

Focused fluid transfer through the mantle above subduction zones

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ABSTRACT

Volcanic arcs above subduction zones are enriched in volatiles and fluid-mobile elements with respect to mid-oceanic ridge basalts. There is general consensus that this particular subduction zone signature is generated by fluid-induced extraction of these elements from subducted oceanic crust and its sedimentary cover. However, how these fluids are transferred through the mantle wedge to the locus of partial melting and what modification the fluids will experience is unresolved. Here we investigate the interaction of slab fluids with the mantle wedge through a series of high-pressure experiments. We explore two end-member processes of focused and porous reactive flow of hydrous slab melts through the mantle. Transfer by porous flow leads to the formation of hydrous minerals that sequester fluid-mobile elements and residual fluids characterized by trace element patterns inconsistent with typical arc lavas. In contrast, no hydrous minerals are formed in the reaction zone of experiments mimicking focused flow, and the typical trace element signature acquired during fluid extraction from the slab is preserved, indicating that this is an efficient process for element transfer through the mantle wedge.

INTRODUCTION

Recycling of elements in subduction zones is a fundamental process that has shaped the differentiation and evolution of Earth. Arc lavas are characterized by high water contents and enrichments of large ion lithophile elements (LILEs) and light rare earth elements (LREEs) compared to oceanic crust formed at mid-ocean ridges (Pearce et al., 2005), and are chemically similar to the average continental crust (Fig. DR1 in the GSA Data Repository¹). Isotopic studies of arc lavas (Ellam and Hawkesworth, 1988) have demonstrated that these enrichments originate from subducted altered oceanic crust, and thus these patterns are called the slab signature of arc lavas (Tatsumi and Eggins, 1995). The recycling of elements from the subducted slab to arc volcanoes is the result of fluid-mediated mass transfer related to the dehydration of altered oceanic crust and sediment melting (Plank and Langmuir, 1993) at depths of 80–150 km. The release of fluids from the slab causes wet melting of the mantle wedge and the transfer of primitive arc lavas to the surface, carrying a crustal signature derived from the slab fluid (fluid, aqueous fluids, and hydrous melts as defined in Pirard and Hermann [2015]). The timing of this recycling is constrained by Be dating to take place in <10 m.y. (Morris et al., 1990). However, it remains unclear how fluids are efficiently transferred from the slab to the locus of partial melting within the mantle wedge without being heavily modified or assimilated by their interaction with the surrounding peridotite.

¹GSA Data Repository item 2015307, experimental conditions and chemical compositions of all phases, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

MODELS OF FLUID TRANSFER IN THE MANTLE WEDGE

Many models have been proposed to explain the water and trace element transfer from the slab to the locus of partial melting in the mantle wedge. One type of model is based on extensive metasomatic reactions between slab fluids and the mantle wedge with the formation of hydrous phases such as micas and amphiboles (Ringwood, 1974; Tatsumi et al., 1986). Metasomatized peridotites can be dragged down with the subducting slab until they reach pressure and temperature conditions leading to the breakdown of the hydrous minerals and the release of fluids. These fluids will metasomatize a part of the overlying mantle wedge that will flow again to greater depth, repeating a cycle until primitive arc melts are created. A variation of this model is that there is extensive interaction of slab-derived fluids at the interface with the mantle wedge, producing a metasomatized peridotite and a residual fluid that is in equilibrium with peridotite minerals and hence is able to travel without further modification in the mantle wedge to the locus of wet melting (Malaspina et al., 2006). A different set of models proposes that the transport of slab fluids through the mantle wedge occurs by focused flow through fractures (Hack and Thompson, 2011). This will result in a less-extensive interaction of slab fluids with peridotite. Finally, it has also been suggested that the wet peridotite solidus is at such low temperatures that fluids released at sub-arc depth from the slab will initiate immediate mantle partial melting, and thus the transfer will entirely be in the form of hydrous basaltic melts (Till et al., 2012). Each of these models is able to account for particular features of fluid transfer in the mantle wedge. However, it is important that multiple factors, such as using realistic slab fluid compositions, mantle wedge

thermal models and melting conditions, water enrichment, and trace element signatures, are considered at the same time, which is the aim of our experimental study.

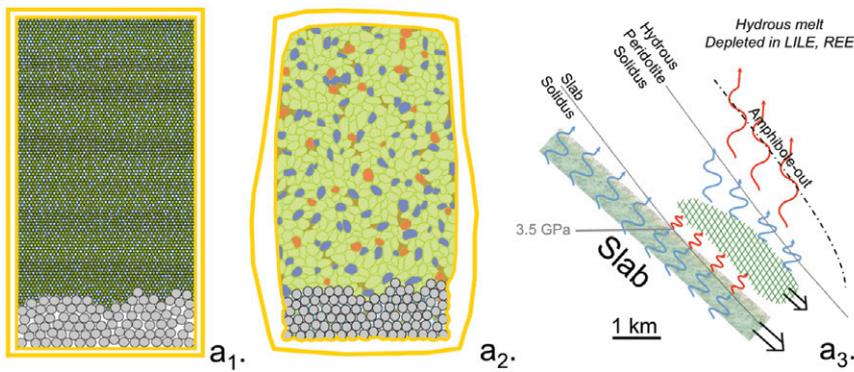
EXPERIMENTAL STRATEGY AND METHODS

We investigated different types of fluid interaction with the mantle wedge through a series of high-pressure experiments at 3.5 GPa, corresponding to ~100 km depth, typical for the position of the subducted slab below volcanic arcs (Tatsumi, 1986). We chose slab melt compositions with defined major element and water concentrations (Hermann and Spandler, 2008) that form from fluid-fluxed melting of sediments at intermediate (800 °C; low K, high H₂O) and hot (950 °C; high K, low H₂O) top slab temperatures according to models (Syracuse et al., 2010). The hydrous slab melts were synthesized from a gel mix doped with trace elements (see the Data Repository). To simulate the two end-member processes of porous and focused flow, we used two different capsule designs (Fig. 1). During porous flow, fluid percolating along the grain boundaries will have intense interaction with peridotite. This process is approximated by mixing 75% of fine-grained (<5 μm) olivine with 25% of slab melt glass. Focused fluid flow results in veins that are modeled in the experiments by placing a distinct layer of slab melt in contact with coarse-grained olivines (~80–100 μm) that more closely approximate the grain size of olivine in the mantle wedge than the fine-grained olivines used in the interaction experiments. The planar interface between the two reactants is analogous to the contact zone on the wall of a vein cutting across the mantle. Starting materials were loaded into 3.5 mm gold capsules that contained a fluid trap consisting of vitreous carbon spheres. The capsules were loaded into piston cylinder apparatuses and run for one week at 3.5 GPa and temperatures ranging from 800 °C to 1050 °C. We investigated the interaction of slab fluids with olivine in 50 °C steps from conditions at the slab-mantle interface, up to the wet peridotite solidus, resulting in 20 experiments (Table DR1 in the Data Repository). All of the data, together with additional details on the experimental and analytical techniques, are presented in the Data Repository.

EXPERIMENTAL RESULTS

Textures of the reaction products of the two types of experiments are radically different. The mixed experiments (porous flow) resulted

A. Mixed experiments – Porous flow



B. Layered experiments – Focused flow

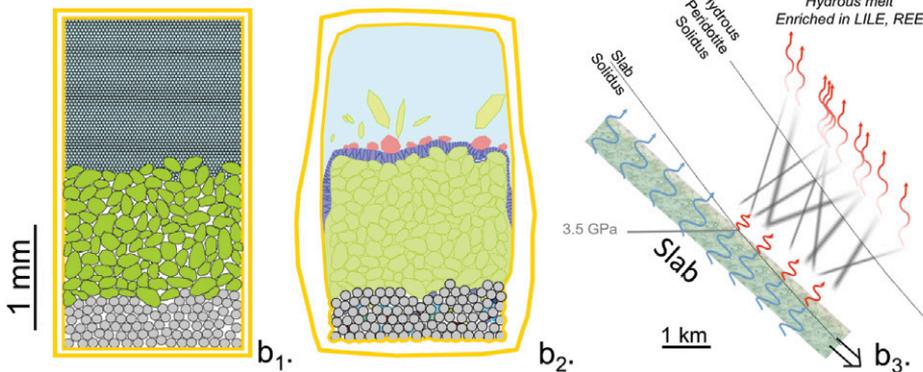


Figure 1. Setup of experiments representing porous flow (mixed charge, a₁) and focused flow (layered charge, b₁). After one week at 3.5 GPa and various temperatures, porous flow experiments (a₂) show assemblage of olivine (green), orthopyroxene (dark blue), garnet (red), and mica (brown), while focused flow experiments (b₂) remain layered with a layer of orthopyroxene and garnet at interface between olivine and hydrous melt (light blue). Rare clinopyroxene or coesite (yellow) form in melt. Carbon spheres are shown as gray circles. Panels a₃ and b₃ are schematic representations of mass transfer at slab-mantle interface through aqueous fluids (blue arrows), hydrous melts (red arrows), and solid rocks (black arrows). Porous flow (a₃) leads to formation of metasomatized mantle (green hatched zone), and focused flow of hydrous melts occurs through fractures at subsolidus conditions (gray lines, b₃). LILE—large ion lithophile element; REE—rare earth element.

in a hybridized garnet harzburgite containing large amounts of phlogopite (Figs. DR2c and DR2d). Na-rich amphibole is present only in the low-K experimental series. Partial melting starts at 1050 °C in the high-K and at 975 °C in the low-K experiments (Pirard and Hermann, 2015) (Table DR2). The fluid traps in subsolidus experiments contain amorphous quench material as well as some hydrous phases that result from dissolution-precipitation reactions during the runs. Layered experiments (focused flow) mainly consist of a recrystallized layer of pure olivine and a distinct felsic glass zone that rarely contains some coesite or jadeite. Olivine and felsic melt are separated by a small reaction zone of orthopyroxene ± garnet (Figs. DR2a and DR2b). No hydrous minerals are observed in any of these layered experiments, and the fluid trap contains relatively little quench material.

The major and trace element compositions of hydrous and fluid phases are given in the

Data Repository. Phlogopite is characterized by strong enrichments of Rb and Ba with respect to the starting felsic glass (Fig. DR4; Tables DR2 and DR4). Sodic amphibole can compose up to 13% of the assemblage and is a considerable host for sodium, water, and REEs. Amphibole preferentially incorporates heavy REEs (HREEs) over LREEs and contains only modest amounts of Nb, Ta, Th, and U. Garnet preferentially incorporates HREEs, while olivine and orthopyroxene are main hosts for transition metals (Table DR3).

Hydrous melt compositions in experiments constraining porous flow range from phonolitic at low temperature to phonotephritic at high temperature, and water contents decrease from ~30% at 975 °C to ~10% at 1100 °C. Amphibole in the low-K experiments breaks down at less than 50 °C above the wet solidus, but phlogopite is a residual phase at least up to the upper temperature limit of 1100 °C of our ex-

periments. The resulting hydrous melt trace element patterns are enriched in LREEs and high field strength elements (HFSEs), but relatively depleted in LILEs (Fig. 2A). The quantification of trace element concentrations in aqueous fluids requires an iterative mass balance approach that also takes into account the presence of dissolution-precipitation reactions (see the Data Repository). These calculations indicate that Si, Al, and alkalis are the main solutes in the subsolidus fluids. The water content in aqueous fluids of the low-K experiments varies between 85% and 70%, whereas fluids in high-K experiments have an intermediate solute content between aqueous fluids and hydrous melt. LILEs and REEs are only moderately enriched in the residual aqueous fluids of porous flow experiments, whereas HFSEs are not sequestered by any phase and therefore remain in the fluid phase. Trace element ratios such as Ba/La or Rb/Nb are ~10× lower in the residual aqueous fluid than in the starting hydrous melt and move toward unity once partial melting is initiated (Fig. DR5). In layered experiments, hydrous melts are mostly unchanged with the exception of depletion in HREEs caused by the presence of garnet in the reaction zone (Fig. 2B).

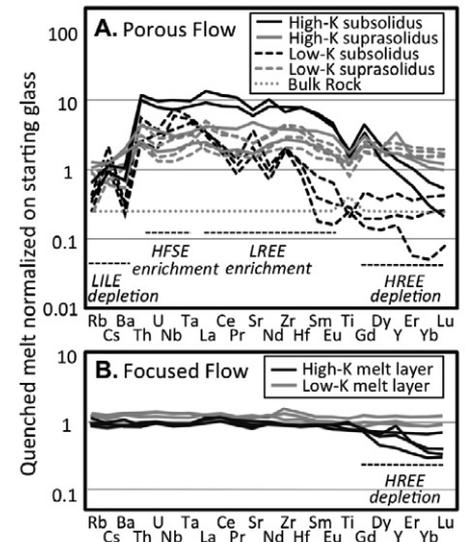


Figure 2. Trace element patterns of fluid phases. A: Trace element composition of quenched fluids of mixed experiments (porous flow) normalized to starting sediment melt composition. Both aqueous fluids and hydrous melts display depletion in large ion lithophile elements (LILEs), variable rare earth element (REE) patterns (as function of coexisting garnet and amphibole), and enrichment in high field strength elements (HFSEs). B: Quenched melt in layered experiments (focused flow) normalized to their respective starting sediment melt. Slab melt geochemical signature is unmodified with exception of heavy REEs (HREEs) in high-K experiments due to presence of garnet. LREE—light rare earth element.

TRACE ELEMENT FINGERPRINT ON FLUID TRANSPORT IN THE MANTLE WEDGE

The way fluids interact with the mantle wedge results in distinct trace element signatures that can be used to distinguish between different transport processes. It is especially important to consider the behavior of water, LILEs, and LREEs, the main subduction components in arc lavas (Pearce et al., 2005) (Fig. DR1).

Recent studies have shown that the liberation of K (as a LILE) and Ce (as a REE) combined with H₂O provides insight into slab temperatures and the nature of the fluid phase (Hermann and Spandler, 2008; Plank et al., 2009). There is an excellent match of observed K₂O/H₂O and H₂O/Ce in arc lavas with what is expected from hydrous melts formed at 750–900 °C during fluid-fluxed melting of sediments at sub-arc depth (Fig. 3). On the other hand, the K₂O/H₂O and H₂O/Ce of aqueous fluids released from altered oceanic crust or sediments are far removed from the compositional range of arc lavas, justifying our approach of using sediment melts as the fluid phase to interact with the mantle rocks. Additionally, estimated slab temperatures derived from K₂O/H₂O and H₂O/Ce in arc lavas are generally found to be in good agreement with thermal models (Cooper et al., 2012). From this it appears that insignificant modification of these ratios occurs as fluids travel through the mantle wedge, but this has not been tested experimentally.

The simplest way of avoiding any fractionation is if slab fluids directly induce wet melting in the mantle wedge (Till et al., 2012). However, our experiments show that there is a subsolidus zone between conditions at the top of the subducted slab and first onset of melting in the mantle wedge. In the low-K series the difference between the slab-wedge interface temperature and partial melting is 175 °C, whereas in the high-K series it is ~100 °C. Given the compressed isotherms in a subduction zone setting (van Keken et al., 2002), this temperature interval might be a zone with a thickness of only a few kilometers. Our experiments show that if fluids breach this zone through porous flow, extensive phlogopite forms and amphibole is present for the low-K composition. The results from our study agree with the results of Sekine and Wyllie (1982) that phlogopite forms in the interaction of hydrous granitic melt with peridotite. Amphibole and phlogopite retain significant amounts of trace elements, and the residual fluids show HFSE enrichment and LILE depletion (Fig. 2), i.e., opposite of what is observed in arc lavas. Moreover, the residual fluids move to lower K₂O/H₂O and higher H₂O/Ce during the interaction so that they no longer match the compositions of arc lavas (Fig. 3). Wet melting of the mantle wedge peridotites by influx of such fluids is thus not suitable to explain the composition of arc lavas.

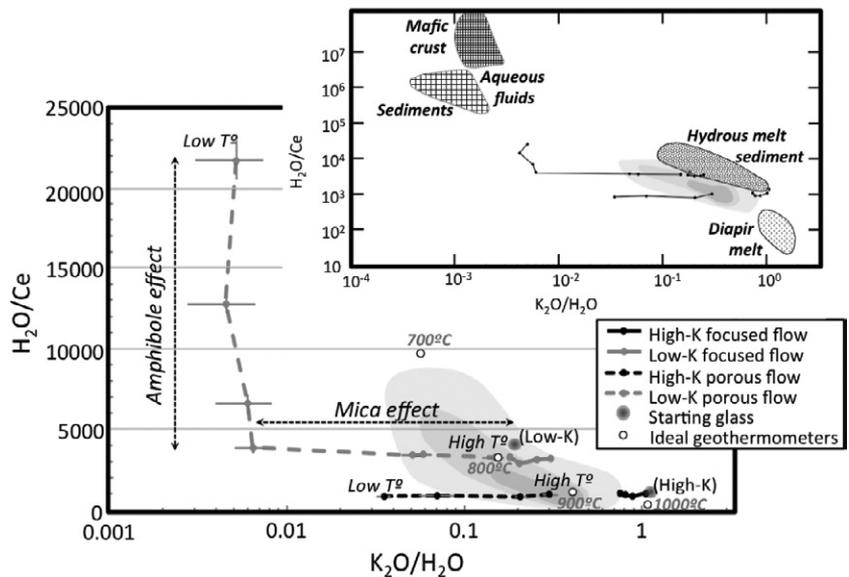


Figure 3. Comparison of experimental fluid to arc lava compositions in terms of water, K₂O (as proxy for large ion lithophile elements) and Ce (as proxy for light rare earth elements). Glass layers in focused flow experiments preserve K₂O/H₂O and H₂O/Ce similar to initial slab melt. In contrast, fluids and melt ponds in porous flow experiments show extreme modification of these ratios between high-temperature (high T^o) and low-temperature (low T^o) experimental runs. H₂O/Ce is essentially controlled by presence of amphibole in equilibrium with fluids, whereas K₂O/H₂O is dependent on presence of phlogopite in solid residue. Gray fields show distribution of natural arc lavas (Cooper et al., 2012) contoured for 50%, 75%, and 99% of total analyses. Porous flow modifies residual fluid compositions such that they are not overlapping anymore with compositions of arc lavas, whereas good agreement exists for focused flow. Fluid compositions calculated for slab temperatures of 700–1000 °C following methods of Hermann and Spandler (2008) and Plank et al. (2009) are given. Inset shows that aqueous fluids derived from sediments (Zheng and Hermann, 2014) and from altered oceanic crust (Green and Adam, 2003) are far removed from arc lava ratios, whereas hydrous sediment melts formed at 750–900 °C (Hermann and Spandler, 2008; Hermann and Rubatto, 2009) largely overlap with composition of arc lavas. Composition of sediment melts derived from phengite breakdown in diapirs at 1050 °C has been constrained from sediment melting and monazite solubility experiments (Hermann and Spandler, 2008; Stepanov et al., 2012). Such diapir melts are not consistent with composition of arc lavas in the K₂O/H₂O–H₂O/Ce space.

Alternatively, the melting of metasomatized peridotites formed by such interaction has been considered as a potential source for arc magmas (Ringwood, 1974; Tatsumi et al., 1986; Manning, 2004). Phlogopite and amphibole are particularly rich in alkalis, LILEs, LREEs, and water, and are depleted in HFSEs. However, the stability fields of amphibole and phlogopite are vastly different, with amphibole being restricted to pressures below 3 GPa for most peridotite compositions (Fumagalli et al., 2009). Additionally, amphibole preferentially incorporates HREEs over LREEs (Fig. DR4), and thus amphibole breakdown is unable to produce the REE signature of arc lavas where LREEs are enriched.

Our experiments demonstrate that focused flow in veins does not lead to the formation of mica nor amphibole in the reaction zone. Orthopyroxene rims form at the interface between the felsic melt and the peridotite, and thus focused transport through veins or channels of slab melt in the mantle wedge would lead to very limited interaction. Once the wet solidus is crossed by the focused melts, partial melting occurs also in the peridotite (Fig. 1). Hybrid melts would

then travel up the temperature gradient into the hottest part of the mantle wedge, diluting the slab signature by increased melting of peridotites. The positive LILE and LREE anomalies and negative HFSE anomalies present in the initial slab melt would be preserved throughout this process. Focused fluid flow allows fast transport of fluids through the mantle wedge as required by U-series isotopic measurements that predict transport times as short as a few tens of thousands of years between the liberation of the slab fluid and the eruption of the arc volcanic rocks (Elliott et al., 1997; Turner et al., 2001). Felsic veins walled by orthopyroxene in mantle xenoliths (Kepezhinskis et al., 1995; Arai et al., 2003) indicate that melt-olivine interaction is limited by orthopyroxene reaction zones even over geological time scales. Slab diapirs, where buoyant metasediments or slab mélange are mechanically removed from the slab, represent an alternative model for fast element transfer (Behn et al., 2011; Marschall and Schumacher, 2012). High-temperature melting of phengite in such metasediments or mélange without the addition of an aqueous slab fluid will produce melts that

are high in K and Ce and low in H₂O and that plot outside the field of the slab signature of arc lavas (Fig. 3). Additionally, studies of natural samples have shown that such melting produces trace element patterns that are not in agreement with arc lavas (Stepanov et al., 2014). Therefore, we conclude that focused fluid flow is the most simple and feasible way for fluid-mediated transport of trace elements through the subsolidus zone in the mantle wedge that preserves the distinct slab signature found in arc lavas worldwide.

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