The Hikurangi margin, New Zealand: an important natural laboratory to understand subduction thrust behavior

Laura Wallace (l.wallace@gns.cri.nz), Susan Ellis, Stephen Bannister, Stuart Henrys, Rupert Sutherland, Daniel Barker, Agnes Reyes, ***GNS Science, Lower Hutt, New Zealand*****; Philip Barnes and Joshu Mountjoy,** ***Nat. Inst. Of Water and Atmospheric Res., Wellington, NZ*****; John Townend,** ***Victoria University of Wellington, NZ*****; Rebecca Bell,** ***Imperial College, London, UK*****, Nathan Bangs,** ***UTIG, University of Texas-Austin*****, Harold Tobin,** ***University of Wisconsin*****, David Okaya,** ***University of Southern California*****, Susan Schwartz and Eli Silver,** ***University of California – Santa Cruz*****, Demian Saffer,** ***Pennsylvania State University*****, Kelin Wang,** ***Geological Survey of Canada,*** **Ake Fagereng,** ***Univ. Capetown, South Africa***

Why is the Hikurangi margin ideally suited to investigation of subduction thrust processes? In the past decade, a number of geophysical and geological studies at the Hikurangi subduction margin reveal that pronounced along-strike changes in subduction interface behavior also correspond to observed changes in other fundamental subduction margin characteristics (see reviews by Wallace et al., 2009, and Barnes et al., 2010; Fig. 1). These observations have been made possible by New Zealand's large investment (more than 60 Million NZD over the last decade) in land-based monitoring (cGPS and seismometer network; www.geonet.org.nz), >7000 km of offshore and onshore active source seismic surveys, and other studies at the Hikurangi margin. GPS measurements reveal that deep interseismic coupling and slow slip events (SSEs; 30-60 km depth) occur at the southern portion of the Hikurangi interface, while the northern Hikurangi subduction thrust is dominated by steady aseismic slip and shallow SSEs (<10-15 km depth). These changes in the depth to SSEs and the downdip limit of the likely seismogenic zone are accompanied by along-strike changes in convergence rate, sediment thickness on the incoming plate, degree of accretion vs. subduction erosion, upper plate stress regime (i.e., a shift from back-arc extension to transpression in the upper plate), geochemical signature of fluids emerging within the forearc, among other characteristics (Fig. 1). Southern Hikurangi is a useful analogue for margins such as Nankai and Cascadia, while the northern Hikurangi margin bears many similarities to Costa Rica. Moreover, this margin offers an opportunity to study a locked subduction thrust capable of producing great megathrust events (southern Hikurangi) and one dominated by aseismic creep (northern Hikurangi), all at a single plate boundary.

Shallow slow slip events at northern Hikurangi enable detailed characterization of the physical properties of the SSE source area. Well-documented SSEs at subduction zones worldwide typically occur at 25-60 kilometers depth, so highly accurate imaging and characterization of the SSE source area is difficult with current technological capabilities. Unlike other SSE locations, the shallow depth of the northern Hikurangi SSEs (<5-15 kilometers depth) makes it amenable to highly detailed investigations, and is an ideal location for testing and developing ideas regarding the genesis of slow slip and the nature of the down-dip transition from stick-slip to aseismic creep behavior. Recently acquired 2-D multichannel seismic (MCS) data from the offshore northern Hikurangi margin reveal a zone of high-amplitude reflectivity near the subduction interface, 5–15 kilometers below the seafloor, that coincides with geodetically determined SSE source areas (Bell et al., 2010) (Fig. 2). These high-amplitude reflective zones are interpreted to correspond to fluid-rich sediments, suggesting that fluids may play an important role in the occurrence of SSEs at the northern Hikurangi margin.

A sampling of the fundamental questions that can be addressed at this margin:

What determines the location of the seismogenic zone and the occurrence of subduction thrust earthquakes**?** The major along-strike changes that we observe in the spatial extent of the likely seismogenic zone at the Hikurangi margin (Fig. 1) cannot be easily explained by one or two simple parameters. For example, thermal models suggest temperatures at the down-dip limit of interseismic coupling and SSEs range from 100-400°C (McCaffrey et al., 2008). Instead, an interplay between upper and lower plate structure, subducting sediment, temperature, regional tectonic stress regime, and fluid pressures probably controls the extent of the subduction thrust's seismogenic zone (e.g., Wallace et al., 2009). However, the extent to which each of these processes plays a role in the seismogenic zone geometry is currently unknown.

Mounting efforts for detailed geophysical transects (active source seismic, MT, heat flow, to name a few) of the stick-slip southern Hikurangi margin and the aseismically creeping northern Hikurangi margin combined with along-strike transects (Fig. 1) have potential to reveal changes in physical properties of the interface and upper plate that may help to solve the long-standing mystery of why some margins produce Great subduction thrust events and others do not. Marked along-strike variations in the geochemistry of fluids emerging in the subaerial forearc suggest variations in the source of the fluids (Reyes et al. 2010), and has implications for the permeability of the upper plate; this setting also offers an opportunity to assess the role that the release of fluids plays in the behavior of the megathrust.

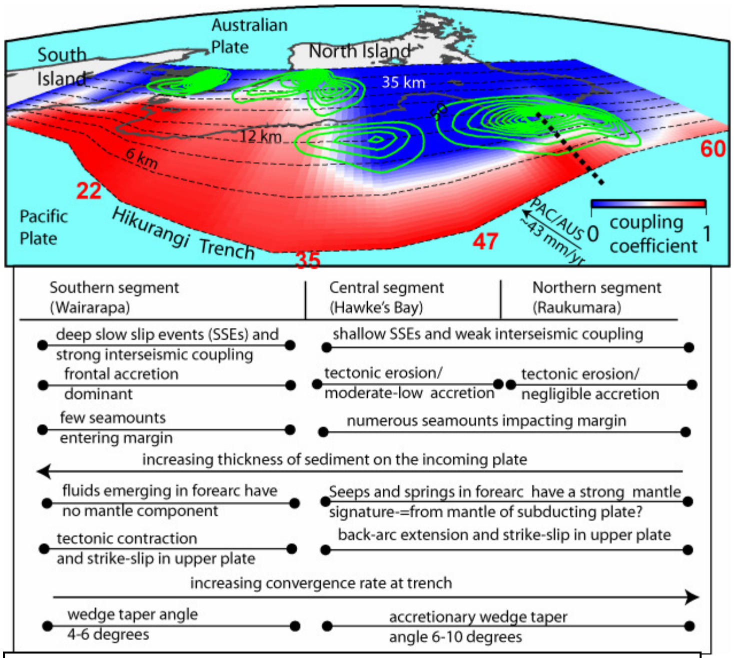

Fig. 1. Perspective view of the Hikurangi margin illustrating the portions of the subduction interface that undergo stick-slip (red to white) versus aseismic creep (dark blue) in terms of interseismic coupling coefficient. Green contours show areas of slip in slow slip events since 2002 (from Wallace and Beavan, 2010). Convergence rates at the trench are labelled as red numbers (mm/yr) near the trench. Motion of the Pacific Plate relative to the Australian Plate (PAC/AUS) is shown with the black arrow. The black dotted line marks the approximate location of the seismic profile in Fig. 2. Along-strike changes in various subduction margin properties are summarized beneath the perspective plot.

What physical mechanisms control the occurrence of slow slip events? Since 2002, the installation of a continuous GPS network in New Zealand has enabled the discovery of ~15 slow slip events at the Hikurangi subduction margin (Wallace and Beavan, 2010). These SSEs follow the down-dip transition from interseismic coupling to aseismic creep, similar to subduction margins elsewhere (Fig. 1). The deep (35-50 km depth) southern Hikurangi margin events have long durations (1-1.5 years) and larger equivalent moment release (> Mw 7.0; depth, duration and magnitude similar to Alaska SSEs), while the shallow (<15 km depth) northern Hikurangi margin SSEs occur more frequently (every two years), have shorter durations (1 week up to 2 months; depths and duration somewhat similar to Costa Rica SSEs) and smaller equivalent moment release (~6.5-6.8). The systematic along-strike variations in SSE recurrence, duration and magnitude characteristics that we observe at Hikurangi provide an ideal setting to assess the physical controls on the SSE characteristics. Borehole seismometers in the SSE regions at the Hikurangi margin could help to resolve whether or not tremor and/or low frequency earthquakes occur in concert with Hikurangi SSE, while high-quality tiltmeters and densification of cGPS sites would enable detection of smaller SSEs and reveal the full spectrum of SSE behavior.

A broad, international group of researchers recently submitted a pre-proposal to IODP to drill into the northern Hikurangi SSE source area and associated high-amplitude reflectivity zone on the subduction interface at about 5 kilometers below the seafloor in 700-1000 m water depth (Fig. 2). This target is unique, as it is the only well-documented subduction SSE source area on Earth within range of modern offshore drilling methods. The potential for active-source seismic imaging, drilling, down-hole measurements, sampling, and monitoring of the northern Hikurangi margin SSE source area provides a world-class opportunity to definitively test hypotheses regarding the properties and conditions leading to SSE occurrence, and ultimately, to unlock the secrets of slow slip and the nature of the down-dip transition from stick-slip to aseismic creep on megthrusts.

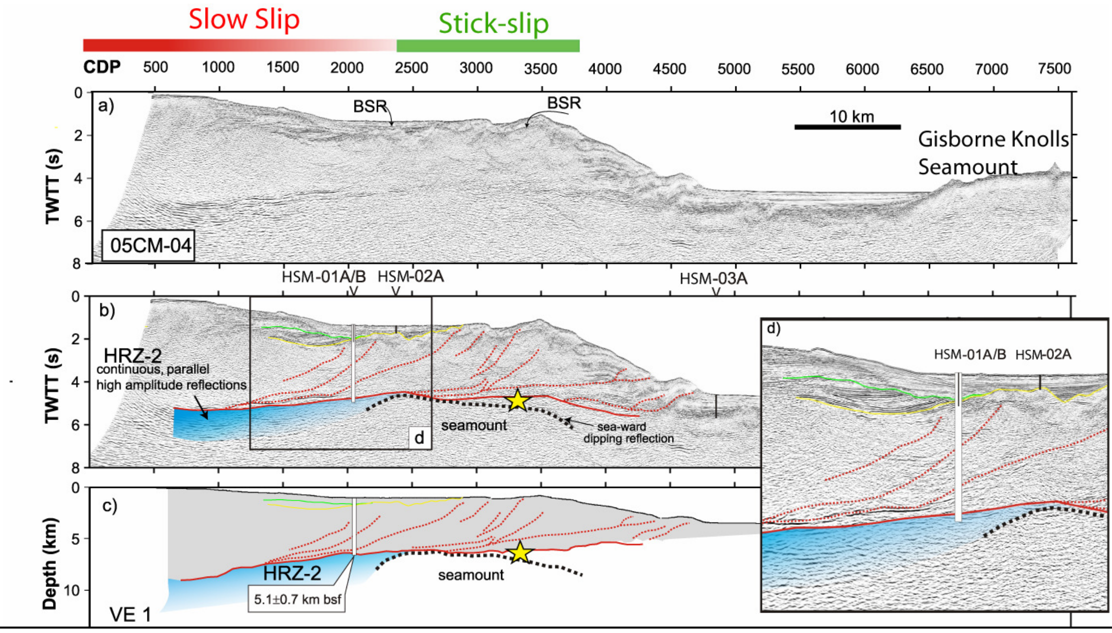

Fig. 2. (a) Uninterpreted and (b) interpreted seismic profile from the northern Hikurangi margin (see location on Fig. 1). Solid red line is the subduction interface, dotted red lines are splay faults within the upper plate. Yellow star denotes position of the March 1947 tsunamigenic earthquake (Doser and Webb, 2003). (c) Depth-converted interpretation. Areas of high-amplitude reflectivity (HRZ; Bell et al., 2010) shaded in blue. Vertical white line shows a potential position for offshore drilling to access the slow slip source area and HRZ intersection the interface at 5.1 km below the seafloor (bsf). Color bar at top of figure schematically denotes the region of the interface that is inferred to undergo stick-slip (green) vs. slow slip (red). BSR = Bottom Simulating Reflector

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