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Review article

Continental transforms: A view from the Alpine Fault

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A B S T R A C T

Continental transform faults are dominantly highly localized strike-slip shear zones hundreds of kilometers long that accumulate tens to hundreds of kilometers of displacement. From work on the Alpine Fault, we pose the questions: what is the deep structure of a continental transform, and how does the displacement become localized? We review research on the Alpine Fault and propose a model in which the fault partitions at depth into a steep zone extending into the mantle with largely fault-parallel motion and a flat ductile decollement in the lower crust. The fault localizes around two-thirds of the plate motion within a 100 km wide zone of distributed deformation. A review of other active continental fault systems suggests that variation between them may reflect their tectonic origins, the nature of the crust in which they develop, the presence of a significant oblique component of motion, and the displacement rate. All however have evidence for the development of a single principal fault zone that carries ≥50% of the total displacement and extends as a localized zone of shear into the upper mantle. We review mechanisms of strain weakening and suggest that localization of a principal fault may be initiated in the seismogenic crust and through a series of positive feedbacks eventually extend through the lower crust into the upper mantle.

1. Introduction

The upper seismogenic part of the continental crust, commonly around 10–15 km thick, deforms predominantly in a brittle fashion by shearing along discrete faults (e.g. Sibson, 1983). This deformation style is normally accompanied by the release of seismic energy, in many cases producing observable earthquakes. A great deal of research has been carried out on the mechanisms of initiation and reactivation of brittle faults ranging from small structures with millimeters of displacement to larger structures with hundreds of meters of displacement (e.g. Martel et al., 1988; Aydin and Schultz, 1990; Peacock, 1991; Peacock and Sanderson, 1993; Aydin and Berryman, 2010). In general, these upper crustal faults obey Coulomb friction criteria as set out by Anderson (1942) and Byerlee (1978) (Sibson, 1994; Sibson et al., 2011) except where there are clear pre-existing low strength zones (e.g. bedding, older fault zones, Yeats, 1986; Sibson, 1990) or high fluid pressures.

A few faults, however, cut through the entire seismogenic zone of the continental crust and penetrate into the lower visco-elastic crustal layers (e.g. Sibson, 1977, 1983). These tend to be higher slip-rate faults and many currently active examples form part of present-day plate boundaries. Some may even cut through the entire crust and extend into the upper lithospheric mantle (e.g. McGeary, 1989; Stern and McBride, 1998). The mechanisms of deformation and overall rheology of these faults within the lower crust are likely to be quite different from the frictional mechanisms in the seismogenic zone. The lack of seismic activity indicates an aseismic continuous creep behavior with viscous dissipation of elastic strain (e.g. Sibson, 1983; Hanmer, 1988; Handy et al., 2007). These crustal-scale fault zones are therefore complex in terms of their rheological behavior and involve deep coupling between continuous and discontinuous deformation regimes. The high slip rates and large total displacements imply they represent major zones of localization of displacement and strain. They produce earthquakes capable of causing significant risk to life and property. Because of this, a great deal of effort has been made to understand the structure, mechanics and evolution of crustal-scale faults, utilizing geophysical measurement, geological observation and experimental investigations.

In this article, we review some of the major questions highlighted by work on the Alpine Fault of New Zealand, work with which we both have been closely associated, and compare the Alpine Fault data with other well-studied active crustal-scale continental fault zones such as the San Andreas Fault of California, the

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North Anatolian Fault of Turkey, the Dead Sea Transform, and the Altyn Tagh Fault of Tibet.

2. The Alpine Fault

The Alpine Fault of New Zealand is one of the world's major active crustal-scale faults, and currently represents the principal structure defining the Australian/Pacific plate boundary in the South Island of New Zealand (Fig. 1). It was one of the first continental transforms to be recognized as a major strike-slip fault with hundreds of kilometers of displacement (Wellman and Willett, 1942; Wellman, in Benson, 1950). The timing of the displacement was a matter of controversy, with the majority view (e.g. Suggate, 1963) favoring a mainly Cretaceous age. With the development of plate tectonic theory, and observations of surface displacements (Wellman, 1953, 1955), an entirely Cenozoic age of development of the fault was proposed and became more generally accepted (e.g. Wellman, 1971; Molnar et al., 1975; Carter and Norris, 1976; Walcott, 1978). As work on the sea-floor spreading data from the southern oceans accelerated, better estimates for the magnitude and timing of displacements through New Zealand were developed (e.g. Molnar et al., 1975; Walcott, 1978; DeMets et al., 1994; Sutherland, 1995; Cande and Stock, 2004).

The present rate of plate motion in the central South Island has been determined from two main data sources, global and local sea-floor spreading data averaged over the last 3 Ma or so (DeMets et al., 1994; Cande and Stock, 2004) and satellite geodetic data collected over the last 20 years (Beavan et al., 1999, 2002, 2007). DeMets et al. (2010) use both data sources in their revised global model, although, as with their Nuvel-1A model (DeMets et al., 1994), no data from the Australian/Pacific plate boundary are used. The various estimates of current rates of interplate

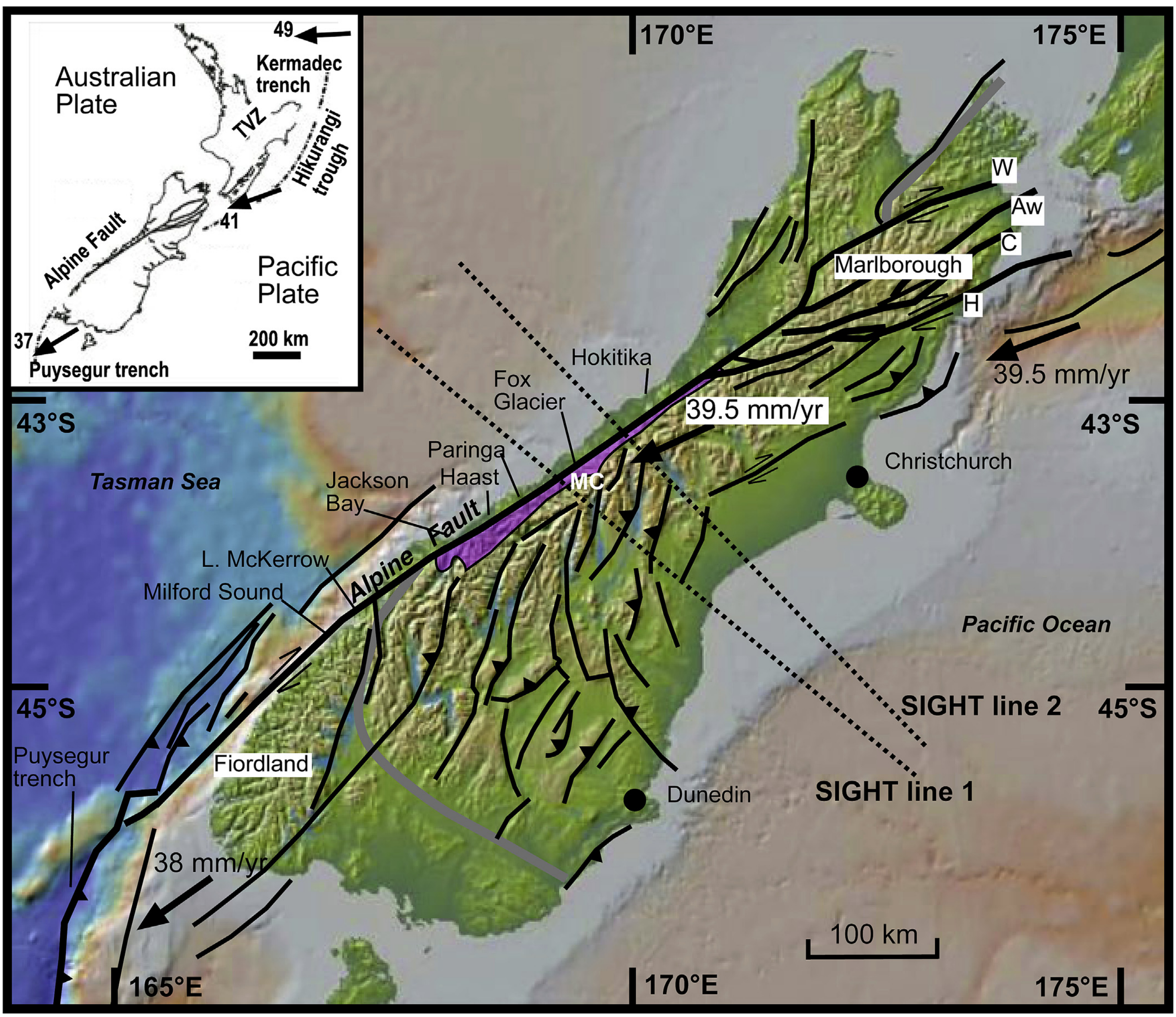

Fig. 1. Map of South Island showing topography, Alpine Fault and other significant faults (based on Litchfield et al., 2014: note that for clarity, not all mapped faults are shown). Heavy arrows show interplate slip vector calculated from Morvel global model (DeMets et al., 2010). Area of purple shading adjacent to Alpine Fault depicts area of exhumed amphibolite facies schists. Dashed lines are lines of SIGHT geophysical transect (Stern et al., 2007). Inset map shows wider tectonic setting of New Zealand. Heavy arrows with numbers show direction of plate motion between the Pacific and Australian plates and rate in mm/yr, calculated from the Morvel-1 solution (DeMets et al., 2010). The Morvel-1 Euler pole for the two plates is located at lat. 60.1°S, long. 173.7°W, i.e. to the SE of New Zealand. TVZ: Taupo Volcanic Zone.