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Formation of plate boundaries: The role of mantle volatilization

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ABSTRACT

In the early Earth, convection occurred with the accumulation of thick crust over a weak boundary layer downwelling into the mantle (Davies, G.F., 1992. On the emergence of plate tectonics. Geology 20, 963–966.). This would have transitioned to stagnant-lid convection as the mantle cooled (Solomatov, V.S., Moresi, L.-N., 1997. Three regimes of mantle convection with non-Newtonian viscosity and stagnant lid convection on the terrestrial planets. Geophys. Res. Lett. 24, 1907–1910.) or back to a magma ocean as the mantle heated (Sleep, N., 2000. Evolution of the mode of convection within terrestrial planets. J. Geophys. Res. 105(E7): 17563–17578). Because plate tectonics began operating on the Earth, subduction must have been initiated, thus avoiding these shifts. Based on an analogy with the continental crust subducted beneath Hindu Kush and Burma, we propose that the lithosphere was hydrated and/or carbonated by H_2O–CO_2 vapors released from magmas generated in upwelling plumes and subsequently volatilized during underthrusting, resulting in lubrication of the thrust above, and subduction of the lithosphere along with the overlying thick crust. Once subduction had been initiated, serpentinized forearc mantle may have formed in a wedge-shaped body above a dehydrating slab. In relict arcs, suture zones, or rifted margins, any agent that warms and dehydrates the wedge would weaken the region surrounding it, and form various types of plate boundaries depending on the operating tectonic stress. Thus, once subduction is initiated, formation of plate boundaries might be facilitated by a major fundamental process: weakening due to the release of pressurized water from the warming serpentinized forearc mantle.

Contents

1. Introduction

At present, plate tectonics operates on the Earth. This was probably not the case during the magma ocean stage (Warren, 1993; Sleep,

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2000). Paleomagnetic, geochemical, and isotope studies suggest that plate tectonics had started earlier than the Archean/Proterozoic boundary (Burke et al., 1976; Campbell and Griffiths, 1992). However, even if we accept that it had started by that time, it is not easy to describe how it began. Because of the strongly temperature-dependent viscosity of the mantle material (e.g. Kirby, 1983), the lithosphere is not easy to rupture. A number of studies show that subduction initiation requires high levels of stress to disrupt the lithosphere, which is a few tens of kms thick (e.g. McKenzie, 1977; Cloetingh et al., 1984; Mueller and Phillips, 1991). Meanwhile, the largest available plate tectonic forces are of the order of 10^{13} N/m (Molnar and Gray, 1979; Parsons and Richter, 1980; England and Molnar, 1991; Fleitout, 1991); these forces are insufficient to cause top-to-bottom disruption of a plate. Strain-weakening is thus required to form new plate boundaries (e.g. Bercovici, 1998; Moresi and Solomatov, 1998; Tackley, 1998; Regenauer-Lieb et al., 2001; Tommasi and Vauchez, 2001; Bercovici, 2003). Because plate tectonics does not operate on Venus or Mars, it is inferred that the weakening mechanisms should include effects of volatiles like H_2O and CO_2 (e.g. Bercovici, 1998; Regenauer-Lieb et al., 2001; Solomatov, 2004; O'Neill et al., 2007). Their effects on the thermo-mechanical properties of the lithosphere have been considered in numerical simulations of the initiation of plate boundaries (e.g. Bercovici, 1998; Regenauer-Lieb et al., 2001). They are, however, in general, not in the context of the formation of each type of plate boundary during the Earth's tectonic history. Eclogitization of granulites induced by fluid injection might have played an important role in deforming the lithosphere (Austrheim et al., 1997; Bjornerud et al., 2002) and could be an example of the effects of volatiles. However, it is not yet clear how eclogitization played a role in the initiation of plate tectonics.

Another difficulty in initiating plate tectonics is the production of a large amount of basaltic crust at the surface by upwelling of the mantle. This occurred due to the high mantle potential temperature during the Archean (Sleep and Windley, 1982; Bickle, 1986; McKenzie and Bickle, 1988; Vlaar et al., 1994). The buoyant crust does not cool enough, which prevents subduction and leads to heating-up of the Earth's mantle and a shift back to a magma ocean (Sleep, 2000).

In this paper, we present a scenario where H_2O and CO_2 play a role in the initiation of plate boundaries in the context of realistic tectonic situations. We propose that subduction was initiated by volatilization of the underthrusting lithosphere that was once hydrated or carbonated by upwelling plumes. The ultramafic minerals that constitute the lithospheric mantle are affected by vapors rich in H_2O–CO_2 released from solidifying magmas in a plume head, and are altered to minerals such as amphibole, phlogopite, dolomite, magnesite, chlorite, and serpentine (Menzies et al., 1987; Spera, 1987; Wyllie, 1988). If such hydrated/carbonated lithosphere approaches a convergent zone and is underthrust, volatilization from it would occur due to increases in temperature and pressure. The released volatiles would lubricate the thrust above, and make subduction initiation possible. This inference is obtained from the fact that subduction of the lithosphere with thick continental crust is now occurring beneath Hindu Kush and Burma according to intermediate-depth seismicity observed there (Seno and Rehman, 2011), although the nature of the crust is chemically different from that in the Archean. The lower portion of the lithosphere in these regions is likely to have been hydrated/carbonated by plumes when it passed over the Reunion and Kerguelen hotspots. This will be described later in more details.

Once subduction started, formation of serpentinized forearc mantle in a wedge-shaped body above a dehydrating slab followed. Kirby et al. (2003, 2013) proposed that the San Andreas fault system (SAF) was mobilized by weakening of the warming and dehydrating serpentinized forearc mantle, following the cessation of subduction of the Farallon plate. Serpentinized wedge mantle formed in a forearc may be found in certain tectonic settings, such as relict arcs, suture zones, and rifted margins. If the wedge is warmed by any agent, the resultant released pressurized water will weaken the region surrounding the wedge, and will form various types of plate boundaries, depending on the stress regime. In the latter half of this paper, we show application of this weakening mechanism to the creation of each type of plate boundary during the stage after subduction had been initiated.

2. Subduction initiation

In this section, we treat the case where we consider that the initiation of subduction has not occurred. In uniform-viscosity convection, both convergent and divergent motions occur at the surface. This may mimic the convection that occurred during the early stages of the Earth with a weak boundary layer sinking into the mantle (Fig. 1a and b, Davies, 1992). However, in these conditions, crust thicker than the modern one would form over the lithosphere (Sleep and Windley, 1982; McKenzie and Bickle, 1988). Such crust results from primordial melt production of the mantle having a basaltic composition and a density of ~2900 kg/m^3 (McKenzie and Bickle, 1988). It is still prevented from subduction due to the plate being thin during the Archean (Davies, 1992; See also Cloos, 1993). At convergent margins, the crust is offscraped, thrust upward, and juxtaposed over crustal slivers, as in modern collision zones (Mattauer, 1986), with the mantle boundary layer downwelling alone, leaving the surface tectonics behaving unlike plate tectonics (Davies, 1992; Fig. 1a and b). In such a tectonic situation, if the average Earth's surface heat flow is larger than the radioactive heat production, the mantle is cooled. If the boundary layer is too strong to be subducted, there occurs a shift to stagnant-lid convection like that on Venus (Solomatov and Moresi, 1996, 1997; Sleep, 2000). Conversely, if the average surface heat flow is smaller than the radioactive heat production, the mantle becomes hotter, and large-scale melting of the mantle (i.e. a magma ocean) resumes (Sleep, 2000). Therefore, for plate tectonics to start on the Earth, the lithosphere must be subducted along with its thick crust as a whole, avoiding the shift to stagnant-lid convection or to a magma ocean. However, it seems unlikely to occur in preference to the buoyant crust piling up at the surface.

2.1. Subduction of the continental lithosphere beneath Hindu Kush and Burma

We propose a mechanism that describes the start of plate tectonics on the Earth. The locations where continental lithosphere with thick crust subducts into the modern Earth give us a clue. Hindu Kush and Burma provide evidence of the mechanism (See Rehman et al., 2011 and the references therein for the geologic history of this region, and see Seno and Rehman, 2011 for the tectonic setting). Hindu Kush is located within the Asian plate, southwest of Pamir and west of Karakorum. To the south, there is the Mesozoic Kohistan–Ladakh arc, which was welded to Asia during the late Mesozoic. India later collided with this arc in the early Tertiary. The geological terranes associated with the collision between India and Kohistan–the high Himalaya, the lesser Himalaya, and the Siwaliks–are similar to those in other Himalayan regions where India and Asia collided. However, the widths of the high and lesser Himalayas are only ~1/2 of those in other regions. This indicates that offscraping and accretion of the underthrusting Indian continental margin crust have had a smaller extent south of Kohistan.

The plate boundary where the Indian plate is currently underthrust is located south of Kohistan (Searle et al., 2001). To the north, intermediate-depth seismicity dips steeply northward to a depth of ~300 km beneath Hindu Kush and dips southward to a depth of ~150 km beneath Pamir (e.g. Billington et al., 1977; Searle et al., 2001). Studies of this seismicity using focal mechanisms and seismic tomography (e.g. Van der Voo et al., 1999; Pavlis and Das, 2000) show that the seismic zone beneath Hindu Kush is contiguous to that beneath Pamir. Because India has been colliding against Kohistan since the early Tertiary, no oceanic plate is recently subducting beneath this region, as pointed out by Searle et al. (2001). It is thus difficult to relate