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Accommodation of compressional inversion in north-western South Island (New Zealand): Old faults versus new?

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Abstract

In the NW South Island, New Zealand, high-angle faults inherited from episodes of Late Cretaceous–Paleocene and Eocene extension have, since the early Miocene, undergone compressional inversion in association with right-lateral shearing and transpression on the Alpine Fault. Active reverse faulting and large historical earthquakes occur along N–S to NNE–SSW trending faults which at the surface dip 45–75° to both the east and west. The faults truncate subparallel folds that deform the Tertiary sequence overlying a composite Paleozoic–Mesozoic crystalline basement. However, the deep geometry of these faults, their penetration into the middle-to-lower crust and their relationship to the Alpine Fault are poorly understood. The tectonic architecture of this compressional inversion province is analysed by reconstructing structural contours at the base of the Oligocene carbonate sequence in the north-west of the South Island. Deformation of the Oligocene carbonate sequence, structural analyses in the field and subsurface data indicate a mixed style of inversion with (1) reactivation of some high-angle normal faults and (2) thrusting on new, moderate-dipping cross-cutting faults that detach slivers of basement and cause flexural folding in the sedimentary cover. These faults may remain blind or concealed beneath cover sequences but are likely to control seismic rupturing in the basement at depths of ~10–15 km.
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1. Introduction

The crustal architecture of the South Island of New Zealand is dominated by lithological and structural heterogeneities, inherited from a complex sequence of tectonic events. Following collision and accretion of Terranes on the Gondwana margin during the Tuhua (Devonian–Carboniferous) and Rangitata (Jurassic–Early Cretaceous) orogenies (Bishop et al., 1985), the continental block of New Zealand separated from Australia and Antarctica during episodes of Middle–Late Cretaceous and Late Cretaceous–Paleocene rifting in the Tasman Sea (Nathan et al., 1986). Spreading halted in the Late Paleocene (c. 56 Ma), but a new extensional plate boundary was initiated at c. 45 Ma across the South East Tasman and Emerald Basins (Fig. 1), and propagated into continental crust on the western margin of the South Island (Lebrun et al., 2003). In the late Eocene–Oligocene, an alignment of extensional basins extended across the whole length of the South Island and in the Taranaki region (King, 2000). During the time interval 25–20 Ma, a change in orientation of the Pacific–Australia plate motion vector initiated the processes of oblique compression across the plate boundary (Sutherland, 1995). Timing of the inception of the Alpine Fault remains controversial (see Sutherland, 1999 for a discussion), but plate reconstructions (e.g. Sutherland, 1995; King, 2000) constrain the establishment of a through-going right-lateral transform to around 25 Ma (late Oligocene–Early Miocene), with a progressive increase in convergence rates since the late Miocene (10 Ma).

With average strike-slip rates of 25–30 mm year^{-1} the Alpine Fault has taken up 60–80% of the Australia–Pacific

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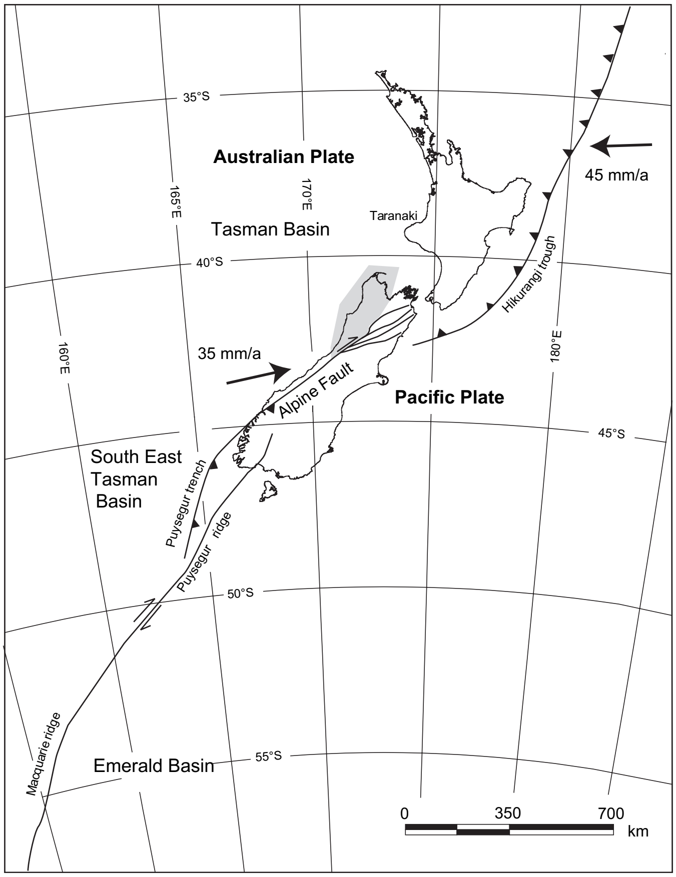

Fig. 1. Regional setting of the study area (in light grey) relative to the transpressive Australia–Pacific plate margin in the South Island and the Alpine Fault. Interplate slip vector from Nuvel 1A model of DeMets et al. (1994).

lateral motion in the last 5 Ma (Figs. 1 and 2). In contrast, dip slip rates vary significantly along strike (from 2 to 8 mm year^{-1}; cf. Norris and Cooper, 2000) on fault segments dipping 45–70° SE. Thus, a significant fraction of the plate-perpendicular shortening is not accommodated along the Alpine Fault and is likely partitioned onto an array of other faults and folds.

Quaternary strike-slip and thrust faulting (Norris and Cooper, 1995, 2000) and GPS data (e.g. Holt and Haines, 1995; Beavan and Haines, 2001) indicate accumulated and ongoing deformation over a wide area in the hanging-wall of the Alpine Fault, consequent on crustal thickening within the Pacific plate in the convergent collisional orogen of the Southern Alps (Norris et al., 1990).

In contrast, deformation of the Australian plate is generally regarded as being of lower intensity, with passive flexuring and underthrusting along the west margin of the South Island (e.g. Koons, 1990). However, accommodation of shortening in the Australian plate west of the Alpine Fault is well testified by Neogene inversion of Late Cretaceous and Eocene normal faults along the western margin of the South Island (Wellman, 1949; Bishop and Buchanan, 1995) and in the Taranaki Basin (King and Thrasher, 1996). In these regions, offshore seismic data and geological mapping on land (Nathan et al., 1986; Bishop, 1992a) show that high-angle, N–S faults have controlled—through multiple episodes of compressional inversion—localisation and progressive foundering of the Miocene–Pliocene siliciclastic basins, contemporaneous with activity on the Alpine Fault. In addition, the two largest earthquakes of the last century in the South Island (1929 Buller M_s 7.8, and 1968 Inangahua M_s 7.4) occurred in the region west of the Alpine Fault, and were generated by reverse faulting (with secondary components of left-lateral slip) on N–S fault planes, respectively dipping 45° east and west (Anderson et al., 1994; Doser et al., 1999). From inversion of focal mechanisms in the northern South Island Balfour et al. (2005) deduce a compressional contemporary stress field with the greatest compressive stress σ_1 subhorizontal and trending 295 ± 16°. Moderate to steeply dipping seismically active N–S faults therefore dip at high angles to σ_1, and are poorly oriented for frictional reactivation in the contemporary stress field (Sibson, 1990). A number of studies have focused on different structural characteristics of the deformed Australian crust (e.g. Berryman, 1980; Lihou, 1993; Anderson et al., 1994; Pettinga and Wise, 1994; Bishop and Buchanan, 1995; Kamp et al., 1996; Yeats, 2000; Nicol and Nathan, 2001), but the percentage of plate-perpendicular shortening partitioned onto faults in the Australian crust is largely unquantified. In fact it remains unclear whether deformation is distributed through a large network of faults or is associated with reactivation of a few master faults with very long recurrence intervals (e.g. Anderson et al., 1993).

Understanding selectivity of fault reactivation and slip partitioning in an array of faults are problems common to many inversion provinces (e.g. Buchanan and Buchanan, 1995). The South Island of New Zealand offers favourable conditions to address these problems because of the well-documented sequence of syntectonic sedimentary events (Nathan et al., 1986), coupled to high rates of deformation in one of the most active oblique margins in the world.

The aim of this paper is: (1) to assess the fault geometry in the footwall of the Alpine Fault in the NW of the South Island; (2) to define the style of compressional deformation—thin-skinned detachments vs. fault penetration into the basement, and (3) to evaluate the partitioning of shortening between folding, reactivation of old faults, and creation of new faults. The analysis is based on the reconstruction of the structural contours of a key marker horizon (the base of the Oligocene carbonate sequence), and is complemented by structural analyses in selected key areas, and available seismic profiles and drill-holes. Interpretation of these data is summarised in a regional cross-section that emphasizes the coexistence of inverted, steep faults inherited from earlier extensional phases, moderate-dipping blind thrust faults favourably oriented in the present stress regime, and layer-parallel detachments within folded sedimentary covers. The geometry of faulting in the lower-mid crust and structural connections to the Alpine Fault remain highly speculative, but analysis of available data and quantification of shortening suggest that blind thrusts, concealed beneath thick panels of detached sedimentary cover, may rupture in large earthquakes at 10–15 km depth. Given the short-term historical record of seismic activity in New Zealand,

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