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Morphometric and critical taper analysis of the Rock Garden region, Hikurangi Margin, New Zealand: Implications for slope stability and potential tsunami generation

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ABSTRACT

New high-resolution swath bathymetry data show a complex seafloor morphology from the Rock Garden area, offshore Hikurangi Margin, that coincides with the subduction of a seamount presently located beneath the summit of Rock Garden. Another ridge-shaped lower plate feature is initially colliding with Rock Garden, forming a re-entrant at its seaward flank. The slopes of the accretionary ridges are steeper than 10° and often more than 20° regionally. Slumping mostly occurs on the trench-ward slopes, with individual slumps affecting areas up to several km^2. Critical taper analysis, using realistic wedge geometries and fluid pressures scenarios, shows that much of the seaward slopes in the region are most likely outside the stability field and therefore subject to failure. The most prominent feature revealed by seafloor maps is the trench-ward flank of Rock Garden with a height of 1800 to 2000 m and an average slope of more than 10°. Extensional faults arranged in two sub-circular arcs indicate that Rock Garden may be on the verge of failure. Critical taper analysis also supports this claim and shows that if basal fluid pressure approaches lithostatic pressure, e.g. during a large Mw>8 earthquakes, then a complete failure of the entire trench-ward flank of Rock Garden would potentially affect an area as large as 150 km^2 and a rock volume of 150 to 170 km^3. This worst case scenario would generate a tsunami wave some tens of meters high. Therefore, the observation that a number of seamounts are buried beneath the outer Hikurangi accretionary wedge suggests that a thorough assessment of these features needs to be undertaken and its results incorporated into tsunami hazard models for the East Coast of New Zealand's North Island.

1. Introduction

Along the world's convergent margins, sufficiently thick sedimentary trench fill leads to the formation of imbricate wedges. While such accretionary wedges typically are built of numerous thrust slices, the relative amount of material accreted to the front and base, may vary considerably. Regionally, accretionary wedges mostly have a shallow surface slope of only a few degrees and in the first tens of kilometers landward of the trench the subducting plate usually also dips at an angle of a few degrees leading to taper angles between 3° and 8°. However, the flanks of individual accretionary ridges may be relatively steep (Kukowski et al., 2001, McAdoo et al., 2004) and prone to slope failure. Whereas the style of accretion over several thrust cycles (Gutscher et al., 1998; Kukowski et al., 2002; Hoth et al., 2007) mainly depends on the material supply in the trench and the mechanical stratigraphy of the sediment pile available for accretion, subduction of basement ridges and seamounts may dramatically change material transfer, accretion processes, and wedge morphology. When entering an accretionary wedge, seamounts may generate a re-entrant through the deformation front, i.e. the tip of the wedge (Ranero and von Huene, 2000) and leave a scar in their wake (von Huene et al., 1997). During subduction seamounts cause the overriding wedge to steepen, and therefore may lead to sudden and voluminous mass wasting (e.g. Lewis et al., 2004).

The internal structure of an accretionary wedge as imaged with reflection seismics (e.g. Bangs et al., 1999; Kopp and Kukowski, 2003; Moore et al., 2007; Barker et al., 2009; Barnes et al., 2010-this issue) and its morphology allow for characterization of the mechanical state of a wedge and identification of potentially unstable portions. High resolution swath bathymetry data can be used to identify key morphological structures like slump scars, gullies, or canyons and also serve as a basis to compute morphometric parameters like curvature attributes and local slope gradient (McAdoo et al., 2004; Kukowski et al., 2008). The critical taper concept (Davis et al., 1983; Dahlen, 1990)

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based on the Mohr–Coulomb failure criterion for an elasto-plastic rheology adequately describes the mechanical behaviour of upper crustal rocks and sediments. Critical taper theory links the frictional and fluid dynamic properties of a wedge and its base with its mechanical state. This theory has been applied to natural wedges to estimate their frictional properties and to identify potential instability (e.g. Lallemand et al., 1994, Kukowski et al., 2001, Suppe, 2007). Recently, Wang and Hu (2006) expanded the theory of critical taper wedges introducing the concept of the "dynamic wedge" to explain fluctuations of the mechanical state of a convergent margin driven by changes of the pore fluid pressure during a seismic cycle.

The central Hikurangi Margin, located off the North Island of New Zealand, is characterized by accretion in its southern part, whereas further north than Hawke's Bay, subduction erosion dominates (Barnes and Mercier de Lepinay, 1997). The giant (>3200 km^2) Ruatoria avalanche off East Cape is thought to have been caused by a subducting seamount, which is now probably located beneath the coast (Lewis et al., 2004). Seamounts have been identified on the Hikurangi Plateau, and along the entire East Coast, suggesting that seamount subduction is a fairly common phenomenon at this convergent margin. In the Rock Garden area east of Hawke's Bay, a subducting seamount located approximately 40 km landward of the trench has been identified from seismic data (Henrys et al., 2006; Barnes et al., 2010-this issue). The presence and absence of gas hydrates, identified by a bottom simulating reflector (BSR), in this region may be due to uplift caused by the subducting seamount (Pecher et al., 2005; Ellis et al., 2010-this issue).

Here, we study the bathymetric morphology of the Rock Garden area based on swath bathymetry data from several recent cruises. We identify reasons for local slope failure and use the critical taper concept to determine the mechanical state of this area. Finally, we discuss the potential for slumping above the subducting seamount and likely implications for tsunami generation.

2. Regional setting

The study region (Fig. 1) lies at the southern end of the Tonga–Kermadec–Hikurangi subduction zone and forms part of the obliquely converging (42 mm/yr) (DeMets et al., 1994) boundary between the Australian and Pacific plate, that initiated 20–25 Ma ago (Ballance, 1976). The oblique motion is partitioned into margin-parallel motion on faults in the overlying Australian Plate and margin-normal motion on the plate interface (Beanland and Haines, 1998). There is a marked decrease in extension rate and a change to net shortening towards the south within the overriding plate of the North Island. The kinematic description is approximated as a clockwise rotation of the forearc, relative to a fixed Australian plate (Walcott, 1987; Wallace et al., 2004). As a consequence of this forearc rotation, subduction at a rate of c. 42 mm/yr is nearly orthogonal to the plate boundary near Rock Garden (Fig. 1). The subduction thrust has accommodated a large proportion, (>80%) of Neogene and Quaternary crustal plate boundary convergence (Nicol and Beavan, 2003; Nicol et al., 2007).

The wedge of accreted sediment in the central part of the Hikurangi Margin, offshore Hawke's Bay, was imaged using seismic reflection data as a >100 km wide prism that encroaches onshore in both northern and southern parts (Barnes et al., 2010-this issue; Davey et al., 1986; Lewis and Pettinga, 1993; Henrys et al., 2006). The accretionary wedge comprises a backstop of Mesozoic greywacke rocks and pre-existing passive margin sediments, that range in age from mid Cretaceous to Palaeogene and have been thrust faulted and back tilted since 25 Ma (Lewis and Pettinga, 1993). These rocks, deposited on the active margin of Gondwanaland, are now exposed in the axial ranges of the North Island. The outer wedge beneath the lower trench slope in southern and central parts of the margin (Hawke's Bay and south) is primarily composed of Neogene slope-basin sediments that accumulated behind thrust ridges cored by splay faults (Henrys et al., 2006). Voluminous sediment accretion near the toe of the wedge in the south reflects the very high sediment supply in that region, whereas sediment supply is much less in the north, where subduction erosion is inferred (Barker et al., 2009; Barnes et al., 2010-this issue), leading to the formation of re-entrants and considerable mass wasting in the wake of subducting seamounts (Lewis et al., 2004).

Subduction beneath the central North Island is affected by collision with the Hikurangi Plateau, a large igneous province on the incoming Pacific plate. This plateau has a crustal thickness of ~15 km to the east of the central North Island and the leading edge is suggested to lie ~65 km deep beneath the North Island (Reyners et al., 2006). The buoyancy of the subducted plateau has resulted in exposure of the forearc above the shallow dipping part of the subduction thrust (Davy and Wood, 1994). The coastal region thus overlies the shallow, cool part of the plate interface, which may be capable of producing large subduction thrust earthquakes, although no such earthquakes have been unambiguously identified along the Hikurangi Margin over the past 160 yr. However, marginal marine sediments obtained from shallow coring in lagoons in Hawke's Bay (Cochran et al., 2006) preserve a record of tsunami inundation and sudden subsidence consistent with rupture on the plate interface and perhaps also splay faults at ca. 7100 and 5550 yr B.P.. In the period from 1840 to the present day there have been 10 large (Mw>7.0), damaging earthquakes in the overriding Australian plate including the devastating 1931 Hawke's Bay Mw = 7.8 event (see Fig. 1) which killed 256 people (Webb and Anderson, 1998; Doser and Webb, 2003). In addition, two earthquakes offshore Gisborne in 1947 (Mw 7.2 and Mw 6.9) appear to have occurred along the plate interface and were associated with local tsunamis (Downes and Stirling, 2001; Doser and Webb, 2003). Although no one died in either event the maximum run-up height reached 10 m and affected about 120 km of coastline north of Hawke's Bay.

The Rock Garden area (Fig. 1) is located at the northern edge of the broadest part of the accretionary wedge, east of Hawke's Bay and comprises the outermost accretionary ridges west of the Hikurangi trench. Here a flat topped ridge overlying a subducting seamount on the Pacific Plate was identified from seismic and bathymetric data (e.g. Pecher et al., 2005, Henrys et al., 2006, Barnes et al., 2010-this issue).

The occurrence of gas hydrates is widespread along the accretionary prism and also in the Rock Garden area, as revealed by BSRs in reflection seismic data (Pecher et al., 2005; Crutchley et al., 2010-this issue). At the flat topped ridge, the gas hydrate stability zone intercepts the seafloor, which has led Pecher et al. (2005) to hypothesize that flat bathymetry may result from weakening of the seafloor and subsequent erosion due to repeated hydrate formation and dissociation with fluctuating bottom water temperatures. Alternatively, fast uplift of the ridge caused by the subducting seamount may shift the base of the gas hydrate stability zone and lead the BSR to fall outside of the hydrate stability field (see discussion in Ellis et al., 2010-this issue). In either case a clear BSR is visible on all seismic data collected across Rock Garden (Crutchley et al., 2010-this issue) and can be mapped at near the seafloor on the summit, to a subsurface depth of 1000 m at the foot of the trench-ward flank.

3. Data and methods

Multibeam data were acquired during three cruises with EM300 (cruises TAN0607 and TNA0617 of the New Zealand *RV Tangaroa*) and EM120 (cruise SO191 of the German *RV Sonne*) systems (Greinert et al., 2010-this issue). All data were processed with the MB-System software (Caress and Chayes, 1996) applying a common sound velocity file. Data acquired during the surveys that were recorded when the vessel speed was less than 2 km/h were rejected. The resulting data were exported from MB-System as *xyz* data for further manual editing using the 3D editing capabilities in Fledermaus; no CUBE or automatic filtering was applied. Finally, the cleaned data were exported from Fledermaus as an ASCII *xyz* data set for gridding and plotting.