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Subduction zone decoupling/retreat modeling explains south Tibet (Xigaze) and other supra-subduction zone ophiolites and their UHP mineral phases

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A B S T R A C T

The plate tectonic setting in which proto-ophiolite 'oceanic' lithosphere is created remains controversial with a number of environments suggested. Recent opinions tend to coalesce around supra-subduction zone (SSZ) forearc extension, with a popular conceptual model in which the proto-ophiolite forms during foundering of oceanic lithosphere at the time of spontaneous or induced onset of subduction. This mechanism is favored in intra-oceanic settings where the subducting lithosphere is old and the upper plate is young and thin. We investigate an alternative mechanism; namely, decoupling of the subducting oceanic lithosphere in the forearc of an active continental margin, followed by subduction zone (trench) retreat and creation of a forearc oceanic rift basin, containing proto-ophiolite lithosphere, between the continental margin and the retreating subduction zone. A template of 2D numerical model experiments examines the trade-off between strength of viscous coupling in the lithospheric subduction channel and net slab pull of the subducting lithosphere. Three tectonic styles are observed: 1) C, continuous subduction without forearc decoupling; 2) R, forearc decoupling followed by rapid subduction zone retreat; 3) B, breakoff of subducting lithosphere followed by re-initiation of subduction and in some cases, forearc decoupling (B-R). In one case (BA-B-R; where BA denotes backarc) subduction zone retreat follows backarc rifting. Subduction zone decoupling is analyzed using frictional-plastic yield theory and the Stefan solution for the separation of plates containing a viscous fluid. The numerical model results are used to explain the formation of Xigaze group ophiolites, southern Tibet, which formed in the Lhasa terrane forearc, likely following earlier subduction and not necessarily during subduction initiation. Either there was normal coupled subduction before subduction zone decoupling, or precursor slab breakoff, subduction re-initiation and then decoupling. Rapid deep upper-mantle circulation in the models during subduction zone retreat can exhume and emplace material in the forearc proto-ophiolite from as deep as the mantle transition zone, thereby explaining diamonds and other 10–15 GPa UHP phases in Tibetan ophiolites.

1. Introduction

Ophiolites represent on-land exposures of oceanic lithosphere, many but not all of which have been detached and tectonically emplaced onto continental plate margins (Dewey and Bird, 1971; Anonymous, 1972; Dilek and Furnes, 2011, 2014). Although they may form in a variety of tectonic environments, many ophiolites appear to have been created within a supra-subduction zone (SSZ) setting, by the extension and rifting of either a forearc, or intra-arc region above subducting oceanic lithosphere (Pearce et al., 1984; Shervais, 2001; Pearce, 2003; Metcalf and Shervais, 2008; Whattam and Stern, 2011; Dilek and Furnes, 2014).

An increasing number of SSZ ophiolites are thought to have formed in a forearc setting during the initiation of a new subduction zone, an interpretation made by analogy with the more recent Izu–Bonin–Mariana (IBM) forearc – inferred to have undergone subduction initiation ∼52 Ma (Stern and Bloomer, 1992; Metcalf and Shervais, 2008; Dilek and Furnes, 2009; Reagan et al., 2010; Stern et al., 2012). The hallmark of these 'subduction initiation ophiolites' is a distinct evolution in the composition of proto-ophiolite crust, whereby early MORB-like rocks with "distinct Ti/V and Yb/V ratios reflecting a greater depletion in mod-

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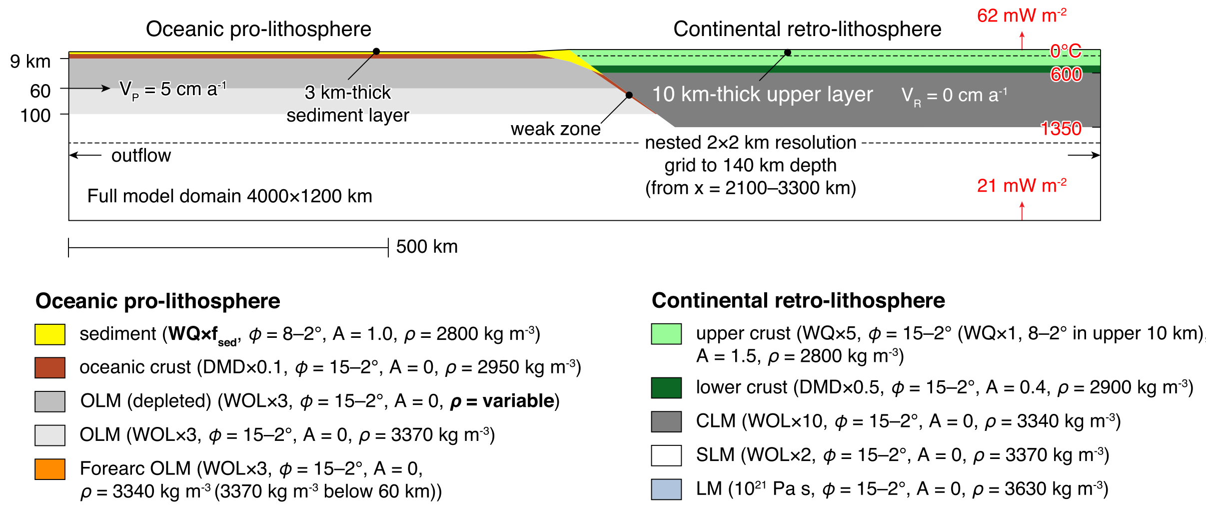

Fig. 1. Design of two-dimensional models (see Section 2 and Appendix A for more details). The full model 4000 × 1200 km domain is represented by a coarse computational grid with a maximum resolution of 10 × 2 km. A higher-resolution, 'nested' computational grid (dashed line) is embedded within the coarse grid in the vicinity of the subduction zone and retro-lithosphere, and has a maximum resolution of 2 × 2 km. CLM = continental lithospheric mantle, OLM = oceanic lithospheric mantle, SLM = sub-lithospheric mantle, LM = lower mantle. Forearc OLM (orange) appears in subsequent figures, formed by cooling of sub-lithospheric mantle. Black arrows show velocity boundary conditions in schematic form. Red shows thermal boundary conditions (basal heat flux) and resulting surface heat flux and continental temperatures. WQ = wet quartzite, DMD = dry Maryland diabase, WOL = wet olivine. ϕ = range of effective angle of internal friction (ϕ_{eff}) owing to pore-fluid pressure and frictional-plastic strain-softening; A = radiogenic heat production ($\mu W\,m^{-3}$) (A_R in text); ρ = density (Table 1).

erately incompatible elements" (the 'Forearc basalts' of Reagan et al., 2010) give way to arc tholeiites and boninites, a trend reflecting increasing input of subducting slab-derived fluids and enhanced depletion of the mantle wedge (Dilek and Furnes, 2009; Stern et al., 2012; Pearce, 2014). This interpretation is often linked to a model in which spontaneous foundering of old oceanic lithosphere at a fracture zone leads to the gradual formation of a new subduction zone, and hence progressively increasing input of slab-derived fluids (Stern and Bloomer, 1992; Stern, 2004; Metcalf and Shervais, 2008).

Spontaneous subduction initiation may operate when coupling between the upper and lower plates is weak, e.g. a ridge-transform boundary where the upper plate comprises thin young oceanic lithosphere (Stern, 2004). However, it is less likely at rifted continental margins, where the stiffness of thick/cool lithosphere will resist bending (Gurnis et al., 2004). We present 2D thermomechanical models that are used to explore an alternative geodynamical model, that of subduction zone decoupling and forearc spreading at an active continental margin, an application of Royden (1993) concepts to active continental margins. It is not our intention to investigate whether spontaneous or induced subduction initiation (Hall et al., 2003; Stern, 2004; Nikolaeva et al., 2010; Baes et al., 2011) operates when the upper plate is continental, nor to present a general review of subduction modeling and over-riding plate dynamics, which is comprehensively reviewed by Gerya (2011). Instead, we focus on what controls subduction zone decoupling and subsequent forearc spreading, and demonstrate that forearc proto-ophiolitic crust with subduction initiation signatures likely forms in tectonic settings other than subduction initiation.

We first present key results from a set of numerical experiments that demonstrate behaviors ranging from normal coupled subduction, to subduction zone decoupling and 'proto-ophiolite' formation (where we mean oceanic-like lithosphere that is later tectonically emplaced as an ophiolite), to subducting slab breakoff. This is followed by a discussion of the sensitivity of the models to the effective slab pull force and interplate coupling. We then compare the model results with the predictions of a basic theoretical analysis to develop a greater understanding of the model decoupling behavior.

We conclude with a discussion of the models in the context of south Tibetan ophiolites, particularly the Xigaze ophiolite, where mounting evidence points to formation in a forearc setting adjacent the Lhasa terrane during a hiatus in arc magmatism (Dai et al., 2013; An et al., 2014; Huang et al., 2015; Maffione et al., 2015; Xiong et al., 2016). Rather than being intrinsically related to subduction zone initiation *per se*, we suggest that forearc proto-ophiolite genesis at active continental margins is the product of subduction zone decoupling and subduction zone/trench retreat.

2. Methods

2.1. Model design

We use the 2D finite element software SOPALE-nested to solve thermomechanical creeping flows at the mantle scale (Fullsack, 1995; Beaumont et al., 2009; Appendix A.1). The starting model geometry (Fig. 1; Table 1) represents a simplified active continental margin subduction system comprising oceanic pro-lithosphere and continental retro-lithosphere, overlying upper mantle, base 660 km, and lower mantle, base 1200 km. The oceanic lithosphere is 100 km thick, corresponding to a thermally-old (∼100 Myr) lithosphere, and comprises 3 km sediment, 6 km oceanic crust, and 91 km lithospheric mantle. The 120-km thick retro-continent comprises an upper 10-km thick weak layer, 14 km normal upper crust, 12 km lower crust, and 84 km lithospheric mantle. A small oceanic sediment accretionary wedge separates the oceanic and continental lithospheres and is underlain by a thin dipping layer of weak oceanic crust that serves as a guide during subduction initiation.

Model materials deform by either frictional-plastic (brittle) or power-law viscous (ductile) flows that include the effects of strain-softening/strain-weakening, respectively. At high stress, a saturation stress approximation to the Peierls flow law modifies power-law flow. Frictional-plastic deformation depends on the dynamical pressure and effective angle of internal friction (ϕ_{eff}; hereafter simply ϕ). For most model materials, ϕ varies from 15–2°, (15° is the initial effective angle of internal friction including pore fluid pressure, and 2° is fully strain-softened material). Oceanic sediment