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The thermal structure of the subduction thrust within accretionary and erosive margins

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ABSTRACT

We investigate differences in the thermal structure of the subduction thrust between accretionary and erosive margins using a finite element model. Global averages of plate margin geometries, sediment thickness, plate age, and convergence rate are used to construct generic models of accretionary and erosive margins. Of these parameters, our analysis shows that the largest uncertainty in these models is the geotherm for the incoming oceanic plate. Despite these uncertainties, the subduction thrust of similarly aged accretionary margins is slightly warmer than erosive margins primarily due to the effect of sediment insulating the subduction thrust at accretionary margins. If the updip limit of seismicity is thermally controlled, warmer accretionary margins suggest shallower seismogenic updip limits, counter to the observation that erosional margins are more likely to generate tsunamigenic earthquakes. This discrepancy can be reconciled if frictional heat generation at erosive margins is larger than at accretionary margins.

1. Introduction

Understanding the processes that influence the location and width of the seismogenic portion of the subduction thrust is an important step to better understand seismicity (e.g., Dixon and Moore, 2007). Slip between the subducting and overriding plates is localized on the subduction thrust, and the seismogenic zone is defined as the region where large interplate earthquakes nucleate. The seismogenic zone is often conceptualized as being bounded updip and downdip by regions of aseismic slip where the fault zone material transitions from velocity weakening in the seismogenic zone to velocity strengthening material in the aseismic zones. Within this transition from velocity strengthening to velocity weakening is a region of conditional stability.

A good predictor to these bounds appears to be temperature (Hyndman and Wang, 1993, 1995; Hyndman et al., 1997; Oleskevich et al., 1999; Tichelaar and Ruff, 1993). The downdip extent of observed seismicity is approximately correlated with the 350 °C isotherm or the intersection of the overriding Moho with the subduction thrust, whichever is shallower (e.g. Hyndman, 2007). This correlation is generally understood in terms of a change in frictional properties along the fault, either the brittle–ductile transition or the intersection of the subduction thrust with hydrated mantle (Hyndman et al., 1997; Peacock and Hyndman, 1999). However earthquakes that extend below the shallow mantle wedge at Sumatra, northeastern Japan, and the Mariana trench are leading to challenges of this view (Dessa et al., 2009; Emry et al., 2011; Heuret et al., 2011; Hino et al., 2000; Klingelhoefer et al., 2010; Simoes et al., 2004). The updip extent of observed seismicity appears well correlated with temperatures along the subduction thrust between 100° and 150 °C (Hyndman and Wang, 1993, 1995; Hyndman et al., 1997; Oleskevich et al., 1999). The updip limit likely reflects the complex interplay of temperature–dependent processes with the composition, thickness, progressive lithification of incoming sediment, the concentration of interstitial and bound water being subducted, and basement relief (Bilek et al., 2003; Hyndman and Wang, 1993; Lay and Bilek, 2007; Marone and Saffer, 2007; Moore and Saffer, 2001; Schwartz and DeShon, 2007; Underwood, 2007). Along the subduction thrust a range of slip behavior, that includes slow slip and tremor, creep and VLF events, is now recognized and bounds limiting the seismogenic zone are spatially and temporally more complicated than previously thought (e.g., Lay and Bilek, 2007; Lay et al., 2012; Peng and Gomberg, 2010; Schwartz and Rokosky, 2007).

In addition to correlations between the thermal regime and the seismogenic zone, a dichotomy between accretionary and erosive margins has been identified and studied (e.g., Clift and Vannucchi, 2004; von Huene and Scholl, 1991). A fundamental difference between these margins is the nature of mass transfer between the overriding and downgoing plates (Clift and Vannucchi, 2004; von Huene and Scholl, 1991). At accretionary margins the subduction thrust cuts down through the incoming sediments so that some fraction of sediment is transferred from the downgoing plate to the overriding plate to

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generate the accretionary wedge. At erosive margins little to no mass is transferred from the downgoing to overriding plate and instead the plate fault appears to cut up through the overriding plate leading to margin subsidence and landward migration of the trench axis (Clift and Vannucchi, 2004). The near-trench forearc typically consists of lithified sediments previously accreted to the margin or crystalline rocks. This bimodal classification of erosive and accretionary convergent margins is an oversimplification as margins likely transition back and forth in both space and time. Intriguingly, there appears to be a statistical difference in the nature of seismicity at accretionary and erosive margins. Bilek (2010) notes that tsunami earthquakes, events that produce large tsunamis relative to their seismic moment, arise from slip in the shallowest portion of the subduction zone (Abercrombie et al., 2001; Ammon et al., 2006; Bilek and Lay, 2002; Kanamori, 1972; Kanamori and Kikuchi, 1993; Polet and Kanamori, 2000; Satake and Tanioka, 1999), and are primarily associated with erosive margins. In contrast, the largest events on record ($M > 9$) are primarily associated with accretionary margins (Bilek, 2010; Scholl et al., 2011).

If the subduction thrust at accretionary and erosive margins behaves differently as suggested by the different styles of seismicity, or has different characteristics as suggested by the presence or absence of active accretion, we might expect that differences in the temperature structure correlate with differences in the updip and downdip limits of seismicity. Such observations may assist in the understanding of differences in the mechanics of these margins. Investigating this supposition assumes systematic differences in temperatures along the subduction thrust and being able to resolve these temperatures and the updip limit of seismicity to a relatively high precision. In this study we explore these assumptions. Our goal is to emulate in a simple way the gross differences between the thermal structure of accretionary and erosive margins and to investigate the predicted position and likelihood ranges of the intersection of the 150° and 350 °C isotherms with the subduction thrust. We start by documenting systematic differences in thermally relevant parameters between accretionary and erosive margins, constructing generic thermal models for these systems and exploring associated model uncertainties.

2. Accretionary and erosive margins

Previous studies of subduction thermal models have found that the thermal regime of the shallow subduction zone is largely governed by the convergence rate, the slab geometry, and the thermal state of the incoming plate (e.g., Dumitru, 1991; Hyndman and Wang, 1995; McCaffrey, 1997; Molnar and England, 1995; Van den Beukel and Wortel, 1988). Thermophysical rock properties such as thermal conductivity and heat production also play an important but lesser role in governing the thermal structure (Dumitru, 1991).

We develop generic thermal models using parameters based on the compilations of Clift and Vannucchi (2004) and Heuret et al. (2011, 2012). Clift and Vannucchi (2004) compiled 32 transects across well imaged accretionary and erosive margins and catalogued characteristics of the shallow margin. Although the dynamics of accretionary and erosive margins are incompletely understood, margins are more likely to be accretionary if the incoming trench sediment thickness is greater than 1 km thick and the convergence rate is less than about 60 km/my (Clift and Vannucchi, 2004). Incoming trench sediment thicknesses less than 1 km and convergence rates greater than about 60 km/my tend to be associated with erosive margins. These parameters, thick incoming sediment and slow convergence rate act in concert to warm margins, while thin sediment cover and fast convergence rates lead to cooler margins. However the effect of these parameters is mitigated by margin geometry. In general, erosive margins have steeper forearc slopes and greater taper angles that result in warmer subduction thrusts at a given distance from the trench (Clift and Vannucchi, 2004). Erosive margins have steep bathymetric slope >3° to as high as 8° and taper angles >7° to as large as 20°. In contrast, accretionary margins have bathymetric slopes <3° and taper angles <10°. Clift and Vannucchi (2004) found no correlation between incoming plate age and accretionary or erosive margins.

Heuret et al. (2011, 2012) mapped the subduction interface seismogenic zone of 44 subduction plate boundaries using global earthquake catalogues and catalogued sediment thickness at the trench. In this study the seismogenic zone is defined by the distribution of $5.5 \leq M \leq 7$ earthquakes (Heuret et al., 2011). We differentiated these segments into accretionary and erosive margins based on the compilation of Clift and Vannucchi (2004). The good correlation between sediment thickness and margin type is illustrated in Fig. 1. This figure also shows the general correlation between convergence rate and margin type. The average and standard deviations of thermally important parameters for accretionary and erosive margins are summarized in Table 1. This table shows clear differences of thermally important parameters between accretionary and convergent margins.

3. Thermal models

Our generic subduction models are presented in Fig. 2. The geometry of our accretionary models consist of a forearc slope of 2° over a distance of 150 km and a slab dip of 3° over a distance of 75 km yielding a taper angle of 5°. Our erosive margins consist of a forearc slope of 5° and a slab dip of 5° over a distance of 100 km yielding a taper angle of 10°. At distances of 75 and 100 km we use seismogenic dip angles of 20° and 18° for accretionary and erosive margins, respectively. The plate dip through the forearc wedge is 34° for both models. For these geometric parameters, erosive margins have a greater overall taper than accretionary margins. The difference in the subduction thrust depth has a maximum of approximately 6 km at a distance of 75 km. All models use a maximum continental crustal thickness of 40 km, split evenly between the upper and lower continental crust.

We use the steady-state thermal model of Hyndman and Wang (1993) and Wang et al. (1995) updated to include isoviscous mantle wedge flow (Currie et al., 2002; Peacock and Wang, 1999). In this study we fix the onset of the mantle flow to a constant distance of 250 km from the trench that corresponds to a slab depth of approximately 80 km consistent with the decoupling depth of Wada and Wang (2009). This rheology leads to a somewhat cooler wedge corner than a more realistic rheology (Wada and Wang, 2009). This numerical model solves the heat conduction–advection equation using a two-dimensional finite-element approach. Each element is assigned a constant thermal conductivity, heat capacity, heat source and velocity. The convergence velocity is also prescribed. The landward boundary condition uses a continental geotherm assuming a back arc heat flow of 80 mW m^{-2} based on the global average (Currie and Hyndman, 2006). The horizontal heat flux is set to zero and this boundary is far enough away from the trench that it has little effect on subduction thrust temperatures. The upper boundary is set to 0 °C and the lower boundary is given a value consistent with the plate model geotherm (Stein and Stein, 1992) as described later. The thermal regime of the subduction thrust is largely insensitive to this basal boundary condition but is sensitive to the details of the incoming geotherm. Our models assume no hydrothermal circulation and unless otherwise stated we assume no frictional heating along the plate interface.

An important boundary condition is the depth of the subduction thrust at the trench. The position of the décollement depends on many factors that include the lithostratigraphy and the hydrogeology (Underwood, 2007). In our accretionary models we assume that the subduction thrust immediately cuts down through the incoming sediments so that some fraction of the sediments are accreted while the rest are subducted and the décollement has a boundary temperature set by its position and the initial geotherm. Clift and Vannucchi (2004) found that in general about 20% of the sediment is accreted and we