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Effective strength of incoming sediments and its implications for plate boundary propagation: Nankai and Costa Rica as type examples of accreting vs. erosive convergent margins

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ABSTRACT

The location of the seaward tip of a subduction thrust controls material transfer at convergent plate margins, and hence global mass balances. At approximately half of those margins, the material of the subducting plate is completely underthrust so that no accretion or even subduction erosion takes place. Along the remaining margins, material is scraped off the subducting plate and added to the upper plate by frontal accretion. We here examine the physical properties of subducting sediments off Costa Rica and Nankai, type examples for an erosional and an accretionary margin, to investigate which parameters control the level where the frontal thrust cuts into the incoming sediment pile.

A series of rotary-shear experiments to measure the frictional strength of the various lithologies entering the two subduction zones were carried out. Results include the following findings: (1) At Costa Rica, clay-rich strata at the top of the incoming succession have the lowest strength ($\mu_{res} = 0.19$) while underlying calcareous ooze, chalk and diatomite are strong (up to $\mu_{res} = 0.43$; $\mu_{peak} = 0.56$). Hence the entire sediment package is underthrust. (2) Off Japan, clay-rich deposits within the lower Shikoku Basin inventory are weakest ($\mu_{res} = 0.13$–0.19) and favour the frontal proto-thrust to migrate into one particular horizon between sandy, competent turbidites below and ash-bearing mud above. (3) Taking in situ data and earlier geotechnical testing into account, it is suggested that mineralogical composition rather than pore-pressure defines the position of the frontal thrust, which locates in the weakest, clay mineral-rich (up to 85 wt.%) materials. (4) Smectite, the dominant clay mineral phase at either margin, shows rate strengthening and stable sliding in the frontal 50 km of the subduction thrust (0.0001–0.1 mm/s, 0.5–25 MPa effective normal stress). (5) Progressive illitization of smectite cannot explain seismogenesis, because illite-rich samples also show velocity strengthening at the conditions tested.

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1. Introduction

Approximately half of the sediment currently overlying Earth's oceanic crust is travelling towards the ~43,000 km length of active convergent margins (Rea and Ruff, 1996). Those margins release >90% of the stress accumulated by plate kinematics in often devastating subduction megathrust earthquakes (EQs). Along these subduction zones, the fundamental processes governing seismogenesis are the mineralogy and physical properties of the sedimentary inputs, and how the latter changes with depth and increasing pressure and temperature. Other factors that contribute to EQ nucleation as well as magnitude include the roughness of the downgoing plate (Behrmann and Kopf, 2001; Clift and Vannucchi, 2004; Tanioka et al., 1997), the availability and composition of sediment in the trench (Rea and Ruff, 1996), and the rate of plate convergence (Clift and Vannucchi, 2004). The position of the up-dip end of the thrust further defines how much sediment is scraped off the oceanic plate and added to the overriding continent (i.e. accretion [A], Fig. 1A), and how much gets thrust beneath the continent and then either underplated or recycled in the mantle and/or the volcanic arc (i.e. non-accretion [NA], Fig. 1A). During subduction, the material along the plate boundary thrust undergoes dewatering, and further diagenetic and metamorphic alteration caused by increasing pressure and temperature (PT). These processes ultimately cause unstable sliding behaviour and seismicity. It appears as if both accreting and non-accreting or even erosive margins are capable of generating EQs of various magnitudes (Tichelaar and Ruff, 1993).

Peak fluid production occurs near the deformation front (mostly compaction and mechanical fluid expulsion; see Bekins and Dreiss, 1992; Moore and Vrolijk, 1992) and beneath the mid-forearc at moderate temperature (60–120 °C, due to chemical and mineralogical effects and release of bound water; e.g. Moore and Vrolijk, 1992; Spinelli and Saffer, 2004). It is suggested by indirect evidence from previous work that, consequently, the down-dip evolution of the fault considerably influences frictional behaviour and the onset of earthquake faulting. And although clay-dominated subduction thrusts remain relatively weak down to seismogenic depths, they are capable of causing the

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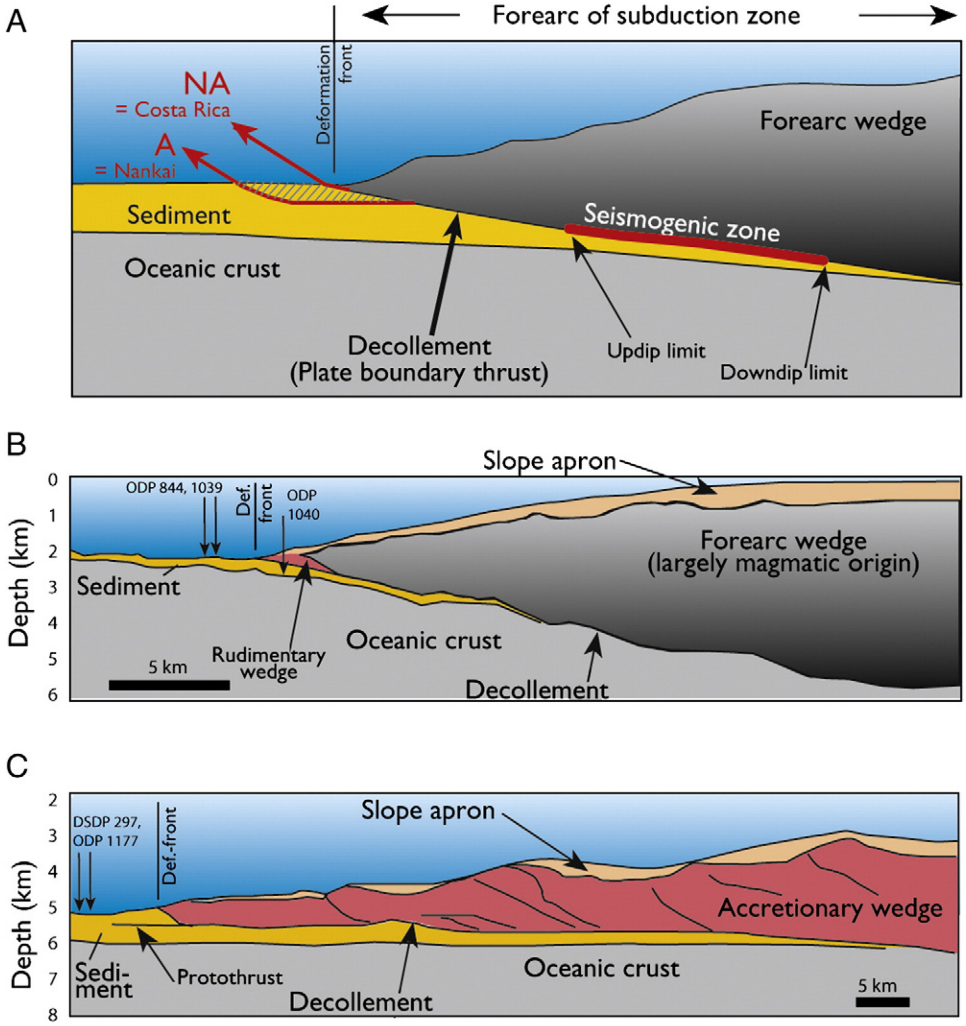

Fig. 1. A) Schematic cross section through an active convergent margin, showing the paths the plate boundary thrust (frontal decollement) could take: A = accretion, where sediment is scraped off the incoming sedimentary sequence and added to the forearc (Nankai Trough scenario); NA = non-accretion, where the plate boundary develops on top of the incoming sediments (Costa Rica scenario). Schematic drawings of interpreted seismic reflection profiles across the Costa Rica (B) and Nankai margins (C). Arrows indicate the (sometimes projected) locations of drill sites by the DSDP and ODP; samples originated from sites 297/1177 and 1039/1040.

largest, most devastating earthquakes (Kanamori, 1986; Oleskevich et al., 1999; Romanovicz, 1993; Tichelaar and Ruff, 1993). On the other hand, brittle failure of fault zones is believed to be caused by increasing induration of the material, either by shallow strain accumulation or triggered by deeper slip after rupture (Lay and Bilek, 2007), the latter of which most likely accounts for the relatively large stress drops during vigorous subduction zone earthquakes. Both increasing rigidity and high angularity of the gouge material enhance velocity-dependent dilation and compaction (Morrow and Byerlee, 1989). Such coseismic stress drops cannot easily be explained by weak, phyllosilicate-rich gouge.

One mechanism to repeatedly weaken a healed fault zone at seismogenic depth would be elevated pore pressures and hydrofracture, which is feasible given that reactions like smectite/illite and opal/quartz transformation release significant quantities of water (e.g. Moore and Saffer, 2001). Even a little water may account for high excess pore pressures at depth since porosity is low in the lithified rocks. However, it has been argued that it is problematical to maintain those pore pressures near lithostatic (=overburden stress) over time (Byerlee, 1993; Rice, 1992). Excess pore pressures have been measured in situ occasionally (Becker et al., 1997; Foucher et al., 1997), however, are relatively low to moderate in magnitude (ca. 1–2.2 MPa). Most of the evidence is inferred from a variety of indirect approaches at Costa Rica (Saffer, 2003) and Nankai (Screaton et al., 2002). An alternate explanation of weakening is the alteration of the gouge and formation of authigenic minerals with low friction coefficients, such as talc, serpentinite, and some clay phases (e.g. Kopf, 2001; Moore and Rymer, 2007; Moore et al., 1997). Many natural systems may represent some combination of elevated pore pressure and low intrinsic friction, so careful analyses is critical in any given region.

It has long been known that fault initiation, propagation and slip are a function of fault zone mineralogy and transient pore pressure (Hubbert and Rubey, 1959) as well as second-order factors such as temperature, stress regime, coupling or relief within the fault zone. Pore pressure transients are governed by reaction kinetics of hydrous phases such as smectite and opal A and their ability to release water under increased PT (pressure–temperature) conditions (e.g. Pytte and Reynolds, 1989). Transformation reactions do not only release fluid, but also cause an overall increase in frictional strength owing to illitization and quartz formation (e.g. Saffer and Marone, 2003). In general, the controversial perception of the importance of the respective role of friction coefficient of the minerals (Byerlee, 1978; Marone 1998) versus pore pressure (Brown et al., 2003; Rice, 1992; Saffer, 2003, 2007) in rock mechanics is here applied to fault initiation at the seaward tip of a plate boundary thrust. As a by-product, we tested the hypothesis whether clay mineral transformation is crucial for the mechanics at

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