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Review Article

Arclogites and their role in continental evolution; part 1: Background, locations, petrography, geochemistry, chronology and thermobarometry

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ABSTRACT

Arclogites, or clinopyroxene-, garnet-, amphibole-, and Fe—Ti oxide-bearing cumulates and restites (collectively representing residues) to andesitic continental arc magmas, are reviewed here and in a companion paper (Ducea et al., 2020). Experimental petrology and petrologic observations suggest that these eclogite facies rocks form magmatically in deep crustal hot zones beneath arcs with crustal thicknesses exceeding 35–40 km. Volcanic and plutonic products of thinner arcs may instead be entirely extracted from amphibolite to granulite facies and garnet-free pyroxenite residues. Arclogites are perhaps best known as xenoliths, with notable examples from young (Sierra Nevada and Central Arizona) and modern (Colombia) sub-arc environments. We suspect that arclogite occurs more commonly than currently recognized in the xenolith record from orogenic and cratonic domains. Arclogite is also found as discrete intervals in the deepest exposures of the Kohistan arc and as small volume inclusions in tectonically exposed peridotite massifs (e.g., Beni Bousera, Morocco). Geochemically, these rocks are low silica ($SiO_2 < 50\%$) assemblages with low Nb/Ta and Sr/Y ratios and enrichments in heavy REEs such that they represent the complement to the andesitic-dacitic liquids that make up the surface volcanics and batholiths of most arcs. Virtually all rock-forming minerals in arclogites are of similar or greater density than the underlying mantle, making them ideal candidates for foundering. Arclogites are formed in the lowermost crust of arcs at 35–70 km depth and record high temperatures (~800–1000 °C) at the time of formation which then cool and metamorphose at ~650–750 °C if they remain attached to the crust for an extended period of time. Ages of these rocks are obtainable by Sm—Nd and Lu—Hf garnet isochron geochronology as well as titanite or rutile U—Pb geochronology, although these ages can be reset through long-term storage in hot lower crustal environments. Recent discovery of zircon accessory minerals in arclogites makes these rocks datable with greater precision and greater chance of preserving crystallization ages by U—Pb chronology.

1. Introduction

Sub-arc residual eclogite facies assemblages dominated by clinopyroxene-garnet-amphibole and iron-titanium oxides are together known as “arclogites”, a new term introduced to simplify the description of these rocks (Lee and Anderson, 2015). These rocks are cumulates and/or restites left behind by the fractionation/partial melting processes that produces the extensive intermediate melts found in both continental and oceanic arcs (Ducea and Saleeby, 1998a; Ducea, 2001, 2002). However, not all residual masses of large batholiths are arclogitic; thinner arcs are complemented by either plagioclase-rich cumulate sequences (Kay and Kay, 1985; Ducea et al., 2003) that survive in the geologic record as granulite terrains or as ultramafic masses dominated by garnet-free clinopyroxenites (Jagoutz and Kelemen, 2015). Sub-arc garnet-free pyroxenites can founder in the mantle under certain circumstances (Jull and Kelemen, 2001), but when garnet is present in any reasonable amounts (>5%), these residual masses are almost certain to return to the convective upper mantle due to their extreme negative buoyancy (Lee, 2014). Moreover, the more garnet and/or amphibole and iron oxides present in such assemblages, the higher the silica in the differentiated upper crust. Cumulates of pyroxene and plagioclase have silica concentrations similar to or higher than the bulk basaltic compositions of

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mantle-derived arc magmas, thus they alone cannot explain the diversification of magmatic arc liquid compositions toward intermediate and silicic values. It has thus been hypothesized that the formation of arclogite residues (restite and cumulates) is an important driver for making bulk continental crustal materials at subduction margins in modern tectonic settings (Ducea, 2002). Similar assemblages could have also formed in the distant geologic past, by remelting of thick basaltic keels at depths of tens of kilometers beneath the surface; these basaltic protocontinents likely formed by processes other than subduction (Ernst, 2009).

Although continentalization and the driving of continental crust toward intermediate compositions may rely on subduction-related arc magmatism (Gill, 1981, Taylor and McLennan, 1985, Stern, 2002, Davidson et al., 2007, Ducea et al., 2015, many others), the bulk composition of the continental crust is also influenced by the formation and removal of low-silica arclogitic residues. Yet relatively little is known about these arclogitic assemblages in nature. Rocks of arclogitic composition are known as xenoliths from a few selected sub-arc locations worldwide and perhaps also from the lowermost parts of exposed arc roots. Due to their deep origin and high density, these assemblages are unlikely to be exhumed to the surface and preserved in the geologic record (see discussion below). Nevertheless, their significance in magmatic and tectonic processes is suggested by experimental petrologic results. Moreover, arclogites are the most likely candidates to undergo foundering (sensu *lato*) because they are significantly denser than any other materials hypothesized to engage in sub-crustal vertical tectonics, for which many names have been used in the literature: dripping, delamination, convective removal, deblobbing (in the case of arc roots: Kay and Kay, 1993, Ducea and Saleeby, 1998a, Ducea, 2002, Lee, 2014, Currie et al., 2015, Lee and Anderson, 2015, in the more general sense: Arndt and Goldstein, 1989). From this perspective alone, the details of arclogite petrology and geochemistry are of great significance not only to subduction-centric arc petrologists but to continental tectonicists in general.

Below we review the main xenolith and tectonically exposed locations of these rocks, experimental findings predicting their distribution under arcs at depth, and their petrography, thermobarometry, chemical and isotopic characteristics, and ages. In a companion paper, we will review how arclogites influence the major elemental composition of arcs, arclogite density and susceptibility to convective removal, the composition of melts formed during their descent into the mantle, long-term arclogite production on Earth, and their long-term isotopic signatures once recycled into the mantle.

2. Eclogites and arclogites

Eclogites were defined as bimineralic mafic rocks consisting of garnet and jadeitic clinopyroxene (Hauy, 1822). It later became clear that these rocks represent high pressure assemblages, perhaps at the highest end of plausible pressure conditions of crustal metamorphism. Through this revelation, an “eclogite facies” was defined (Eskola, 1920), at first for mafic assemblages and then for all other major chemical compositions. Due to its constituent minerals, the most salient feature of a mafic eclogite is its high density. Garnet in particular is denser than most other common rock-forming minerals. Eclogites represent a minuscule fraction of the known continental crust yet have become a significant influencer of plate tectonics theory due to the realization that the oceanic crust turns into eclogite upon subduction (Godard, 2001, for references and a view on history of eclogite research). The negative buoyancy of any dense eclogite-facies subducting slab is a major driver of plate tectonics.

Consequently, eclogite has to a first order become synonymous in modern geology with a high pressure metamorphic equivalent of basalt, and in particular, the subducting oceanic crust. Of course, any composition other than mafic can become an eclogite facies rock if subjected to high enough metamorphic pressures. These rocks would display the signature garnet and clinopyroxene association among other phases stable in that assemblage at high pressure (Philpotts and Ague, 2009). Because eclogitic high-pressure equivalents of basalt typically have high clinopyroxene to garnet ratios and contain jadeite-rich clinopyroxene, rocks that appear eclogitic but do not display these characteristics have been referred to as garnet clinopyroxenites, ariegites, pyrigarnites, and other names (Godard, 2001). As noted in a seminal paper (Coleman et al., 1965), there are “eclogites and eclogites” and that diversity is immediately obvious in their clinopyroxene as well as garnet composition.

A different type of eclogites, termed igneous eclogites, were first observed in the 19th century (e.g. Holland, 1896). High pressure experimental work beginning in the 1960s later predicted that these igneous eclogites form at high pressures as a result of fractionation of basalts at mantle depths (e.g. Green and Ringwood, 1967a, 1967b; Banno, 1970; Basaltic Volcanism Study Project, 1981). As a result, many eclogite assemblages found in the mantle, e.g. as xenoliths in kimberlites, were interpreted as primary igneous products (cumulates) rather than as pieces of slabs recycled in the mantle. Terminology is uneven here too, since eclogitic xenoliths in kimberlites are in some cases called pyroxenites and in others eclogites. Kimberlite eclogite literature is too vast and complex to review here (Jacob, 2004; Aulbach and Arndt, 2019 and references therein) and the origin of olivine-free, garnet-pyroxene xenoliths in such rocks is still debated. Without a doubt, however, these rocks were sampled from the lithospheric mantle at the time of entrainment in the host kimberlite. Some are true eclogites, others are garnet pyroxenites, yet they all formed in ancient tectonic environments from processes difficult to constrain due to lack of geologic context.

The presence of small bodies of cumulate-textured garnet pyroxenites within larger masses of peridotites in the classic “upper mantle” sections exposed tectonically in Europe and Northern Africa (Harz, Lherz, Beni Bousera) is also consistent with an igneous origin (Pearson et al., 1993). These are viewed as products of peridotite-melt interaction or as cumulates of basaltic melts (Obata, 1980). It has also been recently suggested that some of these rocks, which have metamorphic textures (El Atrassi et al., 2013), have the characteristics of arc root cumulates and are presumably small fragments of foundered bodies in the mantle (Gysi et al., 2011).

A new class of igneous eclogites, commonly referred to today as *arclogites* (Anderson, 2005; Lee and Anderson, 2015), represent arc root assemblages. These arclogites are the main subject of this contribution. Following Coleman et al. (1965), these rocks are Group B eclogites, and are found as xenoliths in subduction related magmatic arc regions (Mukhopadhyay, 1989; Ducea and Saleeby, 1996; Weber et al., 2002). They have cumulate/restite textures, have been documented to be cogenetic with arc rocks such as batholiths (Ducea and Saleeby, 1998b), and originate from 1.2 to over 3.0 GPa pressures (Mukhopadhyay, 1989; Ducea and Saleeby, 1996). Their discovery coincided with a series of new petrology experiments aimed at producing tonalites and granodiorites by dehydration melting of amphibolites (Rushmer, 1991; Wolf and Wyllie, 1993, 1994; Rapp and Watson, 1995). These experiments noted that at pressures in excess of 1 GPa, abundant garnet forms in equilibrium with intermediate melts. With a better understanding of the roles of plagioclase, pyroxene, garnet, and amphibole fractionation in intermediate melts at deep crustal levels in thick arcs (the so-called MASH zones, Hildreth and Moorbath, 1988, or hot zones, Annen et al., 2006), a leading hypothesis emerged that these eclogite-like igneous assemblages may dominate the roots of thick arcs at lower crustal levels and may be the main complement at depth to near-surface batholiths or thick Andean-like volcanic arcs. The high density of such assemblages also made them likely candidates for detachment and foundering into the mantle (Ducea and Saleeby, 1998a), which can be entertained as a hypothesis for continental evolution toward a more silicic crust (Rudnick, 1995; Ducea, 2002). These rocks, which often contain amphibole in addition to pyroxenes and garnet, were referred to as eclogite (Dodge et al., 1986, 1988), garnet pyroxenites

(Mukhopadhyay, 1989, Ducea and Saleeby, 1996), low Mg-pyroxenites (Lee et al., 2006), garnet-pyroxene-amphibole rocks (Smith et al., 1994), pyribolites, pyroxenites, pyrigarnites (Weber et al., 2002), "arc-eclogites" (Anderson, 2005), and eventually arclogites (Lee and Anderson, 2015).

Note that in contrast to Lee and Anderson (2015), we do not include in the umbrella term "arclogite" the so-called high-Mg pyroxenites, which are garnet websterites found in virtually all arclogite locations described below. In contrast to the low-Mg pyroxenites (garnet clinopyroxenites), which are actually arclogites, garnet websterites equilibrated at higher pressures that are indubitably located within the mantle (2.5 GPa or more) and are more likely former mafic melts (not residues) frozen in the uppermost mantle. These rocks are in our view spatially associated with peridotites as veins within the subcontinental lithospheric mantle, whereas the arclogites are true deep residues of the arcs, straddling the complex boundary between the crust and mantle in supra-subduction environments and transitioning at shallower depths to granulite assemblages. Websterites, as cumulates of mafic melts in the mantle, are common in many mantle environments, and are not limited, petrographically, to sub arc environments.

Table 1 presents the defining characteristics of arclogites in contrast to other types of common eclogitic-type materials that are mafic/ultramafic in composition. The upshot is that in order for a rock to be an arclogite, it needs to have a Group B garnet and clinopyroxene as the main rock forming minerals and could (but does not need to) also contain abundant amphibole, and Fe—Ti oxides. An arclogite does not contain plagioclase. Clinopyroxene could be of any composition, but only rarely is jadeitic.

3. Locations

Most arclogites are known as xenoliths entrained in volcanic rocks sampling thick sub-continental arc domains of the Americas. Xenolith localities of the thin oceanic arcs of the Circum-Pacific (Conrad and Kay, 1984; Kay and Kay, 1985; DeBari et al., 1987; McInnes et al., 2001) do not contain arclogitic assemblages. They do however contain garnet-free pyroxenites, wehrlites, and other garnet-free ultramafites which could make up the dense roots of island arcs (as envisioned in the theoretical study of Jull and Kelemen, 2001).

The main North American xenolith arclogite localities are in the central Sierra Nevada, California (Domenick et al., 1983, Dodge et al., 1986, 1988, Ducea and Saleeby, 1996, 1998a, 1998b, c, Mukhopadhyay, 1989, Mukhopadyay and Manton, 1994, Lee et al., 2000, 2001a and Lee et al., 2001b, Lee et al., 2006, Chin et al., 2012) and central Arizona (Arculus and Smith, 1979; Esperanca et al., 1988; Chapman et al., 2019, 2020; Rautela et al., 2020), and possibly include some of the sub-Colorado Plateau xenolith localities. In South America, arclogites are known from one notable locality, Mercaderes in southern Colombia (Weber et al., 2002; Bloch et al., 2017), which is the only known arclogite xenolith locality from an active Andean-type arc. Similar rocks may be present in Miocene volcanics from the western shores of Lake Titicaca (Chapman et al., 2015a) but they have not been studied in detail.

Table 1
Features of arclogites and other eclogites.

Rock Name	Defining Features	Synonymous Terms	True Arclogite?
Eclogite	High pressure assemblage with a high jadeitic clinopyroxene to garnet ratio		No
Igneous eclogite	Garnet-pyroxene high pressure assemblage formed from fractionation of basalt at depth (cumulates)	In kimberlite studies, called pyroxenites or eclogites	In some cases
Arclogite (igneous eclogite subgroup)	Low-Mg Group B eclogites with restite/cumulate textures that represent arc root assemblages	Eclogite, garnet pyroxenite, low Mg-pyroxenites, garnet-pyroxene-amphibole rocks, pyribolites, pyroxenites, pyrigarnites	Yes
Garnet websterites (igneous eclogite subgroup)	High-Mg pyroxenites equilibrated at mantle depths		No

All known arclogite xenoliths are entrained within trachyandesitic, latitic, or other intermediate volcanic material. This is in contrast to peridotite xenoliths, which are commonly hosted by basaltic rocks (Nixon, 1987). Another common feature within these xenolith localities is the abundance of xenoliths of many different lithologies, ranging from arclogites to igneous granulites, metasedimentary granulite facies rocks, garnet-free clinopyroxenites, high-pressure garnet websterites, and garnet (± spinel) peridotites. As is commonly the case with xenoliths, secondary breakdown of some phases occurred during their entrainment in the host magma; for example, kelyphitic rims on garnet are ubiquitous.

Sierra Nevada arclogite xenolith localities include 8–12 Ma trachyandesite plugs that intruded the Sierra Nevada batholith long after its demise (80 Ma). These are small volume exposures, the most extensively studied of which are located at Pick and Shovel Mine, Chinese Peak, and near the town of Big Creek, California (Domenick et al., 1983, Dodge et al., 1986, 1988, Mukhopadhyay, 1989, Mukhopadyay and Manton, 1994, Ducea and Saleeby, 1996, 1998a and b, Ducea, 2002, Lee et al., 2000, Lee et al., 2001a, 2001b, Lee et al., 2006, Chin et al., 2012). A number of other small localities in the same region have not been investigated (Ducea and Saleeby, 1996). The Sierra Nevada localities are particularly instructive because the variety of mineral assemblages within the xenoliths allows construction of a cross section through the lithosphere (Saleeby et al., 2003, Fig. 1). Younger (3–4 Ma) xenolith-bearing mafic lavas from the same area in the central Sierra Nevada do not contain any arc root xenoliths; they are much hotter and dominated by spinel peridotites (Ducea and Saleeby, 1996). This has led various authors to suggest that the sub-central Sierra arc root was delaminated at some point during the Pliocene (Ducea and Saleeby, 1996, 1998a; Farmer et al., 2002). In fact, the existence today of a high density ("eclogitic") anomaly in the mantle beneath the south-central Sierra Nevada as revealed by seismic tomography data has been proposed to represent the delaminated (or foundered) body (Zandt et al., 2004; Jones et al., 2014).

Sierra Nevada arclogites range from garnetites to garnet clinopyroxenites with or without amphibole and Fe—Ti oxides. There are also cumulate rocks with alternating layers of garnet clinopyroxenite and plagioclase (Ducea and Saleeby, 1996), suggesting that a transition from plagioclase-bearing to plagioclase-free assemblages existed in the root of the arc. In addition, hornblende is present in many of the known arclogite localities. Many clinopyroxene grains in in these rocks have amphibole cleavages, which suggests clinopyroxene formation as a result of amphibole dehydration. Garnet-free clinopyroxenites with abundant magnetite-ilmenite are also rather abundant. Garnet peridotites are rare but are among the very few samples of the mantle lithosphere underlying western Cordilleran magmatic arcs (Mukhopadyay and Manton, 1994; Lee et al., 2000, 2001a). Furthermore, garnet websterites are distinct from arclogites in that they are much more magnesian (Mukhopadyay and Manton, 1994; Lee et al., 2006; Chin et al., 2012; Chin et al., 2014a) and yield significantly higher equilibration pressures (on average ~ 1 GPa greater than arclogite). As such, garnet websterites are thought to represent fragments of the lithospheric mantle that reside much deeper than the arclogite-bearing near-Moho region.

The central Arizona xenolith localities are hosted by late Oligocene

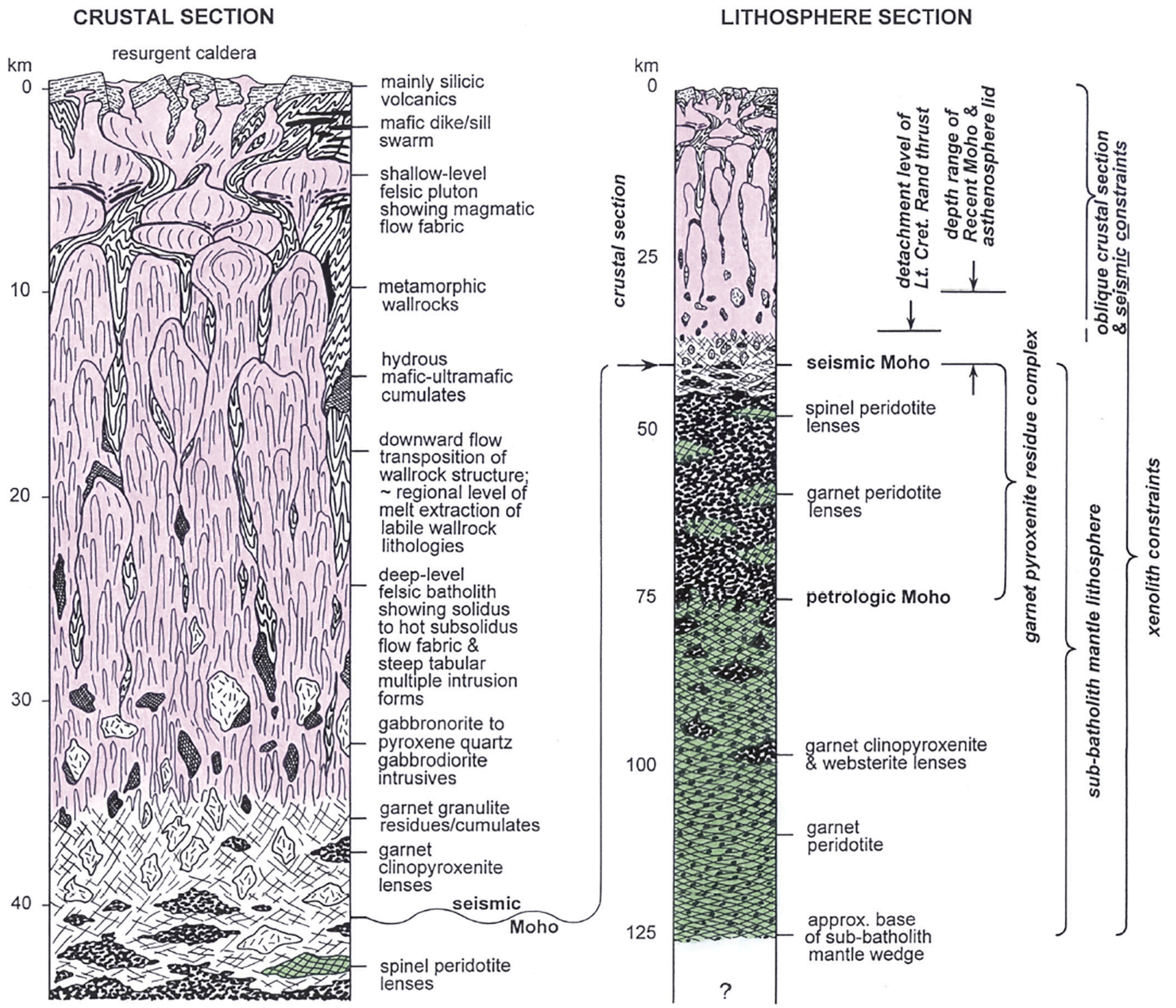

Fig. 1. Schematic vertical composition of the lithosphere beneath a Cordilleran arc (modified after Saleeby et al., 2003), as revealed by the Sierra Nevada exposures (0–30 km paleodepths) and various post batholithic xenolith localities described in text. The lithosphere is about 125 km thick and is characterized by a significantly different depth to petrologic and seismic Moho, given the abundance of ultramafic residues. Rocks referred to as "garnet clinopyroxenites" in this figure by Saleeby et al. (2003) and most other researchers at the time, are now renamed arclogites.

latites (Arculus and Smith, 1979; Esperanca et al., 1988, 1997; Smith et al., 1994; Erdman et al., 2016; Chapman et al., 2020). The best studied localities are Camp Creek and Chino Valley (see Chapman et al., 2019, for a field guide describing locations). Xenolithic rocks are very similar to those of the Sierra Nevada and range in composition from metasedimentary and metaigneous xenoliths representing the local basement to garnet granulites, garnet websterites, garnet-free peridotites, and recently recognized arclogites (Erdman et al., 2016). Arclogites in this locality have been shown to be roots of the southern California arc displaced eastward (Rautela et al., 2020; Chapman et al., 2020) by ultra-shallow subduction along the Laramide corridor (Saleeby, 2003; Ducea and Chapman, 2018).

The Mercaderes xenolith locality (hosted by the Granatifera Tuff) in southern Colombia is a small presumed Quaternary sequence of satellite eruptions to the greater Dona Juana stratovolcano (Weber et al., 2002). Beneath this locality, the depth to seismic Moho is around 50–60 km (Bloch et al., 2017), although global seismic databases (Laske et al., 2013) shows it closer to 40–45 km. Like the North American localities, the Granatifera Tuffs, which are a sequence of tuffs and lahars, are intermediate in composition (andesites and lamprophyres, Rodriguez-Vargas et al., 2005) and host a variety of xenoliths ranging from volcanic, metasedimentary, granulite, pyroxenite (with and without garnet), garnet-bearing peridotite, to other more exotic assemblages (Rodriguez-Vargas et al., 2005). Based on their age and high recorded temperatures, the latter of which is which is unique among documented arclogitic localities, these rocks are inferred to represent fragments of a residual root formed by the 10–5 Ma arc magmatism that resulted in the buildup of the Dona Juana stratovolcano (Bloch et al., 2017).

A reexamination of published xenolith studies indicates that other possible arclogitic xenoliths exist elsewhere on the planet given their petrographic composition (Kara et al., 2020), although they have not always been identified as such in the literature and await further study. A good example is the wealth of eclogite-like xenoliths with seemingly arclogitic characteristics found in SE Australia in small-scale Holocene volcanic rocks from western Victoria within the greater Lachlan Fold Belt province (Griffin and O'Reilly, 1986). However, no studies to date have interpreted those eclogite xenoliths as arc root assemblages. Another, albeit less convincing example of arclogite xenoliths is from the North China Craton (Gao et al., 2004; Lee, 2014).

Most ancient segments of the North, Central and South American Cordilleran arcs are exposed to relatively shallow levels (Ducea et al., 2015) less than 10 km on average. Few tectonic windows exist into deeper, usually no more than 30 km paleodepths (Ducea et al., 2015 for a review) that are not quite deep enough to represent the realm of plagioclase-free cumulates. In deeply exhumed arc sections of the North American Cordillera (e.g., the North Cascades, Salinian Block, and Tehachapi Mountains, all of which yield 0.8–1.0 GPa paleo-pressures), peritectic garnet textures are observed in migmatitic amphibolite-bearing mafic rocks (e.g., Whitney, 1992; Pickett and Saleeby, 1993; Wernicke and Getty, 1997; Kidder et al., 2003). However, these rocks are still dominated by plagioclase. In other deep crustal arc sections, such as the Sierra Valle Fertil (Otamendi et al., 2009, 2012), garnet is not present even in the deepest exposures (Walker Jr. et al., 2015). One notable exception to the lack of arclogites in outcrop is the Kohistan arc (Pakistan) (e.g. Jagoutz and Schmidt, 2012), which preserves an extraordinary cross-sectional view of a transitional island arc down to paleodepths of over 30 km (Dhuime et al., 2009). Within the Kohistan arc, garnet-rich rocks include rare exposures that could be categorized as arclogites.

The Kohistan paleo-island arc complex is sandwiched between India and Asia proper (Burg et al., 1998) and is believed to have formed above an oceanic subduction zone within the Neotethys between 117 and 85 Ma (Dhuime et al., 2009). Exposures include arc volcanics in the north and the Kohistan batholith farther south. Southernmost exposures are best described along the Indus river and contain units that represent the root of the arc (Zeilinger, 2002; Garrido et al., 2006, and references therein). The deepest complex of the Kohistan arc, the Jijal complex (Jan and Howie, 1981; Burg et al., 1998), is believed to expose the paleo-Moho of the arc due to the presence of >1 GPa rocks that equilibrated at probably no more than 35 km paleodepths (Yamamoto and Nakamura, 1996; Yamamoto and Nakamura, 2000; Anczkiewicz and Vance, 2000). The Jijal complex consists of a 3 km-thick section of garnet granulites and garnet gabbros, below which the section transitions to olivine-rich ultramafic rocks (spinel peridotites) that represent the paleo-upper mantle. At outcrop scale, the garnet granulite section does show transitions toward arclogitic assemblages, including garnet-clinopyroxene-amphibole assemblages with various modal proportions of these three minerals (Dhuime et al., 2009). The presence of arclogites that record 35 km paleodepths is consistent with experimental results, which predict the stabilization of arclogite assemblages at these depths.

4. Experimental results

Dehydration melting experiments of wet basalts (amphibole-bearing gabbros or amphibolites) at pressures over 1 GPa have shown convincingly that amphibole dehydration melting reactions produce intermediate compositions similar to the tonalites and granodiorites of modern subduction-related arcs (Rushmer, 1991; Wolf and Wyllie, 1993, 1994; Rapp and Watson, 1995) or that tonalitic liquids are in equilibrium with such assemblages (Carroll and Wyllie, 1990). These experiments provide the foundation for understanding melting reactions along with the solid phases present in equilibrium with realistic melting fractions in young lowermost orogenic crust or some ancient thickened oceanic plateau-like crust (10–50%). Likewise, these experiments provide an excellent framework for understanding the "second stage" process that occurs in the lower crust of arcs, which is required for generating intermediate rocks (Dufek and Bergantz, 2005; Jagoutz, 2014; Ducea et al., 2015). Although these experiments simulate partial melting, one can think of running them down temperature in order to view the results as products of fractionation in deep-crustal hot zone magma chambers. Amphibole is a key phase undergoing melting in these experiments and provides the water for calc-alkaline intermediate melts. Fundamentally, these classes of experiments can be viewed simply as amphibole dehydration melting reactions, which take place at higher temperatures (850–950 °C) than muscovite and biotite dehydration reactions. The main phases in equilibrium with tonalitic and granodioritic melts are plagioclase and clinopyroxene. At higher pressures, plagioclase is replaced by garnet, leading the way to an igneous "eclogitic" (arclogitic) assemblage at pressures in excess of 1.5 GPa. These experiments show that garnet pyroxenite assemblages are not only expected to be in equilibrium with basaltic melts at mantle pressures (Green and Ringwood, 1967a, 1967b) but also with intermediate and silicic melts (Carroll and Wyllie, 1990). Amphibole remains on the liquidus if not entirely consumed by the melting reaction but can also crystallize from fractions of melt left unextracted from the source (or magma chamber). The gradual disappearance of plagioclase in favor of garnet with depth is predicted to take place over a large range of pressures between 1 and 2 GPa and depends on the bulk composition of the system. Therefore, these experiments reveal that the transition from plagioclase-only to garnet-only assemblages within the deep crust of arcs is most likely not sharp, and instead occurs gradually in the depth region of 35–50 km.

Fig. 2 shows pMELTS-predicted (Ghiorso and Sack, 1995) assemblages on the liquidus of a tonalitic melt for a bulk basaltic calc-alkaline composition (Schmidt and Jagoutz, 2017) undergoing dehydration melting at 1 and 2 GPa respectively as a function of partial melt fraction. The composition of garnet is shown in Fig. 3 in the classic Coleman et al. (1965) garnet classification diagram. Note that the garnets predicted to form in these conditions are predominantly almandinic (Group B of Coleman et al., 1965). Almandine-bearing arclogites are significantly denser than eclogites from subducting environments (which contain Group C garnets), mainly because these group B garnets are more Fe-rich and are also more abundant in the rocks (see Section 5). These simple forward models anchored in vast amounts of experimental data illustrate the predicted minerals that are expected to play a role in the differentiation of granitoid magmas at depth.

5. Petrography

Petrographically, arclogites globally are very similar; consequently, we will describe them as a group and mention specific localities only when a feature stands out at that locale. These rocks are relatively coarse-grained (typically 1 ± 0.5 cm in diameter although finer equivalents exist) and commonly exhibit cumulate textures with the two main phases (clinopyroxene and garnet) displaying orthocumulate features. Almost all arclogitic xenoliths contain breakdown products most clearly visible around garnets; these are known as kelyphitic rims which consist of very fine assemblages of plagioclase, spinels, aluminous pyroxenes, and silicate glass. These features are generally interpreted to represent breakdown reactions in the host magma carrying the xenolith and do not have any pre-entrainment geologic significance. In addition to garnet and clinopyroxene, relatively common minerals within arclogitic assemblages include pargasitic amphibole, phlogopite, rutile, Fe—Ti oxides (magnetite, ilmenite, pseudobrookite), and orthopyroxene (sometimes as exsolution lamellae in clinopyroxene). Of these phases, amphibole and Fe—Ti oxides are the most abundant and can make up as much as 50% of the rock volume. The difficulty of assigning a common name to these rocks arises from the fact that due to the small size of xenoliths and large grainsize of constituent minerals, only portions of the rock may be exposed. As a result, in some cases, true arclogites may be labeled as garnetites (with minor clinopyroxene and amphibole), while others may be dominated by clinopyroxene or amphibole (Smith et al., 1994 named them "pyroxene-garnet-amphibole" rocks, recognizing their common lineage). Apatite is also present in some arclogites, as are titanite, aluminous spinel, Cu—Fe sulfides, and zircon, although these are all accessory phases never exceeding 1% by volume. Interestingly, native gold has been found in an arclogitic xenolith from Chino Valley in central Arizona (Arculus and Smith, 1979).

Many clinopyroxenes have relic amphibole cleavages suggesting that

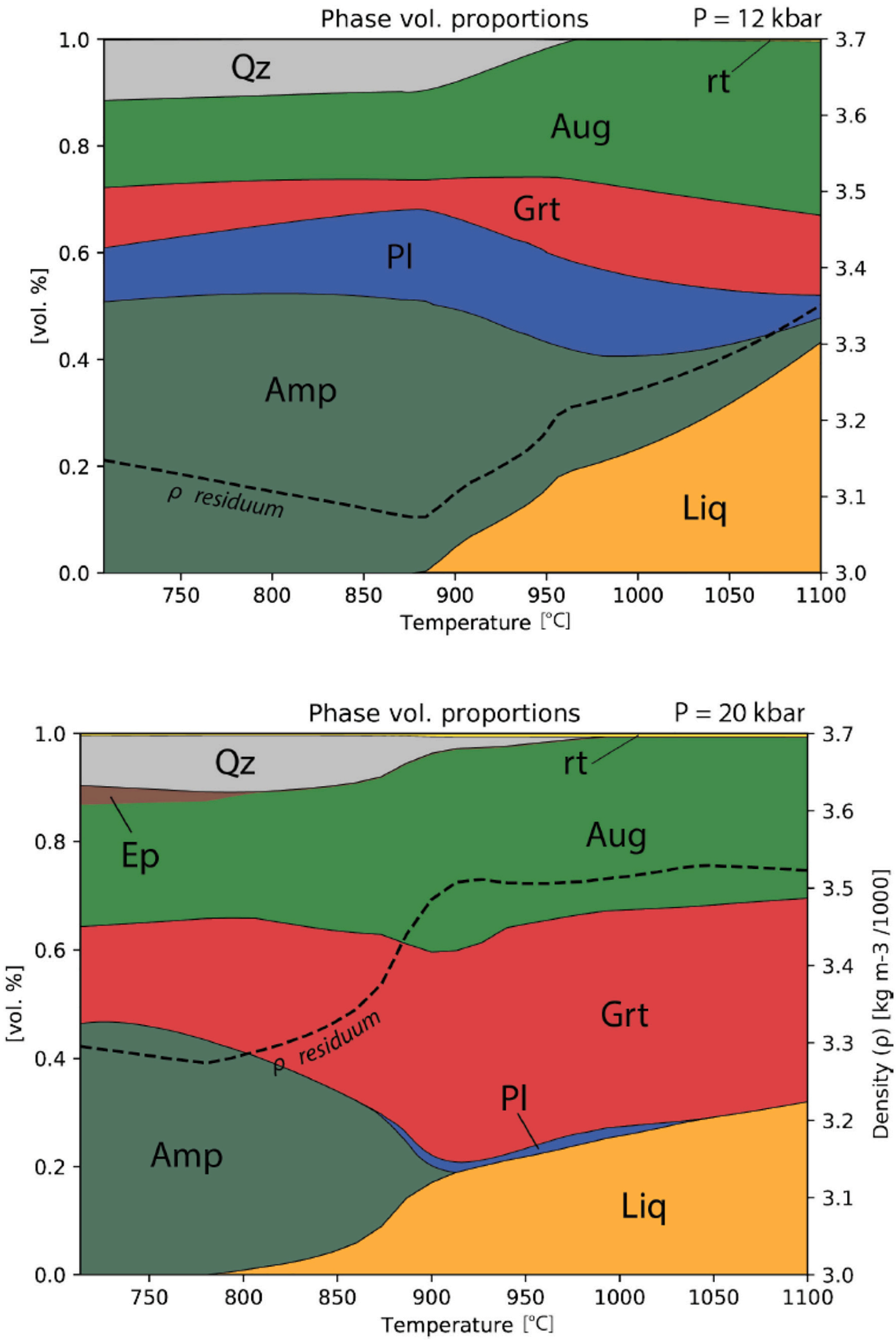

Fig. 2. Experimental prediction of proportions of garnet, plagioclase, amphibole and other phases on the liquidus of an intermediate melt and below the solidus for an average arc basalt starting composition (with 4% water). Phases are shown at 1.2 GPa (panel above) and 2 GPa (panel below). Density of the residual phases are shown on the right in g/cm^3. Calculated using deCapitani & Petrakakis (2010). Abbreviations: Qz-quartz, Amp-amphibole, Pl- Plagioclase, Ep-Epidote, Rt-rutile, Grt-garnet, Aug-Augite, Liq-liquid.

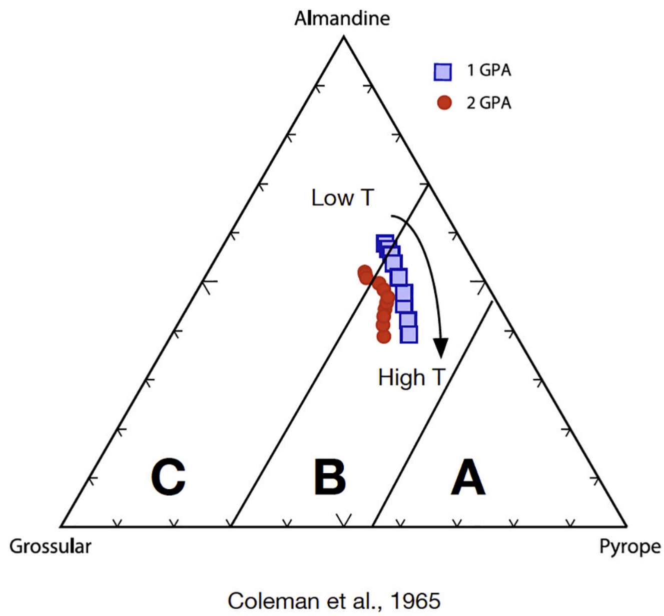

Fig. 3. Predicted garnet compositions for the fractionation of an intermediate magma at 1 and 2 GPa, using pMELTS (Ghiorso and Sack, 1995). Starting material is an average arc basalt (Schmidt and Jagoutz, 2017). The ternary classification diagram for garnets is from Coleman et al. (1965).

these rocks record the dehydration melting of amphibolites (Ducea and Saleeby, 1996). However, the opposite is also recorded: some amphiboles display a pyroxene-like orthogonal cleavage, suggesting that some of these amphiboles are secondary and come about due to hydration of the nominally anhydrous garnet-clinopyroxene assemblage (Rautela et al., 2020). In arclogites, amphiboles are reactants in some occurrences and reaction products in others.

Garnets are typically the most euhedral of phases and also contain the largest amounts of inclusions. When they are not transformed to secondary phases, they are orange red in hand specimen. Acicular rutile, zircon, apatite, and titanites are most commonly found as inclusions in garnets, which may also contain more minor inclusions of clino- and orthopyroxenes. Garnets fall in the middle of the Group B field of Coleman et al. (1965); they have more or less equal proportions of almandine-pyrope and grossular, and if one end member does dominate, it is the almandinic term. Cooled arclogites such as those from the Sierra Nevada and central Arizona exhibit clear diffusional profiles (Ducea and Saleeby, 1996) and diffusionally modified growth zonation (Rautela et al., 2020), respectively. In contrast, recently formed arclogites from Mercaderes display flat major element profiles (Bloch et al., 2017). Kelyphitic rims are common to all arclogite garnet samples.

Clinopyroxenes are the most abundant of all arclogite phases and probably make up ~50% of these rocks by volume on average. Most clinopyroxenes are salites and augites in composition. This is consistent with the composition of arclogitic garnets, which also comprise roughly equal amounts of the Mg, Fe, and Ca end members. Some rare jadeitic clinopyroxenes as well as grospyditic varieties were described from the Sierra Nevada localities (Domenick et al., 1983). Grospyditic clinopyroxenes are green to black when not altered, while the rarer jadeitic clinopyroxenes found at all localities appear bright green. Orthopyroxenes occur as exsolution lamellae in clinopyroxene and/or as small anhedral intercumulus phases together with clinopyroxenes. In some Sierra Nevada arclogites, orthopyroxene occurs as small inclusions in garnet (Ducea and Saleeby, 1996). While orthopyroxene is merely an accessory phase in arclogites and does not occur in many of these rocks, its presence is important in determining the pressure of equilibration of the assemblage.

Amphiboles are ferroan pargasitic hornblendes and may be an absent or dominant phase in arclogites, although in most cases they do not comprise more than 20% of the rock. Many amphiboles have a relatively high concentration of Ti, which gives them a yellow brownish color in hand specimen.

Fe—Ti oxides are rather common in arclogites, although they remain the least investigated mineral at all localities. Magnetite, ilmenite, and rutile are most commonly described. While magnetite and ilmenite can occur as large cumulate crystals that make up as much as 30–40% of some arclogites, rutile is typically found as inclusions within garnet. Some garnet-free arclogites (clinopyroxenites), especially those from the Chinese Peak locality in the Sierra Nevada, have up to 50% titanium magnetites and form distinct layers at the scale of the thin section (Ducea and Saleeby, 1996).

While plagioclase is not a common phase in arclogites, transitions from arclogite to layered granulite are observed in Sierra Nevada (Dodge et al., 1986), central Arizona (Esperanca et al., 1988), and Mercaderes collections (Weber et al., 2002). In addition, small inclusions of plagioclase are found in garnets at all locations. They have compositions ranging from oligoclase to andesine and average out near the boundary between the two among all locations.

Phlogopite is an accessory mineral found in some hydrated arclogites along with amphibole at all locations. Phlogopite rarely makes up more than 0.5% of the rock volume and is characterized by high Ti content (up to 5%). Scapolite is a rare accessory mineral in arclogites and is typically a sulfate-rich mizzonite (Weber et al., 2002). Apatite is included in garnets and is a fluorapatite with a more minor hydroxyl component. Zircon, titanite, monazite and clinozoizite, when present, are included in garnets. Chalcopyrite and other rare arclogitic minerals are not described further here.

6. Cumulates or restites?

The cumulate versus restite origin of arclogitic assemblages has been extensively debated (Lee et al., 2006; Jagoutz, 2014; Bloch et al., 2017). Geochemically, there is no clear way to uniquely distinguish between a restite and cumulate origin by studying magmas that were extracted upwards into the volcanic arc or subvolcanic batholith (Ducea et al., 2015). Petrographically, most of these rocks have cumulate textures (Fig. 4) and thus they are probably collections of minerals that fractionated and separated within magma chamber environments sensu *lato*. However, the most likely ratio of arc to residue in these environments is 1:1 to 1:3 (Ducea, 2002), meaning that if these assemblages were restites of partial melting at high melt fraction, cumulate textures would probably form anyway. One clear conclusion from Sierra Nevada and central Arizona localities is that pre-existing lower crust was involved in the mass budget of the batholith (Ducea and Barton, 2007), which is evident in the radiogenic and stable isotopes of the arclogites (Esperanca et al., 1988; Smith et al., 1994; Ducea, 2002) and the presence of inherited Precambrian zircon grains contained within them (Murphy and Chapman, 2018). This incorporation of the local lowermost crust rules out a closed system fractionation environment. Altogether, the study of arclogites has not at present sufficiently resolved the debate regarding cumulate versus restite origin, which has implications for how hot zones (Annen et al., 2006) (or MASH zones, Hildreth and Moorbath, 1988) form under long-lived arcs and what they may look like in detail. Without a doubt, hot zones are areas where partial melt resides for a long time (possibly millions of years) with heat constantly added through intrusions of mantle-derived magma (Dufek and Bergantz, 2005; Annen et al., 2006) over large areas (Ward et al., 2017; Delph et al., 2017). At high melt fraction in these solid-liquid systems, searching for the difference between a cumulate and a restite may prove futile.

7. Geochemistry

Because most arclogites occur as cumulate-textured xenoliths that are 10–20 cm in diameter and consist of relatively large minerals, they

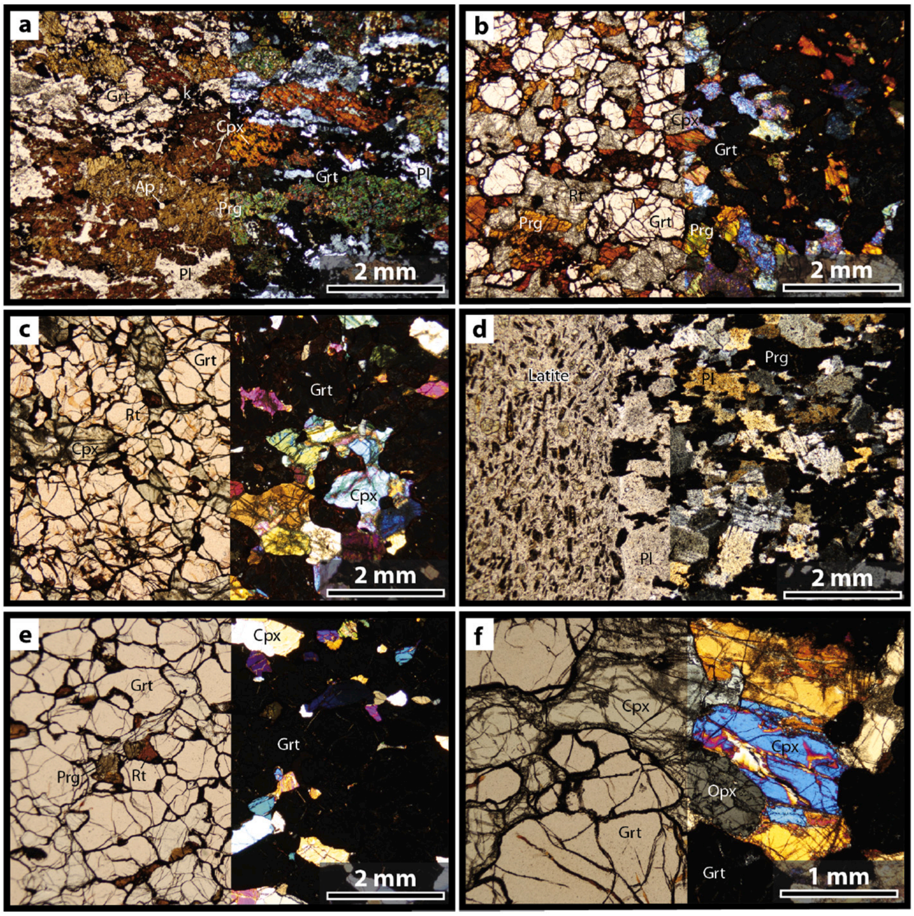

Fig. 4. Photomicrographs of petrologic features in Central Arizona localities: arclogites and related xenoliths (from Chapman et al., 2019). All panels show plane-polarized light on the left and cross-polarized light on the right, respectively. (A) Camp Creek garnet clinopyroxenite (group 1) with relict clinopyroxene in cores of amphibole, which has replaced most of the primary clinopyroxene. Note plagioclase-rich injected melt pockets, kelyphitized garnet rim domains, and moderately strong foliation defined by elongate amphibole running from left to right of frame. (B) Camp Creek arclogite with a higher proportion of primary clinopyroxene to secondary amphibole than sample shown in A. (C) Equigranular Camp Creek fresh arclogite. (D) Chino Valley amphibolitized felsic granulite gneiss. Note biotite-clinopyroxene latite showing flow foliation from top to bottom of photo. (E) Chino Valley fresh arclogite with minor secondary pargasitic amphibole replacing clinopyroxene (group 2).(F) Chino Valley fresh garnet-websterite. Sample yields Late Jurassic garnet–whole rock isochron age. Mineral abbreviations: Ap— apatite; Krs—kaersutitic amphibole; Cpx—clinopyroxene; Grt—garnet; Ilm—ilmenite; K—kelyphite; Opx—orthopyroxene; Prg—pargasitic amphibole; Pl—plagioclase; Rt—rutile.

are inherently potentially unrepresentative. For this reason, it is difficult to determine the average mineral abundance or bulk chemistry of arclogites. Nevertheless, efforts to average various compositions have been made by various researchers (e.g. Ducea, 2002; Lee, 2014). Average mineralogy or chemistry aside, a number of important features of these rocks do stand out: (1) they are high-Fe, low-Mg eclogitic rocks, (2) contain little to no orthopyroxene, (3) have a larger fraction of garnet than oceanic eclogites, averaging ~50% by volume, (4) are rich in Fe—Ti oxides (magnetite, ilmenite, and rutile), (5) have a variety of other accessory minerals such as zircon, apatite, and titanite, and (6) are not quartz normative.

These common threads among all arclogites helped researchers estimate their average composition. Arclogites are anomalously low silica, which makes them ideal candidates for residues of intermediate melts. Consistent with this interpretation are the high FeO, and TiO_2, which reflects differentiation toward intermediate melts envisioned by many to produce a trend like that shown in Fig. 5 (from Lee et al., 2006). If there is no involvement (assimilation) of pre-existing intermediate crust, an average arc basalt requires roughly one-part average continental arc and two to three parts arclogite (Ducea, 2002; Ducea et al., 2015). If pre-existing continental crust is incorporated during partial melt residence in hot zones of the lowermost crust, the ratio of granitoid to arclogite decreases toward 1:1. Furthermore, the range of crystallization pressures in Sierra Nevada arclogites is consistent with a 1:1.5 ratio between batholith and residue (Ducea and Saleeby, 1996; Saleeby et al., 2003).

Arclogites are enriched in heavy REE (Chin et al., 2014b) due to their affinity for garnet, amphibole, and clinopyroxene. They are also enriched in HFSE such as Nb and Ta (Tang et al., 2019), providing a reservoir for storage of these elements depleted in arc magmas. An average REE profile of Sierra Nevada arclogites shows they are overall

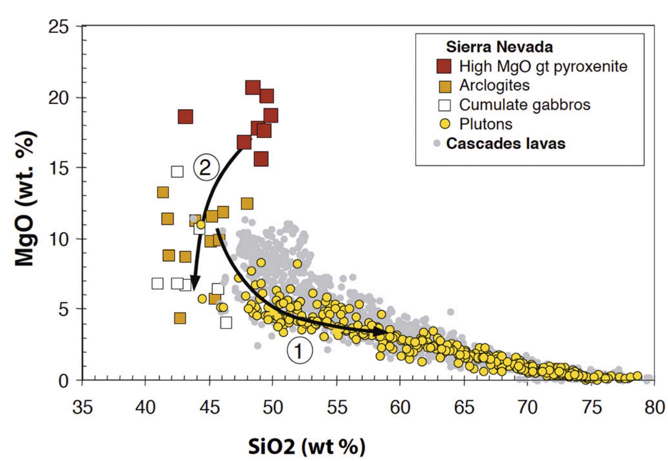

Fig. 5. Harker diagram showing compositional trends of two major arcs (plutons from the Sierra Nevada and volcanic rocks from the modern Cascades) (trend 1) and the opposite trend (2) typical for cumulate and restites of the Sierra Nevada (modified from Lee et al., 2006). This trend is identical to those seen in other studies (see Ducea, 2002 for example). High Mg garnet pyroxenites here are high pressure (mantle-derived) garnet westeritic assemblages (see text for details).

great complements of the upper- to mid-crustal batholith (Ducea, 2002; Fig. 6).

One of the debated aspects of the chemical evolution of the Earth is the imbalance of the Nb/Ta ratio in major continent-forming reservoirs – the Nb/Ta ratio is sub-chondritic (~19) in the crust and the depleted

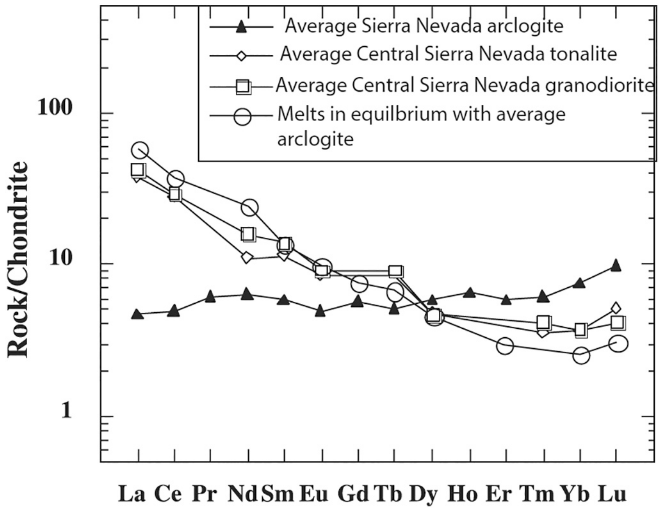

Fig. 6. Rare earth elemental chemistry of average Sierra Nevada arclogite (Ducea, 2002), calculated melts in equilibrium with that residue (using partition coefficients listed in Ducea, 2002), as well as average composition of the main lithologic types in the central Sierra Nevada batholith, tonalites and granodiorites (numerous sources compiled in NAVDAT.org).

mantle (Rudnick et al., 2000). The missing high Nb/Ta reservoir was proposed to be some rutile-bearing eclogite from studies of kimberlitic eclogites, which are interpreted to be recycled oceanic crust (Rudnick et al., 2000). A more convincing explanation providing a direct link to continental formation was provided by Tang et al. (2019), who noted that rutile-bearing arclogites from central Arizona have high Nb/Ta ratios. Similarly, high Nb/Ta ratios have been measured within arclogites of the Sierra Nevada. These highly heterogeneous Nb/Ta ratios range from 20 to over 100 (Ducea, 2002) and are suggested to result from crystallization of rutile, a high Nb/Ta phase abundant in arclogites (Tang et al., 2019) as inclusions within garnet. Additionally, ilmenite may have high Nb/Ta ratios, but this has yet to be precisely quantified. Because oceanic eclogites (Group C) do not typically contain rutile (Coleman et al., 1965), arclogites are the most likely reservoir to balance out the sub-chondritic Nb/Ta of the crust and depleted mantle.

Radiogenic isotopes, such as Sr, Nd, and Pb, of the Sierra Nevada arclogites have been studied in detail at the whole-rock scale (Domenick et al., 1983; Ducea, 2001, 2002). On average, the isotopic signatures of these arclogites, as well as their ages, are identical to those of the Dinkey Creek intrusive suite, which makes up the surface geology of the central Sierra Nevada (Kistler, 1990). Similarly, whole-rock isotopic values determined from central Arizona arclogite xenoliths overlap those of Mojave Desert plutons, the inferred original (i.e., pre-shallow-angle subduction) location of central Arizona arclogite (Esperanca et al., 1988, 1997; Smith et al., 1994; Rautela et al., 2020). As such, both California and Arizona xenolithic arclogites are suspected to be petrogenetically related to the batholith. Garnet websterites (also referred to as high-Mg pyroxenites by Lee et al., 2006) and garnet peridotites have slightly more depleted isotopic values indicative of a subcontinental *enriched* lithospheric mantle (DePaolo, 1981). The similarity in radiogenic isotopes between arclogites and batholith also argues against massive upper crustal contamination during the evolution of the arc, since the pre-batholithic framework of the Sierra Nevada is significantly more enriched in radiogenic isotopes (Ducea, 2001). Whatever assimilation of pre-existing crustal rocks occurred must have taken place in the deepest crustal hot zone.

Oxygen isotopes add important constraints on the amount of local pre-existing crust that has been recycled in these systems. Sierra Nevada whole rock $\delta^{18}O$ calculated based on laser ablation individual mineral measurements (clinopyroxenes, garnets, amphiboles) within arclogites are 6.5–8.5‰ relative to SMOW (Standard Mean Ocean Water), with an average of 7.5‰. This is significantly higher than mantle values (typically $\delta^{18}O$ of 5.3–5.5‰) and those of garnet websterites from the Sierra Nevada ($\delta^{18}O = 6$–6.5‰). These values argue strongly for the incorporation of sedimentary rocks that were buried to lower crustal levels after having interacted with the hydrosphere (Ducea, 2002). Metasedimentary xenoliths are known from the central Sierra Nevada (Chin et al., 2013, Ducea and Saleeby, 1996, 1998b) and are most likely miogeoclinal (passive margin) rocks transferred to the deep crust through some combination of thrusting from the east (Ducea, 2001; DeCelles et al., 2009) and convective downward flow from above (e.g., Saleeby, 1990; Paterson and Farris, 2008). Since these sedimentary rocks have $\delta^{18}O$ around 10‰ on average, one can estimate that about 15–25% of the mass of the arclogite-batholith system is made of these materials. This constraint is important in that it documents a non-trivial amount of assimilation of local lower crust, bringing the size of the postulate "root" to no more than twice, and probably more likely ~1.5 times, the size of the batholith.

8. Ages

There are two successful methods employed so far in the dating of arclogites: (a) Sm—Nd or Lu—Hf garnet (and another mineral or whole rock) isochron geochronology (Ducea and Saleeby, 1998a; Chin et al., 2015b) or (b) zircon or titanite U—Pb chronology. Since the community has only recently become aware of the presence of accessory zircon in arclogites (see Rautela et al., 2020), we expect most future chronology studies of these rocks will be done by U—Pb. Only two studies so far have attempted to measure U—Pb ages on titanite, which appears to be reset ages (Erdman et al., 2016). Garnets are great candidates for Sm—Nd or Lu—Hf chronology; however, the hot environments in which these rocks form and possibly reside in for long periods of time renders them susceptible to resetting, as the closure temperatures for these techniques are in the 600–900 °C range (Ducea and Saleeby, 1998b; Wendlandt et al., 1996). An additional complication comes from textural observations and chemical zonation patterns suggesting that garnet growth can occur during cooling of the sub-batholithic root to temperatures as low as ~600 °C (Smith et al., 1994; Rautela et al., 2020). In these circumstances, garnets are likely to yield ages younger than the corresponding arc (perhaps 10s of Ma younger, if the cooling rate is slow). On the other hand, if isochron ages of arclogites are much older than their corresponding arc, we must reject the developing hypothesis for the origin of these rocks. Below, we give examples of ages measured so far in these types of rocks along with their significance, implications, and limitations.

The Sierra Nevada arclogites are cogenetic with the surface batholith. This has been established not only by the coherence of isotopic measurements between the arclogites and the surface Dinkey Creek and Shaver Intrusive suites but also by age dating using garnet-clinopyroxene Sm—Nd chronology (Ducea and Saleeby, 1998b; Chin et al., 2015a). The ages of these assemblages are 80–120 Ma (with relatively large errors typical for garnet Sm—Nd dating in this age range), coincident with the age of the surface batholith. The Sierra Nevada arclogites remained in place for at least 70 Myr after the cessation of batholith-forming magmatism, since they came up as cold xenoliths entrained in Miocene volcanic rocks that erupted through the batholith. Cooling of these rocks commenced with the demise of the great batholith at 80 Ma and they were never heated regionally again. The coincidence of isotopic characteristics (Ducea, 2002) and Sm—Nd garnet ages (Ducea and Saleeby, 1998b; Chin et al., 2015b) between the arclogites and the upper crustal batholith was taken to show these arclogites are sub-batholith rocks.

Mercaderes arclogites have been dated to around 5 ± 20 Ma by multi-grain garnet and whole rock Sm—Nd isochron (Ducea, unpublished) and to 5 ± 5 Ma by garnet Lu—Hf isochron (Bloch et al., 2017) (same rock samples). Given the extremely large half-lives of these systems, 5 Ma ages come with errors that make these numbers indistinguishable from zero ages. This is not surprising because the temperatures recorded in these rocks exceed 1000 °C (and the eruption ages are close to zero) so even if they formed at a distinct age in the past these isochrons would be reset.

Central Arizona arclogites have Sm—Nd garnet ages that are largely reset to a mid-Cenozoic value (Esperanca et al., 1988, Chapman et al., 2020, Fig. 7). These rocks have been dated by zircon U—Pb to be Mesozoic. However, because the sub-Arizona lowermost crust was hot and was likely part of a thick and magmatically active orogenic plateau until around the end of the Oligocene (J Chapman et al., 2015b), these rocks stayed above the closure temperatures for these systems long after they formed (Rautela et al., 2020). An Eocene (57 Ma) titanite U—Pb age for one arclogite from Chino Valley (Chin et al., 2015b) is consistent with these findings.

The discovery of zircon in arclogites (Smith et al., 1994; Chapman et al., 2020, Rautela et al., 2020, Fig. 8) paves the way for new geochronologic efforts aimed at unraveling their igneous crystallization ages. Since these rocks were in equilibrium with intermediate magmas, the presence of zircon is not surprising. Rautela et al. (2020) show that the central Arizona arclogites have U—Pb zircon ages coincident with the major pulses of magmatism in the California arc (Fig. 8) and therefore argue that these arclogites represent the southern California arc root that was translated eastward toward the continental interior during the Laramide orogeny (Chapman et al., 2020). Future studies of xenoliths or other rocks suspected to be arclogites will certainly use zircon U—Pb as a main tool for dating their formation age. The only difficulties in this approach is that sample size is usually small in xenoliths and recovery of zircon is not always straightforward (Rautela et al., 2020).

9. Thermobarometry: modern and decayed

Thermometry of arclogitic rocks is performed via classic garnet-clinopyroxene (and orthopyroxene when present; Ellis and Green, 1979 calibration or more modern updates, e.g. Nakamura, 2009), garnet-amphibole calibrations, Ti-in-zircon thermometry (Watson et al., 2006), and garnet-clinopyroxene rare-earth element (REE) thermobarometry (Sun and Liang, 2015). Barometry is performed on orthopyroxene-garnet pairs (using Harley and Green, 1982, Harley, 1984 or equivalent Al-in-orthopyroxene in equilibrium with garnet barometers) whenever orthopyroxene (particularly when included in garnets) is present, even in small amounts. Otherwise the garnet-clinopyroxene barometer (Mukhopadhyay, 1989) is used. Another method is to calculate minimum pressures using garnet-pyroxene-plagioclase-quartz barometers (Perkins III and Newton, 1981; Newton and Perkins III, 1982 or equivalent) (lack of quartz and feldspar providing a minimum estimate). In more recent papers, some arclogite pressures and temperatures were determined using the Gibbs free energy minimization software package THERIAK-DOMINO (de Capitani and Petrakakis, 2010). A good example of this method is a recent study of arclogites from the central Arizona localities (Rautela et al., 2020).

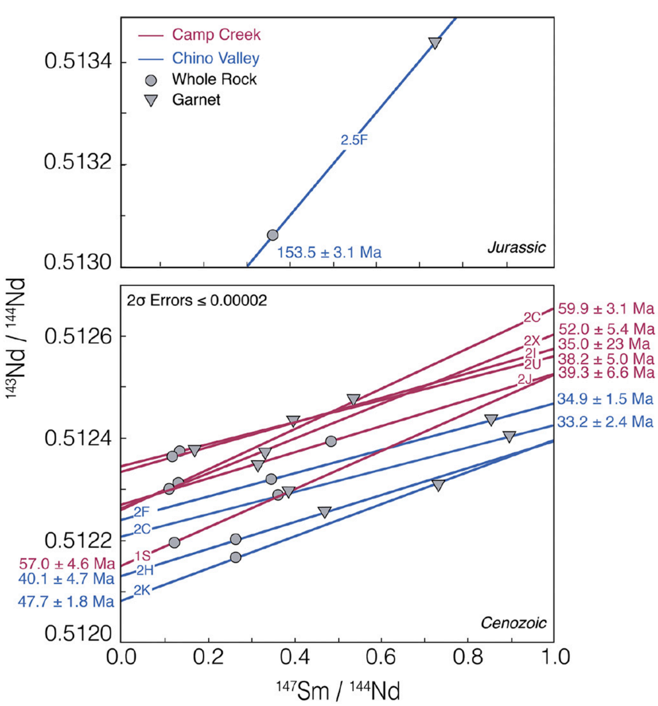

Fig. 7. Sm—Nd garnet-whole rock geochronology for the central Arizona arclogites. One Chino Valley sample 16CV2.5F records a Jurassic age. Remaining samples yield Late Cretaceous – Early Cenozoic ages, suggesting partial re-equilibration of the samples with host latite (Chapman et al., 2019; Rautela et al., 2020).

Despite the difficulty of estimating pressures on garnet-clinopyroxene rocks, it is fairly well established that arclogites equilibrated between 1.5 GPa and 2.5 GPa at all known localities and that they transition to granulitic assemblages at lower pressures. This is precisely the pressure range over which garnet- and pyroxene-rich residues are predicted by experimental petrology to be stable (e.g. Rapp and Watson, 1995). One published arclogite pressure determination (0.33 GPa at 801 °C, Chin et al., 2015b), based on the new garnet-clinopyroxene REE thermobarometer of Sun and Liang (2015), is significantly lower than the 1.5–2.5 GPa range. We consider this value to be spurious given that granulitic assemblages are predicted at those conditions and also because the LREE distribution in clinopyroxene from this sample is significantly lower than that expected at equilibrium (E. Chin, personal communication, 2020).

None of the arclogites studied so far display mineral chemistry (and by inference barometric) evidence for major upward or downward vertical movement, with downward migration being relevant to foundering. Some form of foundering has been postulated by Bloch et al. (2017) for the Mercaderes arclogites, but this is more of a proposed hypothesis rather than a valid interpretation due to the fact that evidence for this process does not exist at the mineral grain scale in these arclogites. Garnet websterites and garnet peridotites from Sierra Nevada and Colombian locations, which originate at greater pressures (1.5 to >4 GPa) than arclogites, are not related to foundering and instead represent sub-continental lithospheric mantle assemblages (Mukhopadhyay and Manton, 1994; Ducea and Saleeby, 1996; Lee et al., 2001a; Rodriguez-Vargas et al., 2005) (Fig. 9).

All xenolithic arclogites display well constrained temperatures in the range of 700–950 °C (Fig. 9). The only outliers are arclogites measured by Bloch et al. (2017), which are much hotter (1150–1250 °C) than the 700–900 °C temperatures reported for similar assemblages by Weber et al. (2002). It is unclear why this discrepancy exists between the Bloch et al. study and all other temperature measurements of arclogitic assemblages. One possible explanation for the Bloch et al. (2017) data is that the Colombian arclogites are young (modern) and did not have the time to cool down from magmatic temperatures yet. Garnet websterites and peridotites also record much higher temperatures with estimates similar to those for arclogites reported by Bloch et al. (2017). However, altogether, the temperatures recorded on arclogites in studies from California (Ducea and Saleeby, 1996; Lee et al., 2006; Chin et al., 2015b), Arizona (Esperanca et al., 1988; Smith et al., 1994; Erdman et al., 2016; Rautela et al., 2020), the Kohistan arc (Dhuime et al., 2009), and in Beni Bousera (Gysi et al., 2011) are consistent with the relatively limited temperature range known to define the sub-arc lower crust (Depine et al., 2008), which is near-isothermal with a 800–900 °C temperature range.

An intriguing aspect of arclogite thermobarometry is the apparent negative PT slope of the Sierra Nevada arclogitic xenoliths, which has been produced independently on at least two datasets using different

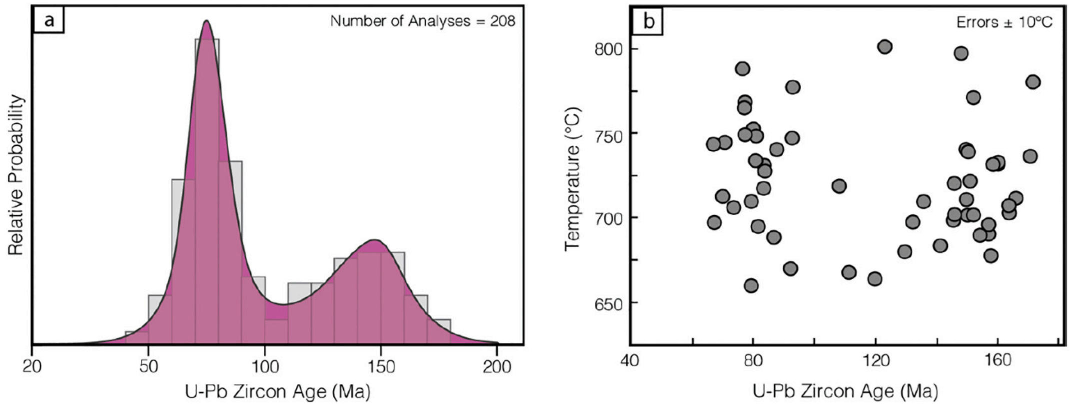

Fig. 8. Zircon U—Pb age distribution and Ti-in-zircon thermometry trend over time for the central Arizona arclogites (from Chapman et al., 2019, 2020 and Rautela et al., 2020). (a) A probability density diagram of U—Pb zircon ages of the samples (data from Chapman et al., 2020). Note two age peaks at ca. 150 Ma and ca. 70 Ma. (b) Ti-in-zircon thermometry (Watson et al., 2006) showing elevated temperatures (>650C) from Jurassic through Cenozoic time.

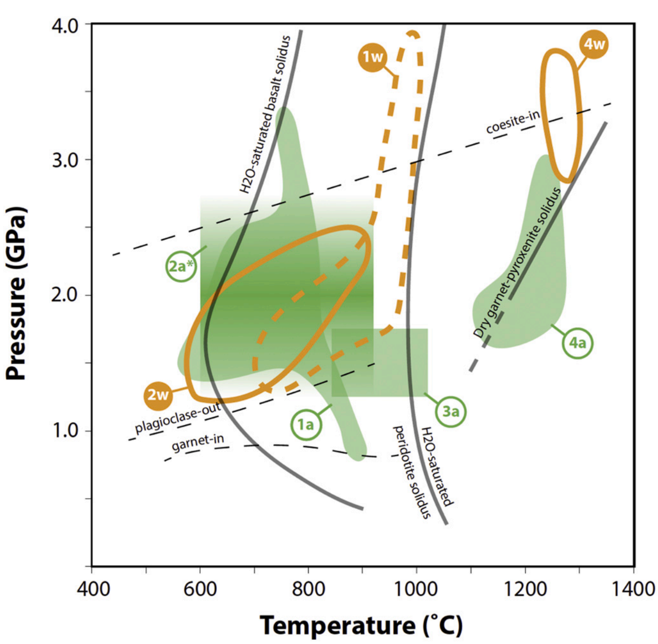

Fig. 9. Summary of pressure-temperature constraints available from garnet clinopyroxenite (i.e., arclogite, labeled "a" in green filled fields) plus garnet websterite and garnet peritotite (combined and labeled "w" in fields with orange outlines) xenoliths. Fields 1–4 contain data from central Sierra Nevada (California; Mukhopadhyay and Manton, 1994; Ducea and Saleeby, 1996; Ducea, 1998; Lee et al., 2000, 2001, 2006; Chin et al., 2015), central Arizona (Esperanca et al., 1988; Smith et al., 1994; Erdman et al., 2016; Rautela et al., 2020), Beni Bousera (Morocco; Gysi et al., 2011), and Mercaderes (Colombia; Bloch et al., 2017) localities, respectively. Results from sample BCX (Chin et al., 2015) excluded due to probable disequilibrium (E. Chin, personal communication, 2020). Field 3w not shown as quantitative thermobarometry of websterite is not available from the Beni Bousera locality. Plagioclase- out and garnet-in isograds from Wolf and Wyllie (1993, 1994), Hydrous basalt and peridotite solidi from Rapp and Watson (1995) and Vielzeuf and Schmidt (2001), dry garnet clinopyroxenite solidus and low P-T projection (dashed) from Petermann and Hirschmann (2003).
*Temperatures calculated at 20 kbar (garnet-orthopyroxene thermobarometry on websterite xenoliths from Chino Valley). A minimum pressure constraint of 0.9 GPa on central Arizona garnet clinopyroxenite is provided by garnet – plagioclase - orthopyroxene-quartz barometry on granulite xenoliths from Camp Creek. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

samples (Mukhopadhyay, 1989, Ducea and Saleeby, 1996). Evidently, prior to convective removal, these rocks had cooled from near-magmatic temperatures to the much colder conditions of the late Cenozoic Sierra Nevada (Ducea and Saleeby, 1996, 1998a). A likely explanation for such cooling is the refrigeration of the Sierra Nevada from below (Dumitru, 1990; Chin et al., 2015b) immediately following the cessation of arc magmatism and during the Laramide orogeny. Another explanation was that the negative slope mimics the solidus of wet basalts (amphibolites) and that temperatures locked in represent near solidus values (Saleeby et al., 2003).

10. Densities of the hot zones

It is well known that arclogites are denser than the underlying mantle (Ducea, 2002; Lee, 2014; Lee and Anderson, 2015 and references therein) as garnet and other phases are all among the densest rock-forming minerals in an igneous environment. Consequently they will be negatively buoyant with respect to the underlying mantle and will likely founder, although the size of foundered fragments, the frequency of foundering events, and the consequences of foundering on magmatism and surface evolution are debated (Kay and Kay, 1993; Ducea and Saleeby, 1998a; Jull and Kelemen, 2001; Lee, 2014). These aspects are summarized in the companion paper (Ducea et al., 2020). Here, we point out that while arcs are active, the negative buoyancy argument may be offset by the presence of positively buoyant granitic partial melt in the deep crustal hot zones (Bowman and Ducea, 2020 in prep.)

Large areas of partial melt are known to exist beneath the frontal arc of the southern and central Andes and beneath the Altiplano-Puna toward the back arc (Ward et al., 2017; Delph et al., 2017; Gonzales Vidal et al., 2018). While researchers originally focused on a mid-crustal (~20 km deep) partial melt reservoir in the Altiplano-Puna (Chmielowski et al., 1999) named the "Altiplano-Puna Magma Body", it is now clear that partial melting is extensive in the lowermost part of the central Andean crust in areas where arc magmas are present at the surface. This is not surprising and is predicted by most models of intermediate storage of arc magmas (Hildreth and Moorbath, 1988, Dufek and Bergantz, 2005, Annen et al., 2006 and many others).

If one assumes that the average melt stored in the lowermost crust in an arclogitic reservoir is similar to the major element average of Andean volcanoes or North American batholiths (Ducea et al., 2015), one can calculate the density of the arclogite-intermediate magma system at depth. Densities of liquids are calculated using Bottinga and Weill (1970) and inserted into a modified version of Abers and Hacker (2016) to average the density of the system (Fig. 10).

Fig. 10 shows that for melt fractions of 0.22 (melt percentage of 22%) and higher (which are expected as discussed elsewhere in this review),

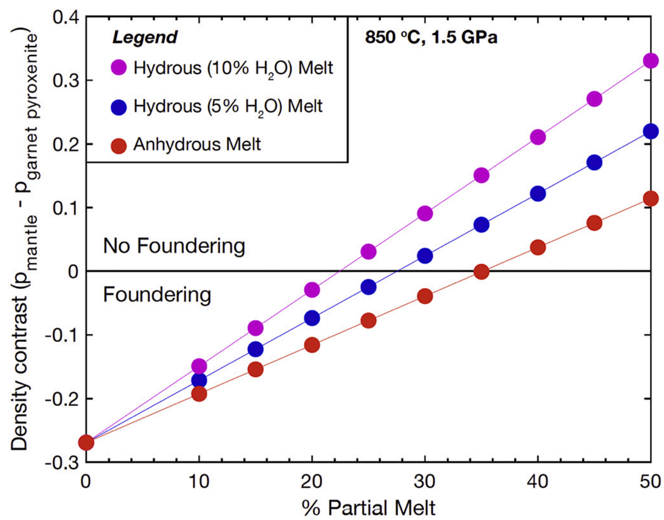

Fig. 10. Diagram showing the density contrast between typical upper mantle peridotite and arclogite at 850 °C and 1.5 GPa, with various fractions of intermediate partial melt for anhydrous melt, 5% H_2O and 10% H_2O. If density contrast is positive (root denser than melt), foundering is possible, otherwise not. Diagram shows that if percentage of partial melt is >22–35%, arclogitic roots are not gravitationally unstable. Average arclogitic compositions from Ducea (2002) Lee et al. (2006) was used here. Density calculated with a modified version of Hacker and Abers (2016).

the "hot zone" will not be negatively buoyant while magma is present even if all cumulates are arclogitic. As magma is extracted out of this reservoir (and evidence suggests that it takes place in peaks and lulls, Ducea and Barton, 2007), the density of the root increases significantly (up to 600 kg/m^3); post-arc cooling of the root contributes additionally to an increase of density (150 kg/m^3). However, for as long as the melt fraction remains at around 22% or more in an active arc, the root is not negatively buoyant, and this is an important constraint to keep in mind when one models specific dripping scenarios. Foundering can take place much after the arc ceased to form, as it cools down and gains additional negative buoyancy.

11. Crustal or mantle rocks?

Arguably, arclogites are petrologically crustal rocks; they represent the processed residues (cumulates or restites) of mafic melts extracted out of the mantle at subduction zones. They are, however, mantle-like rocks because they are ultramafic in composition and have densities and seismic velocities similar to the Earth's upper mantle (Ducea, 2002; Lee, 2014). Since they are located in the deepest parts of the crust in active arc environments, the question is: are arclogites identified as crustal or sub-crustal rocks by geophysical techniques?

The continental crust to mantle transition, known as the Mohorovicic discontinuity or simply the Moho, is typically well-defined in areas that are either cratonic or have undergone extensional collapse at the end of orogenic cycles (Meissner, 1986). The Basin and Range in the Western US is one such example (Klemperer et al., 1986), where the Moho is fairly flat and typically found at 30 km below the surface. The Sierra Nevada batholith, which presumably has undergone foundering and has been affected by nearby extension, has a flat and well-defined Moho at 33 km (Fliedner and Ruppert, 1996; Wernicke et al., 1996). Beneath active convergent margins and especially those that contain magmatic arcs, it is much more difficult to resolve depth to Moho using seismic data. For example, the depth to Moho in the Puna plateau in South America ranges from 35 km to over 70 km within 1-degree grids over which teleseismic receiver function data was acquired (Yuan et al., 2002), although better resolutions have been more recently obtained (Assumpcao et al., 2013; Gonzales Vidal et al., 2018). Additionally, large discrepancies exist between the seismically determined Moho and the Moho inferred from Bouguer anomalies under the Andean frontal arc (Tassara et al., 2007). These discrepancies bring to light the question of whether the seismically defined Moho in these areas truly represents the "petrologic" transition from crustal mafic to mantle ultramafic (peridotitic) lithologies as implied by most studies seeking the location of the Moho, or whether the seismic and petrologic "Mohos" are actually rather different in sub-arc environments (Herzberg et al., 1983; Griffin and O'Reilly, 1987). It is quite plausible that the transition from granulite to arclogite facies in deep crustal hot zones is recorded as the seismic Moho in these areas, which in reality may be over 20–30 km shallower than the transition to true lithospheric mantle (Fig. 1). The complexities that arise from the addition of partial melt (discussed in Section 10) additionally influence the depth to Moho; a greater fraction of melt within hot zones would drive both the density of the residue and the location of the Moho toward greater depths. Consequently, it may be impossible to identify a single major refractor that represents the Moho beneath thick arcs like the modern Andes, and in particular the central Andes and parts of the northern Andes. At peak magmatism and before melt has been largely extracted from hot zones, the seismic and petrologic Moho may coincide and are deep, whereas at the end of magmatism but before any major foundering, the seismic Moho may be tens of km shallower than the petrologic one (Fig. 1). The post-foundering Moho may be a much sharper feature (Jagoutz and Behn, 2013).

12. Continental evolution implications

If the complements to thicker arcs (transitional, thicker island and continental) are mostly arclogites, then their crust-mantle architecture is somewhat unusual in that a dense root of sizable mass develops, perhaps making as much as twice the mass of intermediate magmatic rocks in the upper to middle crust (Fig. 1). This picture emerges from many studies of arc sequences in the geologic record (Ducea, 2002; Saleeby et al., 2003; Lee et al., 2006; Jagoutz and Schmidt, 2013). Elevated Sr/Y and La/Yb ratios (Profeta et al., 2015), a lack of Eu anomalies, and other average chemical parameters in surface intermediate volcanics (Mamani et al., 2010) or the corresponding batholith (Ducea et al., 2015) require that many arcs have a deep counterpart, with plagioclase playing only a limited role in magmatic diversification. However, not all arcs display these signatures: numerous arcs, including some that are locally exposed to deep crustal levels, are thin enough such that they require only a granulitic residue, not an arclogitic one. For example, both Famatinian (Otamendi et al., 2009) and Salinian (Chapman et al., 2014) arcs lack garnet signatures. Similarly, there is no garnet-rich lower crust where the Sierra Valle Fertil (Otamendi et al., 2009, 2012; Walker Jr. et al., 2015) or Salinia (Ducea et al., 2003) are exposed to 30 km paleodepths.

However, garnet and amphibole (Davidson et al., 2007; Profeta et al., 2015; Ducea et al., 2015) signatures resembling arclogitic residues seem to be dominant in global databases. Simply put, if only Sr/Y and the REEs are taken into consideration, the average of most young Cordilleran batholiths are intermediate rocks straddling the border between adakitic and non-adakitic compositions (Ducea et al., 2015). In contrast to the original hypothesis for the origin of adakites, the isotopes in all Cordilleran batholiths are inconsistent with slab melting as a main mechanism of magma generation (Ducea and Barton, 2007). Therefore, these garnet and amphibole markers and the lack of a plagioclase signature must have been acquired in a deep crustal, arclogitic-like environment.

Balica et al. (2020) used zircon petrochronology on Hadean to Phanerozoic detrital zircons in an effort to calculate the trace elemental chemistry and in particular the REE chemistry of granitoids in equilibrium with those zircons. This global approach showed two remarkably consistent trends over time. First, most of the zircon archive is made of igneous zircons (low U/Th zircons) that crystallized in the Ti-in-zircon temperature window most consistent with granitic melts (650–858 °C). Second, granitoids of all ages require a garnet-pyroxene-amphibole residue based on the La/Yb and Sm/Yb ratios calculated for whole rocks in equilibrium with these zircons over time (Fig. 11). This does not require that the processes taking place at modern convergent margins have operated since the Hadean; granitoids and by inference the continental crust could have been extracted out of thick oceanic-like plateaus or other tectonic environments (Dhuime et al., 2015). However, the global zircon dataset does imply that conditions for arclogite generation must have existed since the time in Earth's history when felsic magmas began being generated.

Yet a still common perception is that only continental (also known as Andean or Cordilleran) arcs can be complemented by arclogites. This raises the following question: if Andean/Cordilleran arcs are continental crust-forming factories, how can continental crust only be formed on pre-existing continental crust, and how did it all start? The resolution is two-fold: first, the widely held opinion that island arcs are mafic (Rudnick, 1995) has no real global basis in the modern geologic record and has been repeatedly proven false as some modern island arcs are intermediate in bulk chemistry (e.g. Gill, 1981; Jagoutz and Kelemen, 2015). Different arcs built onto oceanic or continental crust can in reality have surprisingly variable average silica contents – some continental arcs are more mafic on average than other oceanic ones (Ducea et al., 2015). Secondly, it has also been suggested that some island arcs

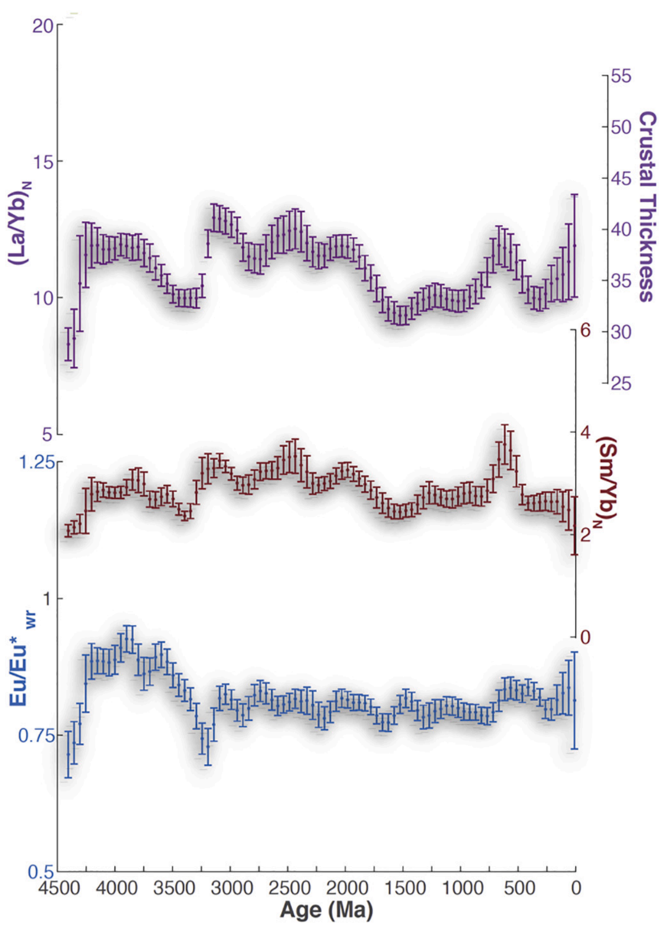

Fig. 11. Global calculated whole rock La/Yb$_n$, Sm/Yb$_n$ and Eu/Eu* from zircon petrochronology (Balica et al., 2020). Crustal thickness over time is also shown on the right (as determined by Profeta et al., 2015 based on La/Yb). 98% all analyzed zircons are from granitoid magmas (Balica et al., 2020). Diagram shows that to a first order, granitoids were fractionated out of magmatic systems at 35–45 km over time, similar to conditions required to make arclogitic roots. Mechanisms for fractionating or remelting basalts under lower crustal conditions may however have been different in the geologic past compared to modern arc settings (Balica et al., 2020).

of the recent geologic past have been thickened to more than 40 km (Jagoutz and Schmidt, 2012; Davidson and Arculus, 2006). Environments that are more easily studied on land (the western North American batholiths or the central Andes volcanic arcs) do exist in an intra-oceanic realm as well.

Overall, the arclogite model proposes that these rocks complement large intermediate magmatic arcs at depth. Arclogite formation drives silica up in the corresponding melt due to the crystallization of the low silica minerals that characterize these assemblages. Melt extraction from lower crustal melt-solid zones allows these arclogites to reach a critical density such that they founder into the mantle and leave behind a continental crust that is intermediate in composition (Ducea, 2002; Lee, 2014; Lee and Anderson, 2015).

13. Implications moving forward

The big picture implications and questions for the arclogite model are:

(1) With clinopyroxene, garnet, amphibole, and Fe—Ti oxides within the residue, intermediate rocks formed at magmatic arcs have a much easier path to high silica contents than magmatic systems that start out with bulk basaltic chemistries and form granulitic residues. Garnet, amphibole, and all oxides have lower silica (or no silica in the case of oxides) than a basalt. Plagioclase, in contrast, has a silica content that is similar to or higher than a basaltic bulk composition, while clinopyroxene is neutral in that respect;

(2) After significant melt extraction, the extreme density of these materials ($>3.5\ g/cm^3$) make the roots of arcs prone to detachment, removal (foundering), and integration into the convective mantle. These rocks are significantly denser than typical oceanic eclogite in subduction systems because they are richer in garnet, are more Fe-rich, and contain other dense phases, like magnetite and ilmenite, that contribute significantly to the negative buoyancy;

(3) After removal via some form of foundering into the mantle, these assemblages are prone to remelting (Elkins-Tanton, 2007; Ducea et al., 2013; Tang et al., 2019). It is critical to understand the products of this process, as these types of garnet pyroxenites are already massively depleted of a felsic component. Arclogitic garnet pyroxenites thus significantly differ from generic basaltic garnet pyroxenites (Hirschmann and Stolper, 1996; Petermann and Hirschmann, 2003), which are capable of producing intermediate melts or at least a sizable fraction of mafic melt compared to peridotite.

(4) If these assemblages undergo long term storage in the mantle, what is the isotopic signature of a long-term archived arclogite if its signature were to reappear in an oceanic island basalt (Tatsumi, 2000; Tatsumi, 2005)? Where in the mantle geodynamics isotopic space (Zindler and Hart, 1986) can one identify ancient recycled arclogites?

These issues and questions are dealt with in a companion paper (Ducea et al., 2020).

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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