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Geodynamics of rapid voluminous felsic magmatism through time

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ABSTRACT

Two end member geodynamic settings produce the observed examples of rapid voluminous felsic (rhyolitic) magmatism through time. The first is driven by mantle plume head arrival underneath a continent and has operated in an identifiable and regular manner since at least 2.45 Ga. This style produces high temperature (≤1100 °C), low aspect ratio rheoignimbrites and lavas that exhibit high SiO_2/Al_2O_3 ratios, high K_2O/Na_2O ratios, and where available data exists, high Ga/Al_2O_3 ratios (>1.5) with high F (in thousands of parts per million) and low water content. F concentration is significant as it depolymerizes the silicate melt, influencing the magmas' physical behavior during development and emplacement. These rhyolites are erupted as part of rapidly emplaced (10–15 Myr) mafic LIPs and are formed primarily by efficient assimilation-fractional crystallization processes from a mafic mantle parent. The second is driven by lithospheric extension during continental rifting or back arc evolution and is exclusive to the Phanerozoic. SLIPs (silicic large igneous provinces) develop over periods <40 Myr and manifest in elongate zones of magmatism that extend up to 2500 km, contrasting with the mafic LIP style. Some of the voluminous felsic magmas within SLIPs appear to have a very similar geochemistry and petrogenesis to that of the rhyolites within mafic LIPs. Other voluminous felsic magmas within SLIPs are sourced from hydrous lower crust, and contrast with those sourced from the mantle. They exhibit lower temperatures (<900 °C), explosive ignimbrites with lower SiO_2/Al_2O_3 ratios, and lower K_2O/Na_2O ratios. Rapid voluminous felsic magmatism represents both extreme examples of continental growth since the Archean, and also dramatic periods of crustal recycling and maturation during the Phanerozoic.

1. Introduction

The enrichment of lithophile elements in the earth's continental crust is the result of a combination of processes that lead to silica enrichment, driven primarily by the generation of silicate melts (e.g. Rudnick, 1995).The generation of silicate melts provides a significant control on secular change in the Earth because they provide a first order control on the relatively low density of continental crust. Therefore magmatism, and principally the generation of silicic magmas, is a major contributor to the continental crust's resistance to re-homogenization and recycling through subduction. Additionally, highly siliceous mineral phases are more stable than ferromagnesian phases under surface conditions, and therefore exhibit higher attrition rates which contribute to the maturation of the continental crust. The source, scale and timeframes of silicic melt production can therefore be used as a proxy to understand the nature, scale and timeframes of recycling and production of silicic continental crust. Generating highly silicic (or felsic) melts represents the natural end member of this process. The term felsic is used here in preference to 'highly silicic' or 'silicic' to avoid confusion when discussing the generation of silicate magmas; all large volume melts on earth are *silicic*, but not all are *felsic*.

A number of examples of rapid, large volume felsic melt production punctuate earth history and stand out as remarkable geologic phenomena in the rock record. Some are described and defined as the silicic large igneous provinces (SLIP) (Bryan and Ernst, 2008; Bryan et al., 2002), others are present as felsic portions of mafic LIPs (e.g. Bryan and Ernst, 2008; Sheth, 2007). For consistency the term SLIP will be maintained throughout. The geological record of large volume felsic magmatism extends from as far back as the Archean and is represented by the classic TTGs suites (e.g. Condie, 2005; Rollinson, 2006; Smith, 2003). In terms of rate of emplacement and volcanic style however, useful comparisons between TTGs and their eruptive equivalents and more modern examples of voluminous felsic magmatism are inhibited by preservation issues and unclear contextual relationships; resulting in a consequent lack of verifiable data regarding their petrogenesis and geodynamic setting.

A number of distinct processes can produce felsic melts; assimilation, fractionation, and degree of partial melting with respect to source composition are by far the most significant factors for the resultant liquid composition. Deciphering which of these processes is the most important for a given felsic-dominated igneous event is often contentious, given that no one of the three ever occurred in isolation. Such debate is important, since the relative contribution of these factors in a given scenario record the operation of very different thermal and

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chemical regimes within source, transport and emplacement/eruption settings. Consequently this interplay accords different significance to subsequent geodynamic interpretations for these magmatic events. Such debate is ultimately of central importance to how we understand the production and evolution of continental crust.

This contribution reviews key examples of voluminous felsic magmatism in terms of their melting processes, source characteristics and geodynamic settings. It seeks to illuminate any patterns of volumetrically and high-production rate end-member examples of felsic melt generation through time to inform our view of the evolving continents.

1.1. Nature of the rapid voluminous felsic magmatism record

Total magmatic volume and emplacement rates of these phenomena are clearly central to their inclusion or exclusion from discussion. These characteristics however, are not straightforward to constrain. Intrusive volumes are difficult to estimate, and remote sensing cannot prove their chemical nature and unambiguous genetic relation to surface observations. As we consider older examples back through geologic time, preservation of key data becomes increasingly problematic, and initial volume descriptions necessarily become less constrained.

Recently efforts have been made to reclassify large igneous provinces, including an important sub-class termed SLIPs (Bryan and Ernst, 2008; Sheth, 2007). Both these recent reviews focus on preserved areal extent and volume of LIPs as a first order criteria for classification, while at the same time describe heavily denuded remnants of LIPs (e.g., dyke swarms, batholiths) also as potential LIPs. These accommodations honor the data and make reasonable assumptions based on comparison with other, better constrained examples. They must still however, be considered as LIPs with caution, as would any extrapolated data set. Using the intrusive 'footprint' of a system is a useful proxy for areal extent, especially in those provinces which exhibit high level plutonism. These footprints linked with provenance studies of adjacent basins could be the way forward in constraining total initial volumes. Attempting to imply ancient magmatic volumes based on modern examples and at the same time comparing the two in search for patterns is (unfortunately) begging the question. Due to this uncertainty, ascribing tectonic setting to a LIP using inferred volume as a line of evidence is also problematic. As a consequence in this contribution we instead focus on magmatic style, source region and geodynamic setting of the better constrained examples, and when extending the discussion back through time we have selected what we feel are the most representative and illustrative examples that can be rigorously constrained by both magmatic footprint and sedimentary provenance. To this end we have collated volume, temperature, dominant volcanic eruption style, isotopic and geochemical data from both SLIPs and silicic portions of mafic LIPs as well as typical early Archean TTG suite rocks, S-I- and A-type granites and topaz rhyolites (Table 1).

1.2. Key features of the rapid voluminous felsic magmatism record within mafic LIPs and SLIPS

The most striking observation when comparing the geochemistry, eruptive temperature and emplacement style of these high volume rhyolites is how similar they are, regardless of age. They exhibit high SiO_2/Al_2O_3 ratios (~5–7), high K_2O/Na_2O ratios (>1.5), and where available data exists, high Ga/Al_2O_3 ratios (>1.5) with high F (in thousands of parts per million), low water content, and record high temperatures (900–1100 °C) (Table 1 and references therein). This suite of characteristics is shared with A-type granites (Turner et al., 1992), and contrasts with I- and S-types (Chappell and White, 1992). The large volume rhyolites are most often described as low aspect ratio rheoignimbrites or lavas, and occur as laterally homogenous sheets that extend over wide areas; up to 8800 km^2 (Milner et al., 1992). Large volume rhyolites occur as part of mafic LIPs and also as part of SLIPs. Within the latter mafic magmatic rocks are either absent, not reported, or represent a negligible fraction of the total magmatic volume. Some of these magmas are very similar to those from mafic LIPs, although others contrast with each of the characteristics discussed above (Table 1 and Figs. 1–3). The mafic LIP rhyolites occur throughout the rock record, from at least as early as 2.45 Ga (Woongarra Rhyolite; Barley et al., 1997) through the Proterozoic (1.1 Ga Keweenawan; Green and Fritz, 1993) to the Phanerozoic (e.g. Paraná–Etendeka; Ewart et al., 2004b) and recent times (e.g. Yellowstone magmatic system; Leeman, 2005; McCurry et al., 2008). This wide spread of ages of magmatic systems with numerous shared characteristics (Fig. 4) implies the existence of a prevailing geodynamic mechanism since at least 2.45 Ga. Some examples of voluminous felsic volcanism within mafic LIPs and SLIPs can be linked with major geologic events such as supercontinent breakup, global climate change and mass extinctions (Courtillot et al., 2003; Deckart et al., 1998; Milner et al., 1995; Wignall, 2001).

The influence of halogens is a key factor in understanding the physical behavior and emplacement style of felsic magmas (Kirstein et al., 2001). Halogens, particularly F, act as depolymerizing agents effectively reducing the melt viscosity (Giordano et al., 2004). Therefore, considering halogens as important geochemical indicators of physical processes is critical to the discussion of rapid voluminous felsic magmatism through time.

2. Rapid voluminous felsic volcanism as a proportion of mafic LIPs

While recent reviews illustrate that a range of characteristics are present within large igneous provinces (LIPs) (Bryan and Ernst, 2008; Bryan et al., 2002; Ernst et al., 2005; Sheth, 2007), they are traditionally and best recognized as voluminous outpourings of basalt onto the earth's surface, which occur on both continental and oceanic crust (e.g. Jerram and Widdowson, 2005). They are widely interpreted as the surface manifestation of the arrival of a mantle plume head beneath continental and oceanic lithosphere.

Mantle plume head arrivals are phenomena linked to ore formation (Pirajino, 2001), triple junction formation (Burke and Dewey, 1973; Ernst and Buchan, 2001), rifting (Bryan et al., 1997) and continental break-up (Deckart et al., 1998; Milner et al., 1995) as well as climate change and mass extinction events (Wignall, 2001).

During the past decade, felsic portions of dominantly mafic LIPs have attracted increasing attention (Bryan et al., 2002; Miller and Harris, 2007). Among these eruptive units are the largest known in the world (Ewart et al., 1998b), and as such represent the most violent and catastrophic terrestrial phenomena (Bryan et al., 2002), contrasting with the relatively slow, effusive, self-inflation style of basalt emplacement in these LIPs (e.g. Self et al., 1996; Thordarson and Self, 1998; Waichel et al., 2006). As such, their impact upon the geosphere, atmosphere and biosphere is suggested to be among the most dramatic single-events on earth (e.g. Cather et al., 2009; Wignall, 2001).

2.1. Source and production of rhyolites within mafic LIPs

Descriptions of the best constrained LIPs with an emphasis on their felsic units can be found in Bryan et al. (2002) and references therein. Classic LIP magmas show a distinct silica gap, with chemical groupings around 45–56 and 65–75 wt.% (Bryan and Ernst, 2008), and as such LIPs are often referred to as 'bimodal'. This first order observation intuitively suggests that the mafic magmas and felsic magmas do not correspond to an unbroken liquid line of descent, and thus fractional crystallization from a mantle parent may not the most important process in generating felsic liquids (Annen et al., 2006; Huppert and Sparks, 1988), although a number of examples to the contrary are described (Ayalew and Gibson, 2009; Ewart et al., 2004b). Rather, partial melting of anhydrous lower crust as a response to underplating of high temperature mafic magmas is offered by many to be the principle trigger for rhyolite production (Bryan et al., 2002; Harris et