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Arc crustal differentiation mechanisms

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ABSTRACT

The detailed vertical compositional and thermal structure of the entire Kohistan arc section is constructed using ~63 P/T constraints and 209 plutonic whole rock analyses. The aim is to better understand the nature of the chemical differentiation in the plutonic arc crust at different crustal levels.

Results indicate that a distinct difference in character exists between the upper and lower plutonic arc crust. Plutonic rocks in the lower crust (⩾25–30 km) have whole-rock chemical characteristics that indicate mineral accumulation and residual melt loss. In these cumulate rocks there is a systematic chemical stratification of decreasing incompatible trace elements with depth (e.g. Rb, K_2O). In contrast, the plutonic rocks of the upper crust represent mainly frozen liquids and show no systematic relationship between chemical composition and intrusion depth. These results clearly indicate that magmatic differentiation in the Kohistan arc dominantly occurred in the deeper arc crust (⩾30 km) consistent with the lower crustal 'hot zone model'. To understand the role of density barriers for melt stagnation in the crust, and thereby for the observed chemical stratification, the detailed density structure of the plutonic arc crust is compared to melt densities calculated for plutonic rocks with near liquid compositions. Results indicate that melts are consistently less dense than rocks, and there is no evidence for a "neutral buoyancy line" controlling melt emplacement. It is speculated that melt stagnation in the lower arc crust and subsequent chemical differentiation of a felsic upper and mafic lower continental crust is dominantly controlled by temperature and to a lesser extent to density or rheological barriers.

1. Introduction

The continental crust is thought to be chemically stratified into a felsic upper crust and mafic lower crust (Rudnick and Gao, 2003) based on the observed increase of the seismic velocity of the continental crust with depth (Christensen and Mooney, 1995). The chemical stratification of the crust results in a density stratification that is thought to play a crucial role for melt stagnation and differentiation either at (1) shallow crustal levels (Ryan, 1987), (2) at mid-crustal level (Glazner and Ussler III, 1988) or (3) at the crust–mantle interface (Herzberg et al., 1983).

Chemical differentiation within the continental crust occurs over a wide range of time scales and different geodynamic settings. Based on trace element systematics it is widely accepted that new (post-Archean?) continental crust (or proto-continental crust) is formed in subduction zones (Rudnick, 1995). So an important question is if the observed chemical stratification is predominantly formed during arc processes, or whether secondary processes, such as arc–continent collision, are required?

To understand the importance of chemical differentiation in arcs it is essential to constrain the effect of magmatic differentiation at different crustal levels. For years it was thought that chemical differentiation occurs predominantly in the shallow arc crust (Bateman and Chapell, 1979; Glazner, 1994; Halliday et al., 1989). Support for shallow crustal differentiation comes from geophysical evidence of sizeable melt reservoirs (e.g. magma chambers) in the upper crust (~<20 km), as well as geochemical estimates from arc magmas that generally indicate pre-eruptive storage depths of <15 km (Blundy and Cashman, 2008). Magnetotelluric and seismological observations, as well as the presence of large calderas, also indicate that large-scale magma chambers must be present in the upper crust (e.g., Jellinek and DePaolo, 2003; Schilling and Partzsch, 2001; Zandt et al., 2003). Rheological and density considerations have suggested the presence of major barriers for melts in mid- to upper-crustal levels, leading to preferential trapping of melt in this part of the crust (e.g., Glazner and Ussler III, 1988).

Experiments have shown that the observed intermediate metaluminous ASI < 1; ASI = molar $(Al_2O_3/CaO + Na_2O + K_2O)$ composition of the upper crust can be formed by hydrous, shallow-level fractionation at 2–3 kbar (Blatter et al., 2013; Grove et al., 2003; Sisson and Grove, 1993). The low ASI content of the basaltic to andesitic melts is due to early saturation of plagioclase at shallow pressures, which inhibits further Al-enrichment of the derivative liquid during differentiation. One fundamental problem with the shallow crustal differentiation model is the paucity of

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mafic–ultramafic cumulates in the upper crust that would be necessary to balance the observed granites to a mafic parental melt. As a solution to this apparent paradox, it has been proposed that dense mafic to ultramafic cumulates or restites might sink down into the lower crust as so-called ‘reverse diapirs’ (Glazner, 1994).

As an alternative to this model, Annen et al. (2006) proposed that magmatic differentiation in arcs dominantly occurs in the lower arc crust in so-called ‘deep crustal hot zones’, essentially an extension of the MASH model of Hildreth and Moorbath (1988). This model is attractive as it can explain the general lack of mafic to ultramafic cumulates in the crust by foundering of the lower arc crust directly back into the upper mantle without requiring them to sink through the highly viscous continental crust (Arndt and Goldstein, 1989; Behn et al., 2007; Herzberg et al., 1983; Jagoutz and Behn, 2013; Jagoutz et al., 2011; Jagoutz and Schmidt, 2013; Jull and Kelemen, 2001; Kay and Mahlburg Kay, 1993).

At high pressure and elevated water content amphibole and garnet can become important early fractionating phases (Alonso-Perez et al., 2009; Grove et al., 2003; Müntener et al., 2001; Prouteau and Scaillet, 2003), leading to significant silica-enrichment of the derivative liquids over a limited fractionation interval. However, at high P ($>\sim$5–7 kbar) and/or high a_{H_2O}, plagioclase generally fractionates after clinopyroxene and amphibole in basaltic to basaltic–andesitic compositions and will generally produce peraluminous derivative liquids (ASI > 1, Blatter et al., 2013), not metaluminous as is observed. While, the effect of late crystallization of plagioclase at high pressure may be offset by the increased incorporation of Al_2O_3 into pyroxene with increasing pressure (Müntener et al., 2001), these experiments nevertheless imply that derivative liquids from deep level crustal differentiation can become peraluminous, conflicting with the scarcity of peraluminous intermediate compositions observed in arcs (Blatter et al., 2013).

It is noteworthy that these high pressure experimental studies were conducted on primitive melts with high Al-content ($\sim$17 wt%) as are found in the Cascades Arc (e.g., Mt. Shasta). The primitive melts from the Cascades, however, have significantly higher Al-content (15–17 wt%) compared to primitive arc melts from most other subduction zones globally that are as low as 12–13 wt% Al_2O_3 (Jagoutz and Schmidt, 2013). If deep crustal differentiation is the predominant process to create the granitic compositions of the upper crust, then parental melts must be either relatively Al-poor (as is more globally observed), or additional Al-rich phases such as garnet or spinel must be important early fractionating phases to explain the overall low-Al content of the upper crust.

The problem in testing the deep fractionation hypothesis is that exposed lower crustal sections are rare in general, and those that exist often have a complicated and protracted geological history (e.g., Harley, 1989). Additionally, very few lower crustal sections have a complementary upper crustal section making it difficult to correlate and integrate processes occurring at different crustal levels. The Kohistan arc is the only known intact, full arc section preserved in the geological record (Tahirkheli, 1979) and is representative of juvenile continental crust formed in arcs (Jagoutz and Schmidt, 2012). Reworking of the arc crust due to later India–Eurasia collision is minor (Bouilhol et al., 2013). Therefore, the Kohistan arc provides an ideal testing ground for these two conflicting end-member models of magma differentiation in arcs.

The aim of this publication is to constrain, for the first time, the detailed chemical stratification of a complete arc section by integrating the chemical variation observed at different crustal levels. This approach necessitates a statistically significant dataset of whole rock compositions for each of which the original emplacement level should be known. Constraining the emplacement depth of plutonic rocks is often difficult due to the lack of appropriate mineral assemblage for reliable pressure estimates; however, as will be outlined in detail below, the Kohistan arc exposes a continuous crustal arc section in which major discontinuities in exposure level are absent, and thus geostatistical methods are used to interpolate the detailed exposure surface of the entire Kohistan arc from the existing 67 published reliable pressure constraints. The results of these calculations are used to approximate the intrusion depth of 209 arc-related whole rock samples, the detailed chemical stratification of the arc is discussed in terms of a statistically significant set of whole rock compositions. MELTS and PerpleX calculations are used to constrain density of rocks and melts in respect to the preserved P–T gradient. The results clearly indicate that chemical differentiation occurred predominantly in the deep arc crust during the build up of the arc. The results presented here strongly support the idea of a deep crustal ‘hot zone’ (e.g. Annen et al., 2006).

2. Geologic setting

The Kohistan arc, exposed in NE Pakistan, is the best-preserved complete arc section (Bard, 1983; Tahirkheli, 1979) in the geological record, with volcanic rocks and unmetamophosed sediments overlying a predominantly felsic plutonic upper crust in the northern exposures (Fig. 1). To the south, mafic and ultramafic plutons characterize the lower crust at the base of the arc section. The Cretaceous to Tertiary oceanic arc formed in the equatorial part of the Neotethyan ocean (Khan et al., 2009; Zaman and Torii, 1999). It is composed of three main complexes from north to south (Fig. 1): (1) the Gilgit Complex, comprising the mid- to upper-level of the arc, including the Kohistan Batholith composed of variable granitoids and its volcano-sedimentary cover sequences (Jagoutz et al., 2013; Khan et al., 2009; Petterson and Treloar, 2004; Petterson and Windley, 1985, 1991); (2) the Chilas Complex mafic–ultramafic, rift related mid- to lower-crustal intrusions (Jagoutz et al., 2006, 2007; Khan et al., 1989, 1993); (3) and the Southern Plutonic Complex (SPC), a heterogeneous sequence dominated by ultramafic to mafic plutonics, constituting the deepest exposed arc crust (Burg et al., 2005, 2006; Dhuime et al., 2007, 2009; Garrido et al., 2006; Jagoutz et al., 2011). U–Pb zircon age dating indicates that the dominant magmatic activity recorded in the SPC ($\sim$105–85 Ma) ended with the intrusion of the Chilas Complex at $\sim$85 Ma (Schaltegger et al., 2002). In contrast, the magmatic activity recorded in the Kohistan Batholith ranges from at least the Cretaceous ($\sim$110 Ma) to the Miocene (Bouilhol et al., 2013).

The Kohistan Arc is separated in the north from the former southern Eurasian margin (the Karakoram) by the Shyok suture zone (or “the Northern-”, or “Karakoram–Kohistan suture zone”) and in the south is separated from India by the Indus suture zone (Fig. 1). The collision of the arc with India is well constrained at $\sim$50 Ma (Rowley, 1996). While the formation age of the Shyok suture zone has been discussed for decades (e.g., Bard, 1983; Brookfield and Reynolds, 1981; Petterson and Windley, 1985), it was recently shown to postdate the formation of the Indus suture by $\sim$10 Ma (Bouilhol et al., 2013). This indicates that the Kohistan arc, until its collision with India at $\sim$50 Ma, formed as an intra-oceanic arc (Burg, 2011).

Accordingly, with the exception of the post-collisional leucogranites (see below), the igneous rocks of the Kohistan arc formed entirely in an oceanic island arc environment (Bouilhol et al., 2013).

2.1. Estimates on the emplacement pressure recorded in the Kohistan arc

Emplacement pressures of various plutons throughout Kohistan arc have been determined quantitatively (Fig. 1) using existing