Earth and Planetary Science Letters 299 (2010) 54-68

Contents lists available at ScienceDirect



Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl



Subduction-triggered magmatic pulses: A new class of plumes?

Claudio Faccenna ^{a,*}, Thorsten W. Becker ^b, Serge Lallemand ^c, Yves Lagabrielle ^c, Francesca Funiciello ^d, Claudia Piromallo ^e

^a Dip. Scienze geologiche, Università "Roma TRE" and CNR-IGAG Rome, Italy

^b Dep. Earth Sciences, University Southern California, Los Angeles, USA

^c Laboratoire Geosciences Montpellier, Université Montpellier II, CNRS, France

^d Dip. Scienze geologiche, Università "Roma TRE", Roma, Italy

^e Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

ARTICLE INFO

Article history: Received 14 December 2009 Received in revised form 5 August 2010 Accepted 6 August 2010 Available online 20 September 2010

Editor: R.D. van der Hilst

Keywords: subduction magmatism upper mantle convection geodynamic modeling

ABSTRACT

A variety of atypical plume-like structures and focused upwellings that are not rooted in the lower mantle have recently been discussed, and seismological imaging has shown ubiquitous small-scale convection in the uppermost mantle in regions such as the Mediterranean region, the western US, and around the western Pacific. We argue that the three-dimensional return flow and slab fragmentation associated with complex oceanic subduction trajectories within the upper mantle can generate focused upwellings and that these may play a significant role in regional tectonics. The testable surface expressions of this process are the outside-arc alkaline volcanism, topographic swell, and low-velocity seismic anomalies associated with partial melt. Using three-dimensional, simplified numerical subduction models, we show that focused upwellings can be generated both ahead of the slab in the back-arc region (though ~ five times further inward from the trench than arc-volcanism) and around the lateral edges of the slab (in the order of 100 km away from slab edges). Vertical mass transport, and by inference the associated decompression melting, in these regions appears strongly correlated with the interplay between relative trench motion and subduction velocities. The upward flux of material from the depths is expected to be most pronounced during the first phase of slab descent into the upper mantle or during slab fragmentation. We discuss representative case histories from the Pacific and the Mediterranean where we find possible evidence for such slab-related volcanism.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

A variety of thermal plumes, including splash (Davies and Bunge, 2006), baby (e.g., Wilson and Downes, 2006) and edge (King and Ritsema, 2000) plumes, have been recently described as focused vertical upwellings that are not directly rooted in the lower mantle, as would be predicted by the original hotspot model (Courtillot et al., 2003; Morgan, 1971). Moreover, high-resolution seismological images have shown a large amount of apparent small-scale convective heterogeneities in the uppermost mantle of margins such as the western US (e.g., Sigloch et al., 2008; West et al., 2009) and the Mediterranean (Faccenna and Becker, 2010). Small scale mantle flow could explain, for example, the velocity distribution beneath the Rio Grande Rift (van Wijk et al., 2008), the uplift and magmatism of the Colorado plateau (Roy et al., 2009) and extension beneath the Great basin (West et al., 2009). Subcontinental small-scale convection may be also excited by sharp temperature gradients at a craton's edge, where decompression melting may cause volcanism (King and Anderson, 1995). Here, we suggest an indirect connection to slab

E-mail address: faccenna@uniroma3.it (C. Faccenna).

0012-821X/\$ – see front matter $\textcircled{\sc 0}$ 2010 Elsevier B.V. All rights reserved. doi:10.1016/j.epsl.2010.08.012

return flow, which may interact with a hydrated layer in the transition zone (Leahy and Bercovici, 2007) to facilitate localized upwellings.

In several regions, there is evidence for volcanism that is spatially and temporally connected to subduction zones but not associated with mantle wedge melting. Related magmas show ocean island basalt (OIB)-type signatures developing from volcanoes located either far off the arc, ahead of the trench, or at slab edges. Relationships between subduction and anomalous volcanism, though already postulated to explain regional cases of intraplate magmatic activity (Changbai volcano, East Asia: Zhao et al., 2009; New Hebrides-North Fiji: Lagabrielle et al., 1997; Mediterranean-European: Goes et al., 1999; Piromallo et al., 2008; Lustrino and Wilson, 2007), have never been framed and modeled in a subduction-related convecting system.

The purpose of this work is to illustrate that subduction within the upper mantle could generate focused, sub-lithospheric, non-thermal mantle upwellings. The surface expressions of these small-scale convective features are outside-arc alkaline volcanism, positive nonisostatic topography and melting zones seismically recorded in the mantle as low-velocity anomalies. We show that focused upwellings are likely generated around the slab (at the lateral edges or ahead of the back-arc region) and are most pronounced during the first phase of subduction into the upper mantle, or after the occurrence of slab

^{*} Corresponding author.

2. Mantle circulation during subduction

The downwelling of cold lithospheric material into the mantle triggers return flow, which has been extensively investigated in the context of the subduction wedge, the uppermost region confined between the slab and the overriding plate. Convection models have evaluated the overall flow produced by a single slab. For example, Garfunkel et al. (1986) modeled such circulation by means of twodimensional (2D) Cartesian calculations evaluating how the 660-km viscosity jump and trench rollback can influence streamlines. The 2D cylindrical models by Zhong and Gurnis (1995) confirmed the close dependence of trench migration and mantle return flow patterns for a self-consistently subducting lithosphere with a fault. Enns et al. (2005) analyzed the influence of slab strength, thickness and side boundary conditions on 2D mantle circulation. Some of the first 3D subduction models were performed experimentally by Buttles and Olson (1998) and Kincaid and Griffith (2003), both of whom prescribed the velocity of a rigid subducting plate by investigating the pattern of deformation induced in the surrounding mantle. The feedback between subduction and the induced 3D mantle circulation has been quantified by means of laboratory models (Faccenna et al., 2001; Funiciello et al., 2003, 2004). These experimental results were later confirmed by the laboratory work of Schellart (2004) and by the numerical work of Stegman et al. (2006) and Di Giuseppe et al. (2008). Piromallo et al. (2006) and Funiciello et al. (2006) provided further detailed analysis of mantle flow during subduction and, in particular, studied the toroidal/ poloidial partitioning as a function of slab strength.

Here, we explore the time-dependent evolution of subductioninduced mantle circulation adopting a 3D self-consistent (i.e., no motions are prescribed) setup. These models are not meant to match any specific subduction zone, but allow us to illustrate features whose dynamic relevance for volcanism ahead of the arc and regional tectonics appear to have not been fully recognized previously.

We approximate subduction dynamics by solving for incompressible Stokes flow in the infinite Prandtl number regime. We use the finite element code CitcomCU (e.g., Moresi and Solomatov, 1995; Zhong et al., 1998) as modified from the CIG (geodynamics.org) version and compute the time-dependent flow solutions for a cold slab sinking into the mantle, which is approximated by a visco-plastic material with temperature-dependent viscosity. Our model setup is fairly standard and is inspired by previous subduction models (e.g., Christensen, 1996; Enns et al., 2005; Stegman et al., 2006), but we neglect complexities such as the buoyancy effect of phase transitions.

The computational domain is meant to represent the upper mantle and has dimensions of 3960 km length (x), 1320 km width (y), and 1320 km depth (z) (non-dimensional aspect-ratio: $3 \times 1 \times 1$). The mechanical boundary conditions are free slip. We use 288 elements with uniform spacing in x, 96 elements subdividing the y direction and 96 elements for z, 80 of which define the upper mantle. The element refinement reflects our focus on the upper mantle and has been chosen for computational convenience. The modeling details can depend on the numerical implementation of near-surface yielding (Schmeling et al., 2007), but we have found the general system behavior to be robust with respect to mesh resolution.

Our initial condition for the non-dimensional temperature *T* includes an isolated oceanic plate that is fixed at the "ridge" location of x=0. This is implemented by prescribing a half-space cooling profile that applies 0 < y < 0.5, corresponding to the zero age at x=0, and an equivalent (T=0.9) lithospheric thickness of ~150 km at x=0. At the old leading edge of the plate, we also prescribe a slight initial dip to facilitate the initiation of subduction, though this is not critical

(cf. Tetzlaff and Schmeling, 2000). All other mantle temperatures are initially set to unity, the surface is kept at T=0, and the bottom boundary is zero heat flux (we only consider non-adiabatic processes, consistent with the incompressible framework). Defined by a non-dimensional reference viscosity of $\eta = 1$, we use a Rayleigh number of 5.7×10^6 , with the typical non-dimensionalization scheme and definitions (e.g., Zhong et al., 1998). The effective viscosity, η , within the fluid is given by a joint rheology

$$\eta = \eta_p \eta_T / \left(\eta_p + \eta_T\right) \tag{1}$$

where the regular, fluid-creeping viscosity η_T has a simplified temperature dependence as

$$\eta_T = \eta_T^0 \exp\left(E(T_0 - T)\right) \tag{2}$$

using E = 6.21 and $T_0 = 1$ for an equivalent viscosity contrast of 500 between the slab and mantle, for consistency with earlier such models. The constant prefactor η_T^0 is set to unity in the upper mantle and to 100 in the lower mantle to represent the probable increase in viscosity due to the phase change at 660 km (e.g., Hager and Clayton, 1989).

The pseudo-plastic "viscosity" η_p is computed from a constant yield stress at $\sigma_y = 10^5$ and the second (shear) strain-rate invariant

$$\varepsilon_{II} \text{ as } \eta_p = \sigma_v / (2\varepsilon_{II}) \tag{3}$$

If the yield stress is taken to be depth dependent, this approximation to plasticity is sometimes called "Byerlee" plasticity in reference to the stress-limiting effect of brittle faulting in the cold lithosphere (e.g., the discussion in Enns et al., 2005). For simplified subduction models with free-slip surface boundary conditions, yielding facilitates the formation of a properly detached slab, as opposed to a Rayleigh-Taylor instability-like drip (e.g., Enns et al., 2005). In our models, the parameter choices lead to substantial viscosity reduction in the trench region close to the surface and the formation of angular weak zones, and they eventually led to the complete detachment of the oceanic plate. However, none of these rheological details matter for the general flow patterns discussed below as long as a relatively stronger and denser slab is able to sink into the mantle. We tested various other setups, including purely compositionally driven slabs (Enns et al., 2005), a range of different choices for the yield stress, a free "ridge" location at x=0, and additional weak zones ("transform faults") on the sides of the slab. The dynamic behavior of all of these models was qualitatively similar to what we discuss here.

Figure 1 shows snapshots of the slab sinking into the mantle. The subduction velocity, v_s , (i.e., $|v_s|$ equal to $|v_t|$ in the fixed ridge setup) progressively increases during the development of subduction into the upper mantle (cf. Becker et al., 1999; Fig. 1a–b). Afterward, v_s decreases once the slab reaches the upper-lower mantle discontinuity and temporarily ponds at the viscosity contrast (cf. Funiciello et al., 2003). Subsequently, the subduction process is taken up by trench rollback. As discussed by Funiciello et al. (2004), the pattern of mantle circulation is strongly variable during the three aforementioned evolutionary stages. To better describe the subduction-induced mantle flow, it is instructive to perform decomposition into the toroidal and poloidal components (e.g., Tackley, 2000; Fig. 2). The poloidal component is associated with vertical mass transport, whereas the toroidal corresponds to vortex-like stirring and rigidbody rotation. The balance between these two components is representative of the vertical descent of the slab and the lateral translation of the trench. Toroidal motion is then mostly excited during the retrograde motion of the slab because the mantle material placed beneath the slab flows laterally from the sides of the slab and produces vortex-like structures.



Fig. 1. The eight-step evolution of the reference model. Each panel is composed of two parts. The upper part shows the lateral cross-section of the model taken through the middle of the plate. The color plot gives the magnitude of the non-dimensional lithospheric temperature, assuming the initial mantle temperature is fixed at 1. Arrows illustrate the x–z flow pattern in the mantle. The lower part shows the horizontal cross-sections taken at x km depths from the top. In this case, the color plot gives the magnitude of the vertical velocity component. Arrows illustrate the x–y flow pattern in the mantle. Non-dimensional units and unity time correspond to ~15 Ma.



Fig. 2. Temporal evolution of the a) TPR ratio, b) toroidal to total velocity field RMS ratio and c) poloidal and toroidal velocities for the whole domain (WM, dashed line) and the upper mantle only (UM, plain line). The poloidal component dominates during the whole evolution, reaching its maximum weight during the first phases of the process. WMP (black dashed line) and UMP (black plain line) is for whole and upper mantle poloidal component, respectively; WMT (grey dashed line) and UMT (grey plain line) is for whole and upper mantle toroidal component, respectively.

Here, we wish to point out that the rapid vertical descent of the slab material during the initial stages of subduction, with a dominance of poloidal flow, induces a convective cell ahead of the slab with a wavelength on the order of the upper mantle height (Figs. 1a-b and 2). The maximum vigor of the poloidal flow is attained just before the slab encounters the 660 km discontinuity (Figs. 1b and 2). The toroidal/poloidal ratio (TPR) is less than 0.5 (for selected model parameters) during the slab subduction into the upper mantle and reaches maximum values on the order of 0.6 after the slab interaction with the 660-km discontinuity (Fig. 2a). The poloidal cell involves an upwelling component ahead of the slab, and, consequentially, leads to a thinning of the thermal boundary layer (i.e. lithosphere) in regions that would be ahead of the arc in nature. This effect, combined with decompression melting, could explain the existence and timing of some of the anomalous volcanism we discuss below. We note that this upwelling component is mainly active during the transient stage of slab descent into the upper mantle, while it fades away after the slab's interaction with the 660 km discontinuity.

Figure 1 also shows an extended region of rising material along the slab's edge that is active throughout the model. However, the vertical flow at the slab's edges is always spatially limited, and its magnitude correlates with the upwelling ahead of the slab recorded in the first stages only for t>0.5, when the form a blob-like downwelling (Fig. 1h). This is an artifact of the visco-plastic yielding and could be suppressed by adapting the rheology. However, we show this type of flow as a proxy for the kinds of currents that might be expected to be enhanced during slab fragmentation.

3. Mantle upwelling within the back-arc region

A number of examples of anomalous volcanism have been described to be directly or indirectly related to the subduction zones. In the following, we analyze in detail four regions, namely western North America, the Central Mediterranean, the North Fiji–Lau Basin, and the West Philippine basin, and we more briefly review other examples.

3.1. Western North America

Very large volumes of magmatic products were emplaced in western North America to the east of the Juan de Fuca subduction system during the last 20 Myrs. Three main magmatic provinces have been identified: the Columbia River Basalts province, the Yellowstone Hotspot Track and the High Lava Plains of Oregon, or Newberry Hotspot Track (Fig. 3a). The Columbia River Basalts extend over a huge area and consist of 17–14 Ma lava flows (e.g., Camp and Ross, 2004; Christiansen et al., 2002) and N-S oriented dyke swarms (Fig. 3a). The Newberry Hotspot Track consists of a sequence of volcanic domes and lava flows with north-westward age progression (Fig. 3a) (Jordan, 2005). The Yellowstone Hotspot Track is associated with the eastnortheastward migration of silicic volcanism along the Eastern Snake River Plain ending at the Yellowstone Caldera (e.g., Pierce and Morgan, 1992; Smith and Braile, 1994; Fig. 3a). Both the Newberry and Yellowstone tracks show age-progressive volcanism migrating away from a region near McDermitt Caldera, which was first active at around 17 Ma.

The massive and voluminous basaltic effusion has been related to the impact of the head plume at around 17 Ma. In this model, the tail of the plume is responsible for the Yellowstone track, since the absolute plate motion of the North American Plate is in a southwesterly direction. This is consistent with the associated high-gravity, high-topography, high heat flow, low-velocity anomalies (Humphreys et al., 2000; Sigloch et al., 2008; Xue and Allen, 2007; Xue and Allen, 2010) and geochemical signature (such as the ${}^{3}\text{He}/{}^{4}\text{He}$), which are characteristics of many hotspots. Yet, despite these features, evidence for an upwelling conduit through the upper mantle beneath Yellowstone remains unclear, and the debate continues as to whether a mantle plume is relevant as a source for volcanism (e.g., Christiansen et al., 2002; Humphreys et al., 2000; Jordan et al., 2004; Obrebski et al., 2010; Smith et al., 2009; Waite et al., 2006; Yuan and Dueker, 2005). The plume model, in addition, shows discrepancies with classical hotspot model. First, the position of the oldest center is about 200-300 km west of the location where the trends of both the younger hotspot track and the inferred plate motions would place the hotspot at 16–17 Ma (Fig. 3c). Possible explanations for this discrepancy is the westward deflection of the plume (Geist and Richards; 1993; Pierce et al., 2000; Smith et al., 2009; Xue and Allen, 2007), or that the plume rises up along a slab tear (Sigloch et al., 2008). Second, the Newberry track is opposite to the Yellowstone one. Third, and more important, recent tomographic model shows that the low-velocity anomaly positioned below Yellowstone is not rooted at depths but is positioned on top of a broad, high-velocity anomaly (Burdick et al., 2008; Sigloch et al., 2008). Given the proximity of the slab and the proposed Yellowstone plume, it is likely that the subduction and the upwelling processes, in fact, interact with one another (e.g., Geist and Richards, 1993; Obrebski et al., 2010; Pierce et al., 2000; Sigloch et al., 2008; Smith et al., 2009; Xue and Allen, 2007, 2010). To explore the possible interaction, we reconstruct in an absolute reference frame the evolution of the Juan de Fuca subduction zone and of the position of the volcanic centers back over the last 17 Ma, starting from the distribution of the velocity anomaly as recently imaged by Burdick et al. (2008).

During the last 20 Ma, the subduction rate estimate summing overriding plate and subducting plate velocity normal to trench is on

Author's personal copy

C. Faccenna et al. / Earth and Planetary Science Letters 299 (2010) 54-68



Fig. 3. a) Map of the Western North America region (redrawn from Xue and Allen, 2007). Three main magmatic provinces can be recognized: the Columbia River Basalts, the Yellowstone Hotspot Track (with red showing the location of magmatic centers and related ages) and the High Lava Plains of Oregon, or Newberry Hotspot Track (with red showing the location of magmatic centers and related ages, and black thin solid lines indicating the location of magmatic centers and related ages). Dashed lines show the depth of the subducting lithosphere. MC indicates McDermitt Caldera. The A–B line indicates the cross-section of panels b–g. b) The tomographic cross-section along the Western North America margin from Li et al. (2008). c–g) Reconstruction of the evolution of the Juan de Fuca subduction zone and of the position of the volcanic centers back over the last 17 Ma, starting from the distribution of the velocity anomaly in panel b). Arrows indicate the net motions of the subducting plate, the overriding plate and the trench. The age of the volcanic centers is expressed in Ma.

average of ~4.5 \pm 0.5 cm/yr, with north American plate preserved its southwestward rate of ~2 cm/yr (Gordon and Jurdy, 1986). The total amount of subduction is ~900 km. This value could be underestimated as it does not consider back-arc extension, whose rate is still poorly defined. The tomographic model shows a widespread, high seismicvelocity anomaly that broadens in the transition zone and continues further to the east below the Yellowstone low-velocity anomaly (Fig. 3b). The model also shows a marked low-velocity anomaly down to 350 km below Yellowstone and surrounding regions in the shallow layer except for the narrow strip corresponding to the Juan de Fuca plate.

We consider the cross-section of Fig. 3b as representative of the mantle structure below the Yellowstone hot-spot track, bearing in mind the complexity of the mantle structure (Xue and Allen, 2010). We restore it (Fig. 3c), considering the absolute motion of the plate system during the last 17 Ma. This exercise points out that the emergence of volcanism occurred just about the slab arrived at the

660 km discontinuity and that the position of the volcanism lines up with the slab tip (Fig. 3b). Based on seismological observation and plate tectonic reconstruction, we speculate that a mechanism of subduction-driven upwelling, similar to the one shown in Figure 1, could be adapted to the Yellowstone case. We also speculate that the massive onset of volcanism in the surrounding area could be triggered by a shallow upper mantle source, perhaps triggered by the separation of the oldest portion of the slab and the onset of the new subduction cycle (Sigloch et al., 2008).

3.2. Central Mediterranean

Continental Europe and the Mediterranean Sea have been affected by diffuse intraplate volcanism that has been particularly active from the Oligocene onward (Lustrino and Wilson, 2007; Fig. 4a). Even if sparse evidence of Early Tertiary manifestation is found during late Cretaceous–Paleocene times, an increased surge of volcanism spread



C. Faccenna et al. / Earth and Planetary Science Letters 299 (2010) 54-68

Fig. 4. a) Map of the Central-Western Mediterranean region showing the location of alkaline volcanic centers in the last 30 Ma. For each volcanic center, a coarse subdivision of alkaline activity in 10 Ma time intervals is indicated by the colors. The background map is a vertical average of the P-wave velocity anomalies in the 450–650 km depth range using model PM0.5 by Piromallo and Morelli (2003). The A–B line indicates the cross-section of panels b–g. b) The tomographic cross-section along the A–B section. c-g) Reconstruction (left panel \rightarrow top view, right panel \rightarrow lateral view) of the evolution of the Central Mediterranean subduction zone back over the last 35 Ma, starting from the distribution of the velocity anomaly in panel b). Red and yellow squares are representative of subduction-related and anorogenic volcanisms, respectively. Red arrows indicate predicted return flow triggered by retreating slabs.

over Europe during the Late Oligocene (including the French Massif Central, Northern Upper Rhine Graben, Eifel, Hocheifel, Veneto, Bohemian, and Pannonian Basin), albeit discontinuously. This magmatism is characterized by Na-rich alkaline basalts, with minor tholeiitic volcanics, which share comparable geochemical features characterized by Na₂O/K₂O weight ratios \geq 1, primitive mantle-normalized multielement diagrams showing noticeable depletion in Pb, K and Rb contents, and high Ta and Nb contents irrespective of the diverse tectonic regimes inferred for the whole area (Cebria and Wilson, 1995; Harangi et al., 2003; Jung and Hoernes, 2000; Lustrino and Wilson, 2007; Wilson and Bianchini, 1999; Wilson and Downes, 1991, 1992). These signatures are typical of intra-plate magmas, namely OIB with a significant HIMU component. Hypotheses about the source of this volcanism are controversial. The HIMU fingerprint, typical of several hot-spot magmas, strengthens the plume origin hypothesis, but, on the other hand, the lack of other features characteristic of plume-related magmatism (i.e., large-scale doming, linear space-time trends of volcanic centers, and large volumes of erupted magmas) has been the main argument against the idea of a pure plume source. Hoernle et al. (1995) first related the HIMU component to the sub-lithospheric mantle reservoir imaged by an upper mantle, low seismic-velocity anomaly (Zhang and Tanimoto, 1992). Goes et al. (1999) suggested an active lower-mantle upwelling under central Europe, on the basis of the present-day correspondence between a lower mantle, low-velocity anomaly and the position of the Tertiary volcanic centers. In the French Massif Central (Granet et al., 1995) and Eifel (Ritter et al., 2001), teleseismic tomography identified small-scale, low seismic-velocity anomalies, but these studies are depth-limited by the seismic array

aperture, and the continuity of the structure at these depths can be only presumed. Accounting for the NE-ward motion of the African plate respect to Eurasia, Piromallo et al. (2008) envisaged the contamination of the Mediterranean upper mantle in the Upper Cretaceous when traveling over the Cape Verde–Canary hot spots and the subsequent occurrence of small-scale upwellings generated by subduction-triggered return flow mechanisms.

Any possible model, however, should consider that the location of volcanic fields active in the last 30 Ma is grouped at the northern edge of the high-velocity anomaly within the Transition Zone, where the cold material conveyed by different subductions is presently accumulated (Piromallo et al., 2008; Piromallo and Faccenna, 2004; Fig. 4 panels a and b). Tectonic reconstructions based on kinematic models show that the accumulation of this material in the western Mediterranean started synchronously, in the late Tertiary, behind the Alps, the Carpathians and the central Mediterranean (Jolivet and Faccenna, 2000; Piromallo and Faccenna, 2004; Wortel and Spakman, 2000). This suggests that volcanism could have been excited by the emplacement of a cold anomaly in the transition zone.

To test this hypothesis, we try to correlate the position of the French Massif magmatism with the Calabrian subduction zone, where the subduction velocity has been accurately reconstructed (Faccenna et al., 2001, 2003; Seranne, 1999). The Calabrian slab accommodates the slow convergence between Africa and Eurasia through the subduction of the Liguro-Piedmont first and the Ionian ocean afterward. The matching of the convergence rates, trench motions and tomographic images reveals that the Calabrian trench rolled back for more than 800 km, inducing the opening of the Liguro-Provencal (30-16 Ma) and Tyrrhenian back-arc basin (12 Ma-present; Cherchi and Montandert, 1982; Burrus, 1984; van der Voo, 1993; Gorini et al., 1994; Seranne, 1999; Speranza et al., 1999). Correcting the highvelocity anomaly in the upper mantle for the amount of back-arc extension (Fig. 4c-g), we find that the intensive phase of volcanism matches the back-arc spreading phase and that the renewal of volcanism in the Oligocene was initiated once the slab approached the 660 km discontinuity. Such mantle circulation, linking the westerncentral Mediterranean mantle, is reflected in the seismic anisotropy (Barruol et al., 2004; Lucente et al., 2006). The good correspondence of the phases of speed-up subduction (20-15 Ma and 12-1 Ma), as detected by back-arc spreading (Faccenna et al., 2001), and the main eruptive phases also corroborates a scenario where the two processes are related to one another. The OIB products can be further justified as originating by the previous mixing between deep sources. Moreover, the occurrence of such volcanism on isolated relatively small and short lived volcanic centers scattered around the Mediterranean rule out any possible direct connection with a deep, hot-spot like upwelling mantle source (Lustrino and Wilson, 2007).

Being aware of the complexity of the region and of the presence of a crustal rifting process and deformation over all of Europe (Ziegler, 1992), we consider the French Massif Central to also be representative of other volcanic centers spread around other zones of downwelling (Fig. 3a), such as the Alps and Carpathian area. However, we acknowledge that more specific studies and reconstructions are needed to extend this simple scenario to other surrounding regions.

3.3. North Fiji and Lau Basins

The North Fiji and Lau basins are currently opening between the New Hebrides- and the Tonga-facing subduction zones (Fig. 5f; Falvey, 1975; Weissel, 1977; Auzende et al., 1988, 1994, 1995; Lagabrielle et al., 1997; Pelletier et al., 1998, 2001; Schellart et al., 2006). These basins represent both the most active and the largest present-day back-arc spreading system on Earth. Oceanic spreading in the North Fiji Basin initiated around 12 Ma, in relation with a shift in the sense of subduction at the Australia–Pacific converging boundary, followed by rapid rotations of fragments of the Vitiaz paleo-arc, which



Fig. 5. a–f) Reconstruction (left panel \rightarrow top view, right panel \rightarrow lateral view) of the evolution of the North Fiji and Lau Basins region back over the last 12 Ma, starting from the distribution of the velocity anomaly of Hall and Spakman (2002). VT: Vitiaz Trench, NH: New Hebrides arc, F: Fiji Platform, T. Tonga arc, NC: New Caledonia ridge, NFB: North Fiji Basin, LBT: Lau basin-Tonga arc.

now forms the basement of the active Vanuatu arc and the volcanically inactive Fiji islands. The Lau Basin started to open at 5 Ma, after a long period of the crustal stretching of the former Tonga arc. The oceanic ridge system now propagates following the migration of the eastern tip of the Louisville Ridge along the Tonga trench (Parson and Wright, 1996; Ruellan et al., 2003; Taylor et al., 1996; Zellmer and Taylor, 2001). The compilation of bathymetric and geophysical surveys shows that the cumulative length of active spreading ridges, which can be traced within the region comprising

the North Fiji Basin (NFB) and the Northern part of the Lau Basin (LB), reaches 5000 km. Therefore, this domain is characterized by an extremely high anomalous ratio of active spreading ridges versus the surface of recently created oceanic lithosphere that is not observed in any back-arc context worldwide (Lagabrielle et al., 1997). This may reflect an actively convecting mantle beneath these regions, but the mechanisms that enhance this convection are not fully understood (Pysklywec et al., 2003). In particular, the spreading system of the North Fiji and Lau basins shows a number of striking features in relation with a complex convecting system in the upper mantle underlying the region:

- 1. In most of the surface of the NFB and in the northern LB, the spreading ridges are not parallel to the subduction boundaries, in contrast to recent back-arc environments, such as the Mariana or the East Scotia systems. This indicates that the overall pattern of the trench-arc system at a lithospheric scale does not control the geometry of the ridge axis far inside the central part of the back-arc oceanic spreading system. Moreover, some spreading ridges are perpendicular to the subduction zone and propagate into the arc, triggering intra-arc extensional deformation parallel to the arc direction (e.g., the South Pandora–Hazel Holmes ridge, Lagabrielle et al., 1997).
- 2. The spreading system is characterized by the presence of numerous triple junctions and relay zones of various types. These features are highly unstable, with repeated ridge jumps and local kinematic reorganization at a frequency on the order of 1 Ma.
- 3. In the central domain of the NFB, the spreading ridges are separated by a distance on the order of 400 km and define a series of oceanic microplates. Assuming that the convecting cells in the upper mantle are roughly as wide as they are deep, the size of the microplates might be a proxy to the size of the convecting cells.
- 4. Spreading rates in the North Fiji basins are not very high (max 8 cm/yr), but those in the LB are extremely high in the northern part of the basin (up to 16 cm/yr full rate; Bevis et al., 1995). The spreading axis of the lowest spreading ridges often exhibits morphological and tectonic characteristics typical of regions with high rates of magma production, constructing an oceanic crust with abnormal thickness and abnormal elevation.

To account for a high oceanic spreading activity, it has been first suggested that a lower mantle plume is currently upwelling beneath the North Fiji and Lau basins (Lagabrielle et al., 1997). Based on high-resolution seismic tomographic images, Pysklywec et al. (2003) propose that an ongoing avalanche of cold, dense slab material into the lower mantle causes the development of multiple flows of upwelling asthenosphere material below this region. Although they involve lower and upper mantles in different proportions, both models point to extremely abnormal convection. In addition, the high variability of axial morphologies and the short wave segmentation of the spreading axis on the order of 50 to 100 km have been viewed as reflecting the presence of small-scale convecting cells in the upper mantle that develop over the head of a major plume (Garel et al., 2003).

Therefore, the geochemical signature of basalts emplaced in the central region of the North Fiji Basin is consistent with an upper mantle, MORB-type source. Basalts emplaced along the Lau spreading ridges have similarities with a mantle source that had, or still has, interactions with the Tonga arc. Basalts emplaced along the ridges of the northern regions of the Lau and North Fiji basins are melt products from a mantle showing similarity with the Samoan mantle. This suggests horizontal rather than vertical mantle fluxes and a fast migration rate of the Samoan mantle through a slab tear window opened north of the Tonga slab (Fischer et al., 2000; Harta et al., 2004; Turner and Hawkesworth, 1998). Tomographic models of the mantle beneath the NFB and Lau basin region show that the Tonga slab tends

to flatten at the 660 km discontinuity below the North Fiji, over a rather long distance (Hall and Spakman, 2002; van der Hilst, 1995). The N–S Central Spreading Ridge (CSR) of the NFB originated about 3 Ma ago, possibly above the tip of the flat-lying Pacific slab, and it still remains in about the same position today. The E–W branch of the spreading center that propagated to the east of the CSR, as well as the Lau spreading centers that developed above the same flat-lying slab, prevent any deep origin for the magma source.

For these reasons, the hyper-spreading activity and strong thermal anomaly in the region (Garel et al., 2003; Lagabrielle et al., 1997) are better explained by enhanced convection in the upper mantle (which generates MORB-lavas) rather than by the presence of a plume head beneath the basins. Starting from the tomographic images by Hall and Spakman (2002), we reconstruct the evolution of the upper mantle slabs beneath the region during the Neogene (Fig. 5). Our reconstruction shows that, at about 12 Ma, the New Hebrides subduction zone was just initiating and that most of the production rate of the back-arc areas was achieved during the fall of the Australian slab inside the upper mantle. Our reconstruction also points out that the presence of two facing, retreating subduction zones could have favored strong upwelling currents in the upper mantle and the origin of multiple spreading centers.

3.4. West Philippine Basin

The origin of the Philippine Sea Plate (PSP) has been debated. It is presently composed of four different oceanic basins that are younger from west to east. There is agreement that the three youngest basins, Shikoku, Parace-Vela and Mariana, opened behind the Izu-Bonin-Mariana (IBM) trench system from 30 Ma to the present, and there are disagreements (Hilde and Lee, 1984; Lewis et al., 1982; Mrozowski et al., 1982; Seno and Maruyama, 1984; Uyeda and Ben-Avraham, 1972) regarding the largest one, i.e., the West Philippine Basin (WPB). Based on a new compilation of geological and geophysical data, Deschamps and Lallemand (2002) demonstrated that the WPB also has a back-arc origin with an initial rift sub-parallel to the "proto-W-Philippine" trench (around 53 Ma, see Fig. 6b) and a further multi-rift evolution. Figure 6b-f gives six characteristic steps of the evolution of the WPB, which combine the paleomagnetic constraints on paleolatitudes and rotations from Hall (2002) with the geological and geophysical constraints from Deschamps and Lallemand (2002). The "proto-W-Philippine" trench was active prior to 55 Ma, whereas the "proto-Izu-Bonin-Mariana" (proto-IBM) trench was probably initiated at around 53 Ma (Fig. 6a–c). Some studies (e.g., Hilde and Lee, 1984; Uyeda and Ben-Avraham, 1972) suggest that a former transform fault, separating a hypothetical North Guinea Plate to the south from the main Pacific Plate to the north, evolved into a subduction zone and gave birth to the PSP (Fig. 6a). Then both trenches underwent a roll-back at that period that triggered the rifting of the trapped microplate. The initial spreading between 53 and 50 Ma occurred along a single axis parallel to and in back of the E–W-trending "proto-Philippine" arc (Fig. 6a). Based on the detailed reconstruction of the basin (Deschamps and Lallemand, 2002), it has been shown that secondary spreading axes developed oblique to the main one at 50 Ma (Fig. 6b). Then rearrangements occurred at 47.5 Ma with the abandonment of some branches and the birth of a new spreading axis perpendicular to and south of the main one (Fig. 6d-e). Excess magmatism along that new branch resulted in the Benham Rise (BR). The final spreading stage occurred between 35 and 30 Ma along a single axis again (Fig. 6e-f). We thus observe that the "classical" way of back-arc spreading, i.e., with a single axis subparallel to the trench, was realized only during the first and last millions of years of the evolution of the WPB, whereas most of its growth (during 15 Myrs) was accommodated through multiple spreading axes with ridge-ridge-ridge triple junction and even ridge-arc intersections that probably promoted boninites emplacements (Deschamps and Lallemand, 2002). It is difficult to



Fig. 6. a-f) Reconstruction (left panel \rightarrow top view, right panel \rightarrow lateral view) of the evolution of the N West Philippine basin region between 53 Ma and 30 Ma. Symbols are as in Figure 5.

estimate with confidence the location of slabs tips beneath the WPB at each stage because the evolution of the PSP is poorly constrained. We thus have proposed reasonable lengths based on the periods of rollback and the supposed great obliquity of the convergence along the proto-IBM trench. What is quite clear is that secondary spreading centers appeared above the slabs.

All of the basement rocks drilled, dredged or sampled using submersibles in the West-Philippine Basin are tholeiitic basalts, i.e., typical MORBs. There were seven sites drilled during DSDP legs: holes 290 and 447 in the eastern part of the WPB north of the fossil spreading center, sites 291, 292 and 293 in the western part of the WPB, one of them being on the BR, and sites 294 and 295 in the northern part of the WPB just south of the Oki-Daito Ridge (Hickey-Vargas, 1998). All the geochemical analyses done on these cores concluded that they are basalts derived from tholeiitic initial melts, with no evidence for OIB-type basalts such as those found on the Daito Ridge or the Daito Basin to the north (e.g., Hickey-Vargas, 1998; Louden, 1976; McKee and Klock, 1974; Ozima et al., 1977; Watts et al., 1977; Zakariadze et al., 1980). Some samples were collected using the Shinkai 6500 submersible along the fossil-spreading ridge, attesting for the last spreading episode of the basin. Based on the Nd/Zr and Ba/Zr values, these were also classified as MORBs (Fujioka et al., 1999). This story offers many similarities with those of the North-Fiji

Basin.

3.5. Other regions

In several other regions, intraplate volcanism has been related to subduction zones and described as due to the combined effect of corner flow in the mantle wedge and slab dehydration. One of the most impressive intraplate volcanic regions is located in northeastern China. Beneath this province, a prominent low seismic velocity anomaly extends down to 400-km depths, but at further depths the Pacific slab is stagnant in the mantle transition zone (Lei and Zhao, 2005; Li and van der Hilst, 2010). Zhao (2004) emphasized the role of the large-scale return flow ('big mantle wedge') above the stagnant Pacific slab in the formation of the intraplate volcanism in NE Asia. The corner flow in the big mantle wedge and deep slab dehydration may have caused the active intraplate volcanoes in NE Asia, similar to the process generating the arc volcanoes above the regular mantle wedge. Recent results of S-wave splitting (Liu et al., 2008), electrical conductivity (Ichiki et al., 2006), and geochemical analysis (Chen et al., 2007) all suggest a hot and wet upper-mantle wedge above the stagnant Pacific slab and a close relationship to the intraplate volcanism in NE China.

Another example is represented by the Tengchong intraplate volcanoes in southwest China. Tomographic images beneath the volcanoes show a low-velocity anomaly in the shallower region of 400 km on top of a high-velocity anomaly dominating the transition zone and related to the Indian plate subduction (Lei et al., 2009; Li and van der Hilst, 2010). Lei et al. (2009) additionally suggest that the upwelling flow under the Tengchong area may originate at about a 400-km depth and be related to slab dehydration at this depth.

Intraplate back-arc-volcanism is also known in southern South America, where very large volumes of basalts were erupted in the piedmont domain of the Andean Cordillera during the Cenozoic. The Meseta de Somuncura forms one of the largest exposures of back-arc lavas in Argentina and contains tholeitic-to-alkaline basalts that were extruded during the late Oligocene. According to de Ignacio et al. (2001), the origin of this volcanism is strongly linked to circulations of the upper mantle in relation with slab dynamics. The formation of a first mantle melting anomaly within the lithosphere below the South American Plate is interpreted as the result of a vigorous adiabadic upwelling of hot mantle in relation with rapid changes in slab geometries due to a major plate reorganization at 25 Ma (de Ignacio et al., 2001).

4. Subduction plumes at slab edges

Several worldwide sites show anomalous volcanism developed at slab edges. This volcanism is usually abundant and does not present the typical geochemical characteristics of arc-volcanism. Two examples are briefly reported here.

Mt. Etna is the largest European volcano, with a large, though pulsating, production rate. Its construction started at about 500 ka, with a fissure-type tholeiitic magma shifting to a more central-style eruption of Na-alkaline-type magma. The overall geochemical signature of Mt. Etna basalts is akin to that of within-plate (HIMU-type) oceanic island basalt (OIB) (Schiano, 2003), with differences that often contrast a depleted asthenospheric source model with an enriched source/component model (Tonarini et al., 2001). Silicate melt inclusion has been interpreted to show a progressive transition from a predominantly mantle–plume to an island-arc magmatic source (Schiano, 2003).

Mt. Etna is positioned just at the southern edge of the Calabrian Wadati-Benioff zone (Fig. 7a). Gvirtzman and Nur (1999) proposed that the Mt. Etna magmatic source derives from the lateral inflow of asthenospheric material from the slab side, produced by slab rollback. However, tomographic images show that Mt. Etna evolved on top of

an upper mantle low-velocity anomaly at the edge of the Calabrian slab, extending laterally and at significant depths (Fig. 7a, c; Lucente et al., 1999; Piromallo and Morelli, 2003; Montelli et al., 2004; Montuori et al., 2007). Our modeling results show that the contradiction between these classes of models, slab-induced asthenospheric flow and hot-spot, is only just apparent. We propose that Mt. Etna can be considered an upwelling structure confined in the upper mantle as a consequence of the complex 3-D mantle circulation triggered by the subducting lithosphere.

The topography and the Holocene and Upper Pleistocene marine markers all agree in showing that Mt. Etna developed on top of a morphological bulge (Fig. 7b) with an uplift rate higher than 1–2 mm/yr (e.g., Ferranti et al., 2006) started around the Middle Pleistocene (about



Fig. 7. Mantle structure beneath and around Mount Etna from PM01 model (Piromallo and Morelli, 2003). Note the low velocioty anomalies located around the Calabria slab. a) Sections at 150 and 250 km depth. b) Topography and elevation of the MIS 5.5 marine terrace along the section (from Ferranti et al., 2006) illustrating uplift in correspondence of Mount Etna. c) AA' cross section shown in a) of the seismic tomography model showing marked low-velocity anomaly around slab.

700 kyr ago). The volcanism, uplift and the seismic velocity structure all evolved during the last million years in the region. The development of Mt. Etna occurred during a period of quiescent activity of the Tyrrhennian basin, indicating that rollback, if any, was strongly reduced during the last 700 kyr (Faccenna et al., 2005). This pattern of uplift and magmatism positioned on top of the low seismic-velocity anomaly at the slab's edges indicates upwelling material, and it appears similarly to the rising material active in our model along the slab's edges since the beginning of the subduction process. This mechanism may also enhance the mixing between deep sources, producing magma with affinities to OIB.

Other, although inactive, volcanoes are located at the edges of slabs inside the Mediterranean, including Trois Fourches, found in Morocco at the eastern edge of the Gibraltar narrow subduction zone (Duggen et al., 2003; Faccenna et al., 2004). Those volcanoes show alkaline, OIB-to-HIMU composition and are, again, positioned on top of low seismic-velocity anomalies.

Volcanism at the slab edges has been described in the northwest Pacific Ocean where the Pacific plate subduction zone is interrupted along the southern half of the Kamchatka Peninsula. The Shiveluc area of volcanism in Kamchatka presents distinct geochemical features with respect to the normal island arc volcanoes of the Kluchevskoy group (the world's most productive island arc volcano) and the Aleutian adakites. The strong adakite geochemical imprinting of these groups has been interpreted as a result of little fractionation and mixing with arc magmas related to mantle circulation around the edge of a subducting lithosphere (Yogodzinski et al., 2001). Yet, tomographic studies suggest that the absence of a clear Wadati-Benioff zone at the Pacific corner is indeed related to a strong, lowvelocity anomaly created by episodes of slab break during the opening of a large slab window (Levin et al., 2002). This anomaly probably extends all the way down into the upper mantle, following the progressive lateral shoaling of deep seismicity (Davaille and Lees, 2004; Gorbatov et al., 2000). Further evidence for such upward flow, together with some material ascent towards the surface beneath northwestern Kamchatka, comes from seismic anisotropy (Peyton et al., 2001) and from an exceptionally low V_S anomaly to the northwest of the Aleutian-Kamchatka junction (Levin et al., 2002).

The rejuvenation of volcanism along some Samoa hotpot volcanoes (Lalla Rookh, Sava'i) has also been related to the interaction of the hotspot with the northern edge of the retreating Tonga trench during the spreading of the Lau basin. This could have not only trapped and deviated the pre-existing hotspot conduit but also enforced and fed the upwelling process (Harta et al., 2004; Hawkins and Natland, 1975; Natland, 1980).

The narrow South Sandwich arc also presents anomalous features at the slab edges. Geochemical analysis on the Kemp and Nelson seamounts at the southern edge, plus investigation of ridge segments near the northern edge, shows enhanced subduction fluxes when compared to the rest of the arc. Moreover, Leat et al. (2004) described sediment melt as an active process in the same areas. So, although there is no evidence of basaltic crust melting in Southern Sandwich (i.e., adakites; Yogodzinski et al., 2001), the possible sediment melting reveals anomalous thermal gradient action at slab edges related to mantle flux. A similar situation can be found at Grenada at the southern end of the Lesser Antilles arc. Additionally, this case recognized an exceptional enrichment in Th, which may be attributed to sediment melting, although Grenada has high Na and is alkalic in composition whereas Nelson is not.

Near Taiwan, the southernmost Ryukyu slab underwent an episode of fast rollback during the Pleistocene (Lallemand et al., 2001), as revealed by the 80 km of extension recorded in the southernmost Okinawa Trough (Sibuet et al., 1998). Contemporaneously, alkali basalts and tholeiites have erupted near the edge (and out) of the slab to form the Penghu islands plateau (Chen, 1973; Greenough and Fryer, 2008).

5. Discussion

Volcanic activity away from the plate boundaries occurs in a variety of settings. Linear, age-progressive volcanic chains have been typically explained as surface manifestations of hot plumes. However, a number of intraplate volcanoes over both oceanic and continental plates violate the age progression expected for hot spot tracks and need alternative mechanisms. The small-scale, upper mantle convection associated with slab retreat has been found as a viable alternative mechanism to explain volcanism at a craton edge (King and Ritsema, 2000), as in complex mobile settings such as the Western US (Sigloch et al., 2008) or Mediterranean (e.g., Faccenna et al., 2005), as well as inside continental plates such as Europe (Wilson and Downes, 2006). A melting in mantle upwellings that results from decompression is considered as a mechanism of intraplate volcanism (Raddick et al., 2002). This mechanism can easily triggered by upwelling if the mantle is at, or sufficiently near, its solidus.

Here, we suggest that the decompression melting produced by 3D slab-induced mantle circulation could produce intraplate off-volcanic arc-volcanism. Since the melting temperature of the mantle increases with pressure or depth more rapidly than the adiabatic temperature, any small upward displacement of a parcel of upper mantle at or very near its melting temperature will cause decompression melting. This melting creates buoyancy because the presence of melt reduces the overall density and because the residual mantle, after melt is extracted, is less dense than the undepleted mantle.

Buoyancy forces due to melting cause additional upwelling, which further induce melting, creating a process that may become self-sustaining.

The examples shown here from North America, the Central Mediterranean and North Fiji illustrate that volcanism develops on top of regions of low-velocity anomalies in the uppermost mantle, floored in the transition zone by high-velocity anomalies. Decompression melting could produce high reductions of V_p and V_s, up to 3% and 7% per percent melt, respectively (Hammond and Humpreys, 2000).

A more quantitative estimate is necessary to calculate the fraction of melt production during return flow. Petrological models and seismic velocity variations show that the back-arc basin mantle is about 100 °C hotter than expected, depending on the intensity of the subduction-induced flow (Wiens et al., 2006). The heat flow distribution on non-extending back-arc region confirms that the lithosphere is thinner than expected (Currie and Hyndman, 2006). The 2D numerical models indicate that slab-induced mantle flow may induce melting structures not only in the arc but also in the back-arc environments (Conder et al., 2002). Petrological models also indicate that back-arc magmas are characterized by a variable but high concentration of H₂O, presumably derived from the dehydratation of the subducted plate (Kelley et al., 2006). A concomitant mechanism that could feed volcanism is the release of water by hydrous Mg-Si minerals in the subducting lithosphere at the depths of the mantle transition zone (e.g., Fyfe, 1997; Maruyama and Okamoto, 2007). Recent mineral physics experiments also show that the mantle transition zone contains several times more water than the other portions of the mantle, and the transition zone could be an important water reservoir in the Earth's interior (Inoue et al., 2004; Santosh and Omori, 2008). This process can be particularly efficient for fast slabs, for which reactions may not fully complete at shallow mantle depths (100-200 km). Deep dehydration reactions have also been found in the Tonga subduction zone (Zhao et al., 1997) and in the Mediterranean transition zone (van der Meijde et al., 2003). This process has been proposed as the driving one for the Changbai volcanism in China (Zhao et al., 2009). Numerical modeling indeed confirm that the presence of water could induce Rayleigh-Taylor type instabilities, wtplumes rapidly transporting fluid from stagnant slab to the base of the lithosphere and triggering off-axis volcanism (Richard and Iwamori, 2010).

The impact of fluid release in the upper mantle has been tested in Nicaragua, where wet volcanism is considered as fed by slab-derived fluids, and the subducted crust exhibits 2–3 times the hydration inferred for other slabs (Abers et al., 2003). S-wave velocity models imaged an upper mantle low-velocity (hot) body beneath the North China Basin, rooted at the edge of the stagnant Pacific subducted lithosphere and generated in the overlying asthenospheric mantle due to the infiltration of fluids/melts from the slab itself (An et al., 2009).

Our model is based on numerical simulations showing that a largescale return flow, associated with subduction and particularly vigorous during infant subduction stages, can produce decompression melting far from the trench. We also present some natural examples of ambiguous Na-alkaline magmatism that show neither linear geographic age progression, nor anchorage to deep mantle plumes. These volcanic provinces, instead, are connected and placed nearby convergent and subducting margins. With the awareness that each volcanic province can have a more complex history, we relate the origin of this volcanism to the subduction process. Combining the physical rules extracted from modeling with the case history, we deduce physical relationships between subduction and volcanism that can also be used in validating this model in other regions.

Numerical modeling and tectonic reconstructions reveal that the initiation of strong volcanic activity is expected during peaks of poloidal mantle circulation. This condition is reached when the subducting lithosphere approaches the transition zone (Fig. 8a). In this phase the slab attains its peak velocity (Funiciello et al., 2006). The case of the Massif Central or Yellowstone shows this correlation. Volcanism is likely positioned between 600 and 700 km from the trench (Fig. 8a). During this phase, the source of magmatism is completely related to decompression melting. At the surface this process is accompanied by a dynamic topography signal, such as broad uplift, elevated heat flow, and normal faulting. For the case of opposite subduction zones, such as the Tonga and West Philippine basins, the mechanism is similar but the kinematics of the process need further investigation. As for the case of Yellowstone, it is plausible that the renewal phase of subduction and, in turn, the intense poloidal flow followed old subductions.



Fig. 8. Cartoons showing scenarios able to trigger the decompression melting produced by slab return flow, and the resulting development of off-axis volcanism. a) Slabmantle interaction; b) Steady-state condition of subduction with the slab lying on the 660 km discontinuity.

- Volcanism also remains active during the following phases of subduction (Fig. 8b). In several cases, we observe that the locus of volcanism can shift accordingly towards the subduction zones. In other cases it is rather stable. Due to its initial position, the upwelling is often rooted onto the edge of the high-velocity anomaly stagnating in the transition zone (Fig. 8b). It is possible that, during this phase, slab dehydration could also contribute to melt asthenosphere and feed volcanism (Richard and Iwamori, 2010). Petrological and numerical modeling are needed to better constraints this mechanism.
- Slabs can also show peculiar volcanism positioned at slab edges. Examples of such kinds of volcanoes are frequent, including South Sandwich, Kamchatka, Taiwan, Tonga and Mt. Etna, the latter of which is probably one of the most evident cases. The mechanism propelling melting is still decompression, due to the vertical component of the upper mantle circulation around the slab edge being active since the beginning of the subduction process. However, it cannot be excluded that slab dewatering could be another efficient mechanism active in this peculiar position. Some of the cited natural examples, in fact, exhibit a complex geochemical signature that could reveal mixing between deep components and shallow ones. Shear heating between the slab and the surrounding mantle could be invoked as an alternative interpretation to localized low-velocity zones at slab edges, but its contribution has been quantified as extremely weak (Rupke et al., 2004).

6. Conclusion

We address the possible subduction-related origin of focused upwellings, not rooted in the lower mantle, by exploring the 3D timedependent numerical models of mantle circulation induced by selfconsistent subduction. Our models are simplified and not meant to match any specific subduction zone, but they allow us to illustrate general features that appear relevant for volcanism and regional tectonics.

We show that focused mantle upwellings can be generated both ahead of the slab in the back-arc region (~five times further from the trench than arc-volcanism) and around the lateral edges of the slab. The upward flux of material from significant depths and the associated decompression melting is more vigorous during the first phase of slab descent into the upper mantle, or during slab fragmentation. The vertical mass transport in these regions appears to be strongly correlated with the interplay between relative trench motion and subduction velocities.

Acknowledgements

We wish to thank the editor Rob van der Hilst, Massimo Coltorti, Luigi Beccaluva, Jeroen van Hunen for discussions and insights. Support of C.F. and S.L. from a joint CNR–CNRS project.

References

- Abers, G.A., Plank, T., Hacker, B.R., 2003. The wet Nicaraguan slab. Geophys. Res. Lett. 30 (2), 1098. doi:10.1029/2002GL015649.
- An, M., Feng, M., Zhao, Y., 2009. Destruction of lithosphere within the north China craton inferred from surface wave tomography. Geochem. Geophys. Geosyst. 10, Q08016. doi:10.1029/2009GC002562.
- Auzende, J.M., Eissen, J.P., Lafoy, Y., Gente, P., Charlou, J.L., 1988. Seafloor spreading in the North Fiji Basin (Southwest Pacific). Tectonophysics 146, 317–351.
- Auzende, J.M., Pelletier, B., Eissen, J.P., 1995. The North Fiji Basin: geology, structure and geodynamic evolution. In: Taylor, B. (Ed.), Back-arc Basin: Tectonics and Magmatism. Plenum Press, New York, pp. 139–175.
- Auzende, J.M., Pelletier, B., Lafoy, Y., 1994. Twin active spreading ridges in the North Fiji Basin (S.W. Pacific). Geology 22, 63–66.
- Barruol, G., Deschamps, A., Coutant, O., 2004. Mapping Upper mantle anisotropy beneath SE France by SKS splitting: evidence for a Neogene asthenospheric flow induced by the Apulian slab rollback and deflected by the deep Alpine roots. Tectonophysics 394, 125–138.

Author's personal copy

- Becker, T.W., Faccenna, C., O'Connell, R.J., Giardini, D., 1999. The development of slabs in the upper mantle: insight from numerical and laboratory experiments. J. Geophys. Res. 104, 15207-15225.
- Bevis, M., Taylor, F.W., Schutz, B.E., Recy, J., Isacks, B.L., Helu, S., Singh, R., Kendrick, E., Stowell, J., Taylor, B., Calmant, S., 1995. Geodetic observations of very rapid convergence and back-arc extension at the Tonga Arc. Nature 374, 249-251
- Burdick, S., Li, C., Martynov, V., Cox, T., Eakins, J., Mulder, T., Astiz, L., Vernon, F.L., Pavlis, G.L., van der Hilst, R.D., 2008. Upper mantle heterogeneity beneath North America from travel time tomography with global and USArra Transportable Array data. Seismological Res. Lett. 79, 384-392.
- Burrus, J., 1984. Contribution to a geodynamic synthesis of the Provencal basin (northwestern Mediterranean). Mar. Geol. 55, 247-269.
- Buttles, J., Olson, P., 1998. A laboratory model of subduction zone anisotropy. Earth Planet, Sci. Lett. 164, 245-262.
- Camp, V.E., Ross, M.E., 2004. Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest. J. Geophys. Res. 109, B08204. doi:10.1029/ 2003 B002838.
- Cebria, J.M., Wilson, M., 1995. Cenozoic mafic magmatism in Western/Central Europe:
- a common European astenospheric reservoir. Terra Nova 7 162 abstract Suppl. Chen, J.C., 1973. Geochemistry of basalts from Penghu islands. Proc. Geol. Soc. China 16, 23 - 26.
- Chen, Y., Zhang, Y., Graham, D., Su, S., Deng, J., 2007. Geochemistry of Cenozoic basalts and mantle xenoliths in Northeast China. Lithos 96, 108-126.
- Cherchi, A., Montandert, L., 1982. Oligo-Miocene rift of Sardinia and the early history of the western Mediterranean basin. Nature 298, 736-739.
- Christensen, U.R., 1996. The influence of trench migration on slab penetration into the lower mantle. Earth Planet Sci. Lett. 140, 27–39.
- Christiansen, R.L., Foulger, G.R., Evans, J.R., 2002. Upper-mantle origin of the Yellowstone hotspot. Geol. Soc. Amer. Bull. 114, 1245-1256.
- Conder, J., Douglas, A., Wiens, A., Morris, J., 2002. On the decompression melting structure at volcanic arcs and back-arc spreading centers. Geophys. Res. Lett. 29 (15), 1727. doi:10.1029/2002GL015390.
- Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. Earth Planet. Sci. Lett. 205, 295–308.
- Currie, C.A., Hyndman, R.D., 2006. The thermal structure of subduction zone back arcs. J. Geophys. Res. 111, B08404. doi:10.1029/ 2005JB004024.
- Davaille, A., Lees, M.J., 2004. Thermal modeling of subducted plates: tear and hotspot at the Kamchatka corner. Earth Planet. Sci. Lett. 226, 293. doi:10.1016/j. epsl.2004.07.024.
- Davies, H.J., Bunge, H.P., 2006. Are splash plumes the origin of minor hotspots? Geology 34 (5), 349–352. doi:10.1130/G22193.1.
- de Ignacio, C., Lopez, I., Oyarzun, R., Marquez, A., 2001. The Northern Patagonia Somuncura plateau basalts: a product of slab-induced, shallow asthenospheric upwelling? Terra Nova 13 (117–121), 2001.
- Deschamps, A., Lallemand, S., 2002. The West Philippine Basin : an Eocene to Early Oligocene back-arc basin opened between two opposed subduction zones. J. Geophys. Res. 107 (B12), 2322. doi:10.1029/2001[B001706.
- Di Giuseppe, E., van Hunen, J., Funiciello, F., Faccenna, C., Giardini, D., 2008. Slab Stiffness control of trench motion: insights from numerical models. Geochemistry Geophysics Geosystems 9, Q02014.
- Duggen, S., Hoernle, K., van den Bogaard, P., Rupke, L., Morgan, J.P., 2003. Deep roots of the Messinian salinity crisis. Nature 422, 602–606. Enns, A., Becker, T.W., Schmeling, H., 2005. The dynamics of subduction and trench
- migration for viscosity stratification. Geophys. J. Int. 160, 761–775. Faccenna, C., Becker, T.W., 2010. Shaping mobile belt from small scale convection.
- Nature 465. doi:10.1038/nature09064
- Faccenna, C., Funiciello, F., Giardini, D., Lucente, P., 2001. Episodic back-arc extension during restricted mantle convection in the Central Mediterranean. Earth Planet. Sci. Lett. 187. 105-116.
- Faccenna, C., Jolivet, L., Piromallo, C., Morelli, A., 2003. Subduction and the depth of convection in the Mediterranean mantle. J. Geophys. Res. 108 (B2), 2099. doi:10.1029/2001JB001690.
- Faccenna, C., Civetta, L., D'Antonio, M., Funiciello, F., Margheriti, L., Piromallo, C., 2005. Constraints on mantle circulation around the deforming Calabrian slab. Geophys. Res. Lett. 32, L06311. doi:10.1029/2004GL021874.
- Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L., Rossetti, F., 2004. Lateral slab deformation and the origin of the western Mediterranean arcs. Tectonics 23, TC1012. doi:10.1029/2002TC001488.
- Falvey, D.A., 1975. Arc reversals, and a tectonic model for the North Fiji Basin. Austr. Soc. of Explor. Geophys. Bull. 6, 47–49. Ferranti, L, et al., 2006. Markers of the last interglacial sea level highstand along the coast of
- Italy: tectonic implications. Quat. Int. 145–146, 30–54. doi:10.1016/j.quaint.2005.07.009. Fischer, K.M., Parmentier, E.M., Stine, A.R., Wolf, E.R., 2000. Modeling anisotropy and
- plate-driven flow in the Tonga subduction zone back arc. J. Geophys. Res. 105 (B7), 16,181–16,191. doi:10.1029/1999JB900441.
- Fujioka, K., Okino, K., Kanamatsu, T., Ohara, Y., Ishizuka, O., Haraguchi, S., Ishii, T., 1999. Enigmatic extinct spreading center in the West Philippine back-arc basin unveiled. Geology 27 (12), 1135-1138.
- Funiciello, F., Faccenna, C., Giardini, D., 2004. Flow in the evolution of subduction system: insights from 3-D laboratory experiments. Geophys. J. Int. 15, 1393-1407.
- Funiciello, F., Faccenna, C., Giardini, D., Regenauer-Lieb, K., 2003. Dynamics of retreating slabs (part 2): insights from 3D laboratory experiments. J. Geophys. Res. 108. doi:10.1029/ 2001JB000896.
- Funciello, F., Moroni, M., Piromallo, C., Faccenna, C., Cenedese, A., Bui, H.A., 2006. Mapping flow during retreating subduction: laboratory models analyzed by feature tracking. J. Geophys. Res 111. doi:10.1029/2005JB003792.

- Fyfe, W.S., 1997. Deep fluids and volatile recycling: crust to mantle. Tectonophysics 275, 243–251. doi:10.1016/S0040-1951(97)00023-1.
- Garel, E., Lagabrielle, Y., Pelletier, B., 2003. Abrupt axial variations along the slow to ultraslow spreading centers of the northern North Fiji Basin (SW Pacific): evidence for short wave heterogeneities in a back-arc mantle. Marine Geophys. Res. 24, 245–263.
- Garfunkel, Z., Anderson, C.A., Schubert, G., 1986. Mantle circulation and the lateral migration of subducted slabs. J Geophys. Res. 91, 7205-7223.
- Geist, D., Richards, M., 1993. Origin of the Columbia Plateau and Snake River plaindeflection of the Yellowstone plume. Geology 21, 789-792.
- Goes, S., Spakman, W., Bijwaard, H., 1999. A lower mantle source for central European volcanism. Science 286, 1928-1931.
- Gorbatov, A., Widiyantoro, S., Fukao, Y., Gordeev, E., 2000. Signature of remnant slabs in the North Pacific from P-wave tomography. Geophys. J. Int. 142, 27-46
- Gordon, R.G., Jurdy, D.M., 1986. Cenozoic global plate motions. J. Geophys. Res. 91 (12389), 12406.
- Gorini, C., Mauffret, A., Guennoc, P., Le Marrec, A., 1994. Structure of the Gulf of Lions (Northwest mediterranean Sea): a review. In: Mascle, A. (Ed.), Hydrocarbon and Petroleum Geology of France, Eur. Assoc. Petrol. Geol, pp. 223-243.
- Granet, M., Wilson, M., Achauer, U., 1995. Imaging a mantle plume beneath the Massif Central (France). Earth Planet. Sci. Lett. 136, 281–296. Greenough, J.D., Fryer, B.J., 2008. Trace-element evidence for volatile-influence
- differentiation in a flow of alkali basalts. Peng Hu islands, Taiwan, Mineral. Assoc. Canada 46 (2), 305-315.
- Gvirtzman, Z., Nur, A., 1999. The formation of Mount Etna as the consequence of slab rollback. Nature 401 (6755), 782-785.
- Hager, B.H., Clayton, R.W., 1989. Constraints on the structure of mantle convection using seismic observations, flow models, and the geoid. In: Peltier, W.R. (Ed.), Mantle convection: Plate tectonics and global dynamics. The Fluid Mechanics of Astrophysics and Geophysics, 4. Gordon and Breach Science Publishers, New York, NY, pp. 657–763.
- Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific; computer-based reconstructions, model and animations. J. Asian Earth Sci. 20.353-431.
- Hall, R., Spakman, W., 2002. Subducted slabs beneath the eastern Indonesia-Tonga region; insights from tomography. Earth Planet. Sci. Lett. 201, 321-336.
- Hammond, W., Humpreys, E.D., 2000. Upper mantle seismic wave velocity: effect of realistic partial melt geometries. J. Geophys. Res. 105, 10975-10986.
- Harangi, S., Tonarini, S., Vaselli, O., Manetti, P., 2003. Geochemistry and petrogenesis of Early Cretaceous alkaline igneous rocks in Central Europe: implications for a longlived EAR-type mantle component beneath Europe. Acta Geol. Hung. 46, 77-94.
- Harta, S.R., Coetzeeb, M., Workmana, R.K., Blusztajna, J., Sintonc, J.M., Steinberger, B., Hawkinse, J.W., 2004. Genesis of the Western Samoa seamount province: geochemical fingerprint and tectonics. Earth Planet. Sci. Lett. 227, 37-56.
- Hawkins, J.W., Natland, J.H., 1975. Nephelinites and basanites of the Samoan linear volcanic chain: their possible tectonic significance. Earth Planet. Sci. Lett. 24, 427-439.
- Hickey-Vargas, R., 1998. Geochemical characteristics of oceanic island basalts from the Philippine Sea Plate: implications for thye sources of east Asian Plate margin and intraplate basalts. In: Flower, M.F.J., et al. (Ed.), Mantle Dynamics and Plate Interactions in east Asia; Geodyn. Ser, 27. AGU, Washington DC, pp. 365-384.
- Hilde, T.W.C., Lee, C.S., 1984. Origin and evolution of the West Philippine Basin: a new interpretation. Tectonophysics 102, 85-104.
- Hoernle, K., Zhang, Y.S., Schmincke, H.U., 1995. Seismic and geochemical evidence for large-scale mantle upwelling beneath the eastern Atlantic and western and central Europe. Nature 374, 34–39.
- Humphreys, E.D., Dueker, K.G., Schutt, D.L., Smith, R.B., 2000. Beneath Yellowstone: evaluating plume and nonplume models using teleseismic images of the upper mantle, GSATodav 10, 1-7,
- Ichiki, M., Baba, K., Obayashi, M., Utada, H., 2006. Water content and geotherm in the upper mantle above the stagnant slab: interpretation of electrical conductivity and seismic P-wave velocity models. Phys. Earth Planet. Inter. 155, 1-15.
- Inoue, T., Tanimoto, Y., Irifune, T., Suzuki, T., Fukui, H., Ohtaka, O., 2004. Thermal expansion of wadsleyite, ringwoodite, hydrous wadsleyite and hydrous ring-woodite. Phys. Earth Planet. Inter. 143–144, 279–290.
- Jolivet, L., Faccenna, C., 2000. Mediterranean extension and the Africa-Eurasia collision. Tectonics 19 (6), 1095-1106.
- Jordan, B.T., 2005. Age-progressive volcanism of the Oregon High Lava Plains: overview and evaluation of tectonic models. In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (Eds.), Plates, Plumes, and Paradigms 388. Geological Society of America Special Paper, pp. 503-515.
- Jordan, B.T., Grunder, A.L., Duncan, R.A., Deino, A.L., 2004. Geochronology of ageprogressive volcanism of the Oregon High Lava Plains: implications for the plume interpretation of Yellowstone. J. Geophys. Res. 109. doi:10.1029/2003JB002776.
- Jung, S., Hoernes, S., 2000. The major-and trace-element and isotope (Sr, Nd, O) geochemistry of Cenozoic alkaline rift-type volcanic rocks from the Rhon area (Central Germany): petrology, mantle source characteristics and implications for
- asthenosphere–lithosphere interactions. J. Volcanol. Geotherm. Res. 99, 27–53. Kelley, K.A., Plank, T., Grove, T.L., Stolper, E.M., Newman, S., Hauri, E., 2006. Mantle melting as a function of water content beneath back-arc basins. J. Geophys. Res. 111, B09208. doi:10.1029/2005jb003732.
- Kincaid, C., Griffith, R.W., 2003. Laboratory models of the thermal evolution of the mantle during rollback subduction. Nature 425, 58-62.
- King, S.D., Anderson, D.L., 1995. An alternative mechanism of flood basalt formation. Earth Planet. Sci. Lett. 136 (3–4), 269–279.
- King, S.D., Ritsema, J., 2000. African hot spot volcanism: small-scale convection in the upper mantle beneath cratons. Science 290 (5494), 1137-1140.

- Lagabrielle, Y., Goslin, J., Martin, H., Thirot, J.L., Auzende, J.M., 1997. Multiple active spreading centers in the hot North Fiji Basin (Southweast Pacific): a possible model for Archean seafloor dynamics ? Earth Planet. Sci. Lett. 149, 1-13.
- Lallemand, S., Font, Y., Bijwaard, H., Kao, H., 2001. New insights on 3D plates interaction near Taiwan from tomography and tectonic implications. Tectonophysics 335, 229-253.
- Leahy, G.M., Bercovici, D., 2007. On the dynamics of a hydrous melt layer above the transition zone. J. Geophys. Res.-Solid Earth 112 (B7), B07401.
- Leat, P.T., Pearce, J.A., Barker, P.F., Millar, I.L., Barry, T.L., Latter, R.D., 2004. Magma genesis and mantle flow at subducting slab edge: the South Sandwich arc-basin system. Earth Planet. Sci. Lett. 227, 17–35. doi:10.1016/j.epsl.2004.08.016
- Lei, J., Zhao, D., 2005. P wave tomography and origin of the Changbai intraplate volcano in Northeast Asia. Tectonophysics 397, 281-295. doi:10.1016/j.tecto.2004.12.009.
- Lei, J., Zhao, D., Su, Y., 2009. Insight into the origin of the Tengchong intraplate volcano and seismotectonics in southwest China from local and teleseismic data. I. Geophys. Res. 114, B05302. doi:10.1029/2008JB005881.
- Levin, V., Shapiro, N., Park, J., Ritzwoller, M., 2002. Seismic evidence for catastrophic slab loss beneath Kamchatka. Nature 418, 763-767.
- Lewis S.D., Hayes, D.E., Mrozowski, C.L., 1982. The origin of the West Philippine basin by inter-arc spreading, Geology and Tectonics of Luzon and Marianas region; Proceedings of CCOP-IOC-SEATAR Workshop, Manila, Philippine, Philippine SEATAR Committeee specioal publication, ed. By G.R. Blace and F. Zanoria, 1, 31-51.
- Li, C., van der Hilst, R.D., Engdahl, E.R., Burdick, S., 2008. A new global model for Pwavespeed variations in Earth's mantle. Geochem. Geophys. Geosyst. 9, Q05018. doi:10.1029/2007GC001806.
- Li, C., van der Hilst, R.D., 2010. Structure of the upper mantle tranition zone beneath Southeast Asia from traveltime tomography. J. Geophys. Reasearch 115, B07308. doi:10.1029/2009JB006882.
- Liu, K., Gao, S., Gao, Y., Wu, J., 2008. Shear wave splitting and mantle flow associated with the deflected Pacific slab beneath northeast Asia. J. Geophys. Res. 113, B01305.
- Louden, K.E., 1976. Magnetic anomalies in the West Philippine Basin. In: Sutton, G.H., Manghnani, M.H., Moberly, R. (Eds.), The geophysics of the Pacific Ocean Basin and its margin; Geophys. Monograph Ser, 19. AGU, Washington DC, pp. 253–267. Lucente, F.P., Margheriti, L., Piromallo, C., Barruol, G., 2006. Seismic anisotropy reveals
- the long route of the slab through the western-central Mediterranean mantle. Earth Planet. Sci. Lett. 241, 517-529.
- Lucente, P.F., Chiarabba, C., Cimini, G.B., Giardini, D., 1999. Tomographic constarints on the geodynamic evolution of the Italian region. J. Geophys. Res. 104, 20307-20327.
- Lustrino, M., Wilson, M., 2007. The circum-Mediterranean anorogenic Cenozoic igneous province. Earth Sci. Rev. doi:10.1016/j.earscirev.2006.09.002.
- Maruyama, S., Okamoto, K., 2007. Water transportation from the subducting slab into the mantle transition zone. Gondwana Res. 11, 148-165. doi:10.1016/j.gr.2006.06.001. McKee, E.H., Klock, P.R., 1974. K-Ar ages of basalts, Benham Rise, West Philippine Basin,
- Leg 31. Rep. DSDP, 31. US Gov. Printing Office, Washington DC, pp. 299-600.
- Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R., Hung, S.H., 2004. Finitefrequency tomography reveals a variety of plumes in the mantle. Science 303 (5656), 338-343.
- Montuori, C., Cimini, G.B., Favali, P., 2007. Teleseismic tomography of the southern Tyrrhenian subduction zone: new results from seafloor and land recordings. J. Geophys. Res. 112, B03311. doi:10.1029/2005JB004114.
- Moresi, L., Solomatov, V.S., 1995. Numerical investigations of 2D convection with extremely large viscosity variations. Phys. Fluids 7, 2154-2162.
- Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 42–43.
- Mrozowski, C.L., Lewis, S.D., Hayes, D.E., 1982. Complexities in the tectonic evolution of the West Philippine basin. Tectonophysics 82, 1-24. Natland, J., 1980. The progression of volcanism in the Samoan linear volcanic chain. Am.
- J. Sci. 280-A, 709-735.
- Obrebski, M., Allen, R.M., Xue, M., Hung, S.H., 2010. Slab-plume interaction beneath the Pacific Northwest. Geophys. Res. Lett. 37, L14305. doi:10.1029/2010GL043489. Ozima, M., Kaneokam, I., Ujiie, H., 1977. ⁴⁰Ar–³⁹Ar age of rocks and the development
- mode of the Philippine Sea. Nature 267, 816-818.
- Parson, L.M., Wright, I.C., 1996. The Lau-Havre-Taupo back-arc basin: a southwardpropagating, multi-stage evolution from rifting to spreading. Tectonophysics 263, 1-22.
- Pelletier, B., Calmant, S., Pillet, R., 1998. Current tectonics of the Tonga–New Hebrides region. Earth Planet. Sci. Lett. 164, 263–273.
- Pelletier, B., Lagabrielle, Y.M., Cabioch, G., Calmant, S., Garel, E., Guivel, C., 2001. Newly identified segments of the Pacific-Australia plate boundary along the North Fiji Transform Zone. Earth Planet. Sci. Lett. 193, 347-358.
- Peyton, V., Levin, V., Park, J., Brandon, M.T., Lees, J., Gordeev, E., Ozerov, A., 2001. Mantle flow at a slab edge: seismic anisotropy in the Kamchatka region. Geophys. Res. Lett. 28, 379-382. doi:10.1029/2000GL012200.
- Pierce, K.L., Morgan, L.A., Saltus, R.W., 2000. Yellowstone Plume Head: Postulated Tectonic Relations to the Vancouver Slab, Continental Boundaries and Climate. 39.
- Pierce, K.L., Morgan, W.J., 1992. The track of the Yellowstone hotspot: volcanism, faulting, and uplift. In: Link, P.K., Kuntz, P.L.B., A., M. (Eds.), Regional Geology of Eastern Idaho and Western Wyoming 179: Geological Society of America Memoir, pp. 1-53.
- Piromallo, C., Morelli, A., 2003. P wave tomography of the mantle under the Alpine-Mediterranean area. J. Geophys. Res.-Solid Earth 108 (B2), 2065 10.129/2002JB001757.
- Piromallo, C., Faccenna, C., 2004. How deep can we find the traces of Alpine subduction? Geophys. Res. Lett. 31. doi:10.1029/2003GL019288.
- Piromallo, C., Gasperini, D., Macera, P., Faccenna, C., 2008. A late Cretaceous contamination episode of the European–Mediterranean mantle. Earth Planet. Sci. Lett. 268, 15-27.

- Piromallo, P., Becker, T.W., Funiciello, F., Faccenna, C., 2006. Three dimensional instantaneous mantle flow induced by subduction. Geophys. Res. Lett. 33. doi:10.1029/2005GL025390.
- Pysklywec, R.N., Mitrovica, J.X., Ishii, M., 2003. Mantle avalanche as a driving force for tectonic reorganization in the southwest Pacific. Earth Planet. Sci. Lett. 209, 29-38.
- Raddick, M.J., Parmentier, E.M., Scheirer, D.S., 2002. Buoyant decompression melting: a possible mechanism for intraplate volcanism. J. Geophys. Res. 107 (B10), 2228.
- doi:10.1029/2001IB000617. Richard, G.C., Iwamori, H., 2010. Stagnant slab, wet plumes and Cenozoic volcanism in
- East Asia. Phys. Earth Planet. Inter. doi:10.1016/j.pepi.2010.02.009. Ritter, J.R.R., Jordan, M., Christensen, U.R., Achauer, U., 2001. A mantle plume below the
- Eifel volcanic fields. Germany. Earth Planet. Sci. Lett. 186, 7-14. Roy, M., Jordan, T.H., Pederson, J., 2009. Colorado Plateau magmatism and uplift by
- warming of heterogeneous lithosphere. Nature 459. doi:10.1038/nature08052.
- Ruellan, E., Delteil, J., Wright, I., Matsumoto, T., 2003. From rifting to active spreading in the Lau Basin-Havre Trough backarc system (SW Pacific)-locking/unlocking induced by seamount chain subduction. Geochem. Geophys. Geosyst. 4 (5), 8909. doi:10.1029/2001GC000261.
- Rupke, L.H., Morgan, J.P., Hort, M., Connolly, J.A.D., 2004. Serpentine and the subduction zone water cycle. Earth Planet. Sci. Lett. 223 (1-2), 17-34.
- Satosh, M., Omori, S., 2008. CO₂ flushing: a plate tectonic perspective. Gondwana Res. 13, 86–102. doi:10.1016/jgr.2007.07.003.
- Schellart, W.P., 2004. Kinematics of subduction and subduction-induced flow in the upper mantle. J. Geophys. Res.-solid earth 109 (b7), b07401.
- Schellart, W.P., Lister, G.S., Toy, V.G., 2006. A Late Cretaceous and Cenozoic reconstruction of the Southwest Pacific region: Tectonics controlled by subduction and slab rollback processes. Earth-Sci. Rev. 76, 191-233.
- Schiano, P., 2003. Primitive mantle magmas recorded as silicate melt inclusions in igneous minerals. Earth Sci. Rev. 63 (1-2), 121-144.
- Schmeling, H., Babeyko, A., Enns, A., Faccenna, C., Funiciello, F., Gerya, T., Golabek, G., Grigull, S., Kaus, B.J.P., Morra, G., van Hunen, J., 2007. A benchmark comparison of subduction models. Phys. Earth Planet. Inter. 171, 198-223.
- Seno, T., Maruyama, S., 1984. Paleogeographic reconstruction and origin of the Philippine Sea. Tectonophysics 102, 53–84.
- Seranne, M., 1999. The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. In: Durand, B., et al. (Ed.), The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen: Geol. Soc. Spec. Publ., 156, pp. 21-53.
- Sibuet, J.C., Deffontaines, B., Hsu, S.K., Thareau, N., Le Formal, J.P., Liu, C.S., the ACT party, 1998. Okinawa Trough backarc basin: early tectonic and magmatic evolution. J. Geophys. Res. 103, 30245-30267.
- Sigloch, K., McQuarrie, N., Nolet, G., 2008. Two-stage subduction history under North America inferred from multiple-frequency tomography. Nat. Geosci. 1, 458-462.
- Smith, R.B., Braile, L.W., 1994. The Yellowstone hotspot. J. Volcanol. Geotherm. Res. 61, 121-187
- Smith, R.B., Jordan, M., Steinberger, B., Puskas, C.M., Farrell, J., Waite, G.P., Husen, S., Chang, W.L., O'Connell, R., 2009. Geodynamics of the Yellowstone hotspot and mantle plume: seismic and GPS imaging, kinematics, and mantle flow. J. Volcanol. Geotherm. Res. 188, 26-56.
- Speranza, F., Maniscalco, R., Mattei, M., Di Stefano, A., Butler, R.W.H., Funiciello, R., 1999. Timing and magnitude of rotations in the frontal thrust systems of southwestern Sicily. Tectonics 18, 1178-1197.
- Stegman, D.R., Freeman, J., Schellart, W.P., Moresi, L., May, D., 2006. Influence of trench width on subduction hinge retreat rates in 3-D models of slab rollback. Geochem. Geophys. Geosyst. 7. doi:10.1029/2005GC001056.
- Tackley, P.J., 2000. Self-consistent generation of tectonic plates in time-dependent, three-dimensional mantle convection simulations 1. Pseudoplastic yielding. Geochem. Geophys. Geosyst. 1 2000GC000036.
- Taylor, B., Zellmer, K., Martinez, F., Goodliffe, A., 1996. Sea-floor spreading in the Lau back-arc basin. Earth Planet. Sci. Lett. 144, 35-40.
- Tetzlaff, M., Schmeling, H., 2000. The influence of olivine metastability on deep subduction of oceanic lithosphere. Phys. Earth Planet. Inter. 120, 29-38.
- Tonarini, S., Armienti, P., D'Orazio, M., Innocenti, F., 2001. Subduction-like fluids in the genesis of Mt. Etna magmas: evidence from boron isotopes and fluid mobile
- elements. Earth Planet. Sci. Lett. 192, 471–483. Turner, S., Hawkesworth, C.J., 1998. Using geochemistry to map mantle flow beneath the Lau Basin. Geology 26 (11), 1019–1022. doi:10.1130/0091-7613.
- Uyeda, S., Ben-Avraham, Z., 1972. Origin and development of the Philippine Sea. Nature 240, 176-178.
- Van der Hilst, R.D., 1995. Complex morphology of subducted lithosphere in the mantle beneath the Tonga trench. Nature 374, 154-157.
- van der Meijde, M., Marone, F., van der Lee, S., 2003. Seismic evidence for water deep in earth's upper mantle. Science 300, 1556. doi:10.1126/science.1083636.
- Van der Voo, R., 1993. Paleomagnetism of the Atlantic Thethys and Iapetus Oceans. Cambridge Univ, Press, New York.
- van Wijk, J., van Hunen, J., Goes, S., 2008. Small-scale convection during continental rifting:
- evidence from the Rio Grande rift. Geology 36, 575–578. doi:10.1130/G24691A.1. Waite, G.P., Smith, R.B., Allen, R.M., 2006. Vp and Vs structure of the Yellowstone hot spot from teleseismic tomography: evidence for an upper mantle plume. J. Geophys. Res. 111 (B4), B04303. doi:10.1029/2005JB003867.
- Watts, A.B., Weissel, J.K., Larson, R.L., 1977. Seafloor spreading in marginal basins of the western Pacific. Tectonophysics 167-182.
- Weissel, J.K., 1977. Evolution of the Lau Basin by the growth of small plates. In: Talwani, M., Pitman, W.C. (Eds.), Island Arcs, Deep Sea Trenches, and Back-Arc basins: Am.
- Geophys. Union, Maurice Ewing Series, 1, pp. 429–436. West, J.D., Fouch, M.J., Roth, J.B., 2009. Vertical mantle flow associated with a lithospheric drip beneath the Great Basin. Nat. Geosci. 2 (6), 438-443.

Author's personal copy

- Wiens, D.A., Kelley, K.A., Plank, T., 2006. Mantle temperature variations beneath backarc spreading centers inferred from seismology, petrology, and bathymetry. Earth Planet. Sci. Lett. 248, 30–42.
- Wilson, M., Bianchini, G., 1999. Tertiary–Quaternary magmatism within the Mediterranean and surrounding regions. In: Durand, Jolivet, Horvath, Seranne (Eds.), The Mediterranean Basins: Tertiary extension within the Alpine orogen: Geol. Soc. London, 156, pp. 141–168.
- Wilson, M., Downes, H., 1991. Tertiary-Quaternary extension-related alkaline magmatism in western and central Europe. J. Petrol. 32, 811–849.
- Wilson, M., Downes, H., 1992. Mafic alkaline magmatism associated with the European Cenozoic rift system. Tectonophysics 208, 173–182.
- Wilson, M., Downes, H., 2006. Teriary–Quaternary intra-plate magmatism in Europe and its relationships to mantle dynamics. In: Gee, D., Stephenson, R. (Eds.), European Lithosphere Dynamics: Geol. Soc. Lond. Mem., 32, pp. 147–166.
- Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean–Carpathian region. Science 290, 1910–1917.
- Xue, M., Allen, R.M., 2010. Mantle structure beneath the western United States and its implications for convection processes. J. Geophys. Res. 115, B07303. doi:10.1029/ 2008/B006079.
- Xue, M., Allen, R.M., 2007. The fate of the Juan de Fuca plate: implications for a Yellowstone plume head. Earth Planet. Sci. Lett. 264, 266–276.
- Yogodzinski, G.M., Lees, J.M., Churikova, T.G., Dorendorf, F., Woerner, G., Volynets, O.N., 2001. Geochemical evidence for the melting of subducting ocean lithosphere at plate edges. Nature 409, 500–504. doi:10.1038/35054039.
- Yuan, H.Y., Dueker, K., 2005. Teleseismic P-wave tomogram of the Yellowstone plume. Geophys. Res. Lett. 32, L07304. doi:10.1029/2004GL022056.

- Zakariadze, G.S., Dmitriev, L.V., Sobolev, V., Suschevskaya, N.M., 1980. Petrology of basalts of holes 447A, 449, and 450, South Philippine Sea transect, DSDP Leg 59. In: Kroenke, L., Scott, R., et al. (Eds.), Init. Repts. DSDP, 59. US Govt. Printing Office, Washington, pp. 669–680.
- Zellmer, K.E., Taylor, B., 2001. A three-plate kinematic model for Lau Basin opening. Geochem. Geophys. Geosyst. 2 2000GC000106.
- Zhang, Y.S., Tanimoto, T., 1992. Ridges, hotspots and their interaction as observed in seismic velocity maps. Nature 355, 45–49.
- Zhao, D., 2004. Global tomographic images of mantle plumes and subducting slabs: insight into deep Earth dynamics. Phys. Earth Planet. Inter. 146, 3–34. doi:10.1016/ j.pepi.2003.07.032.
- Zhao, D., Tian, Y., Lei, J., Liu, L., Zheng, S., 2009. Seismic image and origin of the Changbai intraplate volcano in East Asia: role of big mantle wedge above the stagnant Pacific slab. Phys. Earth Planet. Inter. 173, 197–206.
- Zhao, D., Xu, Y., Wiens, D., et al., 1997. Depth extent of the Lau back-arc spreading center and its relation to subduction processes. Science 278, 254–257.
- Zhong, S., Gurnis, M., 1995. Mantle convection with plates and mobile, faulted plate margins. Science 267, 838–842.
- Zhong, S., Gurnis, M., Moresi, L., 1998. Role of faults, nonlinear rheology, and viscosity structure in generating plates from instantaneous mantle flow models. J. Geophys. Res. 103, 15255–15268.
- Ziegler, P.A., 1992. European Cenozoic rift system. In: Ziegler, P.A. (Ed.), Geodynamics of rifting, vol. 1. Tectonophysics 208, 91–111.