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Effect of strain-weakening on Oligocene–Miocene self-organization of the Australian-Pacific plate boundary fault in southern New Zealand: Insights from numerical modelling

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ABSTRACT

Tectonic inheritance acquired from past geological events can control the formation of new plate boundaries. The aim of this paper is to explore the role of inherited NE and NW trending fabrics and their rheological influence on the propagation of Oligocene–Miocene strike-slip faulting that matured to become the Australian-Pacific plate boundary fault in southern New Zealand. Strain weakening plays a significant role in controlling the formation, growth and evolution of strain localization. In this study, three-dimensional thermo-mechanical models have been used to explore the effect of strain weakening on the Oligocene–Miocene self-organization of strain localization. Strain weakening is simulated through decreasing either the coefficient of friction of upper crust, its cohesion, or the rheological viscosity contrast between the inherited structures and their surrounding wall rocks. Viscosity contrast is obtained by varying the viscosity of inherited structures. Softening coefficient (α) is a measure of strain weakening. Our experiments robustly demonstrate that a primary boundary shear zone becomes mature quicker when softening coefficients are increased. Deformation is focused along narrow high-strain shear zones in the centre of the model when the softening coefficients are high, whereas the strain is more diffuse with many shear zones spread over the model and possibly some high-strain shear zones focused near one border at lower softening coefficients. Varying the viscosity contrast has less effect on the distribution of maximum finite strain.

Under simple-shear boundary conditions, NW trending inherited structures make a major contribution to forming early zones of highly focused strain, up to a shear strain of about $\gamma = 3.7$. During this process, most NE-trending structures move and rotate passively, accommodate less strain, or even be abandoned through time.

1. Introduction

Continental deformation originates from the local concentration of strain resulting from heterogeneous stress fields and the persistent evolution of discrete weaknesses (Sutherland et al., 2000; Ariyoshi et al., 2009). Most discontinuities are deformed into linked networks of faults and shear zones through geological time (Tavarnelli and Pasqui, 2000; Aktug et al., 2013; Jessell et al., 2005, 2009, 2012; Chousianitis et al., 2013). These shear zones have a lower resistance than that of their surrounding wall rocks (Rutter et al., 2001). The sliding stability of a shear zone is controlled by frictional properties (Scholz, 1998; Carpenter et al., 2012) and accommodation of net shear strain (Beeler et al., 1996; Marone, 1998; Ikari et al., 2011).

The formation and growth of faults are mainly influenced by heterogeneous stress fields (Chester et al., 1993), characterized by systematic increase in displacement and length relating to earthquake slip events on a regional scale or by relative motion of plates on a larger scale (Walsh and Watterson, 1987, 1988; Scholz and Cowie, 1990; Dawers et al., 1993; Kokkalas and Doutsos, 2001;

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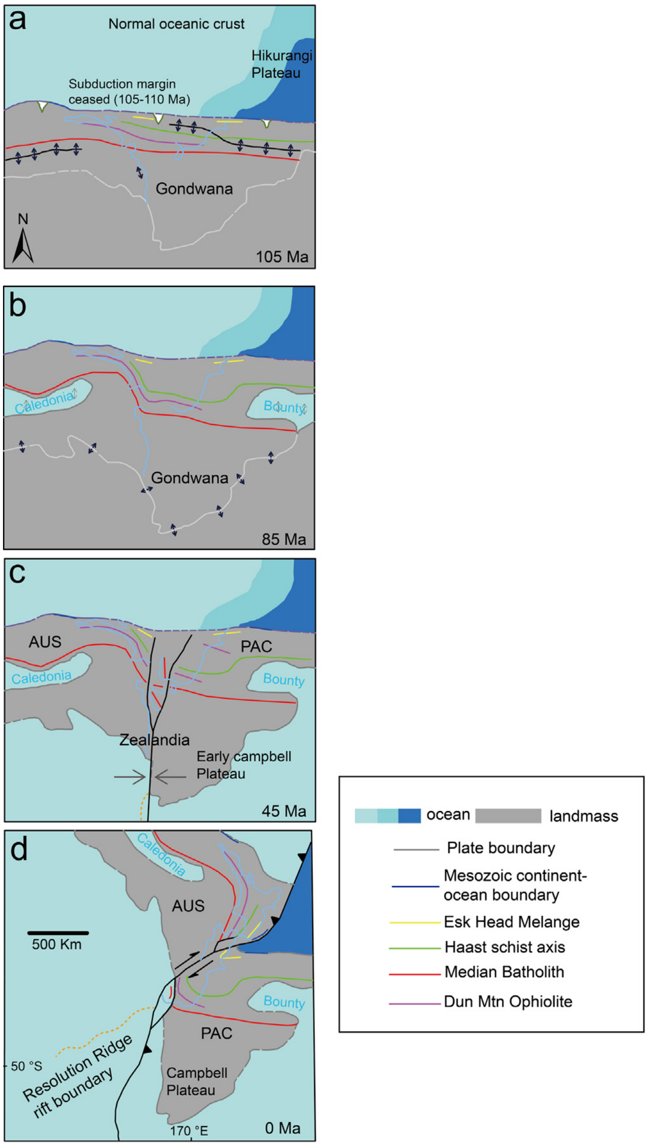

Fig. 1. Schematic diagram, showing the evolution of the Australian-New Zealand plates from Cretaceous to recent time (modified after Mortimer, 2014).

Walsh et al., 2003; Kim and Sanderson, 2005; Xu et al., 2010). With regards to global tectonics, plate boundary faults (such as the Alpine Fault and the San Andreas Fault) play a dominant role in the formation of lineaments observed at the present day (Woodcock and Daly, 1986), as well as the accommodation of plate motion (Dokka and Travis, 1990). Rheological heterogeneity and mechanical anisotropy in the lithosphere resulting from past tectonic events commonly provide preferential zones for strain concentration, which are thought to play a dominant role in controlling the formation of new plate boundaries (Vauchez et al., 1998; Thomas, 2006; Audet and Bürgmann, 2011). For example, during the Pangaea breakup, tectonic inheritance of large scale structures coincides with the distribution of large transform offsets of the continental margins (cf. Bahamas transform margin in Thomas (2006) and Whalen et al. (2015)).

Inherited structures within the crust can play a significant role in initializing the distribution and controlling the evolution of deformation and relief (Dooley and Schreurs, 2012; Tong et al., 2014; Feng et al., 2016). Such inherited structures can offer favoured sites for strain accumulation because of their function as a stress concentrator with respect to the host rock (Jessell and Lister, 1991; Jessell et al., 2008). This is manifested by the operation of narrow and foliated high strain zones through geological time (Tchalenko, 1970). Within a shear zone, strain can either focus in intensity towards the central part of the shear zone, or as a localized simple shear component within the broader high strain zone (Fossen and Tikoff, 1998; Dooley and Schreurs, 2012; Gueydan et al., 2014).

In southern New Zealand, continental regions inherited intricate fabrics resulting from the accretion, localized uplift, and subsidence of the landmass through geological history (Little and Mortimer, 2001; Claypool et al., 2002; Upton et al., 2014). The early deformation history can be observed in the modern South Island. Its structural expression is consistent with the regional NE trending ridge segments and NW trending faults (Lamarche et al., 1997; Deckert et al., 2002; Gray and Foster, 2004). These inherited fabrics are thought to play an important role in controlling the evolution of strain localization during the Oligocene–Miocene early development of modern dextral strike-slip boundary conditions across the Alpine Fault. However, the details of the occurrence of this self-organization of strain localization as well as the modern coherent plate boundary development from the inherited fabrics in the study area is not completely understood (Barnes, 1994; Lamarche et al., 1997; Sutherland et al., 2000; Upton et al., 2014). Also the manner by which these mechanical and rheological parameters (i.e. viscosity, cohesion and friction coefficient; Gueydan et al., 2014; Upton et al., 2014) influence the process of strain localization and accumulation at a crustal scale in the study area is unclear.

In this paper, we use three-dimensional thermo-mechanical models to explore the Oligocene–Miocene self-organization of the Australian-Pacific (AUS-PAC) plate boundary fault in southern New Zealand. In our study we simulate strain weakening through decreasing either the coefficient of friction of upper crust, its cohesion, or the rheological contrast in viscosity between the inherited structures and their surrounding wall rocks. The aim of this paper is not to reproduce the exact evolutionary history of the Alpine Fault, but rather to broadly use this system as a geological basis for exploring and quantifying the effect of strain weakening on crustal deformation. This work will also shed light on the self-organization process of crustal deformation in southern New Zealand during the Oligocene–Miocene times, as well as quantifying the effect of strain weakening on the process of strain localization at a crustal scale.

2. Geological context

The continental portions of the Australian-New Zealand landmass started to split from the southern part of Gondwana during the late Cretaceous (Fig. 1). Separation of the Zealandia plate from Australia and Antarctica was initiated around 85 Ma, with rifting from south to north to form the new Tasman Sea (Gaina et al., 1998; Sutherland, 1999). At about ~45 Ma, the Resolution Ridge rift boundary (Fig. 1) is believed to have formed as a consequence of a spreading ridge propagating through southern New Zealand along the line of the Emerald fracture zone (Sutherland, 1999; Sutherland et al., 2000). From Oligocene to Early Miocene times, the plate boundary developed transform characteristics as the Australian-New Zealand spreading direction became progressively more oblique with respect to the nascent Challenger rift zone, with strike-slip motion dominant through much of the central South Island by around 21 Ma (King, 2000). Strike slip deformation subsequently dominated strain localization through on land continental New Zealand until a step-change in the Australian-New Zealand pole of rotation to the west at around 7–8 Ma introduced substantial oblique transpression across the system (Walcott, 1998; King, 2000; Batt, 2001), leading to rapid uplift of the Southern Alps.

Basement geology of the South Island of New Zealand is divided into Eastern and Western Province domains by the Median Tec-