The mechanisms of transfer of crustal material from the subducting slab to the overlying mantle wedge are still debated. Mélange rocks, formed by mixing of sediments, oceanic crust, and ultramafics along the slab-mantle interface, are predicted to ascend as diapirs from the slab-top and transfer their compositional signatures to the source region of arc magmas. However, the compositions of melts that result from the interaction of mélanges with a peridotite wedge remain unknown. Here we present experimental evidence that melting of peridotite hybridized by mélanges produces melts that carry the major and trace element abundances observed in natural arc magmas. We propose that differences in nature and relative contributions of mélanges hybridizing the mantle produce a range of primary arc magmas, from tholeiitic to calc-alkaline. Thus, assimilation of mélanges into the wedge may play a key role in transferring subduction signatures from the slab to the source of arc magmas.
Subduction zones are widely studied because they are a major locus of volcanic and seismic hazards. In particular, the compositions of arc magmas have been used to understand the magmatic processes operating in the deep Earth. During subduction, hydrated oceanic crust and sediments are subducted and recycled back into the Earth’s interior. Although the fate of subducted sediments is uncertain, their signature is imprinted in the chemistry of most arc magmas around the world. Sediments are globally enriched in many trace elements (e.g., K, Rb, Th, rare earth elements) relative to peridotite mantle, thus small volumes of sediments can drastically shift the trace element budget of the mantle wedge. Arc magmas are also characterized by enriched in fluid-mobile large-ion lithophile elements (LILE) such as Ba and Sr, and depleted in high field strength elements (HFSE) such as Nb, relative to mid-ocean ridge basalt (MORB). The LILE enrichment has usually been attributed to mantle wedge metasomatism by slab-derived fluids produced during dehydration of the subducting slab. The HFSE depleted character, on the other hand, has been attributed to different processes such as a ‘pre-subduction’ mantle depletion, selective retention of HFSE by accessory phases (e.g., rutile, sphene, and perovskite) stabilized in the mantle wedge and/or in the slab, and preferred partitioning of HFSE into orthopyroxene during melt-rock reaction. Although extensive geochemical studies have suggested that arc magma chemistry reflects variable contributions from a depleted MORB mantle (DMM), altered oceanic crust (AOC) and sediments, experimental studies have faced challenges to simultaneously reproduce both the major and trace element characteristics of tholeiites and calc-alkaline melts, the most common types of arc magmas. In addition, the processes by which typical trace element signatures are produced and transferred to arc magmas remain a matter of debate. In particular, it has been recently argued that the trace element and isotope variability of global arc magmas could not be reconciled with the classic model of arc magma genesis, which invokes hybridization of the mantle wedge by discrete pulses of melted sediments and aqueous fluids from dehydrating AOC. Instead, the trace element and isotope data of global arcs can only be reconciled if physical mixing of sediments + fluids + mantle takes place early on in the subduction process before any melting occurs. This prerequisite redefines the order of events in subduction zones and supports an important role for mélange rocks in arc magmatism. However, the trace and major element chemistry of melts that would result from the interaction of natural mélange rocks with a peridotitic mantle in subduction zones has never been investigated experimentally and remains unknown. Such information is critical to determine whether mélange rocks are viable contributors to arc magmatism worldwide.

Mélange rocks are observed in field studies worldwide and are believed to form by deformation-assisted mechanical mixing, metasomatic interactions and diffusion at different P-T conditions along the slab-mantle interface during subduction. Mélanges are hybrid rocks composed of cm to km-sized blocks of altered oceanic crust, metasediments, and serpentinitized peridotite embedded in maﬁc to ultramafic matrices. These matrix rocks include neomonomineralic chlorite schists, talc schists, and jadeiteites with variable amounts of Ca-ampiphile, omphacite, phengite, epidote, and accessory minerals (e.g., titanite, rutile, zircon, apatite, monazite, and sulfides), among others. Although the volumes of mélange rocks at depth are poorly constrained, several km-thick low-seismic velocity regions observed at the slab-top in subduction zones worldwide indicate the persistence of hydrated rocks – mélange zones – at the slab-mantle interface. This km-scale estimate of mélange rocks from seismic observations is corroborated by numerous ﬁeld studies of exhumed high-pressure terranes reporting thicknesses ranging from several hundreds of meters up to several kilometers. Mélange rocks display signiﬁcant spatial heterogeneity, but detailed ﬁeld observations indicate that chemical potential gradients between juxtaposed lithologies (e.g., metasediments, eclogite, and serpentinitized peridotites) may be reduced to homogenous matrices through diffusion and ﬂuid advection processes as mélange matures. For the purpose of this ﬁrst study, we will assume that mélange matrices are broadly representative of the bulk composition of the mélange and provide a relevant ﬁrst-order approximation of mélange compositional variability as they form at the expense of, and reﬂect chemical contributions from their protoliths. Although more compositions will be studied in the future, the mélange matrix samples used here reﬂect two contrasting members in the range of mélange materials that we use to explore possible melt compositions produced by mélange-peridotite interaction.

Laboratory and numerical simulations of subduction processes have shown that hydration and partial melting may induce gravitational instabilities at the slab-mantle interface, which can develop into diapirc structures composed of partially molten materials. Although these diapirs have not been unambiguously imaged in active subduction zones, we note that along-arc geophysical studies are rare, that the current resolution of seismic techniques may not be appropriate to image mixed mélange-peridotite lithologies, and that magnetotelluric approach, sensitive to interconnected free ﬂuids, would not easily detect the presence of mélanges, where most of the water may be crystallographically bounded. With their intrinsic buoyancy, mélange diapirs have been predicted to form at the slab-top, migrate to the overlying mantle, and transfer the compositional signatures of slab-derived rocks to the source region of arc magmas. In particular, physical mixing and homogenization of viscous mélange diapirs and sub-solidus mantle peridotites is predicted in the hot zones of the mantle wedge. Recent ﬁndings on ophiolitic zircon grains also support the idea that material can be transported in the wedge via cold plumes. However, as stated previously, the major and trace element compositions of melts that would be produced by melting of a mélange-hybridized mantle wedge remains unexplored.

Here we present the ﬁrst experimental study on the generation of arc-like magmas by melting of mélange-hybridized mantle sources. We perform piston-cylinder experiments at 1.5 GPa and 1150–1350 °C and simulate a scenario where mélange materials rise as a bulk into the hot corner of the wedge and homogenize with the peridotite mantle. Using powder mixtures of DMM-like natural peridotite (LZ-1, Supplementary Fig. 1; 85–95 vol. %) and natural mélange rocks from a high-pressure terrane (SY400B, SY325; 5–15 vol. %), we show that experimentally produced glasses display the major and trace element characteristics typical of arc magmas (e.g., high Ba contents, high Sr/Y ratios, and negative Nb anomaly). Our study provides evidence that the compositional signatures of sediments and ﬂuids, initially imparted to mélange rocks during their formation at the slab-mantle interface, can be delivered to the source region of arc magmas by mixing of mélange materials with mantle wedge peridotites, and variably enhanced during melting of mélange-hybridized peridotite source. We show that depending on the types and relative contributions of mélange materials that hybridize the mantle wedge, the compositions of the melts vary from tholeiitic to calc-alkaline. We further discuss how lithological heterogeneities observed in supra-subduction ophiolites and arc xenoliths could represent direct evidence for peridotite-mélange interactions.
**Results**

**Experimental techniques.** We performed piston-cylinder experiments to investigate the composition of melts produced by partial melting of a natural DMM-like peridotite hybridized by small proportions of natural mélangé matrix. We used two starting mixes that consisted of homogenized ‘peridotite + sediment-dominated mélangé matrix’ (PER-SED mix) and homogenized ‘peridotite + serpentinite-dominated mélangé matrix’ (PER-SERP mix). Both mélangé matrices are fine-grained chlorite schists from Syros (Greece) with estimated water contents between 2–3 wt.%. These two types of natural mélangé matrices span a range of compositions that reflect the first-order variability of global mélangé rocks in terms of mineralogy (Supplementary Data 1), immobile element chemistry (Fig. 2), and trace element chemistry (Supplementary Fig. 6). As mélangé rocks should be volumetrically small compared to peridotite in the mantle wedge, we only added limited volumes (5–15%) of natural mélangé matrix to a natural lherzolite powder (85–95%). We note that mélangé rocks would not necessarily represent 5–15 vol.% of the sub-arc region at all times because of the 3-D nature of mélangé diapirs. Certain regions of the wedge could be hybridized by different amount of mélangé materials at different times. Although this experimental design is more challenging because it produces small melt pools, it simulates a more realistic scenario. Experimental melts were collected using glassy carbon spheres placed at the top of Au-Pd capsules. The natural peridotite (LZ-1; from Lherz, France) displays modal proportions and major and minor element compositions similar to DMM (Supplementary Fig. 1). The PER-SED and PER-SERP starting materials were partially melted at 1.5 GPa and 1280–1350 °C, conditions applicable to arc magmatism.23,33,34 In addition, near-solidus (1230 °C) and solids (1150 °C) experiments were performed to better constrain the solid phase assemblage at the beginning of and before melting, respectively. The quenched, dendrite-free glasses were analyzed for major elements using electron microprobe (EPMA) at the Massachusetts Institute of Technology. In addition, chemical maps for major elements were acquired on all experiments (Fig. 3 and Supplementary Fig. 2). Trace element compositions of glass pools were analyzed using a Cameca 3 F secondary ion mass spectrometer (SIMS) at the North East National Ion Microprobe Facility (Woods Hole Oceanographic Institution). Backscattered electron (BSE) images and energy dispersive spectroscopy (EDS) maps were acquired on all experiments using a Hitachi tabletop SEM-EDS TM-3000. The major and trace element compositions of starting mixes and experimental melts are summarized in Supplementary Data 1 and 2, respectively. We assessed approach to equilibrium by performing a time-series of experiments at 1.5 GPa and 1280 °C, with run durations ranging from 3 h to 96 h. The capsules were preconditioned to minimize Fe loss, although we still observed a decrease in FeO (total iron) with increasing run duration. We observed that melt compositions performed between 72 and 96 h were indistinguishable in terms of SiO2, Al2O3, MgO, Na2O, CaO, K2O, MnO, and TiO2, within 1 s.d. value (Supplementary Fig. 4). Thus, a 72-h run duration was chosen to closely approach equilibrium in those experiments. Mass balance calculations yielded a sum of squared residuals <0.39 (FeO excluded), attesting for a close system for all other major oxides. Phase proportions for each experiment were calculated from mass balance calculations and are reported in Supplementary Data 3. Additional information is provided in the Supplementary Information.

**Phase assemblages.** Solidus (PER-SED 95–5 at 1150 °C) and near-solidus (PER-SED 85–15 at 1230 °C and PER-SERP 85–15 at 1230 °C) experiments were performed at 1.5 GPa to determine the phase assemblages at and near the onset of melting. The solidus experiment produced an assemblage of olivine (ol) + orthopyroxene (opx) + clinopyroxene (cpx) + spinel (sp) (± isolated melt drops), while both near-solidus experiments produced silicate melt + ol + opx + cpx + minor sp which typically occurred as small inclusions (~2 μm diameter) in olivine. The compositions of these melts were not analyzed due to their limited exposure. Also, abundant dendrites have compromised their composition. These near- and solidus experiments show that although mélanges have complex mineralogies (Supplementary Data 3), the hybrid peridotite assemblage is standard. At 1280–1315 °C, PER-SED experiments produced the following assemblages: silicate melt + ol + opx + cpx (Supplementary Data 3). Melt proportions vary from 10 to 31%. PER-SERP experiments produced an assemblage of silicate melt + ol + opx + cpx from 1280 to 1350 °C. Melt proportions vary from 3 to 25%. In all experiments, no accessory phase was observed in the chemical maps (Fig. 3 and Supplementary Fig. 2) and high-resolution BSE images (Supplementary Fig. 3). In all 72-hour experiments, an opx-rich reaction band developed along the interface of the accumulated melts and the residue (Fig. 3). The thickness of the opx-rich reaction zone is similar in all experiments, ranging from 125–370 μm. The opx-reaction zone is not present in the 3-hour experiment due to the short run duration (Supplementary Fig. 2). Mineral compositions are homogeneous in individual experiment and show variability between experiments (Supplementary Data 5). Modal proportions in each experiment were calculated using the mass balances (excluding FeO) and are reported in Supplementary Data 3. Representative EDS maps and BSE images are presented in Supplementary Fig. 3.

**Major element composition of the melts.** The major element compositions of hybrid peridotite-mélangé melts are reported in Supplementary Data 2 (volatile-free basis). They range in composition from trachyandesite to basaltic trachyandesite and basaltic compositions (49.9–56.5 wt. % SiO2, 2.2–8.8 wt.% Na2O + K2O) with increasing melting temperatures. The water contents of the melts range from ~0.6 to ~5 wt.% and were estimated from the difference between major element totals and 100%. The melts also show a large range in Al2O3 contents (14.8–19.5 wt.%) and MgO contents (7.0–15.9 wt.%) (Supplementary Fig. 5). The melt composition is homogeneous throughout the capsule and

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**Fig. 1** Conceptual illustration of mélangé-peridotite interaction in subduction zones. Experiments performed in this study simulate the partial melting of a wedge peridotite, hybridized by mélangé material that ascended from the slab-top.
Figure 2: Global variability of mélanges plotted in terms of immobile elements, Cr/Al versus Al₂O₃. The two types of mélanges matrices used in this study cover a large range of the natural variability of mélanges, with one matrix that carries a serpentinite/ultramafic flavor and one matrix that carries a sediment (GLOSS) flavor. Literature data sources: Global mélange compilation, abyssal, mantle wedge and subducted serpentinite compilation, MORB compilation, DMM composition, and GLOSS.

Figure 3: Mg compositional map of a representative experiment, PER-SERP (85-15), performed at 1.5 GPa and 1315 °C. An opx-rich reaction zone was observed along the interface between the melt pool and the residual minerals (green band). PER-SERP experiments produced hydrous melt + ol + opx + cpx at all temperatures investigated.

Experimental melts from PER-SERP experiments range from the boundary between tholeiitic and calc-alkaline fields to high-K calc-alkaline field (Fig. 5). On the other hand, experimental melts from PER-SERP experiments plot tightly within the tholeiitic field. Experimental mélange-type 2 melts show a strong enrichment in K₂O and plot in the ultrapotassic shoshonitic field. Our results, along with the experimental data of Cruz-Uribe et al., highlight a continuum in alkali enrichment from tholeiitic melts produced by melting of mantle hybridized by serpentinite-dominated mélangé, to calc-alkaline melts produced by melting of mantle hybridized by sediment-dominated mélangé materials, to ultrapotassic shoshonitic melts from melting of pure sediment-dominated mélangé materials.

Trace element composition of the melts. The trace element compositions of hybrid peridotite-mélange melts are presented in N-MORB-normalized spider diagrams (Fig. 6) along with global arc data, with emphasis on the dominant primitive arc magma types (i.e., calc-alkaline and tholeiite), and published experimental studies that provided both major and trace element contents of experimental melts (Supplementary Data 4). Primitive calc-alkaline arc magmas are geochemically characterized by up to two orders of magnitude higher trace element concentrations compared to primitive arc tholeiites. Pure sediment melts and melts from olivine hybridized by sediment melts have higher trace element concentrations than global arc magmas and display elemental fractionations that are different from global arcs (e.g., Ba/Th, Sr/Nd). Other previous studies display trace element abundances that plot in the highest range for natural arc magmas, but with major element compositions that are missing CaO or reflect ultra-potassic melts (high K₂O). Here we show that, compared to N-MORB, partial melts of hybrid peridotite-mélange materials display enrichment in LILE (e.g., Ba, Th, Sr, K), high LREE/HREE (e.g., Ce/Yb), high LILE/HFSE (e.g., high...
Th/Nb, Ba/Nb, and K/Ti), and plot tightly within the trace element fractionation range defined by global arc data (Fig. 7). Experimental melts from PER-SED experiments record elevated trace element concentrations and show fractionations that are characteristic of primitive calc-alkaline magmas. Sr/Nd ratios still fall within the range of global arcs (Fig. 7), although within the lower range of values. Experimental melts from PER-SERP experiments display trace element concentrations that are an order of magnitude lower than melts from PER-SED experiments, and show a slight enrichment in Sr relative to Ce and Nd. In PER-SED experiments, Zr-Hf are slightly enriched compared to Sm and Ti, whereas in PER-SERP experiments, Zr-Hf are not fractionated from Sm and Ti. Trace element concentrations in the melts generally decrease with increasing temperature, consistent with dilution at higher melting extents in the absence of accessory phases that would retain trace elements in the residue. Overall, melts produced from melting of a peridotite source hybridized by mélange rocks (this study) carry trace element characteristics of arc tholeiites and calc-alkaline magmas, respectively.

Discussion

Geodynamic models of rising mélange diapirs have predicted an uneven distribution of mélange rocks in the mantle wedge that involves both complete and incomplete mixing of mélange rocks and peridotites\(^3\). Our experiments investigate a scenario where the peridotite mantle wedge and limited volumes of mélange rocks are fully mixed and form a new hybrid source that partially melts (Fig. 1). As the extent and volumetric significance of mélange rocks at the slab-mantle interface are still debated, a growing number of studies support their ubiquitous occurrence and importance at the slab-mantle interface. Petrologic modeling\(^4\), numerical instability analysis of subduction zones\(^4\,4\text{a}\,4\text{b}\), and metamorphic P-T-t histories of exhumed high-pressure mélange terranes\(^4\,4\text{e}\,4\text{f}\) strongly support the possibility of exhumation of high-pressure rocks through diapirism within the mantle wedge. Further experiments will model how the path of mélange materials would be affected by the thermal structure of individual subduction zones but are beyond the scope of the current study.

For the purpose of this study, we consider that the two end-member mélange matrices from Syros (Fig. 2) offer compositions that represent a reasonable first-order approximation of global mélange variability. Our choice of using natural chlorite schist
matrix from Syros (Greece) was guided by the fact that the Syros mélange record the mechanical and metasomatic interactions at P–T conditions appropriate for slab-mantle interface at depths of about 50–60 km in subduction zones. In addition, the chloride ± calc-dominated assemblage in global mélange matrices (including Syros mélange) is relatively insensitive to pressure, making them a reasonable proxy to the type of mélange extending down to sub-arc depths. Importantly, our natural starting mélange materials record minimal late-stage modification and overprinting during their exhumation, making their mineralogy, elemental, and volatile concentrations closely approximate the in-situ compositions of mélange rocks at the slab-mantle interface. Thus, the present study offers a reasonable approximation of subduction dynamics where mélange rocks formed at 1.6–2.2 GPa, detach from the slab and homogenize in the hot zones of the mantle wedge at 1.5 GPa (~45 km depth).

Results from our experiments support the idea that primary melts in arcs are not only limited to MgO–rich (up to 15.9 wt.%) basalt but may also resemble trachyandesite and basaltic trachyandesite with MgO contents of around 7 wt.% (Supplementary Data 2), covering the MgO range of primitive magmas. All of our experiments display CaO, K2O, Na2O, TiO2, and P2O5 that more accurately reproduce the chemistry of global arc magmas compared to previous studies that simulated hybridization of the wedge by discrete slab melts or discrete sediment melts. The fact that the hybrid source is largely peridotite-like (85–95%) explains why realistic, arc-like major element compositions can be produced in our experiments. Indeed, the large dominance of mantle-equilibrated arc magmas from different subduction zones should reflect the fundamental control of mantle peridotites in controlling the major element compositions of primary arc melts.

The presence of mélange components within the mantle wedge significantly affects the trace element budget of melts generated by melting of a mélange-hybridized mantle source. Although hydrous melting of peridotite would typically produce melts that display a MORB-like trace element pattern, the trace element compositions of peridotite-mélange melts show striking similarity with global arc magmas, with enriched LIL and LREE such as Ba, Th, and K, and depleted HFSE such as Nb and Ti. Previous experimental studies on mantle hybridization by slab melts and sediment melts also produce melts enriched in LIL and depleted in HFSE. The peridotite-mélange melts plot tightly within the range defined by global arcs for ratios that have traditionally required discrete sedimentary, slab melt, and/or AOC fluid addition to the arc magma source. In particular, the peridotite-mélange melts carry arc-like Sr/Y, Th/Nb, Ba/Th, K/Ti ratios among others.

In nature, there exists a large compositional variability in primitive arc magmas, ranging from arc theoleites to calc-alkaline and shoshonites. However, such compositional variability and their spatial distributions (or the lack thereof) have not been satisfactorily explained. Primitive arc theoleites are usually thought to be produced by decompression style melting (similar to MORB), whereas the classically invoked model for the formation of primitive calc-alkaline magmas envisages their production by flux melting of the mantle induced by the addition hydrous slab components. These slab components are responsible for the up to two orders of magnitude higher trace element concentrations of primitive calc-alkaline magmas relative to N-MORB. For instance, the elevated Th–Zr–TiO2 concentrations of primitive calc-alkaline magmas reflect higher slab contributions in their sources. We have shown that melts produced from melting of a mantle hybridized by sediment-dominated mélanges (PER-SED) strongly resembled primitive calc-alkaline magmas whereas melts produced from melting of a mantle hybridized by serpentinite-dominated mélanges (PER-SERP) strongly resembled primitive arc theoleites, both in terms of major (e.g., K2O, TiO2) and trace element abundances (e.g., Ba, Th, Zr) and in terms of fractionation characteristics.

It is critical to determine whether those abundances and fractionations are simply inherited from the starting material or if they are enhanced during melting of the mélange-hybridized peridotite. We make several important observations regarding elemental abundances and fractionations in the melt compared to the starting materials. The bulk starting compositions of PER-SED 95–5 and PER-SERP 85–15 experiments (the two types of experiments that are dominated by ultramafic component – either peridotite or serpentinite) fall either outside of the global arc range or within the lower range of values observed in arcs. It is thus clear that melting plays an important role in producing elemental abundances that are similar to values observed in global arc magmas.

The bulk composition of PER-SED 85–15 experiments (more strongly influenced by a sediment-dominated mélange) is already similar to global arcs for most elements, and less surprisingly, melting produces melts that are also similar to arcs. Yet, regardless of abundances, characteristic element ratios acquire a slightly enhanced "arc-like" signature for most elemental ratios.
during melting of mélange-hybridized peridotite. Specifically, Ba/Th, Sr/Y, Zr/Hf, Zr/Sm, and K/Ti slightly increased in melts compared to the starting materials; Ba/Nb, Sr/Nd, and Sm/Nd stay relatively unchanged whereas Th/Nb and Th/Zr slightly decreased compared to the starting materials (Fig. 7).

Experimental melts produced from PER-SED experiments have higher Ba than melts produced from PER-SERP experiments because the sediment-dominated mélange matrix initially had a higher Ba content than the serpentinite-dominated mélange matrix (Supplementary Figs. 6 and 8). Still, melts that are produced during melting of PER-SED and PER-SERP starting materials have slightly higher Ba/Th, Sr/Y, Zr/Hf, Zr/Sm, and K/Ti and slightly lower Th/Nb and Th/Zr ratios (compared to starting materials), and thus are not only inherited from the starting materials.

In Supplementary Fig. 9, we show that primitive arc magmas mainly record Nb/Ce< 1 (normalized to N-MORB)38, but their Zr/SmN can be below or above 1 and is unrelated to the magma type. In addition to Nb depletion and low Nb/Ce ratios, depletion in Zr and Hf is seen for example in shoshonites from Sulawesi and Fiji, and in calc-alkaline basalts from Solomon and Bismarck43. However, Zr, Hf, and Zr/Hf are actually variable in natural primitive arc magmas. Elevated Zr/Hf and Zr/SmN (> 1) observed in low-degree melts from PER-SED experiments are features that are observed in natural arc magmas such as calc-alkaline andesites from Japan and New Zealand, calc-alkaline basalts from Mexico, and depleted andesites from Izu-Bonin. Meanwhile, low-degree melts from PER-SERP experiments have Zr/SmN < 1 that overlap with some HFSE-depleted arc magmas such as tholeiitic basalts and andesites from Japan, Cascades and Tonga arcs. We note that in PER-SED experiments, elevated Zr/Sm (and Hf/Sm) does not reflect inheritance from the mélange matrix (Supplementary Fig. 6). Instead, the variability in Zr-Hf contents and Zr/Hf in natural mélange matrices most likely reflect some Zr-Hf mobility in the absence/destabilization of zircon15. Overall, the trace element characteristics of our experimental melts plot well within the range of primitive arc magmas (Fig. 7). Thus, these experiments do not only reproduce elemental abundances (major and trace) but also elemental fractionations observed in global arc magmas. In addition, we show that although the trace element compositions of peridotite-mélange melts are partly inherited from the mélanges themselves (i.e., some characteristic subduction signatures may be already imprinted at the slab interface), those arc-like abundances and fractionation signatures can be readily produced and variably enhanced during melting of a mélange-hybridized mantle source (i.e., additional fractionation should occur in the mantle wedge).

Using chemical maps and high-resolution BSE images, we did not observe accessory phases, unlike what had been found in pure mélange melt residues48. Our results indicate that elements that have similar incompatibilities during pure peridotite melting can still be slightly fractionated during mélange-hybridized peridotite
melts. Previous experimental\textsuperscript{17,59} and field-based studies\textsuperscript{60–62} have pointed out that orthopyroxenites should form as reaction products of hydrous melts and mantle minerals. The ubiquitous occurrence of orthopyroxenites exposed in supra-subduction zone ophiolites such as in the Josephine\textsuperscript{62}, Coast range ophiolites\textsuperscript{63}, and UHP Maowu Ultramafic Complex\textsuperscript{64}, and sampled in arc-related xenoliths\textsuperscript{65}, may also potentially record the hybridization of mantle wedge by mélangé materials\textsuperscript{13,11}. Thus, the incorporation of mélangé diapirs into the mantle wedge may also have implications for the formation of mineralogical and lithological heterogeneities in the mantle.

This study has important implications for the understanding of subduction zone magmatism. During subduction, mélangé diapirs may propagate, and dynamically mix with the overlying mantle. Our study shows that depending on the nature and relative contributions of the hybridizing mélangé materials in the source of arc magmas, a large variety of primary magmas with characteristic arc-like signatures can be produced. As LILE-enriched shoshonitic melts are expected to form from melting of pure sediment-dominated mélangé materials\textsuperscript{40}, our study shows that both primitive arc tholeiites and primitive calc-alkaline magmas, which are the two most abundant magma types in subduction zones worldwide, can be produced by melting of mantle hybridized by serpentinite-dominated and sediment-dominated mélangé materials, respectively. The rarer occurrence of ultrapotassic shoshonites as compared to tholeiites and calc-alkaline arc magmas likely reflects the volumetric significance of peridotites in the wedge and the dilution effect due to mixing of mélangé materials with mantle wedge peridotites. The absence of systematic along- and across-arc spatial distributions of primitive tholeiitic and calc-alkaline arc magmas is consistent with the complexity involved in mélangé-diapir ascent paths, and their eventual distributions and mixing with peridotite in the mantle wedge.

In summary, this experimental study provides unique constraints for the role of mélangé materials in arc magmatism, as invoked in previous studies. We have shown that melting of a mélangé-hybridized peridotite represents a mechanism to generate melts with major element, trace element and trace element ratios characteristic of tholeiitic and calc-alkaline arc magmas. In these experiments, the compositions of starting materials, $P$–$T$ conditions, and melting degrees were designed to be as realistic as possible compared to natural processes in the mantle wedge. Where mélangé can form and ascend into the wedge, variations in their compositions, thicknesses, and relative contributions in the arc magma source will likely result in the formation of compositionally diverse primary arc melts and can result in the formation of lithological heterogeneities in the mantle. Mélange transfer from the subducting slab to the mantle wedge may be one of several mechanisms by which arc magmas are produced, but we emphasize that both major and trace element of experimental melts need to be reported to better assess how closely we can simulate arc processes. Although further experiments will help decipher the type and amount of mélangé materials that could be involved in individual subduction zones, we show that hybridization of peridotite by buoyant mélangé rocks is a viable process to transfer crustal signatures from the slab surface to arc magmas.

**Methods**

**Starting material preparation.** Alteration-free, natural peridotite (LZ-1; type-locality in Lherz, France) was ground to a fine powder using agate ball mill. The bulk composition of LZ-1 is similar to DMM\textsuperscript{66} in major and trace element compositions (Supplementary Fig. 1) and is here considered to be representative of peridotite mantle wedge. Following grinding, the LZ-1 powder was loaded into a nickel basket and preconditioned in a 1-atm vertical gas-mixing furnace at 1100 °C with $\mathrm{O}_2$ maintained at the FMQ buffer (Fayalite-Magnetite-Quartz buffer) for 96 h. This $\mathrm{O}_2$ was adjusted by changing the partial pressures of CO and $\mathrm{CO}_2$ gases.

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**Fig. 7** Trace element ratios of experimental melts compared to natural arc magmas. Trace element fractionations of experimental peridotite-mélange melts (a–c) compared to the bulk starting compositions (yellow, green, and red lines) and global arc ratios defined by Turner and Langmuir database\textsuperscript{35} (white rectangles).
in the furnace, and is within the range of estimated $\bar{O}/F$ for sub-arc mantle. Two chloride schist matrixes from Syros (Greece) were selected to represent two end-member compositions of global mélange rocks: the sediment-dominated mélange matrix (SY400B) and the serpentinite-dominated mélange matrix (SY325). Both natural mélange matrixes contain water contents of ~2–3 wt.%. We acknowledge that there exists a wide range in chemical and mineralogical compositions of exhumed mélange rocks worldwide and that there is no single rock material that closely approximates such wide variability. In order to account for this variability and capture its first-order variability, we selected two mélange matrix rocks from Syros (Greece) based on mineralogical assemblages (Supplementary Data 1), immobile element chemistry (Fig. 1), and trace element chemistry (Supplementary Fig. 5). In Supplementary Data 5, the mélange assemblages of SY400B and SY325 are consistent with being derived from a sediment-like and ultramafic/serpentinite-like protoliths, respectively. Using immobile element systematics, Fig. 1 shows a mixing trend between serpentinites and sediment/upper crustal rocks to account for the range in global mélange variability where mélange material SY400B plotted close to GLOSS composition while SY325 plotted close of DMM composition. In Supplementary Fig. 5, the trace element composition of SY400B closely resemble the GLOSS composition while SY325 broadly resemble the DMM-like peridotite, with exception for some highly fluid-mobile elements (e.g., U, K). SY400B and SY325 from Syros record minimal late-stage modification and overprinting during their exhumation, making their mineralogy, elemental and volatile concentrations closely approximate the in-situ compositions of mélange rocks at the slab-mantle interface. Taken together, the mineralogy, immobile element (Cr vs Cr/Al) and trace element chemistry strongly support for the representability of mélange matrix (SY400B) and SY325 to cover for the first-order variability in global mélange composition. Since Syros mélange is one of the most studied and well-constrained examples of hydrous melting and overprinting melanges in terms of its metamorphic P-T-t condition and mélange matrix16,70 and mélange formation17,17,22, we have more control on the conditions at which our starting materials have been subjected to and the processes that led to their formation.

In this study, natural mélange materials were grinded to fine powders using agate ball mill. PER-SED 95–5 starting material was prepared using 95 vol.% of LZ-1 and 5 vol.% of SY400B, PER-SED 85–15 was prepared using 85 vol.% of LZ-1 and 15 vol.% of SY400B, and PER-SERP 85–15 was prepared using 85 vol.% of LZ-1 and 15 vol.% of SY325. The peridotite and mélange compositions were completely homogenized through a thorough process of mixing under ethanol in an agate mortar for 6 cycles, where each cycle is 1 h of grinding. The resulting powder mixes were stored in a dry box until use. Whole-rock compositions (major and trace elements) of LZ-1, SY325, SY400B as well as PER-SED 95–5, 85–15, and PER-SERP 85–15 are summarized in Supplementary Data 1.

Experimental setup. Partial melting experiments were performed in 0.5” end-loaded solid medium piston cylinder device27 at the Woods Hole Oceanographic Institution (USA). The starting mixes were packed in Au80Pd20 capsules conditioned (Fe-saturated) to minimize Fe loss35. The Au80Pd20 capsules were conditioned by packing MORB-like basalt powder (AI92 29 –) at 1250 °C in a 1-atm vertical gas-mixing furnace with 15% H2 and 85% N2 at 1 log unit below FMQ buffer for 48 h. Ideally, we would have used actual starting materials to condition the capsules, but due to limited quantities of starting materials we considered that a MORB-like basalt would provide enough Fe to saturate the capsules. The silicate glass was removed from the Au80Pd20 capsules using 2H2O/4H2O gases. When loading the starting material into the conditioned Au80Pd20 capsules, approximately 35–45 mg of the starting mix was first packed in the capsule and then topped with 3.5–4 mg of vitreous carbon spheres (80–200 μm in diameter) to act as melt entrapments. The capsule was triple-clamped and welded shut. All the experiments were performed in a CaF2 pressure assembly with pre-dried crushable MgO spacers, straight-walled graphite furnace and alumina linings. The sealed capsule was strategically positioned in the assembly such that the top portion of the capsule is the side that contains the vitreous carbon spheres to facilitate easy migration of melt during the experiment. Silica powder was placed in between the sealed capsule and graphite pressurizing sleeve to fill up the space and maintain the capsule’s position. Lubricated Pb foils were used to contain the friable CaF2 assembly and to provide lubrication between the assembly and the bore of the pressure vessel. The experiments were performed at 1280–1350 °C and 1.5 GPa, relevant to arc magma generation54,55. Run duration was set at 72 h after verifying approach to equilibrium from a 3 h to 96 h time-series (see paragraph below). Pressure was measured with a PtO2–PtO electromotive force thermocouple with 8.4 keV voltage, 500 pA to 1 nA current and ~10 µm beam diameter at 1280 °C at varying run durations of 3 h, 24 h, 48 h, 72 h, and 96 h. We performed the time-series experiments at the lowest temperature used in this study (1280 °C) such that it provided the maximum amount of time necessary to approach equilibrium. We observed that the melt compositions obtained after 72 h to 96 h were indistinguishable within 1 s.d. values in terms of SiO2, Al2O3, MgO, Na2O, CaO, K2O, MnO, TiO2, and P2O5 (Supplementary Fig. 4). It has been shown experimentally that hydrous melting of peridotite produces melts with ~6 wt. % contents as anhydrous equivalents (~8 wt.%), but we also observed a decrease in FeO with increasing run duration, which suggests Fe loss. We speculate that this Fe loss/depletion reflects one or a combination of the following causes: (1) Fe diffusion to the Au80Pd20 capsule due to incomplete Fe saturation for a nominal energy of 4.5 keV. The energy window of the mass spectrometer was set to 30 eV. (2) Some of the Fe may have been lost from the sample due to alkali diffusion in glass, Na was analyzed first for 10 s on peak and 5 s on background. In order to prevent alkali diffusion in glass, Na was analyzed first for 10 s on peak and 5 s on background. All phases (melt and coexisting minerals) were quantified using silicate and oxide standards. The compositional maps for different major elements were performed at similar instrumental setup using a focused beam. Major element compositions of melts and minerals are reported in Supplementary Data 2 and 3, respectively.

Secondary ion mass spectrometry. Concentrations of selected trace elements in melts (primarily <30 μm diameter) were obtained using Cameca IMS 3F ion microprobe at the Northeast National Ion Microprobe Facility (NENIFM) at the Woods Hole Oceanographic Institution (WHOI). Analyses were done using 16O+ primary ion beam with 8.4 keV voltage, 500 pA to 1 nA current and ~10 μm beam diameter. No raster was used in the beam. Positive secondary ions are accelerated to mass 1 (m/z 1) and mass 2 (m/z 2) at 6 keV. We did not calibrate the field aperture size to account for the field of view at each sample from the scan area to the sample. Each measurement consists of four minutes of pre-sputtering, then five cycles with an integration of 10 s/cycle for 36Si and 10 s/cycle for elements 16O, 18O, 89Y, 90Zr, 95Nb, 138Ba, and 30 s/cycle for 148Ce, 142Nd, 146Sm, 111Cd, 187Hf, 232Th, and 235U. Th concentrations are reported if they are above detection limit. The beam diameter varied from 10 to 40 μm for all measurements so U is not reported. In total, each analysis setup requires a total analysis time of approximately 60 min. Reduced trace element concentrations of melts obtained by SIMS are reported in Supplementary Data 2. Internal errors from analyses (2 SE) and error from calibration curves (2SE) have been propagated and are incorporated in the total 2 SE error reported in the figures and Datasets.

X-ray fluorescence technique (XRF). Whole-rock elemental concentrations of LZ-1, SY400B, and SY325 were analyzed using X-ray fluorescence technique for rapid and non-destructive bulk analysis. The beam diameter varied from 10 to 40 μm for all measurements so U is not reported. In total, each analysis setup requires a total analysis time of approximately 60 min. Reduced trace element concentrations of melts obtained by SIMS are reported in Supplementary Data 2. Internal errors from analyses (2 SE) and error from calibration curves (2SE) have been propagated and are incorporated in the total 2 SE error reported in the figures and Datasets.
Major element variability of residual phases. Major element compositions of residual minerals are homogenized through the capsule in individual experiments, and vary between experiments due to differences in temperature and starting compositions (Supplementary Fig. 10). They are within the range of values observed in peridotite worldwide, although Fe loss probably artificially increased Mg# of minerals (93–96 in olivine, 91–95 in clinopyroxene; 92–95 in orthopyroxene). Temperature (1280–1350 °C) has variable effect on mineral compositions. For example, with increasing temperature, olivines display a slight decrease in Al₂O₃, a constant CaO, and a slight increase in MgO. DAl₂O₃ opx/melt decreases with increasing temperature. Orthopyroxenes display a slight decrease in TiO₂ and Al₂O₃ with increasing temperature, whereas SiO₂ and MgO increase, and CaO is constant. As predicted experimentally, DAl₂O₃ opx/melt decreases with increasing temperature and DAl₂O₃ oxp/melt increases with increasing temperature. Clinopyroxenes show limited major element variability between all experiments. The mineral compositions are reported in Supplementary Data 5.

Data availability. The authors declare that all data generated during this study are included in this published article (and its Supplementary Information Files).

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Author contributions
V.L.R. and E.A.C. contributed equally. V.L.R. designed the study, collected the peridotite material in this article are included in the article CC-BY license, and indicate if changes were made. The images or other third party material in this figure accompanies this paper at https://doi.org/10.1038/s41467-018-05313-2.

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