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Arclogites and their role in continental evolution; part 2: Relationship to batholiths and volcanoes, density and foundering, remelting and long-term storage in the mantle

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A R T I C L E I N F O

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A B S T R A C T

Arclogites are eclogite-like rocks formed magmatically as ultramafic residues and cumulates in the roots of thick arcs (Ducea et al., 2021 companion paper). They are inferred to be volumetrically important assemblages to complement subduction-related magmatic rocks at depth, in areas where the upper plate crust is thick. At the surface and in the shallow crust, these arcs form stratovolcanoes found at many sites around the Pacific and batholiths, which are exposed in extinct arcs, such as the western North American Cordillera. Arclogites complement these shallower manifestations of magmatism in subduction zones in that they represent the ultramafic residues left behind following the extraction of intermediate melts. Mass balance calculations constrained by the low silica contents of garnet, amphibole, and iron-titanium oxides dictate that the silica content of a given arc tracks with the volume of arclogitic residues beneath it. We show that melt extraction takes place in punctuated events of hot-zone evacuation of the lower crust which effectively make up the magmatic flare-ups documented in the mid- to upper-crust. These cyclic events lead to the densification of arclogitic residues and trigger their foundering. We show that in addition to garnet, Fe—Ti oxides play an important role in the densification of roots and can trigger foundering even in garnet-free arcs. Recent models show that foundering may be small scale and lateral shearing may have an important role in removing sub arc residues. Consequently, previously postulated large magnitude uplift and large-scale mantle-derived magmatism may not accompany foundering episodes. Partial melting of descending arclogitic bodies is expected to produce small amounts of nepheline (and/or leucite) normative magmas similar in composition to alkaline massifs found in continental interiors, not basaltic or intermediate melts. The foundering rates of arclogites are calculated to be around 20–40 km^3/km/Myr in Phanerozoic arcs. The fate of foundered arclogite may include stalling at the 660 km discontinuity, accumulation and mixing with subducted oceanic material at “slab graveyards” along the core-mantle boundary, and/or disaggregation via ductile flow in the mantle. Regardless, there has to be a reservoir in the mantle representing these lower crustal recycled bodies over time. We show that the most likely such reservoir is EM1, one of the well-known and commonly identified recycled material in ocean island basalts, and that 1–3% of the volume of the mantle may be made of this reservoir.

1. Introduction

Arclogites (Lee and Anderson, 2015; companion paper by (Ducea et al., 2021) and references therein) are clinopyroxene-garnet-amphibole±Fe oxide-bearing rocks representing the residues (the sum of partial melt restites and magma chamber cumulates) found in the root of the thickest magmatic arcs in subduction systems. They complement large scale batholiths and volcanic arcs found in subduction settings where the upper plate is continental and possibly where it is transitional (oceanic-continental) (Ducea et al., 2015a; Ducea et al., 2021) . These rocks are found mostly as xenoliths in volcanic rocks that form in arc regions (Ducea and Saleeby, 1996; Lee et al., 2006); rarely they may be found in

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deep crustal exposures of arc sections or in tectonically exposed mantle massifs (see companion paper by (Ducea et al., 2020) for a description of main occurrences). Not all subduction-related arcs have arclogites in their roots; they are not predicted to exist in short lived arcs or thin arcs, such as those formed in many oceanic settings simply because the root assemblages there would not be rich in garnet, a key mineral in arclogites (Jull and Kelemen, 2001). Where they do exist, they represent the lowermost part of the crust, as it transitions to the sub arc mantle (Fig. 1).

Here we review data pertaining to: 1) the relationship between the development of arclogite and shallower manifestations of arc magmatism, 2) the role of depth of lower crustal hot zones in driving arcs toward a more siliceous average composition, 3) arguments for the foundering of arclogites during and after arc magmatism, 4) predictions for partial melting of dripping arclogites, 4) the rates of foundering, and 5) the possibility of long term storage of these materials in the mantle.

2. Punctuated melt evacuation of arc root zones

Surface volcanism in subduction zones and batholith formation at depth appear to be non-steady state processes, with episodes of high flux (flare-ups) separated by low flux events (magmatic lulls) (Paterson and Ducea, 2015). To our knowledge, there is no place where magmatic fluxes have been positively correlated with convergence rates; in fact, where sufficient data exists, plate rates and other subduction parameters do not appear to influence magmatic tempo in arcs (Ducea, 2001; Ducea et al., 2015a). While it is still possible that mantle processes drive some flare ups (Attia et al., 2020), the more likely scenarios for modulating arc fluxes are: 1) adding melt fertile material to the arc base from the back arc (DeCelles et al., 2009), the forearc (Haschke et al., 2002; Ducea and Chapman, 2018), the trench (Cavazos-Tovar et al., 2020; Straub et al., 2020), or the arc itself (e.g., Paterson and Farris, 2008); and/or 2) punctuated episodes of evacuation of melt-rich lower crustal hot zones. We believe that both processes help trigger high flux events. While the first type of mechanism is supported by temporal correlation of arc flare-ups with structural data from forearcs/back arcs and is relatively well documented (Chapman et al., 2013; Ducea et al., 2015b), the second is less well understood but nevertheless critically important for understanding the evolution of sub arc roots.

One angle for tackling this problem is through the investigation of zircon U—Pb cargo in large batholiths. The example chosen here is the Mesozoic to Early Cenozoic Coast Mountains batholith of British Columbia and SE Alaska (Barker and Arth, 1984; Armstrong, 1988; Gehrels et al., 2009; Cecil et al., 2011). Age-trace element ratio relationships (e.g., Sr/Y and La/Yb) point to several root formation and removal events as the Coast Mountains batholith went through multiple flare-ups and lulls (DeCelles et al., 2009; Gehrels et al., 2009; Girardi et al., 2012). Among the magmatic episodes, the Eocene fare-up was among the most voluminous (Gehrels et al., 2009) and was complemented by garnet and amphibole-rich residues (Girardi et al., 2012), probably arclogite. This latest root has since been removed (Calkins et al., 2010) as Quaternary shallow mantle rocks have completely different isotopic signatures than mafic rocks of the batholith, and different than mid Cenozoic mafic rocks (Manthei et al., 2010).

The zircon archive on the southern Coast Mountains shows that plutons crystallized during high flux events contain numerous inherited zircon crystals that are only slightly older that the crystallization age and which are high U/Th. They are found in these plutons in addition to the dominant low U/Th grains that are used to define a much tighter crystallization age (Gehrels et al., 2009, Fig. 2). High U/Th zircons are believed to have formed in a high temperature metamorphic environment, extending into migmatitic domains (Hoskin and Schaltegger, 2003), where Th is sequestered by another crystallizing phase, particularly monazite. We interpret these "trails" of near crystallization high U/Th zircon to have been formed in the sub batholithic lower crustal hot zones. With addition of basaltic melts from the mantle wedge, the percentage of partial melt in lower crustal hot zones becomes high enough to evacuate intermediate magmas into the mid – to upper crust and form the plutons seen today in the geologic record. Note that the Late Cretaceous and Eocene magmatic flare-up events (shown on right) correspond with events that include high U/Th inherited zircons of near-crystallization ages. On the other hand, the oldest, Jurassic high flux event known regionally, does not appear to be accompanied by a similar peak in metamorphic zircons; this is possibly due to the much lower number of zircons preserved from the older magmatic events.

We propose that such episodes of melt extraction/evacuation are critically dependent on melt fraction and require several tens of percent of partial melt to accumulate. Such episodes lead to the densification of the root which ultimately is prone to foundering in the mantle, as evidenced in above mentioned batholith by the dramatic change in chemistry/isotopic signatures of the post arc mafic magmatism (Manthei et al., 2010).

3. Arclogite: driving arc silica up

A hotly debated issue is what causes the intermediate composition of arc magmas. There are some that envision that andesitic compositions are extractable by various mechanisms (of which slab melting is just one) directly out of the mantle (Kelemen, 1995; Straub et al., 2011; Castro et al., 2013; Gómez-Tuena et al., 2018). This is well within the realm of possibility in some arcs such as the trans Mexican segment of the Pacific-North American subduction system. If and where intermediate rocks are extracted directly out of the mantle, the issues of a sub arc root, their volume and final destinations are not nearly as difficult as they are for the opposite end member hypotheses, which states that mostly basaltic melts are extracted out of the mantle wedge (Hildreth and Moorbath, 1988, Rudnick, 1995 among many others). The authors of this paper have studied numerous mid- to deep-crustal exposures of several Cordilleran arcs (southern Sierra Nevada, Salinia, Famatinia, Coast Mountains batholith) and noted that the great majority of igneous rocks ponded in the deeper crust of these arcs are basaltic (gabbroic) with little to no observational evidence for intermediate magmas making it from below the Moho (Ducea and Saleeby, 1998b; Ducea et al., 2003; Kidder et al., 2003; Ducea et al., 2010; Otamendi et al., 2012; Walker Jr et al., 2015; Ducea et al., 2017). Consequently, we believe that little magmatic differentiation toward higher silica takes place in the mantle wedge. Even if most magmas formed in the mantle beneath arcs are basaltic, subsequent processes in the arc crust modify that extensively. Many modern arcs located within the oceanic realm (such as the Caribbean, Macdonald et al., 2000) are on average andesitic in composition. The well-studied ancient Kohistan and Talkeetna arcs are also oceanic and intermediate in composition (Jagoutz and Kelemen, 2015). Numerous oceanic arcs accreted to the western margins of North and South America are variable in composition and on average andesitic (Morris et al., 2019; Rossel et al., 2020; Oliveros et al., 2020). Precambrian island arcs of the Pan African orogeny have andesitic composition (Triantafyllou et al., 2020). On the other hand, some segments of continental arcs such as the modern Cascades, while andesitic in composition, are significantly more mafic than others in the central Andes (Ducea et al., 2015b). In all, there is quite a range in bulk arc chemistry from primitive, basaltic, as is the case with the western Aleutians (Conrad and Kay, 1984) to average bulk chemistry straddling the boundary between an andesite and a dacite as many continental batholiths are (Ducea et al., 2015b).

By mass balance arguments alone, the composition of the shallow crustal batholiths and their surface equivalents is constrained by the mineral assemblage left in the residue, assuming that an average basaltic composition is the bulk average of the system. In other words, if the bulk starting composition of a subduction system is mafic and presumably mantle-derived, producing intermediate melts that become intermediate rocks in the upper crust require that some ultrabasic (less silicic than a basalt) composition remains in the residue. If pre-existing higher silica

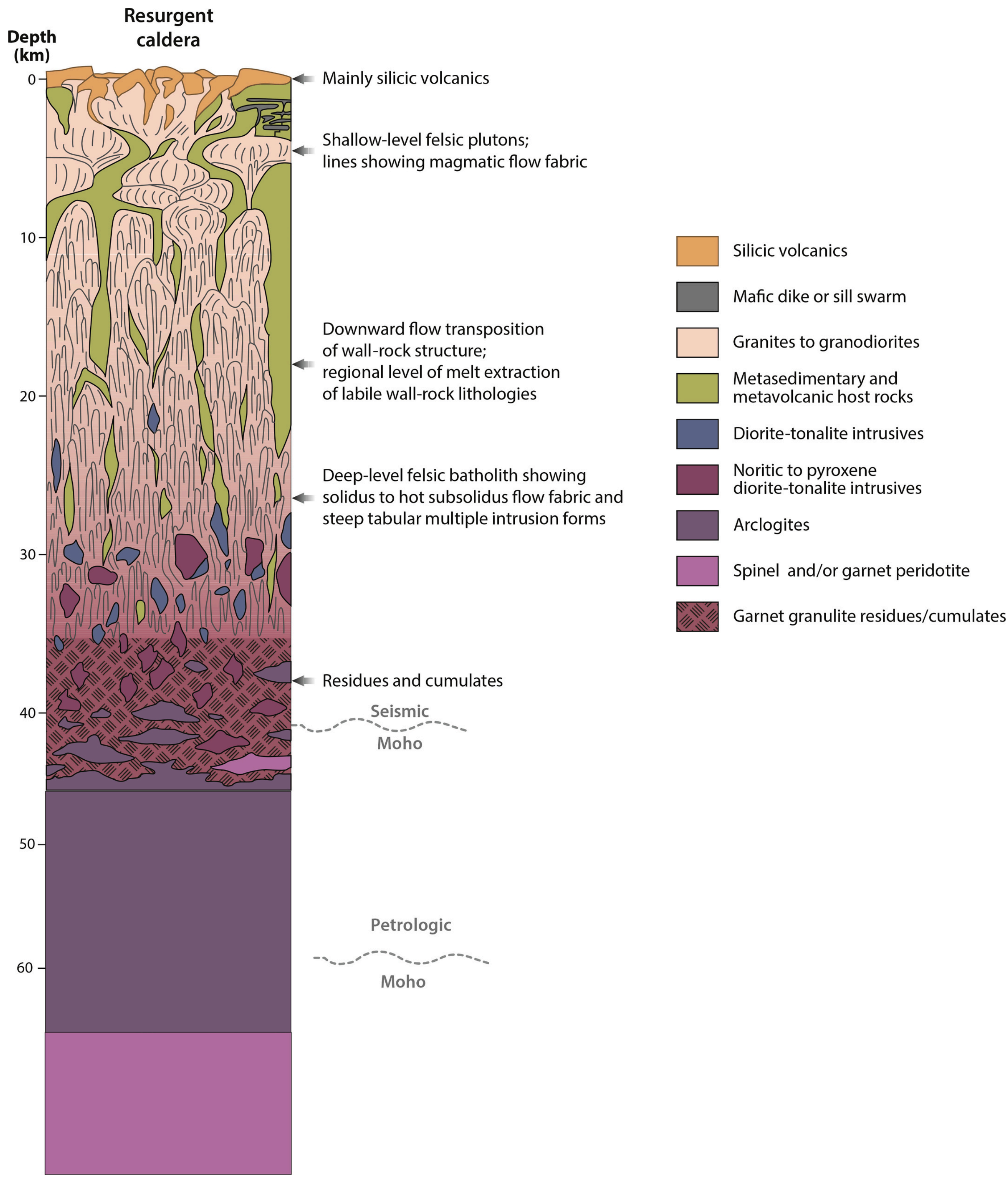

Fig. 1. Schematic cross section through a continental arc from the volcanic cover to the top of the arc root (modified after Ducea et al., 2015b, Saleeby et al., 2003). The vertical composition of the root is represented by granulite facies rocks, followed by abundant arclogites, which gradually give way to typical upper mantle peridotites below 60–100 km depths.

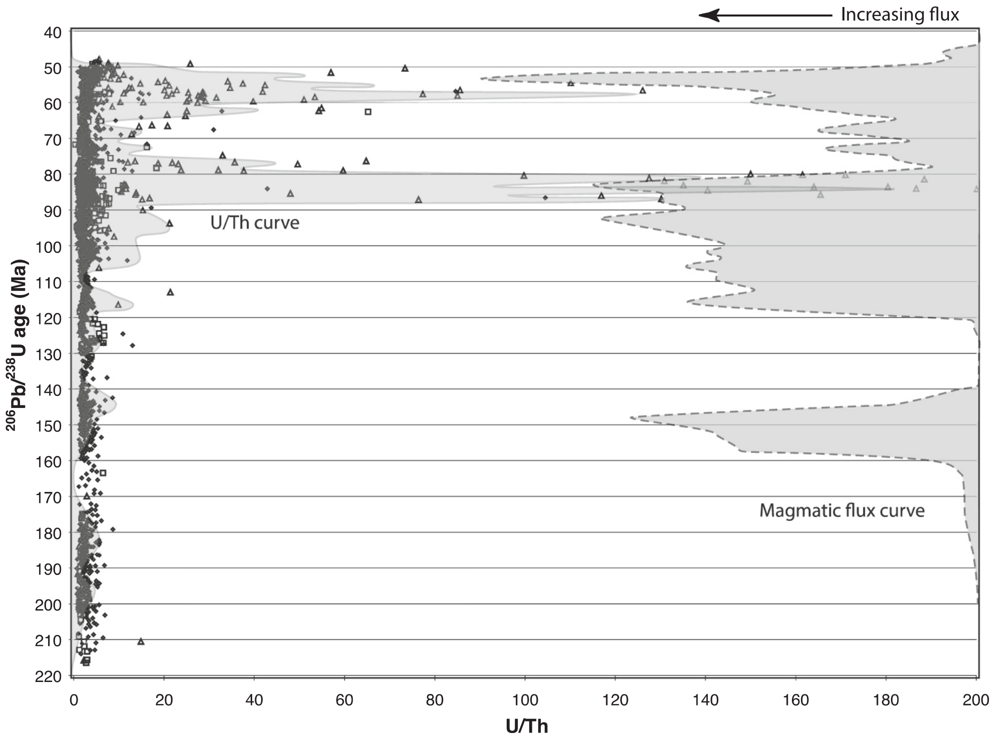

Fig. 2. U/Th values for zircon analyses of the Southern Coast Mountain batholith in British Columbia (52–54^0 N) (modified after Gehrels et al., 2009) conducted by laser-ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS). The U/Th curve (solid line), which is simply the probability density of U/Th values, offers a graphic representation of U/Th through time. Individual zircon grain age and U/Th ratio data are shown as small filled diamonds (considered to be true igneous crystals) and triangles, respectively (metamorphic, inherited grains). The interpreted regional magmatic flux (dashed line, with increasing values to the left) is shown for comparison. We interpret that the late Cretaceous and Eocene high flux events represent episodes of large-scale evacuation of magmas from lower crustal hot zones (see text for discussion).

lower crust is assimilated, the resulting arc will obviously become more silicic (e.g. Ducea et al., 2015b for the Famatinian arc) and the amount of required ultrabasic residue diminishes. If slab melts are involved, as is the case in some parts of the Aleutians (Kay, 1978), that too will drive the arc toward a more silicic composition. But in the simplest scenario, where a mantle-driven basalt ponds into a lower crustal hot zone (Annen et al., 2006; Hildreth and Moorbath, 1988) and fractionates, and/or remelts, the chemistry of the upper part of the arc is complementary to the mineral assemblages of the residue. The shallower the arc (the thinner the crust), the more likely it is that it will be mafic, because the primary minerals on the liquidus are plagioclase and clinopyroxenes, both of which are similar to, or even higher in silica than the basaltic liquid. In thin arcs, amphiboles (Davidson et al., 2007) and oxides are the only residuum phases that drive melts toward higher silica. Crystallization od plagioclase is suppressed in wet basaltic liquids at higher pressures (Blatter et al., 2013). The higher the pressure, with the appearance and then predominance of garnet on the liquidus (with the continuing presence of amphibole and iron titanium oxides), the more silicic the liquid will be (Farner and Lee, 2017). In sum, the thicker the crust of the arc (Profeta et al., 2015), the farther below the surface its "hot zone" will reside, and the more silicic the extracted batholith/surface volcanoes will be. These hot zones occupy a large depth interval and can be tens of kilometers thick (Saleeby et al., 2003; Jagoutz and Kelemen, 2015).

Fig. 3 shows the predicted concentration of silica (red lines) during melting of an average arc basalt (Schmidt and Jagoutz, 2017) as a function of pressure and temperature at the NNO oxygen fugacity buffer. At high melt fractions, silica is almost directly a function of melt fraction. Conversely, at lower melt fractions, melts formed at higher pressure (2–3 GPa) in the 850–1000^{0}C range (one that is reasonable for the temperature of sub arc hot zones) have significantly higher silica (> 60% SiO_2) compared to the those formed at 0.5–1 GPa (55–60% SiO_2). That difference is primarily due to garnet in the residue and is also aided by the presence of Fe—Ti oxides and rutile. The reason why 3GPa is not an unreasonably high pressure to investigate for the behavior of hot zones is that even though crustal thickness is never more than 70 km beneath modern arcs, many of the high density root assemblages are expected to be represent mantle rocks in seismic studies (Saleeby et al., 2003). Arclogites are commonly equilibrated at >2 GPa (Ducea et al., 2021, for a review).

The difference between the average chemistry of the Sierra Nevada and Coast Mountains batholiths and the Famatinian batholith is about 6% in silica (65% SiO2 for the batholiths and 59% SiO_2 for the Famatinian arc, Ducea et al., 2015b). This is broadly consistent with the independently determined 50 km average hot zone depth in North American batholiths (Ducea, 2002) and about 35 km average hot zone depth in Famatinia (Ducea et al., 2015c). Exact matching of depth of arc processing cannot be precisely determined from a diagram like Fig. 3, because of uncertainties in water amount, oxygen fugacities, average arc composition, and the average temperature of the arc. Nevertheless, we

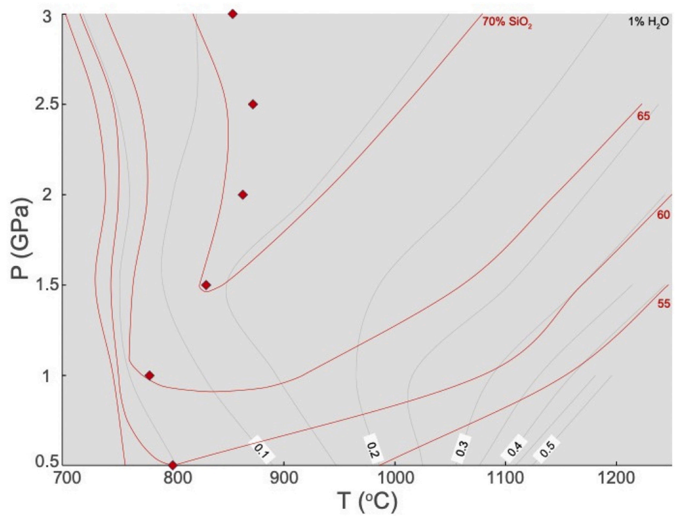

Fig. 3. PT diagram showing the composition of melts formed by partial fusion of average arc basalt with 1% H_2O at NNO oxygen fugacity (modeled using pMelts). Red lines contour the concentration in silica at various P and T conditions, grey lines show fraction of partial melt and red diamonds mark the maximum SiO_2 at 0.5 GPa intervals (0.5, 1.0, 1.5, 2.0, 2.5, 3.0). Diagram shows that within the most plausible temperature range of sub arc root (850–1050 °C) the higher the average pressure, the higher the average silica in arc magmas.

argue that arcs became more silicic if their roots are located deeper, if the crust is thicker.

4. Density and foundering

A major density increase takes place under arcs at around 40 km (Ducea, 2002), below which garnet becomes an important fractionating phase and plagioclase diminishes in abundance. Fig. 4 shows the calculated densities of Sierra Nevada xenolithic arclogites and the pMELTS (Ghiorso and Sack, 1995) predicted distribution of density as a function of depth after melt extraction. Each 100^{0}C cooling also adds roughly 100 kg/m^3 to the overall density of the root. With as little as a more than reasonable 200 kg/m^3 and as much as an extreme and less likely 700 kg/m^3 excess density relative to the underlying mantle, there is little doubt that they are prone to foundering. The foundering of arc roots (as opposed to other forms of lower crustal or lithospheric "delamination" (e.g. Arndt and Goldstein, 1989, Arndt, 2013) was first proposed by Kay and Kay (1991, 1993), supported by experiments (e.g. Rapp et al., 1991, Rapp and Watson, 1995) and followed by the observational recognition of arclogitic compositions beneath some arcs (Ducea and Saleeby, 1996; Ducea and Saleeby, 1998a, 1998b).

Typical densities of arclogites are lowered during arc formation by the presence of partial melt (Ducea et al., 2021). At melt fractions more than about 0.2, arclogitic assemblages are not gravitationally unstable but become so as intermediate melt is extracted (Ducea et al., 2021). The density is greatly influenced by the abundance of garnet and the fact that garnet is relatively iron rich (almandinic). That makes arclogites denser than eclogitized subducted oceanic crust which is relatively poor in garnet (15%) that is relatively magnesium-rich (pyropic). These calculations did not take into account Fe—Ti oxides which can conservatively add another 100 kg/m^3 to the overall density. Magnetite and ilmenite are quite common phases in arclogitic xenoliths, comprising as much as 50% of some xenoliths. Most commonly though they are around 5–10%, with an average of 7%. Fig. 5 shows the effect of iron and titanium oxides on density under different conditions, modeled using Abers and Hacker (2016) for various pressures. An important contributor to density is the amount of melt present in this assemblage (discussed in the companion paper by Ducea et al., 2021).

In sum, arclogitic assemblages are the densest large bodies of any lithosphere, oceanic or continental, and are likely to eventually detach and sink into the underlying mantle. Early models also showed that even garnet free ultramafic roots of oceanic arcs can founder (Jull and Kelemen, 2001). This realization led to early speculations and predictions that wholesale delamination can be fingerprinted by large magnitude magmatism resulting from concomitant mantle upwelling (Kay and Kay, 1993) and isostasy-driven large-scale regional uplift (Garzione et al., 2006). It has become clearer in recent years that both these predictions were slightly off in the magnitude of the process: foundering most likely takes place cyclically under arcs (Jull and Kelemen, 2001; Lee, 2014)

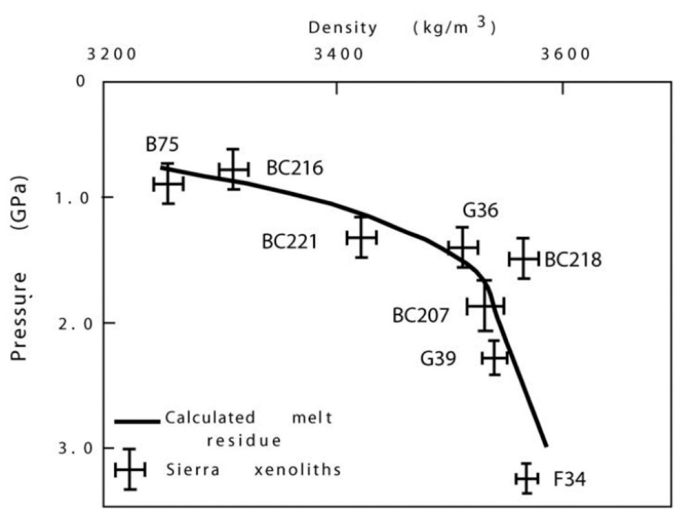

Fig. 4. Diagram showing the calculated densities of the eight arclogites from the Sierra Nevada, against their equilibration pressures (modified after Ducea, 2002). The densities were calculated at the pressures and temperatures of equilibration of the xenoliths using the mineral database of Niu and Batiza (1991) and the modal proportions of various phases. The uncertainties in pressure determinations are given at 1 s level; the uncertainties assigned to the densities are due to errors in pressure and temperature determinations. The solid line represents the pMELTS-calculated density profile for a residual assemblage resulting from partially fusing the average bulk composition of the Sierra Nevada arc plus 1% H_2O at pressures between 0.7 and 3.0 GPa.

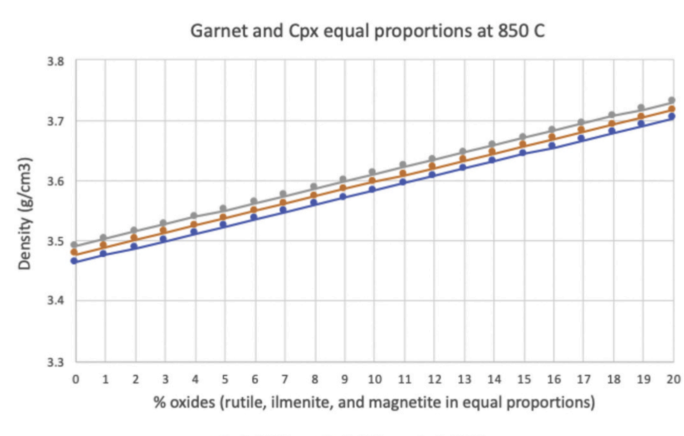

Fig. 5. The role of oxides in increasing density of arclogitic roots. Density is shown for an arclogite consisting of equal proportions of garnet and clinopyroxene to which various amounts of oxides (magnetite, ilmenite and rutile, in equal proportions) are added. Calculations are performed using Abers and Hacker (2016) and arclogitic garnet and clinopyroxene compositions from the literature. Regardless of the pressure, at any given temperature (here shown at 850 °C), about 12–14 kg/m^3 are added for each percent oxide more. At an estimated 7% oxide (average for Sierra Nevada arclogite), oxides add about 100 kg/m^3 to the arclogite density compared to an oxide free assemblage.

and in small volumes (Ducea et al., 2013); consequently, the surface effects on regional elevation and magmatism are much less important than previously envisioned (Currie et al., 2015), at least for this type of foundering.

Lee (2014) lists the basic mechanisms used to model foundering applicable to arclogites and arc roots in general. One is the Rayleigh Taylor instability (Whitehead, 1986; Houseman and Molnar, 1997; Jull and Kelemen, 2001) approach in which the rate at which negatively buoyant material descends into the underlying mantle depends on the magnitude of viscous resisting forces; small perturbations on the instability surface trigger dripping. The second is referred to as wholesale delamination and assumes that a thin, low viscosity layer exists just above the high-density layer promoting the detachment aspect required by the Rayleigh Taylor model (Le Pourhiet et al., 2006; Morency and Doin, 2004). Another plausible mechanism for arclogite as well as mantle lithosphere removal are mechanical "erosion" and/or lateral displacement (tectonic "bulldozing") such as envisioned along the Laramide corridor of the SW USA (see Chapman et al., 2019, 2020, Rautela et al., 2020); here, the ultrashallow subduction (Ducea and Chapman, 2018, and references therein) forces parts of the lowermost crust of the upper plate to be mechanically displaced inboard due to its temporary coupling with the subducting plate. Although not technically foundering, this mechanisms of lateral displacement is considered in the same group of "delamination" sensu *lato* processes. Finally, a fourth, less likely mechanism for foundering is the so-called viscous drainage, in which channel-like instabilities of arclogites "drain" through the underlying mantle lithosphere, without removing it as well (Lee, 2014). This mechanism is much slower than the others and lower viscosities than usually believed to characterize either the drip (the arclogite) or the medium through which it sinks (the mantle lithosphere).

Currie et al. (2015) provide some of the most realistic geodynamic modeling constraints for a sub arc dripping scenario. Those models show that all gravitationally unstable scenarios in sub arc environments lead to foundering of at least 80% of the root. A parameter called root densification, which is the rate of root density increase per time is important for the duration of foundering. Rate of densification is taken as a boundary condition to be proportional with the magmatic flux as more arclogitic root is expected to form if the entire magmatic system is volumetrically more significant. At high densification rates (40 kg/m^3/Myr) drip removal takes less than 3 Myr to complete; at lower rates the process completes within 10 Myr. Currie et al. (2015) also show that there are two competing forces in root instability under arcs: the obvious gravitational one and the lateral shear force driven by the convergence rate (Fig. 6). Depending on how viscous the root is and how large the convergence rate, the mechanism of removal can either be predominantly vertical (drip) or lateral (shear). Fig. 7 shows a model in which the root is strong (twice as strong as the underlying olivine-rich mantle), has a relatively small densification rate and a large convergence rate. The ensuing removal is a mix of drip and shear with the root being removed along a pathway parallel to the subduction interface.

Given the geometric and geodynamic complexities of the mantle wedge region above subducting plate, the removal of arc roots is most likely to be cyclical and relatively small scale (less than a few 10s of km), as envisioned in the models above. These models predict little regional surface uplift (a few hundred meters) based on simple isostatic calculations (Currie et al., 2015). Magmatism of the underlying asthenosphere and/or the sinking drip is discussed below.

5. Remelting arclogites during foundering

Do arclogites melt during foundering? Any foundering lithospheric material is subject to heating and potentially partial melting, especially if it contains water (Elkins-Tanton, 2007). While early foundering (or "delamination") papers suggested that extensive melting of the upwelling asthenosphere is to be expected (Kay and Kay, 1991, 1993; Rapp et al., 1991) rather than the downwelling lithosphere (arclogite or not), this turns out to not be the case in most places were arc root foundering has been proposed (see Ducea et al., 2020, 2021). Lithospheric-derived melts have, on the other hand been described during foundering. In the Sierra Nevada, the *syn*-drip partial melting episode at 3.4 Ma (Farmer et al., 2002) is entirely derived from the downgoing drip, based on geochemistry and radiogenic isotopes of the small-scale basaltic field (Manley et al., 2000 and references therein). From the Sierra Nevada example and lack of extensive asthenospheric basaltic field in foundering are root regions (other tectonic scenarios involving dripping may be responsible for large igneous basaltic provinces) it became more

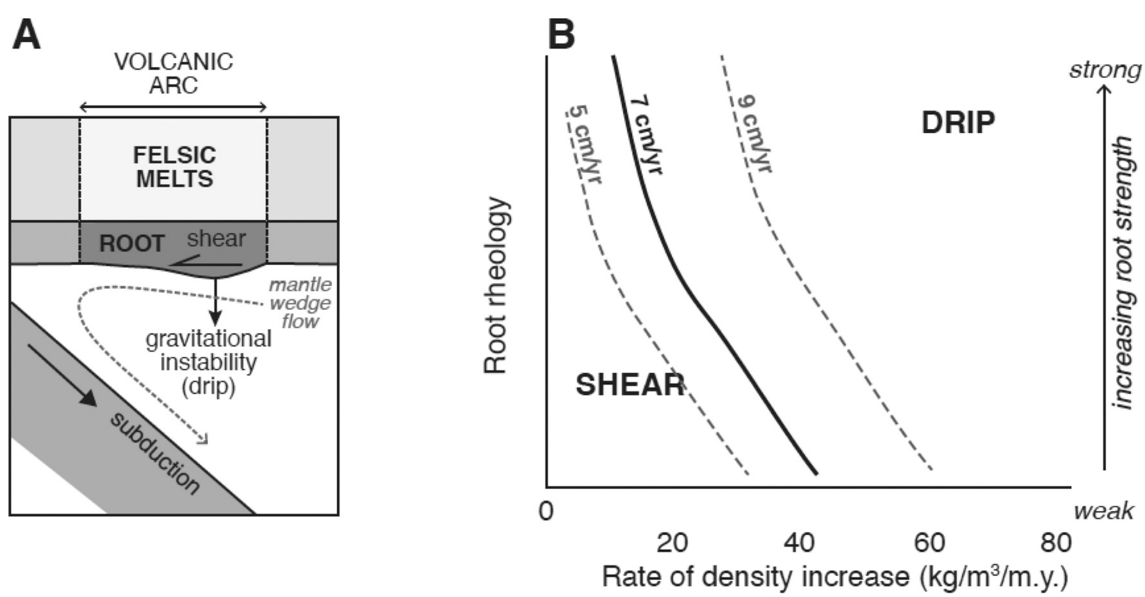

Fig. 6. (modified after Currie et al., 2015) (A) Schematic diagram showing the relationship between root dynamics and subduction-induced mantle wedge flow. Flow perturbs the base of the root, initiating instability. The trajectory of the root as it destabilizes is deter-mined by the relative rates of downward gravity-driven instability growth (Vv) and horizontal entrainment by mantle fl ow (Vh). (B) Diagram showing the style of removal for variations in root densification rate and viscosity (as a linear scaling of the base wet olivine [WO] rheology) for a convergence rate of 7 cm/yr. Drip-like removal occurs where Vv is greater than Vh within the volcanic arc region. Shear entrainment occurs for Vh > Vv. Dashed lines show the boundary between style of removal for variations in subduction rate.

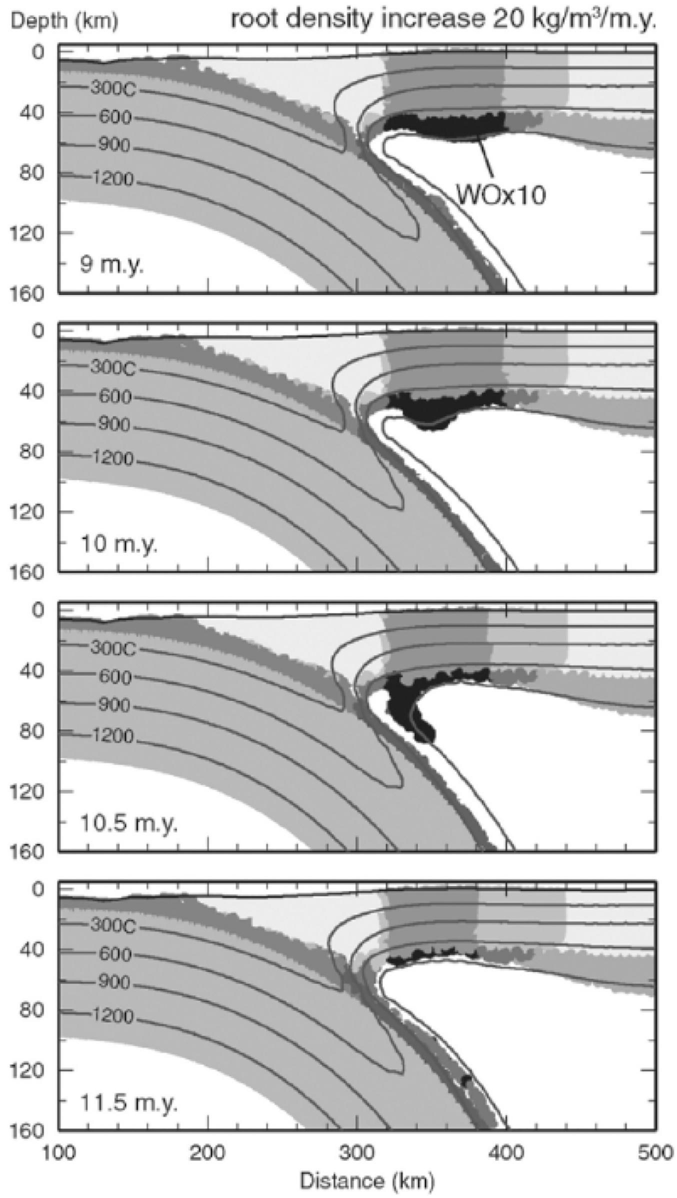

Fig. 7. Evolution of a sub arc foundering model with a strong magmatic arc root with a densification rate of 20 kg/m^3/Myr (modified after Currie et al., 2015). Shading is an indication of various types of crust and lithosphere as in Fig. 6A, except that here two shades of grey are used for the oceanic lithosphere, in order to differentiate oceanic crust (dark grey) from oceanic mantle lithosphere (slightly lighter grey). The darker the shading, the higher the strength. Arclogitic root materials shown in the darkest shade rests on top of an olivine-rich asthenosphere that is 10 times more viscous that that of reference mantle (WOx10) due to the abundance of water in the mantle wedge.

obvious that the downgoing drip may be melting and the best model to explain that was the Elkins-Tanton (2007) paper, even though that conceptual model was not necessarily built for sub arc environments. The key element of the Elkins-Tanton model is that if the drip contains hydrous phases (phlogopite or amphibole) and since the drip is heated as it descends into the mantle, it can cross the wet solidus and partially melt. Melts are expected to be hydrous, rich in alkalis and isotopically lithospheric, just as the Pliocene basalts of the Sierra Nevada are (Manley et al., 2000). Certainly, asthenosphere-derived basalts can form simultaneously as well and they have been documented in some arc regions (Mori et al., 2009).

The model was further developed into a "test for delamination" procedure (Fig. 8, Ducea et al., 2013). The test was to investigate the evolution of a series of basaltic rocks from single or multiple nearby volcanic fields as a function of time (determined by Ar—Ar ages or similar). Primitive, high MgO rocks are used to determine temperatures (Lee et al., 2009; Putirka, 2008), trace elemental chemistry and in particular pyroxenite indicators for the source (Le Roux et al., 2010; Sobolev et al., 2007) together with garnet tracers (high La/Yb, low Nb/Ta). Radiogenic isotopes (Sr, Nd, etc.) are used as secondary tools to determine if perhaps clear lithospheric signals (e.g., radiogenic $^{87}Sr/^{86}Sr$) characterize any of the end members. If temperatures are constant throughout magmatism, there is no indication that a sinking drip is involved in melting; instead decompression along a mantle adiabat (with or without pyroxenites) is the cause of melting. On the other hand, if hotter melts over time are corroborated with geochemical signatures fingerprinting pyroxenites in the source, that is an indicator of some form of vertical tectonics in the mantle (Fig. 8). Positive tests for foundering were found in the central Andes (Ducea et al., 2013) where arclogites most likely play a role, and at the site of slab rollback and detachment of the Vrancea slab (Balica et al., 2020), a well-known site for vertical tectonics in the mantle but not a site of arclogite formation.

One important aspect of drip melting is the composition of arclogite partial melts. While it has been speculated that these drip melts can range from dacitic (Ducea and Saleeby, 1998c) to intermediate and basaltic based on the bulk "basaltic" composition of a garnet pyroxenite (Hirschmann and Stolper, 1996, Petermann and Hirschmann, 2003, see argument in in Lee, 2014), that may not be the case for arclogitic residues. Instead, since arclogites are already residual rocks depleted of an intermediate component, partial melts may be rather different.

Forward models of partial melting of arclogitic rocks with small amounts of water (amphibole) in the pressure-temperature range of 2–3.5 GPa and 900–1300 °C show that these rocks undergo limited partial melting and that melts are highly alkalic, nepheline normative, low silica, titaniferous rocks (Fig. 9). Starting composition is the average Sierran arclogites (originally named average Sierran pyroxenite, Sierra Nevada, California, from Ducea, 2002), which is a good average for a

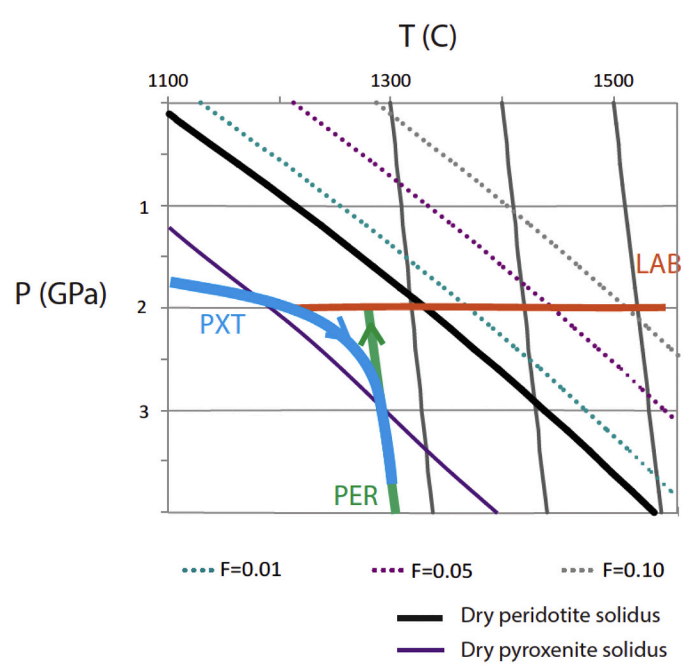

Fig. 8. Pressure temperature diagram illustrating the two plausible sources of melting: arclogite drip (blue line) versus asthenospheric upwelling (green adiabatic line) melting (modified after Ducea et al., 2013). F—fraction of melt (e.g., 0.1 = 10% melt); PXT—hypothetical downward P-T path for a pyroxenite drip; PER—adiabatic upwelling path for mantle peridotite replacing drip; LAB—lithosphere-asthenosphere boundary.

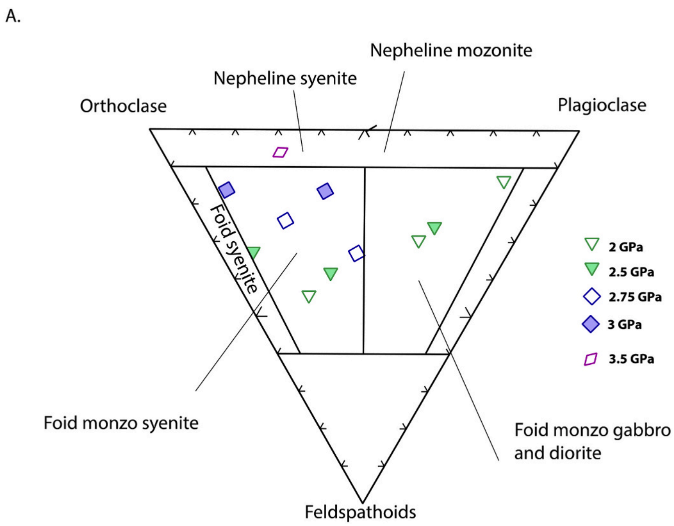

Fig. 9. Normative compositions of modeled products of various arclogite partial melts as a function of pressure, modeled with pMELTS (Ghiorso and Sack, 1995). Starting composition is the Average Sierran Pyroxenite (ASP, Ducea, 2002). All compositions are in the feldspathoid field of the IUGS classification diagram and most are foid monzosyenites and foid monzogabbros.

variety of arclogitic forward models performed in the past. The modeled melt compositions are neither similar to any type of common arc (subduction) rocks, nor are they like the most common post orogenic, extensional mafic magmas. Instead, the predicted melts from foundering (and heating) of arclogites are similar to the composition of the mafic end-member of foid-rich alkaline massifs found in continental interiors (such as Khibina, Lovozero, Kipawa, Ditrau, Ilimaussaq, etc., Wooley, 1987, 1995, 2001, 2019), whose tectonic setting and cause of formation have always been difficult to determine. We show in Harker diagrams in Fig. 10 how our modeled results compare to the lowest silica end member magmatic rocks of the Triassic Ditrau alkaline massif (Morogan et al., 2000) using major element data compiled from a variety of published and unpublished sources for Ditrau. In detail these alkaline massifs have in some cases huge compositional ranges, from mafic to granitic and extend into the realm of carbonatites at some field locations but our comparison here focuses on the low silica end member, feldpathoid (foid)-bearing rocks, which are the more primitive end-member magmatic rocks of the alkaline massifs. Also similar to these compositions are the highly alkaline, tephritic-phonolitic and similar volcanic rocks of the East African rift system (Corti, 2009). Many of the *syn*-foundering (3–4 Ma) volcanic rocks of the central Sierra Nevada (Farmer et al., 2002) are also foid-normative mafic rocks.

We propose that some within plate or rift-related nepheline- and or leucite-bearing syenite, monzosyenite or monzogabbro compositions could be the direct results of partial melting of arclogite, either during syn-arc foundering, at the end-of-cycle plate compression or later during the following continental breakup. This does not preclude the possibility of some basaltic melts or even intermediate ones to form from a foundering arclogite root (Ducea and Saleeby, 1998c); it is just that those melts are going to be subordinate to the predicted ultra-alkalic rocks. Overall, if episodes of foundering occur during arc formation (while subduction is active), these forward models predict that very little melt of the drip will form but they are distinct form typical arc compositions; given their low volume, they may mix with and be difficult to distinguish from the more common arc rocks. Post arc foundering may be more evident through the formation of alkaline massifs and within plate nepheline- and leucite-normative compositions.

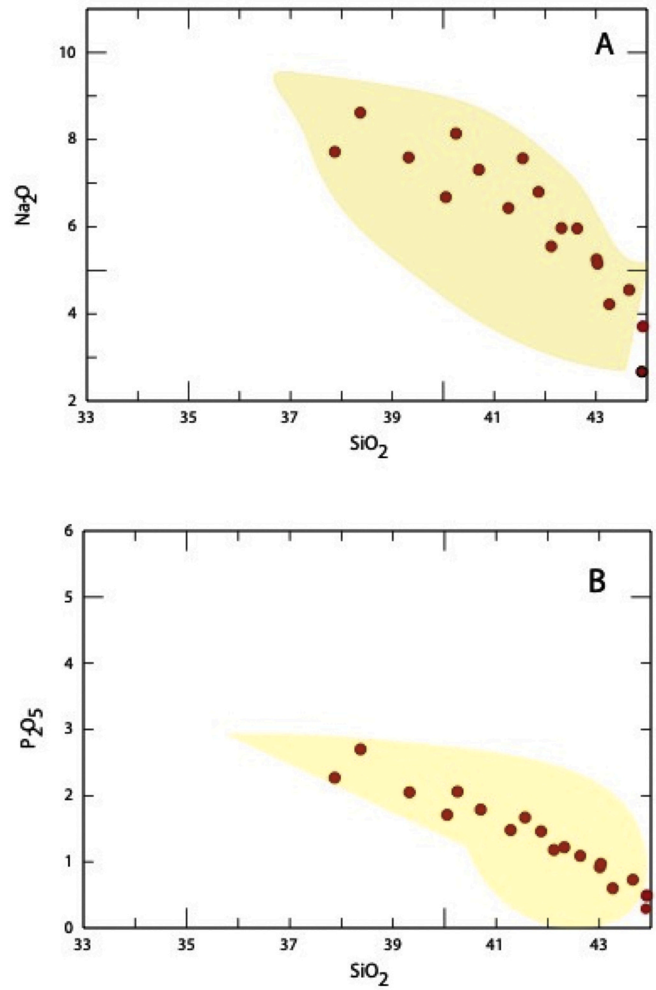

Fig. 10. Harker diagrams (A: Na_2O, B; P_2O_5) for modeled products of arclogite partial melts at 2GPa and various temperatures (900–1200 °C), using pMELTS (Ghiorso and Sack, 1995)- red circles. For comparison, we show the range of compositions for the low silica magmatic rocks of the Ditrau Alkaline Massif are shown (yellow shaded field).

6. Long term arclogite production

The loss of arc roots in individual Cordilleran arcs appears to be a non steady state process, given the cyclical nature of arc magmatism (Haschke et al., 2002; Ducea and Barton, 2007; DeCelles et al., 2009), with fluxes of arc root material into the mantle in the 10–100 km^3/km Myr range (Ducea et al., 2015a). Similar rates were calculated for oceanic arc roots (Jagoutz and Kelemen, 2015). On average, the rate of loss to the mantle is probably 25–40 km^3/km Myr (Ducea, 2002), not different from the global average of magmatic addition rates at subduction margins (Reymer and Schubert, 1984). If most continental crust throughout its history was formed buffered by arclogitic magma chambers/lower crustal melting zones, as indicated by zircon petrochronology (Balica et al., 2020), a volume equal to or as much as three times the continental crust has to exist foundered in the mantle. That represents 1–3% of the volume of the Earth's mantle. For a most likely ratio of felsic arc to root of 0.7 (based on various sesimic results for arc regions, e.g. Ward et al., 2017, and studies of crustal structure in Cordilleran batholiths, Ducea, 2002, Gehrels et al., 2009), about 1.5% of the mantle's volume is represented by these complements to the continental crust.

7. Arclogite signatures in the mantle

If arclogite production and foundering was important throughout the evolution of the continental crust, then these foundered complements to continents should be identifiable in the mantle. It is possible that, like subducting oceanic lithosphere, arclogite persists in the mantle for 100 s of Myr, coming to rest or stagnating along the 660 km discontinuity and/or in "slab graveyards" (e.g., Fukao et al., 2009; Mao and Zhong, 2018) along the core-mantle boundary. Hence, it is conceivable that these important geodynamic interfaces contain mixtures of arclogite and subducted oceanic lithosphere, rather than exclusively the latter. Alternatively, large arclogite fragments may not survive in the long term due to the highly ductile nature of the sublithospheric mantle (marble cake model, Allegre and Turcotte, 1986). Regardless, arclogite should represent a distinct reservoir in the mantle. Indeed, of the two most commonly found continental crustal recycled components in oceanic island basalts, EM1 and EM2 (Zindler and Hart, 1986), the first appears to be a lower crustal one, whereas the second is a more straightforward upper crustal, "sedimentary" component (Fig. 11). EM2 is clearly a component formed by recycling via sediment subduction. EM1, on the other hand remained somewhat puzzling, although it was proposed to represent recycled lower crust via some foundering mechanism (Tatsumi, 2000, 2005). Fig. 10 shows the EM1 component on an $^{87}Sr/^{86}Sr$ - ε_{Nd} isotopic diagram and the projection of the Sierra Nevada arclogites today and after 1 Gyr of decay of Rb and Sm, respectively. With their low Rb/Sr ratios, these rocks will not depart much from the bulk silicate earth $^{87}Sr/^{86}Sr$ values, whereas the super-chondritic Sm/Nd ratios of these residues will also keep them close to relatively high e_{Nd} values over time. We strongly support the assertion that EM1 is potentially continental arc lower crust recycled in the mantle over time. As discussed above, these arc residues are not particularly melt-fertile, and can at best produce highly alkalic, silica undersaturated melts but they are found in most ocean island basalts. Plausible fragments of recycled arc crust in mantle plumes are the garnet pyroxenites found in the post erosional alkalic products associated with the Koolau volcano (Oahu), e.g. the well-studied garnet pyroxenites of Salt Lake Crater (e.g. Keshav et al., 2007). Most of the EM1 reservoir is diluted in an otherwise depleted mantle mixed with CHUR-like materials, which is so common in ocean island basalts (Zindler and Hart, 1986).

8. Conclusions

We show that arclogites form in the root zones of thick magmatic arcs, typically at Andean subduction margins. They may form at thicker island arcs as well, where root zones have a significant role in modulating the composition and evolution of arcs. The thicker the arc, the more likely it is that garnet will be abundant in the root zones, driving bulk arc magma composition toward higher silica. Densification of arc roots renders them prone to foundering in the mantle and is controlled by cooling, cyclic evacuation of hot zones, and equilibration of dense minerals (virtually all rock forming minerals in arclogites are equal in density or denser than underlying mantle, including oxides, which contribute about 100 kg/m^3 to the overall density of the root).

Geodynamic models suggest that foundering of arc roots takes place periodically after evacuation of magmas from the lower crust and may proceed in small batches. Shearing at the bottom of the lithosphere contributes to the lateral movement (toward the trench) of the detached root, in addition to the sinking tendency given by negative buoyancy. Small drips may not trigger any significant magmatism in the mantle, either from the asthenosphere filling up space or the drip itself.

Drip melts are predicted to be nepheline normative, low silica materials of phonolitic to tephritic (intrusive equivalents: nepheline syenite, monzosyenite and monzogabbro) compositions that are similar to some of the continental alkaline massifs or isolated volcanic rocks found within continental plates or in some rifts. They are neither alkali-basaltic, nor intermediate (andesitic) in composition.

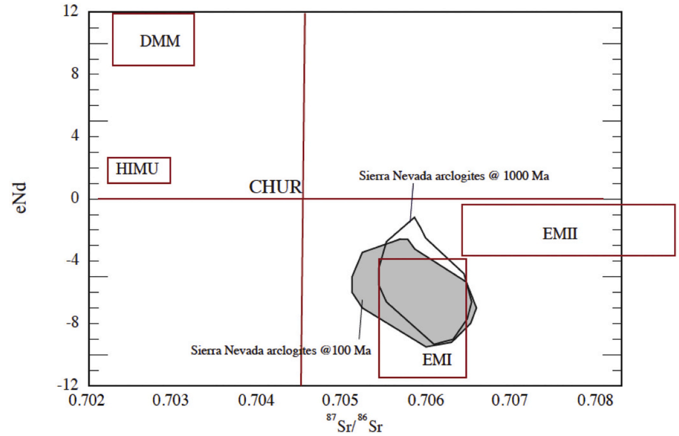

Fig. 11. Sr—Nd isotope diagram showing the principal mantle reservoirs identified in ocean island basalts with these isotopes primarily (modified from Zindler and Hart, 1986). DMM is the depleted mantle of mid ocean ridge basalts, HIMU is a high U/Pb reservoir, CHUR represents the chondritic uniform mantle (undifferentiated silicate mantle), EM1 is a recycled crustal reservoir of lower crustal origin and EM2 is recycled sediment. Arclogite field of Sierra Nevada at the time of formation are shown (100 Ma, from Ducea, 2002) and compared to the values 1000 Myr later.

The rate of returning foundered roots has to be at least equal to the rate of arc production since the ratios of bulk intermediate composition arcs to their root is 0.7 or less. At least about 1% of the mantle is estimated to be made of these types of assemblages, which may concentrate along the 660 km mantle discontinuity and/or the core-mantle boundary. The most likely mantle reservoir fitting arclogite isotopic characteristics is EM1. Melts from this reservoir are commonly and most easily identified in oceanic island basalts (hot spot basalts). While enriched isotopically, these materials are not extremely melt fertile.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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