Earth and Planetary Science Letters 403 (2014) 368–379

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Evolution of 3-D subduction-induced mantle flow around lateral slab edges in analogue models of free subduction analysed by stereoscopic particle image velocimetry technique

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A R T I C L E I N F O

Article history:
Received 19 March 2014
Received in revised form 30 June 2014
Accepted 4 July 2014
Available online 31 July 2014
Editor: J. Brodholt

Keywords:
subduction
mantle flow
slab edges
analogue models
stereoscopic PIV

A B S T R A C T

We present analogue models of free subduction in which we investigate the three-dimensional (3-D) subduction-induced mantle flow focusing around the slab edges. We use a stereoscopic Particle Image Velocimetry (sPIV) technique to map the 3-D mantle flow on 4 vertical cross-sections for one experiment and on 3 horizontal depth-sections for another experiment. On each section the in-plane components are mapped as well as the out-of-plane component for several experimental times. The results indicate that four types of maximum upwelling are produced by the subduction-induced mantle flow. The first two are associated with the poloidal circulation occurring in the mantle wedge and in the sub-slab domain. A third type is produced by horizontal motion and deformation of the frontal part of the slab lying on the 660 km discontinuity. The fourth type results from quasi-toroidal return flow around the lateral slab edges, which produces a maximum upwelling located slightly laterally away from the sub-slab domain and can have another maximum upwelling located laterally away from the mantle wedge. These upwellings occur during the whole subduction process. In contrast, the poloidal circulation in the mantle wedge produces a zone of upwelling that is vigorous during the free falling phase of the slab sinking but that decreases in intensity when reaching the steady-state phase. The position of the maximum upward component and horizontal components of the mantle flow velocity field has been tracked through time. Their time-evolving magnitude is well correlated to the trench retreat rate. The maximum upwelling velocity located laterally away from the subducting plate is ∼18–24% of the trench retreat rate during the steady-state subduction phase. It is observed in the mid upper mantle but upwellings are produced throughout the whole upper mantle thickness, potentially promoting decompression melting. It could thereby provide a source for intraplate volcanism, such as Mount Etna in the Mediterranean, the Chiveluch group of volcanoes in Kamchatka and the Samoan hotspot near Tonga.

1. Introduction

The subduction process is considered as being mainly driven by the negative buoyancy force through the diving of dense oceanic lithosphere into the mantle (Elsasser, 1971; Forsyth and Uyeda, 1975; Chapple and Tullis, 1977; Carlson et al., 1983; Davies and Richards, 1992; Conrad and Lithgow-Bertelloni, 2002; Bercovici, 2003; Schellart, 2004b; Funiciello et al., 2004; Capitanio et al., 2007; Goes et al., 2008). The sinking of slabs involves the motion of subducting plates but it also induces mantle flow through the viscous drag and the pressure difference in the mantle, due to the down-dip and slab-normal component of slab motion, respectively. In turn the mantle flow is supposed to deform both the overriding plate (Sleep and Toksöv, 1971; Toksöz and Hsui, 1978; Duarte et al., 2013; Meyer and Schellart, 2013; Schellart and Moresi, 2013) and the slab, which can be curved in response to the quasi-toroidal return flow around the slab edges, thereby producing the trench curvature (Jacoby, 1973; Schellart, 2004a, 2010a; Morra et al., 2006, 2009; Stegman et al., 2006; Schellart et al., 2007; Loiselet et al., 2009). Furthermore mantle flow can produce upwelling that might result in decompression melting, thereby providing a source for volcanism. In particular, rollback-induced quasi-toroidal flow around the lateral slab edges has been proposed to be an alternative mechanism explaining the occurrence of intraplate volcanism near slab edges (e.g., Jadamec and Billen, 2010, 2012; Schellart, 2010b; Faccenna et al., 2010). Examples of intraplate volcanoes or volcanics that could be explained by this mechanism include Mount Etna located near the southern

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http://dx.doi.org/10.1016/j.epsl.2014.07.007

edge of the Calabrian slab (e.g., Schellart, 2010b) and the Wrangell volcanics located east of the eastern edge of the Alaska subduction zone (e.g., Jadamec and Billen, 2010, 2012).

To better understand the interaction between the slab and ambient mantle, seismic anisotropy and geochemical studies from the last two decades were dedicated to increase our knowledge of the mantle flow pattern in the vicinity of subduction zones. Some seismic anisotropy studies have documented a trench-parallel alignment of the seismic shear wave splitting fast axis in the sub-slab domain, implying trench-parallel flow beneath the slab of various subduction zones (Russo and Silver, 1994; Gledhill and Gubbins, 1996; Marson-Pidgeon et al., 1999; Peyton et al., 2001; Anderson, 2004; Müller et al., 2008; Foley and Long, 2011). Other studies showed a more complicated pattern in the mantle wedge, with often trench-parallel flow close to the trench and trench-perpendicular flow farther away (Smith et al., 2001; Christensen et al., 2003; Levin et al., 2004; Morley et al., 2006; Léon Soto et al., 2009; Huang et al., 2011; and compilations by Long and Silver, 2008; Long and Wirth, 2013). Many other shear-wave splitting analyses and geochemical studies moreover suggested rotating return flow around one or both lateral slab edges as for the Alaska (e.g., Hanna and Long, 2012), Cascadia (Zandt and Humphreys, 2008; Eakin et al., 2010), Rivera–Cocos (Léon Soto et al., 2009), Sandwich (Pearce et al., 2001; Livermore, 2003; Leat et al., 2004; Müller et al., 2008), Calabria (Trua et al., 2003; Civello and Margheriti, 2004; Baccheschi et al., 2007), Kamchatka (Peyton et al., 2001; Yogodzinski et al., 2001), New Hebrides (Durance et al., 2012; Király et al., 2012) and Tonga (Turner and Hawkesworth, 1998; Smith et al., 2001) subduction zones. These studies highlighted a mantle flow pattern consistent with the idea of a return flow driven by slab motion, where slab rollback induces a quasi-toroidal flow around the lateral slab edges from the sub-slab region toward the mantle wedge (e.g., Russo and Silver, 1994; Long and Silver, 2008).

The mantle flow pattern induced by subduction has also been studied in analogue and numerical models. When geometrically two-dimensional (e.g., Garfunkel et al., 1986; Becker et al., 1999; Enns et al., 2005), the models logically predicted the existence of two poloidal flow cells: one occurring underneath the subducting plate and the other in the mantle wedge. However, such 2-D models do not take into consideration the three-dimensional nature of subduction zones. Indeed, 3-D models with a limited trench-parallel slab extent show the existence and the importance of the quasi-toroidal return flow around the slab edges (Dvorkin et al., 1993; Buttles and Olson, 1998; Kincaid and Griffiths, 2003, 2004; Schellart, 2004a, 2008, 2010b; Funiciello et al., 2004, 2006; Morra et al., 2006; Piromallo et al., 2006; Stegman et al., 2006, 2010; Schellart et al., 2007; Di Giuseppe et al., 2008; Honda, 2009; Jadamec and Billen, 2010, 2012; Druken et al., 2011; Husson et al., 2012; Li and Ribe, 2012; Kincaid et al., 2013; Lin and Kuo, 2013; Schellart and Moresi, 2013) as first suggested by Jacoby (1973).

Most previous models focused on the general horizontal flow pattern in map view, or the cross-sectional mantle flow pattern in the centre of the subduction zone and did not investigate the flow pattern in the vicinity of the slab edges, the recent studies of Jadamec and Billen (2010, 2012), Schellart (2010b) and Faccenna et al. (2010) excepted. In this paper, we study the evolution of the 3-D subduction-induced mantle flow from the initial (transient) stage until the mature (steady-state) stage of subduction both close to the slab edges and at depth using analogue models of free subduction. We use a stereoscopic Particle Image Velocimetry (sPIV) technique to map the three-dimensional velocity field in the upper mantle. We present here the results of two similar models from a set of 8 experiments, where the mantle flow has been mapped on four vertical cross-sections for one and on three horizontal depth-sections for the other model. The main goal is to provide predictions for the location of maxima of upwelling and to track their evolution through time in relation with the location of the lateral slab edges.

2. Method

The experimental approach is similar to that of previous works considering the buoyancy force as the main driver for subduction and assuming the rheological response of lithosphere to be dominantly viscous over geological timescales (e.g., Jacoby, 1973, 1976; Kincaid and Olson, 1987; Funiciello et al., 2004, 2006; Schellart, 2004a, 2004b, 2008, 2010b; Bellahsen et al., 2005). The fluid dynamic models involve two linear-viscous layers contained in a rectangular tank of 100 cm length and 60 cm width (Fig. 1). The top layer rests on top of the lower layer at the initial stage of the experiments and is prevented from sinking entirely into the lower layer by surface tension acting around its edges. It is made of a Newtonian silicone (Wacker silicone, from Dow corning company) mixed with fine iron powder and is 2 cm thick, simulating a 100-km-thick subducting oceanic plate. The lower layer is made of transparent glucose syrup, which has a viscosity that is strain and strain rate independent (Newtonian) but strongly dependent on temperature (Schellart, 2011), and simulates the upper mantle. The mixture of silicone and iron powder has a density of 1517 kg/m^3 and a viscosity of $6.32 \pm 0.1 \times 10^4$ Pa s while the glucose syrup has a density of 1422 kg/m^3 and a viscosity of $2.25 \pm 0.05 \times 10^2$ Pa s at 20 °C. The subducting plate-upper mantle density contrast of 95 kg/m^3 reflects natural conditions of 100 km thick 80 Ma old oceanic lithosphere (Cloos, 1993), although it is slightly higher in the models to negate surface tension effects that are negligible in nature (Schellart, 2008), and makes the subducting plate negatively buoyant. Thus, by initiating a sinking instability (up to 2–3 cm long) the mixture of silicone and iron powder (i.e., the subducting plate) dives into the glucose syrup (i.e., the upper mantle) due to the negative buoyancy force only. Thereafter the models continue to evolve without any external influences.

The models were conducted at very low Reynolds number

$$Re = \rho_{UM} V L / \eta_{UM} \tag{1}$$

(Re estimated between 6.3×10^{-7} and 4.72×10^{-5}) where ρ_{UM} is the upper mantle density, V the characteristic flow velocity ($V = 0.5\text{–}5 \times 10^{-5}$ m/s), L the characteristic length scale ($L = 0.02\text{–}0.15$ m) and η_{UM} the sub-lithospheric upper mantle viscosity. Thus the viscous forces dominate and inertial forces are negligible, indicating that the experiments are in the laminar symmetrical flow regime. We scale the models following Jacoby (1973), Schellart (2008) and Duarte et al. (2013). We use a length scale ratio L_m/L_p of 2.0×10^{-7} (1 cm in the models, subscript m, represents 50 km in nature, subscript p), a time scale ratio t_m/t_p of 3.81×10^{-12} (1 min in the models scales to 0.5 Ma), and a subducting plate to upper mantle viscosity ratio of ∼280.

The total depth of the models is 13 cm, with the bottom of the tank representing an impenetrable 660 km discontinuity. The modelled subducting plate is 15 cm wide, simulating a narrow 750 km wide subduction zone, comparable with the Scotia and Hellenic subduction zones. The distance between the lateral edges of the subducting plate and the sidewalls of the tank is 22.5 cm, which allows us to minimise boundary effects that could be produced by the interaction between mantle circulation and the sidewalls. Both the trailing edge and the lateral edges of the subducting plate are free, representing a mid-oceanic ridge and strike-slip faults, respectively, that offer negligible resistance to plate motion.

The monitoring system consists of four high-resolution cameras (2000 × 2000 pixels), a laser, and two step motors, all managed by