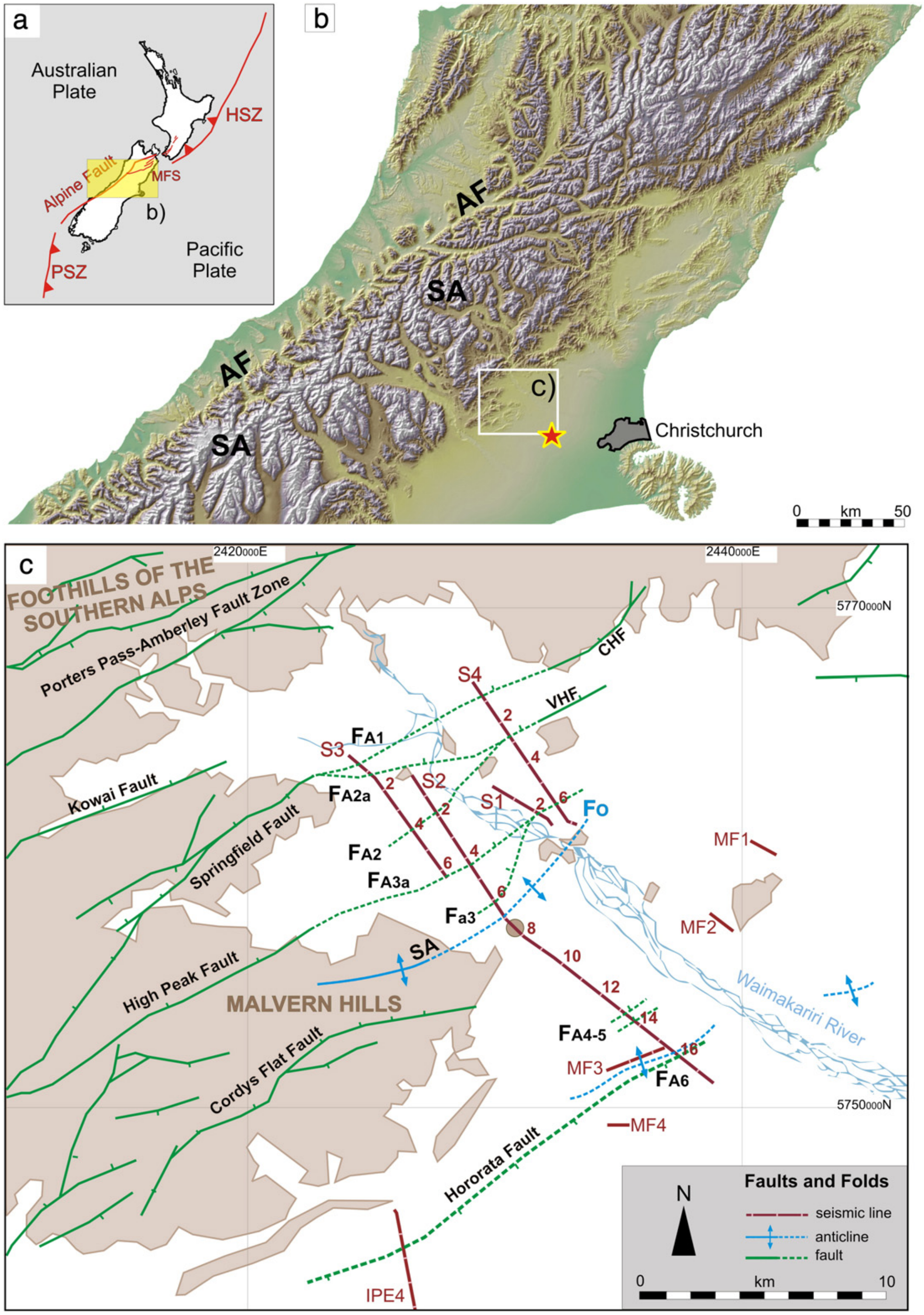

Fig. 1. (a) New Zealand tectonic setting showing the Hikurangi Subduction Zone (HSZ), Marlborough Fault System (MFS), Alpine Fault and Puysegur Subduction Zone (PSZ). (b) Topography of the central part of the South Island (yellow box in (a) shows the location of the image). Note the extremely flat landscape across large parts of the region delineated by the white box. Star shows the location of the M 7.1 earthquake of September 4 (2010). (c) Simplified map of the northwest Canterbury Plains, adjacent mountains and hills, interpreted and interpolated faults (FA) and folds (FO), and seismic reflection/refraction lines (white box in (b) shows the location of the map; modified after Dorn et al., 2010). GPR data were recorded along seismic lines S2, S3 and S4. Rock outcrops are delineated by beige coloured regions. CHF – Chalk Hill Fault, VHF – View Hill Fault, SA – Sheffield Anticline. The circle along S2 identifies the small town of Sheffield.

4.9 events within 60 days of the main event; GeoNet, 2010) on faults hidden beneath the Canterbury Plains and adjacent areas removed any doubt about the dynamic nature of this region (Fig. 3).

Prior to the high levels of seismicity in late 2010, we recorded high-resolution seismic reflection data along the four lines S1–S4 in Fig. 1c with the goal of mapping the faults and folds underlying the northwest Canterbury Plains Dorn et al. (2009, 2010). We also took advantage of the four short seismic reflection lines M1–M4 acquired by Finnemore (2004) and the northern end of the industry seismic reflection line IPE4 described by Jongens et al. (1999). This area was chosen for study because of the nearby rock exposures and isolated rock outcrops (Fig. 1c). The fully processed and migrated seismic reflection images (Fig. 4) revealed an

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