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Evolution and emplacement of high fluorine rhyolites in the Mesoproterozoic Gawler silicic large igneous province, South Australia

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ABSTRACT

The Gawler Range Volcanics (GRV) and the Hiltaba Suite (HS) of South Australia form a silicic-dominated large igneous province (the Gawler SLIP) emplaced in an intracontinental setting during the Mesoproterozoic. Emplacement of the GRV lasted for a short period of time (~2 Ma), and can be separated into two main phases. The first phase (lower GRV) is composed of thick (≤3 km) sequences erupted from distinct centres, and includes small to moderate volume (up to >150 km^3) felsic lavas, ignimbrites, and minor mafic and intermediate lavas. The upper GRV include extensive felsic lavas that are up to >1000 of km^3 in volume and >200 km across. Using well preserved, quartz-hosted melt inclusions, we investigated the composition of the lower GRV, including major, trace, and volatile elements. The results indicate high concentrations of K_2O (≤7–8 wt.%), rare earth and high field strength elements, and low concentrations of Ca, Mg, Ni, Cr, Sr and Ba in comparison with felsic continental crust. Overall, melt inclusion compositions match whole-rock geochemical characteristics. We demonstrate that the GRV magma was F-rich (≤1.3 wt.%), and had high temperature for a silicic magma. High F concentrations and high temperature would have resulted in lower than usual polymerisation of the melt and relatively low viscosity. These characteristics help explain how very voluminous felsic magma was erupted effusively and emplaced as lavas. Other intracontinental SLIP contain extensive felsic lavas and ignimbrites which appear to share similar geochemical characteristics. We also show that selective alteration caused depletion of whole-rock compositions in some trace elements, namely Pb, U, and Sn.

1. Introduction

Large igneous provinces (LIP) are vast amounts of magma erupted onto the Earth's surface or injected into the crust in pulses of relatively short duration and at high emplacement rates (Bryan and Ernst, 2008; Coffin and Eldholm, 1994; Ernst et al., 2005). Emplacement of LIP has occurred throughout geological time in both intraplate and plate margin settings, and is distinct from seafloor spreading and subduction-related magmatism (Mahoney and Coffin, 1997; Hamilton and Buchan, 2010). Most LIP are mainly mafic, and include flood basalts, giant dolerite dyke swarms, and layered intrusions (Head and Coffin, 1997), but in some, felsic units can be conspicuous (e.g. felsic rocks associated with the Paraná-Etendeka continental flood basalt province, Ewart et al., 1998a; Milner et al., 1992; Peate, 1997).

Silicic-dominated large igneous provinces (SLIP) of similar dimensions to the mafic provinces (≥10^5 km^3) are less common. Known examples are mostly Phanerozoic, and include the Sierra Madre Occidental of Mexico (Bryan et al., 2008; Cameron et al., 1980; Ferrari et al., 2002), the Trans-Pecos volcanic field of the USA (Henry et al., 1988; Parker and White, 2008), the Chon-Aike Province of South America and Antarctica (Pankhurst et al., 1998, 2000; Pankhurst and Rapela, 1995; Riley et al., 2001), the Snake River Plain of the western USA, Branney et al., 2008), the Whitsunday Volcanic Province of eastern Australia (Bryan, 2007; Bryan et al., 2000, 2002), and the Gawler Range Volcanics of South Australia (McPhie et al., 2008) (Table 1). Some of these provinces include extensive felsic lavas the dimensions of which are comparable with flood basalts (e.g. Star Mountain Rhyolite, Trans-Pecos, Henry et al., 1988; Yardea Dacite, Gawler Range Volcanics, Allen and McPhie, 2002; Allen et al., 2003; Keweenawan Midcontinent Rift plateau volcanic units, Green and Fitz, 1993), whereas others are dominated by extensive ignimbrites (e.g. Bryan et al., 2000). Some key questions for SLIP research are related to the eruption and emplacement mechanisms: how are these large volumes of felsic magma emplaced over short time spans? Are SLIP erupted explosively or effusively? If extensive felsic units are emplaced effusively (flood rhyolites), how can felsic lava flow for very long distances?

In this contribution, we describe the volcanic facies of the 1.6 Ga Gawler Range Volcanics (GRV)–Hiltaba Suite (HS) silicic-dominated

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Table 1
Characteristics of some felsic and bimodal large igneous provinces.

Volcanic province	Primary emplacement mechanism	Volume (km^3)	Age (Ma)	Extrusion rate (km^3/year)	Reference	Magma temperature (°C)	Paragenesis of felsic rocks
Gawler Range Volcanics, Australia	Lava	25 000	1591–1592	0.0125	Blissett et al. (1993) and Fanning et al. (1988)	900–1100	Qtz, fls, ±CPx, Zrn, Ap, Fe–Ti ox, ±Fl
Keweenawan Midcontinent Rift Plateau, USA	Lava, ignimbrite	–	1100		Green and Fitz (1993)	1000–1100	Pl, Kfs, ±Qtz, ±Aug, Mag, Zrn, Ap, ±Fl
Chon-Aike, Patagonia and Antarctic Peninsula	Ignimbrite	230 000	188–153	0.0066	Pankhurst et al. (1998, 2000)	–	Qtz, Pl, Kfs, Biot, Am, Mag, Il, Ap
Whitsunday, Australia	Ignimbrite	2 200 000	132–95	0.0595	Bryan et al. (2000)	–	Qtz, Pl, Cpx, Biot, Am, Ti-Mag
Sierra Madre Occidental, Mexico	Ignimbrite	390 000	38–20	0.0217	Cameron et al. (1980), Ferrari et al. (2002), and Bryan et al. (2008)	750–900	Pl, Opx, Cpx, Am, Mag, Il
Snake River Plain-Yellowstone	Lava, ignimbrite	–	Neogene		Christiansen and McCurry (2008)	830–1050	Pl, Qtz, Fe–Ti ox, CPx, ±Am, ±Biot
Paraná-Etendeka province (silicic component)	Lava	–	132 ± 1-130		Marsh et al. (2001)	≥1000	Pl, CPx, Fe–Ti ox, ±Opx, Ap

LIP (the Gawler SLIP) of South Australia to evaluate its emplacement mechanisms (explosive versus effusive). We also present analyses of well preserved quartz-hosted melt inclusions to reconstruct the composition of source magmas. Melt inclusions are droplets of silicate melt trapped within crystals growing in a magma. If preserved, they represent samples of pristine silicate liquid (melt) unaffected by modifications occurring as the magma approaches the Earth's surface. Melt inclusions can be studied as a powerful tool to assess the pre-emplacement volatile content of a magma (Métrich and Clocchiatti, 1989; Lowenstern and Mahood, 1991; Lowenstern, 1995) and to reconstruct the magma composition in altered or mineralised rocks (Chabiron et al., 2001). Melt inclusions also give the opportunity to study the influence of crystal fractionation on melt evolution, without the effects of crystal accumulation encountered when using whole-rock analyses.

2. The Gawler SLIP

The GRV and co-magmatic HS granite represent a silicic-dominated LIP (the Gawler SLIP) with a preserved (minimum) volume of ~100 000 km^3, of which ~25 000 km^3 are represented by the volcanic sequence (Blissett et al., 1993; McPhie et al., 2008; Fig. 1). To the east, the province is partially concealed underneath younger Proterozoic and Phanerozoic sediments of the Stuart Shelf (Blissett et al., 1993). The province includes several voluminous (tens of km^3 to >1000 km^3) and extensive (tens to >200 km across) felsic lavas and ignimbrites (Allen et al., 2008; Blissett et al., 1993) and minor mafic to intermediate units. The Gawler SLIP was emplaced in a subaerial intracontinental setting, and lies on Archean and Paleoproterozoic units of the Gawler Craton (Allen and McPhie, 2002; Allen et al., 2008; Betts and Giles, 2006; Blissett et al., 1993; Creaser, 1995). U–Pb zircon dating of the volcanic units has yielded a narrow age range of 1591–1592 Ma (Creaser, 1995; Creaser and Cooper, 1993; Fanning et al., 1988), whereas ages of the HS granites range from 1583 ± 7 to 1598 ± 2 Ma (Flint, 1993).

Emplacement of the Gawler SLIP is temporally related with high temperature low pressure metamorphism in the region (the Hiltaba event; Betts and Giles, 2006; Betts et al., 2002), and coeval with the 1.6–1.3 Ga intraplate magmatic event that occurred throughout Laurentia and Baltica (Anderson and Morrison, 2005). It has been hypothesised that the GRV were emplaced as part of a hotspot-related igneous activity affecting the central part of Australia (Betts et al., 2009). The Gawler SLIP is associated with a major metallogenic event that affected most of the Gawler Craton (Budd and Fraser, 2004; Fraser et al., 2007; Skirrow et al., 2002, 2007). The Au–U Olympic Dam deposit was formed during this event.

The GRV have been subdivided into lower and upper sequences based on the discordance between small to moderate volume, gently to moderately dipping older units and extensive, nearly flat-lying younger units (Blissett et al., 1993). The lower GRV consist of thick (up to 3 km) successions, erupted from several discrete volcanic centres. Evenly porphyritic dacite and rhyolite are interbedded with ignimbrites and volumetrically minor mafic lavas (basalt and basaltic andesite). The Chitanilga Volcanic Complex at Kokatha (Blissett, 1975, 1977b; Branch, 1978; Stewart, 1994) and the Glyde Hill Volcanic Complex at Lake Everard (Blissett, 1975, 1977a,b; Ferris, 2003; Giles, 1977) are the two best exposed parts of the lower GRV (Fig. 1b and c) and are the subject of this study. The upper GRV are composed of at least three large-volume (>1000 km^3), extensive (≤200 km), evenly porphyritic and compositionally homogeneous felsic (dacite and rhyolite) massive lavas (Allen and McPhie, 2002; Allen et al., 2008; Creaser and White, 1991; McPhie et al., 2008). Units in the upper GRV are up to 300 m thick, and as a whole, crop out for 12 000 km^2. Mineral assemblages in the upper GRV are essentially anhydrous and include phenocrysts of plagioclase (oligoclase-andesine), K-feldspar, orthopyroxene (pigeonite Mg#24–43, augite Mg#30–53), Fe–Ti oxide, ±quartz in a quartz-feldspar groundmass (Creaser and White, 1991; Stewart, 1994).

The GRV sequence is cross-cut by numerous porphyritic rhyolite, and less abundant andesite, dykes (Blissett et al., 1993). The Moonamby Dyke Suite (Giles, 1977) includes rhyolite porphyritic dykes that intruded the lower GRV at Lake Everard. The HS granite includes large batholiths and smaller intrusions of granite and minor quartz monzodiorite and quartz monzonite (Flint, 1993). Typical of much of the HS is medium-grained, locally porphyritic pink granite composed of quartz, alkali-feldspar, plagioclase, minor interstitial biotite, apatite and fluorite. HS granite intruded the GRV at various localities with sharp contacts and no major of metamorphic overprint in