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On factors controlling the depth of interseismic coupling on the Hikurangi subduction interface, New Zealand

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ABSTRACT

We apply a finite difference numerical thermal model to the shallow region of the Hikurangi subduction margin, North Island, New Zealand. This subduction zone is characterised by subduction of thick and buoyant crust of the Hikurangi Plateau and along-strike variations in subduction obliquity, onshore surface heat flow (low in the south, high in the north), inferred pore-fluid pressure and seismic style (locked in the south, aseismic in the north).

The model reproduces low onshore surface heat flow observed in the southern Hikurangi margin. We propose that greater surface heat flow in the north is caused by shear heating and convective heat flow by fluids escaping from the interface. The model predicts that the Hikurangi megathrust is comparatively cold, so that if the lower limit of the interface seismogenic zone is thermally controlled, it should occur near the intersection with the hangingwall Moho. This agrees with observation in the southern, locked segment, but thermal control alone cannot explain the shallow interseismic locking depth in the central and northern margin.

In crustal strength curves, changing fluid pressure is capable of moving the brittle-viscous transition vertically by tens of kilometres. We propose that subduction zone seismic style depends on the fluid pressure regime both in the hangingwall and along the interface, and define four end-member types of megathrust fault segments. Contrary to many previous studies, we suggest that the high fluid pressure, low shear strength, end-member is fully coupled, with potential for large interplate earthquakes. In the hydrostatic case the fault is stronger, but the brittle-viscous transition occurs significantly shallower than in the near-lithostatic case, inferred to promote aseismic creep at relatively shallow levels. Along-strike variation in seismic style on the Hikurangi megathrust can therefore be explained by variation in fluid pressure state along the margin.

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1. Introduction

Subduction margins are responsible for approximately 85% of global moment release (Pacheco and Sykes, 1992). While most of this release occurs in large megathrust ruptures, subduction zone seismic activity also results from other deformation modes. Seismic styles like episodic tremor, and steady and episodic slow slip, unusual in other parts of the Earth's crust, are common in well studied active subduction systems (Schwartz and Rokosky, 2007). Along-strike variations in seismic coupling, the ratio of seismic slip to observed convergence rate, are common in many active margins. Such three-dimensional variations in seismic style are also a feature of the Hikurangi Subduction Margin on the North Island of New Zealand, as demonstrated by Reyners (1998) and Wallace et al. (2004).

Subduction zones at continental margins, where cold oceanic crust descends rapidly below warmer continental lithosphere, should have a different thermal structure from any other crustal fault systems. The thermal structure of subduction zones has been modelled by many authors (e.g. Peacock, 1996; Oleskevich et al., 1999; Harris and Wang, 2002; Peacock et al., 2005), but thermal effects on seismic coupling, seismic style and the limits of the seismogenic zone are still debated (Hyndman, 2007). It has been inferred that the upper and lower limits of the seismogenic zone occur at temperatures of 100–150 °C and ~350 °C respectively, the former assumed to represent the dehydration reaction of smectite to illite and the latter correlating with the brittle-viscous transition in quartz lithologies (Sibson, 1984; Tse and Rice, 1986; Vrolijk, 1990; Tichelaar and Ruff, 1993; Hyndman et al., 1997; Oleskevich et al., 1999; Moore and Saffer, 2001). However, the lower limit could also correspond to the intersection between the subducting slab and the mantle wedge (e.g. Tichelaar and Ruff, 1993; Hyndman et al., 1997; Peacock and Hyndman, 1999) and the upper limit could be an effect of diagenetic processes other than

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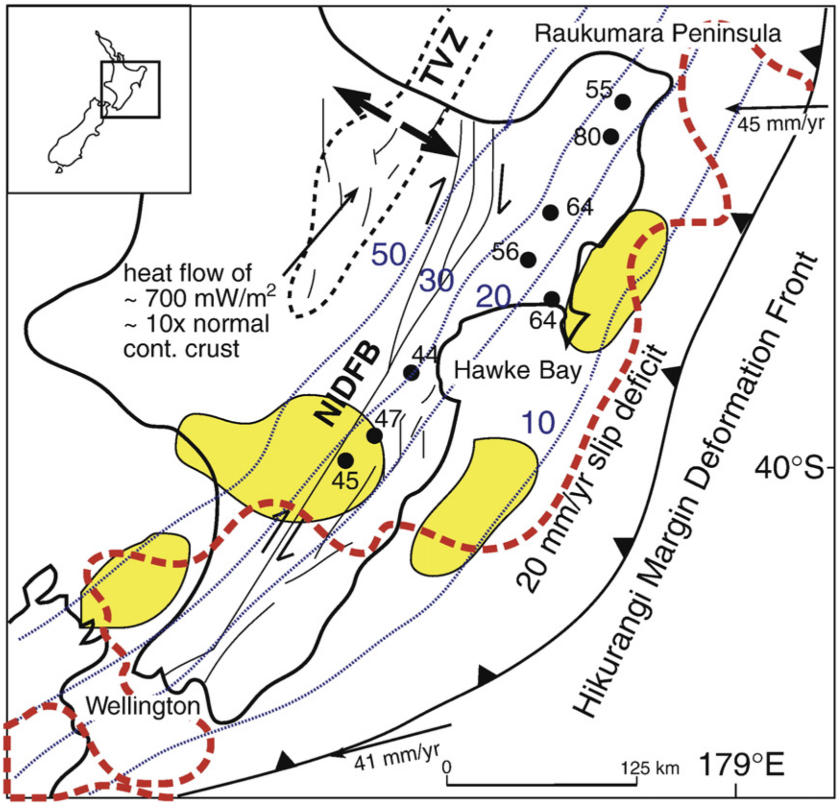

Fig. 1. Map of tectonic and seismic features of the North Island of New Zealand. Arrows represent plate convergence vectors and convergence velocities from Anderson and Webb (1994), black dots and numbers are heat flow in onshore boreholes in mWm^{-2} as in Field et al. (1997). The dashed contour of 20 $mmyr^{-1}$ slip deficit is taken from Wallace et al. (2004) and the area of strong geodetic coupling is between this contour and the deformation front. Shaded areas represent areas of slip in slow slip events, after McCaffrey et al. (2008). Dotted lines are structural contours for the interface (Ansell and Bannister, 1996), depth in km shown in associated numbering. TVZ = Taupo Volcanic Zone, NIDFB = North Island Dextral Fault Belt.

temperature-dependent dehydration (e.g. Moore and Saffer, 2001; Hyndman, 2007).

McCaffrey et al. (2008) have suggested that the transition from locked to free fault slip east of the North Island occurs at temperatures much colder than the expected ~350 °C. To further investigate this unusually cold transition zone, we apply a finite difference thermal model to the shallow region of the Hikurangi subduction margin, simulating end-member segments of the subduction zone to investigate effects of oblique subduction and variable fluid pressure on thermal structure. The temperature profiles obtained are significantly different from constant geothermal gradients usually used to assess crustal strength. We therefore construct crustal strength curves along the interface and vertically through the subduction system, in an attempt to understand the thermal control, if any, on the 3-dimensional variations in seismic style along the New Zealand North Island plate boundary.

2. Regional setting

The Pacific Plate is subducted obliquely under the Australian Plate at a rate of ~40 $mmyr^{-1}$ in the southern North Island, increasing to a rate of 45 $mmyr^{-1}$ in the northeast North Island (Anderson and Webb, 1994; DeMets et al., 1994; Wallace et al., 2004). The angle between direction of plate convergence and the Hikurangi Trough decreases from almost orthogonal in the northern North Island to ~40° in the southern North Island (Fig. 1). The strike-normal and strike-parallel components of motion appear fully partitioned, particularly in the southern Hikurangi where the megathrust appears to be fully locked at present. Most of the transcurrent motion is accommodated by faults (the North Island Dextral Fault Belt) in the overlying plate (Anderson and Webb, 1994) and by clockwise rotation of the eastern North Island (Wallace et al., 2004), More than 80% of the convergent component of motion is accommodated on the subduction thrust interface (Nicol and Beavan, 2003), which amounts to ~20 $mmyr^{-1}$ near Wellington and ~40 $mmyr^{-1}$ north of Hawke Bay (DeMets et al., 1994). Between the Hikurangi Trough and the east coast, the subducted plate dips shallowly at ~10°, and the dip remains shallow until the plate interface is at about 40 km depth (Reyners, 1998). This gentle dip is attributed to the subduction of the unusually thick (10–15 km), and therefore buoyant, crust of the Hikurangi Plateau (Wood and Davey, 1994).

Episodic slow slip events (SSEs) have recently been recognized in well studied subduction zones world wide (e.g. Hirose et al., 1999; Dragert et al., 2001; Larson et al., 2004; Douglas et al., 2005; Schwartz and Rokosky, 2007). Where enough data is available, these events have been found to occur downdip of the seismogenic section of the subduction thrust interface (Hirose et al., 1999; Dragert et al., 2001; Obara et al., 2004), i.e. in the inferred transition zone from velocity-weakening to velocity-strengthening frictional behaviour (Liu and Rice, 2007). In New Zealand, SSEs have been recorded in four locations (Fig. 1) along the Hikurangi Margin (Douglas et al., 2005; Wallace and Beavan, 2006; McCaffrey et al., 2008), all near the base of the geodetically determined locked zone (Fig. 1; McCaffrey et al., 2008). According to best-fit inversions of geodetic and seismic data, the Hikurangi subduction thrust is locked to 35–50 km in the southern North Island, while the width of the fully locked zone decreases to only 10–15 km in the central and northern North Island (Fig. 1; Reyners, 1998; Wallace et al., 2004; McCaffrey et al., 2008). If the down-dip end of the locked zone coincides with the 350 °C isotherm, there must be significant along-strike variation in thermal structure. Alternatively, other factors may control the width of the locked zone and vary significantly along the margin.

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