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Mantle wedge asymmetries and geochemical signatures along W- and E–NE-directed subduction zones

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ABSTRACT

Subduction zone kinematics predict that, assuming a fixed lower plate, the velocity of the subduction equals the velocity of the subduction hinge (Vs = −Vh). In all subduction zones the subduction hinge migrates toward the lower plate. However, two main types of subduction zones can be distinguished: 1) those where the upper plate converges toward the lower plate slower than the subduction hinge (mostly W-directed), and 2) those in which the upper plate converges faster than the subduction hinge (generally E- or NE-directed). Along the first type, there generally is an upward flow of the asthenosphere in the hanging wall of the slab, whereas along the opposite second type, the mantle is pushed down due to the thickening of the lithosphere.

The kinematics of W-directed subduction zones predict a much thicker asthenospheric mantle wedge, larger volumes and faster rates of subduction with respect to the opposite slabs. Moreover, the larger volumes of lithospheric recycling, the thicker column of fluids-rich, hotter mantle wedge, all should favour greater volumes of magmatism per unit time. The opposite, E–NE-directed subduction zones show a thinner, if any, asthenospheric mantle wedge due to a thicker upper plate and shallower slab. Along these settings, the mantle wedge, where the percolation of slab-delivered fluids generates melting, mostly involves the cooler lithospheric mantle. The subduction rate is smaller, andesites are generally dominant, and the lithosphere thickens, there appears to be a greater contribution to the growth of the continental lithosphere.

Another relevant asymmetry that can be inferred is the slab-induced corner flow in the mantle along W-directed subduction zones, and an upward suction of the mantle along the opposite E- or NNE-directed slabs. The upward suction of the mantle inferred at depth along E–NE-directed subduction zones provides a mechanism for syn-subduction alkaline magmatism in the upper plate, with or without contemporaneous rifting in the backarc. Positive δ^{11}B and high ^{143}Nd/^{144}Nd characterize W-directed subduction zones where a thicker and hotter mantle wedge is present in the hanging wall of the slab. However, this observation disappears where large amounts of crustal rocks are subducted as along the W-directed Apennines subduction zone.

1. Introduction

The mantle wedge (Fig. 1) is the triangular section of the mantle confined between the top of the slab and the base of the upper plate (e.g., van Keken, 2003; Wiens et al., 2008). It is generally considered to be composed of asthenosphere, although some authors also include the entire lithospheric mantle section above the slab. The mantle wedge filters fluids released by the slab that melt the overlying mantle (Abers et al., 2006), and feed arc magmatism (Tatsumi et al., 1983; Syracuse and Abers, 2006). The mantle wedge is usually conceived as a relatively "hot" body, where the melting feeding the magmatic arc can take place (>1200 °C?), bounded by lower temperatures at the inclined base (top of the slab) and the top (base of the lithosphere?). The transit and location of melting areas into the wedge have been identified by magnetotelluric or electrical conductivity studies (Brasse et al., 2002; Brasse, 2005).

The mantle wedge is therefore a crucial area for plate tectonics, where relevant chemical transfer occurs and new material is produced and added to the crust. What happens in the mantle wedge can be inferred from seismic tomography, geochemistry of lavas and xenoliths, plus other indirect information such as gravimetric and geoelectrical studies. In the Tonga backarc basin, the mantle wedge has been seismically illuminated showing a series of well-bedded reflectors, indicating a form of stratified architecture (Zheng et al., 2007). Martinez and Taylor (2002) proposed an eastward flow in the mantle wedge to compensate for slab rollback, this flow being distorted by the corner flow associated with the subduction. These

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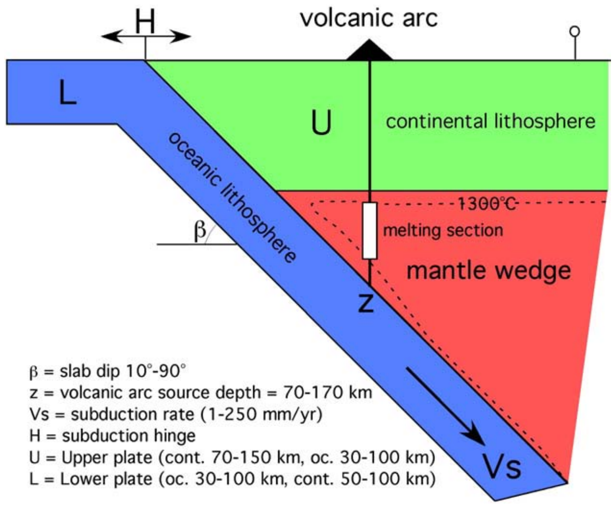

Fig. 1. The mantle wedge is the triangular section of mantle in the hanging wall of subduction zones. It is considered as the source for the magmatic arc, being percolated and metasomatized by the fluids delivered by the dehydration of the descending slab. Relative to the upper plate, the subduction hinge can diverge or converge. The kinematics of the hinge is a good indicator on the mantle wedge geometry. The legend in the figure indicates the range of values of the main parameters.

authors suggest that this flow system can explain the geochemical asymmetries in the backarc spreading and the slab-related volcanic front. Moreover, shear wave splitting analyses often indicate trench-orthogonal direction in the backarc basin, and trench-parallel direction in the forearc (e.g., Levin et al., 2004). This has been interpreted signifying that deformation in the mantle causes lattice-preferred orientation (LPO), which in turn affects the directional dependence of seismic wave velocity (Kneller et al., 2005). Based on shear-wave splitting analysis, trench-parallel ultra-fast velocities (500 mm/year) have been measured in the Tonga mantle wedge (Conder and Wiens, 2007), consistently with the "eastward" mantle flow implicit in the net-rotation, or "westward" drift of the lithosphere (Gripp and Gordon, 2002; Scoppola et al., 2006; Doglioni et al., 2007), although the super fast velocities of Tonga would favour the faster net rotation inferred in the shallow hotspot reference frame (Crespi et al., 2007).

The mantle wedge is considered as a section with higher mantle temperature (anomalies up to 400–600 °C, Koper et al., 1999), rich in fluids released by the downgoing slab (Billen and Gurnis, 2001; Abers, 2005; Grove et al., 2006; Panza et al., 2007a,b; Peccerillo et al., 2008), and marked by low velocity of the seismic waves (Conder and Wiens, 2006), and lower viscosity. In the literature, the mantle wedge is mostly undifferentiated, with variations related to the thickness and composition of the upper and lower plates. However, profound differences occur, for example when comparing the mantle wedge of the western versus the eastern Pacific subduction zones (Plank and Langmuir, 1988), or when comparing the Apennines (W-directed slab) and the Alps (SE-directed slab), (e.g., Peccerillo, 2005; Panza et al., 2007a,b). Multiple subduction components even within a single mantle wedge have been proposed in the arc magmatism of the central and southern America subduction zone (Hickey-Vargas et al., 2002; Tonarini et al., 2007).

It has also been noted that backarc spreading must be part of a mantle flow associated with the mantle wedge. Therefore, significant differences in the mantle wedge should occur as a function of whether or not there is active backarc spreading (Ribe, 1989; Conder et al., 2002; Wiens et al., 2008). Since backarc spreading generally forms along W-directed subduction zones (e.g., Doglioni et al., 2007), we contribute in this article some kinematic and geochemical ideas that support the concept of an asymmetry in the mantle wedge as a function of the subduction polarity. Based on the data compilation in Winter (2001), the W-directed subduction-related volcanic arcs have in general lower K, Na, Al_2O_3 content, and higher FeO, MgO, CaO/MgO with respect to the opposite subduction zones. This may be ascribed to the thinner column (if any) of continental crust percolated by melts along W-directed subduction zones. In fact, even along W-directed zones, K can be very abundant when continental lithosphere occurs both in the lower and in the upper plate (e.g., the central Apennines, Peccerillo, 2005).

2. Subduction asymmetry

Subduction zones can be analyzed in terms of a wide range of parameters, such as convergence rate, topographic and structural elevation of the related orogen, subsidence rate in the trench or foredeep, erosion rate, metamorphic evolution, magmatism, dip of the foreland monocline, depth and geometry of the decollement planes that generate the accretionary prism and the belt of the upper plate, the thickness and composition of the upper and lower plates, gravity, magnetic and heat flow anomalies, seismicity and slab dip. Therefore, there is a long list of parameters, which are relevant to the geometry and evolution of each particular subduction zone. However, since the lithosphere has a net-rotation relative to the mantle (the so-called "westward" drift, e.g., Le Pichon, 1968; Bostrom, 1971), subduction zones appear to be sensitive to this polarization, that is not E–W, but along an undulated flow that has the pole of rotation displaced about 30° with respect to the Earth's rotation pole (Crespi et al., 2007). Therefore, two main different classes can be distinguished as a function of the subduction polarity, i.e., in favour or against the westerly polarized tectonic mainstream that depicts the predominant direction of plate motion (Doglioni et al., 1999, 2007).

Indeed, subduction zones directed to the west (Barbados, Apennines, Marianas, Tonga) show a number of common characteristics, such as low topography and low structural elevation, a deep trench or foredeep with high subsidence rates, generally a steep slab, an accretionary prism mostly composed by the shallow rocks of the lower plate and a conjugate backarc basin. In contrast, subduction zones directed to the east (e.g., Andes) or north-east (Himalayas, Zagros) exhibit opposite signatures such as high structural and morphological elevation, generally no backarc basin, shallower trench or foredeep with lower subsidence rate, deeply rooted thrust planes affecting the whole crust and lithospheric mantle, ultra-high pressure rocks and wide outcrops of metamorphic rocks, and dominantly shallower dip of the slab. Basalts and less evolved lavas are more typical along W-directed subduction zones, whereas andesites are abundant along the opposite E- or NE-directed subduction zones (Andes, Indonesia arc).

All these asymmetries have generally been interpreted as related to the older age of the subducting lithosphere along W-directed subduction zones; however, they occur regardless the age and composition of the subducting slab, being more sensitive to the geographic polarity of the subduction (Doglioni et al., 1999; Cruciani et al., 2005; Lenci and Doglioni, 2007). A study on the consequences of these two end members on the mantle wedge has not yet been carried out. The westward drift of the lithosphere should affect the nature and geometry of the mantle wedge, such as the tensional or compressional tectonic regime in the upper plate, the dip of the slab, and the composition and thickness of the upper plate, all parameters that seem chiefly dictated by the subduction polarity.

3. Slab–mantle kinematics

The subduction hinge is a helpful indicator of the kinematics and nature of subduction zones. The behaviour of the subduction hinge can be studied either relative to the upper plate (Fig. 1), or the lower plate (Fig. 2), or relative to the mantle. It has been shown that subduction zones have rates faster or slower than the convergence rate as a function of whether the subduction hinge migrates away or toward the upper plate (Doglioni et al., 2007). When the subduction hinge moves toward the upper plate a double verging orogen forms, whereas if the subduction moves away from the upper plate, a single verging, low-elevation prism and a backarc basin form. We present here a further simple kinematic analysis of the subduction system