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A Mesoproterozoic continental flood rhyolite province, the Gawler Ranges, Australia: the end member example of the Large Igneous Province clan

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Abstract. Rhyolite and dacite lavas of the Mesoproterozoic upper Gawler Range Volcanics (GRV) (>30 000 km³ preserved), South Australia, represent the remnants of one of the most voluminous felsic magmatic events preserved on Earth. Geophysical interpretation suggests eruption from a central cluster of feeder vents which supplied large-scale lobate flows >100 km in length. Pigeonite inversion thermometers indicate eruption temperatures of 950–1100 °C. The lavas are A-type in composition (e.g. high Ga/Al ratios) and characterised by elevated primary halogen concentrations (~1600 ppm fluorine, ~400 ppm chlorine). These depolymerised the magma such that temperature-composition-volatile non-Arrhenian melt viscosity modelling suggests they had viscosities of <3.5 log η (Pa s). These physico-chemical properties have led to the emplacement of a Large Rhyolite Province, which has affinities in emplacement style to Large Basaltic Provinces. The low viscosity of these felsic magmas has produced a unique igneous system on a scale which is either not present or poorly preserved elsewhere on the planet. The Gawler Range Volcanic Province represents the erupted portion of the felsic end member of the family of voluminous, rapidly emplaced terrestrial magmatic provinces.

1 Introduction

The viscosity of silicate magmas is a critical control on the rate and scale of planetary differentiation, material and heat transfer, and crustal growth (Reese et al., 1998; Zaranek and Parmentier, 2004). Large Igneous Provinces (LIPs) represent relatively short periods of time during which significant volumes of material are emplaced in or onto the crust (<50 Myr, >0.1 Mkm³ respectively, according to the classification of Bryan and Ernst, 2008). Most LIPs manifest as dominantly low-viscosity mafic magma outpourings (e.g. Coffin and Eldholm, 1994), during which large volumes of mantle-derived lava are expelled onto the Earth's surface in short geologic timescales (5–10 Myr; Jerram and Widdowson, 2005). These principally basaltic occurrences are often described as the result of mantle plume activity, and although a variety of models exist, and debate continues (Bryan and Ernst, 2008 and references therein). In contrast, Silicic Large Igneous Provinces are rare, dominated by explosive eruptions, generally accumulate as pulses over longer timescales, and occur as a result of plate margin processes (Bryan, 2007; Bryan et al., 2002). In addition to the magmatic products of SLIPs, Pankhurst et al. (2011) recognise examples of rapid voluminous felsic magmatism within otherwise mafic-dominated LIPs.

This contribution investigates a Continental Flood Rhyolite Province, and argues that its characteristics are a function of the inherent low viscosity of the magmas involved. We suggest that a typical plate margin setting does not adequately explain the geometry, duration, temperatures, chemistry and magmatic processes of the GRV, placing it outside



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the conceptual model for “normal” Silicic Large Igneous Provinces.

The viscosity of natural silicate melts ranges over more than 10 orders of magnitude (Cashman et al., 1998; Romano et al., 2001) and represents a complex interplay between temperature and compositional factors. These include silica content, crystallite content, alkali/Al ratio, water content, halogen concentration and oxygen fugacity (Dingwell et al., 1985, 1988, 1993; Dingwell and Virgo, 1988; Giordano et al., 2004b; Mysen and Virgo, 1989; Mysen, 1990; Webster and De Vivo, 2002; Webster and Rebbert, 1998). The viscosity of felsic magmas is generally many orders of magnitude greater than that of mafic magmas because the former are inherently more polymerised and usually more crystal rich (e.g. Giordano et al., 2006). Further, felsic magmas generally erupt at significantly lower temperatures than do mafic magmas, and thus substantial lava flows analogous to those of flood basalt provinces are rare in the geologic record (Christiansen et al., 1984; Haapala et al., 2007; Milner et al., 1992). A-type felsic magmas though, tend to be lower viscosity than magmas of comparable silica concentration. Clemens et al. (1986) postulated that this could be due to higher temperatures and elevated halogen content most often associated with A-types. Recent advances in physicochemical models (e.g. Giordano et al., 2008) which incorporate a large number of variables for felsic compositions now allows quantitative calculation of magma intensive parameters, and thus more rigorous testing of geological and geophysical observations.

In this contribution we apply a combination of aeromagnetic and physicochemical analysis to the Mesoproterozoic (1592 ± 2 Ma; Fanning et al., 1988) upper Gawler Range Volcanics, South Australia. We demonstrate that a large felsic magmatic system can behave like a mafic large igneous province given an appropriate combination of viscosity-lowering factors, notably eruption temperature and halogen content.

2 Age and morphology of the upper Gawler Range Volcanics

The upper Gawler Range Volcanics are one component of an extensive, dominantly A-type (Blissett et al., 1993) felsic large igneous province (Allen et al., 2008) comprising the ca. 1595–1592 Ma Gawler Range Volcanics and coeval Hiltaba Granite Suite (ca. 1600–1575 Ma; Fanning et al., 1988). The upper Gawler Range Volcanics are composed of three thick (>250 m), chemically and isotopically laterally homogeneous dacite to rhyolite (67–74 wt % SiO_2) lavas with preserved outcrop extent of over 12 000 km² across the central Gawler Craton (Allen and McPhie, 2002; Allen et al., 2003, 2008; Fig. 1). The Eucarro Rhyolite and Pondanna Dacite member of the Yardea Dacite are investigated within this study. The duration of upper Gawler Range Volcanics

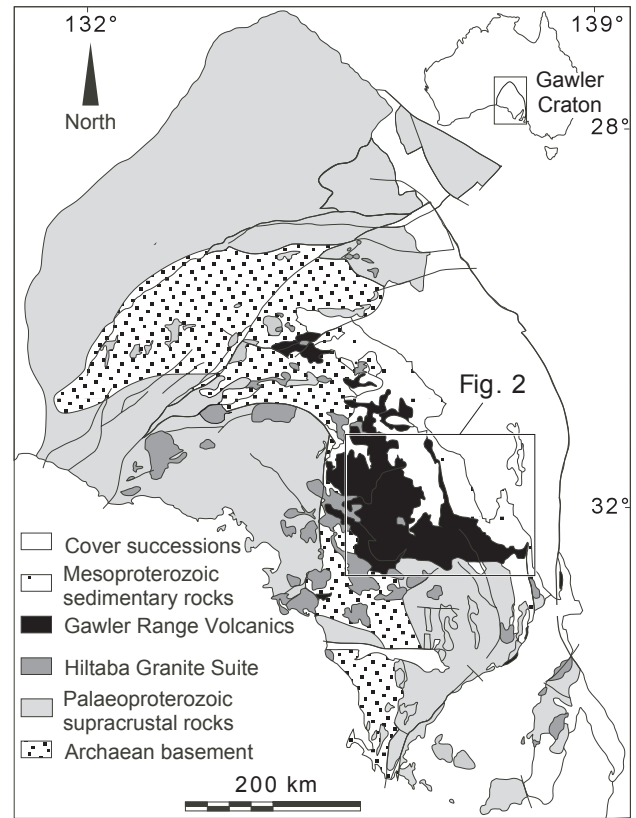


Fig. 1. Simplified geological map of the Gawler Craton.

magmatism is currently constrained to be <2 Ma (Fanning et al., 1988). Significantly, basalts and basaltic-andesites comprise a volumetrically miniscule proportion of the complete terrain ($\ll 10\%$; Allen et al., 2008), and are absent (except for some mafic enclaves) in the lithologies investigated here.

These volcanic rocks, which are a constituent of the last tectonothermal event to occur within the central Gawler Craton, are imaged in regional high-resolution aeromagnetic data as a series of overlapping radiating lobes characterised by a heterogeneous (wavelength 1–5 km) moderate-high magnetic signal (Fig. 2). Lobe fronts are arcuate features defined by a combination of changes in magnetic intensity and texture. Recent anisotropy of magnetic susceptibility (AMS) data obtained in independent studies from the interpreted lobe fronts in the southern Gawler Ranges (McPhie et al., 2008) preserve steeply dipping and bimodal orientations. We consider these orientations to be consistent with flow patterns at the termination of individual lobes, and a magma source to the northeast, contrasting with McPhie et al. (2008) interpretation of a southwest source. In exposed southern areas, these lobes correspond with mappable single lobes within the upper Gawler Range Volcanics (e.g. Allen et al., 2003), whereas in the northeast of the province aeromagnetic data suggest that the lobes clearly persist beneath younger sedimentary cover (Fig. 2). The total preserved distribution

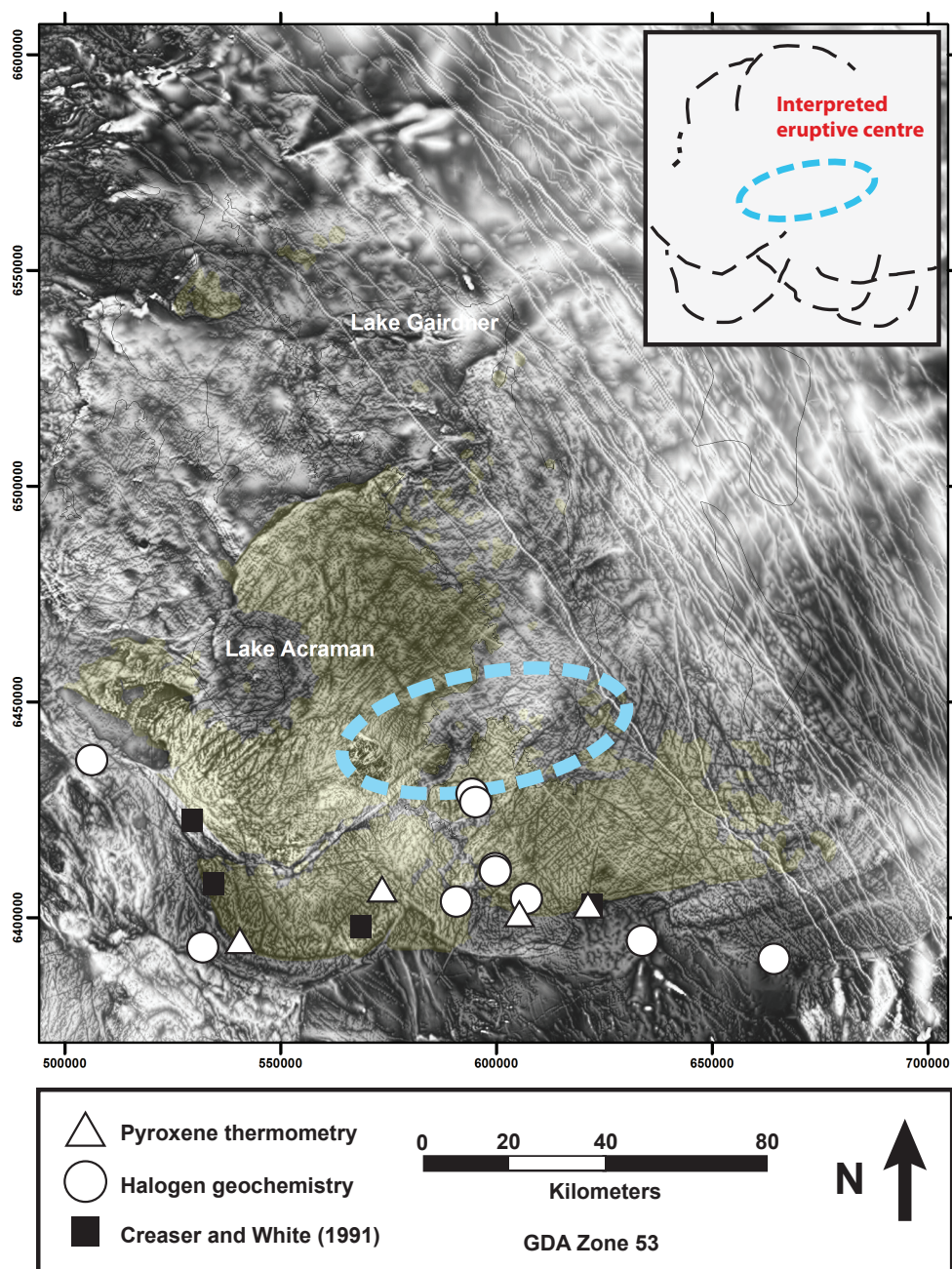


Fig. 2. Sample sites superimposed onto reduced-to-the-pole greyscale aeromagnetic image of the Gawler Range Volcanics. The lobe morphology of the lava flows can be observed as regions of similar magnetic texture defined by arcuate shapes. The (preserved) flow fronts closely follow the modern outcrop distribution (inset) in the SW and these shapes are also imaged undercover (NE of Lake Gairdner).

of the upper Gawler Range Volcanics suggests an elliptical-shaped lobate architecture in which the median lines of each lobe emanate from a central cluster, which is characterised by a longer wavelength, elliptical medium wavelength (~ 5 – 10 km) magnetic signal interpreted as sub-volcanic features, including pipes/feeder complexes and frozen magma chambers (Fig. 2). Previous geophysical work interpreted the apparent lobate geometry of the lavas to be caused by the

intersection of the Earth's surface and gentle tilting of the province (Rajagopalan et al., 1993). If the geometry was due to erosion only, all the lobes would have the same geometry – i.e. they would curve in the same direction no matter where they exist in the belt. This is not the case; above and below sedimentary cover the lobes are radial, implying a central source, and thus appears to reflect the primary lava distribution (Fig. 2).

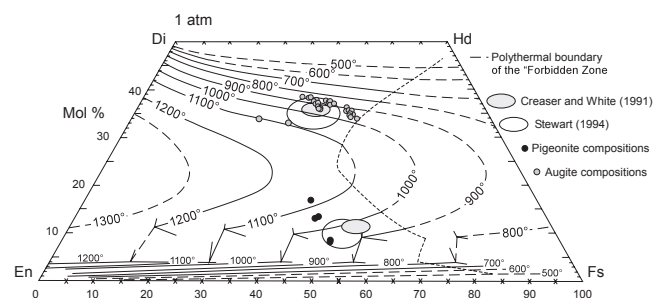


Fig. 3. Graphical pyroxene geothermometer after Lindsley (1983). Pigeonite and augite data from Creaser and White (1991), Stewart (1994) and this study indicate magmatic temperatures between 900 °C and 1110 °C for the upper Gawler Range Volcanics.

3 Viscosity calculations

Recent advances in quantitative modelling of silicate melt viscosity, based largely around improvements in experimental constraints (Giordano and Dingwell, 2003; Giordano et al., 2004a, b, 2006, 2008) allow rigorous calculation of viscosity, particularly for magmas with low crystallite content. These models incorporate the effects of depolymerising agents, such as halogens, for bulk compositions and temperatures appropriate for the GRV. We utilise a conservative approach where whole rock fluorine contents are used to provide a minimum estimate for the de-polymerising agents, resulting in maximum values for calculated viscosities at the lowest measured reasonable temperature estimates.

Pyroxene and feldspar geothermometry studies of the Yardea Dacite indicate that the upper Gawler Range Volcanics record temperatures between 950–1100 °C (Creaser and White, 1991; Stewart, 1994). New temperature data from a range of new localities within the province (Figs. 2 and 3) based on pigeonite inversion geothermometry (Lindsley, 1983) support these observations (Fig. 3). Hence we consider the best estimate for the eruptive temperature of the upper Gawler Range Volcanics to be between ~950–1050 °C. Due to the remarkable chemical homogeneity of the single lavas over hundreds of kilometres (Creaser and White, 1991; Giles, 1988; Stewart, 1994), we can make the reasonable assumption that the magma system feeding the volcanism was thoroughly mixed via convection, and therefore maintained a relatively constant temperature throughout. Since the geothermometry data range over ~200 °C, and the geothermometer (Lindsley, 1983) generally records cooling, we suggest that surface cooling was mostly responsible for the observed spread (Fig. 3) and therefore it is possible that eruptive temperature exceeded 1100 °C. Samples from this study were invariably obtained from the terminal portions of the lava lobes (Fig. 2), which are more likely to record cooling during emplacement.

Samples of Gawler Range Volcanics (Fig. 2) were observed visually in the field, hand sample and microscopi-

cally to possess a high degree of homogeneity (phenocrysts of K-feldspar > quartz > pyroxene > Fe-oxides totaling < 20–25% within a microcrystalline matrix). The observation of such homogeneity over their wide geographical extent is significant when considering the degree of alteration (or lack thereof) for the GRV samples. Alteration would be predicted to have acted non-systematically in both a petrographic and geochemical sense, and this is not observed within the units investigated in this study. Following petrological work to confirm the primary nature of their textures and low abundance of microphenocrysts within the microcrystalline matrix, the cores of twelve ~5 kg samples of unaltered upper Gawler Range Volcanics were analysed for major, minor (including halogens) and trace elements using a Bruker-AXS S4 Pioneer XRF Spectrometer and processed through Bruker-AXS Spectra-plus Software at the Advanced Analytical Centre at James Cook University. The standard used for F and Cl was FSL, lower detection limits for both F and Cl were 0.02%. Pellets were kept in a desiccator from the time of pressing to the analytical run to minimize the risk of Cl contamination. Mineral assemblages (feldspar, ferromagnesian phases and rare quartz) and their abundances, and major (see Table 2) and trace element results duplicate that of previous studies (Allen and McPhie, 2002; Allen et al., 2003; Fanning et al., 1988; Giles, 1988). Fluorine and chlorine concentrations averaged ~1600 ppm and ~400 ppm respectively (Table 1). These values are significantly higher than those of typical felsic intrusions (300–515 and 50–180 ppm respectively (Gao et al., 1998), which have not experienced volcanic degassing and hence should be expected to have higher halogen contents than their extrusive equivalents. The upper Gawler Range Volcanics exhibit A-type chemical affinities (Fanning et al., 1988; Giles, 1988), and due to their absence of common granitic hydrous phases (e.g. biotite), consistent with the low values of loss on ignition (LOI) typically between 1–2 wt %, magmatic water content during emplacement can be considered low (1–2 wt %).

Crystallite content has an important positive influence on magma viscosity (e.g. Pinkerton and Stevenson, 1992), particularly at concentrations >45% (Bagdassarov et al., 1994). Experimental work by Lejeune and Richet (1995) suggests that magmas with crystallite concentrations <40% exhibit Newtonian behaviour. Since the upper GRV observable crystallite content is low (excluding phenocryst abundance), phenocryst abundance does not exceed 40% (average ~20–25%, max 39%; Allen et al., 2003), this influence is minimal, and is considered less important relative to thermal and chemical controls.

Temperature and major element data have been input to the Giordano et al. (2008) magmatic liquid viscosity model, chosen since it is calibrated for fluorine. Currently, there is debate concerning the specific role chlorine plays in depolymerising the melt structure (Zimova and Webb, 2006, 2007), and for this reason we withheld chlorine data from our calculations. Results of the combined modelling encapsulating

Table 1. Measured (XRF) halogen concentrations for the Eucarro Rhyolite and Yardea Dacite. Note values are likely to be minimum measurements due to devolatilisation and degassing during eruption.

Detection Limit	F ppm 200	Cl ppm 200
Eucarro Rhyolite		
GRER01	1400	380
GRER03	290	680
GRER07	1960	310
GRER09	1920	360
Pondanna Dacite		
GRYD18	1470	330
GRYD19	1670	430
GRYD20	1340	390
GRYD23	1390	290
GRYD24	1290	310
GRYD25	1840	360
GRYD28	1790	460
GRYD29	1770	490

non-Arrhenian behaviour are summarised in Table 2. The most significant outcomes are that for bulk compositions appropriate to the upper GRV, viscosities are typical for dry compositions at typical rhyolitic eruption temperatures ($\sim 800^\circ\text{C}$). Calculated viscosities drop by several orders of magnitude (Table 2) at $950\text{--}1100^\circ\text{C}$ for both the Eucarro Rhyolite and Pondanna Dacite (Fig. 4), and there is a further viscosity decrease when volatile contents appropriate for the Gawler Range Volcanics (~ 1.5 wt % H_2O and ~ 0.2 wt % fluorine) are included in the models; resulting in viscosities of ~ 3.25 and ~ 4.25 log η (Pa s) for the Pondanna Dacite and Eucarro Rhyolite respectively. Given that the volatile (particularly halogen) estimates are conservative (Cl is not included), and that evidence for eruptive temperatures as high as 1100°C exists, it is conceivable that viscosity could be as low as $\sim 2.5\text{--}3$ log η (Pa s) for the upper Gawler Range Volcanics (Table 2, Fig. 4).

4 Discussion

A consequence of the Giordano et al. (2008) model is that an increase in eruptive temperature of 100°C or 1 wt % volatiles in solution equates to a viscosity decrease of around one order of magnitude. Hence the calculated viscosities are sensitive to the input parameters, and we now explore the consequences of this. Firstly, we may consider the actual abundance, and therefore influence, of volatiles to be greater than that recorded. Final degassing of the lava pile producing amygdaloidal flow tops (Allen et al., 2003) could lead to undervaluing of the halogen influence. Conversely, we may be over-estimating the water content of these liquids by as-

Table 2. Calculated viscosities (log η (Pa s)) for the Upper Gawler Range Volcanics with reference to a typical (theoretical) tholeiite composition using the equations of Giordano et al. (2008). Note the ~ 7 orders of magnitude difference between rhyolitic and basaltic viscosities at their respective typical eruptive temperatures, compared with the ~ 1 order of magnitude between calculated Gawler Range Volcanics at 1100°C with ~ 2.2 wt % total volatiles and a typical tholeiitic basalt composition at typical eruptive temperature.

	Eucarro Rhyolite*	Pondanna Dacite*	Tholeiitic Basalt**	
(all in wt %)				
SiO ₂	70.9	67.6	50.0	
TiO ₂	0.5	0.7	1.5	
Al ₂ O ₃	13.3	13.8	15.0	
FeO(<i>T</i>)	2.8	4.3	11.0	
MnO	0.1	0.1	0.2	
MgO	0.1	1.1	8.0	
CaO	0.9	1.1	11.5	
Na ₂ O	3.2	3.4	2.0	
K ₂ O	5.7	5.2	0.2	
P ₂ O ₅	0.1	0.2	0.1	
<i>F</i>	0.20	0.23	0.00	
Viscosity (all in log η Pa s)				Temperature (°C)
Dry***	10.3	9.7	5.4	800
	7.8	7.2	3.2	950
	6.0	5.5	1.8	1100
	7.5	7.0		800
1 wt % H ₂ O	5.8	5.3		950
	4.5	4.0		1100
	6.5	6.0		800
2 wt % H ₂ O	5.0	4.6		950
	3.8	3.4		1100

* Data are averages; Eucarro Rhyolite $n = 4$; Pondanna Dacite $n = 8$

** Typical, theoretical composition

*** “Virtually dry” input used = 0.02 wt % H_2O in accordance with Giordano et al. (2006) tholeiitic basalt input used = 0.50 wt % H_2O

suming that LOI corresponds broadly to H_2O . Creaser and White (1991) estimated water content in the Yardea Dacite by comparing the assemblages of quartz, plagioclase, and alkali feldspar phenocrysts at a temperature of $900\text{--}1000^\circ\text{C}$ and an assumed pressure of 2 MPa with experimentally derived data (Nekvasil, 1988). This estimate yielded a maximum water content of 1 wt %, consistent with the typical estimate obtained from LOI.

This water content would increase further to 2 wt % if the pressure was increased to 8 MPa (Creaser and White, 1991). Hence our conservative estimate of $\sim 1\%$ H_2O may be considered to be a reasonable minimum.

Estimates of halogen contents are also likely to be minima. Fluorine is abundant in all units sampled, implying it was elevated throughout the magma. This is consistent with studies that suggest that F is soluble in silicate melts at eruptive conditions and hence the majority of loss through volatilisation would not have occurred before eruption (Aiuppa et al.,

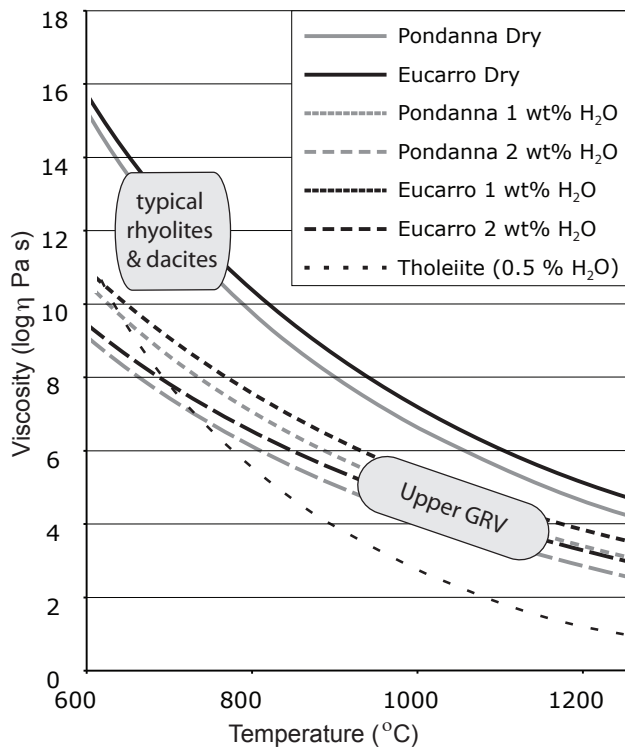


Fig. 4. Viscosity vs. Temperature plot illustrating calculated palaeo-viscosities of Pondanna Dacite and the Eucarro Rhyolite using measured fluorine and 0.02, 1 and 2 wt % H_2O contents for these units. A typical theoretical tholeiitic basalt composition (see Table 2) has also been modeled for comparison. The results indicate that a combination of unusually high magmatic temperatures and elevated halogen content decrease the viscosity of melts of the composition of the Gawler Range Volcanics towards typical values of basalts.

2002; Holtz et al., 1993). This contrasts with the behaviour of Cl and water, both of which are highly volatile and would be expected to be variably degassed within and between units during eruption (Aiuppa et al., 2002). Therefore, our estimates for the total volatile content must be regarded as conservative minima, and any increase in concentration of these species will be accompanied by a concomitant decrease in total viscosity.

The second major source of uncertainty in the calculated viscosities is derived from the estimates of eruptive temperature. The calculations are therefore informed by the lowest reasonable eruptive temperature estimates in order to constrain the maximum probable eruptive viscosities. Temperature calculations are based on samples collected from within the frontal part of individual lobes or at the lobe front where temperatures are likely to record maximum cooling. Hence this parameter is one of the least significant in terms of uncertainty in the viscosities obtained.

The physico-chemical modelling suggests that a combination of elevated temperatures during eruption coupled with high fluorine and moderate H_2O contents reduced the

eruptive viscosities of the upper Gawler Range Volcanics to values approaching those of tholeiitic basalts at eruption temperatures of 950 °C (Fig. 4). The role of fluorine is double in such a system because it increases water solubility as well as acting as a depolymerising agent itself (e.g. Dingwell et al., 1985). Such low viscosities in felsic compositions are exceedingly rare in the geologic record (e.g. topaz rhyolites; Taylor and Fallick, 1997), particularly in volcanic piles that have experienced degassing and halogen loss. More significantly, the Gawler Range Volcanics are anomalous in that they maintained these conditions throughout such a large volume, and were erupted over such a short time (<2 Myr) in comparison with other felsic LIPs (≤ 40 Myr; Bryan et al., 2002).

The morphology of the volcanic province is characterised by an overlapping lobate flow pattern that radiates from a central zone (Fig. 2). The length scale of single lobes varies between 60 and 120 km, with single lobe fronts and associated terminal lobes between 30 and 120 km across. The protracted denudation history of the Gawler felsic large igneous province is of great importance to note. Since emplacement at ~ 1600 Ma the province has been extensively eroded, and now we observe the remains of (if the distribution of similar-aged granitic plutons is a useful proxy, see Fig. 1) what would have probably been a far larger volcanic expression of the system. The dimensions of such a system are characteristic of “classic” mafic large igneous provinces (Bondre et al., 2004; Coffin and Eldholm, 1994; Courtillot et al., 2003; Jerram and Widdowson, 2005; White and McKenzie, 1995), in which the high magma flux rates and low viscosities enable long lava flow lengths. The radiating morphology of the lobes emanating from a central zone is consistent with that observed in modern shield volcanoes (Thouret, 1999). Hence emplacement and eruption of the high temperature, voluminous upper Gawler Range Volcanics may be considered to be physically analogous to the plume head processes associated with Continental Flood Basalts. Indeed, they are preserved on a comparable scale to the more familiar analogues and have been argued to represent plume derived magmatism from independent chemical and temporal studies. Betts et al. (2007) use palaeomagnetic data and age progression of A-type magmatism across the Gawler Craton, Curnamona province and Mount Isa Inlier to define an equivalent small circle that relates to Australia’s polar wander up to the emplacement event. This suggests hotspot progression, and therefore plume activity, independent of geochemical constraints. Betts et al. (2009) incorporate these observations into a regional geodynamic model that appeals to plume-modified orogenesis in eastern Precambrian Australia.

Perhaps then, the tectonic setting of the GRV has hallmarks of the voluminous, (often A-type) felsic magmatism associated with the evolution of the Yellowstone hotspot (e.g. Hildreth et al., 1991) and the Parana-Etendeka plume (e.g. Ewart et al., 1998).

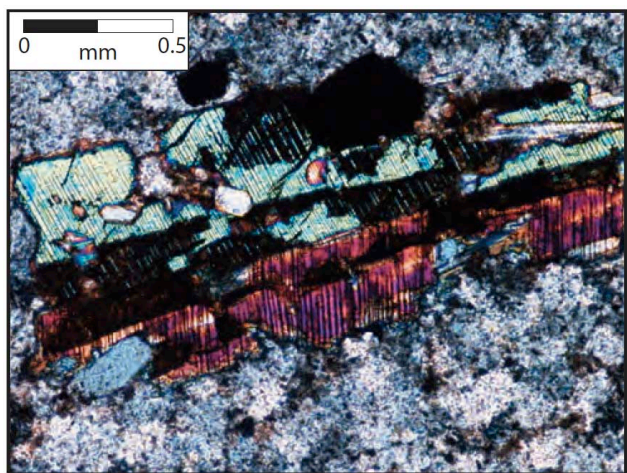


Fig. 5. Photomicrograph (sample YD23, crossed-polarized light) of a pigeonite crystal within unaltered microcrystalline matrix displaying classic “Christmas tree texture”; a result of exsolution lamellae indicating high temperatures (especially for dacite-rhyolite compositions).

We therefore envisage a spectrum of volcanic flood provinces which range from the familiar, mafic dominated end members (e.g. the Deccan Traps, Siberia) through those containing appreciable volumes of felsic magmatism (Yellowstone, Parana-Etendeka) to the Gawler Range system in which magmatism is overwhelmingly felsic with rare, volumetrically minor ($\ll 10\%$) basalts and basaltic andesites. Significantly, it is clear that the mode of emplacement and possibly even magma transport and eruption mechanisms are controlled by their viscosity.

5 Conclusions

The calculated viscosities of the upper Gawler Range Volcanics range between $3.4\text{--}5.0 \log \eta$ (Pa s): a range closer to those viscosities exhibited by basalts ($< 3 \log \eta$ (Pa s)) than that of typical felsic melts (Giordano et al., 2008). This viscosity range has been obtained by considering elevated temperatures ($\sim 950\text{--}1100\text{ }^{\circ}\text{C}$), elevated halogen concentrations and low-moderate water content resulting in a depolymerised melt structure. The low viscosity magma erupted from a central cluster of feeder vents from which emanated large-scale lobate flows, representing a viable emplacement mechanism to produce a flood rhyolite province with volumetrically insignificant basalts and andesites. The volumes considered and high degree of homogeneity reported here and elsewhere in the literature (e.g. Allen et al., 2003) are suggestive of a well mixed magma system/chamber of batholithic proportions. The geodynamic implications of the production and expulsion of such extreme quantities of felsic magma in such a short time frame are non trivial. The volume and areal extent of such a flood rhyolite is directly analogous

to that of preserved mafic LIPs, which are present throughout the geologic record, and are often attributed to upwelling of anomalously hot mantle in the form of mantle plumes. We view the fundamental driving force of the development of the GRV magmas to be a transient thermal anomaly analogous to such events. The evacuation of an anomalously hot and felsic (and therefore buoyant) magma chamber would be facilitated in this case by the low viscosities calculated, possibly at the expense of any cogenetic mafic magmas. We therefore present a viable mechanism for sustaining a large volume felsic igneous province, and suggest that the Gawler Range province represents an end-member of the Large Igneous Province clan.

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