Pre-eruption recharge of the Bishop magma system

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DATA REPOSITORY ITEMS

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DR1. Summary of Ti analyses of Bishop quartz

Table DR1.

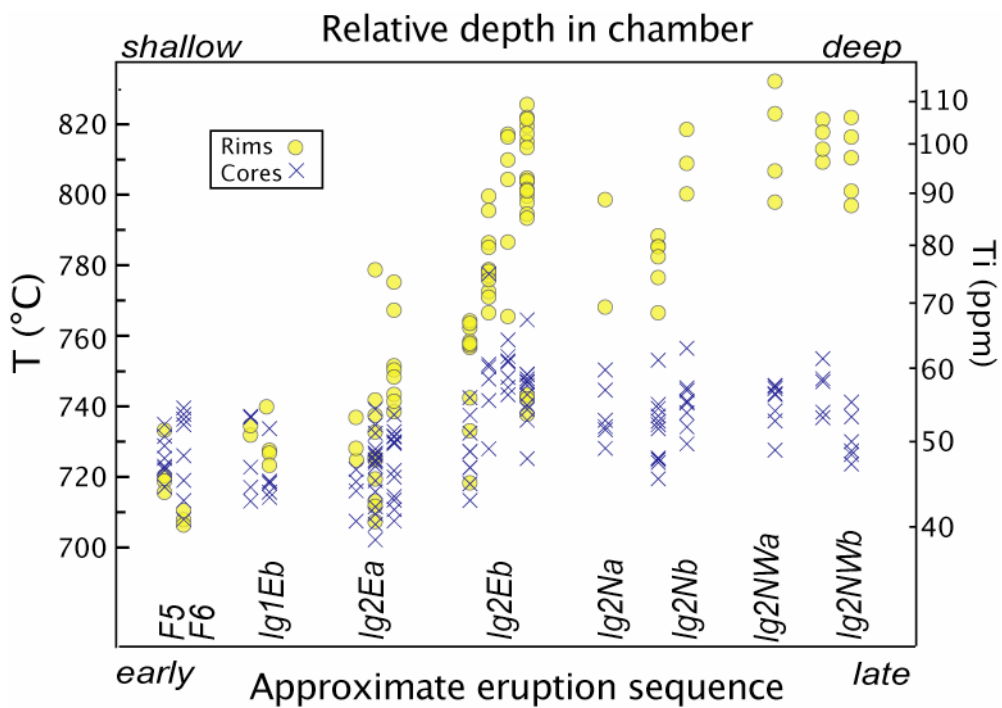| Sample Number	Eruption Package	Mean Ti (ppm) in Quartz Cores [b,c]	T, avg (°C)	Mean Ti (ppm) in Quartz Rims [b,c]	T,avg (°C)
B-83	F5	47.8 ± 2.6 (8)	721	45.3 ± 3.2 (4)	715
B-657	F6	48.5 ± 5.3 (8)	722	39.8 ± 0.8 (3)	700
B-94	Ig1Eb	47.9 ± 4.9 (5)	721	50.1 ± 1.1 (2)	726
B-80	Ig1Eb	45.0 ± 2.8 (6)	714	48.2 ± 3.3 (4)	722
B-413B	Ig2Ea	44.3 ± 3.5 (6)	712	46.5 ± 4.7 (4)	718
B-315A	Ig2Ea	45.2 ± 3.9 (19)	715	49.3 ± 10.6 (10)	728
B-125	Ig2Ea	48.3 ± 3.2 (4)	722	63.0 ± 11.8 (2)	753
B-439A	Ig2Eb	46.0 ± 3.7 (9)	716	58.6 ± 7.0 (10)	745
B-397	Ig2Eb	57.2 ± 7.8 (6)	742	74.9 ± 6.3 (11)	775
B-394C	Ig2Eb	56.9 ± 3.2 (7)	741	87.7 ± 13.2 (6)	795
B-412B	Ig2Eb	54.5 ± 4.7 (12)	736	86.5 ± 16.0 (19)	793
B-133	Ig2Na	53.5 ± 4.0 (6)	734	76.7 ± 13.0 (2)	778
B-69	Ig2Nb	51.5 ± 4.3 (11)	729	75.1 ± 4.4 (6)	775
B-514D [a]	Ig2Nb	55.2 ± 4.0 (8)	737	93.7 ± 6.8 (3)	804
B-610C	Ig2NWa	54.9 ± 3.1 (8)	737	98.2 ± 11.8 (4)	810
B-77	Ig2NWb	56.9 ± 3.5 (5)	741	98.2 ± 3.9 (4)	810
B-529A [a]	Ig2NWb	50.2 ± 3.2 (6)	726	93.7 ± 7.7 (5)	804

[a] B-514D and B-529A are dark, "enriched" pumices
[b] Reported analyses determined by ion microprobe except for B-413B and all Ig2Eb samples; Sample B-315A was analyzed by both ion and electron microprobes.
[c] Also shown are standard deviation and number of analyses (in parentheses).
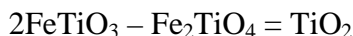
Figure DR1.
Plot of individual Ti analyses and TitaniQ temperatures for Bishop quartz.

DR 2. Calculation of TiO₂ activity from ilmenite + magnetite assemblages

Equilibrium between ilmenite and magnetite can be used to define the activity of TiO_2 through the relationship

$$2FeTiO_3 - Fe_2TiO_4 = TiO_2$$

And

$$K = \frac{a_{TiO_2}}{\left(a^{Ilm}_{FeTiO_3}\right)^2 a^{Mag}_{Fe_2TiO_4}}$$

Choosing as a standard state the pure phases ilmenite, ulvöspinel, and rutile at the temperature and pressure of interest, the value of the equilibrium constant can be calculated from tabulated thermodynamic data and the value of $a(TiO_2)$ relative to pure rutile can be calculated from the compositions of coexisting ilmenite and magnetite.

In this study, the thermodynamic data of Holland and Powell (1998) was used at the temperature of the Fe-Ti oxide pair as calculated from the thermometer of Andersen and Lindsley (1988), from new Fe-Ti oxide analyses of Bishop Tuff samples presented in Hildreth and Wilson (in review). Ideal solution models were assumed for both ilmenite and spinel.

References

Andersen, D.J. and Lindsley, D.H. (1998) Internally consistent solution models for Fe-Mg-Mn-Ti oxides: Fe-Ti oxides. American Mineralogist, 73, 714-726.

Hildreth, W., and Wilson, C.J.N., (in review) Compositional zoning of the Bishop Tuff: Journal of Petrology.

Holland, T.J.B., and Powell, R. (1998) An internally-consistent thermodynamic dataset for phases of petrological interest. Journal of Metamorphic Geology, 16, 309-343.

Table DR2. Calculated $a(TiO_2)$ values

Sample	X_{Ilm}	X_{Usp}	T C	$a(TiO_2)$
525A	0.863	0.262	702	0.58
525A	0.840	0.263	748	0.63
522C	0.762	0.261	818	0.63
355B	0.841	0.238	719	0.64
332C	0.770	0.292	834	0.60
383B	0.856	0.244	716	0.64
610c	0.775	0.251	803	0.65

250	0.807	0.245	756	0.63
275	0.824	0.242	762	0.68
275_2	0.808	0.249	782	0.67
276	0.833	0.245	753	0.67
277_b	0.784	0.255	795	0.64
277_A	0.796	0.306	816	0.58
279	0.831	0.253	760	0.66
290	0.771	0.257	810	0.64
294	0.839	0.260	725	0.60
315A	0.835	0.263	764	0.65
327	0.783	0.259	802	0.64
353F	0.848	0.264	733	0.61
358_a	0.851	0.253	728	0.63
358_b	0.843	0.265	749	0.63
364_a	0.814	0.259	768	0.63
364_b	0.833	0.258	745	0.63
			Mean	0.63 ± 0.03

DR3. Temperature and melt Ti content.

Here we address a common misconception regarding the relationship between
temperature and the Ti content of a rhyolite melt and of the quartz that precipitates from
that melt. Readers will recognize that the Ti concentrations reported for Bishop melt and
quartz co-vary, in the sense that (a) melt inclusions in quartz, and the quartz itself, both
contain higher Ti contents rim-ward, and (b) Ti contents of matrix (groundmass) glass
and of the rims of quartz crystals increase with eruption sequence (downward in the
magma chamber). A correlation between the Ti content of quartz and the Ti content of
the host melt is not surprising, of course, because the Ti content of quartz reflects the Ti
content of the melt from which it crystallizes, as described by a partition coefficient. This
does not, however, imply that the Ti content of quartz is not dependent on temperature,
because at uniform TiO_2 activity, *the Ti content of the host melt is temperature
dependent, too*.

For application of the TitaniQ thermometer (Wark and Watson, 2006), TiO_2 activity is
expressed as the amount of TiO_2 present relative to the amount of TiO_2 required for rutile
saturation. At high enough TiO_2 concentration in a melt, the mineral rutile (TiO_2) will
precipitate and a_{TiO2} will be one. The concentration of Ti (ppm) in the melt can be
calculated from:

$$\log(X_{Ti}^{melt}) = (7.95) - \frac{(5305)}{T(K)} + 0.124 \cdot FM$$

which is the rutile solubility equation of Hayden et al. (2005) that is discussed in Wark
and Watson (2006). The amount of TiO_2 in any quartz precipitating from the melt can
also be calculated, using equation (6) of Wark and Watson (2006):

$$\log(X_{Ti}^{qtz}) = (5.69) - \frac{(3765)}{T(K)}.$$

For this rutile-saturated case, as long as rutile remains a stable phase, a_{TiO2} will remain
unchanged (unity), even if temperature varies. However, any temperature increase will
result in dissolution of some rutile, thereby increasing the concentrations of TiO_2 in the
melt *and in quartz crystallizing from it*. Any temperature decrease will result in additional
crystallization of rutile, thereby lowering the TiO_2 concentration in the melt, *while also
lowering the TiO_2 concentration in any quartz that precipitates from that melt*. In other
words, the concentrations of TiO_2 in the melt and in the quartz change (as described by
the equations above) with changing T, but the activity of TiO_2 remains fixed.

The same principles apply even if rutile is not present, as long as TiO_2 activity is
relatively well "buffered" by the mineral assemblage. As temperature goes up, more of
the Ti-essential phases (such as ilmenite, in the case of the Bishop magma) go into
solution. Consequently the TiO_2 content of both the melt, and of the quartz crystallizing

from the melt, increase. As temperature decreases, more ilmenite will precipitate, lowering the TiO_2 content of the melt and of newly precipitated quartz. As discussed by Wark and Watson (2006), the TiO_2 content of each should follow curves like those for the $a_{TiO2}=1$ case, but displaced downward on the plot of log(Ti) vs 1/T.

This reasoning explains, then, the observation that the TiO_2 content of Bishop melt (both matrix melt, and melt trapped as inclusions in feldspar and quartz) is variable, and that it tracks the trends shown by quartz. Since TiO_2 activity in Bishop magma was relatively well "buffered" by the presence of magnetite and ilmenite over a temperature range of roughly 100°C (see DR2 above), the variation in Ti content of both melt and of quartz must be attributed to the temperature differences.

DR4. Mafic recharge: thermal calculations

Using standard heat balance equations, we estimated that a minimum of $20 - 25$ km^3 of mafic melt was required to account for the observed amount of crystal resorption, using the following assumptions:

  Volume of magma heated: 15 to 20% of the erupted volume (650 km^3)
  Crystal content of the volume heated: 40%
  Amount of phenocryst resorption: 15%

  Temperature drop in mafic melt: 200°C
  Crystallization of mafic melt during cooling: 40%

  Average temperature increase in Bishop magma: 60°C

The following constants were used:

  Mafic recharge melt
  　　　Density　　　　　2900 Kg m^{-3}
  　　　Latent heat　　　 4×10^5 J Kg^{-1}
  　　　Heat capacity　　 1484 J Kg^{-1} K^{-1}

  Silicic (Bishop) magma
  　　　Density　　　　　2250 Kg m^{-3}
  　　　Latent heat　　　 2.7×10^5 J Kg^{-1}
  　　　Heat capacity　　 1370 J Kg^{-1} K^{-1}