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Experimental constraints on the origin and evolution of the Bishop Tuff

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The Bishop Tuff has benefited from extensive field, petrological and geochemical studies for more than 50 years to the point of becoming a classical example of a zoned magma chamber in many geological textbooks. The mechanism(s) leading to the development of geochemical zoning in such magmas are still vigorously debated, however. Fractionation mechanisms invoked so far call upon some sort of separation between early formed phenocrysts and liquid (Wallace et al., 1999; Anderson et al., 2000), mixing between various end-members, or on the establishment of chemical gradients within the liquid resulting from thermal gradients in the magma body (Hildreth, 1981). Early work rejected the possibility of fractionation being driven by crystal settling (Hildreth, 1981), but recent melt inclusion studies have resurrected some kind of crystal-liquid separation (Anderson et al., 2000). Interest in the petrogenesis of large silicic magma chambers revived in the early nineties when detailed isotopic work concluded that phenocryst crystallisation in rhyolitic magma chambers might precede by several hundred thousand years the time of eruption (Halliday et al., 1989), implying maintaining largely liquid for protracted periods huge amounts of relatively cold magma in upper crust. This model was questioned, mainly on physical grounds, on the basis that the thermal regime even of large silicic bodies would be unable to ensure magmatic lifetimes in excess of 100 kyr (Sparks et al., 1990), unless the heat supplied by putative underlying basalt strictly balances that resulting from conductive cooling atop the silicic magma body. Subsequent isotopic works have either supported the hypothesis of enhanced longevity (e.g., van den Bogaard and Schirnick, 1995; Reid et al., 1997; Davies and Halliday, 1998) or criticized it (Reid and Coath, 2000).

Central to these issues is the concept of crystal-liquid equilibrium. Indeed, interpreting the textures and compositional variations between matrix glass, phenocrysts and their glass inclusions

in volcanic rocks ultimately rests on whether or not crystal-liquid equilibrium was reached at depth, and if so for how long maintained, before eruption. As an example, the process of crystal growth during sinking advocated by Anderson et al. (2000) to explain the reverse zoning in both trace element and volatile contents of melt inclusions hosted in quartz supposes that the latter sank through a magma column that was continuously oversaturated in quartz in order to avoid dissolution and enable further quartz crystallisation. This implies that, despite the near eutectic bulk composition of Bishop rhyolites together with their multiply saturated or low variance characters (especially in late erupted units), the addition of quartz to an already quartz saturated magma caused further quartz crystallisation. This can be tested by hydrothermal experiments. Crystal-liquid relationships obviously bear upon the mode of generation of rhyolite magmas as well. Remelting of still hot granitoid plutons is a commonly proposed alternative to magmatic fractionation for producing pluton-sized volcanic ejecta (Sparks et al., 1990; Mahood, 1990), in particular to overcome the long standing relative proportion problem of exposed felsic-mafic associations. Given that heating rates by basalt underplating are high, disequilibrium melting conditions are often thought to prevail under such circumstances, and if the Bishop rhyolites were so produced there should be opportunity to find some mineralogical evidence of such disequilibrium, be it with respect to the phase compositions, textures and modal abundances. Although the continuous T-fO₂ trend as well as the progressive and smooth change of feldspar compositions throughout the eruptive sequence (Hildreth, 1979) do not argue for such a mechanism of magma production, disequilibrium in magmatic phase assemblages can be readily addressed through laboratory experiments. Finally, the isotopic age differences between eruption and phenocryst growth have led to the important but as yet untested concept that fractionation in silicic systems might be a discrete rather than a continuous process. If phenocryst growth is the leading factor of differentiation, then this implicitly assumes that crystal growth is also a discontinuous process in magma chambers, a view again at variance with the continuous FeTi oxides and two-feldspars records and also at odds with phase equilibrium constraints. In fact, a common view more or less explicitly stated in isotope-based models is that phenocryst growth is to a large extent decoupled from the differentiation mechanism that gave rise to the Bishop

rhyolites. If so, then crystal-liquid equilibria have little to do with the evolution of silicic magmas in upper crust or, stated otherwise, liquid and crystals largely ignore each other in such contexts.

In this work we use a conventional phase equilibrium approach to evaluate the role of crystal-liquid equilibria on the petrogenetic pathway(s) followed by the Bishop magmas. We build upon previous experimental works carried out on a variety of silicic to andesitic magmas that have clearly shown that severe constraints can be placed on the magmatic conditions of evolution of volcanic/plutonic silicic rocks using phase equilibrium data (Clemens and Wall, 1981; Scaillet and Evans, 1999; Dall'Agnol et al., 1999; Martel et al., 1999). The experimental strategy we have adopted is to perform crystallisation experiments whereby a dry glass obtained by fusing twice the powdered pumice is used as a starting material. This enhances nucleation and avoids the presence of inherited minerals, thus facilitating the interpretation of the experimental data. Among the most notable achievements of such an approach are the phase equilibrium studies of Pichavant (1987) and Holtz et al. (1992) that reinvestigated the haplogranite system under various P-T and water fugacity (f_{H_2O}) conditions, confirming and refining the pioneering work of Tuttle and Bowen (1958). Besides the fact that these works are of direct relevance to the present study, they demonstrate that crystal-liquid equilibrium can be attained or at least very closely approached under laboratory conditions, even in silica-rich systems that display notoriously sluggish kinetics of crystallisation and diffusion, and for which the conventional wisdom predicts that attainment of equilibrium conditions is not possible within reasonable laboratory durations (viz., several weeks). In contrast, the recent works referred to above have demonstrated that comparison of laboratory based results and the magmatic rock record provides one direct and powerful equilibrium test of crystal-liquid relationships in magma chambers prior to eruption. Information gained from such an approach goes beyond this strict test, however. Not only does it give the conditions of chemical equilibrium between liquid and crystals but it provides constraints on phase proportions that can be directly compared to natural modal abundances which in turn allows one to distinguish between bulk and local equilibrium regimes. It also defines the liquid line of descent under the investigated conditions and thus allows one to test for possible parent-daughter relationships between felsic and mafic end members belonging to a common rock suite. All these

points make phase equilibrium a useful tool for understanding petrogenetic processes. Quite surprisingly, despite the pivotal role that Bishop Tuff has played over the last two decades in our understanding of silicic rocks, no detailed phase equilibrium studies have been performed on Long valley silicic magmas (except preliminary data by Rutherford on the Plinian fall (in Johnson et al., 1994)). Thus, although the equilibrium condition between crystal and liquid for radiogenic isotopes has been already extensively evaluated in a number of recent studies, that concerning major elements, a first order observation when interpreting the rock record, still awaits strict assessment.

We are establishing isobaric T-H₂O phase relationships of two representative rhyolite samples that bracket the compositional spectrum displayed by the Bishop eruptive sequence: a pumice from very early in the eruption (Package Ig1Ea; 77.3% SiO₂) and a densely welded glassy fiamma from the Mono lobe (Ig2NWb; 72.6% SiO₂), a late erupted ignimbrite unit. In addition, we are doing experiments on a trachytic pumice (Ig1Eb; 67% SiO₂), a minor but ubiquitous component present throughout much of the eruptive sequence, except in the Plinian, and whose potential petrogenetic importance has been widely ignored. The experimental and analytical techniques are basically the same as in Scaillet and Evans (1999) and are only briefly summarized here. Experiments were performed either in cold seal or internally heated pressure vessels (CSPV or IHPV), using dry powdered glass loaded in Au capsules with variable proportions of H₂O and CO₂, to vary fH₂O. Temperature and pressure are known to $\pm 8^\circ\text{C}$ and 20 bar, respectively. The oxygen fugacity (fO₂) is monitored either using solid sensors or via H₂ membranes (± 0.2 log units). The vessels were pressurized with either Ar or Ar-H₂ mixtures. Most runs were done in the range NN0 to NN0+1, but some in the CSPV were run at NN0+3. Quench was isobaric, and temperature dropped by 100°C in less than 60 s. Run durations varied according to temperature from two to six weeks. Run products characterisation was performed with SEM and EMPA techniques, in addition to optical observations. The water content of quenched melts was determined using the by-difference method. Preliminary P-T conditions were 200 MPa and 700-800°C for the rhyolites, broadly matching available FeTi oxides and melt inclusion thermobarometry constraints (Hildreth, 1979; Wallace et al., 1999). For the trachyte the

temperature coverage was extended up to 850°C. We are now performing phase equilibrium experiments on both the Mono lobe and trachyte compositions at 400 and 600 MPa over a similar temperature interval in an effort to shed light on deeper-level processes.

Phase relationships of the earliest-erupted pumice at 200 MPa display the following remarkable features. At H₂O-saturation, quartz is the liquidus phase appearing at 710°C. It is followed by alkali feldspar at 695°C and then plagioclase at around 680°C. This order of crystallisation is not maintained over all the section, however. At 725°C and for melt water contents of 5 wt%, there is a cross over between plagioclase and alkali feldspar stability curves, so that above 725°C plagioclase is next to quartz in the sequence. Biotite and the oxides (both magnetite and ilmenite) are stable all over the T-H₂O conditions explored. Phase assemblages in which alkali feldspar dominates over plagioclase, as thin section observations demand, imply a restricted set of T-H₂O conditions that are basically in agreement with FeTi oxides and FTIR constraints, that is temperatures lower than 730°C and melt water contents higher than 5 wt%. A final point is that nowhere was pyroxene identified, even at temperatures higher than 737°C, a temperature above which their first appearance is noted in the eruptive sequence (Hildreth, 1979).

The phase relationships of the Mono rhyolite differs from the previous in the following: Plagioclase is now the tectosilicate liquidus phase, crystallizing at 775°C at H₂O-saturation. It is followed by alkali feldspar which appears at 717°C at saturation and then quartz at around 710°C. This crystallisation order is preserved throughout the entire T-H₂O domain explored, the three curves running parallel to each other. The higher liquidus temperature relative to the earlier-erupted rhyolite reflects the less evolved composition of the Mono rhyolite. Biotite and the oxides are equally present everywhere. A notable feature is that, at 200 MPa, only clinopyroxene crystallises, and it does so down to the lowest temperature investigated (717°C). Despite intensive search, both with EPMA and SEM techniques, no evidence for orthopyroxene could be found. We believe that the lack of orthopyroxene is real, reflecting that Mono-like rhyolites are indeed under-saturated in orthopyroxene under the investigated conditions, and is not due to an experimental artefact such as a nucleation problem. One reason for believing so is that previous experimental

work carried out on similar high silica compositions (A-type granites) found no difficulties in delineating a stability field for orthopyroxene (Clemens et al., 1986; Dall'Agnol et al., 1999). Moreover, orthopyroxene is widely present in the trachyte, which was run under T-fH₂O and fO₂ conditions similar to the Bishop rhyolites, and thus inappropriate choice of these intensive parameters cannot be the cause for orthopyroxene absence in the Mono rhyolite.

Clearly then, the equilibrium phase relationships fail in reproducing two of the major mineralogical attributes of the Bishop Tuff, namely, (1) the presence of orthopyroxene, which in the rock occurs in equal, or even slightly higher, proportion relative to the clinopyroxene, and (2) the fact that plagioclase is subordinate to the other tectosilicates whereas in the experiments it predominates over alkali feldspar and quartz. This is despite that the investigated conditions broadly conform to those indicated by thermobarometric analyses. Albeit the experimental pressure could be 50-70 MPa too low (Wallace et al., 1999), such a pressure difference is not expected to dramatically alter the topology, in particular the plagioclase to alkali feldspar relative order of crystallisation (Holtz et al., 1992). Thus taken at face value this result would indicate that the phase assemblage in late erupted units, notably the cotectic proportion of tectosilicates, is largely out of equilibrium if the magma were residing at around 200 MPa (7 km) before eruption. If this were true, models of enhanced longevity need to account for maintaining such outstanding disequilibrium while preserving delicate textural evidence of equilibrium. In the rocks, both alkali feldspar and orthopyroxene display euhedral shapes hardly indicative of ongoing dissolution. The alternative is to consider that the thermobarometric estimates are somehow incorrect. Given that FeTi oxides constraints work pretty well in the fO₂ range of the Bishop Tuff (Evans and Scaillet, 1997), it appears that pressure, as estimated from melt inclusion data, might be in error. Because orthopyroxene is in general more stable at high pressure, we decided to extend to higher pressures our experimental study. This work is in progress now.

The trachyte has the same experimental mineralogy as the Mono rhyolite, except that it crystallises orthopyroxene and that, conversely, no clinopyroxene could be found. Plagioclase is also the tectosilicate liquidus phase crystallising at 860°C at H₂O-saturation, quartz and alkali

feldspar appearing in that order at a temperature around 750°C. In contrast to both rhyolite compositions, the biotite stability field is restricted to the water-rich portion of the diagram, and it displays a broad peritectic relation with orthopyroxene, which is never stable at H₂O saturation or below 775°C. Biotite may be the liquidus phase at H₂O-saturation. Magnetite is the first oxide to crystallise, followed by ilmenite at lower fH₂O. At 400 MPa, the phase relationships are basically the same. At H₂O-saturation, plagioclase crystallises at around 830°C, whereas quartz and alkali feldspar appear below 750°C. There is, however, a major difference relative to 200 MPa in that amphibole is stable at 400 MPa, although it occupies a rather small T-H₂O domain, centered at 800°C and intermediate melt water contents. This finding might be of real significance since the phenocryst-poor trachyte pumice does have amphibole but no orthopyroxene, in addition to quartz, two-feldspars, and biotite phenocrysts. The very small stability field of amphibole in the trachyte at 400 MPa implies that this pressure is possibly a minimum for amphibole crystallisation in such potassium-rich compositions. In fact, application of the Al-in-hornblende barometer to the natural hornblende in trachyte gives pressures in the range 500 to 600 MPa which also point to significant higher pressure storage conditions for the trachyte before incorporation and co-eruption with the Bishop rhyolites, if amphibole is indeed phenocrystic. Additional experiments are underway at 600 MPa, to explore the phase equilibria behaviour of the trachyte under middle to lower crust conditions.

In summary, the phase equilibrium constraints suggest that early-erupted rhyolites were close to equilibrium prior to eruption while later erupted units were not if their pressure of storage was close to 200 MPa. Experiments carried out on the trachyte component suggest that the magma reservoir may have been tapped down to levels corresponding to pressures of 400 MPa. These arguments have to be taken chiefly as indications for future work, however. In particular, phase relationships currently being worked out for the Mono rhyolite at 400 MPa and 600 MPa should establish whether such high pressure phase equilibria can fit natural observations. In addition, the compositions of all coexisting phases, including liquids, should provide an additional, we hope more definitive, test on the role of crystal-liquid equilibria in the Bishop Tuff evolution. Such analytical work is in progress and we expect to present the general results at the meeting.

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