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Deep plate serpentinization triggers skinning of subducting slabs

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ABSTRACT

Most of the present-day ocean floor is continuously being consumed in subduction zones, but large fragments of oceanic crust (ophiolites) have also been recognized on land. The process by which oceanic crust is separated from the subducting slab remains enigmatic, and several competing hypothesis have been proposed in the past.

Based on numerical experiments we suggest that serpentinized mantle, formed in the outer rise regions of subduction zones, may provide a mechanically weak horizon within which basal detachment of the oceanic crust is feasible. Deformation of this serpentinized layer may lead to decoupling and separation of oceanic crust from the downgoing slab. Fragments of the former oceanic crust can underplate the accretionary wedge or be exposed on continental crust, whereas the skinned lithospheric part of the slab subducts into the mantle.

INTRODUCTION

Hydration of the oceanic crust and uppermost mantle occurs mainly at mid-ocean ridges (Johnson and Puris, 2003), fracture zones (Manea and Manea, 2008), and in the outer rise region of subduction zones (e.g., McAdoo et al., 1985; Ranero et al., 2003; Faccenda et al., 2008, 2009; Grevemeyer et al., 2007; Lefeldt et al., 2012). Because of the high porosity and permeability caused by lava drainbacks, normal faulting, and volume changes, hydrothermal circulation at mid-ocean ridges allows seawater to penetrate into the base of the crust, promoting seawater intrusion and mantle serpentinization (Johnson and Puris, 2003). In the outer rise region, bending-related faulting of oceanic crust and upper mantle promotes deep hydration of the oceanic crust and uppermost mantle (e.g., McAdoo et al., 1985; Ranero et al., 2003; Faccenda et al., 2008, 2009; Grevemeyer et al., 2007; Lefeldt et al., 2012). Such fluid-mantle-rock interactions lead to partial serpentinization of the initially dry (peridotitic) mantle lithosphere (Schmidt and Poli, 1998), altering its chemical and physical properties. Although direct information on the extent and degree of serpentinization below oceanic crust is not available and complete serpentinization of the mantle is unlikely (Schmidt and Poli, 1998), seismic low-velocity zones indicate that partial serpentinization (10%–20% serpentine) along fracture zones is pervasive down to at least several kilometers depth (Ranero et al., 2003; Grevemeyer et al., 2007; Lefeldt et al., 2012). The brittle strength of partially serpentinized mantle rocks (peridotite with 10%–15% serpentine) has been demonstrated to be as low as those of pure serpentines, because deformation is primarily accommodated by serpentine (the weakest phase), rather than olivine that remains nominally undeformed (Escartín et al., 2001). Likewise, the creep viscosity (ductile strength) of serpentinized mantle is much lower than that of nonserpentinized mantle (Hilairet et al., 2007). Consequently, deep slab serpentinization can create a rheologically weak layer below the subducting oceanic crust. This layer will, in turn, strongly enhance the possibility of slab "skinning," a process by which the oceanic crust is decoupled from the subducting slab and accreted within the accretionary wedge to form ophiolite complexes.

METHODS

This work documents results from high-resolution thermomechanical numerical experiments of ocean-continent subduction zones to investigate the physical conditions for decoupling and imbrication of oceanic crust in present-day subduction zones. In these experiments, we assume that the presence of a sufficiently thick and serpentine-rich mantle region may produce a horizon of low effective viscosity and low brittle-plastic strength, located directly below the oceanic crust (Fig. 1).

All numerical experiments were performed with the I2VIS code (Gerya and Yuen, 2003). This code is based on conservative finite differences and a marker-in-cell technique. The momentum, continuity, and energy equations are solved on a Eulerian frame, and Lagrangian markers that move according to the velocity field interpolated from the fix grid transport physical properties. The model uses non-Newtonian viscoplastic rheologies to simulate mul-

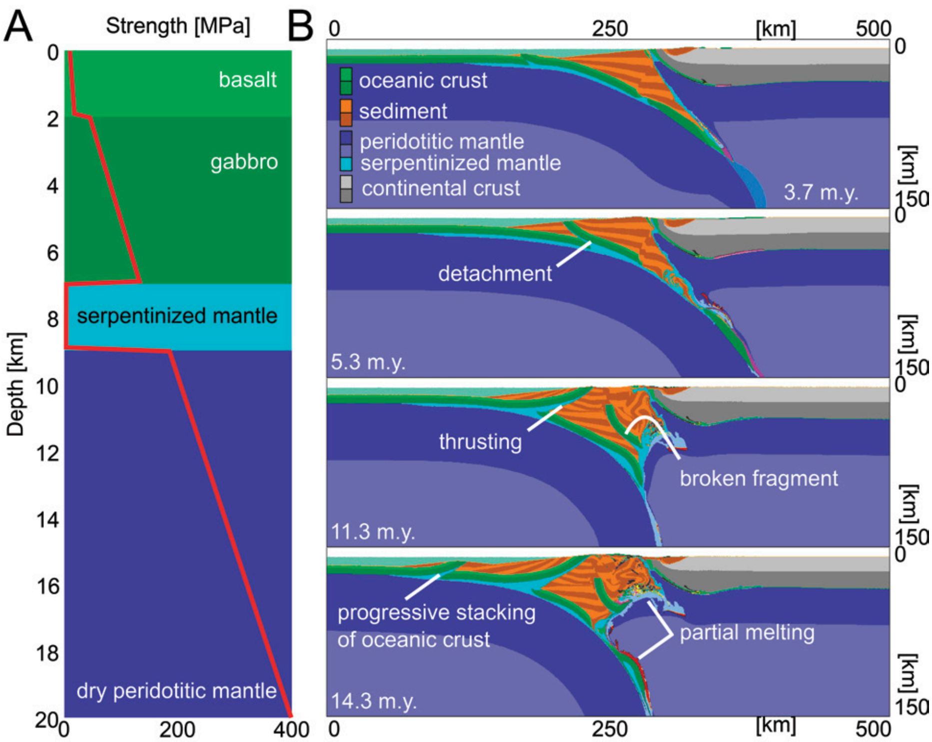

Figure 1. A: Strength profile of the oceanic crust and uppermost mantle for constant strain rate of $\dot{\varepsilon} = 1 \times 10^{-13}$. Serpentinized mantle provides mechanically weak subcrustal horizon within which basal detachment of the oceanic crust is feasible. B: Thermomechanical model of slab skinning. Compositional (lithological) map. Oceanic crust detaches along the weak serpentinized horizon, breaks, and is incorporated into the accretionary wedge. Skinned lithospheric part of the subducting slab sinks into mantle.

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tiphase flow (see the GSA Data Repository[1]). The computational domain is two dimensional and spans 2000 × 200 km (Fig. DR1 in the Data Repository). It contains a (1000-km-wide) high-resolution area of 0.5 × 0.5 km in the center of the domain. The rest of the model remains at a lower resolution. All mechanical boundary conditions are free slip.

Model Setup

The oceanic plate is pushed toward a fixed continental plate at an imposed convergence rate of 3.5 cm/yr and bends spontaneously under the control of realistic viscoplastic rheologies (Fig. 1A; for details on the rheological properties, see the Data Repository). The thermal structure of the oceanic plate was computed from the half-space cooling model (Turcotte and Schubert, 2002), in which the plate age was varied from 1000 yr at the origin (mid-oceanic ridge) to 40 m.y. at the trench. The initial temperature field of the continental plate increases linearly from 0 °C at the surface to 1344 °C at the base of the continental lithosphere (72 km depth). For the asthenospheric mantle (>72 km), a thermal gradient of 0.5 °C km^{-1} is used.

Both the asthenosphere and the upper mantle are composed of anhydrous peridotite and are defined by the temperature profile. The subducting oceanic crust is represented by 2 km of basalt and 5 km of gabbroic rocks. In the outer rise region (~50 km away from the trench), the uppermost mantle comprises a 3–9-km-thick hydrated layer of varying serpentine content (Fig. 1; Fig. DR2) that is assumed to have evolved mainly due to bending related faulting. This is consistent with recent studies indicating that most serpentinization occurs at the trench, rather than at mid-ocean ridges.

RESULTS

We carried out 20 numerical experiments by systematically varying the thickness of the hydrated subcrustal mantle horizon and its volumetric degree of serpentinization (Fig. DR2). Detachment of large oceanic crustal fragments from the subducting slab is clearly documented for experiments (Fig. 1B; Fig. DR2) in which the hydrated horizon is thick and serpentine rich (≥3km, ≥25% serpentine). The oceanic crust decouples from the downgoing slab along this serpentinized horizon, breaks, and thrusts over the accretionary wedge or is incorporated into the accretionary complex. The underlying mantle lithosphere remains mainly undeformed and continues to subduct (Fig. 1B). New incoming oceanic crust may underthrust these broken oceanic fragments, subduct, or break at greater depth. Remnants of the former oceanic crust underplate the accretionary wedge and could be exposed during subsequent collisional events.

At asthenospheric depths, the large thermal contrast between the skinned slab and overlying mantle causes remnant serpentine breakdown and fluid release. Aqueous fluids percolate into the mantle wedge and alter the physical and chemical properties of the overlying mantle (e.g., Schmidt and Poli, 1998; Gerya and Meilick, 2011). Where such fluids encounter the wet mantle solidus they induce partial melting of the mantle, the process by which most arc magmas are believed to have formed (e.g., Schmidt and Poli, 1998). Dehydration of serpentine at greater depth (~200 km) may have profound implications for the Earth deep-mantle water cycle (Ranero et al., 2003).

The efficiency of this separation process, i.e., the oceanic crust detaching from the subducting slab, is critically controlled by the thickness of the subcrustal hydrated layer, its volumetric degree of serpentinization (Fig. DR2), and the rheological degree of plate coupling (Figs. DR3–DR6). In particular, a limited volumetric degree of serpentinization (<25%) leads to continuous subduction of oceanic crust to mantle depth, as described for most subduction zones. Additional experiments suggest that for lower degrees of plate coupling (Gerya and Meilick, 2011), higher degrees of serpentinization (>50%) are needed in order to imbricate and detach the oceanic crust from the downgoing slab (Figs. DR4–DR6). This implies that slab skinning can be strongly variable in nature, depending on the degree of plate coupling and physical conditions for normal faulting and plate hydration.

DISCUSSION

Geological Observations

Comparison of ophiolite occurrences throughout modern Earth history (Vaughan and Scarrow, 2003) indicates that ophiolite emplacement has occurred in various tectonic environments, including both ocean-ocean and ocean-continent subduction zones (Fig. 2). Oceanic fragments are common features of all modern and ancient accretionary complexes (Kimura and Ludden, 1995) and have been attributed to the progressive stacking of coherent ophiolitic thrust slices against the leading edge of the continental crust (Coleman, 1971) or the offscraping and underplating of smaller ophiolitic slivers from the upper oceanic crust (Kimura and Ludden, 1995), but examples may also be found in collisional orogens. Exhumed ophiolitic terranes in the Western Alps are believed to represent fossil examples of oceanic crust brecciation under eclogite facies conditions (~23 kbar) and suggest deep burial (~80 km) prior to fluid-assisted fragmentation and subsequent emplacement at crustal levels (Angiboust et al., 2012). Brecciation in the middle part of the oceanic crust has been suggested to invoke intermediate-depth earthquakes, consistent with eclogite breccias in ophiolite complexes (Angiboust et al., 2012). The exhumation of oceanic crust and associated mantle is discontinuous and short lived, but may occur early with respect to the subduction zone cycle (e.g., Chilean subduction zone; Franciscan subduction zone in California, USA; possibly Makran subduction zone in Iran), at the midst of convergence (e.g., Zagros, Himalaya, Andes) or late in the subduction cycle (e.g., Western Alps; New Caledonia, southwest Pacific Ocean) (Agard et al., 2009). The rate at which oceanic crust is incorporated into accretionary prisms or obducted on land has rarely been reported; however, ophiolite accretion rates of at least 50 km^3/km/m.y. were derived from the Great Valley ophiolite in California (Godfrey and Klemperer, 1998), while ophiolite accretion rates in the Philippine archipelago yielded somewhat smaller rates of ~2–30 km^3/km/m.y. (Dimalanta and Yumul, 2003).

The close spatial association of exhumed oceanic fragments with mechanically weak serpentinites in most ophiolitic complexes (Spaggiari et al., 2004) suggests an intimately related tectonic history and emphasizes its physical role in the emplacement mechanism. Unlike other exhumed oceanic crust rocks, serpentines are commonly highly deformed and therefore likely to have governed stress buildup and strain localization (Hilairet et al., 2007). Structural analyses of fossil accretionary complexes indicate that ophiolitic thrust silvers may either decouple along a weak hydrothermally altered horizon (Kimura and Ludden, 1995) or detach along serpentinized sections at greater depth (Spaggiari et al., 2004). Therefore, décollement formation is considered a critical condition for the detachment and emplacement of oceanic fragments by either offscraping or underplating (Spaggiari et al., 2004).

Geophysical Observations

The subsurface distribution of stacked layers of imbricated oceanic crust, and smaller ophiolitic thrust slivers within modern accretionary complexes of currently active subduction zones, has been determined by combined geophysical methods (Godfrey and Klemperer, 1998; Dimalanta and Yumul, 2003). Seismic, gravity, and magnetic field studies indicate that these oceanic fragments can often be related to on-land exposures of ophiolite complexes (Fig. 2). For example, magnetic structures of the southern Boso Peninsula in Japan indicate fragmented pieces of oceanic plate emplaced at a paleoboundary at 1–3 km depth, consistent with rocks in the Mineoka ophiolite belt (Fujiwara et al., 1999). Dissected oceanic crust, fragmented by normal

[1]GSA Data Repository item 2014269, supplementary materials and methods (including Figures DR1–DR6 and Table DR1), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

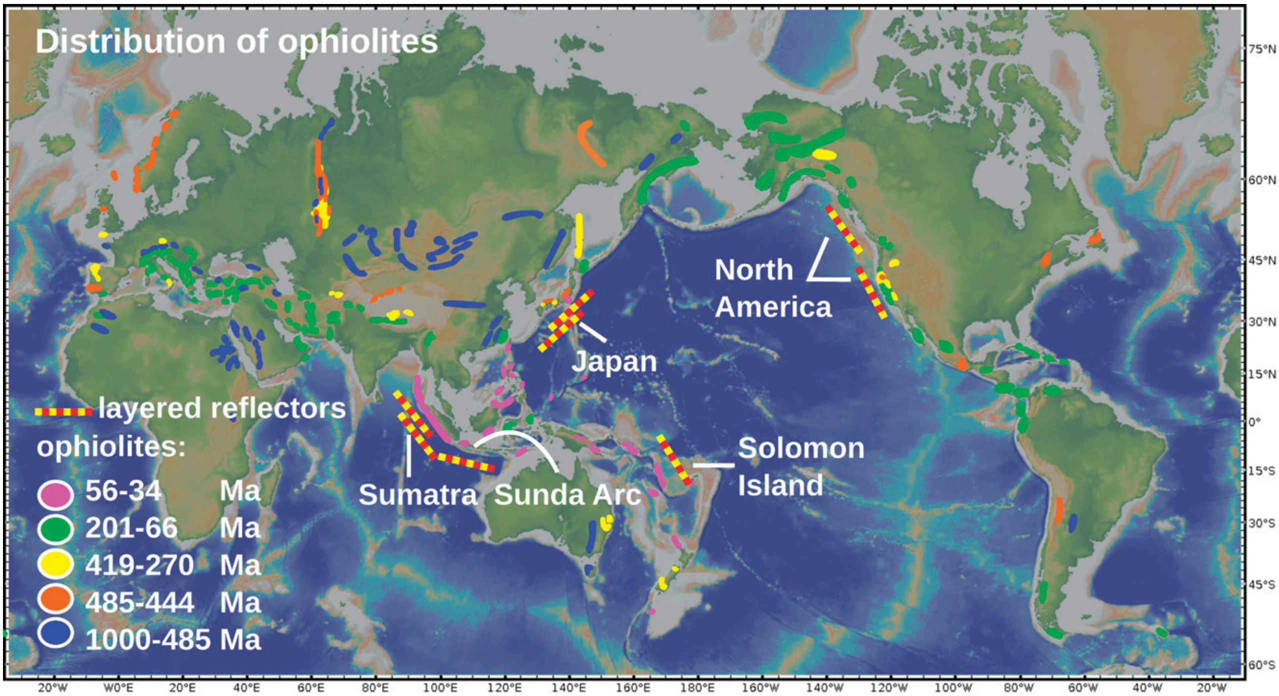

Figure 2. Distribution of Phanerozoic and Neoproterozoic ophiolites (modified after Vaughan and Scarrow, 2003) and layered reflectors at 10–30 km depth (Fujiwara et al., 1999; Lüschen et al., 2011; Singh et al., 2008, 2012; Calvert, 2004; Kimura et al., 2010; Bernstein-Taylor et al., 1992). Such imaged reflection zones indicate faulted, underplated, and/or imbricated oceanic crust below the subsurface.

faulting into 5–10-km-sized blocks, below the forearc of the eastern Sunda Arc has been proposed to account for the ophiolite sheets and nappes of the island arc east of Java (Lüschen et al., 2011). Multichannel reflection seismic data obtained in this region clearly image normal faulting in the outer trench slope and may indicate the onset of detachment. The tectonic activity detected by Lüschen et al. (2011) compares well with results of our numerical simulations (Fig. 3). Large coherent fragments of broken oceanic crust imaged in the Sumatran epicentral region led Singh et al. (2008) to propose that imbrication of the oceanic lithosphere (oceanic crust and uppermost mantle) may cause earthquakes; i.e., brittle failure of mantle rocks can account for megathrust earthquakes with exceptional magnitudes, such as the 2004 Sumatran event. Most recent images of the Sumatran subduction system from the subducting front to the volcanic arc have confirmed that the subducting oceanic plate is fragmented, forming shallowly dipping segments of 50 km, separated by 5–15 km depth intervals, indicating faulting of the oceanic crust (Singh et al., 2012). Exhumed ophiolites identified on the Mentawai-Andaman island chain have been suggested to represent the long-term outcome of such successive episodes of oceanic underplating, based on the high free-air gravity anomaly and the seismic reflection image at the southwestern part of the accretionary complex (Singh et al., 2008). Other locations where layered reflectors have been identified at 10–30 km depth include western North America (Calvert, 2004), the central region of Japan (Kimura et al., 2010), and the western Solomon Sea basin (Bernstein-Taylor et al., 1992). Such reflection zones are generally believed to represent crustal-scale duplexes associated with underplating, or imbricated crustal rocks of the oceanic crust and ophiolitic slivers (Fig. 2).

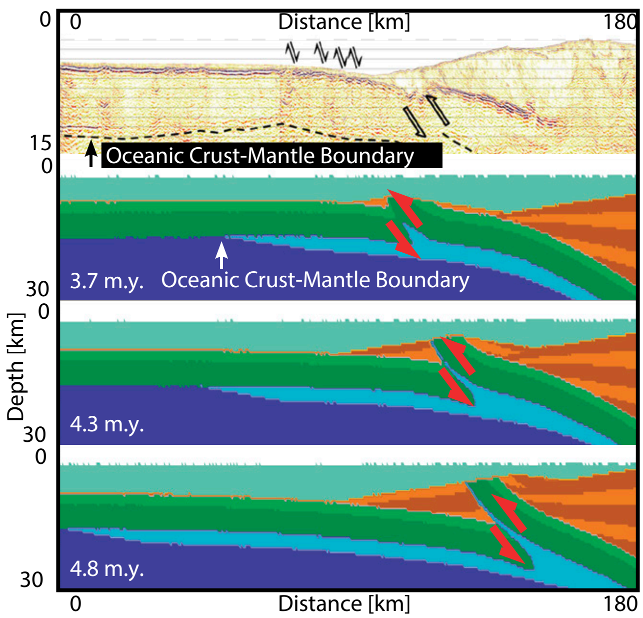

Figure 3. Comparison of seismic reflection data imaged below the forearc of the eastern Sunda Arc (Lüschen et al., 2011) with our numerical simulations. Oceanic crust is faulted at the toe of the accretionary wedge. Arrows mark relative motion of the imbricated oceanic crust and indicate future detachment, as suggested by our numerical simulations.

Layers of low seismic wave speed associated with subducting slabs in numerous subduction zone settings are commonly interpreted as hydrated oceanic crust that has not transformed into eclogite (Bostock, 2013). However, some of these zones of low seismic wave speed extend to greater depth than the model predicted by basalt-peridotite transformation, and have been suggested to represent fluid or hydrous phase minerals rather than the variable metastability of anhydrous gabbro (Abers, 2005). Therefore, we propose that such extended low seismic-wave-speed layers could indicate the skinned, serpentinized lithospheric part of the subducting plate, rather than the hydrated oceanic crust.

CONCLUSIONS

Fossil oceanic crust (ophiolite) has been recognized in various tectonic settings throughout the modern Earth rock record. Ophiolite emplacement is a fundamental problem, because oceanic lithosphere is significantly denser than crustal rocks of the upper continental crust. Here we have shown that detachment of oceanic crust is feasible along a mechanically weak, partially serpentinized horizon. The strong rheological contrast between oceanic crust and serpentinized mantle can lead to decoupling, separation, and detachment of oceanic crust from the downgoing slab. The efficiency of this process depends critically on the existence of a mechanically weak and continuous detachment horizon, i.e., serpentinized mantle. The greater its thickness or the higher its serpentine content, the easier it is to decouple oceanic crust from the downgoing slab. Nevertheless, other factors, such as the rheological degree of plate coupling, are also likely to influence the tectonic evolution of oceanic crust, and further studies will be needed to determine its global significance.

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