

Magmatic implications of mantle wedge plumes: Experimental study

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Abstract

Numerical and laboratory experiments beside natural observations suggest that hydration and partial melting along the subducting slab can trigger Rayleigh–Taylor instabilities that evolve into partially molten diapiric structures (“cold plumes”) that rise through the hot asthenospheric wedge. Mixed cold plumes composed of tectonic melanges derived from subduction channels can transport the fertile subducted crustal materials towards hotter zones of the suprasubduction mantle wedge leading to the formation of silicic melts. We investigate magmatic consequences of this plausible geodynamic scenario by using an experimental approach. Melt compositions, fertility and reaction between silicic melts and the peridotite mantle (both hydrous and dry) were tested by means of piston–cylinder experiments at conditions of 1000°C and pressures of 2.0 and 2.5 GPa. The results indicate that silicic melts of trondhjemite and granodiorite compositions may be produced in the ascending mixed plume megastructures. Our experiments show that the formation of an Opx-rich reaction band, developed at the contact between the silicic melts and the peridotite, protect silicic melts from further reaction in contrast to the classical view that silicic melts are completely consumed in the mantle. The mixed, mantle–crust isotopic signatures which are characteristic of many calc-alkaline batholiths are also expected from this petrogenetic scenario.

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1. Introduction

It is well known that plate convergence zones are sites of intense magmatic activity associated with hydration and melting processes in the mantle wedges (Stern, 2002). Consequently, this phenomenon has been investigated from geophysical (Zhao, 2001; Fluck et al., 2003), numerical (Arcay et al., 2005; Gerya et al., 2006), experimental (Poli and Schmidt, 1995), and geochemical (Ito and Stern, 1986; Schiano et al., 2000) perspectives. Despite the progresses achieved in under-

standing mantle wedge processes, details about spatial distribution, P–T conditions and dynamics of magma production and transport above slabs still remain almost unknown. Of particular interest are mantle wedge convection and mixing processes (Gorczyk et al., 2006) involving partially molten rocks as evidenced by exhumed fragments of strongly layered wedge mantle possibly representing results of magmatic differentiation and mixing within a molten plume (Obata and Takazawa, 2004).

An important advance in understanding mantle dynamics and mantle–crust interaction in relation to subduction has been Gerya and Yuen’s (2003) identification of cold plumes by means of high-resolution

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numerical experiments in which rheological and thermal parameters are considered. Cold plumes, or cold diapirs are ascending low density structures formed at the Wadatti–Banihoff zones in response to gravitational instability of compositionally buoyant subducted crustal materials and hydrated regions of the mantle wedge (Gerya and Yuen, 2003). Rayleigh–Taylor instabilities at the top of subducting slabs lead to the nucleation of rising structures, 200–400°C cooler than the surrounding mantle, that may include fertile material from the subduction channel such as sediments and hydrated oceanic crust (Figs. 1 and 2).

The interaction of the cool diapir with the hot mantle wedge may produce magmatic rocks of expected varied compositions in agreement with the heterogeneity of the sources involved in the process. Strong chemical interactions between these magmas and the surrounding mantle wedge can also be envisaged. In the present paper we for the first time analyse these major magmatic consequences of cold plumes by means of laboratory experiments. The aim of our experimental study is twofold: on the one hand, we investigate the role that the subducted materials that are transported by the cold diapirs play in the production of silicic magmas; and on the other hand, we explore the interaction of the silicic melts produced within the cold diapirs with the mantle peridotite. We also discuss implications of mixed mantle wedge plumes for the generation of silicic magmatism associated with subduction at active continental margins.

2. Compositional zoning and thermal structure of evolved cold diapirs

Numerical experiments predict that cold diapirs should be formed in plate convergence settings including intraoceanic subduction zones (Fig. 1) (Gerya and Yuen, 2003; Gerya et al., 2004, 2006), active continental margins (Fig. 2) (Gerya and Stöckhert, 2006) and continental collision zones (Gerya et al., 2008-this volume). In all cases the Rayleigh–Taylor instability that evolves to a cold diapir is nucleated at the subduction plane (Figs. 1 and 2, left column). In case of mixed diapiric (plume) structures composed of both mantle and crustal rocks, materials derived from serpentinized subduction channel (Gerya et al., 2002) are accumulated at the core of the diapir, which tends to move upwards into the mantle wedge traversing hotter zones. The core of the diapir is 200–400°C colder than the surrounding mantle and it is heated from outside. During this thermal re-equilibration, temperatures of around 1000°C at pressures of 1.5–2.5GPa are reached (Figs. 1 and 2,

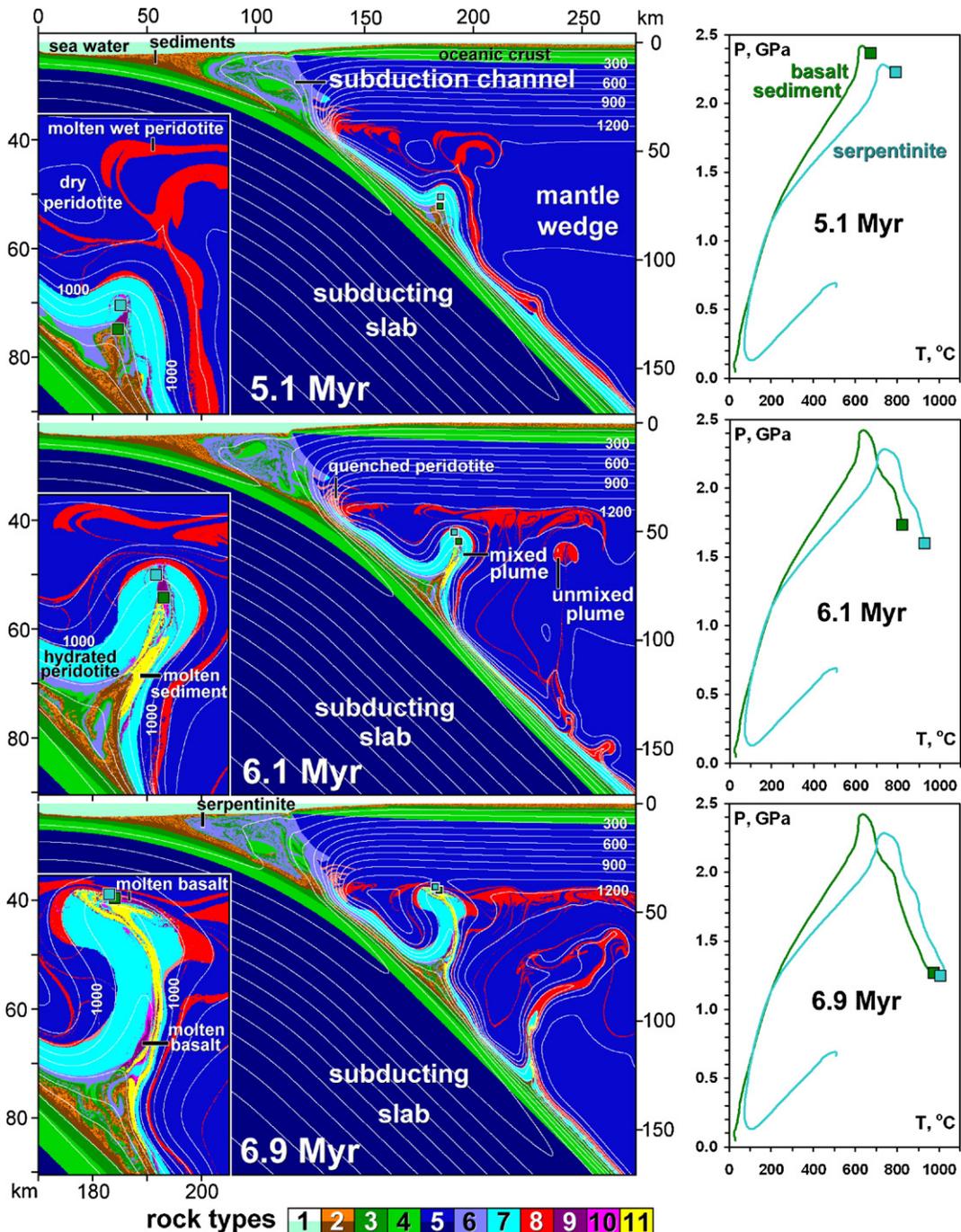
right column). At these conditions, and considering the low melting point of sediments and subducted oceanic crust, large melt fractions are expected to be produced.

In the case of intraoceanic subduction (Fig. 1), mélanges formed by sediments and oceanic crust often form only a small fraction of the whole diapir, which is essentially composed of hydrated peridotite resulting from partial dehydration of serpentinite. It is important to note that serpentinite is still stable at the core of the incipient diapir (Fig. 1, left column). This means that important amounts of water released in the course of serpentinite dehydration in deeper and colder levels may travel upward, being then consumed in the partial melting reactions produced at the silicic core of the diapir at shallower and hotter levels. These observations have to be taken into account in petrogenetic modelling and capsule designs for melting experiments. After 6.9million years of continued subduction, the cold diapir has overpassed the conditions required for the melting of all the involved source materials including the hydrated peridotite. Melts of a wide compositional range, from basalts and andesites to granites, are expected to be developed. The core of the diapir, where sediments and basaltic oceanic crust are located, may reach conditions of about 1000°C and 1.5GPa. At this evolved stage of the diapir, partially molten peridotite forms a carapace around the ascending body. Basaltic and andesitic melts will be formed at this place as the diapir is being heated from outside and the hydrous peridotite is being melted. As melting is produced in the presence of water, the composition of melts would approach to andesites and basaltic andesites, according to previous experimental data (e.g. Kushiro, 1990). The small amounts of sediments and oceanic crust that form the core of the diapir may produce large melt fractions at these high-temperature conditions. These silicic melts may ascend through the mantle wedge giving rise to adakite-type magmatism. They may also react with the surrounding peridotite mantle (Prouteau et al., 2001) leading to its hybridization and adding a crustal component that characterizes calc-alkaline magmas in island arcs (Plank and Langmuir, 1998). According to the composition of diapirs formed in intraoceanic settings, basalts and andesites tend to dominate over silicic magmas in agreement with the common magmatic associations of intraoceanic arcs.

The cases of active continental margins and continental collision zones can be very different from the point of view of the materials forming the cold diapirs (Gerya and Stöckhert, 2006; Gerya et al., 2008-this volume). In this case, large amounts of upper crust rocks can be dragged down by subduction erosion and

introduced deeply into the mantle (Fig. 2). The upper crust, dominantly formed by sedimentary rocks, is mixed with minor amounts of trench sediments, oceanic rocks and large amounts of serpentinites forming a classical Franciscan mélangé (Shreve and Cloos, 1986; Cloos and Shreve, 1988; Engi et al., 2001). Silicic rocks will dominate the diapir and, thus, the production of

silicic magmas will dominate over andesites and basalts, in contrast with the intraoceanic subduction. Also in this case, temperatures of the order of 1000°C at about 2.0 GPa are reached at the core of the diapir (Fig. 2, 20Myr). These temperatures exceed by more than 200°C the biotite breakdown for greywacke compositions and the water-absent melting of amphibolites (Castro et al.,



2000; López and Castro, 2001). Similar to the intraoceanic setting, serpentinite accompanies the diapir structure at the root zone (Fig. 2, 15–20Myr).

Consequently, the water released by serpentine dehydration will have an important part in melting reactions, thus favouring the production of large amounts of melt within the diapir. It is interesting to note that a carapace of hydrated mantle can be absent in this case and that partially molten sediments can be directly in contact with the anhydrous peridotite surrounding the ascending diapir. This particular situation is considered in our reaction experiments, which are aimed at evaluating the ability of the silicic melts produced in the diapir to survive a reaction with the peridotite mantle. The fact that portions of hydrated mantle are located at the core of the diapir together with partially molten oceanic metabasalts is also relevant. Molten sediments are preferentially located at the outer rims of the diapir. This zonation in source materials may have implications in the zonal distribution of magmatic rocks, in zoned calc-alkaline intrusions and in the formation of composite magma chambers above ascending diapirs.

We therefore propose that mixed diapirs (mixed cold plumes, Gerya et al., 2006) could possibly be a key in the understanding the magmatic associations of active continental margins and collisional orogens. The partially molten peridotite incorporates melt from the oceanic crust and sediments. This process is analysed to account for the geochemical and isotopic features of andesites and in general of all the terms of the calc-alkaline series. Cold diapirs formed in plate convergence settings can play an important role in magma generation because they transport hydrated fertile material to hot zones of the mantle wedge where extensive partial melting may occur. Therefore, the magmatic consequences of these large mixed structures have to be studied experimentally. These consequences are explored here by means of melting and reaction experi-

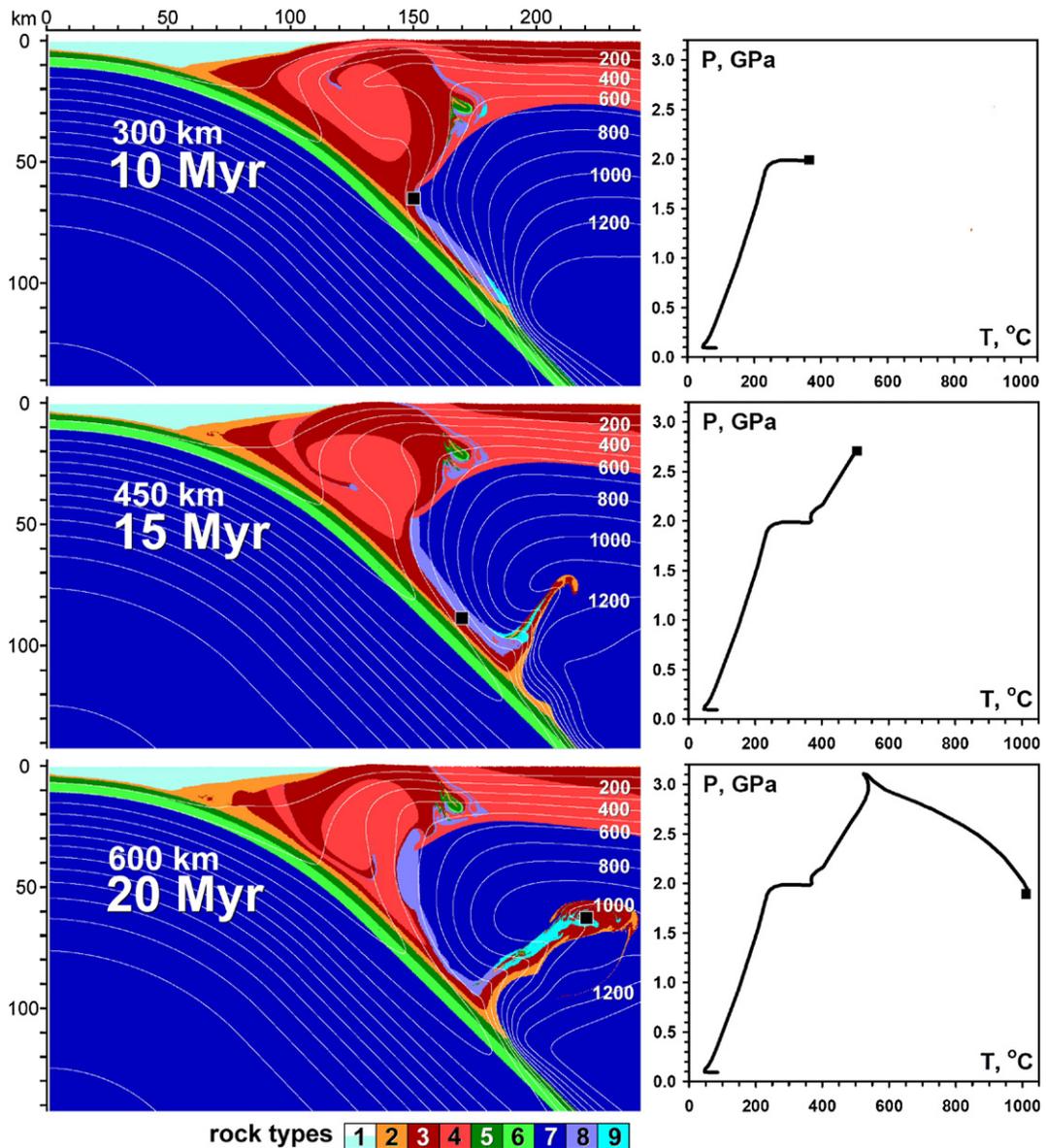
ments at pressures and temperatures predicted by the numerical models (cf. Figs. 1 and 2, right column).

3. Starting materials, experimental design and conditions

The three most important source materials involved in this study are (1) the suprasubduction mantle wedge, (2) the hydrated oceanic crust and (3) the continental materials, dominantly greywacke sediments. Hydrated oceanic crust and sediments may form composite mélanges as described by Engi et al. (2001) and Cloos and Shreve (1988). In this study we use natural materials whose petrological features have been known by previous experimental studies. Hydrated oceanic crust is modelled by a MORB-derived amphibolite from the Aracena metamorphic belt of the Variscan massif in South Spain. Melting phase relations for these amphibolites were studied by López and Castro (2001). The starting material for continental materials is chemically a metagreywacke from the Iberian massif, whose melting relations were previously studied in detail (Castro et al., 2000). Hydrated peridotite is a serpentinite from the Ronda massif (Spain) and anhydrous peridotite is the KLB1 lherzolite, classically used in many experimental studies (cf. Hirose, 1997). Whole compositions and mineral assemblages of these natural starting materials are given in the above-referred publications.

Melting experiments using a homogeneous mixture of both systems, to favour inter-diffusion and reaction, were addressed for the first time by Patiño-Douce (1995). At conditions of 1000°C, a homogeneous melt of granodiorite composition was formed in these experiments. Similar experiments using an Hb-rich gabbro and mica-rich gneiss were reported by Castro et al. (1999) with similar results. A third set of melting experiments using a similar composite source were reported by Castro (2001) with important results on the peculiar morphology of plagioclases formed in the course of melting of the

Fig. 1. Development of cold diapir (mixed cold plume) composed of subducted oceanic crust, sediments and hydrated mantle in intraoceanic subduction zone (left column) and P–T paths for rocks composing the diapir (right column) (Gerya and Yuen, 2003; Gerya et al., 2006). Colours correspond to different rock types: 1=air/sea water, 2=Sediments, 3=basaltic crust, 4=gabbroic crust, 5=unhydrated mantle, 6=serpentinized mantle, 7=hydrated mantle outside of serpentine stability field, 8=molten hydrated peridotite, 9=molten basaltic crust, 10=molten gabbroic crust, 11=molten sediments. Numbered white lines are isotherms in Celsius. The model of intraoceanic subduction is based on results of high-resolution 2-D coupled petrological–thermomechanical numerical experiments with 120 Myr old slab subducted at 8 cm/yr (see Gerya et al. (2006), Gerya et al. (2008-this volume) for explaining technical details of modelling). Positive buoyancy of relatively cold (cf. isotherms) both mixed (i.e. composed of crustal and mantle rocks) and unmixed (i.e. composed of mantle rock only) plumes is related to the lowered density of partially molten hydrated rocks compared to the hotter dry mantle wedge. Mélange of subducted crustal rocks and serpentinites composing the mixed plume is initially formed in the rheologically weak subduction channel resulted from the serpentinization of overriding mantle lithosphere by aqueous fluids released from dehydrating subducting slab (Gerya et al., 2002). Partial dehydration of serpentinite occurs inside the diapir due to the decomposition of serpentine with increasing temperature (cf. boundary between light blue serpentine-free (color code 7) and medium blue serpentinized (colour code 6) mantle). Solid rectangles in the left column correspond to subducted oceanic crust (green rectangle) and serpentinite (blue rectangle) for which P–T paths are shown in the right column. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



to the dominant rock type of calc-alkaline batholiths. These experiments and those shown in this paper, simulate a subducted mélange of the type described by [Engi et al. \(2001\)](#) in which the crustal component is represented by a basaltic oceanic crust, and the recycled component is a plagioclase-bearing, mica-rich greywacke. The use of a greywacke as the sedimentary component is also justified on geochemical grounds from trench sediments and arc lavas ([Plank and Langmuir, 1998](#)) that predict the implication of a subducted sedimentary component in the source of arc magmas.

In order to study the expected interactions between the melts developed from these composite mélanges and the peridotite mantle, we have designed composite capsules in which a layer containing a homogeneous mixture of the mélange materials, sediments and oceanic crust, is attached to a layer of mantle peridotite represented by a serpentinite or a dry lherzolite. It is expected that fluids released by serpentinite dehydration are not pure water, but they contain important amounts of dissolved silicates. In order to simulate the chemical transfer process between the molten diapir and the surrounding mantle we have opted to use a real serpentinite instead of adding water to the capsules. It is obvious that at 1000°C the dehydration reactions in serpentinites are overpassed in more than 400°C; however, the use of this material mimics the situation expected in cold diapirs where fluids released by dehydration of serpentinite at deeper and colder levels move upward being then consumed by melts formed at shallower and hotter levels of the diapir ([Figs. 1 and 2](#), left column). This choice is also justified by the possibility to observe reactions related to a more realistic situation concerning the composition of the high-pressure aqueous fluid phase dissolving silicate components of the dehydrating serpentinite and transporting them toward the melting zone. These experiments may be compared with those using the dry lherzolite KLB1.

Two different designs were developed with the serpentinite. In one of them, a layer of serpentinite powder was used. This layer is five times thicker than the mélange layer. We have opted for this design to simulate a reactive system in which the hydrated mantle component is infinite with respect to the silicic magma chamber represented by the cold diapirs (e.g. [Fig. 1](#), left column). In the other case, a rock fragment of serpentinite was used. Serpentinite powder is used to minimize kinetic problems in the chemical reactions and matter interchange. The results may be compared with those by using a rock fragment, in which mixing between the two powders is avoided.

Pressure and temperature conditions have been chosen according to the results of numerical simula-

tions. A reference temperature of 1000°C at pressures of 1.5, 2.0 and 2.5 GPa were the conditions used for this preliminary experimental study. These conditions are expected at the core of evolved mixed diapirs ([Figs. 1 and 2](#)). Experiments were carried out using end-loaded piston-cylinder apparatus at the University of Huelva, Spain. Starting materials were disposed in 3mm diameter gold capsules and embedded into NaCl containers. Mineral and glass (quenched melt) compositions were determined by WDS with a JEOL JXA-8200 SuperProbe at the University of Huelva. A combination of natural and synthetic standards was used for calibration and ZAF correction procedures.

4. Experimental results

[Fig. 3](#) shows the compositional images (back scattered electron images) of the experimental runs. Conditions and compositions of mineral phases and melts (quenched glass) are displayed in [Table 1](#). Run 1 was designed to evaluate the effects of serpentinite dehydration in promoting melting in the crustal components of the mélange (sediments + oceanic crust). It was carried out at 1000 °C and 2.0 GPa. A layer of finely crushed serpentinite was attached to a layer composed of a mixture of greywacke and amphibolite, following the zoning pattern of mixed diapirs with a carapace of dehydrating serpentinite ([Fig. 1](#), left column). Short and long duration experiments were carried out ([Table 1](#)). In both cases serpentinite was dehydrated and transformed into an anhydrous assemblage dominated by olivine and pyroxene. In the short duration experiment (Run 1a) a reaction band rich in orthopyroxene and amphibole was developed ([Fig. 3a, b](#)). This reaction band is similar to the amphibole-rich ultramafic complexes associated to the more basic facies of calc-alkaline batholiths. As denoted in previous experiments using the similar crustal components of the mélange at 1000 °C and 1.0 GPa ([Castro et al., 1999](#)), the composition of melt (ca. 50 vol.%) in equilibrium with orthopyroxene and plagioclase is granodioritic, with $\text{Na}_2\text{O} < 4.0$ wt.%. The absence of plagioclase at higher pressure makes the melt richer in Na. In a closed system the maximum Na content in the melt for the crustal mélange used in our experiments will be about 6 wt.% Na_2O for a melt fraction of 0.5 and about 2.4 wt.% Na_2O for a melt fraction of 0.8, according to mass balance estimations. However, the measured Na_2O contents are higher than expected by mass balance in a closed system. Na_2O is higher than 8 wt.% for melt fractions of more than 0.8 in our experimental runs simulating an open system in which water released by serpentine dehydration is

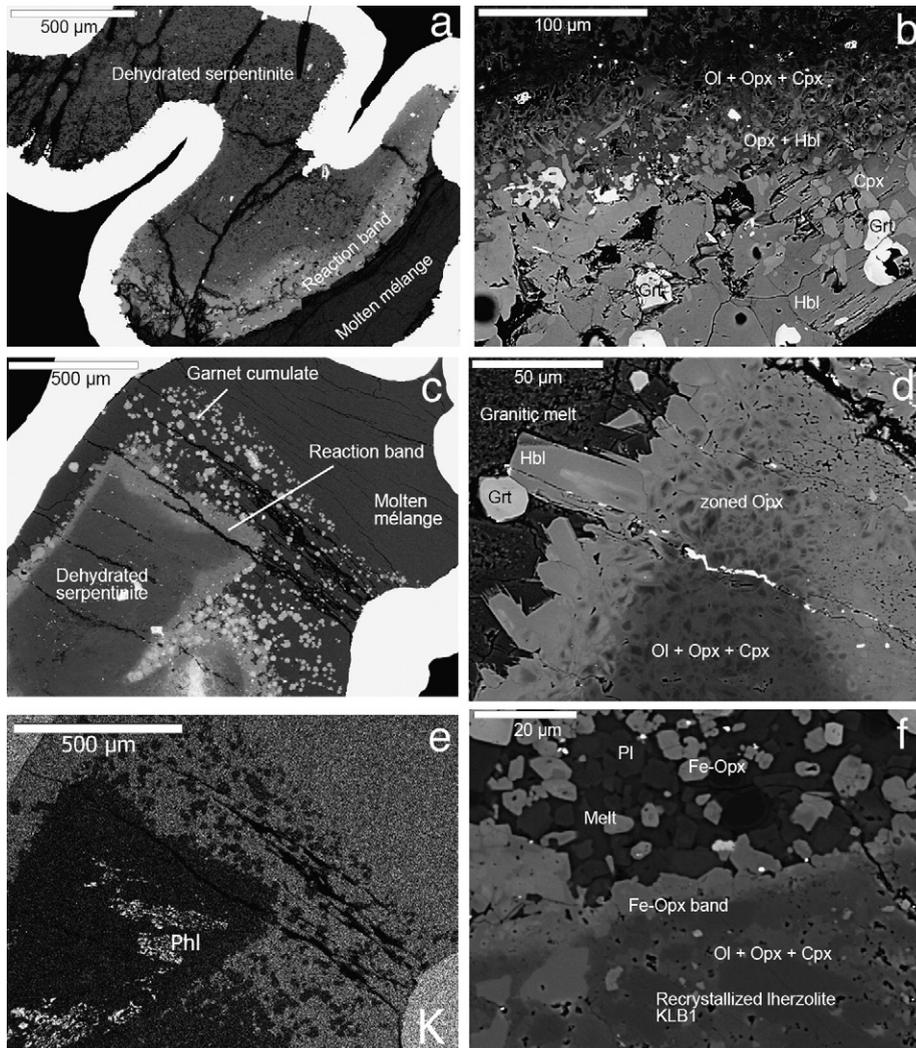


Fig. 3. Representative backscattered electron images (Z contrast) of experimental runs simulating the reaction between silicic magmas developed by melting of a subducted *mélange* and the mantle wedge. a: Reaction band rich in Hbl, Opx and Grt developed at the contact between a serpentinite layer and an *mélange* at 1000 °C and 2.0 GPa. b: is a detail of this band. c: Reaction band between the same material at 1000 °C and 2.5 GPa pressure. In this case, a rock fragment of the serpentinite is used instead of powder as in the former run. d: Detail of this reaction band showing the close similarity with the former case (a,b). Serpentinite is transformed into an olivine (Ol)+clinopyroxene (Cpx) aggregate, and all the water from serpentine dehydration is dissolved in the melt of the *mélange* zone which has a typical adakitic composition ($\text{SiO}_2 > 62 \text{ wt.}\%$, $\text{Na}_2\text{O} > 6 \text{ wt.}\%$). e: is an X-ray map for K showing the growing of phlogopite inside the dehydrated serpentinite at 2.5 GPa as resulting by K-rich fluid migrating from the molten *mélange*. f: Shows the thin reaction band developed in an experiment with the dry peridotite KLB1 at 1000 °C and 2.0 GPa. The absence of a fluid phase makes ionic diffusion slower and a thin Opx band is formed. In this case the composition of the melt in the *mélange* layer is not modified by ionic interchange with the peridotite, preserving a granodioritic composition (K-rich), in equilibrium with Pl and Opx. Mineral abbreviations are according to Kretz (1983).

transferred to the crustal part of the *mélange* promoting extensive melting. The only explanation for Na enrichment in the *mélange* melt is the loss of other components namely Fe, Mg and K that are incorporated to the surrounding dehydrating serpentinite, which is then converted to a phlogopite peridotite.

Run 2 was carried out at 1000 °C and 2.5 GPa using a serpentinite fragment surrounded by a finely crushed

mixture of greywacke and amphibolite. A reaction band (Fig. 3c, d) with abundant amphibole and orthopyroxene was again formed. Garnet originated in the melt of the crustal *mélange* surrounding the deserpentinized fragment. All the water expelled by serpentine dehydration was dissolved by the melt surrounding the ultramafic body. Interestingly, this acted as a trap for K as evidenced by the development of large intergranular phlogopite

Table 1

Summarised microprobe analyses of melts (quenched glass) and minerals in experimental runs at 2.0 and 2.5 GPa and 1000 °C

	<i>n</i>	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Total	ASI	Mg#
<i>Run 1(a): Serpentinite powder (layer 1) + crustal mélange (layer 2). T=1000 °C; P=2.0 GPa; Duration=72 h</i>														
Glass	6	61.23	0.80	18.74	0.00	4.07	1.67	0.12	3.67	8.19	1.52	100.00	1.50	0.42
		0.54	0.09	0.71		0.74	0.32	0.01	0.49	2.8	0.04			
Amphibole	7	45.61	1.71	11.12	0.20	9.65	15.04	0.15	9.72	3.18	0.65	97.01		0.73
		1.15	0.42	0.40	0.25	0.77	1.08	0.17	0.42	0.18	0.09	1.46		0.03
Clinopyroxene	2	52.53	0.49	4.08	0.02	7.04	14.24	0.00	20.46	1.23	0.00	100.07		0.78
		0.23	0.07	0.73	0.01	0.10	0.04	0.00	0.35	0.27	0.00	0.69		0.00
Garnet	4	39.98	0.40	21.10	0.15	18.62	11.74	0.80	6.72	0.11	0.00	99.61		0.53
		0.74	0.65	0.73	0.12	1.25	1.12	0.25	1.06	0.22	0.00	2.06		0.04
Orthopyroxene (cores)	2	55.82	0.00	3.71	0.66	9.80	29.84	0.00	0.81	0.00	0.00	100.62		0.84
		0.23	0.00	0.40	0.77	3.59	1.70	0.00	0.32	0.00	0.00	1.25		0.06
Orthopyroxene (rims)	5	54.61	0.18	1.76	0.12	15.48	26.20	0.37	1.05	0.05	0.00	99.82		0.75
		0.62	0.19	0.60	0.26	1.61	0.82	0.09	0.45	0.11	0.00	0.79		0.02
Olivine	1	41.80				11.21	46.99					100.00		0.88
<i>Run 2: Serpentinite rock + crustal mélange (powder). T=1000 °C; P=2.5 GPa; Duration=146 h</i>														
Glass	20	71.26	0.88	17.61		1.49	0.72	0.04	2.99	2.44	2.56	100.00	4.45	0.46
		1.40	0.13	0.34		0.39	0.21	0.04	0.66	0.26	0.26			
Orthopyroxene	15	55.82	0.00	2.24		9.46	30.37		0.79	0.00	0.00	98.68		0.85
		1.16	0.00	1.08		4.25	3.14		0.32	0.00	0.00	1.15		0.07
Clinopyroxene	12	52.99	0.32	4.14		6.80	14.34		18.88	1.56		99.03		0.79
		0.88	0.30	0.99		1.32	0.69		1.05	0.32		0.88		0.040
Olivine	2	41.92				6.31	50.05					98.28		0.93
		0.44				0.18	0.48					0.74		0.00
Garnet	6	40.39	1.24	20.67		16.65	12.21	0.33	7.57			98.80		0.56
		1.16	0.99	1.06		1.41	2.04	0.47	1.50			0.92		0.06
Phlogopite	1	42.76	1.16	15.24		2.08	26.89				8.86	97.00		0.96
<i>Run 3: Peridotite KLB 1 (layer 1) + crustal mélange (layer 2). T=1000 °C; P=2.0 GPa; Duration=145 h</i>														
Glass (Mélange zone)	5	74.16	0.44	15.07		1.14	0.49		2.16	2.47	4.07	100	3.77	0.43
		2.05	0.08	1.13		0.45	0.56		0.84	0.89	0.36			

Major oxides were determined by WDS with the EPMA. Wt.% oxides are average values. *n*. number of analyses. Numbers in cursives are standard deviations. Glass analyses recast to sum 100. ASI (Alumina saturation index)=molar Al₂O₃/Na₂O+K₂O+CaO. Mg#=molar MgO/MgO+FeO. Crustal mélange is a homogeneous mixture of finely crushed greywacke and MORB-derived amphibolite in the proportion 1:1. Mineral assemblages and chemical compositions are given in López and Castro (2001) for the amphibolite, and in Castro et al. (2000) for the greywacke. Serpentinite is coming from the Ronda massif in Spain. Serpentine is in a proportion of more than 80 vol.% with minor relics of orthopyroxene and olivine. The composition of peridotite KLB-1 is given in Hirose (1997).

crystals (Fig. 3e). Consequently, the resulting melt is rich in Na and approaches a trondhjemitic (adakitic) composition very similar to the former run.

Another similar experiment in two layers (Run 3, 1000 °C and 2.0 GPa) was developed by using the KLB-1 anhydrous peridotite instead of the serpentinite, in order to check the role of water in the process. A reaction band rich in orthopyroxene (Fig. 3f) is always formed independently of the duration of the experiment. It is interesting to note the absence of amphibole in the reaction band and also the absence of intergranular phlogopite within the peridotite. Thus, the composition of melt in the crustal layer is typically granodioritic as it retains all the K supplied mainly by micas (Table 1). These results strongly contrast with those using serpentinite, in which all the K migrated to the dehydrating

serpentinite to form phlogopite, producing a Na-rich, hydrous melt that survives in equilibrium with forsteritic olivine.

5. Discussion

5.1. Melt compositions, fertility and stability

The most prominent result is that the composition of melts developed from the composite mélange attached to the mantle layer is very rich in silica and approaches the composition of typical tonalites and granodiorites that form the large calc-alkaline cordilleran batholiths. In all the experiments at 1000 °C, the melt fractions are very high in the order of 80 vol.%. The effects of reaction with the surrounding mantle are: (1) the production of a

pyroxene-rich reaction band that prevents further chemical interaction and isolates the inner silicic core of the diapir from the surrounding mantle, making possible that large volumes of silicic melt are mechanically transported through the mantle wedge toward the bottom of the overriding lithospheric plate with the possibility of subsequent emplacement into the crust through magmatic channels (Gerya and Burg, 2007); and (2) the cation and water interchange between the silicic magma and the mantle. This interchange is dominated by the net flux of water to the *mélange* favouring the formation of large melt fractions. Other cations, such as K and Si, are transferred to the peridotite leading to the formation of phlogopite. The absence of water in the experiments with the dry peridotite implies the absence of amphibole in the reaction rim and the lack of relevant cation interchange between both systems. Consequently, the *mélange* system may behave as a closed system with the implication of a less fertility (ca. 50 vol.%), in contrast to the former cases. In both cases the formation of the reaction band prevents further reaction, allowing silicic melts to survive transport through the mantle wedge.

According to the results of run 1, aqueous fluids released by serpentinite dehydration in cold diapirs may play an important role in mantle metasomatism, giving rise to large volumes of silicic melts at the cores of cold diapirs emerging from the subduction channel. These fluids transport Si, K, Fe, Mg to the peridotite, and also the more mobile elements as the light rare earths (LREE) and diagnostic large-ion lithophile (LIL) elements, namely Rb, Sr, Ba, which are concentrated in intermediate, dioritic magmas produced by the melting of metasomatized mantle sources, as exemplified by the appinite–sanukitoid association (Stern et al., 1989) that accompanies calc-alkaline batholiths since the Archaean times. This open system process can also account for the observed depletion in incompatible elements of adakitic magmas produced by partial melting of subducted slab (Defant and Drummond, 1990).

The fact that open system processes in which water and alkalis are interchanged between the crustal components of the diapir and the dehydrating surrounding mantle (serpentinites) makes the process of magma generation more complex than it was believed, and the application of classical closed-system experiments may have little or no sense in these complex processes. For instance, the crustal component of the *mélange* is completely transformed into a Na-rich (adakitic) melt at 1000 °C departing from a whole composition close to an andesite (sediments + oceanic crust). In consequence, a K-rich, silicic melt (granodiorite) retaining geochemical crustal signatures (rich in LREE and LIL elements)

imposed by sediments, may survive within the mantle if protected of extensive reaction with the hydrated mantle. Granodiorite magmas generated by this mechanism will display depletion in HREE due to garnet fractionation. The presence of plagioclase feldspar in the solid residues will produce the negative Eu anomaly that characterizes granodiorite rocks that form an important part of calc-alkaline batholiths. It is expected that in the course of diapir ascent through the mantle wedge, important *mechanical and chemical* interaction will occur between different magmatic and solid zones of the diapir and between these and the surrounding peridotite mantle. Consequently, Mg-rich pyroxene and olivine crystals of the surrounding peridotite may be dragged by the ascending granodioritic magma and transformed into new orthopyroxene. It may be inferred that these crystals can accompany the granodiorite melt forming a melt-crystal (magma) system with the consequent increase in the Mg content.

5.2. Implications: from cold plumes to nested diapirs and zoned batholiths

According to Paterson and Vernon, (1995), concentrically zoned plutons with sharp contacts between pulses are interpreted as nested diapirs. As follows from our study this is a plausible scenario for the crustal evolution from a cold diapir in which every magma type is related to a distinct solid source. At the early stages gabbroic magma produced in the hydrated fertile mantle (c.f. red partially molten hydrated peridotite in Fig. 1) may be emplaced at the bottom of the weak ductile continental crust by underplating (e.g. Gerya and Burg, 2007). The next pulse of magma can be the granite melt forming the great part (cf. Fig. 2, 20 Myr) of the mixed diapir in the case of active continental margin. This granite pulse will find a rheological barrier formed by the previously emplaced gabbroic magma. The result will be the formation of a nested diapir and the intrusion of one magma into the other. The result may be comparable to the common zoning pattern observed in calc-alkaline batholiths, in which mafic rocks are disposed at the rims of the plutons, which are older, at least in the emplacement sequence, than the more silicic magmas that occupy the core of composite intrusions. The reason for this zoning remained unexplained and it has been the subject of many conjectures (Paterson and Vernon, 1995). It has been argued that the mafic magmas may be transported faster due to their low viscosity in comparison with the supposedly more viscous and less dense granitic magmas. These assumptions imply that mafic and felsic magmas are using the same ascent conduits. Considering the fact

that both magmas, mafic and felsic, come from different source regions—being the mafic magma generated in the mantle and the silicic in the crust—, it is surprising that both use the same conduits and form concentrically zoned plutons. In this situation it will be expected to find individual plutons composed of a single magma pulse. However, there are scarce or null intrusions of purely mafic rocks associated to pure silicic plutons. On the contrary, they are always associated in zoned plutons with the mafic rocks disposed at the margins and the silicic rocks at the core. The mafic layer acts as a screen that prevents the silicic magma from ascending further upwards. The result is some kind of “underplating” of the silicic magma under a layer of mafic magma.

Mafic magma is generated in the mantle at the hydrated carapace surrounding the felsic diapir. These are segregated and ascent faster than the silicic magma. Both magmas are ascending through the same conduits as both are coming from a common place in the mantle wedge. Once in the crust the mafic magma may be underplated at the mantle-lower crust interface (Gerya and Burg, 2007) because this is a major rheological barrier. At this place, the composite magma chamber is formed; the felsic magma is arrested also at the rheological barrier and intrudes into the mafic magmas as a nested diapir. Gravitational instabilities within this reversely stratified magma chamber will produce the observed features related to the formation of enclaves and top-to-down intrusions (Castro et al., in press). Once this magma chamber is configured, further emplacement at the upper crust may be produced by the action of extensional tectonics allowing the formation of composed batholiths. Thus, the formation of the batholiths may be the result of a three-stage process: 1) Formation of a reversed composite source at the mantle in the form of a cold diapir. 2) Intrusion at the bottom of the lower crust forming a reversely stratified, composite magma chamber with gravitational instabilities. 3) Final emplacement at the upper crust of composite batholiths transporting partially the original zoned distribution of rocks and other heterogeneities as enclaves and synplutonic relations between basic and felsic magmas. It is possible in some cases to observe the process arrested at the second stage in a composite batholith. This is possibly the case of the Valle Fértil complex in the Famatinian belt of western Argentina, where the sequence of processes and the original relations are well preserved.

6. Conclusions

Thermal conditions predicted by numerical modeling at the core of cold diapirs ascending through the mantle wedge are sufficient to produce large proportions

of silicic melts. Melt fractions on the order of 50 vol. % are produced in the case of a dry mantle envelope, and fractions of the order of 80 vol.% in the case of a hydrated mantle. Silicic melts of granodiorite and tonalite compositions may develop reaction bands, with dominant Opx and amphibole, in contact with the mantle peridotite, preventing further reaction and allowing silicic melts to survive diapiric transport through the mantle wedge. Magmatic pulses coming from distinct parts of the diapir and its mantle envelope may reach the continental crust at different times, forming reversely stratified, composite magma chambers that fairly account for the observed zoning patterns of zoned calc-alkaline, cordilleran batholiths.

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