GEOTHERMOBAROMETRY OF THE FLUORINE- AND BERYLLIUM-RICH SPOR MOUNTAIN RHYOLITE, WESTERN UTAH

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I. Abstract

The Miocene rhyolites of the Spor Mountain Formation host the world's largest beryllium deposit. We have examined the rhyolite to understand the magmatic Be enrichment (up to 75 ppm in matrix glass). The Spor Mountain rhyolite contains ~40% quartz, ~40% sanidine, ~10% biotite, and ~10% plagioclase, along with accessory fluorite, columbite, euxenite, fergusonite, monazite, thorite, and zircon. Two types of lava erupted, a less evolved magma (1150 ppm Rb, 42 ppm Be, 0.68 wt% F in matrix glass) and evolved magma (1710 ppm Rb, 75 ppm Be, 1.56 wt% F).

Eruption temperatures estimated using zircon saturation, feldspar-liquid, two feldspar, and Ti-in-quartz geothermometers converge on 718 °C for the less evolved magma and 682 °C for the evolved magma. Zircon saturation temperatures using whole-rock compositions were as much as 70°C higher than those based on glass compositions. Using the Ti-in-Qz equation of Thomas et al. (2010) and a temperature of 700°C gives unreasonably high P of 8-12 kb. Using the Huang and Audetat (2012) calibration, the pressure of the Spor Mountain rhyolite system is estimated to be ~ 2 kb at 700°C. Water content of the rhyolite melt was less than <5 wt%, based on the presence of all four major mineral phases at 700°C and the magma was water undersaturated (Webster et al., 1987) before eruption. The calculated viscosity of the melt is about 6.2 log Pa·s for the less evolved rhyolite and 5.8 log Pa·s for the evolved rhyolite. Fluorine lowered the melt viscosity, though not by a large amount (less than 0.5 log units at 1.7 wt% F compared to an F-free melt). Thus, it seems that the crystal fractionation may not have been greatly accentuated by a low viscosity melt. Instead, the principal role of F may have been to allow the melt to remain close to low temperature.

II. Introduction and Methods

Figure 1. Geologic map of Spor Mountain and the surrounding area in western central Utah. The Spor Mountain Formation dominantly contacts Devonian to Precambrian carbonates, though at a few locations, it contacts the Eocene Drum Mountain Rhyodacite. The Be mines are located in the SW portion of the map (labeled 1 through 7). Samples were taken from the following mines: Taurus (SM-14, -831, -86), Roadside (SM-31), and Blue Chalk (SM-35, -37). Modified from Lindsey (1979).

Figure 2. Whole-rock variation diagrams. A) Total alkali silica (TAS) diagram with whole rock (WR, closed symbols) and matrix glass (MG, open symbols) for the Spor Mountain rhyolite, Utah. All samples plot well within the rhyolite field, similar to other topaz rhyolites. B) SiO₂ vs Be. C) F vs Be. D) F v s Cl. E and F) Tectonic discrimination diagrams (Pearce et al., 1984). All samples (with the exception of two glass analyses from the evolved samples) plot in the "Within plate" fields, consistent with the Spor Mountain rhyolite's A-type signature. Blue dots represent rhyolite obsidians from the compilation of Macdonald et al. (1992).

Figure 3. Representative photomicrographs of the three groups of rocks studied. A and B) SM-14 (evolved vitrophyre); C and D) SM-31 (less evolved vitrophyre); E and F) SM-37 (less evolved devitrified). G and H show an example of magmatic fluorite within SM-37. Note the evolved samples have more phenocrysts than the less evolved samples. Biotite in devitrified sample has altered to magnetite and ilmenite. Qz = quartz; Sa = sanidine; Pl = plagioclase; Bt = biotite; Fl = fluorite.

Figure 4. Phase diagram of the Spor Mountain rhyolite at 2 kbar, modified from Webster et al. (1987). The Spor Mountain rhyolite crystallized at about 700 °C at 2 kbar and under water-undersaturated conditions. Qz = quartz; Sa = sanidine; Pl = plagioclase; Bt = biotite. These phase co-crystallized before eruption.

III. Geothermometry

Table 1. Eruption temperature (°C) estimates for the Spor Mountain rhyolite at 2 kbar and 5 wt% H₂O

Sample		SM-31		SM-35		SM-37		SM-14		SM-831		SM-86	
Lithology	Thermometer	V		V		D		V		V		V	
Group	Model	LE		LE		LE		EV		EV		EV	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Boehnke et al., 2013	Zrn-sa. (MG)	689	34	724	9					633	10	619	23
Boehnke et al., 2013	Zrn-sat. (WR)	715	10	716	11	726	12	692	11	696	15	690	17
Putirka, 2008	Pl-Liq	763	3	754	3			701	5	703	5	752	5
Putirka, 2008	Afs-Liq	752	2	693	2			693	3	678	4	698	1
Putirka, 2008	Two Fsp	704	3	711	3			682	11	668	7	663	9
Elkins & Grove, 1990	Two Fsp	707	4	715	4	739	5	648	25	670	13	665	20
Benisek, 2010	Two Fsp	496	13	492	13	496	15	462	35	401	28	408	36
Huang and Audetat, 2012	Ti-in-Qz	678	18	689	19					703	14	702	28
Thomas et al, 2010	Ti-in-Qz	536	14	545	15					556	11	555	22
Righter et al., 1996	Biotite	799	3	804	3			783	5	787	6	788	7
a TiO₂		0.39	0.10	0.35	0.10					0.18	0.10	0.24	0.20

Figure 5. Comparison of the different geothermometers used in an attempt to estimate the crystallization temperature. Columns match Table 1. Most thermometers agree that the temperature of crystallization was around 700 ± ~30 °C. Of note, however, is that the Righter et al. (1996) model, based on biotite and glass composition, is consistently too high whereas the Thomas et al. (2010) values, based on Ti in Qz, are too low. V = vitrophyre, D = devitrified, LE = less evolved, EV = evolved, SD = standard deviation, MG = matrix glass, WR = whole rock.

IV. Geobarometry

Figure 6. Comparison of temperatures calculated over a range of pressures for A) SM-31, a less evolved rhyolite and B) SM-831, an evolved rhyolite. The temperatures were calculated at pressures from 0-15 kbar. Geothermometers that are not pressure sensitive (have no pressure term) are vertical. The degree of pressure sensitivity can then be estimated by the slope of a geothermobarometer's curve. The Benisek 2-Fsp thermometer and the Righter biotite thermometer give anomalously low and high temperatures. The intersections of these thermobarometeric curves are estimates of the crystallization pressure of the system. The Huang and Audétat (2012) Ti in Qz curve crosses most of the less pressure sensitive models between 1-3 kbar, while the Thomas et al. (2010) model for Ti in Qz requires a crystallization pressure of 5 to 13 kbar, much too high for this volcanic system.

Figure 7. Cathodoluminescence (CL) images of quartz in sample SM-831 (A and C) and SM-31 (B and D). Quartz commonly displays oscillatory zoning in CL images. Numbers are Ti concentrations (ppm) determined by LA-ICP-MS. Most of the grains show small oscillations in the brightness and Ti concentrations but individual bands are smaller than the laser spot size (50 microns). Grain B displays evidence of rapid dendritic growth followed by infilling.

Figure 8. Histograms depicting Ti concentration (ppm) in A) Spor Mountain quartz and B) Bishop Tuff quartz (Anderson, 2000). Quartz from Spor Mountain has very low Ti concentrations, which could be explained by either low crystallization temperatures or high pressures.

V. Viscosity

Table 3. Calculated viscosity (in log Pa s) of the Spor Mountain rhyolite

Sample	SM-31	SM-35	SM-14	SM-831	SM-86
Lithology	V	V	V	V	V
Group	LE	LE	EV	EV	EV
Melt viscosity					
Giordani et al.	6.1	6.3	5.9	5.8	5.7
Hui et al.	5.5	5.5	5.5	5.5	5.5
Ardia et al.	8.3	8.3	8.3	8.3	8.3
Magma viscosity					
Einstein-Roscoe	6.6	6.8	7.1	7.0	7.0

Figure 10. Viscosity of the Spor Mountain melt. The Spor Mountain rhyolite has a calculated melt viscosity (using the Giordani et al., 2008 method) comparable to a high-silica rhyolite with between 5 and 6 wt% H₂O. Modified from Best and Christiansen (2000).

Figure 9. Comparison of viscosity models used for the Spor Mountain melt. The models by Giordani et al. (2008) and Hui et al. (2009) are similar (within 1 log Pa*s), whereas the model by Ardia et al. (2008) gives viscosities approx. 2-3 log Pa*s higher. The model developed by Giordani et al. (2008) is taken to be the best fit for the Spor Mountain melt, due to the fact that their model utilizes both a F and H₂O term, whereas the models by Hui et al. (2009) and Ardia et al. (2008) only utilize a H₂O term. For all samples, 5 wt% H₂O was used, and for the Giordani et al. (2008) equation, the weight% measured in the matrix glass (~1 wt% F for less evolved samples and ~2.2 wt% F for evolved samples). Despite its lower temperature, the evolved melt has a lower viscosity due to the increased F content (nearly double that of the less evolved melt). The Einstein-Roscoe equation was used to estimate viscosity of the magmas, assuming 20% crystallinity for the less evolved samples and 40% crystallinity for the evolved samples, based on observations with a petrographic microscope.

VI. Conclusions

• The Be-mineralized Spor Mountain rhyolite (21.4 Ma) is a highly evolved, topaz rhyolite associated with Basin and Range extension.

• The rhyolite formed by partial melting (~30%) of continental crust hybridized with mantle components, followed by extensive fractional crystallization (75% crystallization). (Dailey et al., in preparation).

• Be is highly enriched in the matrix glass (up to 75 ppm), 30 times greater than average continental crust; other rare elements (e.g., Li, Ga, Rb, Nb, Sn, and Ta) are similarly enriched.

• Fractional crystallization set the stage for later hydrothermal alteration, which subsequently concentrated the Be into the Be Tuff Member of the Spor Mountain Formation.

• Water content of the Spor Mountain rhyolite was around 5 wt% H₂O, based on experimental results of Webster et al. (1987).

• Ti-in-Qz, feldspar saturation, two feldspars, and zircon saturation temperatures calculated for the crystallization of the Spor Mountain magma converge at 660° and 710° C, with the evolved rhyolite crystallizing at a slightly lower temperature than the less evolved rhyolite.

• Pressure-dependent geothermobarometers suggest that the Spor Mountain magma crystallized at ~2 kbar, consistent with the experiments of Webster et al. (1987).

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