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On the development of the calc-alkaline and tholeiitic magma series: A deep crustal cumulate perspective

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A B S T R A C T

Two distinct igneous differentiation trends – the tholeiitic and calc-alkaline – give rise to Earth's oceanic and continental crust, respectively. Mantle melting at mid-ocean ridges produces dry magmas that differentiate at low-pressure conditions, resulting in early plagioclase saturation, late oxide precipitation, and Fe-enrichment in mid-ocean ridge basalts (MORBs). In contrast, magmas formed above subduction zones are Fe-depleted, have elevated water contents and are more oxidized relative to MORBs. It is widely thought that subduction of hydrothermally altered, oxidized oceanic crust at convergent margins oxidizes the mantle source of arc magmas, resulting in erupted lavas that inherit this oxidized signature. Yet, because our understanding of the calc-alkaline and tholeiitic trends largely comes from studies of erupted melts, the signals from shallow crustal contamination by potentially oxidized, Si-rich, Fe-poor materials, which may also generate calc-alkaline rocks, are obscured. Here, we use deep crustal cumulates to "see through" the effects of shallow crustal processes. We find that the tholeiitic and calc-alkaline trends are indeed reflected in Fe-poor mid-ocean ridge cumulates and Fe-rich arc cumulates, respectively. A key finding is that with increasing crustal thickness, arc cumulates become more Fe-enriched. We propose that the thickness of the overlying crustal column modulates the melting degree of the mantle wedge (lower F beneath thick arcs and vice versa) and thus water and Fe^{3+} contents in primary melts, which subsequently controls the onset and extent of oxide fractionation. Deep crustal cumulates beneath thick, mature continental arcs are the most Fe-enriched, and therefore may be the "missing" Fe-rich reservoir required to balance the Fe-depleted upper continental crust.

1. Introduction

The calc-alkaline and tholeiitic magma series are the two most important igneous differentiation trends on Earth and are broadly expressed by the crustal dichotomy of andesitic continental crust and basaltic oceanic crust (MORB), respectively. Whereas tholeiitic magmas may occur in all tectonic settings, calc-alkaline magmas appear to be uniquely associated with the convergent margin setting (Miyashiro, 1974; Zimmer et al., 2010). Convergent margin (arc) magmatism is thought to be a key process by which continental crust is formed (Taylor, 1977). Thus, understanding the processes that govern the calc-alkaline magma series is of importance to understanding the origin and evolution of continental crust.

The behavior of Fe defines the calc-alkaline and tholeiitic trends. This is illustrated in the classic AFM (alkali–FeO_T–MgO) plot (Fig. 1). Magmas evolving along the calc-alkaline trend evolve towards Fe-depletion, whereas magmas evolving along the tholeiitic trend become Fe-enriched. It has also long been recognized that calc-alkaline lavas, when they erupt, tend to be more oxidized than MORB (Christie et al., 1986; Richards, 2015), but the reasons for this are unclear.

Controversy surrounds a fundamental issue: whether the calc-alkaline signature originates from the mantle source (Carmichael, 1991) or whether magmatic fractionation (Bowen, 1928) or contamination and mixing with Si-rich, Fe-poor crustal materials (Grove et al., 1982) could also generate Fe-depleted calc-alkaline magmas. Current prevailing hypotheses favor the source as the culprit. One popular view is that, unlike the dry and low fO_2 MORB mantle, calc-alkaline magmas result from elevated water content and fO_2 inherited from a mantle wedge hydrated and oxidized by slab-derived material (Brounce et al., 2014; Eggins, 1993; Evans et al., 2012; Kelley and Cottrell, 2009; Parkinson and Arculus, 1999). Other hypotheses implicating a source origin for

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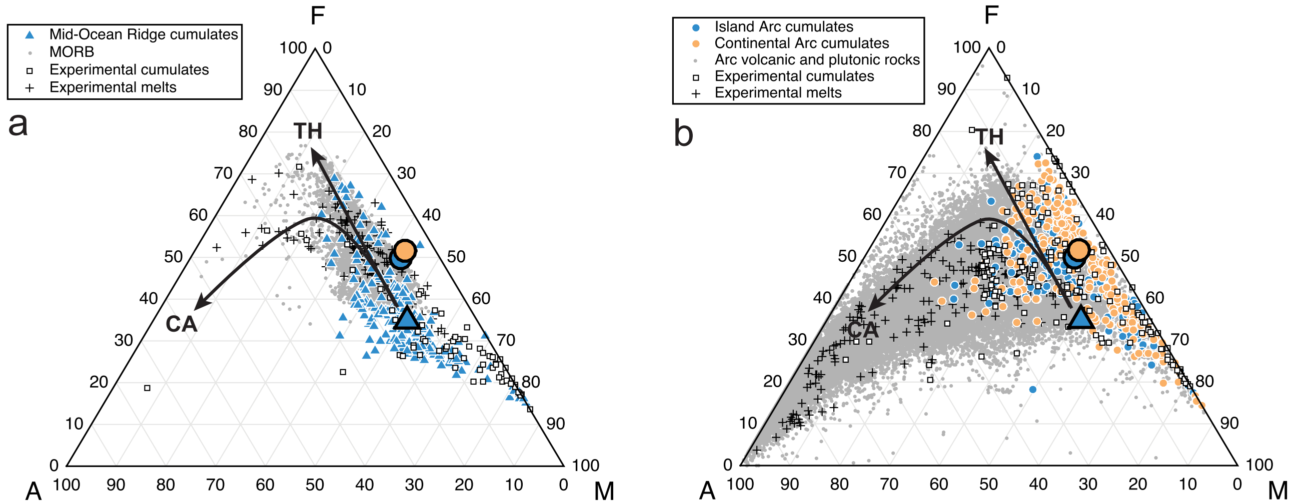

Fig. 1. AFM (A = Na_2O+K_2O, F = FeO_T, and M = MgO) diagrams showing oceanic vs. arc cumulates. For clarity, data are plotted based on provenance: blue triangles and circles = mid-ocean ridges and island arcs, respectively; orange circles = continental arc (full data references available in Supplementary Information). Arrows are schematic and show calc-alkaline (CA) vs. tholeiitic trends (TH). Large symbols represent median values. (a) AFM diagram showing mid-ocean ridge cumulates (blue triangles), MORBs (from Gale et al., 2013), and experimental cumulates and melts (full data references available in Supplementary Information). (b) AFM diagram showing arc cumulates (blue circles = island arcs; orange circles = continental arcs), arc volcanic and plutonic rocks from GEOROC database, and experimental cumulates and melts (see Supplementary Information for references). For simplicity, experimental cumulates and corresponding experimental melts are shown as open squares and crosses, respectively (experiments, sorted by individual studies, are plotted with unique symbols in Supplementary Figs. 1, 2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

calc-alkaline magmas involve a mantle wedge that has experienced significant melt-rock reaction to explain the genesis of high Mg# arc andesites (Kelemen, 1990). More recently, variation of mantle wedge oxidation state with potential temperature (Gaetani, 2016) or variation in the wedge melting regime itself (Plank and Langmuir, 1988; Turner and Langmuir, 2015) have also been proposed.

On the other hand, a number of studies are at odds with the popular view of a uniquely oxidized arc mantle source for calc-alkaline magmas. For example, studies of arc lavas using redox-sensitive element ratios (Lee et al., 2010) and Fe isotopes (Dauphas et al., 2009) show that the oxidation state of the arc lavas' source is identical to that of MORB, and thus the oxidized nature of arc lavas may arise instead from differentiation and/or mixing processes that occur in the lithosphere and/or crust. Melt oxidation has also been attributed to shallow-level degassing of H_2O (Humphreys et al., 2015); however other studies argue that degassing has no effect on melt oxidation (Crabtree and Lange, 2012; Waters and Lange, 2016). Tectonic controls may also be important. Two recent studies of global arc magmas observed a positive correlation between crustal thickness and degree of Fe depletion in arc magmas (Chiaradia, 2014; Farner and Lee, 2017), suggesting that intracrustal processing of magmas or, arc crustal thickness itself, may also control primary magma water content and fO_2 and therefore promote the generation of calc-alkaline rocks.

A common thread in the vast majority of studies concerning arc redox conditions, and more broadly, genesis of the calc-alkaline versus tholeiitic suites, is that the melts/liquid perspective has been the dominant focus. However, there are several factors that potentially complicate reliance on melt evolution paths alone. The most obvious one is that all erupted lavas, including primitive MORBs, experience some extent of crystal fractionation during ascent to the surface (O'Hara, 1968). Transport of magmas through pre-existing thick crust, as found in mature continental arcs such as the Andes (Hora et al., 2009; Leeman, 1983), further increases the likelihood of crustal contamination and assimilation (Annen et al., 2006; Dufek and Bergantz, 2005; Hildreth and Moorbath, 1988). Thus, the combined processes of crystal fractionation and/or contamination/assimilation may obscure primary signals from the mantle wedge source of arc magmas. Recently, studies on primitive olivine-hosted melt inclusions (Kelley and Cottrell, 2012; Plank et al., 2013) aim to circumvent some of these issues, but melt inclusions may also suffer from diffusive re-equilibration and thus do not necessarily reflect the fO_2 or H_2O conditions of their origin (Gaetani et al., 2012; Hartley et al., 2017). Lastly, owing to the large variance of silicate liquids due to their absence of stoichiometry and high compressibilities, thermobarometry on silicate/liquid systems is more challenging compared to thermobarometry using subsolidus mineral equilibria (Putirka, 2008). As such, it is difficult to pin down precisely the depth within the crustal column a magma may first become calc-alkaline, because such magmas will have likely re-equilibrated to shallower conditions prior to eruption.

Here, we "see through" shallow crustal processes by examining deep crustal cumulates – the crystalline solids fractionated from differentiating magmas (Irvine, 1982). Deep crustal cumulates, while not as abundant and well-exposed as lavas or shallow intrusive rocks, are nevertheless sampled as exhumed terranes and xenoliths or by cores and dredges in arcs and ocean ridge settings, respectively. Despite numerous studies of cumulates from arcs and mid-ocean ridges, there is a lack of synoptic studies of the role of cumulates in crust formation. Thus, the goals of this paper are twofold: 1) to present a comprehensive survey of global mid-ocean ridge and arc cumulates and 2) to use these cumulates, together with published experimental data and simple petrologic models, to better understand the development of calc-alkaline and tholeiitic magma trends. Although we systematically surveyed a wide compositional range of cumulates (Mg# 40–90), we emphasize high Mg# cumulates (Mg# > 75), as such cumulates are closest in equilibrium with primary mantle-derived melts and therefore less susceptible to shallow crustal processes. Our approach provides an intuitive, yet less well-recognized, complementary "crystal" view to the melt perspective on the long-standing debate over the origins of tholeiitic and calc-alkaline magmas.

2. Geologic background

2.1. Oceanic magmas and cumulates

Fractional crystallization at low pressures and anhydrous conditions and evolution toward Fe-enrichment characteristic of the