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Geodynamics of trench advance: Insights from a Philippine-Sea-style geometry

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ABSTRACT

For terrestrial parameter sets, trench retreat is found to be nearly ubiquitous and trench advance quite rare, largely due to rheological and ridge-push effects. Recently updated analyses of global plate motions indicate that significant trench advance is also rare on Earth, being largely restricted to the Marianas–Izu–Bonin arc. Thus, we explore conditions necessary for terrestrial trench advance through dynamical models involving the unusual geometry of the Philippine Sea region. In this subduction system, a slab-pull force from distal subduction is transmitted to the overriding plate at the Pacific trench. Our 2D modeling demonstrates that trench advance can occur for terrestrial rheologies in such special geometries. We observe persistent trench advance punctuated by two episodes of back-arc extension. Characteristic features of the model, such as time interval between extensional episodes, high back-arc heat flow, and stress state of Philippine plate correspond to processes recorded in the region.

1. Introduction

Among the results of our recent study (Čížková and Bina, 2013), of the effects on slab stagnation and rollback of mantle and subduction-interface rheology and phase-transition buoyancy, was the striking observation that exploration of an extensive parameter space yielded only trench retreat. Even in cases of minimal trench retreat, involving high crustal viscosity and hence strong slab coupling, no persistent trench advance was observed. In retrospect, perhaps this should not be overly surprising. Previous models have suggested that, while a stiff overriding plate can moderate trench retreat (Yamato et al., 2009; Garel et al., 2014), parameters favoring trench-advance regimes typically fall at the extremes of or outside the realm of Earth-like conditions – requiring, for example, very strong slabs (Billen, 2010; Stegman et al., 2010) or a very stiff lower mantle (Ribe, 2010), perhaps combined with extremely strong slab coupling (Baitsch-Ghirardello et al., 2012). Any contribution from slab elasticity also should favor retreat over advance (Fourel et al., 2014). Indeed, it has been suggested (Chertova et al., 2012) that a far-field lithospheric "pull" stress acting on the overriding plate, countering the ridge-push force that enhances trench retreat, may be necessary to generate meaningful trench advance. Here we introduce a slab-pull force on the overriding plate to test the hypothesis that persistent trench advance can arise in such a scenario.

In seeking a suitable geometry for trench advance on Earth, it is important to note that estimates of trench motions vary significantly with choice of reference frame (Funicello et al., 2008). Using a reference frame optimized to minimize trench advance, a recent analysis (Schellart et al., 2008) nonetheless suggested the occurrence of trench advance at ∼25% of global subduction-zone segments. However, a new analysis of global plate-motion constraints (Mathews et al., 2013), combining corrections to the MORVEL model (DeMets et al., 2010) and statistical error propagation with a reference frame based on SKS seismic anisotropy (Zheng et al., 2014), indicates that most previous indications of terrestrial trench advance actually correspond to stationary or retreating motion. Statistically significant trench advance is found to persist in only two regions: weakly in southern Kermadec and strongly in Marianas–Izu–Bonin. Given the relatively shallow extent of subducting slab beneath southern Kermadec (Zhou, 1990; Chen et al., 2004), this region perhaps reflects transient advance associated with early subduction prior to the slab encountering resistance near 660 km depth (Yamato et al., 2009). We thus choose to focus upon the Marianas–Izu–Bonin region, where persistent trench advance is consistent with early analysis of Marianas advance (Carlson and Melia, 1984) and with the observation that Marianas–Izu–Bonin advances in all reference frames (Funicello et al., 2008). We pursue the suggestion (Mathews et al., 2013) that the unique situation – in which the overriding Philippine Sea

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plate, beneath which the Pacific plate subducts along Marianas–Izu–Bonin, is itself subducting to the west – may account for the strong trench advance in this area, as this geometry imparts just such a slab-pull force to the overriding plate as hypothesized above.

2. Model and methods

2.1. Model geometry

The Philippine Sea is a complicated three-dimensional region, exhibiting complex bathymetry and plate shape (Yamazaki et al., 2010) and a complex patchwork of seafloor ages (Müller et al., 2008). The bounding subduction zones exhibit significant north–south variation in slab morphology and stagnation behavior. In Izu–Bonin–Marianas, gently dipping slab stagnation in the north gives way to nearly vertical slab penetration in the south (Stern et al., 2003). For both the eastern and western subduction zones, north–south variations in dip angle can be observed in Wadati–Benioff zone seismicity (Chen et al., 2004; Smoczyk et al., 2013). Furthermore, seismicity exhibits a backwards bending of the deep slab (i.e., a change of sign in the dip angle at depth) in the southern Izu–Bonin and Marianas (zones Mar and Izu3 in Chen et al., 2004; profile F in Smoczyk et al., 2013), in apparent concord with a proposed relationship between slab curvature and advance/retreat mode (Bellahsen et al., 2005; Funicello et al., 2008). Moreover, such patterns can also be seen in seismic tomography (latitude 30° and 25° sections of Huang and Zhao, 2006; S. Bonin and N. Mariana sections of Fukao and Obayashi, 2013). Such spatial variability is further complicated by temporal variation, in that the age of onset of subduction along the Pacific trenches is estimated at ∼50 Ma (Cosca et al., 1998; Stern et al., 2003) while that along the Philippine trench may be much younger at ∼10 Ma (Ozawa et al., 2004). Overall, subduction exerts strong slab pull (Handayani, 2004) imposing extension across the Philippine Sea plate, as evidenced by both relict and active back-arc rifts and related features. For example, Stern et al. (2003) report recurring episodes of extension at 20–30 Myr intervals.

Of course, we cannot hope to capture such complexity in a simplified two-dimensional model, but here we abstract a representative geometry and explore the first-order dynamical consequences. Relative to our previous reference model (Čížková and Bina, 2013), we insert a third plate, yielding an overriding plate which is itself subducting, thereby changing the conceptual force-balance from one of ridge-push compression at the primary subduction interface to one of slab-pull extension (Fig. 1). (While the central overriding plate is clearly mobile, we explore cases in which the third, marginal, overriding plate is either fixed or mobile.) Although these plates are 2D idealizations, we refer to them as the Philippine plate and Pacific plate for convenience. Our 2D rectangular model domain is 10 000 km wide and stretches from the surface to 2000 km deep. In the upper left and upper right corners, spreading ridges are positioned. (Both ridges are offset by ∼200 km from the corners to avoid complications at the vertical boundaries.)

Initial temperature distribution follows a halfspace cooling model in the uppermost part of the domain, with lithospheric age increasing from the left ridge to 140 Myr at the Pacific trench, from the right ridge to 40 Myr at the Philippine trench, and within the middle plate from 30 Myr at the Pacific trench to 40 Myr at the Philippine trench. Below the plates the temperature follows an adiabatic profile with a potential temperature of 1573 K. We set the initial inter-arc distance (i.e., the central plate width) at ∼1500 km, as a median value of the range seen in the Philippine Sea. Our model thus represents a simplified view of the Philippine Sea plate and its margins as viewed from the north looking southward (Fig. 2a).

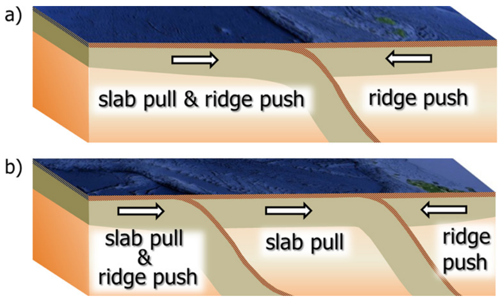

Fig. 1. Schematic force-balance diagrams for (a) a two-plate system in which one plate subducts beneath an overriding plate and (b) a three-plate system in which one plate subducts beneath an overriding plate which is itself subducting beneath an adjacent overriding plate. In the two-plate system, ridge-push exerted by the overriding plate inhibits trench advance. In the three-plate system, slab-pull exerted by the central plate may enhance advance of the leftmost trench.

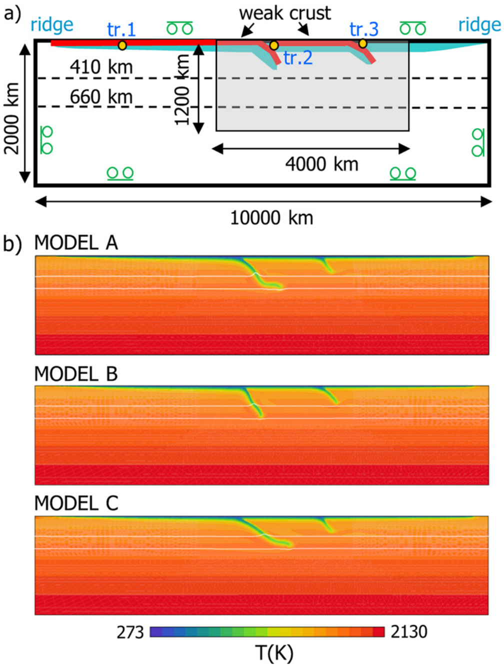

Fig. 2. Model configuration (a) showing initial conditions, including full model space, focused study area (gray rectangle), plates (blue), crust (red), selected tracers (yellow), and transition-zone boundaries (dashed). Starting configurations (b) after short initial runs with prescribed surface velocities to attain three initial temperature distributions (A, B, C) commensurate with differential times of subduction onset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

At the top of both subducting plates a weak crustal layer of 15-km thickness is prescribed. The low viscosity η_{crust} of this layer facilitates decoupling of the subducting and overriding plates. This crust is tracked using particle tracers, and it is not associated with any compositional density contrast. (Rather than try to capture the full complexity of a chemically layered crust, we abstract the essential property controlling coupling and represent it simply as a layer of reduced viscosity of sufficient thickness for numerical resolution.) At a depth of 200 km, where the decoupling effect is no longer needed, the crustal layer is replaced by mantle material for numerical convenience. As we previously demonstrated that higher crustal viscosities minimize trench retreat, we choose our initial crustal viscosity to be at the high end of the values explored previously, at 10^{21} Pa s. In other respects the model follows the reference case from our prior study (Čížková and Bina, 2013).