ON THE IMPORTANCE OF CRYSTALLIZATION-DIFFERENTIATION FOR THE GENERATION OF SiO$_2$-RICH MELTS AND THE COMPOSITIONAL BUILD-UP OF ARC (AND CONTINENTAL) CRUST

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ABSTRACT. In this paper we review processes responsible for the formation of granites in subduction systems. While there is robust evidence that strongly peraluminous, so-called S-type granites are formed by melting of metasediments in the (lower) crust, the processes that form metaluminous, so-called I-Type granites are less certain. We review four lines of evidence that have been presented in support of a dominantly crustal origin for these granites: 1) field observations; 2) isotopic compositions; 3) the missing cumulate problem; and 4) the bimodal distribution of igneous rock compositions. We show that in most cases the evidence is at least equally permissive of a process dominated by crystallization-differentiation. Moreover, we show that this mechanism is more efficient than re-melting and avoids additional difficulties associated with the source of heat and or fluids necessary for productive partial melting. Lastly, we show with a simple stochastic model that crystallization-differentiation also explains the first-order compositional and density stratification of arc crust and hence continental crust. We conclude that the structure of arc crust is comparable to oceanic crust at fast spreading ridges and may be controlled by analogous melt transport and stagnation mechanisms.

Keywords: granite formation, hydrous crystallization, arc crust formation, continental crust formation

INTRODUCTION

The generation of evolved, SiO$_2$-rich, acidic igneous rocks has been the subject of vigorous discussion for over one hundred years. In their seminal paper, Tuttle and Bowen (1958) made a compelling observation that granites (s.s.) are similar to the minimum melt composition in the system Ab-Or-Qz and concluded that granites must be derived from a basaltic parental melt by crystallization-differentiation (Bowen, 1915, 1919; Tuttle and Bowen 1958). Even so, while Bowen was an adamant proponent of the crystallization-differentiation mechanism, (and specifically of fractional crystallization), ultimately Tuttle and Bowen (1958) concluded that large-scale batholiths are most likely formed by re-melting of basalt or sediments rather than direct fractional crystallization, as "the so-called room problem is nonexistent for granite batholiths formed in this fashion, as is also the heat problem" (Tuttle and Bowen, 1958, p. 124).

In the late 19th century and up through much of Bowen's career, numerous mechanisms were still entertained for the genesis of granite, including Bowen's hypothesized crystallization-differentiation, the possibility of primary granitic magmas, liquid immiscibility, and "granitization", the formation of granite through metasomatic processes during metamorphic events (for historical context, the reader is referred to Geological Society of America Memoir No. 28 - 1948; Read, 1957; and more recent summaries in Pitcher, 1997; and Grove and Brown, this issue). Today it is accepted that granites are igneous rocks. Moreover, in the discussion of granitic batholiths in their classic textbook, Carmichael and others (1974) conclude that the presence of only small volumes of mafic rocks associated with these batholiths "rule out

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all possibility that the Cordilleran granites are differentiates of basaltic magmas" before continuing that "this is the view of most geologists who have recently considered the origin of granitic batholiths in this province" (Carmichael and others, 1974, p. 582). Although more than 40 years have passed since that publication, most researchers today would still fully concur with these assertions.

However, in recent years, field and experimental studies have revitalized the idea that I-type granites found in large batholiths can indeed be formed dominantly by crystal-differentiation of a hydrous basaltic parental magma (for example Jagoutz and others, 2009; Jagoutz, 2010; Dessimoz and others, 2012; Bucholz and others, 2014; Lee and Bachmann, 2014; Nandedkar and others, 2014; Walker and others, 2015) with minor contribution from host rock assimilation. (For simplicity we will use Bowen's preferred term, crystallization-differentiation to refer to all crystal fractionation dominated magmatic differentiation processes, which can vary from near fractional- to near equilibrium- crystallization, except when explicitly referring to one of the end-member processes.) One of the major advantages of this hydrous fractionation mechanism is that it does not requiring an external heat source (compare, for example Grunder, 1995).

Despite this recent work, the production of large granite batholiths through crystallization-differentiation remains an often-dismissed idea. The primary arguments presented against this mechanism are 1) field observations that are interpreted as evidence for partial melting; 2) the isotopic compositions of felsic rocks, which are often distinct from the isotopic composition of strictly mantle-derived material; 3) the volume problem, which notes that an implausibly large cumulate pile is required to generate felsic melts through fractionation; and 4) the composition problem, which argues that crystallization-differentiation produces a continuous distribution of magmatic rock compositions, while the observed distribution of magmatic rocks composition is bimodal, with a dearth of intermediate compositions. In this review we address each of these arguments in turn, quantitatively evaluating their validity and significance with a combination of field observations, compiled geochemical data, and models of partial melting and crystallization-differentiation processes. We then outline a number of additional lines of evidence that point to crystallization-differentiation as an important process in the generation of felsic batholiths.

The global distribution of Phanerozoic felsic igneous rocks show that most granitic batholiths form linear belts that are indicative of formation at subduction zones (fig. 1). This strongly argues that granite formation occurs dominantly within supra-subduction zone settings. As it has been shown that arc crust resembles bulk continental crust (Jagoutz and Schmidt, 2012), understanding the formation of felsic rocks in arcs is highly relevant to understanding continental crust formation. Unlike other tectonic settings that produce granite (for example: continental collisions, Laurent and others, 2017; continental rifts, MacDonald and others, 1987; post-collisional settings, Moyen and others, 2017), subduction zone magmas are often characterized by H_2O content in excess of 4 weight percent (Wallace, 2005; Grove and others, 2012; Plank and others, 2013; Schmidt and Jagoutz, 2017). The presence of water is a critical difference between subduction zone magmas and the magmas produced at other settings; throughout this paper we highlight the importance of elevated H_2O content to the processes responsible for the formation of felsic melts in hydrous (arc) systems. Because of the importance of water, the results of this paper dominantly apply to the formation of granites in arcs (both continental and oceanic) and less to granites formed in other tectonic settings. Finally, although not strictly faithful to the original definition (Chappell and White, 1974), for simplicity we use I-type throughout the text to refer to these arc granitoids.
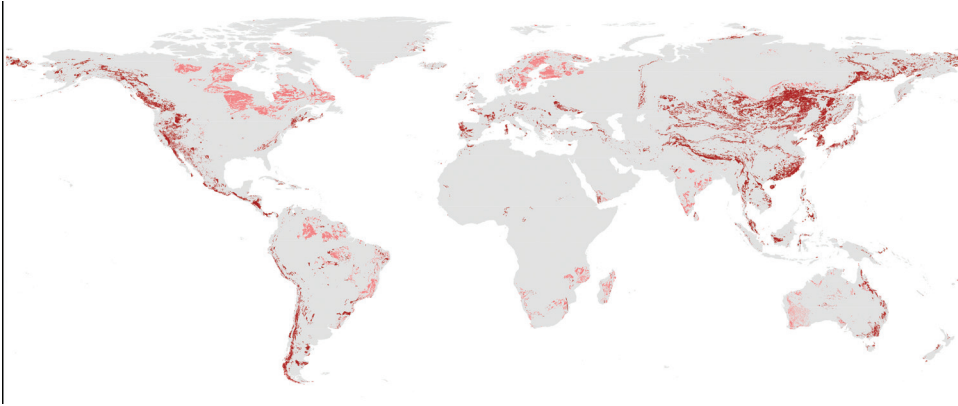
Fig. 1. Global map of felsic igneous rocks. Phanerozoic units mapped in dark red, Precambrian units in pink. Map compiled from global lithologic map database (GLiM, Hartmann and Moosdorf, 2012) and from continent scale maps published by the USGS World Energy Project (https://energy.usgs.gov/OilGas/AssessmentsData/WorldPetroleumAssessment/WorldGeologicMaps.aspx).

ARGUMENT 1: FIELD OBSERVATIONS

Field Evidence for Partial Melting and the Systematics of S- and I-types Granitoids

Migmatite textures, commonly observed in high-grade metasedimentary rocks, are produced when these rocks are partially molten and, during deformation, the partial melts pond and segregate to form coherent larger bands and pools (fig. 2A). As the protoliths of these migmatites are solid sedimentary rocks prior to the metamorphic event, these observations require that partial melting of the metasedimentary protolith occurred, followed by segregation of the melt into leucosomes, and that this process is capable of producing felsic melts. In detail, many leucosomes do not represent melt compositions; some leucosomes appear to preserve cumulate signatures, with significant Eu/Eu* anomalies, and there is also evidence that the composition of leucosomes are additionally strongly modified by diffusive exchange (Solar and Brown, 2001). Despite these complications present at the outcrop scale, experiments show that partial melts of metasediments have compositions similar to strongly peraluminous S-type granites (for example, Patiño Douce, 1999 and references therein), which typically crystallize additional aluminum bearing minerals beyond biotite and feldspar, such as muscovite, garnet or cordierite.

Additionally, S-type granites frequently have highly radiogenic isotopic compositions (McCulloch and Chappell, 1982; Villaros and others, 2009, 2012; Bouilhol and others, 2013; Farina and others, 2014), and often exhibit complex records of inherited zircons derived from the metasedimentary precursor (for example, Gaschnig and others, 2013). This record of inheritance is well preserved, as the temperature of the melting reactions that produce these granites rarely exceeds the expected zircon saturation temperature (T_{Zrsat}) for these compositions (Watson and Harrison, 1983; Harrison and others, 1987; C. F. Miller and others, 2003). Similarly, a clear age relationship often can be identified in migmatitic metasediments through field relationships and/or geochronology whereby the sedimentary protolith is many millions of years older than the migmatite-forming melting event. Field evidence and geochemical study have been used to link S-type granite plutons to a migmatitic metasedimentary source (for example, Kalsbeek and others, 2001). Because of these collective observations, there is a wide consensus that S-type granites are produced dominantly by melting of metasediments and that juvenile, mantle derived melts can
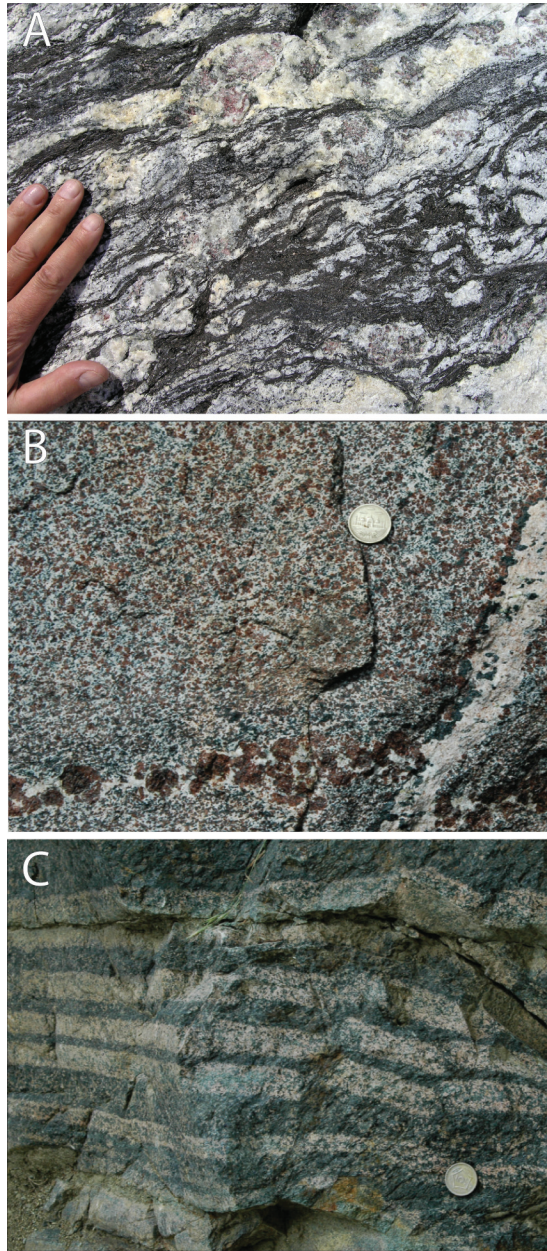
Fig. 2. Field observation from (A) pelitic migmatites from the Fosdick Mountains in West Antarctica. The leucosomes are interpreted as partial melts derived from a pelitic precursor. The leucosomes have garnet and minor cordierite indicating that the partial melt is a peraluminous S-type granitoid (photo courtesy of Michael Brown, University of Maryland). (B) Garnet-rich gabbro from the Jijal complex Pakistan. These rocks have been interpreted as mafic migmatites (Garrido and others, 2006) and alternatively as high pressure cumulates (Ringuette and others, 1999; Jagoutz and others, 2009). (C) Compositional banding defined by modal variability of garnet and hornblende from the Jijal complex. The near monomineralic composition, undeformed texture and narrow banding of compositional layers all indicate that these are magmatic cumulates.

play a secondary (but still significant) role in the generation of these rocks (Collins, 1996; Patiño Douce, 1999; Castro and others, 1999).

Given the compelling evidence for a genetic link between migmatitic metasediments and the generation of S-Type granites, it seems a natural inference that partial melting of (mafic) orthogneiss can also produce felsic melts, albeit with slightly different chemical compositions (for example Chappell and White, 1992). It is often inferred that the melting of less aluminum-rich protoliths, typically assumed to be mafic to intermediate orthogneisses (that is amphibolites), is the dominant process for producing metaluminous to weakly peraluminous I-type granitoids (for example, Kemp and others, 2007). However, there are a number of important characteristics typical of I-type granitoids that distinguish these rocks from S-type granites and possibly challenge the analogy to the formation of S-type granites. First, I–type granitoids occur predominantly in batholiths that are, with few exceptions, significantly larger (fig. 1) and built over significantly longer timescales (typically tens of millions of years) than typical S-type granites (examples include Sierra Nevada and Peninsular range batholiths in California, Ducea Ducea and Barton, 2007; Chapman and others, 2012; Gangdese Batholith, Ji and others, 2009; and Kohistan-Ladakh Batholith, Bouilhol and others, 2013; both in the greater Himalayas). These I-type batholiths appear to form at subduction zones. Second, unlike S-type granites, I-type granitoids rarely have significant inherited zircon populations and the (few) inherited zircons that can be found are often similar in age to surrounding associated igneous rocks (antecrystic rather than xenocrystic zircon in the classification of Miller and others, 2007; see examples in Schaltegger and others, 2009; Leuthold and others, 2012; Barboni and others, 2013). Third, I-type granitoids often have significantly less radiogenic initial isotopic compositions, indicating that there is little need for assimilation of (or derivation from) pre-existing, evolved crustal material (for example, Bouilhol and others, 2013, see also Argument 2 below).

Finally, although typically interpreted to, the presence of migmatite-like textures in orthogneisses need not require that remelting has occurred. The formation of a migmatitic texture only indicates that deformation occurred while both melt and solids were present. Textures resembling migmatites in orthogneisses can be formed during either partial melting or crystallization-differentiation, when a partially crystalized magma (that is, a crystal mush) is deformed, resulting in the segregation of cumulate solids and the residual liquid (Sawyer, 2000; Bea and others, 2005). This mechanism for the generation of migmatite-like textures should be ruled out before migmatitic mafic orthogneisses can be taken as unequivocal evidence of a partial melting event.

One observation that would definitively exclude crystallization-differentiation is a clear age difference between the ages of the protolith and the remelting event (this is challenging in locations with mafic to intermediate protoliths as these lithologies typically lack appropriate mineral assemblages for geochronology). Although migmatitic textures are common in mafic to intermediate orthogneisses from arc terrains (for example, Fiordland, New Zealand, Stowell and others, 2014; and Salinian Block, California, Hansen and Stuk, 1993), very few of these well-studied examples document a clear and measurable (for example, U-Pb zircons ages) age difference between the emplacement and crystallization of the orthogneiss precursor and a subsequent remelting event. One exception, however, is the Arthur River Complex in Fiordland, New Zealand, where bimodal zircon populations are interpreted to record *in-situ* early Cretaceous partial melting of a Carboniferous pluton (Tulloch and others, 2011), although this locality lacks evidence that large volumes of partial melt were extracted to produce new I-type granitoid plutons. A second possible example may be the Klanechina klippe in Talkeetna where Sm/Nd garnet ages postdate the U-Pb zircon
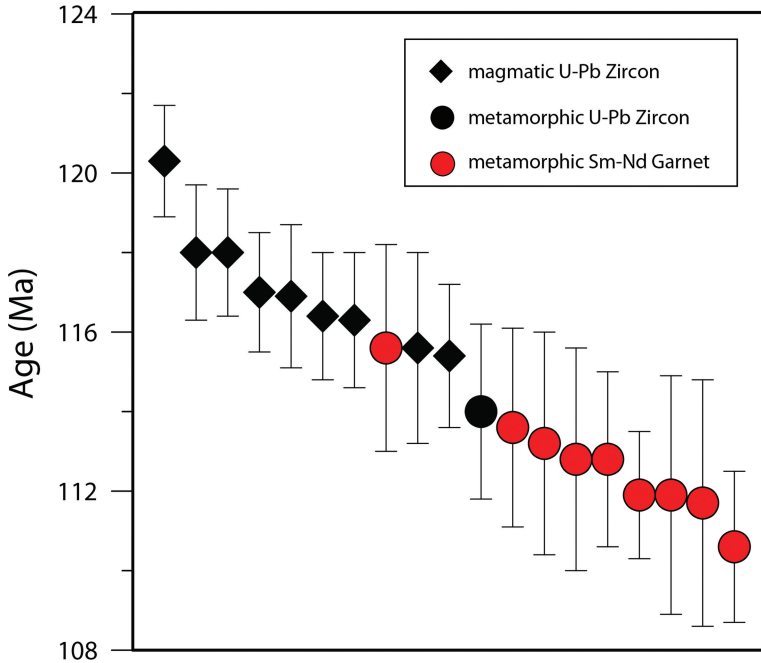
Fig. 3. Geochronology from the Malaspina pluton (Fjordland, New Zealand; after Stowel and others, 2014; Schwartz and others, 2016). The igneous emplacement age of the protolith (dated with U-Pb igneous zircon) overlaps within two sigma uncertainty with the onset of garnet granulite metamorphism (dated with U-Pb metamorphic zircons and Sm-Nd garnet) making it difficult to distinguish between the possibility that granulitization is due to a deep seated pluton cooling into the garnet granulite field, or due to a subsequent reheating event.

ages by ~10 Ma (Rioux and others, 2007; Hacker and others, 2010), although the geochronology of this location is more limited than for the above example, and there are no samples with both garnet and zircon ages.

Other cited examples of partial melting of mafic to intermediate orthogneisses in arc settings rely on more equivocal data. For example, in one of the best studied mafic orthogneiss terranes, the Early Cretaceous Malaspina pluton in the Western Fiordland region of New Zealand, the youngest U-Pb zircon ages are indistinguishable within error from the oldest Sm/Nd garnet ages that are considered to date the granulite facies metamorphism (fig. 3; Stowell and others, 2010, 2014). Similarly, in the Southern Sierra Nevada, granulite facies metamorphism follows immediately after the pluton emplacement (Saleeby and others, 1987, 2007, 2008). In these cases isobaric cooling of a plutonic precursor from magmatic temperatures into the granulite field in the lower crust is possible, and should be excluded before more complicated processes requiring rapid cooling and reheating to cause melting are inferred. Indeed, remelting was similarly proposed as a mechanism to form the garnet granulites of the Jijal complex (Pakistan) from a gabbroic precursor (figs. 2B and 2C; Garrido and others, 2006). However, this proposed remelting event conflicts with field observations that show the apparent precursor rock intrudes the granulites (Burg and others, 2006), and also with the whole rock and mineral geochemistry that indicates that the granulites together with the associated ultramafic rocks formed as cumulates of hydrous melts (Jagoutz and others, 2009; Jagoutz, 2010) and subsequently followed an isobaric cooling path into the garnet granulite field (Ringuette and others, 1999).

In addition to the limited, equivocal field evidence for partial melting in mafic orthogneisses in arcs, there are a number of petrologic arguments that further suggest that partial melting should be a less efficient mechanism for the generation of I-type granitoids compared to S-type. The general reasoning for this mechanism relies on parallels between partial melting of metasediments and amphibolites (for example, Chappell and White, 1992). However, these systems differ in two ways that have important implications for these processes. First, muscovite and biotite, the hydrous minerals in metasediments, become unstable at crustal pressures at temperatures 100 to 200 °C lower than epidote and amphibole, the analogous hydrous minerals in mafic compositions (Vielzeuf and Schmidt, 2001). Therefore, significantly higher temperatures are needed to produce meaningful volumes of partial melt in amphibolites compared to metasediments (Clemens and Vielzeuf, 1987; Annen and others, 2008). Second, muscovite and biotite both contain ~4 weight percent water in their crystal structure, while epidote and amphibole each only contain ~2 percent. Therefore, the melt productivity of the breakdown of hydrous minerals in a biotite-rich metasediment can be much greater than the volume of melt produced by an amphibole-rich amphibolite (Patiño Douce and Beard, 1995), although this may to some extent be offset by the greater modal abundance of amphibole in amphibolite compared to hydrous mineral modes in metasediments (Clemens and Vielzeuf, 1987; Johannes and Holtz, 1996; see also Argument 3).

Field-Based Evidence for Fractional Crystallization

Although the field evidence for partial melting as the mechanism for generating I-type granitoids in arcs is limited, there is compelling evidence in a number of locations for fractional crystallization being an important process for their generation. Deep crustal cumulates that are complementary to shallower level granitoids are exposed in numerous island and continental arc sections including Talkeetna, Kohistan, Famatina, the Chelan complex, and Southern Sierra Nevada. In some locations, these rocks have obvious magmatic, cumulate textures (for example DeBari and Coleman, 1989; Greene and others, 2006; Dessimoz and others, 2012), but many of these terranes are characterized by isobaric cooling into the granulite field and subsequent recrystallization due to elevated temperatures that can persist over millions of years, resulting in re-equilibration and production of metamorphic textures (see for example Fiordland: Stowell and others, 2010, 2014) that obliterate the original igneous textures.

One of the best-exposed arc sections is the Kohistan arc in NE Pakistan. The Kohistan arc exposes a complete ~50 to 55 km thick crustal section with ultramafic cumulates and upper mantle peridotites in the south, progressing through lower crustal gabbros and upper crustal granitoids, and volcanic rocks in the north (Jagoutz and Schmidt, 2012). Structurally, originally sub-horizontal sills characterize the lower crust in Kohistan, whereas the upper crust granitoids are dominated by sub-vertical magmatic dike contacts between larger plutons (Burg and others, 2006; Jagoutz and others, 2013). In this respect, the arc crust structurally resembles the oceanic crust formed at fast spreading ridges, where the lower oceanic crust is made of horizontal gabbroic sills and the upper crust is composed of vertical dikes (Kelemen and others, 1997).

Recent research has demonstrated that the ultramafic and mafic rocks at the base of the arc are dominantly cumulates (accumulated crystals ± interstitial liquids) whereas the upper crust is dominated by felsic granitoids that resemble frozen liquid compositions (Jagoutz, 2014). The cumulate whole rock compositions in the lower Kohistan arc crust are nearly identical to those produced by medium to high pressure hydrous crystallization experiments (Müntener and others, 2001; Alonso-Perez and others, 2009; Jagoutz and others, 2009). Moreover, the lower crustal cumulates can be
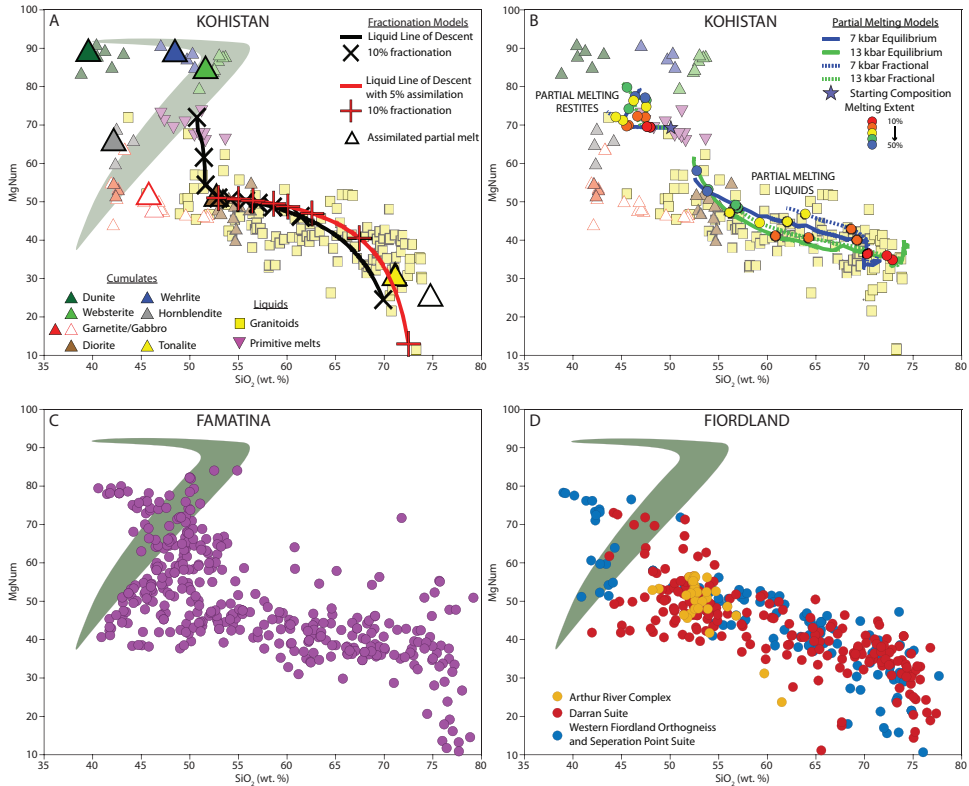
Fig. 4. Compiled whole rock compositions from arc crustal sections, plotted as MgNum (molar Mg/(Mg+Fe)*100) vs. wt. % SiO$_2$. A, B – Data from Kohistan crustal section, Pakistan, modified from Jagoutz (2010). Cumulates are shown with triangles, while evolved liquids are shown as squares. Also shown are fractional crystallization (A) and partial melting (B) models from Jagoutz (2010) and this work, respectively. The fractional crystallization models subtract the enlarged cumulate compositions from a primitive melt composition and track the liquid line of descent of the differentiating liquid (black), allowing for 5% assimilation (red). The partial melting model is described in detail in Argument 2. C, D – additional data compiled from arc crustal sections from the Ordovician Famatina Arc, Argentina (C) and the Cretaceous Fiordland Arc, New Zealand (D). Note that although these are both continental arc sections, the compositional distribution closely mirrors that observed in Kohistan, and also closely resembles the distribution of lower crustal hydrous cumulates (Muntener and others, 2001; Alonso-Perez and others, 2009). Data sources for C and D are available in the Appendix.

related to the upper crustal rocks by a common liquid line of descent (Jagoutz, 2010). Quantitative modeling shows that step-wise removal of observed lower crustal rock compositions from an evolving primitive arc melt composition can produce the volumes and compositions of rocks observed in the upper crust (fig. 4A; Jagoutz, 2010). In contrast, while partial melting models can produce much of the observed granitoid variability, it fails to produce most of the observed cumulate compositions, and requires unreasonably high extents of melting to produce the observed intermediate compositions (fig. 4B, and see detailed discussion in Argument 3 below). One limitation of the modeled liquid line of descent in Kohistan is that not all of the rocks in the lower and upper crust are contemporaneous. However, since this initial study, additional field examples have been described where the (near) completeness of the exposure permits similar modeling, demonstrating that lower crustal mafic rocks are complementary to associated upper crystal granitoids and that they can similarly be modeled by hydrous liquid lines of descent (Dessimoz and others, 2012; Bucholz and

others, 2014; Walker and others, 2015). Moreover, in some of these field locations U-Pb zircon dating shows that rocks used to model cumulates and derivative liquids formed contemporaneously on hundreds of thousand to a few millions of years timescales (Bucholz and others, 2017; Ducea and others, 2017). In figures 4C and 4D we compare the findings from Kohistan with compiled whole rock compositions from two continental arc sections: the Ordovician Famatina Arc in Argentina, and the previously discussed Jurassic-Cretaceous Fiordland section in New Zealand. The distribution of whole rock compositions in these arcs closely mirrors the Kohistan distributions, although they lack samples comparable to the most primitive cumulates in Kohistan. Still, the striking similarity suggests that comparable, fractional crystallization dominated differentiation mechanisms are also active in continental arcs (Walker and others, 2015). The previously mentioned Arthur River Complex in Fiordland appears to be a possible exception, as the range of compositions observed there appear to be consistent with restites of a partially melted, moderately differentiated composition. The dominance of differentiates observed in the lower arc crust (compared to upper arc crust) is consistent with the idea that the lower arc crust exerts an important role of magma differentiation (for example Hildreth and Moorbath, 1988; Dufek and Berganz, 2005; Annen and others, 2006).

ARGUMENT 2: ISOTOPIC EVIDENCE FOR ASSIMILATION/PARTIAL MELTING

As mentioned above, most S-type granites are characterized by highly evolved radiogenic isotope compositions indicative of a significant contribution from crustal reservoirs (for example, McCulloch and Chappell, 1982; Hopkinson and others, 2017). In contrast, I-type granitoids are typically not as evolved as S-type granites, but are also rarely observed to have isotopic compositions consistent with exclusively mantle-source derived material (fig. 5, Chappell and White, 1992; Kemp and others, 2007). These observations are commonly interpreted to be evidence for assimilation or mixing of an evolved crustal component with mantle derived, juvenile material. Indeed, this is an essential motivator for the most-cited models of partial melting dominated generation of granitic batholiths (Hildreth and Moorbath, 1988; Annen and others, 2006). However, these models in fact require a significant contribution from crystallization-differentiation of mantle-derived material.

In figure 5A we show the distribution of isotopic compositions of primitive and near-primitive arc lavas (here defined as MgNum>0.60) from continental and oceanic arcs and compare it to the distribution of the isotopic composition of intrusive rocks from the Sierra Nevada Batholith (SNB). The isotopic compositions of continental primitive arc lavas span the same compositional range as that observed in the SNB, however, lavas with less radiogenic compositions (ϵNd>0) are significantly more abundant than those with evolved isotopic compositions (ϵNd<0) in our dataset. As the whole rock compositions of these lavas are not permissive of significant crustal assimilation, the evolved isotopic signature is likely a character of these melts prior to any crustal interaction, and may be attributable to slab-derived material, most likely contributed via slab-derived fluids. In contrast, in the SNB dataset more radiogenic isotopic compositions (ϵNd<0) are most abundant. This, together with the observation that isotopic compositions systematically increase from west to east across strike of the SNB (Kistler, 1990; Chapman and others, 2012) is evidence that some amount of contamination of primitive mantle-derived material by crustal material occurs in the crust. However, quantifying the amount of assimilation strongly depends on both the assumed isotopic composition of the mantle-derived material as it reaches the base of the crust (accounting for any contamination by slab-derived material), and also on choice of transfer agent. In figure 5C, we use the distribution of continental arc primitive lavas to calculate the probability distribution of extent of assimilation needed to produce the distribution of isotopic compositions observed in the Sierra Nevada. We
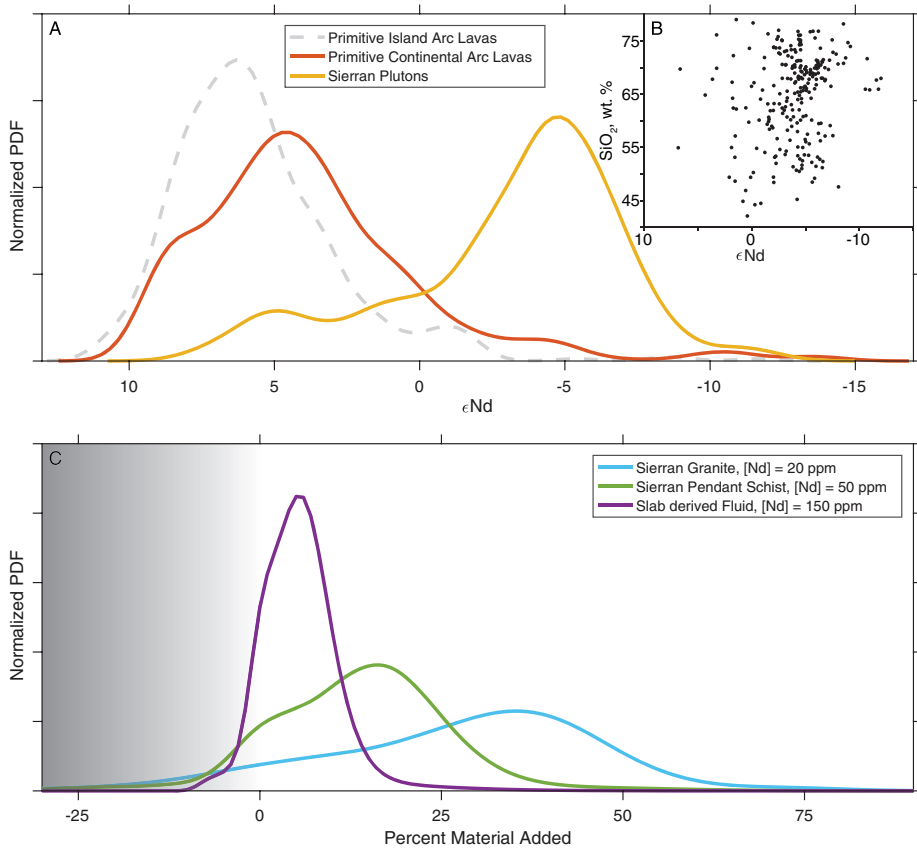
Fig. 5. Isotopic heterogeneity observed in primitive arc lavas and in an example arc batholith, the Sierra Nevada batholith, California. (A) Probability distributions of ϵNd for primitive oceanic and continental arc lavas and for plutonics in the Sierra Nevada. Modern isotopic values are presented for arc lava datasets, while initial isotopic compositions are presented for the Sierra Nevada. As nearly all of the shown arc lavas are $\ll$50 Ma, the correction to initial isotopic compositions will be very small. Primitive arc lava data from pre-compiled datasets available from Georoc (http://georoc.mpch-mainz.gwdg.de/georoc/), filtered for primitive compositions as MgNum>0.60, 47<SiO$_2$ wt.%<62. Sources for Sierra Nevada data available in the Appendix. (B) Sierra Nevada plutonics ϵNd plotted by whole rock SiO$_2$ wt%. (C) Calculated probability distribution for needed degree of assimilation to produce the observed Sierra Nevada isotopic distribution, assuming an initial distribution equal to the distribution of primitive continental arc lavas. Three different curves represent different transfer agents with varying neodymium concentration but equal ϵNd. Gray region denotes non-geological negative assimilation, resulting from calculations with plutonic samples less radiogenic than the source composition.

performed these calculations using three different transfer agents with identical isotopic compositions but different Nd concentrations based on published values: 1) bulk assimilation of country rock (schist in Sierra Nevada metasediment pendants, [Nd] = 50 ppm, DePaolo, 1981); 2) mixing with a granitic (partial) melt ([Nd] = 20 ppm, typical SNB value); and 3) assimilation of a high pressure fluid ([Nd] = 150 ppm, Grove and others, 2002).

Our results show that the amount of material incorporated into the different primitive lavas could be as little as ~0 to 15 percent in the case of fluid assimilation and as high as ~0 to 50 percent for mixing with a granite melt, whereas the needed assimilation of country rock is ~0 to 30 percent. Furthermore, 10 to 15 percent of the calculations require no assimilation, representing instances where the Sierran isotopic

composition is equal to or greater than the primitive arc lava. In summary, for most transfer agents and rock compositions, the isotopic data show that the Nd in SNB granitoids is ~50 to 85 percent derived from mantle derived melts. These results agree with petrologic studies (Patiño Douce, 1999; Kemp and others, 2007) and thermal models (for example Dufek and Berganz, 2005) that similarly find that partial melting of crustal material alone cannot produce most voluminous I-type granitoids and predict that mantle-derived material likely contributes at least nearly equivalent mass to plutonic systems as the products of partial melting (Grunder, 1995). Similarly, variability in oxygen isotopes above traditionally defined mantle values has been observed in primitive arc magmas (for example, Auer and others, 2009; Straub and others, 2015), while closed system hydrous fractionation processes can produce additional +1 to 2 permil fractionation of oxygen isotopes (Bucholz and others, 2017). Once again, if these effects are not taken into account, mixing models will potentially significantly overestimate the amount of assimilated crustal material.

The greatest degree of assimilation is required for mixing of granitic partial melts with mantle-derived material. However, invoking this type of process introduces additional difficulties. Although mingling of felsic and mafic melts occurs on local scales (Jagoutz and others, 2013), there is little evidence for homogenous mixing between felsic and mafic melts in either major element or trace element datasets at the arc scale, with curved distributions instead supporting crystal fractionation dominated differentiation (Jagoutz, 2010; Keller and Schoene, 2012; Lee and Bachmann, 2014). Moreover, the homogenous mixing of mafic and felsic magmas is a highly inefficient process due to strong temperature, viscosity and density contrasts (Sparks and Marshall, 1986). Therefore, mixing is unlikely to occur between crustal partial melts and the basaltic melts inferred to cause the melting event. Instead, mixing in significant volume is more feasible only between crustal partial melts and evolved magmas of similar compositions produced by crystallization-differentiation of mantle-derived basalts.

In light of the expected hindered mixing between mafic and felsic magmas, it is worth reexamining the distribution of isotopic compositions in the Sierra Nevada Batholith. As mixing is likely severely hindered except between two felsic magmas, isotopically evolved mafic and intermediate samples should be very uncommon if this is a dominant process. Instead, in the Sierra Nevada, we observe similar distributions of ϵNd compositions in mafic and felsic samples (fig. 5B). Although some of the analyzed mafic samples are cumulates in equilibrium with more evolved melt compositions, some of the mafic samples likely represent near-liquid compositions, and show that mafic magmas existed with evolved ϵNd compositions. These magmas are unlikely to be produced by magma mixing, and instead suggest that they are derived from isotopically evolved primitive melts. Differentiation of these magmas via crystallization-differentiation would produce isotopically evolved felsic magmas without need for subsequent contamination by crustal material.

ARGUMENT 3: THE VOLUME ARGUMENT

"The gigantic volume of granitic rocks is an unsurmountable objection to this [the fractional crystallization] theory."

H.H. Read in the "The Granite Controversy" (1956) in regard to crystallization of basaltic parents.

Criticism has followed Bowen's suggestion that granitic liquids can be formed by crystallization-differentiation of a basaltic parental melt since his initial proposal. One of the primary objections to crystallization-differentiation as a viable mechanism is the 'volume' argument (Grout, 1926; Daly, 1933; Holmes, 1936). This argument reasons that >90 percent fractionation is needed to generate granitic liquids from a basaltic source, requiring that the observed large volumes of granites be complemented by

roughly 8 to 10 times more voluminous mafic and ultramafic cumulates, which typically form only a minor component of observed intrusive complexes. This 'volume' argument persists today, and is often cited as a primary objection to the importance of fractional crystallization (see for example, Chappell, 2004). Surprisingly, a similar emphasis has rarely been placed on the volume of restite produced during the generation of granites by partial melting. It is critical to quantitatively evaluate the volumes of required restites and cumulates to compare the efficiency of partial melting and fractional crystallization processes. Until recently, addressing this problem was very difficult, as experiments at low temperature with low melt fractions are slow to reach equilibrium (weeks to months or longer), and MELTS software doesn't adequately model the behavior of hydrous minerals (biotite and amphibole) that are critical to correctly modeling vapor-absent partial melting and hydrous fractional crystallization.

To investigate which mechanism is more effective in producing felsic compositions we compare fractional and equilibrium crystallization experiments with new model calculations of batch and equilibrium melting, using Perple_X (version 6.7.7; Connolly, 2005, 2009) and recently developed thermodynamic models constructed specifically to study the partial melting of metabasalts (Green and others, 2016). The calculations use solution models for the following phases: augite, clinoamphibole, melt (Green and others, 2016); chlorite, biotite, orthopyroxene, white mica, garnet (White and others, 2014); olivine, epidote (Holland and Powell, 2011); spinel (White and others, 2002); ilmenite (White and others, 2014); and feldspar (Holland and Powell, 2003). All calculations start with the starting composition (RDC156) from a recent series of fractional crystallization experiments (Nandedkar and others, 2014), to allow direct comparison between the efficiency of the modeled partial melting process and fractional crystallization. All simulations are conducted at constant pressure of either 7 or 13 kbars, and initiated with the maximum amount of H_2O that can be stored in hydrous minerals without stabilizing a free fluid phase (1.44 wt. % at 7 kbar, 1.78 wt. % at 13 kbar). Modeling was conducted for equilibrium, and (near-) perfect fractional partial melting. Additional equilibrium 7 kbar partial melting simulations were also conducted with variable H_2O contents of 0.05, 0.72, 3 and 6 weight percent.

Results

Figure 6 shows the changes in modal mineralogy with increasing temperature for the equilibrium and fractional partial melting simulations at 7 and 13 kbar. In all simulations, the calculation starts at 700 °C with an amphibolite assemblage, composed of ~65 weight percent amphibole, 7 to 10 weight percent clinopyroxene, ~10 weight percent quartz, 2 to 4 weight percent biotite, and ~10 weight percent plagioclase (at 7 kbar) or epidote (at 13 kbar). As temperature increases biotite begins to breakdown and produces the first melt near 720 °C. The final breakdown of biotite shows a weak pressure dependency, as biotite is completely destabilized by ~800 °C (7 kbar) or 750 °C (13 kbar). At these low temperatures epidote also is removed from the system and is replaced by plagioclase, the first appearance of garnet, and additional small volumes of melt.

As the temperature of the system continues to rise, amphibole begins to break down to form additional clinopyroxene and melt (as well as garnet at higher pressure). This reaction continues over a large temperature interval, with a small inflection in the melt production associated with the final exhaustion of quartz which occurs at ~850 °C (7 kbar) to 900 °C (13 kbar), producing orthopyroxene at low pressure and additional garnet at high pressure. Final breakdown of amphibole occurs at 1100 to 1150 °C, at which point melt productivity decreases significantly, as only anhydrous phases are present in the restite. The reactions outlined here are largely similar between the equilibrium and fractional cases, although at high temperatures the fractional melting
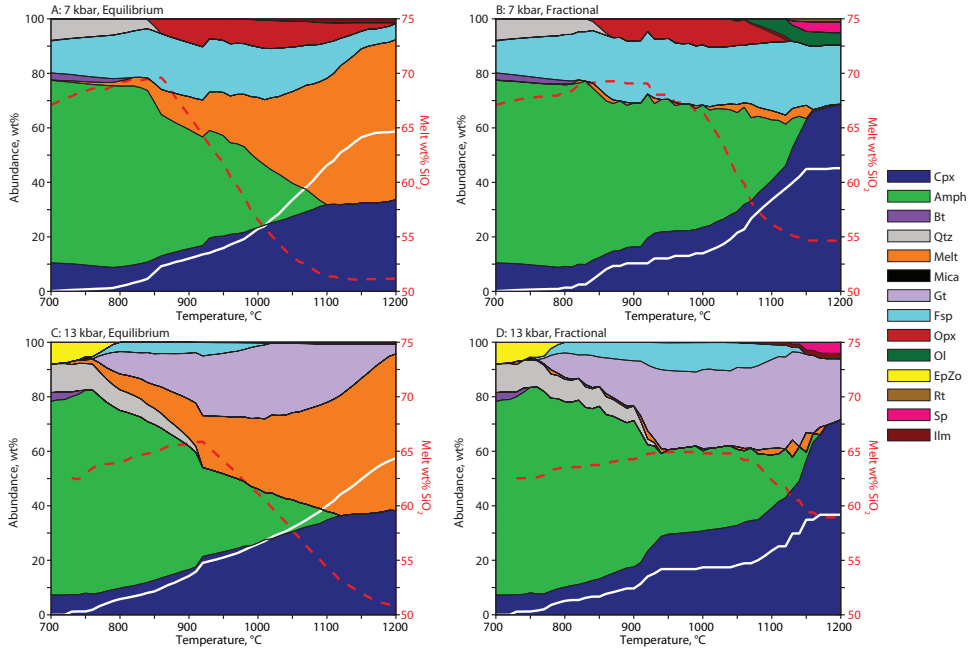
Fig. 6. Phase abundances (mass percent) from partial melting models using Perple_X, and the primitive starting composition (RDC156) from experiments in Nandedkar and others (2014). Results are shown for (near) fractional and equilibrium partial melting at 7 and 13 kbars. Total melt produced is shown with white line; dashed red line tracks the wt. % SiO_2 in the melt. Mineral abbreviations are as follows: Cpx (clinopyroxene); Amph (amphibole); Bt (biotite); Qtz (quartz); Mica (white mica); Gt (garnet); Fsp (feldspar); Opx (orthopyroxene); Ol (olivine); EpZo (epidote and/or zoisite, not differentiated in figure); Rt (rutile); Sp (spinel); Ilm (ilmenite).

restite becomes increasingly depleted and more mafic, with silica undersaturated phases (namely olivine and spinel) eventually stabilized.

In figure 7 we compare the volume and properties of melt produced in these simulations to the melts generated in the Nandedkar and others (2014) fractional crystallization experiments. The fractional crystallization process consistently yields more melt at a given temperature than partial melting, and these melts are consistently more silicic at equivalent melt fractions. The Nandedkar experiments reach felsic melts (SiO₂>wt. 65%) with ~35 weight percent melt remaining in the system, but production of felsic melts in the partial melting models is restricted to lower melting extents (F<15–25%), and the temperatures needed to produce these volumes of felsic melts are in excess of ~850 to 950 °C. A critical difference between the partial melting and fractional crystallization experiments is the amount of water in the two experiments (fig. 7C). In the partial melting system, the amount of water in the system is restricted to the volume of water present initially in hydrous minerals. In contrast, the fractional crystallization experiments begin with 3 weight percent water, more than twice the bulk water present in the partial melting experiments, but a relatively conservative starting water content for mantle derived arc melts (see, for example, Wallace, 2005), and this further increases to ~5 weight percent during the initial high temperature stages when only anhydrous phases are crystallizing. This difference results in a consistently more water-rich (even water saturated at low temperature) liquid in the fractional crystallization experiments compared to the partial melting experiments, depressing the solidus and increasing the amount of melt that can be produced at a given temperature.
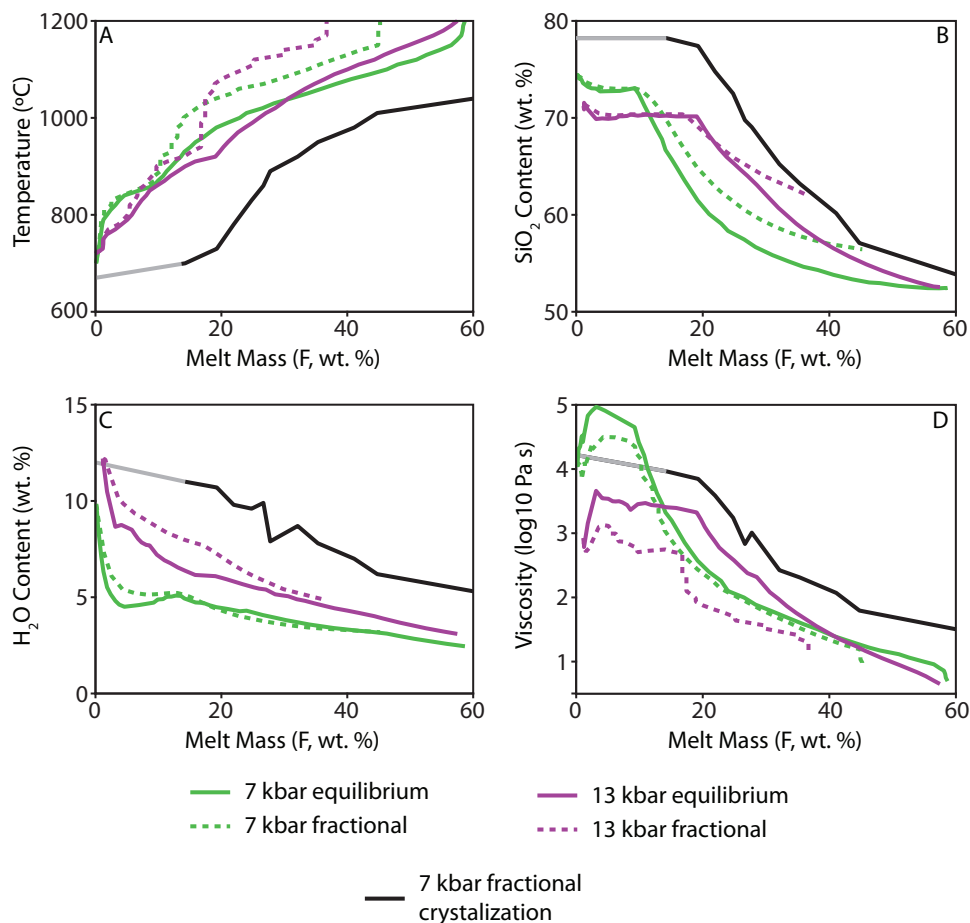
Fig. 7. Melt composition and physical parameters as a function of melt fraction for the 7 and 13 kbar partial melting simulations. Fractional crystallization experimental results from Nandedkar and others (2014) are shown in black for comparison. The gray line extends the fractional crystallization results to an approximate eutectic composition. (A) Change in melt fraction with increasing temperature. All partial melting experiments consistently need higher temperatures (50–100 °C) compared to fractional crystallization. (B) Change in melt SiO_2 wt. %. Here again, partial melting appears less efficient compared to fractional crystallization, with consistently lower SiO_2 content at comparable melt extents. (C) Melt H_2O content in modeled partial melts compared to measured melt H_2O content in fractionation experiments. Note that H_2O in experiments likely increases monotonically, and the spikes observed here are likely due to measurement difficulties. (D) Viscosity as a function of melt mass, calculated using the viscosity calculator from (Giordano and others, 2008). Despite lower water contents, the lower SiO_2 content and higher temperatures for equivalent melt masses in the partial melting experiments compared to fractional crystallization experimental melts result in lower calculated viscosities.

Discussion

The essential conclusion from these models is that fractional crystallization yields felsic melts after crystallization of 65 to 70 weight percent of the original melt mass (felsic melts 30–35 wt.%), while partial melting can only yield at most 25 weight percent felsic melt, and more typically produces only 15 to 20 weight percent Accordingly, to produce 20 km^3 of felsic melts, about 75- to 125 km^3 of restites should be observed in the field, all of which have to have been heated to above 850 °C. This is at best on par with the volume of cumulates predicted for fractional crystallization, and

Fractional Crystallization   Partial Melting

felsic melt
($\rho\sim$ 2800kg/m³)

| 20 km³ | 20 km³ |

felsic melt
($\rho\sim$ 2800kg/m³)

cumulates
($\rho\sim$ 3000kg/m³)

~56 km³

~110 km³

restite
($\rho\sim$ 3000kg/m³)

~60 km³

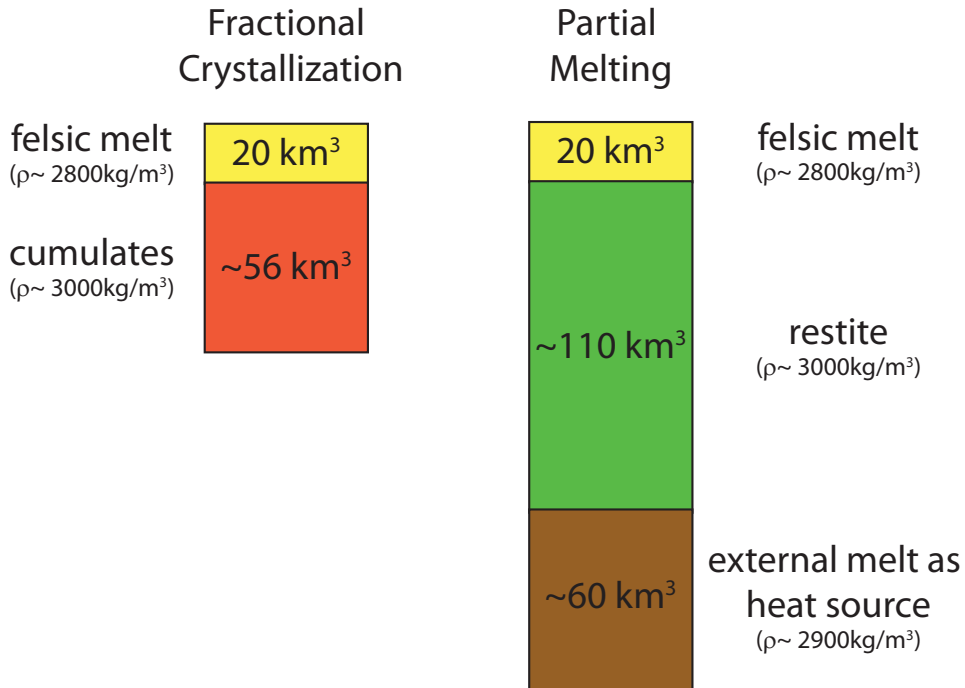external melt as heat source
($\rho\sim$ 2900kg/m³)

Fig. 8. Cartoon illustration of relative thickness of cumulates and restites needed to produce 20 km³ (that is ~upper crust) of granitoid, based on experiments and new calculations. Fractional crystallization requires only a ~3:1 ratio of cumulates to granitoid, while partial melting requires worse than 5:1 ratio of partial melting to granitoid, plus additional mantle derived material to provide the external heat required for partial melting.

at worst requires twice the volume of restites compared to cumulates (fig. 8). Sufficient volumes of mafic material are not observed in crustal sections to accommodate the generation of large felsic batholiths through either of these processes, but this lack of material should not be taken *a priori* to support one of these processes over the other.

There is, however, an additional difficulty inherent to partial melting that is not a factor for fractional crystallization processes. While fractional crystallization assumes that magma evolves along a liquid line of descent as it cools, partial melting requires an external source of heat or fluid, typically assumed to be additional mantle-derived magma, to cause the solid protolith to melt. This is true regardless of background geotherm, including for arc and rift settings where the lower crust is warmer than in other locations (see for example, Dufek and Bergantz, 2005; Annen and others, 2006; Karakas and Dufek, 2015). Thermal models have been used extensively to evaluate the efficiency of this process and typically find that a significant amount of mantle-derived magma is needed to generate appreciable partial melting, with estimates for the ratio of mantle-derived melts to crustal melts ranging from 1:1 to 5:1 (Grunder, 1995; Dufek and Bergantz, 2005; Annen, 2009). This significantly increases the volume of mafic material predicted to be present in the source area for partial melting processes well beyond the volumes of cumulates required by fractional crystallization (fig. 8).

One possible alternative to reduce the need for magmatic heat to drive the partial melting is to instead increase the amount of water present in the system, thereby depressing the solidus temperature. However, it is unlikely that there is a free fluid phase present in the lower crust (see for example Yardley and Valley, 1997), and so the
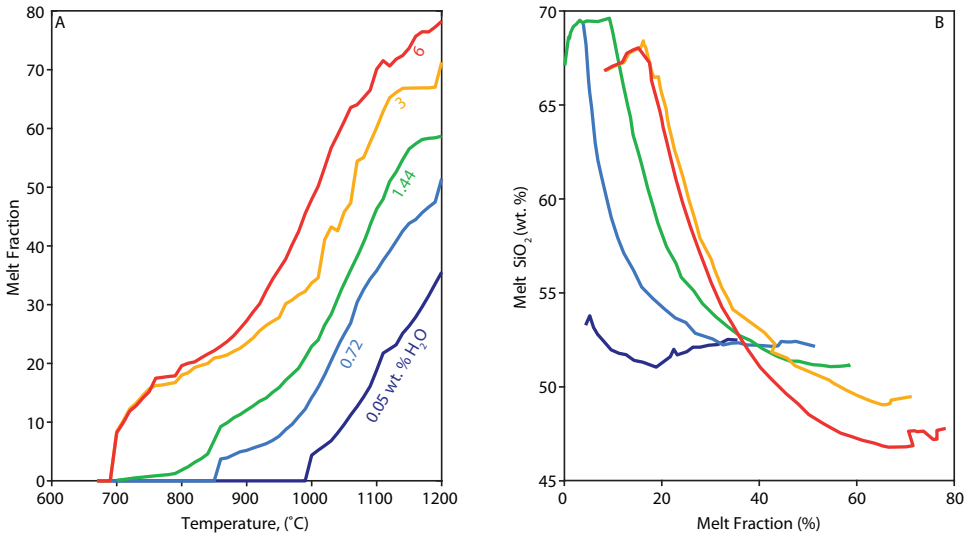
Fig. 9. Results of equilibrium partial melting experiments at 7kbar, with varying water content. (A) As bulk water content increases, the melting efficiency increases, with greater extents of melting at a given temperature. Additionally, the solidus temperature is highly sensitive to water content, and rapidly increases once bulk water content decreases below 1.5 wt. %. (B) With increasing water content, productivity of high SiO_2 increases. Production of melts with >60% SiO_2 increases from ~10% for 0.72 wt. % → H_2O to >20% for H_2O contents greater than 3%.

amount of fluid present is limited to the amount contained within stable hydrous minerals (generally 1–2 bulk wt. %). Increasing the amount of fluid present beyond this amount requires fluxing the system with externally sourced fluids, often inferred to be fluids produced by crystallizing, fluid-rich mantle-derived magmas (for example Weinberg and Hasalová, 2015; Collins and others, 2016). This once again requires additional volumes of magma to be added to the system. Regardless, we have investigated the effects of this additional water on the partial melting process (fig. 9). As expected, increasing the amount of water present significantly reduces the temperature required to produce significant volumes of melt (fig. 9A), and results in moderate increases in the amount of felsic melt that can be generated (amount of felsic melt produced increases to ~25 wt. % for H_2O>3 wt.%; fig. 9B). Although increasing H_2O content may increase melting efficiency, the addition of fluids does not change the fundamental result that there must be at least three times more restite than melt.

We have shown above that large volumes of mafic restites are required to produce voluminous granite batholiths through partial melting. A number of studies have shown that the comparable cumulates produced during crystallization-differentiation are denser than underlying mantle, and that the cumulate volume issue can be mitigated by removal of this density unstable material in viscous instabilities (Arndt and Goldstein, 1989; Kay and Mahlburg-Kay, 1991; Jull and Kelemen, 2001; Müntener and others, 2001; Jagoutz and Behn, 2013). In figure 10 we show analogous calculations, using Perple_X to compare the density of restites at crustal P-T conditions with an average depleted arc harzburgite (Kelemen and others, 2003) at equivalent P-T conditions. We show calculations first for the partial melting modeled above, using composition RDC156 from Nandedkar and others (2014) after 0, 20 and 40 percent melt removal (figs. 10A–10C). Not surprisingly, given the primitive nature of RDC156, the protolith is density unstable in the deepest lower crust, and all subsequent
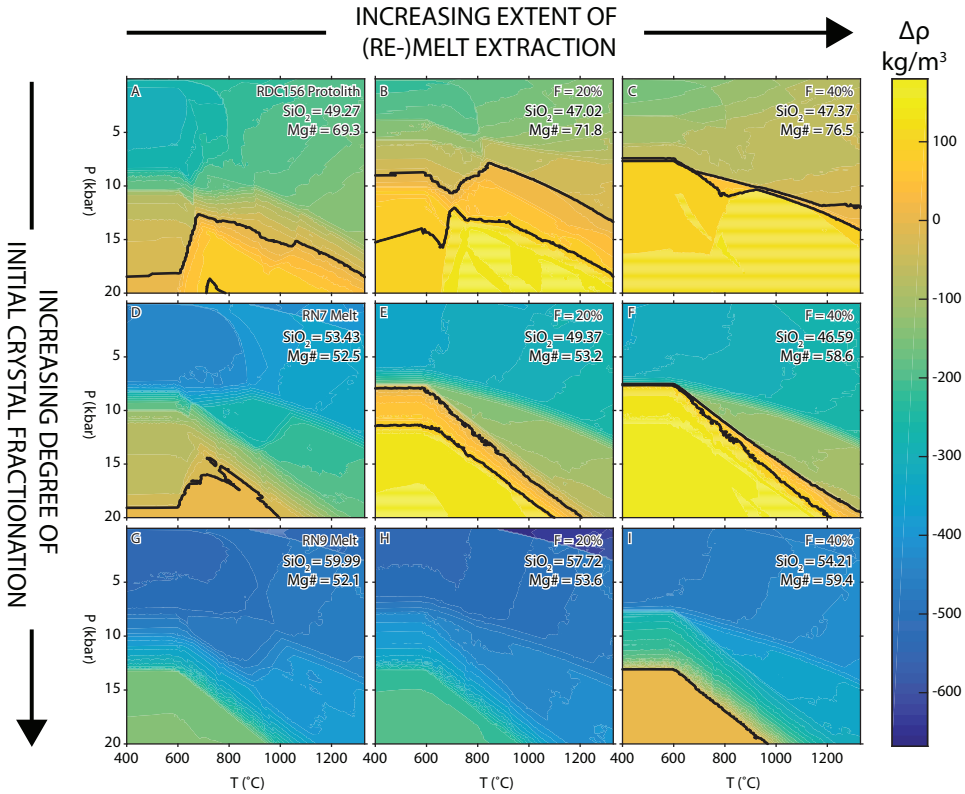
Fig. 10. Perple_X calculated densities for restites of equilibrium 7 kbar partial melting simulations, compared to average sub-arc mantle harzburgite. Extent of partial melting increases from 0% (that is protolith composition) to ~40% moving across rows, while extent of initial fractional crystallization increases moving down columns. Three protoliths from the Nandedkar and others (2014) experiments are considered: primitive basalt (A–C), basaltic andesite (D–F) and andesite (G–I). For better comparison to previous cumulate calculations, the recent solution models from Green and others (2016) are not included in these calculations, and density is calculated only for the solid assemblages. Due to likely slow kinetics, metamorphic reactions are not modeled below 600 °C, with density variation at low temperature only due to compressibility and thermal expansivity.

calculated restites are density unstable at pressures greater than ~9 kbar, regardless of temperature.

We next examine the effects of both crystal fractionation and partial melting by repeating the partial melting and restite density calculations starting with compositions from later steps in the Nandedkar and others (2014) fractional crystallization experiments. This emulates the hypothesized lower crustal processes in which mantle derived melts undergo limited crystallization-differentiation prior to freezing and being later partially melted (for example Hildreth and Moorbath, 1988; Annen and others, 2006). We find that as the protolith for the partial melting becomes more evolved, the restites become less dense. For a basaltic andesite (RN7 melt composition, ~53.5 wt. % SiO₂; figs. 10D–10F), the protolith is density stable at most crustal conditions, but the restites after 20 percent and 40 percent melt extraction are density unstable at lower crustal conditions. Only after we take an andesite as the protolith (RN9 melt composition, ~60 wt. % SiO₂; figs. 10G–10I), are restites after 20 percent melt extraction density stable at all crustal conditions, while the restite after 40 percent melt removal becomes only marginally density unstable at <12 kbar. Based on these

models, it appears that removal of dense lower crustal restites by viscous delamination is likely to be as effective a solution to the volume of restites produced by partial melting dominated processes as it was previously shown to be for the cumulates produced in fractional crystallization dominated regimes.

ARGUMENT 4: THE DISTRIBUTION OF IGNEOUS ROCK COMPOSITIONS: A DEARTH(?) OF INTERMEDIATE COMPOSITIONS

The predominance of felsic ($SiO_2 > 63$ wt. %) and mafic ($SiO_2 < 54$ wt. %) erupted lavas, with limited intermediate compositions, was first documented on Iceland (Bunsen, 1851) and later for the volcanic products of ocean islands (subsequently referred to as the Daly Gap, after Daly, 1925). Since these original observations, similar compositional gaps have been documented in arc lava whole rock and melt inclusion distributions (Brophy, 1991; Shukuno and others, 2006; Reubi and Blundy, 2009), globally for Archean-aged igneous rocks (Barker and Peterman, 1974; Barker and Arth, 1976; Kamber, 2015), and for the present distribution of igneous rocks in continental crust (Keller and others, 2015). However, in detail the distribution of compositions in both the modern and Archean crust differs from the original observations of volcanic rocks on ocean islands: the compositional gap in the crust is typically defined by the combination of smoothly varying unimodal distributions of dominantly mafic volcanic rocks and dominantly felsic intrusive rocks, which taken together define a bimodal distribution.

Although it does not appear that a true Daly gap exists at the arc or global scale, the observation of compositional gaps in single volcanic centers still appears robust, and a variety of additional mechanisms have been put forward to explain these observations. Early explanations for the production of this gap focused on fractional crystallization (Daly, 1925; Clague, 1978; Brophy, 1991), although some argued instead for partial melting (Chayes, 1963). Today, the role of partial melting is frequently emphasized, where the mafic peak is inferred to represent melts from the mantle (with variable, but limited differentiation) and these hot mafic melts are invoked as the heat source to produce low-degree, felsic partial melts of the pre-existing crust (Riley and others, 2001; Wiesmaier and others, 2012). This model is analogous to (and likely in part inspired by) the dominant models for TTG generation in the Archean that assume higher Archean temperatures create thermal regimes in the lower crust more favorable to partial melting (Fyfe, 1974; Rapp and others, 1991; Palin and others, 2016). In contrast, it is often presumed that fractional crystallization will produce a continuum of liquid compositions, starting with primitive mafic compositions and continuously evolving towards the SiO_2-rich end-member (for example Chayes, 1963).

In contrast to the assumption that fractional crystallization cannot produce bimodal distributions, many workers have observed that a non-linear temperature-melt fraction (F) relationship, where F rapidly decreases following the saturation of a new solid phase, will result in gaps in melt compositions and may account for the observed gap in intermediate compositions (for example Grove and Donnelly-Nolan, 1986; Reubi and Blundy, 2009). Recent fractional crystallization experiments indicate two temperature intervals marked by significant increases in the rate of crystallization (for example Nandedkar and others, 2014), which we will refer to as copious fractionation intervals (CFI). Taking the experiments of Nandedkar and others (2014) as an example (fig. 11), the first CFI occurs once the melt is multiply saturated in plagioclase, clinopyroxene, and amphibole (± spinel) between 1100 to 1000 °C. Here the crystallization rate increases by one order of magnitude from 0.1 liq%/ °C to >1 liq%/ °C and the total melt fraction decreases from >90 percent to ~40 percent over only ~100 °C. The cumulates produced during this interval are wehrlites, pyroxenites, and then hornblendite/hornblende gabbros, all with SiO_2 <50 weight percent. The removal of a significant volume of these low SiO_2 cumulates results in a significant
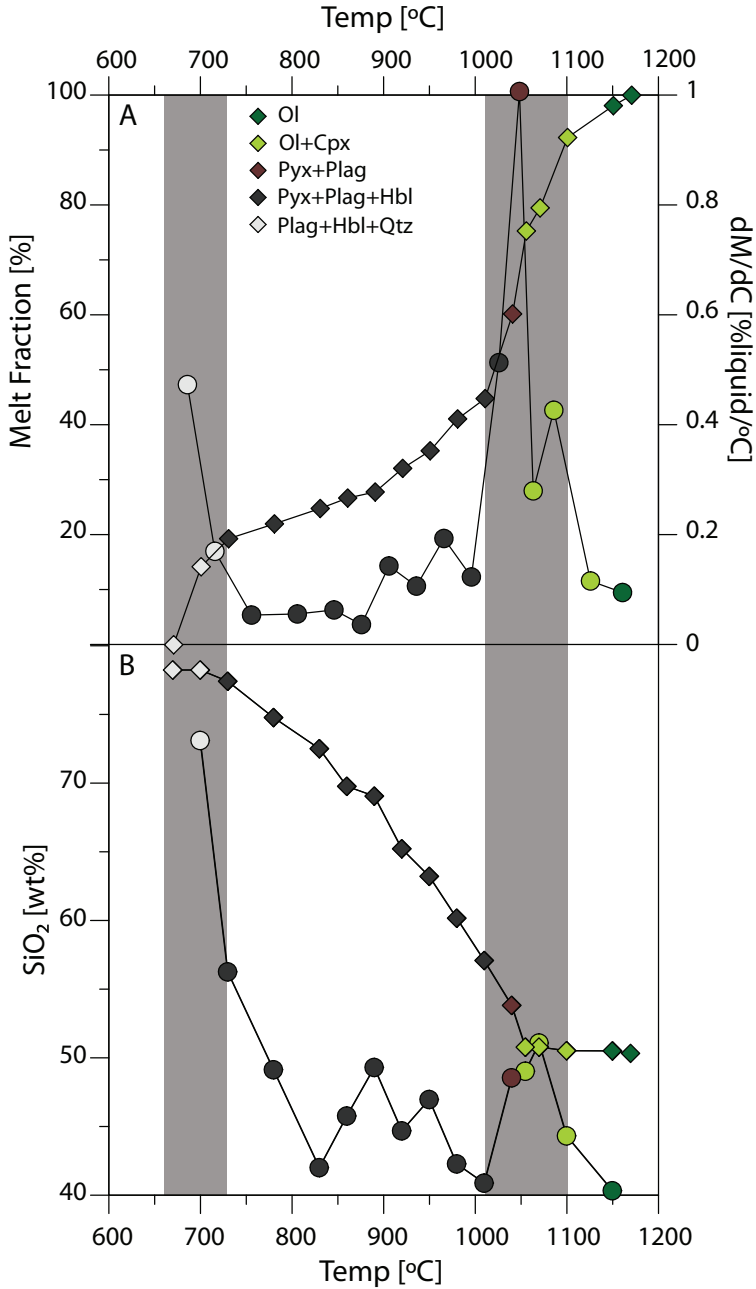
Fig. 11. Summary of results from Nandedkar and others (2014) fractional crystallization experiments. Symbol colors in both plots represent the stable solid phases for each experiment. (A) Melt fraction (in diamonds) and the temperature derivative of melt fraction (in circles) plotted as a function of temperature. (B) Change in melt (diamonds) and solid (circles) SiO₂ content. In both diagrams, the two CFIs are highlighted in gray.

increase in melt SiO_2 from ~50 weight percent to 60 weight percent in the experiments of Nandedkar and others (2014). The crystallization rate remains low over the following ~200 °C temperature interval, yielding fractionation rates <0.2 liq%/ °C and a melt fraction decrease of only ~20 percent. The second CFI occurs at or near the granitic eutectic. Once the melt reaches quartz saturation, the fractionation rate increases again by nearly an order of magnitude from ~0.05 to ~0.4 liq%/ °C until the remaining 20 percent of melt is crystallized.

To constrain the distribution of rock composition predicted by these relationships, we constructed a simple stochastic model. In the simulations, a volume of melt starts at the liquidus temperature and the system is subsequently allowed to cool linearly to the solidus in 1 °C steps. After each step, we calculate the predicted composition and mass of melts and solids. Additionally, we simulate melt extraction events incorporating the derived melt extraction probability as a function of F from a recent multi-phase numerical model (Dufek and Bachmann, 2010). This relationship predicts an extraction probability with increasing crystallinity that is maximal at F ~40 percent. This relationship was derived for a hindered settling/compaction type of melt extraction process, but a similar maximum probability would result from melt extraction via permeability barriers and periodic melt fracturing (Kelemen and Aharonov, 1998), and also roughly corresponds with the rigid percolation threshold (Vigneresse and others, 1996). If melt is extracted, the cumulate present at that step is removed from the system and added to the population of solids, and the system continues to cool with only the remaining melt. To account for trapped interstitial liquid observed in cumulates, at extraction events we retain a random volume of melt between 0 to 10 percent in the removed cumulates as retained melt. We calculate the distribution of both solids and melts from a total of 10,000 model runs weighted by the mass of each component present at each extraction event.

The model represents a cooling, differentiating magma in a highly simplified fashion: it doesn't account for latent heat of crystallization, or for the size or depth of the emplaced magma body (compare Melekhova and others, 2013), and the liquid line of descent can differ from that used here due to variations in pressure, H_2O content, fO_2, and starting composition, as well as for equilibrium vs. fractional crystallization processes. Despite these limitations, we suspect that the general behavior of the system is robust as long as the system is cooling monotonically and has a similar non-linear T-F relationship (which is observed for many differentiating magmas, for example Kelemen and Aharonov, 1998).

Results

The predicted SiO_2 distributions calculated for extracted melts from the model are shown in figure 12, with distributions from a number of natural settings for comparison. As expected, the results are dominated by the processes occurring in the two copious fractionation intervals at ~1000 to 1100 °C and 670 to 830 °C. Accordingly, the liquid compositions show a significant peak at ~50 to 55 weight percent SiO_2 and an extended tail and less pronounced second peak at ~78 weight percent SiO_2. The calculated cumulate distribution (not shown) exhibits significant peaks at low (~46–48 wt. % SiO_2) and at high silica content (78 wt.% SiO_2) with very limited intermediate compositions, with much greater volumes of mafic and ultramafic rocks than are observed in nature. As previously discussed, the fate of the substantial volumes of mafic to ultramafic cumulates expected to be produced during fractional crystallization (but also equivalently restites in partial melting) is an ongoing subject of research (for example Arndt and Goldstein, 1989; Kay and Mahlburg-Kay, 1991; Rudnick, 1995; Jagoutz and Behn, 2013).

Our modeled melt distribution closely resembles the distribution of extrusive rock compositions observed in both modern and paleo-Island Arcs (figs. 12A and 12B). In
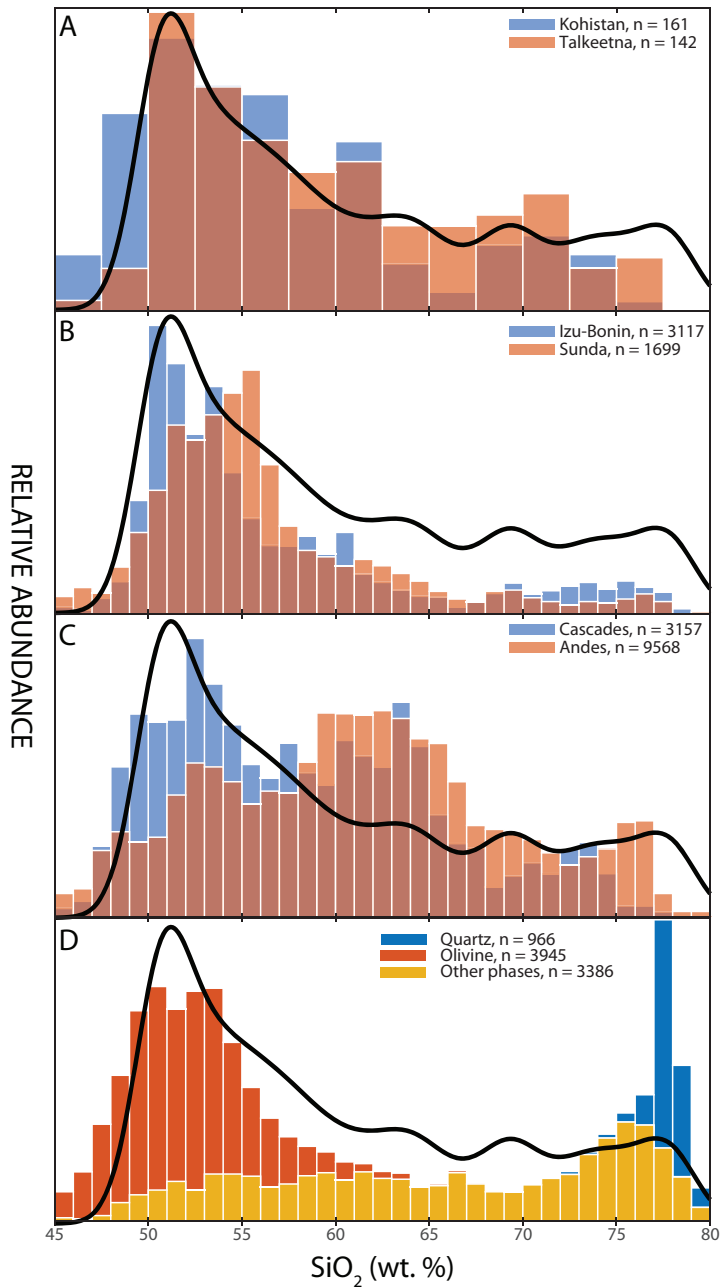
Fig. 12. Calculated stochastic model melt SiO₂ kernel density estimates compared to histograms for natural systems. (A) Kohistan and Talkeetna Paleo-island arcs. Kohistan data from Jagoutz and Schmidt (2012), Talkeetna data from Jagoutz and Kelemen (2015). (B,C,D) Modern island arcs, Modern continental arcs and arc melt inclusions. All data downloaded from precompiled datasets on Georoc (http://georoc.mpch-mainz.gwdg.de/georoc/).

both the paleo-Island Arcs and the modern systems, a large peak is observed in basalt to basaltic andesite compositions, with a pronounced long tail of higher SiO_2 compositions. Our modeled high SiO_2 compositions are slightly more silicic and slightly more abundant than is observed in these systems which may result from the difficulty to determine the low temperature eutectic melt composition experimentally (Nandedkar and others, 2014). Additionally, our modeled distribution only tracks extracted melts but allows all remaining melts to continue to evolve to felsic end-products rather than quench on eruption events, which would further decrease the volume of predicted silicic compositions. There appears to be more variability in the distribution of continental arcs (fig. 12C), with more abundant intermediate compositions than observed in island arcs or predicted in our model. It is possible that this variability results from greater interaction with the overriding plate or perhaps from more abundant high-Mg andesite primitive melts. Finally, the modeled distribution does not closely resemble the distribution of melts observed in arc-derived melt inclusions (fig. 12D). Although this distribution is undoubtedly biased by the abundance of olivine and quartz hosted melt inclusions, melt inclusions hosted in other phases that are in equilibrium with a wider range of melt compositions (namely plagioclase and pyroxene) still result in a distribution unlike the modeled one. Although there certainly are additional processes that effect the distribution of erupted melt compositions, the fact that the distribution of arc volcanic rocks is similar to our modeled distribution indicates that the slight bimodality observed at the arc-scale can be explained by the fractional crystallization processes governed by non-linear relationships between melt fraction and temperature and SiO_2 content with coupled melt fraction dependent extraction probabilities.

Discussion

Using the model outputs from each run (composition including water content, temperature and melt crystallinity), we can additionally calculate the viscosity of both the melt and the magma (including the evolving crystal content), using the viscosity calculators in Giordano and others (2008), and Caricchi and others (2007), respectively (fig. 13). The calculated melt viscosity is the lower bound of the magma viscosity, and increases by two orders of magnitude as the melt cools. This results from the melt cooling and differentiation with the lower temperature and more evolved compositions causing the viscosity to increase and to dominate over the effect of increasing water content, which decreases viscosity. In contrast, the magma (melt + crystals) viscosity varies in each simulation primarily as a function of crystallinity. As crystal content increases, the magma viscosity increases to as much as 4 to 8 orders of magnitude higher than the minimum melt viscosity at the corresponding temperature (fig. 13B). Once an extraction event occurs and the melt is extracted from the solids, the magma viscosity drops again and equals the melt viscosity. At high temperature the calculated magma viscosity is rather constant and very few extraction events occur in the low crystallinity magma. However, at the first CFI between ~970 and 1070 °C, the magma viscosity of the majority of model runs increases sharply by as much as four orders of magnitude until the first extraction event occurs. Typical model runs predict between two and four extraction events, and overall the distribution of predicted magma viscosities continually broadens as the system cools, resulting from the variable melt extraction temperatures.

Implications

Although our model makes no assumptions as to the specific mechanism of magma emplacement or melt extraction, the sharp increase in viscosity associated with
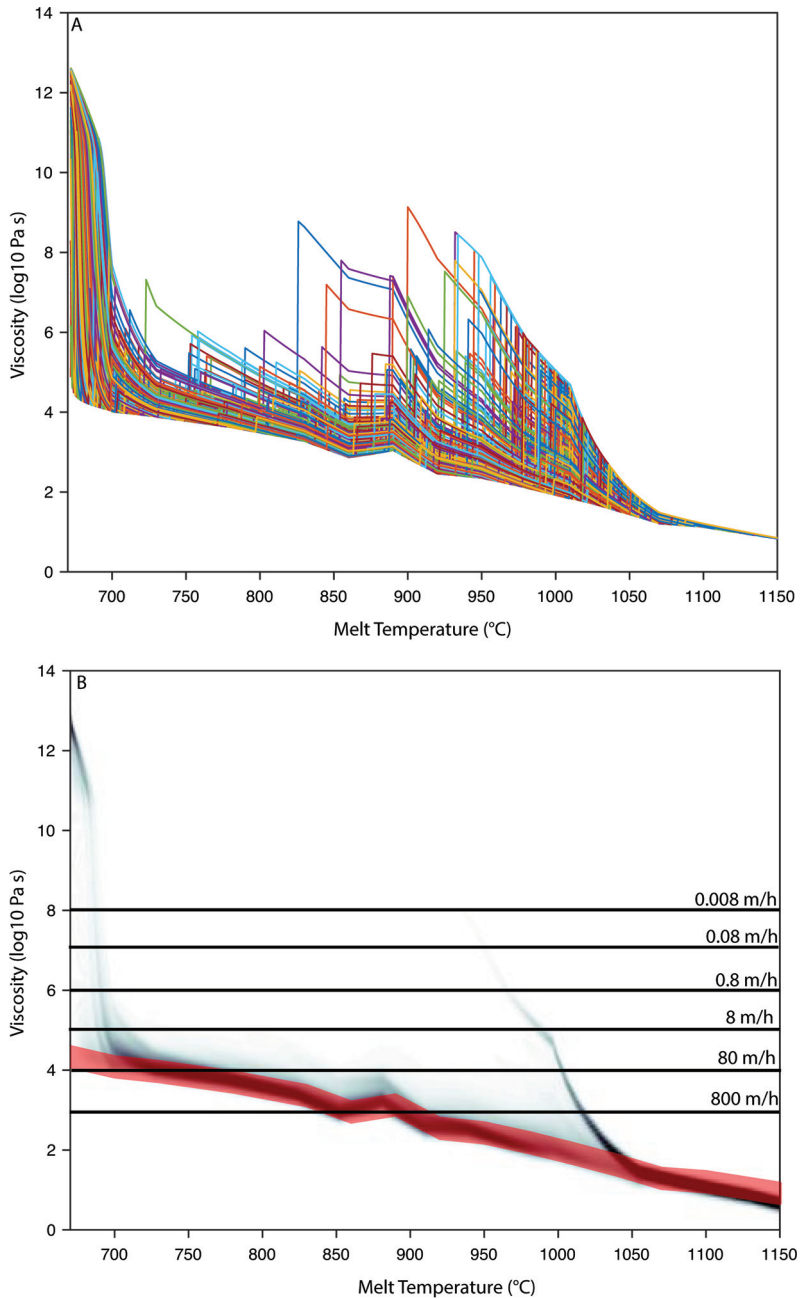
Fig. 13. Melt and magma viscosities calculated using viscosity calculators in Giordano and others (2008) and Caricchi and others (2007), respectively. Results shown for 500 randomly generated individual simulations (A) and 2-d kernel density estimates for the relative probability from all simulations (B). Although there is significant variability between individual simulations, there are clear significant overall increases in magma viscosity at the CFIs.

the two CFIs would reduce magma transport velocity by the same order of magnitude as the viscosity increases (fig. 13B; Annen and others, 2006), resulting in ascent velocity decreases of up to 4 to 8 orders of magnitude. We consider it likely that these reduced magma transport rates enable melt stagnation events.

Our results suggest that there are distinct behaviors likely during melt stagnation at the two CFIs. Given arc geotherms and the possible compositions of primitive arc melts, it is likely that the high temperature CFI occurs deeper in the crust whereas the low temperature CFI should occur dominantly at shallower depth. At the first CFI the system still has 60 to 40 percent total melt mass which is still at elevated temperatures and of relatively SiO_2 poor compositions, resulting in low melt viscosities of 2 to 3 $\log_{10}$ Pa s, and hence a high probability for melt to be extracted from the magma mush. Because this first extraction is likely to be relatively efficient, the rocks produced in this interval will dominantly be cumulates. In contrast, at the low temperature second CFI, melts viscosities are higher (4–5 $\log_{10}$ Pa s), the system approaches the granite eutectic and is near its thermal death. As a result, significant melt extraction is hindered and rocks formed in this interval approach liquid compositions.

Our simple model can explain some first order observation made in exposed arc section and active arcs. In exposed arc sections such as Kohistan and Talkeetna, the lower crust is dominated by plutonic rocks that have chemical and textural characteristics indicating that they are cumulates (fig. 14). In contrast, the upper crustal plutonic rocks are dominantly granitoids that show little evidence for significant crystal accumulation and these rocks often approach liquid compositions. As a result we propose that the compositional stratification observed in arc and continental crust is fundamentally controlled by the relationship between melt fraction and temperature.

Our model of melt transport and stagnation in the lower crust is very similar to the one proposed by Kelemen and Aharonov (1998) for construction of oceanic crust. Kelemen and Aharonov (1998) proposed that the transition from horizontal sills to vertical dikes relates to the buildup of permeability barriers due to CFIs occurring at multiple mineral saturation intervals. In their model, melt extraction from these sills occurs once magma overpressure exceeds a critical pressure necessary to produce new fractures. Melt extracted from these sills is transported in vertical dikes and either erupts on the surface or contributes to the sheeted dike complex typical of fast spreading oceanic crust. Intriguingly, structural observations of many arc sections suggest a similar process may control magma emplacement. In Kohistan (Jagoutz and others, 2013) and in the Sierra Nevada (Saleeby, 1990; Saleeby and others, 2003) the lower crust is characterized by originally horizontal sills that are cumulates (similar to the layered gabbro of the Oman ophiolite), followed by an intermediate zone of cumulates and melt sills (similar to the isotropic gabbro in Oman). In contrast, the upper crustal granitoids generally have vertical contact relationships with surrounding units (Jagoutz and others, 2013) and in a crude sense reflect the sheeted dike complex of the Oman ophilites. The similarity between the oceanic and the arc crust is restricted to the structural build up and the separation of cumulate- and liquid-dominated plutonic rocks in the lower and upper crust respectively; naturally the chemical composition of the rocks in oceanic and arc crust are very different due to differences in initial melt composition, water content, differentiation pressure, fO_2 *et cetera.*

Our results highlight the potential for fractional crystallization, combined with variable melt extractability to cause bimodal distributions of volcanic rocks. The steep increases in crystallinity first between 1100 to 1000 °C, and extending from 800 °C to the solidus, create two intervals where magma viscosity reaches local maxima and where melt extraction becomes most likely over relatively restricted compositional ranges. Between these two intervals, crystallinity and magma viscosity increase relatively
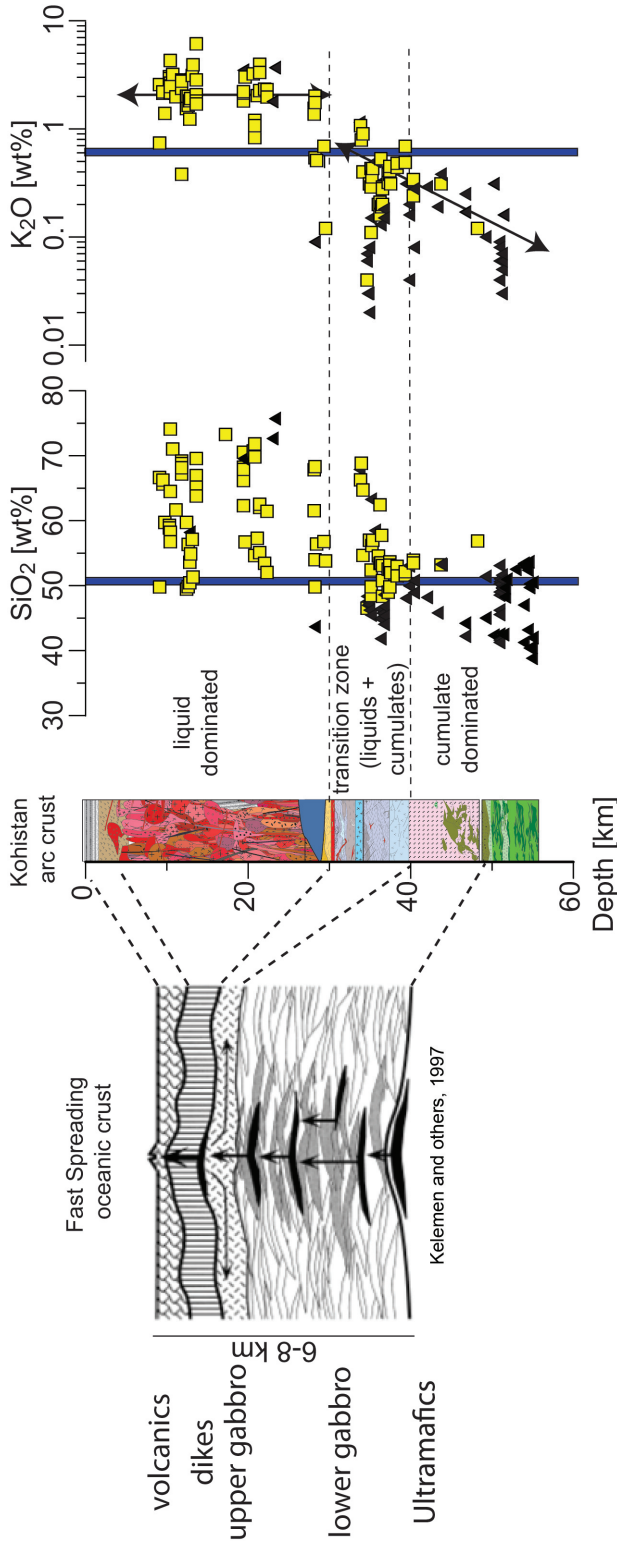
Fig. 14. Comparison of idealized crustal cross sections for fast spreading oceanic crust (Kelemen and Aharonov, 1998) and Kohistan paleo-Island arc (Jagoutz and Schmidt, 2012). In both sections, cumulate rich sills dominate the lower crust, while dikes dominate the upper crust. The contrast between cumulate rich lower crust and liquid-dominated upper crust is also observable in the chemical stratification of the Kohistan arc section, as shown here for SiO₂ and K₂O content as a function of depth. Symbols as in figure 4.

little, and the melts that are extracted span a wide compositional range. Finally, if we imagine that our model starts in the lower crust, and that each magma extraction event is associated with upward magma transport (as would be expected, for example, for permeability barriers), the model can also account for the gravitationally and compositionally stratified structure of the continental crust.

<div align="center">CONCLUSION</div>

In this contribution we examine four of the most commonly cited arguments against a crystallization-differentiation dominated genesis of arc granitoids. Although at other settings there are undoubtedly granitioids produced dominantly by partial melting (S-Types), we find that each of these arguments is equally permissive of fractional crystallization and partial melting, summarized as follows:

1) Field observations – migmatite-like textural observations are often taken as clear evidence for partial melting in orthogneisses. However, as these rocks clearly have igneous protoliths, care must be taken to convincingly exclude generation of these textures by deformation during initial cooling and crystallization before a partial melting origin is required.

2) Evolved Isotopic Compositions – Many I-type granites are characterized by isotopic values distinct from purely mantle-derived values. However, many primitive arc lavas are also characterized by evolved compositions, suggesting that much of "crustal" contribution to I-type batholiths may be slab derived and does not necessitate the extent of upper plate crustal contributions that would be calculated without the initial variability.

3) The cumulate/restite volume problem – It has long been observed that fractional crystallization should produce 4 to 5 times more mafic/ultramafic cumulates than felsic products. However, we've shown that partial melting is at least as inefficient a process. Delamination may provide a solution to this problem in either system.

4) Bimodal compositional distributions – We observe that most arc systems are characterized by only modest compositional gaps, and that these types of distributions can be generated by fractional crystallization, if the non-linear relationship between melt fraction, temperature and composition are accounted for.

In addition to these observations, we present a simple model for fractional crystallization in arc crust that produces SiO_2 contents consistent with observed distributions, and also accounts for the observed structural and compositional variability between upper and lower arc crust. Given these observations, we suggest that fractional crystallization is likely to be the dominant process in the formation of granitoids and of arc crust as a whole, with partial melting and or assimilation a necessary but secondary contributor.

<div align="center">APPENDIX</div>

Additional References for compiled data:

Figure 4

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