Arc magmas sourced from mélange diapirs in subduction zones

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Abstract

At subduction zones, crustal material is recycled back into the mantle. A certain proportion, however, is returned to the overriding plate via magmatism. The magmas show a characteristic range of compositions that have been explained by three-component mixing in their source regions: hydrous fluids derived from subducted altered oceanic crust and components derived from the thin sedimentary veneer are added to the depleted peridotite in the mantle beneath the volcanoes. However, currently no uniformly accepted model exists for the physical mechanism that mixes the three components and transports them from the slab to the magma source.

Here we present an integrated physico-chemical model of subduction zones that emerges from a review of the combined findings of petrology, modelling, geophysics, and geochemistry: Intensely mixed metamorphic rock formations, so-called mélanges, form along the slab-mantle interface and comprise the characteristic trace-element patterns of subduction-zone magmatic rocks. We consider mélange formation the physical mixing process that is responsible for the geochemical three-component pattern of the magmas. Blobs of low-density mélange material, so-called diapirs, rise buoyantly from the surface of the subducting slab and provide a means of transport for well-mixed materials into the mantle beneath the volcanoes, where they produce melt. Our model provides a consistent framework for the interpretation of geophysical, petrological and geochemical data of subduction zones.

Geochemical studies of volcanic rocks erupted at convergent plate margins have identified element and isotopic ratios that seem to require material present in their source that is absent in volcanic rocks from other settings, such as mid-ocean ridge basalts [1]. This subduction zone geochemical fingerprint has led to the establishment of three-component mixing models to explain the composition of magmatic rocks produced at continental and island arcs [2, 3]. Their trace-element characteristics are believed to have originated from two distinct sources added to the depleted mantle source: hydrous fluids derived from subducted altered ocean crust and a component derived from the thin sedimentary veneer of the slab. However, the details of the physical process that allows the mixing of these components within the "subduction factory" are unknown.

Current models propose that a hydrous component, enriched in incompatible trace elements, is released from the subducting slab and migrates into the overlying mantle wedge. The wedge is at much higher temperatures than the slab due to the 'corner flow' of the asthenospheric mantle, driven by viscous coupling of the mantle to the subducting slab [4]. Mantle-wedge peridotite partial melting is thought to be promoted by the influx of slab-derived fluids [5]. Yet, no uniformly accepted model exists for the actual physical mechanism that transports the components from the slab to the source of arc magmas in the hot corner of the mantle wedge.

We present a physico-chemical model for subduction zones based on field observations, numerical models and analogue experiments. We suggest that three-component geochemical mixing takes place at the slab-mantle interface, that this mixed material is transported

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into the mantle wedge by diapirs and carried directly to the source region for the volcanic arc magmas, providing a source for the surface volcanism.

Mélange has it all

Extensive fieldwork in areas displaying exhumed high-pressure metamorphic rocks has led to the establishment of models on the subduction and exhumation of oceanic crust [6, 7]. One type of mechanism includes a narrow channel overlying the subducting slab in which slab-derived rocks are mixed with the mantle-derived ultramafic rocks and are transported from great depths towards the surface [6, 7, 8, 9]. Computer-aided, high-resolution numerical modelling has provided new insight into the dynamics of these subduction channels and of the fore-arc mantle overlying the subducting slab [9]. These models not only provide an explanation for fast exhumation of high-*P* rocks from great depth [7, 9], but also provide a formation mechanism for high-*P* mélange zones as the products of mixing of hydrated mantle rocks with fragments derived from the subducting slab.

Fieldwork in high-*P* mélange zones yielded direct observations of various stages of processes that control mixing of the three dominant components (altered oceanic crust, sediment, mantle wedge). These areas are globally distributed [7], and many of these localities show centimetre to kilometre-sized blocks of eclogite, metasediment and peridotite/serpentinite embedded in a schistose matrix of mafic to ultramafic composition [7, 8, 10, 11, 12]. It is important to note that not all localities were interpreted to represent exhumed sections of the slab-mantle interface or of the metasomatized mantle wedge in fossil oceanic subduction zones. Nevertheless, these localities can be taken as kilometre-scale natural laboratories that allow us to investigate the mechanisms and products of mixing of mafic, sedimentary and ultramafic components at a variety of relevant *P-T* conditions. Pressures recorded in these rocks typically range from 1.0 to 2.5 GPa [7], and field studies have revealed three different mechanisms of mixing that lead to the formation of hybrid rock types [12, 13]: (i) Mechanical mixing, (ii) advective mixing (fluid and melt metasomatism), and (iii) diffusion (see supplement for discussion).

The juxtaposition of crustal rocks of the subducting slab and ultramafic rocks of the mantle wedge with their contrasting chemical compositions leads to the formation of entirely new bulk compositions with no sedimentary or magmatic equivalents on the surface [10, 13]. The mineral assemblages of these newly formed rocks differ from assemblages of both the ultramafic mantle and metamorphosed hydrated basalts and sediments of the slab. The importance of such hybrid rock types is twofold [10, 13, 14, 15]: (i) the new mineralogy affects the redistribution of major and minor elements, creating mixed compositions composed of the three initial components. (ii) the newly formed assemblages have significant potential for storing and releasing H_2O and other volatiles. They are characterised by sets of devolatilisation reactions distinct from each of the initial bulk compositions. Hence, the juxtaposition of disparate rock types strongly impacts the trace-element and volatile fluxes of subduction systems [10, 13, 14, 15].

Composition of mélange rocks

Field studies have identified the dominant newly formed lithologies in a number of exhumed mélange zones. One recurring rock type that is commonly produced where metabasites were juxtaposed with serpentinites is jadeitite, a rock that consists dominantly (or entirely) of jadeite [16, 17, 18]. Jadeitites are typically massive, isotropic rocks with high mechanical strength that have major-element composition high in Na, Al, and Si, and low in Mg, Fe and Ca. They are resistant to deformation and stable over a wide range of *P-T* conditions. Phengite is a very common phase in jadeitites and an important host of large-ion lithophile elements [16, 19] (LILE; e.g. K, Ba, Rb), elements that are characteristically enriched in subduction-related volcanic rocks (Fig. 1). In addition, accessory minerals, such as zircon, rutile and allanite, are abundant in jadeitites [16, 17]. These minerals host large concentrations of trace elements that are employed in geochemical studies, such as rare earth elements (REE), Th, U, and high-field strength elements (HFSE; e.g. Zr, Hf, Nb, Ta). The spatial extent of pure jadeitites is limited in most places and they commonly show a transition into similar, but more Ca-Mg-Fe-rich rock types that contain Ca-amphibole, omphacite and chlorite in various proportions [16, 17].

The second key rock type that has been observed to extend to thicknesses from tens to hundereds of metres (or even kilometres) in a number of high-*P* mélange localities is chlorite schist [10, 13, 15]. This rock type is almost monomineralic chlorite along with minor talc and Ca-amphibole. Chlorite schist commonly forms where metabasic rocks are metasomatised and mechanically mixed with serpentinite. It is distinct from chlorite-bearing greenschist-facies meta-

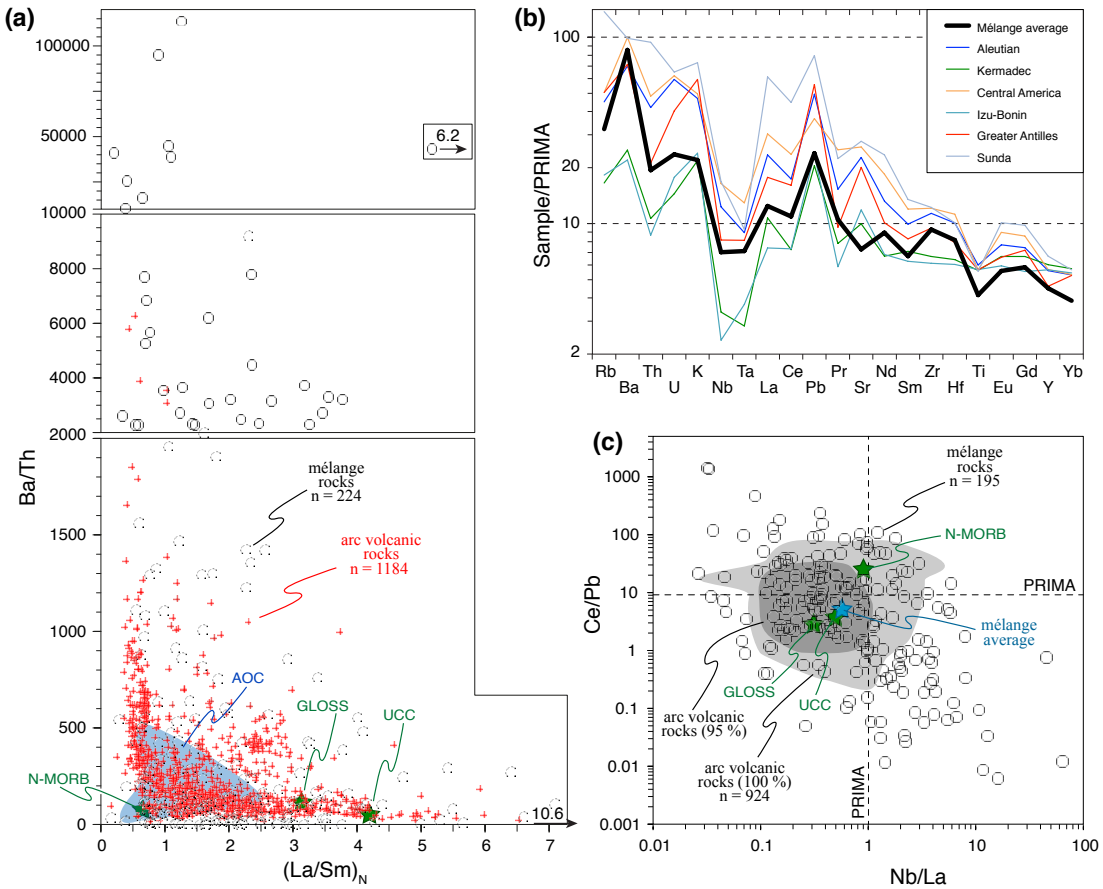

Fig. 1. **Trace element compositions of mélange rocks in comparison to subduction zone volcanic rocks.** (a) Plot of $(\mathrm{La}/\mathrm{Sm})_\mathrm{N}$ versus Ba/Th. (b) Primitive-mantle (PRIMA [47]) normalised multi-element plot arranged according to increasing element compatibility depicting the distinctive anomalies in Pb, Nb-Ta and Ti in both the average mélange composition and average compositions of volcanic rocks from different subduction zones. (c) Plot depicting the magnitude of the Pb and Nb anomalies with respect to the light REE. Also shown are arc volcanic rocks, altered oceanic crust (GEOROC, MPI Mainz), normal MORB [48], average upper continental crust (UCC [48]), and global subducting sediment (GLOSS [49]).

morphosed basalt. Chlorite schist has a low density ($\sim 2800\,\mathrm{kg/m^3}$), very high H_2O contents ($8-12\,\mathrm{wt\%}$), typically a strong foliation, and low mechanical strength, but a significantly higher *P-T* stability than serpentine [10, 20, 21, 22]. Chlorite in mantle rocks or monomineralic chlorite schist (or chlorite-talc schist) is stable to pressures in excess of 4.5 GPa and temperatures of up to 900 °C [10, 20, 21, 22]. Chlorite is not an important carrier of trace elements (except for Li), but chlorite schists formed in mélange zones in many cases contain high concentrations of trace elements hosted in a variety of accessory minerals [13]. For example, monazite-bearing chlorite schist from Syros (Greece) has a major-element composition similar to ultramafic rocks, but carries trace-element abundances intermediate between altered oceanic basalts and sediments [13]. Accessory mineral-rich chlorite schist is a key component of mélanges that has been recognised as spatially extensive in a number of exhumed high-*P* mélange zones around the world (see Supplement).

Petrologic and geochemical studies in high-*P* terrains have mostly focused on meta-igneous and metasedimentary rocks. Less attention has been given to the relatively uniform chlorite-rich matrix of mélange zones (see Supplement). In cases where mélange matrix was sampled, there is still a bias towards samples that are exceptional for their grain sizes, their mineralogical composition or their texture. Hence, the set of available whole-rock geochemical data on mélange rocks includes a wide range of compositions that are not necessarily representative for the bulk composition of high-*P* mélanges. However, the majority of mélange compositions in the available data set and their average composition can still be compared to those of average basalts,

sediments, continental crust and subduction-zone volcanic rocks (Fig. 1).

Plots such as $(La/Sm)_N$ versus Ba/Th (Fig. 1a) are commonly invoked to illustrate the contribution of a crustal component to the mantle source region of arc volcanic rocks in three-component mixing [3]. On Fig. 1, data for arc volcanic rocks concentrate along a curved trend line roughly asymptotic to both axes. The common explanation is that the trend to high $(La/Sm)_N$ at low Ba/Th values results from addition of sediments to the magma source, while the trend to high Ba/Th values at low $(La/Sm)_N$ values is attributed to dehydration of AOC. The trace-element abundances of most mélange rocks follow the same trend (Fig. 1a), demonstrating that the geochemical composition of these rocks reflect their formation by mixing. Yet more importantly, it strongly suggests that the three-component mixing observed in arc magmas takes in fact place in mélange zones at the slab-mantle interface.

The trace-element pattern of average mélange rocks is similar to those of subduction-related volcanic rocks, with their distinctive relative enrichment in Pb and their depletion in Nb, Ta and Ti (Fig. 1b). Enrichment and depletion in Pb and Nb are best expressed relative to the light REE. The published compositions of mélange rocks cover a large range in Nb/La and Ce/Pb ratios, but the majority of samples overlap with the field defined by arc volcanic rocks. The average mélange composition is intermediate between average sediments and MORB in terms of its trace elements (Fig. 1c), while its major element composition is ultramafic (low silica, high MgO; see Supplement). The compilation in Fig. 1 demonstrates that mélange rocks provide the range of geochemical characteristics inferred for the source of arc magma. Hence, the trace element patterns characteristic to arc magmas are already transiently sequestered in hybrid mélange rocks at the slab-mantle interface.

Spatial extent of mélanges

The slab-mantle interface cannot exist as a sharp, discrete plane. The strong geochemical gradients between crustal and mantle rocks, and shearing in combination with intense metasomatism must invariably trigger the formation of a transitional layer of mélange rocks at that interface. The question is what the spatial extent of the mélange zones is and what their impact is on the volatile and trace-element fluxes. Field studies in exhumed high-*P* mélange zones have revealed thicknesses of chlorite ($\pm$talc) schists of several hundreds of metres or even kilometres in mélange zones [10, 23].

Geophysical evidence shows the existence of low-seismic velocity material at the surface of subducting slabs in a number of modern subduction zones that persists to depths of 150 km [24, 25]. These layers form waveguides for seismic signals, which allows for relatively precise estimate of their thicknesses, ranging from 1 to 10 km [25]. These low-velocity zones have been tentatively interpreted as hydrated oceanic crust; yet, they may well represent mélange material composed dominantly of chlorite $\pm$talc travelling on top of the subducting slab [26]. This would also explain the strong velocity contrast to its upper and lower boundaries [25], because it would be sandwiched between the mantle-wedge harzburgite and slab-surface eclogite (see supplementary material for geophysical characteristics of mélange). Samples recovered from the Mariana forearc serpentinite seamounts show a strong dominance of chlorite-talc schists that were formed at the slab-mantle interface in an active subduction system [27]. They strongly resemble mélange rocks found in fossil subduction complexes and are strong evidence for mélange formation in modern oceanic subduction zones [27].

Chlorite schist layers of hundreds of meters at the slab-mantle interface would dominate the H_2O budget of the entire subduction system that developed such zones. The H_2O budget of worldwide subducting slabs beyond a depth of ~ 15 km is estimated to range from 0.4 to $4.8 \times 10^5\,kg/m^2$ in a cross-sectional volume of subducting slab including sediments, fresh and altered oceanic crust, and various portions of hydrated mantle [28, 29]. Chlorite schist layers of only 150 to 1500 m thickness would contain enough water to equal the entire estimated range of water in the slab. These estimates also place a maximum limit on the thickness of pure chlorite schist at the slab-mantle interface at steady-state subduction conditions.

Transport via mantle-wedge diapirs

Diapirs and plumes in the mantle wedge provide a mechanism for transporting buoyant mélange rocks from the slab-mantle interface to the source region of arc magmas. They have long been suggested as a mode of transport and have been both predicted from numerical modelling [30, 31, 32, 33, 34] and produced in analogue experiments [35, 36]. Diapirs are proposed to form relatively close to the slab surface and rise upwards into the hot corner of the mantle wedge, where more extensive melting and melt separation can take place [20, 31, 35].

Numerical models demonstrate how fragments from

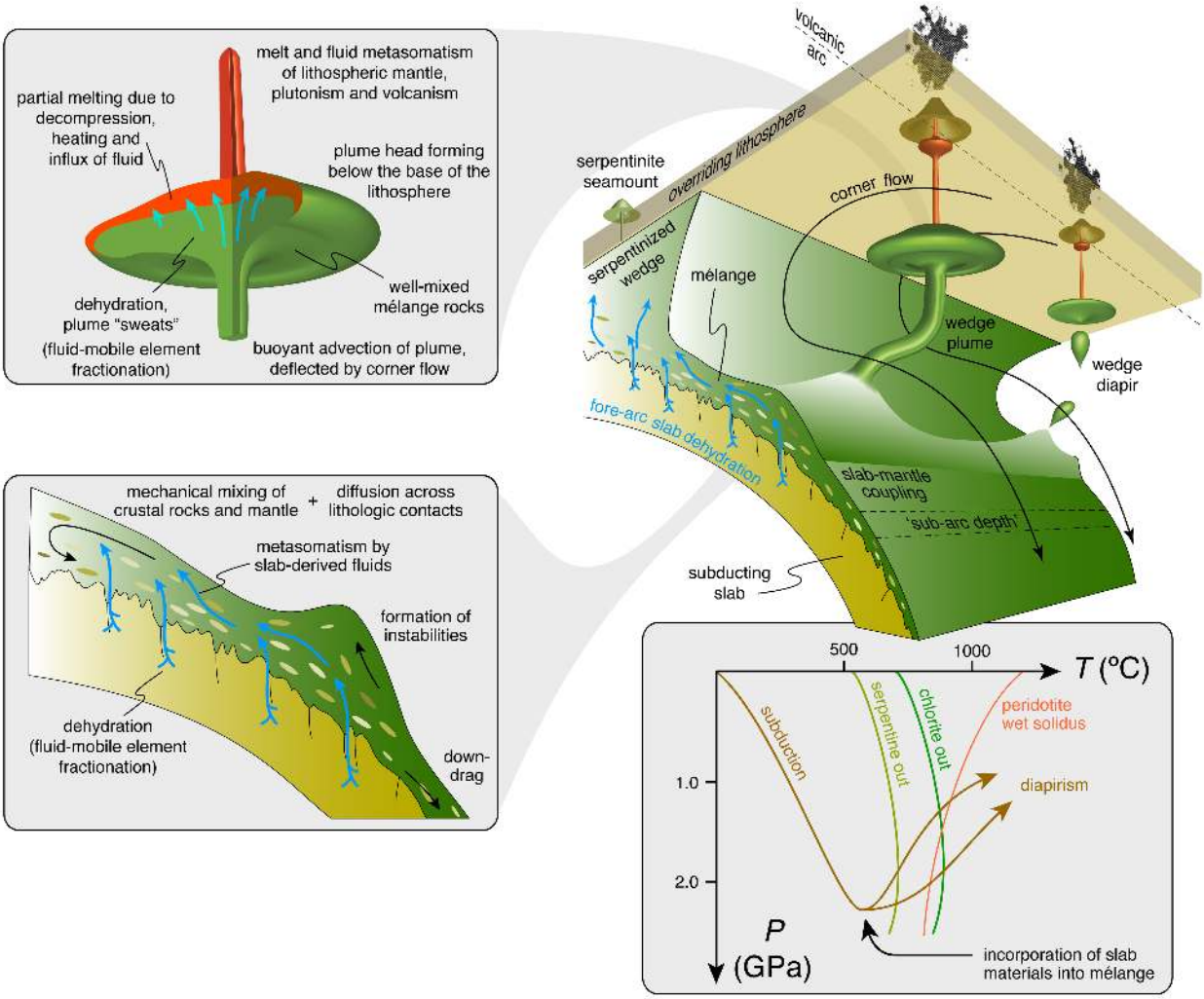

Fig. 2. **Three-dimensional schematic drawing of a subduction zone depicting the principle elements of the mélange-diapir model.** Fluid flow is marked by blue arrows, flow of solid mass is shown by black arrows, and melt zones are marked in red. The insets depict the key processes operating at the slab mantle interface and the arc magma source region, respectively. The lower inset shows a schematic *P-T* diagram of material that is subducted and entrained in a mélange diapir. While heating up and rising into the mantle wedge it crosses the dehydration curves of serpentine and chlorite [22], as well as the H_2O-saturated ("wet") peridotite solidus [22].

the subducting slab (igneous and sedimentary) may mix with the hydrated mantle, forming layers of intensely mixed low-density rock at the surface of the slab [9]. As thickness increases, buoyancy causes the layers to bulge upwards until trench-parallel waves are formed that are then focussed into individual, tubular plumes [32, 34]. Importantly, as plumes rise into the mantle wedge, their trajectories are in many cases not vertical, as would be expected from buoyancy-driven movement; instead, the plumes are affected by the corner flow in the mantle wedge. The resulting vector of motion is such that the plumes move at an oblique angle away from the trench, away form the slab surface and upwards into the hot corner of the mantle wedge (Fig. 2).

The melt region underneath the volcanic arc is separated from the dehydrating slab by several (possibly tens of) kilometres of downwards flowing asthenospheric mantle. Simplified sketches of subduction zones depict the transport of slab components to the site of magma generation in the mantle wedge by vertical lines that symbolise the transport of fluid-mobile components. This implicitly assumes that all slab-to-mantle transport would proceed vertically upwards from the slab, and hence that magma erupted from volcanoes located at a position of 90 to 130 km above the top of the subducting slab would contain components that were released

from the slab at those particular depths. As a consequence, the majority of studies treat dehydration processes in the slab that occur at a depth shallower than 90 km as 'fore-arc processes' with no direct relevance for the generation of arc magmas. This has posed a conundrum for models of most subduction zones except where very old and cool crust is subducted; large portions of the volatiles are released from the uppermost, fluid-rich parts of the subducting oceanic slabs at pressures below ~ 2.5 GPa [14, 28] (corresponding to 80 km depth). At 'sub-arc depths' the hydrated oceanic crust will have already transformed into rock types composed of nearly anhydrous mineral assemblages. Yet, most arc volcanoes are located above that largely dehydrated slab.

Diapirs and plumes that carry fore-arc mélange material diagonally upwards into the melting region beneath arcs, as proposed here, solve this conundrum. Hence, this model provides solutions to a number of questions that are not addressed in current models: (i) the mechanical and metasomatic mixing processes at the slab-mantle interface and in the subduction channel demonstrate a physical process of three-component mixing as required to explain the geochemical patterns of arc magmas; (ii) the buoyant mantle wedge plumes provide a method to rapidly move material from the slab into the source region of arc magmas in the hot corner of the mantle wedge; (iii) the turbulent flow in the subduction channel and the diagonal – not vertical – path of the wedge plumes delivers volatile and trace-element-rich 'fore-arc' materials into the magma source region; (iv) individual arc volcanoes typically show constant ratios between components derived from sediments and those from altered oceanic crust [37, 38]. This suggests that the slab component is well mixed before it interacts with mantle rocks in the arc magma source region. It is difficult to envision how separate fluid pulses derived from the two separate lithologic sources could yield the homogenous slab contribution suggested by the compositions of magmas erupted at individual arc volcanoes. However, mélanges comprise such mixed reservoirs.

Mantle wedge plumes consisting of mélange rocks with a significant component of hydrous minerals would also dehydrate on their way into the hot corner of the mantle wedge as pressure decreases and temperature increases. Partial melting would be most significant at the margins of the plume, while rocks in the slightly cooler internal part would continue to dehydrate. This is expected to lead to a flux of hydrous fluids with fluid-fractionated trace-element signatures into the upper parts of the plume, where partial melting takes place. The plumes would "sweat" and effectively fractionate trace elements between their cores and their intensely melting margins (Fig. 2).

Subduction of hydrated mantle wedge and subsequent dehydration at the stability limit of chlorite could release sufficient fluid over a narrow depth range and trigger fluid-saturated melting of peridotite [20, 22]. However, this fluid can probably not import necessary trace-element signatures to the melts produced in the mantle wedge [33]. The mélange diapir hypothesis presented here does not rely on long-distance fluid-based transport of elements, because the mélange rocks themselves already posses the necessary trace-element characteristics.

Temperature and time constraints

Temperature estimates for the surface of the subducting slab and the thermal structure of the mantle wedge have been a longstanding matter of debate. Currently, these temperatures are thought to be relatively high, mainly based on numerical models, on the composition of melt inclusions in olivine and on the composition of basalts [4, 14, 39, 40, 41]. Numerical models now take into account a strong mechanical coupling between slab and mantle at relatively shallow depth of ~ 50 to 80 km [4, 14, 40, 42]. However, the formation of chlorite- and talc-rich mélanges at the slab-mantle interface could lubricate the interface, and delay the coupling of slab and mantle to greater depth. This would lead to lower temperatures at the slab surface, which, in turn, would lead to the stabilisation of hydrous minerals to greater depth. Hence, a positive feedback is expected between the formation of mélange zones and the decoupling of slab and mantle wedge.

Evidence for temperatures in the mantle wedge comes from the temperature of erupted magmas in volcanic arcs, which may reach values in excess of 1200 °C [43]. For the hot corner of the mantle wedge at a depth of ~ 40 to 80 km, more extreme temperatures in excess of 1300 °C are estimated [39, 41, 43]. These temperatures are calculated based on the assumption that the magmas erupted at arcs were initially derived from depleted harzburgitic mantle with Mg-rich olivine and orthopyroxene in the residue, and that the observed lavas have been modified by olivine fractionation and degassing [39, 43]. However, if mélange rocks are melted, the primary melt composition might differ significantly from compositions that are generally expected to derive from mantle melting [31]. Magmas that are currently considered products of differentiation from basalts may instead be primary melts derived from mélange plumes

in the mantle wedge, and initial temperatures of those magmas in the mantle wedge may be lower than those of the peridotite-derived basalts.

A critical parameter for any numerical model of magma generation in subduction zones is the temperature of the mantle wedge. Two-dimensional mantle-wedge plume models commonly fail to produce these temperatures, because the rising plumes inevitably cut off the mantle corner flow. Recent 3-D numerical modelling shows that individual plumes are separated and equally spaced along the strike of the arc, which enables the continuation of the corner flow among and around the individual plumes (Fig. 2). This allows temperatures in the mantle wedge to remain high, and explains the along-strike distribution of the volcanic activity in clusters [32, 35, 36]. Mantle wedge diapirs also explain significant differences in temperature and composition of magmas that are erupted from spatially closely related volcanoes [39].

Important restrictions on the timescales involved in material cycling in subduction zones comes from isotope geochemistry, most importantly ^{10}Be and U-Th disequilibrium chronology [44, 45]. The abundance of ^{10}Be in some arc volcanic rocks provides evidence that subducted ocean-floor material is transferred to the mantle wedge, entrained into arc magmas, transported through the lithosphere, and erupted at the surface all within $\sim$ 5 million years [44]. The mantle wedge plume model meets this time constraint for a range of parameters, because the plumes and diapirs are predicted to rise from the slab to the magma source region in a timeframe of 10^4 to 10^6 years [32, 36].

The extent of disturbance in the secular equilibria in the U-Th decay scheme has been employed to demonstrate that elemental fractionation in island arcs occurred within 60,000 years of eruption of investigated basalts, based on ^{238}U excess, while estimates from ^{226}Ra excess are as short as 8,000 years [45]. These timescales are extremely short and would place significant restrictions on slab-to-wedge transfer, if the secular equilibrium was violated during dehydration in the slab. However, an alternative location for generating U-Th decay series disequilibria could be within the mantle wedge plumes as their interior parts dehydrate and flux the overlying melting region (Fig. 2). This would relax the time restrictions on material transport, as the set timeframe would only describe the transport of materials from the magma source region to the surface and not include slab-to-wedge transport.

Mélange melting and arc magmatic rocks

An intriguing feature of arc magmas is their extensive range of compositions compared to mid-ocean ridge basalts. This variation is not restricted to trace elements and isotopes, but is equally true for the major elements [46]. This range can in part be traced to crystal fractionation, magmatic differentiation and variations in the initial H_2O contents. Also, the rock compositions used to interpret mantle wedge processes are commonly restricted to 'primitive' basalts, which discriminates against all rocks that are too high in alkali metals or show low Mg/Fe ratios. However, even this rigorous selection process leaves a vast range of compositions [46]. Partial melting of mélange materials entrained into the hot corner of the mantle wedge may in part be responsible for this compositional range. Experimental melts produced from mechanical mixtures of sediment and basalt ranged in composition from diorites to andesites, to granodiorites [31], and it was argued that melting of sediment-rich mélange may produce the large intermediate to felsic batholith and some of the andesitic volcanism associated with subduction zones [31].

The high-temperature breakdown of chlorite, in contrast, produces olivine-orthopyroxene-spinel assemblages [21], i.e. harzburgite or olivine pyroxenite with a high mode of Al-rich spinel. Melts buffered by olivine and orthopyroxene have a low, basalt-like silica content, while the exact melt composition would be a function of the amount of amphibole and talc initially present in the mélange.

Our model also predicts that the magmas produced in and above the mélange plumes will show a certain compositional range in both space and time. The dehydration of the plume interior will flux its margin and the overlying mantle with solute-rich hydrous fluids (Fig. 2), producing melts that will be rich in volatiles and fluid-mobile elements. The composition of these melts will be close to those expected from the melting of the metasomatised mantle wedge as envisaged in traditional subduction-zone models [3]. On the other hand, further heating of the plume will generate magmas that are dryer and hotter with a larger component of incompatible, less-fluid mobile elements such as Th and Be, derived from components that were initially incorporated into the mélange by mechanical mixing. The fully dehydrated mélange rocks will consist of pyroxenes, olivine and spinel with a bulk density similar to the ambient mantle.

Summary

This review outlined an integrated physico-chemical model of subduction zones: mélange formation at the slab-mantle interface is considered the physical mixing process that is responsible for the geochemical three-component pattern of arc magmas. The low mechanical strength and low density of the hydrous mélange rocks triggers the formation of mechanical instabilities and the formation of plumes and diapirs of mélange material. These plumes transport mélange rocks into the hot corner of the mantle wedge, where dehydration and partial melting generate a range of fluid and melt compositions. The proposed model has consequences for the interpretation of geophysical data in subduction zones, as low-velocity zones at the slab-mantle interface and in the mantle wedge may represent layers and diapirs of fluid-rich mélange material instead of hot, melt-bearing mantle. The mélange diapir model also affects the budgets and mechanisms of material recycling in convergent margins, as slab components are transported as solid matter into the source region of arc magmas rather than via the classically envisaged fluids and melts. Temperatures and time scales for the generation of arc magmas determined from isotope and trace-element ratios need to be revisited, as these may reflect processes in the head of the mélange diapirs rather than in the subducting slab or the harzburgitic mantle wedge.

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Author Contributions

Both authors contributed equally to idea development and data compilation. H.M. wrote the manuscript.

References

[1] Arculus, R. J. & Powell, R. Source component mixing in the regions of arc magma generation. *J. Geophys. Res. (B)* **91**, 5913–5926 (1986).

[2] Ellam, R. & Hawkesworth, C. J. Elemental and isotopic variations in subduction related basalts: evidence for a three component model. *Contrib. Mineral. Petrol.* **98**, 72–80 (1988).

[3] Elliott, T. Tracers of the slab. In Eiler, J. (ed.) *Inside the Subduction Factory*, vol. 138 of *Geophys. Monogr. Ser.*, 23–45 (Am. Geophys. Union, Washington, DC, 2003), 1st edn.

[4] Furukawa, Y. Depth of the decoupling plate interface and thermal structure under arcs. *J. Geophys. Res. (B)* **98**, 20005–20013 (1993).

[5] Schmidt, M. W. & Poli, S. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Earth Planet. Sci. Lett.* **163**, 361–379 (1998).

[6] Cloos, M. & Shreve, R. L. Subduction channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description. *Pure Appl. Geophys.* **128**, 455–500 (1988).

[7] Guillot, S., Hattori, K. H., Agard, P., Schwartz, S. & Vidal, O. Exhumation processes in oceanic and continental subduction contexts: a review. In Lallemand, S. & Funiciello, F. (eds.) *Subduction Zone Geodynamics*, 175–205 (Springer, 2009).

[8] King, R. L., Kohn, M. J. & Eiler, J. M. Constraints on the petrologic structure of the subduction zone slab-mantle interface from Franciscan Complex exotic ultramafic blocks. *GSA Bulletin* **115**, 1097–1109 (2003).

[9] Gerya, T. V., Stoeckhert, B. & Perchuk, A. L. Exhumation of high-pressure metamorphic rocks in a subduction channel; a numerical simulation. *Tectonics* **21**, 6–19 (2002).

[10] Bebout, G. E. Field-based evidence for devolatilization in subduction zones: implications for arc magmatism. *Science* **251**, 413–416 (1991).

[11] Sorensen, S. S. & Grossman, J. N. Accessory minerals and subduction zone metasomatism: a geochemical comparison of two mélanges (Washington and California, U.S.A.). *Chem. Geol.* **110**,

269–297 (1993).

[12] Bebout, G. E. & Barton, M. D. Tectonic and metasomatic mixing in a high-T, subduction-zone mélange – insights into the geochemical evolution of the slab-mantle interface. *Chem. Geol.* **187**, 79–106 (2002).

[13] Miller, D. P., Marschall, H. R. & Schumacher, J. C. Metasomatic formation and petrology of blueschist-facies hybrid rocks from Syros (Greece): implications for reactions at the slab-mantle interface. *Lithos* **107**, 53–67 (2009).

[14] van Keken, P. E., Hacker, B. R., Syracuse, E. M. & Abers, G. A. Subduction factory: 4. Depth-dependent flux of H_2O from subducting slabs worldwide. *J. Geophys. Res. (B)* **116**, 01401 doi:10.1029/2010JB007922 (2011).

[15] Spandler, C., Hermann, J., Faure, K., Mavrogenes, J. A. & Arculus, R. The importance of talc and chlorite "hybrid" rocks for volatile recycling through subduction zones; evidence from the high-pressure subduction mélange of New Caledonia. *Contrib. Mineral. Petrol.* **155**, 181–198 (2008).

[16] Harlow, G. E. Jadeitite from Guatemala: new observations and distinctions among multiple occurrences. *Geol. Acta* **9**, 363–387 (2011).

[17] Tsujimori, T. & Harlow, G. E. Petrogenetic relationships between jadeitite and associated high-pressure and low-temperature metamorphic rocks in worldwide jadeitite localities: a review. *Eur. J. Mineral.* **24**, 371–390 (2012).

[18] Sorensen, S. S., Sisson, V. B., Harlow, G. E. & Avé Lallemant, H. G. Element residence and transport during subduction zone metasomatism: evidence from a jadeitite-serpentinite contact, Guatemala. *Internat. Geol. Rev.* **52**, 899–940 (2010).

[19] Sorensen, S. S., Grossman, J. N. & Perfit, M. R. Phengite-hosted lile enrichment in eclogite and related rocks: implications for fluid-mediated mass transfer in subduction zones and arc magma genesis. *J. Petrol.* **38**, 3–34 (1997).

[20] Tatsumi, Y. Migration of fluid phases and genesis of basalt magmas in subduction zones. *J. Geophys. Res. (B)* **94**, 4697–4707 (1989).

[21] Pawley, A. Chlorite stability in mantle peridotite: the reaction clinochlore + enstatite = forsterite + pyrope + H_2O. *Contrib. Mineral. Petrol.* **144**, 449–456 (2003).

[22] Grove, T. L., Till, C. B., Lev, E., Chatterjee, N. & Médard, E. Kinematic variables and water transport control the formation and location of arc volcanoes. *Nature* **459**, 694–697 (2009).

[23] Marschall, H. R., Ludwig, T., Altherr, R., Kalt, A. & Tonarini, S. Syros metasomatic tourmaline: evidence for very high-δ^{11}B fluids in subduction zones. *J. Petrol.* **47**, 1915–1942 (2006).

[24] Helffrich, G. & Abers, G. A. Slab low-velocity layer in the eastern Aleutian subduction zone. *Geophys. J. Intern.* **130**, 640–648 (1997).

[25] Abers, G. A. Seismic low-velocity layer at the top of subducting slabs: observations, predictions, and systematics. *Phys. Earth Planet. Inter.* **149**, 7–29 (2005).

[26] King, R. L., Bebout, G. E., Moriguti, T. & Nakamura, E. Elemental mixing systematics and Sr-Nd isotope geochemistry of mélange formation: obstacles to identification of fluid sources to arc volcanics. *Earth Planet. Sci. Lett.* **246**, 288–304 (2006).

[27] Pabst, S. *et al.* The fate of subducted oceanic slabs in the shallow mantle: insights from boron isotopes and light element composition of metasomatized blueschists from the Mariana forearc. *Lithos* **132-133**, 162–179 (2012).

[28] Hacker, B. R. H_2O subduction beyond arcs. *Geochem. Geophys. Geosys. (G^3)* **9**, Q03001, doi:10.1029/2007GC001707 (2008).

[29] Rüpke, L. H., Phipps Morgan, J., Hort, M. & Connolly, J. A. D. Serpentine and the subduction zone water cycle. *Earth Planet. Sci. Lett.* **223**, 17–34 (2004).

[30] Gerya, T. V., Connolly, J. A. D., Yuen, D. A., Gorczyk, W. & Capel, A. M. Seismic implications of mantle wedge plumes. *Phys. Earth Planet. Inter.* **156**, 59–74 (2006).

[31] Castro, A. *et al.* Melting relations of MORB-sediment mélanges in underplated mantle wedge plumes; implications for the origin of Cordilleran-type batholiths. *J. Petrol.* **51**, 1267–1295 (2010).

[32] Zhu, G. *et al.* Three-dimensional dynamics of hydrous thermal-chemical plumes in oceanic subduction zones. *Geochem. Geophys. Geosys. (G^3)* **10**, Q11006, doi:10.1029/2009GC002625 (2009).

[33] Behn, M. D., Kelemen, P. B., Hirth, G., Hacker, B. R. & Massonne, H. J. Diapirs as the source of the sediment signature in arc lavas. *Nature Geosci.* **4**, 641–646 (2011).

[34] Hasenclever, J., Phipps Morgan, J., Hort, M. & Rüpke, L. H. 2D and 3D numerical models on compositionally buoyant diapirs in the mantle wedge. *Earth Planet. Sci. Lett.* **311**, 53–68 (2011).

[35] Marsh, B. D. Island arc development: some observations, experiments, and speculations. *J. Geol.* **87**, 687–713 (1979).

[36] Hall, P. S. & Kincaid, C. Diapiric flow at subduction zones: a recipe for rapid transport. *Science* **292**, 2472–2475 (2001).

[37] Miller, D. M., Goldstein, S. L. & Langmuir, C. H. Cerium/lead and lead isotope ratios in arc magmas and the enrichment of lead in the continents. *Nature* **368**, 514–520 (1994).

[38] Singer, B. S. *et al.* Along-strike trace element and isotopic variation in Aleutian island arc basalt: subduction melts sediments and dehydrates serpentine. *J. Geophys. Res. (B)* **112**, 06206, doi:10.1029/2006JB004897 (2007).

[39] Tatsumi, Y., Sakuyama, M., Fukuyama, H. & Kushiro, I. Generation of arc basalt magmas and thermal structure of the mantle wedge in subduction zones. *J. Geophys. Res. (B)* **88**, 5815–5825 (1983).

[40] Keleman, P. B., Rilling, J. L., Parmentier, E. M., Mehl, L. & Hacker, B. R. Thermal structure due to solid-state flow in the mantle wedge beneath arcs. In Eiler, J. (ed.) *Inside the Subduction Factory*, vol. 138 of *Monographs*, 293–311 (Am. Geophys. Union, 2003).

[41] Kelley, K. A. *et al.* Mantle melting as a function of water content beneath the Mariana arc. *J. Petrol.* **51**, 1711–1738 (2010).

[42] Peacock, S. M. *et al.* Thermal structure of the Costa Rica-Nicaragua subduction zone. *Phys. Earth Planet. Inter.* **149**, 187–200 (2005).

[43] Currie, C. A. & Hyndman, R. D. The thermal structure of subduction zone back arcs. *J. Geophys. Res. (B)* **111**, 08404, doi:10.1029/2005JB004024 (2006).

[44] Morris, J. D., Gosse, J., Brachfeld, S. & Tera, F. Cosmogenic Be-10 and the solid Earth: studies in geomagnetism, subduction zone processes, and active tectonics. In Grew, E. S. (ed.) *Beryllium: mineralogy, petrology and geochemistry*, vol. 50 of *Rev. Mineral.*, chap. 5, 207–270 (Mineral. Soc. Am., Washington, DC, 2002).

[45] Turner, S., Evans, P. & Hawkesworth, C. J. Ultrafast source-to-surface movement of melt at island arcs from ^{226}Ra—^{230}Th systematics. *Science* **292**, 1363–1366 (2001).

[46] Kelemen, P. B., Hanghøj, K. & Greene, A. R. One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust. In Rudnick, R. L., Holland, H. D. & Turekian, K. K. (eds.) *The Crust*, vol. 3 of *Treatise on Geochemistry*, 593–659 (Elsevier-Pergamon, 2003).

[47] McDonough, W. F. & Sun, S.-S.. The composition of the Earth. *Chem. Geol.* **120**, 223–253 (1995).

[48] Hofmann, A. W. Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust. *Earth Planet. Sci. Lett.* **90**, 297–314 (1988).

[49] Plank, T. & Langmuir, C. H. The chemical composition of subducting sediment and its consequences for the crust and mantle. *Chem. Geol.* **145**, 325–394 (1998).

Arc magmas sourced from mélange diapirs in subduction zones

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Mélange matrix, blackwalls and the spatial extent of chlorite schist

High-pressure mélange zones typically consist of blocks of metamorphosed fragments of oceanic crust embedded in a schistose matrix. The blocks are cm to hundreds of metres in diameter and are metamorphosed sections of the subducted igneous crust (gabbro, basalt or "plagiogranite"), sediments (chert, limestone, pelite or other clastic sediments) or fragments of the mantle (peridotite, serpentinite). The blocks best record their *P-T* histories and their metamorphic overprint at blueschist- to eclogite-facies conditions. They occur as metagabbro, eclogite, glaucophane schist, meta-plagiogranite, serpentinite, marbles or garnet-mica schists in the field, and are typically the focus of petrologic work in high-*P* terrains [e.g. 1, 2, 3, 4].

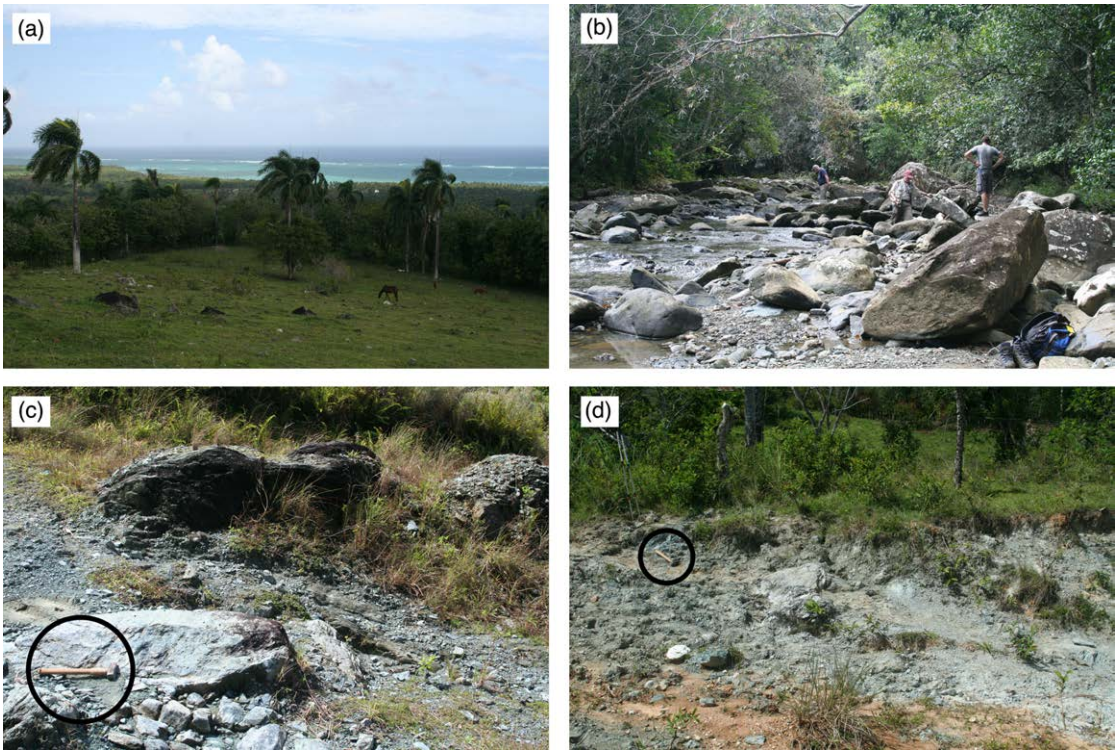

Fig. 1 Typical field conditions of the high-pressure mélange of the Rio San Juan Complex (RSJC, Dominican Republic): (a) hill slope cleared from forest to make way for a horse range. Blocks of serpentinite, garnet-glaucophane schist and jadeitite are readily exposed, while the mélange matrix is more deeply eroded and covered by soil and vegetation. (b) River beds in the RSJC provide ample access to a range of rock types found in the mélange, but the accumulation is strongly biased toward mechanically tough rocks, such as eclogites, garnet-glaucophane rocks and jadeitites. Blocks of chlorite schist and serpentinite are also commonly found in the river beds, but their frequency does not represent their proportion in the mélange zone. (c and d) Exposed chlorite schist matrix of the mélange. In places where roads or trails cause ongoing erosion of the steeper parts of the terrain, the mélange matrix is exposed. In most places it is strongly dominated by chlorite schist. Thicknesses of up to 100 m of this type of chlorite schist are exposed in the RSJC. Serpentinite forms lenses or blocks and is found in contact to the chlorite schist matrix in many places.

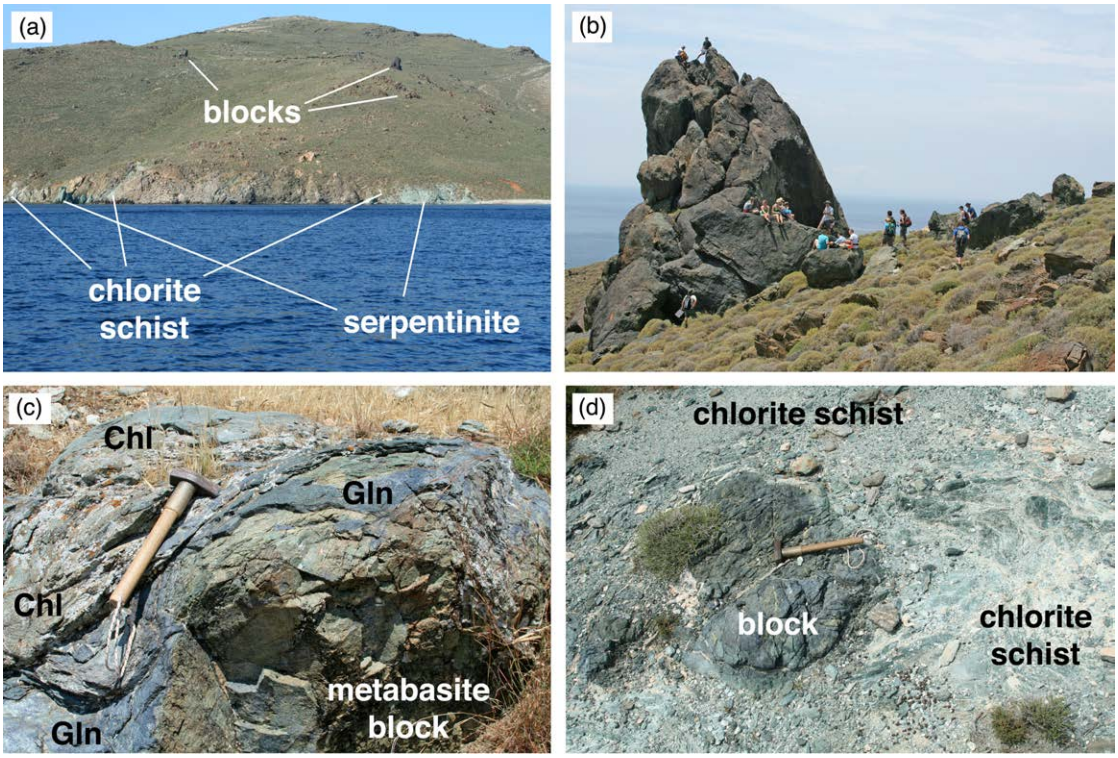

Fig. 2 Typical field conditions of the high-pressure mélange on the island of Syros (Cyclades, Greece): (a) hill slope showing the mélange of Kampos in the north of Syros with blocks of eclogite, garnet-glaucophane schist and jadeitite protruding the slope. Serpentinite is found as large, coherent lenses, but also as smaller, foliated layers in the matrix. The mélange matrix is more deeply eroded and difficult to map. (b) The largest eclogite blocks on Syros stand ~ 20 m tall, and most petrologic and geochemical research has focused on the blocks rather than the matrix of the mélange. (c) The majority of blocks on Syros comprise rinds composed of near mono-mineralic glaucophanite (Gln) or actinolite-talc blackwalls, which are in turn enclosed in chlorite schist (Chl). Thicknesses of the preserved chlorite schist are typically in the range of 0.1 to 1 m. (d) In some places, larger stretches of the mélange matrix are exposed, showing a strongly foliated chlorite schist ($\pm$talc) with partially digested metabasite blocks and thin layers of serpentinite. Thicknesses of up to 150 m of this type of chlorite schist are exposed on Syros.

The matrix of many mélanges contains a significant proportion of low-density, schistose, ultramafic materials. In most cases, however, the mélange matrix has not been described in detail and has not received significant attention. This is due to a number of reasons: **(i)** metaigenous and metasedimentary blocks typically provide mineral assemblages that are highly sensitive to changes in P and T and are of great interest to petrologists. The schistose matrix, in contrast, typically contains a high-variance mineral assemblage that is stable over a wide P-T range and does not provide evidence for reconstruction of the tectonic history of the high-P units. **(ii)** The chemical and isotopic composition of the metaigneous blocks provide clues to the geodynamic setting of the generation of their igneous precursors. It also provides evidence for trace-element and isotope fractionation during subduction zone dehydration processes. The mélange matrix, in contrast, has a history of multi-stage mechanical and metasomatic mixing, and is as such of little value to classical geochemistry. **(iii)** The matrix is typically composed of soft, schistose rocks that are prone to weathering and erosion. The matrix is typically covered by soil and vegetation and is hidden in depressions between the harder, rigid blocks that protrude the landscape (Fig. 1, 2). It is therefore very difficult to identify the composition of the matrix or map larger areas of it. Riverbeds typically provide a wide selection of the blocks that occur in a mélange (Fig. 1b), but they provide very little material of the schistose matrix. **(iv)** During exhumation, the schistose matrix may be mechanically

separated from the blocks, producing outcrops with an overrepresentation of blocks. Evidence for such a process comes from structural and geochemical investigation (e.g., Syros, Tian Shan [5, 6]).

In a number of high-*P* mélange zones, the mélange matrix has been tentatively mapped as serpentinite (Syros: [7]; Rio San Juan Complex: [8]), and serpentinite can indeed be found in these mélanges. Serpentinite commonly occurs, however, as coherent blocks that are exposed on the surface or found as blocks in river beds, equivalent to the metaigneous and metasedimentary blocks. The schistose matrix may also contain sheared serpentinite, but it is commonly mixed with talc and chlorite. Some places, such as Catalina Island, show hardly any serpentine in the matrix, but consist of chlorite schists and chlorite-talc schists, and were mapped as "aluminous matrix" [9]. On Syros Island (Greece), the mélange matrix consists of chlorite schist and chlorite-talc schist throughout large parts of the mélange zones (Fig. 2d), and stretches of ~ 150 m across the foliation of chlorite schist are exposed (our own field work).

In the Rio San Juan Complex (Dominican Republic), most of the matrix is obscured by soil and vegetation (Fig. 1a). However, the matrix is exposed in some places, where fresh road cuts or land slides removed that cover, or where cow trails cause constant erosion of the soil (Fig. 1c,d). In many of these places, the exposed schistose rocks are not serpentinite as previously mapped, but they are chlorite schists. During our field work, we discovered continuous outcrop of chlorite schist with thicknesses (perpendicular to the foliation) of between 20 and 100 m. In many places, tropical weathering has degraded the matrix rocks into thick mud. In those areas it is still possible to infer the mineralogy of the matrix from the colour of the mud: serpentinite produces mud of a reddish-brown colour, while mud produced from chlorite schist is pale green (Fig. 3).

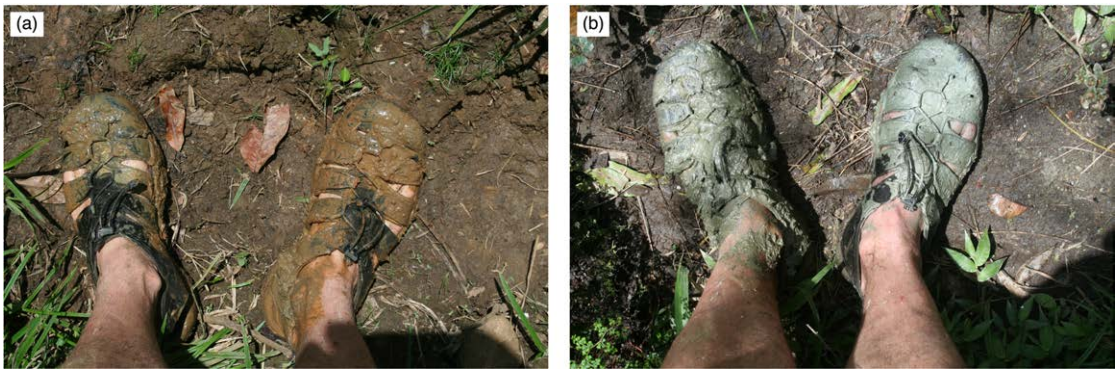

Fig. 3 Tropical weathering is one obstacle against the identification of the matrix of high-pressure mélange zones in the tropical areas. Yet, in some places the colour of the mud provides a clue: (a) reddish-brown mud formed from weathered serpentinite, (b) pale green mud formed from chlorite $\pm$talc schist (Rio San Juan Complex, Dominican Republic).

Clearly, more fieldwork in mélange zones is needed with a focus on mapping the matrix of the mélange zones. Maps often tentatively label the matrix as serpentinite (Syros [7]; Rio San Juan Complex [8]), where large sections are really chlorite schist. Other workers labeled the matrix as "mafic-ultramafic" or "variably silicated and hydrated ultramafic rocks" (e.g., Gee Point, Washington [10]) without a more specific description of the mineralogy. The occurrence of chlorite in the mélange matrix may also lead to the erroneous interpretation of the matrix as retrograde or greenschist facies. In some mélange zones, however, the matrix is actually mapped as chlorite schist or chlorit-talc schist (Port Macquarie, Australia [11]; Sistan Suture Zone, Iran [12]; Pam Peninsula, New Caledonia [13]).

Mixing mechanisms in high-*P* mélanges

The margins of the blocks and the contacts between crustal blocks and the low-silica, Mg-rich matrix are typically covered by cm to metre-thick layers of hydrous mineral assemblages, such as chlorite schists,

amphibole-rich assemblages or talc schist (Fig. 2c). These contact zones have been termed "blackwalls" and they provide insight into the initial stages of homogenisation in mélange zones [10, 14, 15, 16, 17]. Progressive shearing, fluid flux and diffusional exchange between blocks and matrix increases the thickness of these blackwalls and finally leads to the complete digestion of the individual blocks and to the homogenisation of the mélange zone (Fig. 4).

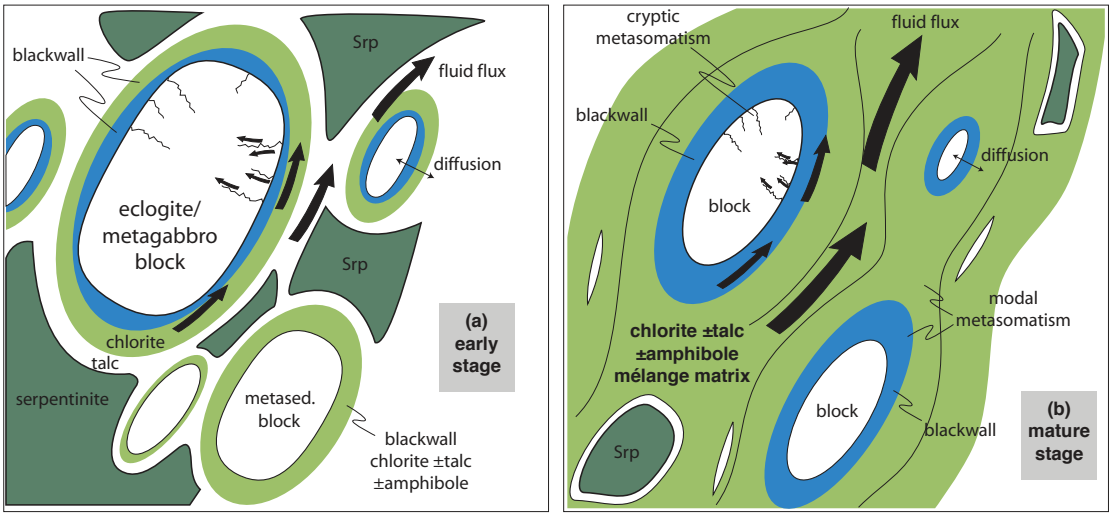

Fig. 4 Schematic drawing of the early (a) and mature (b) stages of a block-matrix mélange. Initially, hydrous reaction zones ("blackwalls") form at the contact between crustal blocks and serpentinite. Ongoing mechanical mixing, deformation, fluid flux and diffusive element exchange leads to the digestion of the blocks and homogenises the mélange zone. With ongoing mixing, blackwalls grow thicker and finally these hybrid chlorite-talc assemblages dominate the entire mélange zone.

Field studies have revealed three different mechanisms of mixing that leads to the formation of hybrid rock types:

Mechanical mixing. The interface between the slab and the overriding plate in the fore-arc represents a very large-scale shear zone reaching dozens of kilometres from the surface to the depth of full slab-mantle coupling with shear rates of several cm/year and continuous activity over up to tens of millions of years [18]. Extensive and complex isoclinal folding, intense fabric formation (foliation and lineation), and common development of faults in the majority of exposed high-*P* rocks all bear witness to the dynamic environment near the surface of subducting slabs. The structure of high-*P* mélanges with blocks of eclogite, glaucophane schist, metagabbro and metasediment embedded in a schistose mafic-ultramafic matrix demonstrates mechanical mixing on scales from cm to kilometres [9, 10, 17, 19, 20, 21, 22].

Advective mixing (metasomatism). Fluids and melts released from any rock volume within the subducting slab will inevitably pass through the slab-mantle interface, as they migrate upwards into the overlying mantle. Petrologic, structural, and geochemical studies employing major and trace elements, as well as stable isotopes have demonstrated that the matrix of high-*P* mélanges was, in many cases, subjected to strong fluid flux [23, 22, 24]. In some cases, new rock formed in veins or fluid-filled cracks that crosscut preexisting structures [25]. Migmatites and pegmatitic and trondjhemitic dykes crosscutting blocks and matrix in mélange zones are evidence for melt metasomatism [3, 26].

Diffusive mixing. Solid-state diffusion is not a process that will have an impact on element distribution in high-*P* mélanges on a larger scale, due to the relatively low temperatures that prevail at the slab-mantle interface. Yet, the fluid-saturated environment enables the diffusion of components along the grain-boundary network in silicate rocks, and the strong chemical gradients that are produced by the close juxtaposition of crustal rocks with the ultramafic mantle provide a strong driving force for diffusional exchange [27, 28]. Grain-boundary diffusion leads to material exchange on the scale of decimetres to

metres in high-*P* mélanges, affecting the bulk chemical and isotopic composition of the rocks [28]. The significance of diffusion in the interpretation of geochemical signals has been discussed in detail for Li isotopes [16, 29].

Geophysical parameters of chlorite schist and jadeitite

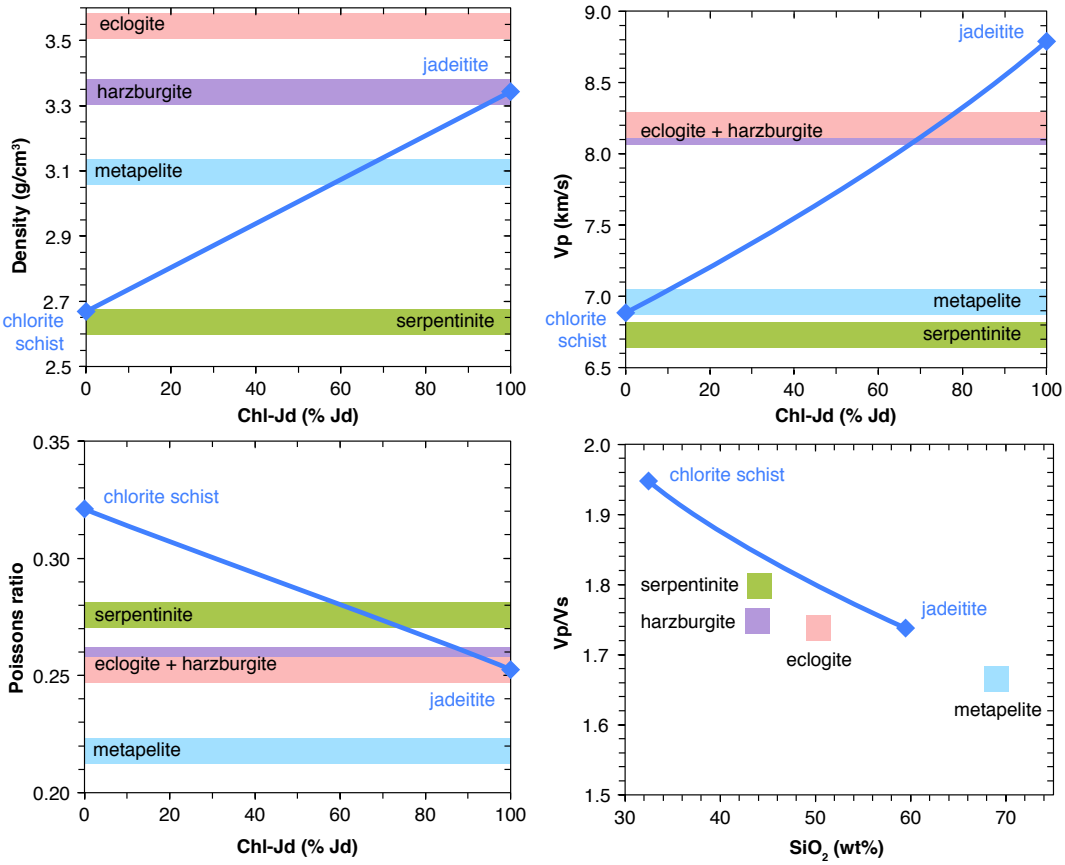

Fig. 5 Geophysical parameters of chlorite schist, jadeitite and intermediate members in comparison to rocks expected in the slab (eclogite, metapelite) and mantle wedge (serpentinite, harzburgite). All parameters were calculated for conditions of $T = 600\,^{\circ}\mathrm{C}$ and $P = 2.0\,\mathrm{GPa}$ using a September 2011 update of [30] (B. Hacker, pers. comm.). Pure jadeitite has a similar density and Poissons ratio, but a $\sim 10\,\%$ faster p-wave velocity than harzburgite and eclogite. Chlorite schist has a similar density and p-wave velocity, but a significantly higher Poissons ratio than serpentinite. Mélange rocks with compositions intermediate between chlorite schist and jadeitite differ in their geophysical character from any of the slab or mantle components.

Chemical composition of mélange rocks and arc volcanic rocks

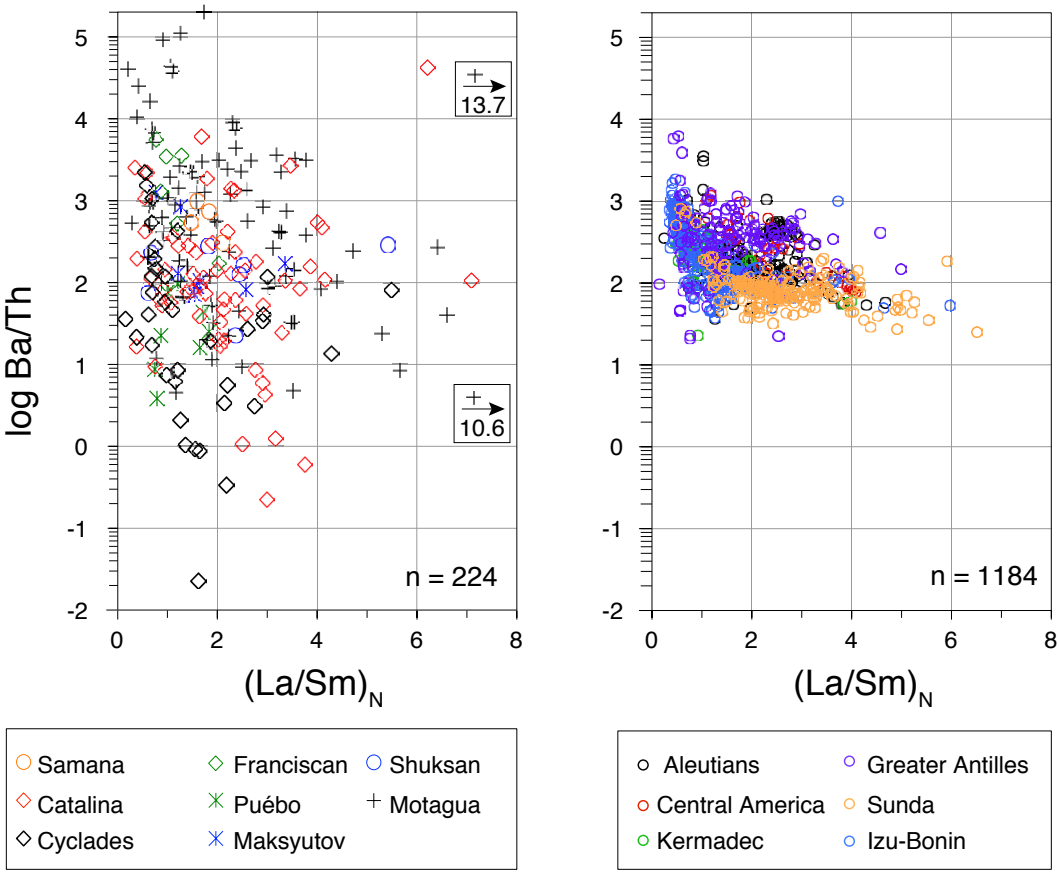

Fig. 6 Plots of $(La/Sm)_N$ versus log Ba/Th showing the same data as in Fig.1 of the paper coded according to different localities. **Left panel**: mélange rocks from various global localities. Data are from: Cycladic blueschist belt (Syros, Tinos, Siphnos) [31, 32, 28, 33], Catalina [14, 34], Franciscan [35], Samana peninsula (Dom. Rep.) [35], Pouébo mélange (New Caledonia) [13], Hochwarth (Alps) [36], Maksyutov complex (Urals) [37], Shuksan suite (Cascades) [10], Motagua zone (Guatemala): G. Harlow pers. comm. **Right panel**: volcanic rocks erupted at various global island arcs and continental arcs. Data from the GEOROCK database, MPI Mainz.

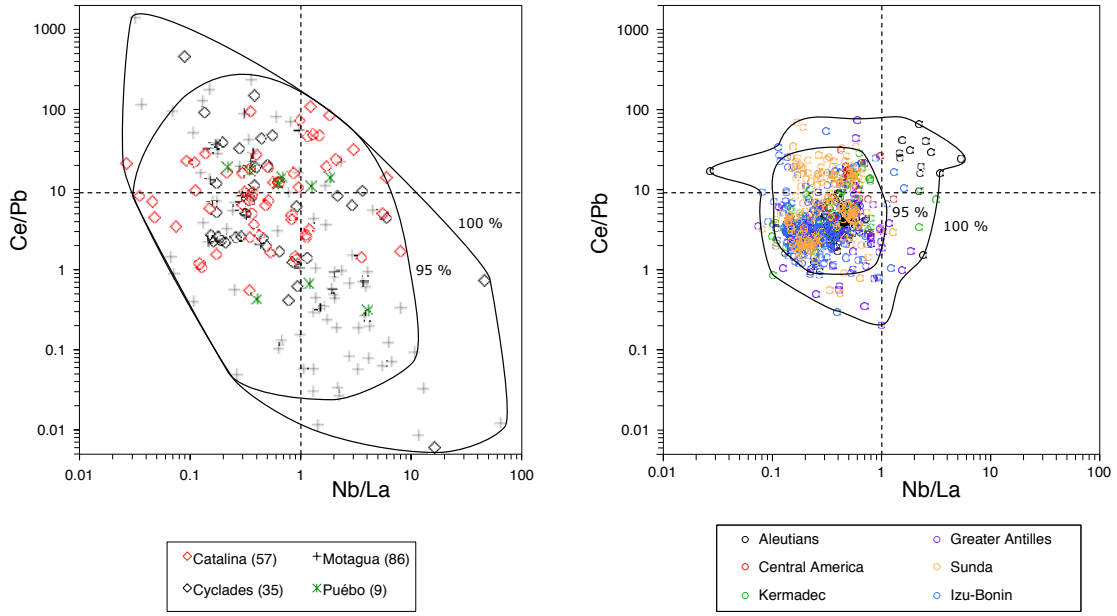

Fig. 7 Plots of (Nb/La) versus Ce/Pb showing the same data as in Fig.1 of the paper coded according to different localities. **Left panel**: mélange rocks from various global localities. The majority of subduction-zone volcanic rocks are enclosed by the black loops and show Ce/Pb and Nb/La ratios lower than PRIMA. Mélange rocks show a larger spread in both ratios than subduction-zone volcanic rocks, but the majority of compositions and the average of all mélange samples investigated overlap with the arc volcanic field (see also Fig.1 of the paper). Data are from: Cycladic blueschist belt (Syros, Tinos, Siphnos) [28, 31, 32, 33], Catalina [14, 34], Pouébo mélange (New Caledonia) [13], Motagua zone (Guatemala): G. Harlow pers. comm. **Right panel**: volcanic rocks erupted at various global island arcs and continental arcs. Data from the GEOROCK database, MPI Mainz.

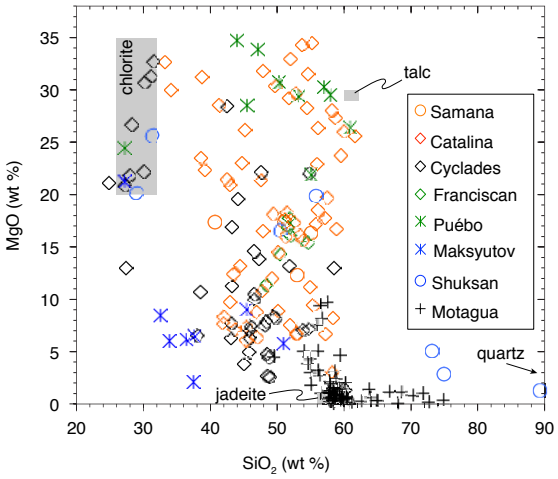

Fig. 8 MgO vs. silica plot showing composition of mélange rocks from different localities. Data are from: Cycladic blueschist belt (Syros, Tinos, Siphnos) [28, 31, 32, 33], Catalina [14, 34], Pouébo mélange (New Caledonia) [13], Motagua zone (Guatemala): G. Harlow pers. comm. Mineral compositions of chlorite, talc and jadeite are also plotted.

References

[1] Baldwin, S. L. & Harrison, T. M. The P-T-t history of blocks in serpentinite-matrix mélange, west-central Baja California. *Geol. Soc. Am. Bull.* **104**, 18–31 (1992).

[2] Trotet, F., Vidal, O. & Jolivet, L. Exhumation of syros and sifnos metamorphic rocks (cyclades, greece). new constraints on the $p-t$ paths. *Eur. J. Mineral.* **13**, 901–920 (2001).

[3] García-Casco, A. *et al.* Partial melting and counterclockwise P-T path of subducted oceanic crust (Sierra del Convento mélange, Cuba). *J. Petrol.* **49**, 129–161 (2008).

[4] Krebs, M., Schertl, H. P., Maresch, W. V. & Draper, G. Mass flow in serpentinite-hosted subduction channels: P–T–t path patterns of metamorphic blocks in the Rio San Juan mélange (Dominican Republic). *J. Asian Earth Sci.* **42**, 569–595 (2011).

[5] Dixon, J. E. & Ridley, J. Syros. In Helgeson, H. C. (ed.) *Chemical transport in metasomatic processes*, vol. 218 of *NATO ASI Series C, Math. Phys. Sci.*, 489–501 (Reidel, Dordrecht, 1987).

[6] van der Straaten, F. *et al.* Tracing the effects of high-pressure metasomatic fluids and seawater alteration in blueschist-facies overprinted eclogites: Implications for subduction channel processes. *Chem. Geol.* **292-293**, 69–87 (2012).

[7] Keiter, M., Piepjohn, K., Ballhaus, C., Bode, M. & Lagos, M. Structural development of high-pressure metamorphic rocks on syros island (cyclades, greece). *J. Struct. Geol.* **26**, 1433–1445 (2004).

[8] Escuder-Viruete, J., Friedman, R., Castillo-Carrión, M., Jabites, J. & Pérez-Estaún, A. Origin and significance of the ophiolitic high-*P* mélanges in the northern Caribbean convergent margin: insights from the geochemistry and large-scale structure of the Río San Juan metamorphic complex. *Lithos* **127**, 483–504 (2011).

[9] Bebout, G. E. & Barton, M. D. Tectonic and metasomatic mixing in a high-*T*, subduction-zone mélange – insights into the geochemical evolution of the slab-mantle interface. *Chem. Geol.* **187**, 79–106 (2002).

[10] Sorensen, S. S. & Grossman, J. N. Accessory minerals and subduction zone metasomatism: a geochemical comparison of two mélanges (Washington and California, U.S.A.). *Chem. Geol.* **110**, 269–297 (1993).

[11] Och, D. J., Leitch, E. C., Caprarelli, G. & Watanabe, T. Blueschist and eclogite in tectonic melange, port macquarie, new south wales, australia. *Mineral. Mag.* **67**, 609–624 (2003).

[12] Fotoohi Rad, G. R., Droop, G. T. R., Amini, S. & Moazzen, M. Eclogites and blueschists of the Sistan Suture Zone, eastern Iran: a comparison of P–T histories from a subduction melange. *Lithos* **84**, 1–24 (2005).

[13] Spandler, C., Hermann, J., Faure, K., Mavrogenes, J. A. & Arculus, R. The importance of talc and chlorite "hybrid" rocks for volatile recycling through subduction zones; evidence from the high-pressure subduction mélange of New Caledonia. *Contrib. Mineral. Petrol.* **155**, 181–198 (2008).

[14] Sorensen, S. S. & Grossman, J. N. Enrichment of trace elements in garnet amphibolites from a paleo-subduction zone: Catalina Schist, southern California. *Geochim. Cosmochim. Acta* **53**, 3155–3177 (1989).

[15] Marschall, H. R., Ludwig, T., Altherr, R., Kalt, A. & Tonarini, S. Syros metasomatic tourmaline: evidence for very high-δ^{11}B fluids in subduction zones. *J. Petrol.* **47**, 1915–1942 (2006).

[16] Penniston-Dorland, S. C., Sorensen, S. S., Ash, R. & Khadke, S. V. Lithium isotopes as a tracer of fluids in a subduction zone mélange: Franciscan Complex, CA. *Earth Planet. Sci. Lett.* **292**, 181–190 (2010).

[17] Penniston-Dorland, S. C., J, W. R., Pitcher, L. & Sorensen, S. S. Mantle–crust interactions in a paleosubduction zone: evidence from highly siderophile element systematics of eclogite and related rocks. *Earth Planet. Sci. Lett.* **319-320**, 295–306 (2012).

[18] Furukawa, Y. Depth of the decoupling plate interface and thermal structure under arcs. *J. Geophys. Res. (B)* **98**, 20005–20013 (1993).

[19] Cloos, M. & Shreve, R. L. Subduction channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description. *Pure Appl. Geophys.* **128**, 455–500 (1988).

[20] Guillot, S., Hattori, K. H., Agard, P., Schwartz, S. & Vidal, O. Exhumation processes in oceanic and continental subduction contexts: a review. In Lallemand, S. & Funiciello, F. (eds.) *Subduction Zone Geodynamics*, 175–205 (Springer, 2009).

[21] King, R. L., Kohn, M. J. & Eiler, J. M. Constraints on the petrologic structure of the subduction zone slab-mantle interface from Franciscan Complex exotic ultramafic blocks. *GSA Bulletin* **115**, 1097–1109 (2003).

[22] Bebout, G. E. Field-based evidence for devolatilization in subduction zones: implications for arc magmatism. *Science* **251**, 413–416 (1991).

[23] Marschall, H. R., Altherr, R., Gméling, K. & Kasztovszky, Zs. Lithium, boron and chlorine as tracers for metasomatism in high-pressure metamorphic rocks: a case study from Syros (Greece). *Mineral. Petrol.* **95**, 291–302 (2009).

[24] Ague, J. J. Models of permeability contrasts in subduction zone mélange: implications for gradients in fluid fluxes, Syros and Tinos Islands, Greece. *Chem. Geol.* **239**, 217–227 (2007).

[25] Harlow, G. E. Jadeitite from Guatemala: new observations and distinctions among multiple occurrences. *Geol. Acta* **9**, 363–387 (2011).

[26] Sorensen, S. S. & Barton, M. D. Metasomatism and partial melting in a subduction complex: Catalina Schist, southern California. *Geology* **15**, 115–118 (1987).

[27] Brady, J. B. Metasomatic zones in metamorphic rocks. *Geochim. Cosmochim. Acta* **41**, 113–125 (1977).

[28] Miller, D. P., Marschall, H. R. & Schumacher, J. C. Metasomatic formation and petrology of blueschist-facies hybrid rocks from Syros (Greece): implications for reactions at the slab-mantle interface. *Lithos* **107**, 53–67 (2009).

[29] Marschall, H. R., Pogge von Strandmann, P. A. E., Seitz, H-M., Elliott, T. & Niu, Y. The lithium isotopic composition of orogenic eclogites and deep subducted slabs. *Earth Planet. Sci. Lett.* **262**, 563–580 (2007).

[30] Hacker, B. R. & Abers, G. A. Subduction factory 3: An excel worksheet and macro for calculating the densities, seismic wave speeds, and H_2O contents of minerals and rocks at pressure and temperature. *Geochem. Geophys. Geosys. (G^3)* **5**, Q01005, doi:10.1029/2003GC000614 (2004).

[31] Mocek, B. Geochemical evidence for arc-type volcanism in the Aegean Sea: the blueschist unit of Siphnos, Cyclades (Greece). *Lithos* **57**, 263–289 (2001).

[32] Marschall, H. R. *Lithium, beryllium, and boron in high-pressure metamorphic rocks from Syros (Greece)*. Dr. rer. nat. thesis, Univ. Heidelberg, Germany (2005). URL `http://www.ub.uni-heidelberg.de/archiv/5634`.

[33] Bulle, F., Bröcker, M., Gärtner, C. & Keasling, A. Geochemistry and geochronology of HP mélanges from Tinos and Andros, Cycladic blueschist belt, Greece. *Lithos* **117**, 61–81 (2010).

[34] King, R. L., Bebout, G. E., Moriguti, T. & Nakamura, E. Elemental mixing systematics and Sr-Nd isotope geochemistry of mélange formation: obstacles to identification of fluid sources to arc volcanics. *Earth Planet. Sci. Lett.* **246**, 288–304 (2006).

[35] Sorensen, S. S., Grossman, J. N. & Perfit, M. R. Phengite-hosted lile enrichment in eclogite and related rocks: implications for fluid-mediated mass transfer in subduction zones and arc magma genesis. *J. Petrol.* **38**, 3–34 (1997).

[36] Tumiati, S., Godard, G., Martin, S., Klötzli, U. & Monticelli, D. Fluid-controlled crustal metasomatism within a high-pressure subducted mélange (Mt. Hochwart, Eastern Italian Alps). *Lithos* **94**, 148–167 (2007).

[37] Beane, R. J. & Liou, J. G. Metasomatism in serpentinite mélange rocks from the high-pressure Maksyutov Complex, southern Ural mountains, Russia. *Internat. Geol. Rev.* **47**, 24–40 (2005).