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

Mihai N. Ducea[1,2]

Alan D. Chapman[3]

Emilie Bowman[1]

[1] University of Arizona, Tucson, AZ 85721, USA

[2] Faculty of Geology and Geophysics, University of Bucharest, 010041, Bucharest, Romania

[3] Geology Department, Macalester College, St. Paul, MN 55105, USA

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 ^{0}C) at the time of formation which then cool and metamorphose at ~650-750 ^{0}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.

Keywords: arclogite, arc roots, residues, cumulates, restites, thermobarometry, U-Pb zircon geochemistry

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, 2010, 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, 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 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 McLemman, 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, 1967 a and b, 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 (Gisy et al., 2011).

A new class of igneous eclogites, commonly referred to today as *arclogite*s (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.

3. Locations

Our main source of information regarding arclogites comes from xenoliths entrained in volcanic rocks sampling sub-continental arc domains. In addition, there exist some xenolith localities in the thin oceanic arcs of the Circum-Pacific (Conrad and Kay, 1984, Kay and Kay, 1985; DeBari et al., 1987, McInnes et al., 2001), but these xenoliths 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, b, c, Mukhopadhyay, 1989, Mukhopadhyay and Manton, 1994, Lee et al., 2000, 2001a and b, 2006) and central Arizona (Arculus and Smith, 1979, Esperanca et al., 1988, Chin et al, 2012, 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 (Webber 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., 2015) but they have not been studied in detail.

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, Mukhopadhyay and Manton, 1994, Ducea and Saleeby, 1996, 1998a and b, Ducea, 2002, Lee et al., 2000, 2001 a and b, 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, Figure 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 at least half of all known arclogites. 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 (up to 50%) 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 (Mukhopadhyay and Manton, 1994, Lee et al., 2000, 2001a). Furthermore, garnet websterites are distinct from arclogites in that they are much more magnesian (Mukhopadhyay and Manton, 1994, Lee et al., 2006, Chin et al., 2012, 2014) 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 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, although they have not 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 et al., 2015). One notable exception to the lack of arclogites in outcrop is the Kohistan arc (Pakistan), 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 (Zellinger, 2002 and 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 Nakanura, 1996, 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 ^{0}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, 1967 a and b) but also in 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.

Figure 2 shows pMELTS-predicted (Ghiorso and Sack, 1995) assemblages on the liquidus of a tonalitic melt for a bulk basaltic calc-alkaline composition (Schimdt 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 Figure 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 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 (Figure 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 (Esperança 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 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 Figure 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., 2014) 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 great complements of the upper- to mid-crustal batholith (Ducea, 2002; Figure 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 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 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 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 (Chin et al., 2015; 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 ^{0}C range (Ducea and Saleeby, 1998b, Wendtland 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 ^{0}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., 2015). 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., 2015) 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 ^{0}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, Figure 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., 2015), 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., 2015) is consistent with these findings.

The discovery of zircon in arclogites (Smith et al., 1994; Chapman et al., 2020, Rautela et al. 2020, Figure 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 (Figure 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 and Newton, 1981; Newton and Perkins, 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 (deCapitani & Petrakakis, 2010). A good example of this method is a recent study of arclogites from the central Arizona localities (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., 2015), 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., 2001, Rodrigues Vargas et al., 2005) (Figure 9).

All xenolithic arclogites display well constrained temperatures in the range of 700-950 ^{0}C (Figure 9). The only outliers are arclogites measured by Bloch et al. (2017), which are much hotter (1150 -1250 ^{0}C) than the 700-900 ^{0}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. 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., 2015), 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 ^{0}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 samples (Mukhopadhyay, 1994, 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)

`

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 (Chiemelowski 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 Moorbaht, 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 (Figure 10).

`

Figure 10 shows that for melt fractions of 0.22 (melt percentage of 22%) and higher (which are expected as discussed elsewhere in this review), the "hot zone" will not be negatively buoyant while magma is present even if all cumulates are arclogitic (Bowman and Ducea, 2020). 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.

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'Reillly, 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 (Figure 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 towards 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 (Figure 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 (Figure 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 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 ^{0}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 (Figure 112). 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 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 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, Peterman 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).

Acknowledgments. MND: I acknowledge support from US National Science Foundation grant EAR 1725002 and the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding project PN-III-P4-ID-PCCF-2016-0014. I want to thank my students and postdocs Steven Kidder, Peter Luffi, Alan Chapman, Jay Chapman, Antoine Tryantafyllou, Robinson Cecil, Costi Balica, and Emilie Bowman for their contributions to arclogite science (direct or indirect), which are reflected in this paper. I thank my PhD adviser Jason Saleeby and my committee members Peter Wyllie, Hugh Taylor Jr and Ed Stolper for guiding me in my early studies. I am forever indebted for the gracious reviews I received from Calvin Miller and Robert Kay on my early manuscripts: they were not just constructive they were career defining. I have learned a lot on the subject of this paper from some extraordinary peers that I am lucky to have

`

within reach of an email or in the building: Cin-Ty Lee, Peter DeCelles, Claire Currie, George Bergantz, and George Zandt. ADC: I would like to thank my PhD advisor Jason Saleeby (yes, MND and I share the same academic parentage), who brought arclogites to my attention, and my coauthor for alerting me to the existence and significance of central Arizona arclogite xenolith localities. Support from NSF grant EAR-1524768 allowed myself and my amazing students Ojashvi Rautela, Jessie Shields, and Michael Murphy to study central Arizona arclogite nodules in more detail, for which I am grateful. This effort benefitted from field and laboratory assistance by D. Abboud, B. Hunter, and J. Thole and discussions with E. Chin, S. Esperança, C.-T. Lee, D. Smith.

References

Abers, G., Hacker, B., 2016. A MATLAB toolbox and Excel workbook for calculating the densities, seismic wave speeds, and major element compositions of minerals and rocks at pressure and temperature. Geochemistry Geophysics Geosystems, 17, 616–624.

Anderson, D.L., 2005, Large igneous provinces, delamination, and fertile mantle: Elements, v. 1, p. 271–275, https://doi.org/10.2113/gselements .1.5.271.

Annen C, Blundy JD, Sparks RSJ. 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology 47:505-39.

Anczkiewicz, R. and Vance, D., 2000, Isotopic constraints on the evolution of metamorphic conditions in the Jijal Patan Complex and Kamila Belt of the Kohistan Arc, Pakistan Himalaya. In: Khan, M. A., Treloar, P. J., Searle, M. P. & Jan, M. Q. (eds) Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya. Geological Society, London, Special Publications 170, 321-331.

Arculus, R.J., and Smith, D., 1979, Eclogite, pyroxenite, and amphibolite inclusions in the Sullivan Buttes latite, Chino Valley, Yavapai County, Arizona, The Mantle Sample: Inclusions in Kimberlites and other Volcanics, American Geophysical Union, Washington, DC, p. 309-317.

Arndt NT, Goldstein SL. 1989. An open boundary between lower continental crust and mantle: its role in crust formation and crustal recycling. Tectonophysics 161:201–12.

Assumpcao, M., Feng, M., Tassara, A., Julia, J.2013, Models of crustal thickness for South America from seismic refraction, receiver functions, and surface wave tomography, Tectonophysics, 609, 82-96.

`

Aulbach, S., Arndt, N., 2019. Eclogites as palaeodynamic archives: evidence for warm (not hot) and depleted (but heterogeneous) Archaean ambient mantle. Earth and Planetary Science Letters, 505, 162–172.

Balica,C., M.N. Ducea G.E. Gehrels, J. Kirk, R.D. Roban, P. Luffi J.B. Chapman, A. Triantafyllou, J. Guo, A.M. Stoica, J. Ruiz, I. Balintoni, L. Profeta, D. Hoffman, L. Petrescu, 2020, A zircon petrochronologic view on granitoids and continental evolution, Earth and Planetary Science Letters, 531, paper 11605 https://doi.org/10.1016/j.epsl.2019.116005.

Banno, S., 1970. Classification of eclogites in terms of physical conditions of their origin. Physics of the Earth and Planetary Interiors, 3, 405–421.

Basaltic Volcanism Study Project, Basaltic Volcanism in the Terrestrial Planets, Pergamon, New York, 1981.

Bloch, E., Ibanez-Mehia, M., Murray, K., Vervoort, J., Muntener, O., 2017, Recent crustal foundering in the Northern Volcanic Zone of the Andean arc: Petrological insights from the roots of a modern subduction zone, Earth and Planetary Science Letters, 476, 47-58.

Bottinga, Y., Weill, D.F., 1970 Densities of liquid silicate systems calculated from partial molar volumes of oxide components, Am J Sci, 269:169-182.

Burg, J.-P., Bodinier, J.-L., Chaudhry, S., Hussain, S. & Dawood, H. ,1998, Infra-arc mantle-crust transition and intra-arc mantle dia- pirs in the Kohistan Complex (Pakistani Himalaya): petro-structural evidence. Terra Nova 10, 74-80.

Carroll, M.R., Wyllie, P.J., 1990, The system tonalite-H2O at 15 kbar and the genesis of calc-alkaline magmas: American Mineralogist; 75 (3-4): 345–357

Chapman, A.D., Riggs, N., Ducea, M.N., Saleeby, J.B., Rautela, O., and Shields, J., 2019, Tectonic development of the Colorado Plateau Transition Zone, central Arizona: Insights from lower lithosphere xenoliths and volcanic host rocks, in Pearthree, P.A., ed., Geologic Excursions in Southwestern North America: Geological Society of America Field Guide 55, p. 209–235, https://doi.org/10.1130/2019.0055(09).

Chapman, A. D., Ducea, M. N., Kidder, S., and Petrescu, L., 2014, Geochemical constraints on the petrogenesis of the Salinian arc, central California: Implications for the origin of intermediate magmas: Lithos, v. 200, p. 126-141.

Chapman, A. D., Rautela, O., Shields, J. E., Ducea, M. N., & Saleeby, J. B., 2020, Fate of Continental Lower Crust and Upper Mantle During Shallow-Angle Subduction: the Laramide Example. GSA Today, v. 30, https://doi.org/10.1130/GSATG412A.1.

Chapman, A.D., Ducea, M.N., McQuarrie, N., Coble, M., Petrescu, L., Hoffman, D., 2015. Constraints on plateau architecture and assembly from deep crustal xenoliths, northern Altiplano (SE Peru). Geological Society of America Bulletin 127, 1777-1797.

`

Chapman, J.B., Ducea, M.N., DeCelles, P.G., Profeta, L., 2015. Tracking changes in crustal thickness during orogenic evolution with Sr/Y: An example from the North American Cordillera. Geology 43, 919-922.

Chin, E., Lee, C.T., Luffi, P., 2012, Deep lithospheric thickening and refertilization beneath continental arcs: case study of the P, T and compositional evolution of peridotite xenoliths from the Sierra Nevada, California, Journal of Petrology, v. 53, p. 477-511.

Chin, E.J., Lee, C.-T.A., Tollstrup, D.L., Xie, L., Wimpenny, J. B., Yin, Q. Z., 2013, On the origin of hot metasedimentary quartzites in the lower crust of continental arcs, Earth Planet. Sci. Lett., 361, 120–133.

Chin, E.J., Lee, C.-T.A., Barnes, J.D., 2014. Thickening, refertilization, and the deep lithospheric filter in continental arcs: constraints from major and trace elements and oxygen isotopes. Earth Planet. Sci. Lett.397, 184–200.

Chin, E.J.,Lee, C.T.A. and Blichert-Toft, J., 2015. Growth of upper plate lithosphere controls tempo of arc magmatism: Constraints from Al-diffusion kinetics and coupled Lu-Hf and Sm-Nd chronology. Geochemical Perspectives Letters, 1, pp.20-32.

Chmielowski, J., Zandt, G., and Haberland, C., 1999, The central Andean Altiplano-Puna magma body, Geophysical Research Letters, 26, 783-786.

Coleman, R.G., Lee, D.E., Beatty, L.B., Brannock, W.W., 1965. Eclogites and eclogites: their diff erences and similarities. Geological Society of America Bulletin 76, 483–508.

Conrad, W.K., Kay R.W., 1984, Ultramafic and Mafic Inclusions from Adak Island: Crystallization History, and Implications for the Nature of Primary Magmas and Crustal Evolution in the Aleutian Arc, Journal of Petrology, 25, 88–125.

Currie, C., Ducea, M.N., and DeCelles, P.G., Geodynamic models of Cordilleran orogens: Gravitational instability of magmatic arc roots, in DeCelles, P.G., Ducea, M.N., Carrapa B., and Kapp, P. (editors), "Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile", Geological Society of America Memoir, 212, p. 1-22; 2015.

Davidson J, Turner S, Handley H, Macpherson C, Dosseto A. 2007. Amphibole "sponge" in arc crust? Geology 35:787-90

Davidson JP, Arculus RJ. 2006. The significance of Phanerozoic arc magmatism in generating continental crust. In Evolution and Differentiation of the Continental Crust, ed. M Brown, T Rushmer, pp. 135-72. Cambridge: Cambridge University Press

DeBari SM, Kay SM, Kay RW. 1987. Ultramafic xenoliths from Adagdak volcano, Adak, Aleutian islands, Alaska: deformed igneous cumulates from the Moho of an island arc. J. Geol. 95:329–41

`

de Capitani, C. & Petrakakis, K., 2010, The computation of equilibrium assemblage diagrams with Theriak/ Domino software, American Mineralogist, 95, 1006-1016.

DeCelles, P., Ducea, M.N., Kapp, P., Zandt, G., 2009. Cyclicity in Cordilleran orogenic systems. Nat. Geosci. 2, 251–257.

Delph, J.R., Ward, K.M., Zandt, G., Ducea, M.N., Beck, S.L., 2017. Imaging a magma plumbing system from MASH zone to magma reservoir. Earth and Planetary Science Letters 457, 313-324.

DePaolo, D.J., 1981, A Neodymium and strontium study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, J. Geophys. Res., v. 86, p. 10470-10488.

Depine GV, Andronicos CL, Phipps-Morgan J. 2008. Near-isothermal conditions in the middle and lower crust induced by melt migration. Nature 452:80-3.

Dhuime B, Bosch D, Garrido CJ, Bodinier JL, Bruguier O, et al. 2009. Geochemical architecture of the lower- to middle-crustal section of a paleo-island arc (Kohistan complex, Jijal-Kamila area, northern Pakistan): implications for the evolution of an oceanic subduction zone. J. Petrol. 50:531–69

Dhuime, B., Wuestefeld, A., Hawkesworth, C.J., 2015. Emergence of modernconti-nental crust about 3 billion years ago. Nat. Geosci.8, 552–554.

Dodge F.C.W., Calk L.C., and Kistler R.W.,1986, Lower crustal xenoliths, Chinese Peak lava flow, Central Sierra Nevada, J. Petrol., 27: 1277-1304.

Dodge F.C.W., Lockwood J.P., and Calk L.C.,1988, Fragments of the mantle and crust beneath the Sierra Nevada batholith: Xenoliths in a volcanic pipe near Big Creek, California, Geol. Soc. Am. Bull., 100: 938-947.

Domenick M.A., Kistler R.W., Dodge F.C.W., and Tatsumoto M., 1983, Nd and Sr study of crustal and mantle inclusions from the Sierra Nevada and implications for batholith petrogenesis, Geol. Soc. Am. Bull., 94: 713-719.

Ducea, M., and Saleeby, J., 1996, Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada; Evidence from xenolith thermobarometry, J. Geophys. Res., v. 101, p. 8029-8044.

Ducea, M., Saleeby, J., 1998a, A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California. International Geology Review 40, 78-93.

Ducea, M.N., and Saleeby, J. B., 1998b, The age and origin of a thick mafic-ultramafic keel from beneath the Sierra Nevada batholith, Contrib. Mineral. Petrol., 133, 169-185.

Ducea, M. N., 2001, The California Arc: thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups, GSA Today, v. 11, p. 4-10.

`

Ducea, M.N., 2002. Constraints on the bulk composition and root foundering rates of continental arcs: A California arc perspective. Journal of Geophysical Research: Solid Earth 107, doi:10.1029/2001JB000643.

Ducea, M.N., Kidder, S., Zandt, G., 2003. Arc composition at mid- crustal depths: Insights from the Coast Ridge Belt, Santa Lucia Mountains, California. Geophysical Research Letters 30, doi:10.1029/2002GL016297.

Ducea, M.N., Barton, M.D., 2007. Igniting flare-up events in Cordilleran arcs. Geology 35, 1047-1050.

Ducea, M.N., Saleeby, J.B., Bergantz, G., 2015. The architecture, chemistry, and evolution of continental magmatic arcs. Annual Review of Earth and Planetary Sciences 43, 299-331.

Ducea, M.N., Seclaman, A.C., Murray, K.E., Jianu, D., Schoenbohm, L.M., 2013. Mantle-drip magmatism beneath the Altiplano-Puna plateau, central Andes. Geology 41, 915-918.

Ducea, M. N., & Chapman, A. D. (2018). Sub-magmatic arc underplating by trench and forearc materials in shallow subduction systems; A geologic perspective and implications. Earth-Science Reviews, 185, 763–779. doi:10.1016/j.earscirev.2018.08.001

Ducea, M.N., Bowman, E., Chapman, A.D., Balica, C., 2020, 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, companion paper submitted to this one.

Dufek J, Bergantz GW. 2005. Lower crustal magma genesis and preservation: A stochastic framework for the evaluation of basalt-crust interaction. Journal of Petrology 46:2167-95.

Dumitru, T. A., 1990, Subnormal Cenozoic geothermal gradients in the extinct Sierra Nevada magmatic arc: Consequences of Laramide and post-Laramide shallow angle subduction, J. Geophys. Res., 95, 4925-4941.

El Atrassi, F., Brunet, F., Chazot, G., Bouybaouène, M., Chopin, C., 2013, Metamorphic and magmatic overprint of garnet pyroxenites from the Beni Bousera massif (northern Morocco): Petrography, mineral chemistry and thermobarometry, Lithos, 179, 231-248.

Ellis, D. J., and E. H. Green, 1979, An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria, Contrib. Mineral. Petrol., 66, 13-22.

Elkins-Tanton, L.T., 2007, Continental magmatism, volatile recycling, and a heterogeneous mantle caused by lithospheric gravitational instabili- ties: Journal of Geophysical Research, v. 112, B03405, doi:10.1029/2005JB004072.

Erdman, M.E., Lee, C.-T.A., Levander, A., Jiang, H., 2016. Role of arc magmatism and lower crustal foundering in controlling elevation history of the Nevadaplano and Colorado Plateau: a

`

case study of pyroxenitic lower crust from central Arizona, USA. Earth and Planetary Science Letters 439, 48-57.

Ernst, W.G., 2009, Archean plate tectonics, rise of Proterozoic supercontinentality and onset of regional, episodic stagnant-lid behavior, Gondwana Research, 15, 243-253.

Eskola, P., 1920. The mineral facies of rocks. Norsk Geologisk Tidsskrift VI, 143–194.

Esperanca, S., Carlson, R.W., and Shirey, S.B., 1988, Lower crustal evolution under central Arizona: Sr, Nd, and Pb isotopic and geochemical evidence from mafic xenoliths of Camp Creek, Earth and Planetary Science Letters, v. 90, p. 26-40.

Esperanca, S., Carlson, R.W., Shirey, S.B., and Smith, D., 1997, Dating crust-mantle separation: Re-Os isotopic study of mafic xenoliths from central Arizona, Geology, v. 25, p. 651-654.

Farmer, G.L., Glazner, A.F., and Manley, C.R., 2002, Did lithospheric delamination trigger late Cenozoic potassic volcanism in the southern Sierra Nevada, California? Geological Society of America Bulletin, v. 114, p. 754–768.

Fliedner M. and Ruppert S.,1996, 3-dimensional crustal structure of the Southern Sierra Nevada from seismic fan profiles and gravity modelling, Geology, 24: 367-370.

Gao, S., Rudnick, R., Yuan, H.-L., Liu, X.-M., Liu, Y.-S., Xu, W.-L., Ayers, J., Wang, X.-C., Wang, Q.-H., 2004. Recycling lower continental crust in the North China craton. Nature 432, 892–897.

Garrido, C. J., Bodinier, J.-L., Burg, J.-P., Zeilinger, G., Hussain, S., Dawood, H., Chaudhry, M. N. & Gervilla, F. , 2006, Petrogenesis of mafic garnet granulite in the lower crust of the Kohistan Paleo- arc Complex (Northern Pakistan): Implications for intra-crustal differentiation of island arcs and generation of continental crust. Journal of Petrology 47, 1873-1914.

Ghiorso, M.S., and Sack, R. O., 1995, Chemical Mass Transfer in Magmatic Processes. IV. A Revised and Internally Consistent Thermodynamic Model for the Interpolation and Extrapolation of Liquid-Solid Equilibria in Magmatic Systems at Elevated Temperatures and Pressures. Contributions to Mineralogy and Petrology, 119, 197-212

Gill J. 1981. Orogenic andesites and plate tectonics. Springer-Verlag, Berlin.

Godard, G., 2001, Eclogites and their geodynamic interpretation: A history, Journal of geodynamics, 32, 163-203.

Gonzales Vidal, D., Obermann, A., Tassara, A., Bataille, K., Lupi, M., 2018, Crustal model of the Southern Central Andes derived from ambient Rayleigh wave tomography, Tectonophysics, 744, 215-226.

Green D.H., Ringwood A.E., 1967a, The genesis of basaltic magmas, Contr Mineral Petrol

`

15:103–190.

Green, D.H., Ringwood, A.E., 1967b. An experimental investigation of the gabbro to eclogite transformation and its petrological applications. Geochimica and Cosmochimica Acta 31, 767–833.

Griffin, W. L., and S. Y. O'Reilly, 1986, The lower crust in eastern Australia: Xenolith evidence, in The Nature of the Lower Continental Crust, edited by J. B. Dawson, et al., Spec. Publ. Geol. Soc. Am., 24, 363-374.

Griffin, W. L., & O'Reilly, S. Y.,1987, Is the continental Moho the crust- mantle boundary? Geology, 15, 241-244.

Gysi, A.P., Jagoutz, O., Schmidt, M.W., Targuisti, K., 2011, Petrogenesis of pyroxenites and melt infiltrations in the ultramafic complex of Beni Bousera, northern Morocco. Journal of Petrology, 22, 1679-1735.

Harley, S. L., 1984, An experimental study of the partitioning of Fe and Mg between garnet and orthopyroxene, Contrib. Mineral. Petrol., 86, 359-373.

Harley, S. L., and D. H. Green, 1982, Garnet-orthopyroxene barometry for granulites and peridotites, Nature, 300, 697-701.

Hauy, R.J., 1822. Traite´ de mine´ ralogie. Seconde e´ dition, revue, corrige´ e et conside´ rablement augmente´ e par l'auteur. Bachelier et Huzard, Paris, 4 Vols+atlas (t. II, p. 456; t. IV, p. 548).

Herzberg, C.T., Fyfe, W.S., and Carr, M.J., 1983, Density constraints on the formation of the continental Moho and crust: Contributions to Mineralogy and Petrology, v. 84, p. 1–5, doi: 10.1007/BF01132324

Hildreth W, Moorbath S. 1988. Crustal contributions to arc magmatism in the Andes of central Chile. Contributions to Mineralogy and Petrology 98:455-89.

Hirschmann, M.M., and Stolper, E.M., 1996, A possible role for garnet pyroxenite in the origin of the "garnet signature" in MORB: Contributions to Mineralogy and Petrology, v. 124, p. 185–208, doi:10.1007/s004100050184

Holland, T.H., 1896. On the origin and growth of garnets and of their micropegmatitic intergrowths in pyroxenic rocks. Records of the geological Survey of India 29, 20–30+1 pl.

Jacob, D.E., 2004. Nature and origin of eclogite xenoliths from kimberlites. Lithos 77, 195–316.

Jagoutz, O.E., Schmidt, M.W., 2012. The formation and bulk composition of modern juvenile continental crust: the Kohistan arc. Chem. Geol.298–299, 79–96.

`

Jagoutz O, Behn MD. 2013. Foundering of lower arc crust as an explanation for the origin of the continental Moho. Nature 504:131–34

Jagoutz O, Schmidt MW. 2013. The composition of the foundered complement to the continental crust and are-evaluation of fluxes in arcs. Earth and Planetary Sciences Letters 371-372:177-190.

Jagoutz O. 2014. Arc crustal differentiation mechanisms. Earth and Planetary Science Letters 396:267-77.

Jagoutz, O. and Kelemen, P.B., 2015, Role of arc processes in the formation of continental crust, Annual Reviews of Earth and Planetary Sciences, 43:363-404.

Jan, M. Q. & Howie, R. A., 1981, The mineralogy and geochemistry of the metamorphosed basic and ultrabasic rocks of the Jijal Complex, Kohistan, NW Pakistan. Journal of Petrology 22, 85-126.

Jones CH, Reeg H, Zandt G, Gilbert H, Owens TJ, Stachnik J. 2014. P-wave tomography of potential convective downwellings and their source regions, Sierra Nevada, California. Geosphere 10(3).

Jull, M., Kelemen, P., 2001. On the conditions for lower crustal convective instability. J. Geophys. Res. 106, 6423–6446.

Kay, S. M., and Kay, R. W., 1985, Role of crystal cumulates and the oceanic crust in the formation of the Aleutian arc: Geology, v. 13, p. 461-464

Kay R.W. and Kay S.M.,1993, Delamination and delamination magmatism, Tectonophysics, 219:177-189.

Kidder, S., Ducea, M., Gehrels, G., Patchett, P.J., Vervoort, J., 2003. Tectonic and magmatic development of the Salinian Coast Ridge belt, California. Tectonics 22, doi:10.1029/2002TC001409.

Kistler, R. W., 1990, Two different types of lithosphere in the Sierra Nevada, California, Geol. Soc. Am. Mem., v. 174, p. 271-282.

Klemperer, S., Hauge, T.A., Hauser, E.C., Oliver, J.E., Potter, C.J., 1986, The Moho in the northern Basin and Range along the COCORP 40^0N seismic reflection transect, Geological Society of America Bulletin, 97, 603-618.

Laske, G., Masters, G., Ma, Z., Pasyanos, M., 2013. Update on CRUST1.0 – a 1-degree global model of Earth's crust. Geophys. Res. Abstr., EGU2013-2658.

Lee, C-T, Yin, Q-Z, Rudnick, R L, Chesley, J T, Jacobsen, S B, 2000, Os isotopic evidence for Mesozoic removal of lithospheric mantle beneath the Sierra Nevada, California, Science 289: 1912-1916.

`

Lee, C. T., Q. Z. Yin, R. L. Rudnick, and S. B. Jacobsen, 2001a, Preservation of ancient and fertile lithospheric mantle beneath the southwestern United States, Nature, 411, 69-73.

Lee, C-T, Rudnick, R L, and Brimhall, G. H., Jr., 2001b, Deep lithospheric dynamics beneath the Sierra Nevada during the Mesozoic and Cenozoic as inferred from xenolith petrology, Geochemistry Geophysics Geosystems 2, 2001GC000152.

Lee, C.-T., Cheng, X., Horodyskyj, 2006. The development and refinement of continental arcs by primary basalt magmatism, garnet pyroxenite accumulation, basaltic recharge and delamination: insights from the Sierra Nevada, California. Contrib. Mineral. Petrol. 151, 222–242.

Lee, C.-T.A., 2014. Physics and chemistry of deep continental crust recycling. In: Holland, H., Turekian, K. (Eds.), Treatise of Geochemistry, 2nd ed. Elsevier, pp.423–456.

Lee, C-T A and Anderson, D., 2015, Continental crust formation at arcs, the arclogite "delamination" cycle, and one origin for fertile melting anomalies in the mantle, Science Bulletin DOI:10.1007/s11434-015-0828-6

Mamani M, Wörner G, Sempere T. , 2010, Geochemical variations in igneous rocks of the Central Andean orocline (13°S to 18°S): Tracing crustal thickening and magma generation through time. Geological Society of America Bulletin 122:162–82.

McInnes, B.I.A., Gregoire, M., Binns, R.A., Hannington, M.D., 2001, Hydrous metasomatism of oceanic sub-arc mantle, Lihir, Papua New Guinea: Petrology and geochemistry of fluid-metasomatised mantle wedge xenoliths, Earth and Planetary Sciences Letters, 188, 169-183.

Meissner, R., The Continental Crust: A Geophysical Approach, Academic, San Diego, Calif., 1986.

Mukhopadhyay, B., 1989, Petrology and geochemistry of mafic and ultramafic xenoliths from the Sierra Nevada batholith, Part 1, PhD dissertation, Univ. Texas Dallas, 215 p.

Mukhopadyay B., Manton W.I. 1994, Upper mantle fragments from beneath the Sierra Nevada batholith: Partial fusion, fractional crystallization and metasomatism in a subduction-enriched ancient lithosphere, Journal of Petrology, 35: 1418-1450.

Murphy, M. and Chapman, A.D., 2018, Rooting around beneath an arc: Zircon U-Pb geochronologic and Hf isotopic constraints on the evolution of the base of the Sierra Nevada batholith. Abstracts with programs - Geological Society of America, 50(6).

Nakamura, D., 2009, A new formulation of garnet–clinopyroxene geothermometer based on accumulation and statistical analysis of a large experimental data set. Journal of Metamorphic Geology, 27: 495-508. doi:10.1111/j.1525-1314.2009.00828.x

`

Newton, R.C. and D . Perkins, III, Thermodynamic calibra. tion of geobarometer based on the assemblages garnet· plagioclase-orthopyroxene (cpx)-quartz, Am. Mineral. 67, 203- 222, 1982

Nixon, P.H. 1987, Mantle xenoliths. Wiley, United States: 884 p, ISBN-13: 978-0471912095.

Obata, M., 1980, The Ronda peridotite: garnet-, spinel-, and plagioclase-lherzolite facies and the P-T trajectories of a high- temperature mantle intrusion. Journal of Petrology 21, 533-572.

Otamendi, J.E., Ducea, M.N., Tibaldi, A.M., Bergantz, G.W., de la Rosa, J.D., Vujovich, G.I., 2009. Generation of tonalitic and dioritic magmas by coupled partial melting of gabbroic and metasedimentary rocks within the deep crust of the Famatinian magmatic arc, Argentina. Journal of Petrology 50, 841-873.

Otamendi, J.E., Ducea, M.N., Bergantz, G.W., 2012. Geological, petrological and geochemical evidence for progressive construction of an arc crustal section, Sierra de Valle Fertil, Famatinian Arc, Argentina. Journal of Petrology 53, 761-800.

Paterson, S.R., Farris, D.W., 2008.Downward host rock transport and the formation of rimmonoclines during the emplacement of Cordilleran batholiths. Transactions of theRoyal Society of Edinburgh: Earth Sciences 97 (n. 4), 397–413 (Special Issue Plutons and Batholiths (The Wallace Pitcher Memorial Volume)).

Pearson, D. G., Davies, G. R. & Nixon, P. H. , 1993, Geochemical constraints on the petrogenesis of diamond facies pyroxenites from the Beni Bousera peridotite massif, North Morocco. Journal of Petrology, 34, 125-172.

Perkins, D., III, and R. C. Newton, 1981, Charnockite geobarometers based on coexisting garnet-plagioclasc-pyroxcnc-quartz, Nature, 292, 144-146.

Petermann, M., Hirschmann, M., 2003. Partial melting experiments on a MORB- like pyroxenite between 2 and 3 GPa: constraints on the presence of pyroxenite in basalt source regions from solidus location and melting rate. J. Geophys. Res. 108, 2125.

Philpotts, A., Ague, J., 2009. Principles of igneous and metamorphic petrology. Cambridge University Press.

Pickett D.A. and Saleeby J.B., 1993, Thermobarometric constraints on the depth of exposure and conditions of plutonism and metamorphism at deep levels of the Sierra Nevada batholith, Tehachapi Mountains, California, J. Geophys. Res., 98: 609-629.

Profeta, L., Ducea, M.N., Chapman, J.B., Paterson, S.R., Gonzales, S.M.H., Kirsch, M., Petrescu, L., DeCelles, P.G., 2015. Quantifying crustal thickness over time in magmatic arcs. Scientific Reports 5, 17786, doi:10.1038/srep17786.

Rapp R.P., Watson E.B., 1995. Dehydration melting of metabasalt at 8-32 kbar; implications for

continental growth and crust-mantle recycling. Journal of Petrology 36:891-931.

Rautela, O., Chapman, A.D., Shields, J.E., Ducea, M.N., Lee, C.-T., Jiang, H., and Saleeby, J., in press, In search for the missing arc root of the Southern California Batholith: P-T-t evolution of upper mantle xenoliths of the Colorado Plateau Transition Zone, Earth and Planetary Science Letters.

Rodriguez-Vargas, A., Koester, E., Mallmann, G., Conceição, R., Kawashita, K., We- ber, M., 2005. Mantle diversity beneath the Colombian Andes, Northern Volcanic Zone: constraints from Sr and Nd isotopes. Lithos 82, 471–484.

Rudnick, R. L., Barth, M., Horn, I. & McDonough, W. F. 2000, Rutile-bearing refractory eclogites: missing link between continents and depleted mantle. Science 287, 278–281.

Rudnick, R., 1995. Making continental crust. Nature 378, 571–578.

Rushmer, T., 1991, Partial melting of two amphibolites: contrasting experimental results under fluid-absent conditions, Contributions to Mineralogy and Petrology, 107, 41-59.

Saleeby, J.B., 1990.Progress in tectonic and petrogenetic studies in an exposedcrosssection of young (~100 Ma) continental crust, southern Sierra Nevada, Califor-nia. In: Salisbury, M.H. (Ed.), Exposed Cross Sections of the Continental Crust. D.Reidel Publishing, Dordrecht, pp. 132–158.

Saleeby, J. B., M. N. Ducea, and D. Clemens-Knott, 2003, Production and loss of high-density batholithic root, southern Sierra Nevada, California, Tectonics, 22, doi: 10.1029/2002TC001374.

Saleeby, J., 2003. Segmentation of the Laramide slab: evidence from the southern Sierra Nevada region. Geological Society of America Bulletin 115, 655–668.

Schmidt, M. W., and O. Jagoutz, 2017, The global systematics of primitive arc melts, Geochemistry Geophysics Geosystems, 18, 817–2854, doi:10.1002/2016GC006699

Smith, D., Arculus, R.J., Manchester, J.E., and Tyner, G.N., 1994, Garnet-pyroxene-amphibole xenoliths from Chino Valley, Arizona, and implications for continental lithosphere below the Moho, Journal of Geophysical Research, v. 99, n. B1, p. 683-696.

Stern RJ. 2002. Subduction zones. Reviews of Geophysics 40:4-34.

Sun, c., Liang, y. (2015) A REE-in-garnet-clinopyroxene thermobarometer for eclogites, granulites and garnet peridotites. Chemical Geology 393-394, 79-92

Tang, M., Lee, C.-T. A., Chen, K., Erdman, M., Costin, G., & Jiang, H. (2019). Nb/Ta systematics in arc magma differentiation and the role of arclogites in continent formation. Nature Communications, 10, https://doi.org/10.1038/s41467-018-08198-3.

`

Tassara, A., Swain, C., Hackney, R., Kirby, J., 2007. Elastic thickness structure of South America estimated using wavelets and satellite-derived gravity data. Earth and Planetary Science Letters 253, 17–36 http://dx.doi.org/10.1016/j.epsl.2006.10.008.

Tatsumi Y. 2000. Continental crust formation by crustal delamination in subduction zones and complementary accumulation of the enriched mantle I component in the mantle. Geochem. Geophys. Geosyst. 1:1053

Tatsumi, Y., 2005, The subduction factory: how it operates in the evolving Earth, GSA Today 15, 4-10.

Taylor S. R., McLennan S.M., 1985, The continental crust; Its compositional evolution, Blackwell Sci. , Cambridge, Mass, 312p.

Vielzeuf, D., and M. W. Schmidt, Melting relations in hydrous systemsrevisited: Application to metapelites, metagraywackes and metabasalts,Contrib. Mineral. Petrol.,141,251–267,2001.

Walker Jr, B.A., Bergantz, G.W., Otamendi, J.E., Ducea, M.N., Cristofolini, E.A., 2015. A MASH zone revealed: the mafic complex of the Sierra Valle Fértil. Journal of Petrology 56, 1863-1896.

Ward, K.M., Delph, J.R., Zandt, G., Beck, S.L., Ducea, M.N., 2017. Magmatic evolution of a Cordilleran flare-up and its role in the creation of silicic crust, Scientific Reports 7, 9047, doi:10.1038/s41598-017-09015-5.

Watson, E. B., Wark, D. A., and Thomas, J. B., 2006, Crystallization thermometers for zircon and rutile, Contributions to Mineralogy and Petrology, 151, 413-433.

Weber, M., Tarney, J., Kempton, P., Kent, R., 2002. Crustal make-up of the northern Andes: evidence based on deep crustal xenolith suites, Mercaderes, SW Colombia, Tectonophysics 345, 49–82.

Wendlandt, E., DePaolo, D.J., and Baldridge, W.S., 1996, Thermal history of Colorado Plateau lithosphere from Sm-Nd mineral geochronology on xenolith, Geol. Soc. Am. Bull., v. 108, p. 757-767.

Wernicke, B., and Getty, S.R., 1997, Intracrustal subduction and gravity currents in the deep crust: Sm-Nd, Ar-Ar, and thermobarometric constraints from the Skagit Gneiss Complex, Washington: Geological Society of America Bulletin, v. 109, p. 1149-1166.

Wernicke B., and 19 others (1996) Origin of high mountains on continents: The Southern Sierra Nevada, Science, 271: 190-193.

Whitney, D.L., 1992, Origin of CO2-rich fluid inclusions in leucosomes from the Skagit migmatites, North Cascades, Washington, USA: Journal of Metamorphic Geology, v. 10, p. 715-725.

`

Wolf M.B., and Wyllie P.J., 1993, Garnet growth during amphibolite anatexis: Implications for a garnetiferous restite, J. Geol., 101:357-373.

Wolf MB, and Wyllie PJ. 1994. Dehydration-melting of amphibolite at 10 kbar; the effects of temperature and time. Contributions to Mineralogy and Petrology 115:369-83.

Yamamoto, H. & Nakamura, E., 1996, Sm-Nd dating of garnet granulites from the Kohistan Complex, northern Pakistan. Journal of the Geological Society, London 153, 965-969.

Yamamoto, H. & Nakamura, E. , 2000, Timing of magmatic and metamorphic events in the Jijal Complex of the Kohistan Arc deduced from Sm-Nd dating of mafic granulites. Geological Society, London, Special Publications 170, 313-319.

Yuan, X., Sobolev, S.V., Kind, R., 2002. Moho topography in the central Andes and its geodynamic implications. Earth Planetary Science Letters 199, 389–402 http://dx.doi.org/10.1016/S0012-821X(02)00589-7.

Zandt, G., Gilbert, H., Owens, T., Ducea, M., and Saleeby, J., 2004. Active foundering of a continental arc root beneath the southern Sierra Nevada in California. Nature 431, 41–46.

Zeilinger, G., 2002, Structural and geochronological study of the lowest Kohistan Complex, Indus Kohistan region in Pakistan, NW Himalaya. PhD thesis, ETH, Zurich.

Zindler, A., Hart, S., 1986, Chemical geodynamics. Annual Review of Earth and Planetary Sciences, 14, 493–571.

Figures

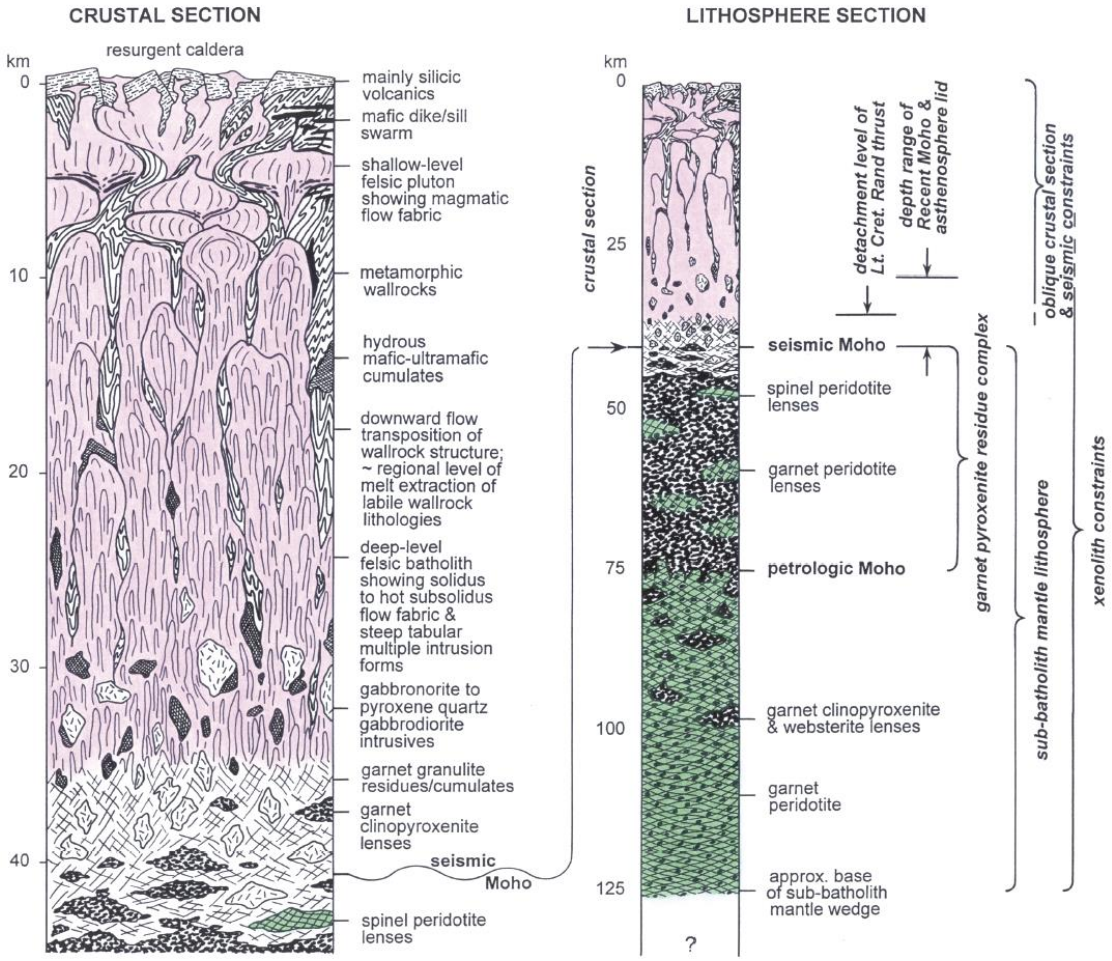

Figure 1. Schematic vertical composition of the lithosphere beneath a Cordilleran arc (modified after Saleeby et al., 2003), as revealed by the Sierra Nevada exposures (0-30 km paleodepths) and various post batholithic xenolith localities described in text. The lithosphere is about 125 km thick and is 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.

`

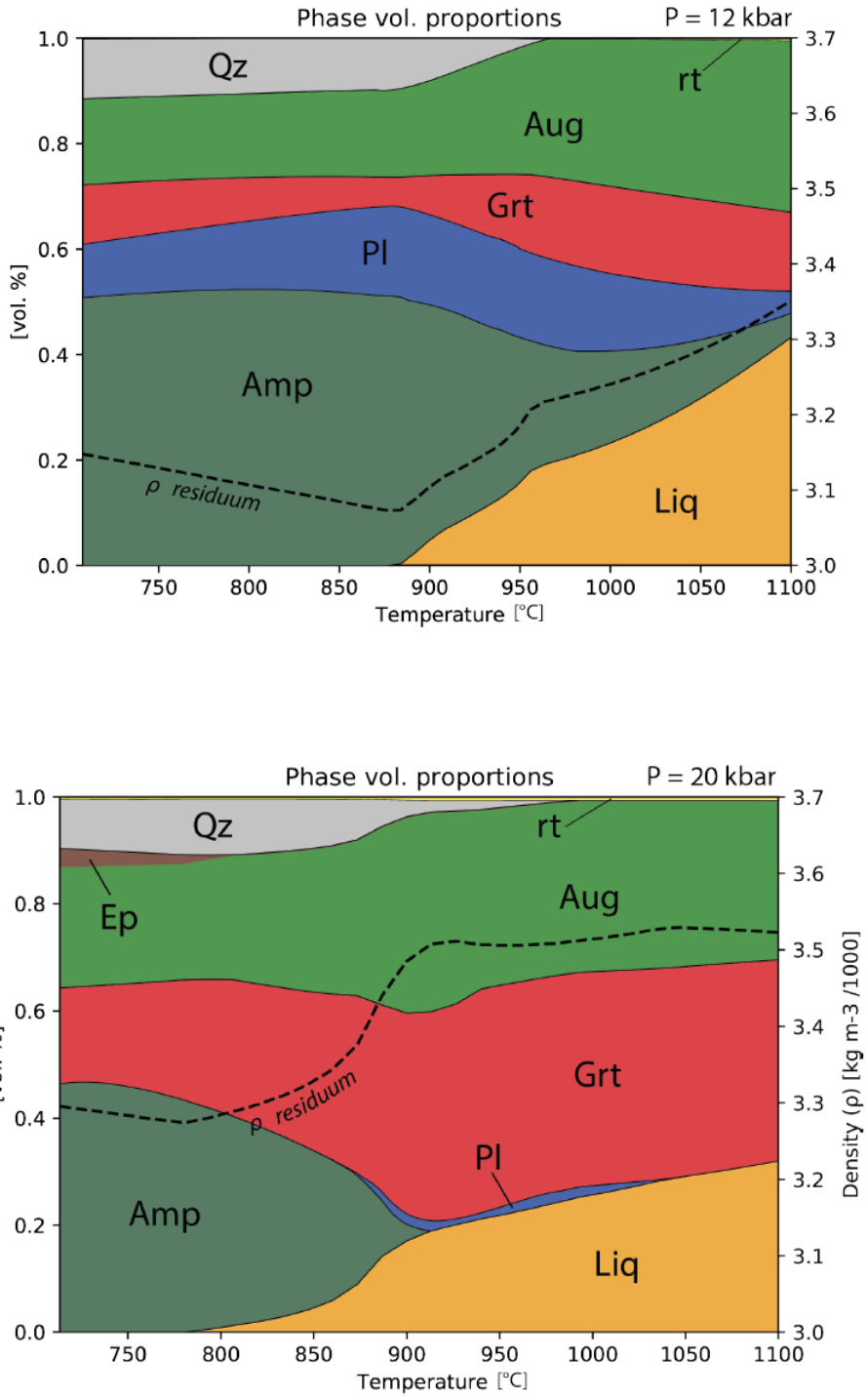

Figure 2. Experimental prediction of garnet, plagioclase, amphibole and other phases on the liquidus of an intermediate melt and below the solidus for an average arc basalt starting

`

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.

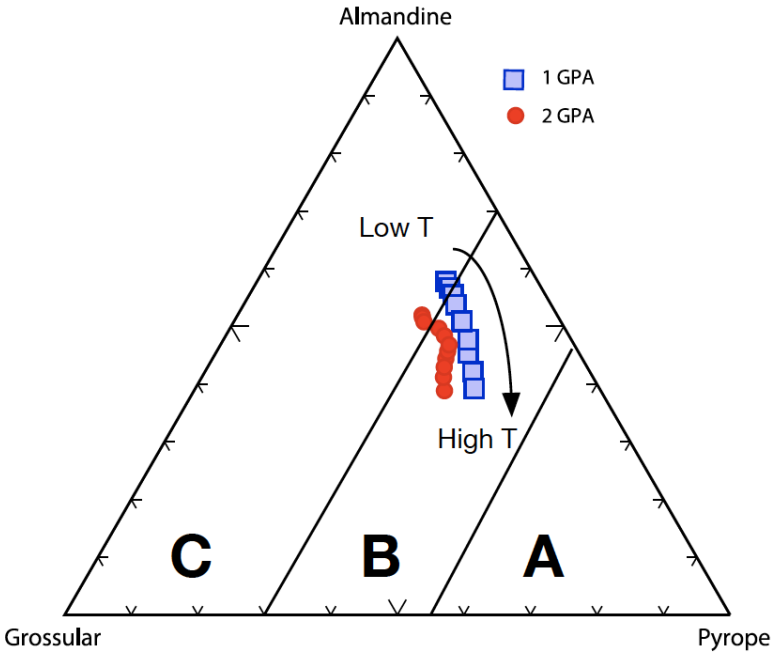

Figure 3. Predicted garnet compositions for the fractionation of an intermediate magma at 1 and 2 GPa, using pMELTS (Ghiorso and Sack, 1995). Starting material is an average arc basalt (Schmidt and Jagoutz, 2017). The ternary classification diagram for garnets is from Coleman et al. (1965).

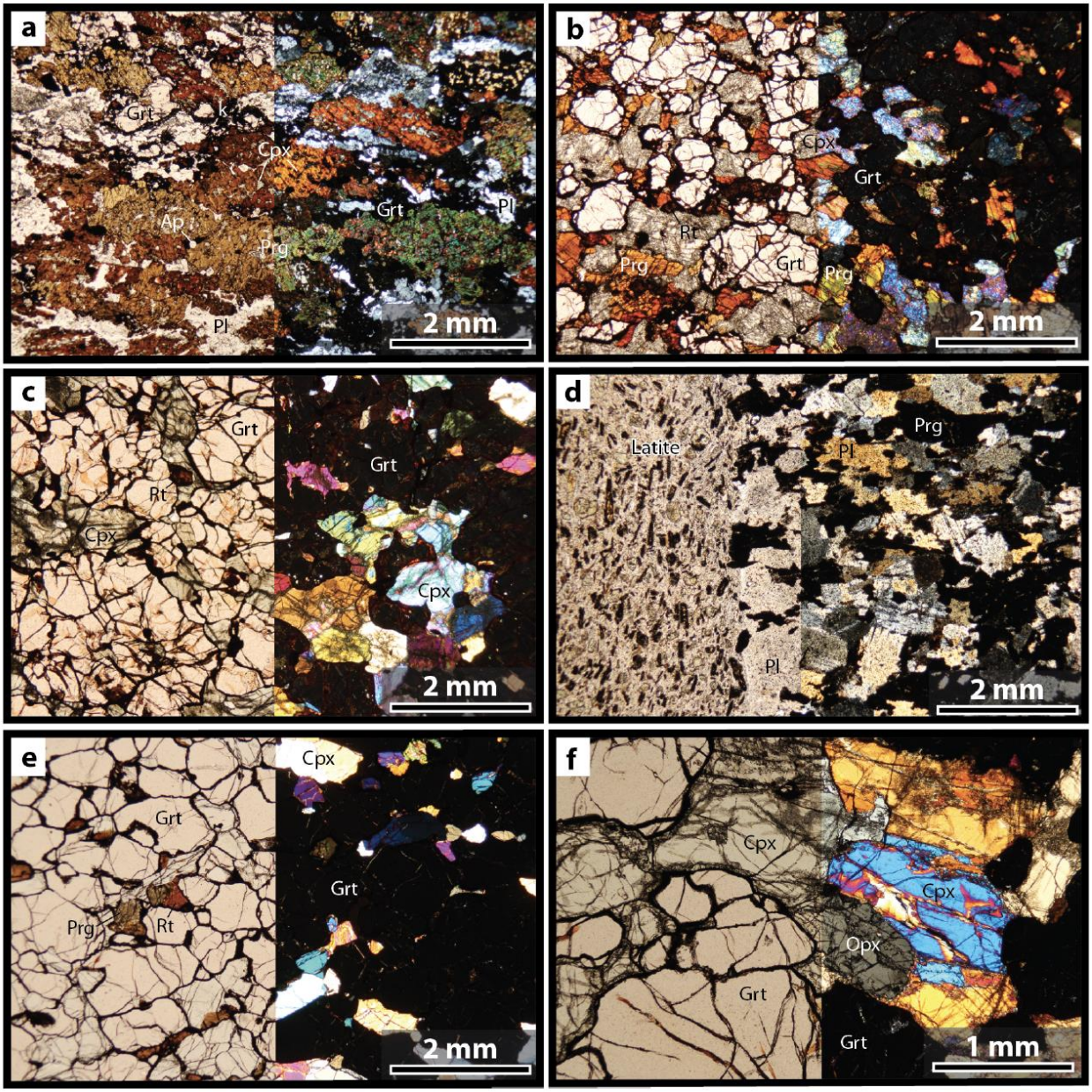

Figure 4. Photomicrographs of petrologic features in Central Arizona localities: arclogites and related xenoliths (from Chapman et al., 2019). All panels show plane-polarized light on the left and cross-polarized light on the right, respectively. (A) Camp Creek garnet clinopyroxenite (group 1) with relict 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.

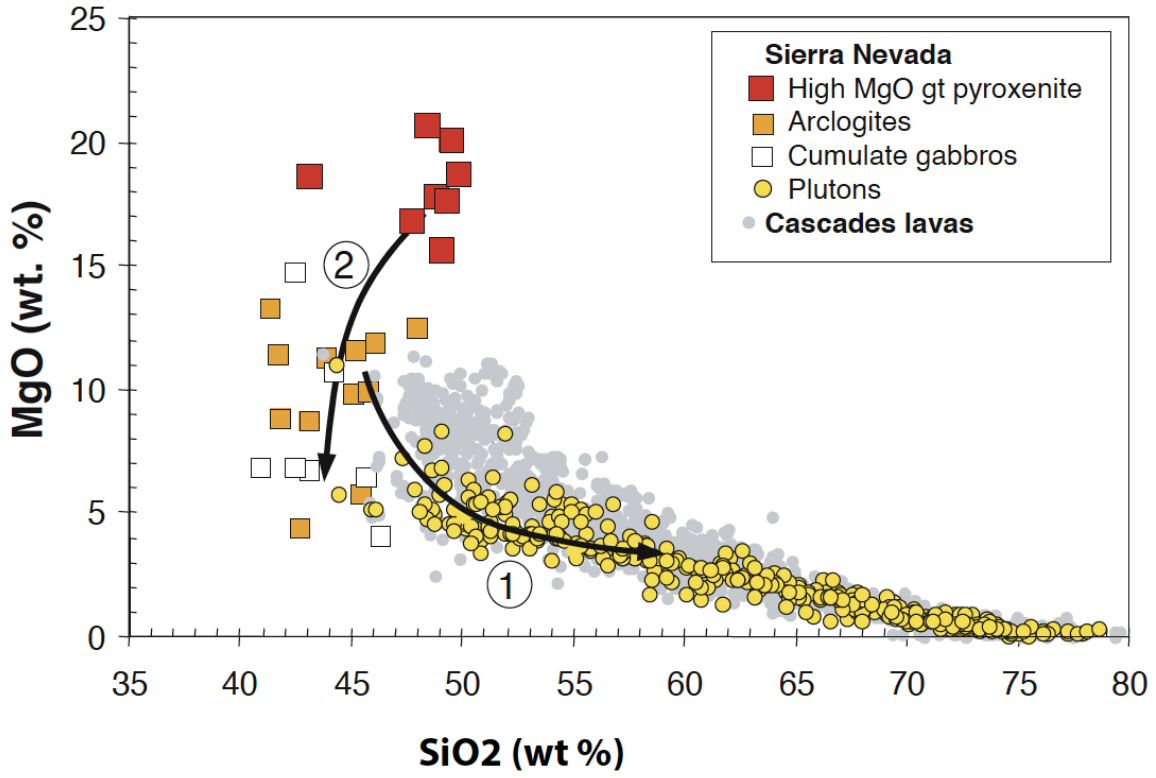

Figure 5. Harker diagram showing compositional trends of two major arcs (plutons from the Sierra Nevada and volcanic rocks from the modern Cascades) (trend 1) and the opposite trend (2) typical for cumulate and restites of the Sierra Nevada (modified from Lee et al., 2006). This trend is identical to 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).

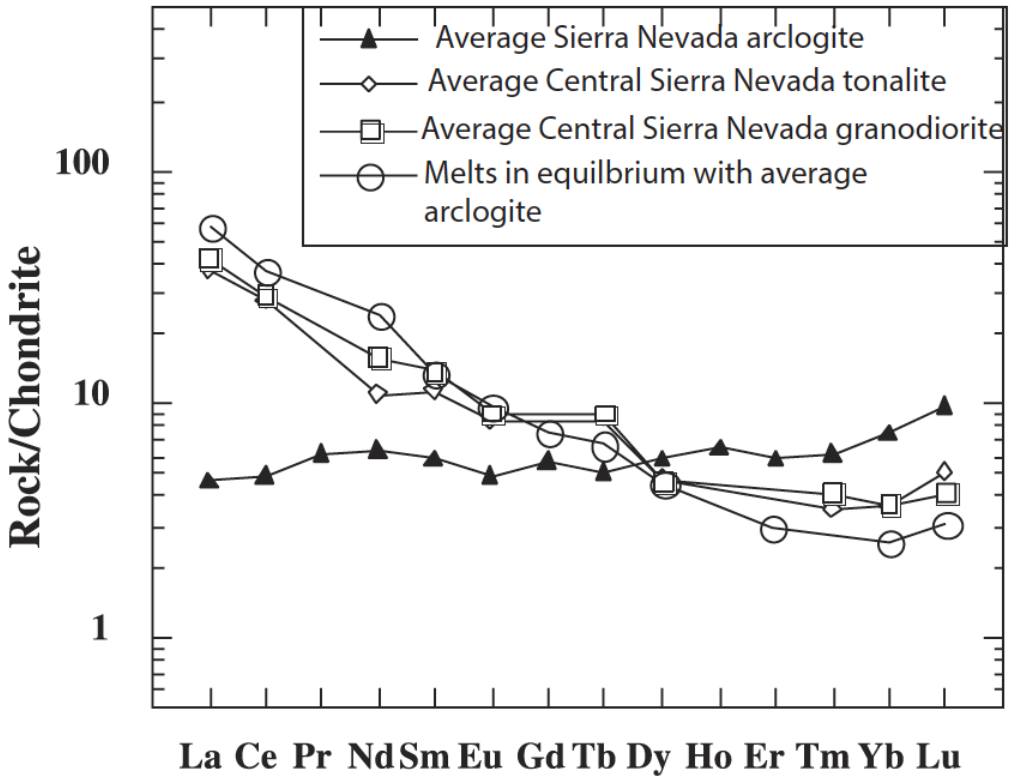

Figure 6. Rare earth elemental chemistry of average Sierra Nevada arclogite (Ducea, 2002), calculated melts in equilibrium with that residue (using partition coefficients listed in Ducea, 2002), as well as average composition of the main lithologic types in the central Sierra Nevada batholith, tonalites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

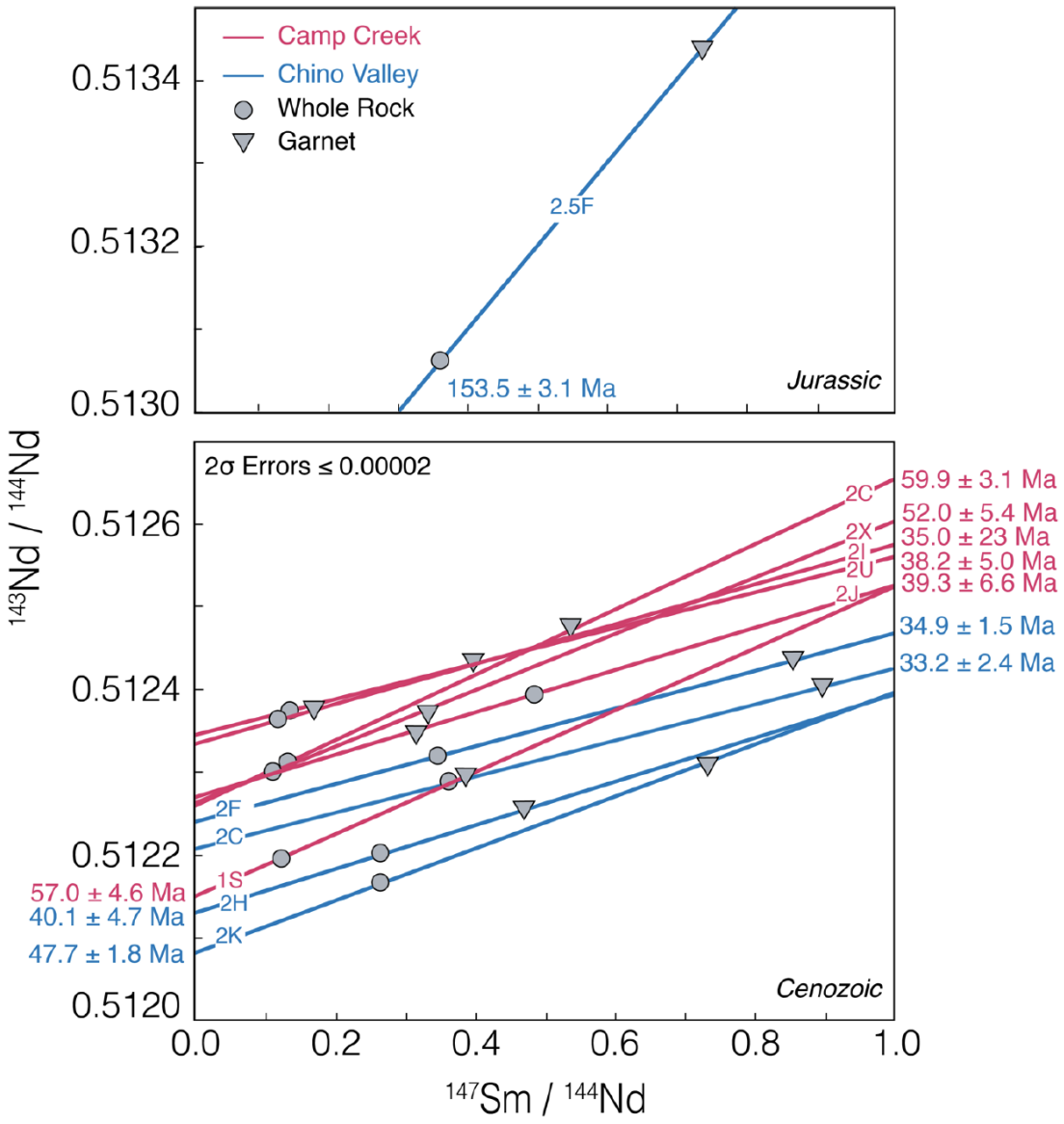

Figure 7. Sm-Nd garnet-whole rock geochronology for the central Arizona arclogites. One Chino Valley sample 16CV2.5F records a Jurassic age. Remaining samples yield Late Cretaceous – Early Cenozoic ages, suggesting partial re-equilibration of the samples with host latite (Chapman et. al. 2019, Rautela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

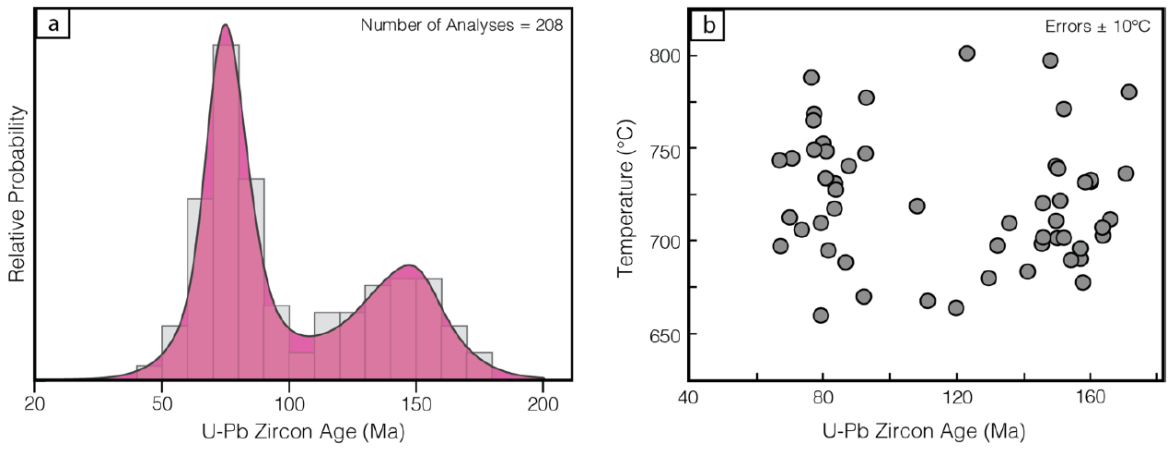

Figure 8. Zircon U-Pb age distribution and Ti-in-zircon thermometry trend over time for the central Arizona arclogites (from Chapman et al., 2019, 2020 and Rautela et al., 2020). (a) A probability density diagram of U-Pb zircon ages of the samples (data from Chapman et al., 2020). Note two age peaks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

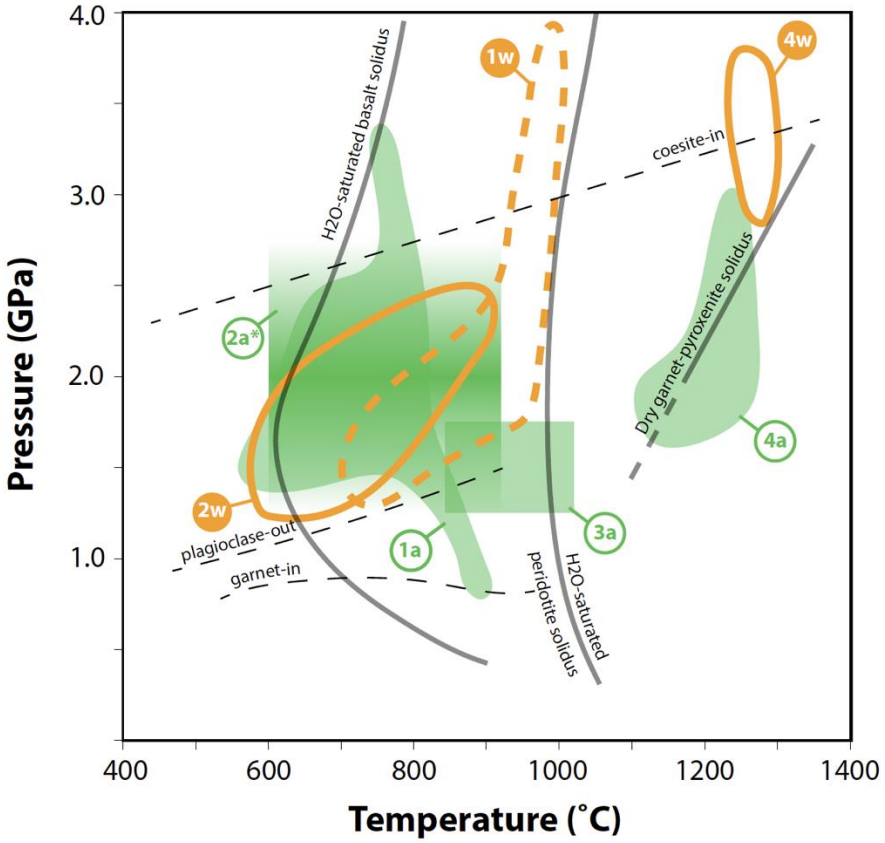

Figure 9. Summary of pressure-temperature constraints available from arclogite (labeled "a" in green filled fields) plus garnet websterite and garnet peritotite (combined and labeled "w" in fields with orange outlines) xenoliths. Fields 1-4 contain data from central Sierra Nevada (California; Mukhopadhyay and Manton, 1994; Ducea and Saleeby, 1996; 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. 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 2.0 GPa (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.

`

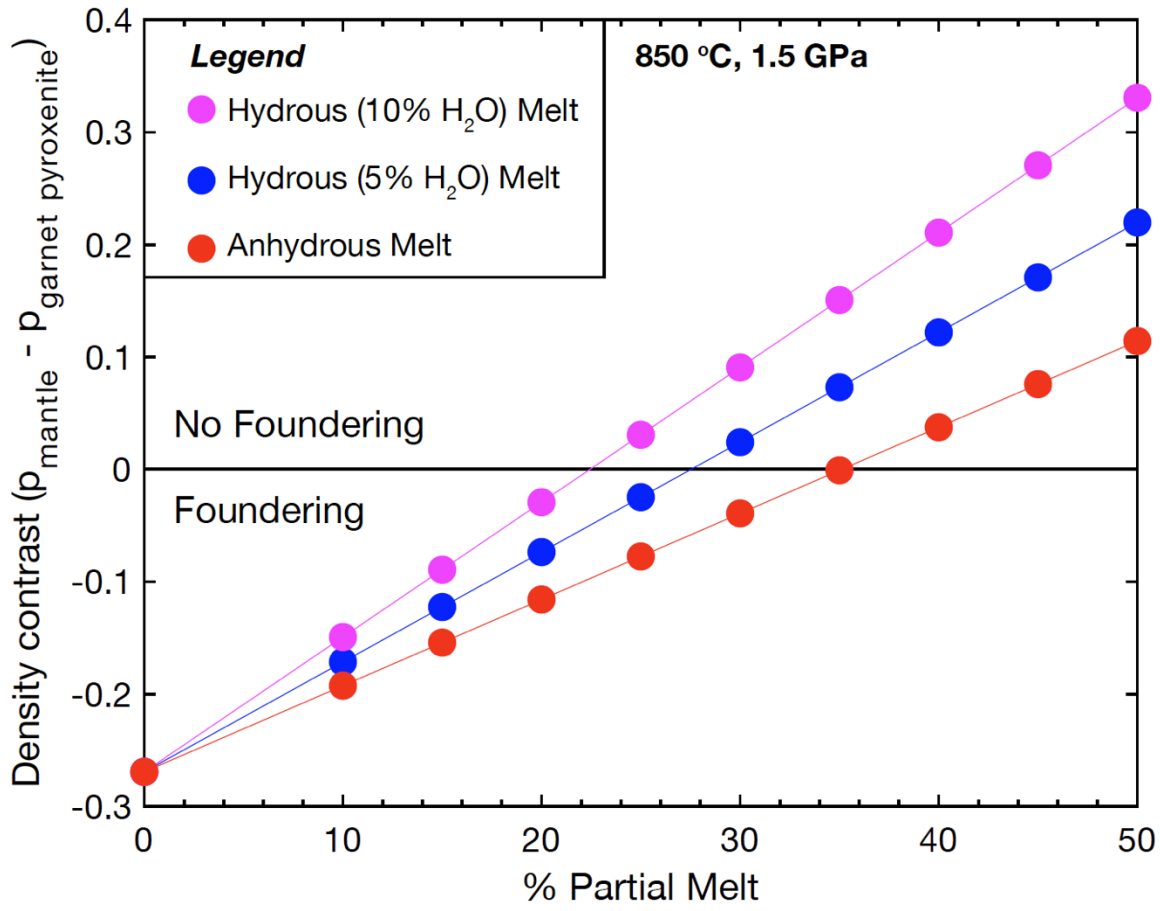

Figure 10. Diagram showing the density contrast between typical upper mantle peridotite and arclogite at 850 ^{0}C and 1.5 GPa, with various fractions of intermediate partial melt for anhydrous melt, 5% H_2O and 10% H_2O. If density contrast is positive (root denser than melt), foundering is possible, 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).

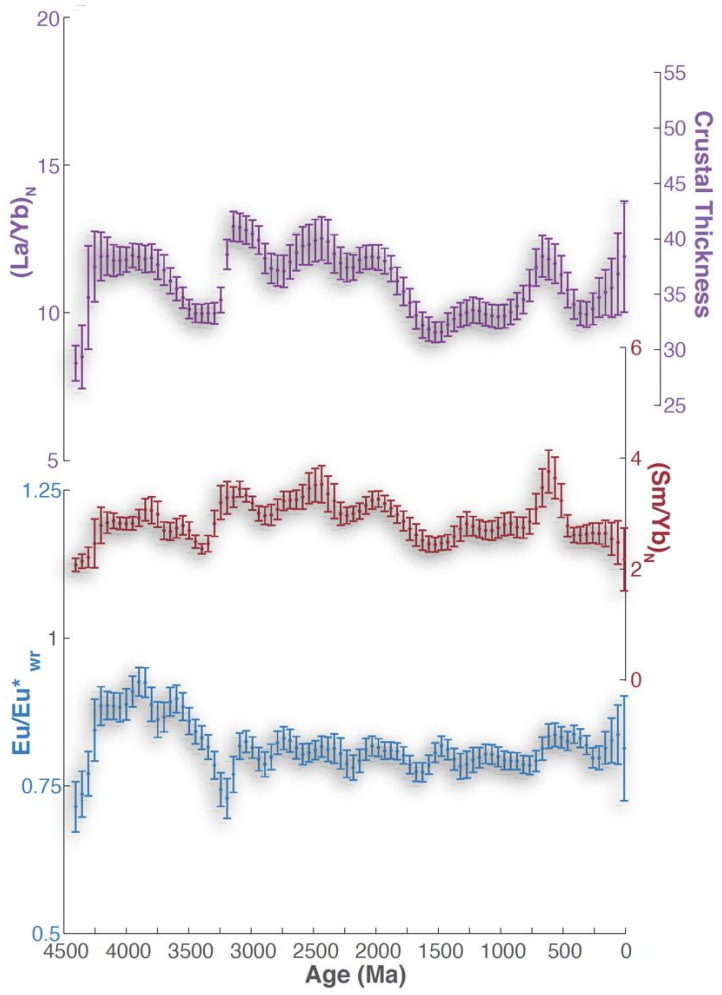

Figure 11. Global calculated whole rock La/Yb_n, Sm/Yb_n and Eu/Eu* from zircon petrochronology (Balica et al., 2020). Crustal thickness over time is also shown on the right (as determined by Profeta et al., 2015 based on La/Yb). 98% all analyzed zircons are from granitoid magmas (Balica et al., 2020). 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).