

Pre-eruption recharge of the Bishop magma system

D.A. Wark* Department of Earth & Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York 12180, USA

W. Hildreth U.S. Geological Survey, MS-910, Menlo Park, California 94025, USA

F.S. Spear

D.J. Cherniak } Department of Earth & Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York 12180, USA

E.B. Watson }

ABSTRACT

The 650 km³ rhyolitic Bishop Tuff (eastern California, USA), which is stratigraphically zoned with respect to temperatures of mineral equilibration, reflects a corresponding thermal gradient in the source magma chamber. Consistent with previous work, application of the new TitaniQ (Ti-in-quartz) thermometer to quartz phenocryst rims documents an ~100 °C temperature increase with chamber depth at the time of eruption. Application of TitaniQ to quartz phenocryst cores, however, reveals lower temperatures and an earlier gradient that was less steep, with temperature increasing with depth by only ~30 °C. In many late-erupted crystals, sharp boundaries that separate low-temperature cores from high-temperature rims cut internal cathodoluminescent growth zoning, indicating partial phenocryst dissolution prior to crystallization of the high-temperature rims. Rimward jumps in Ti concentration across these boundaries are too abrupt (e.g., 40 ppm across a distance of <10 µm) to have survived magmatic temperatures for more than ~100 yr. We interpret these observations to indicate heating-induced partial dissolution of quartz, followed by growth of high-temperature rims (made possible by lowering of water activity due to addition of CO₂) within 100 yr of the climactic 760 ka eruption. Hot mafic melts injected into deeper parts of the magma system were the likely source of heat and CO₂, raising the possibility that eruption and caldera collapse owe their origin to a recharge event.

Keywords: Long Valley caldera, Bishop Tuff, mafic recharge, thermal rejuvenation, rhyolite.

INTRODUCTION

The Bishop Tuff, a sheet of rhyolitic ignimbrite and fallout that was deposited 760 k.y. ago during collapse of the Long Valley caldera (eastern California, USA), is the classic example of a large-volume eruption product that sequentially tapped a chemically and thermally zoned magma system. As first described by Hildreth (1979), increases in temperature (from ~720 to 800 °C), crystal content (from 5% to 25%), and abundances of trace elements that are concentrated within crystallizing phases (such as Ba, Sr, and Zr) occurred with increased chamber depth. During the past quarter century, a general consensus has emerged about the origins of these patterns. Chemical stratification, for example, can be at least partly explained by upward segregation of highly fractionated melts, leaving a cumulate crystal-melt mush at depth. Thermal stratification is consistent with loss of heat to the cool roof, combined with influx of heat from depth, presumably due to injections of basaltic melts that are required to sustain the longevity of magmatism. Gradients in crystallinity can be explained by lower solidus temperatures in the upper parts of the chamber, where H₂O contents are highest (Dunbar and Hervig, 1992; Hildreth, 1979; Wallace et al., 1999).

However, core to rim changes in the composition of trapped melt inclusions in, and in the trace

element contents of, late-erupted phenocrysts that originated deep within the magma chamber are more difficult to explain. Melt inclusions nearest the rims of some quartz phenocrysts are richer in CO₂ and in the same trace elements (Ba, Sr, Zr) that are enriched downward in the magma chamber (Anderson et al., 2000). Sanidine crystals from the same late-erupted pumices are also zoned, exhibiting sharp increases in concentrations of Sr and Ba close to their rims (Hervig and Dunbar, 1992; Anderson et al., 2000). These observations seemingly require a unique explanation, because crystal growth during cooling should lead to opposite trends. One possibility, proposed by Anderson et al. (2000) based in part on the relatively high CO₂ in melt inclusions close to the rims of quartz, is that these zoning patterns reflect sinking of crystals into progressively deeper and hotter magma, into which a Ba-, Sr-, and Zr-rich component had been added.

In this paper we use a new Ti-in-quartz thermometer to confirm that the rims of zoned quartz crystals grew from melt hotter than that from which the cores grew. We propose, however, an alternative explanation for higher-temperature rim growth. Instead of crystal sinking, we argue that all mineral-scale zoning patterns, as well as the relatively steep temperature gradient documented by other mineral thermometers (Bindeman and Valley, 2002; Hildreth, 1979; Peppard et al., 2001), are best explained by thermal reju-

venation and CO₂-induced crystallization due to deep injection of hot, CO₂-rich mafic melt. Based on evidence that high-temperature rim growth on quartz likely took place within 100 yr of Bishop Tuff emplacement, we also speculate that this recharge event may have triggered the 760 ka caldera-forming eruption.

Ti IN BISHOP QUARTZ

Bishop quartz crystals are zoned not only with respect to melt inclusion composition, but also in the intensity of their cathodoluminescence (CL) emissions. Peppard et al. (2001) first described this for late-erupted phenocrysts, in which a sharp interface separates bright CL rims from darker cores. Knowing that CL intensity can be related to Ti content (Wark and Spear, 2005), and in turn crystallization temperature (Wark and Watson, 2006), we suspected that valuable thermal information was retained in Bishop quartz. To explore this possibility, we obtained CL images (Fig. 1) and analyzed (by ion and electron microprobes) the Ti distribution in quartz from samples representing the entire Bishop eruption sequence.

Ti concentrations (Fig. 2; GSA Data Repository item DR1¹) were converted to crystallization temperatures using the TitaniQ thermometer (Wark and Watson, 2006), which specifies that the temperature, *T*, of quartz equilibration can be determined from its Ti content in ppm (*C*_{Ti}) according to

$$T(\text{K}) = -3765 / [\log(C_{\text{Ti}}/a_{\text{TiO}_2}) - 5.69], \quad (1)$$

where *a*_{TiO₂} is defined as the activity of TiO₂ relative to that required for rutile saturation (where *a*_{TiO₂} = 1). To apply the TitaniQ to Bishop quartz, we set *a*_{TiO₂} = 0.6, based on (1) calculated *a*_{TiO₂} of 0.5–0.6 for Bishop melts, based on a new TiO₂ saturation model for rhyolite (Hayden et al., 2005), and (2) a value of 0.63 ± 0.03, which was calculated from equilibria among 23 pairs of coexisting FeTi oxides from the entire eruption sequence, using the relation 2 ilmenite =

¹GSA Data Repository item 2007052, DR1 (summary of Ti analyses of Bishop quartz), DR2 (calculation of Ti activity), DR3 (temperature and melt Ti content), and DR4 (mafic recharge: thermal calculations), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

*E-mail: warkd@rpi.edu.

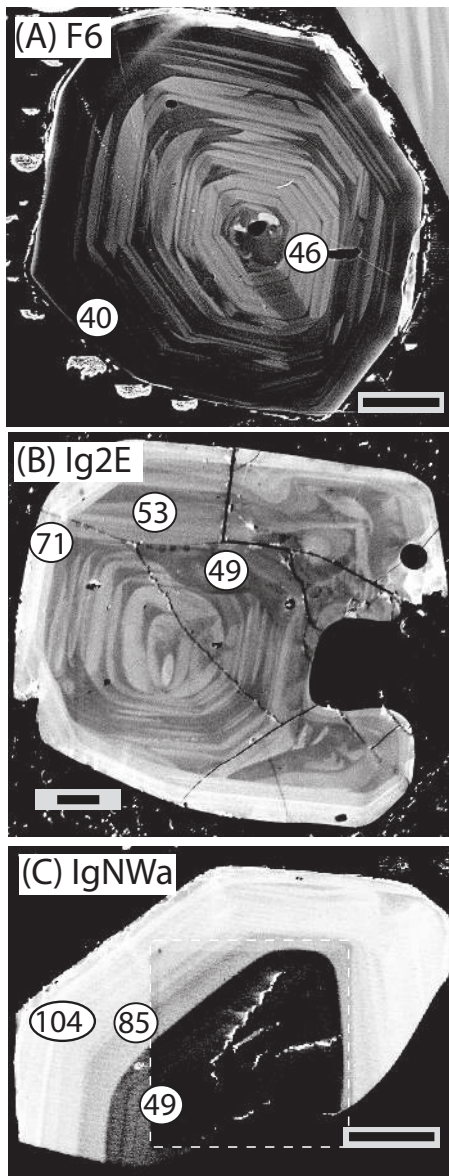


Figure 1. Cathodoluminescence images of Bishop quartz from (A) early pumice-fall deposit F6, (B) mid-sequence ignimbrite Ig2E, and (C) late-erupted ignimbrite Ig2NWa. Eruption temperatures from FeTi oxide thermometry are ~730 °C and 800 °C for A and C, respectively. Numbers in circles are Ti content of different zones in each crystal (in ppm). Scale bars = 250 μm in each. Darkened area in C, enclosed by dashed line, is due to beam damage.

ulvospinel + TiO₂ (DR2; see footnote 1). All calculations indicate that a_{TiO_2} was relatively uniform throughout the erupted volume (despite temperature differences), which can be explained by the fact that all of the erupted magma was near eutectic with the same mineral phases (except for addition of late minor pyroxene) and similar melt and mineral compositions. Evidence from magnetite inclusions indicates that a_{TiO_2} was also the same throughout the history

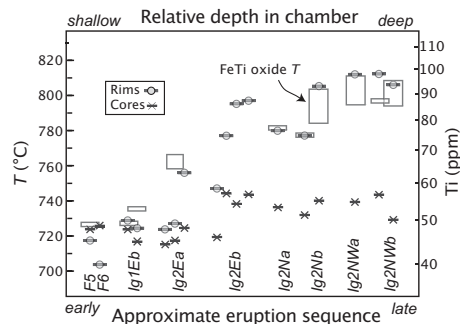


Figure 2. Plots of average Ti contents and TitaniQ temperatures (T) for rims (circle with line) and cores (X with line) of Bishop Tuff quartz phenocrysts, as function of stratigraphic position and presumed relative depth in magma chamber. Ranges of available FeTi oxide temperatures for ten of the pumices are shown by shaded boxes. Eruption package names along bottom axis use nomenclature of Wilson and Hildreth (1997). Rim analyses are from bright cathodoluminescence (CL) rim zones for crystals with strong CL zoning, or are from spots <100 μm from crystal edge for quartz lacking bright CL rims; core analyses include all others (see footnote 1 for more details).

of quartz crystallization. Magnetite inclusions in late-erupted quartz, for example, vary little in Ti content, but with respect to minor element concentrations they include two populations (Lu and Anderson, 1991; Anderson et al., 2000), one of which resembles magnetite from early-erupted (lower temperature) phenocrysts. This observation is consistent with constant a_{TiO_2} but variable temperature during quartz growth. In addition, melt inclusions, regardless of position within a crystal, are uniform (high-silica rhyolite) in major element composition (e.g., Anderson et al., 2000; Dunbar and Hervig, 1992). Their Ti content, however, varies twofold (most analyses in the 400–900 ppm range), which is close to the range (373–933 ppm) expected for a rhyolite magma with TiO₂ activity fixed at 0.6, but with differences in temperature of ~100 °C (for further discussion see DR3; see footnote 1).

CL images (Fig. 1) confirm that quartz rims in all but early-erupted pumices are brighter than phenocryst cores. Rim thickness and CL emission intensity tend to increase with eruption sequence (and presumably with depth in chamber). Ti concentrations in the quartz phenocryst rims (from ~40–100 ppm), and to a lesser extent in the cores (from ~45–55 ppm) (DR1 [see footnote 1]; Fig. 2) also increase with eruption sequence.

TitaniQ temperatures based on Ti concentrations in quartz rims closely match eruption temperatures based on FeTi oxides (available for 10 of the 17 pumices examined; Fig. 2), increasing with eruption sequence from ~720 to 810 °C.

TitaniQ temperatures from the cores of quartz phenocrysts, in contrast, record a much smaller temperature increase with eruption sequence, from ~720 to 750 °C. We interpret these results to indicate that early quartz (represented by cores) crystallized in a chamber with only a modest temperature gradient, but that phenocryst rims crystallized in a gradient that was much steeper, as suggested by Lu and Anderson (1991) based on compositions of magnetite inclusions.

Although consistent with earlier suggestions that rims of late-erupted quartz grew at higher temperatures than cores, our observations do not support crystal sinking for several reasons: (1) sinking should result in a gradual increase of Ti content rimward, but it instead always jumps abruptly (sometimes in steps) from the dark CL core to the bright rim; (2) in many crystals, the high- T rims truncate internal CL zoning (e.g., Fig. 1B), an observation attributed to partial resorption; and (3) if deep, ~800 °C, silica-saturated magma had been resident in the Bishop magma chamber for the tens of thousands of years required for sinking, phenocrysts with Ti-rich cores should also be present, but to our knowledge they are rare, or do not exist.

MAFIC RECHARGE

In view of the sharp and sometimes discordant CL contact (interpreted as a former dissolution surface) separating low-temperature cores from high-temperature rims in quartz, we propose a different explanation: the quartz-saturated magma was heated from below by deep injection of hot mafic melt. Heating associated with mafic recharge explains the steepening of the temperature gradient that caused partial dissolution. It also explains why the crystals affected are those from the deepest levels tapped by eruption: the low thermal conductivity of silicate melts combined with the latent heat of resorbing crystals would have limited upward conduction of heat (Mahood, 1990). Even deeper, more crystal-rich horizons would have also acted as mechanical barriers to ascent of recharge melts, explaining the absence of quenched mafic melt in eruption products.

The relatively deep, crystal-rich cumulate magma—which presumably separated mafic recharge melts from the shallower horizons that ultimately erupted—would have also been subjected to heating and phenocryst resorption, producing rhyolitic melts enriched in elements such as Ba and Sr (both concentrated in feldspars) and Zr (from zircon). Upward migration of such melt, and its addition to the base of the magma column that was later erupted, is required to explain core to rim changes in the trace element contents of feldspars and of melt inclusions in quartz from late-erupted Bishop Tuff (Dunbar and Hervig, 1992; Hervig and Dunbar, 1992). This enriched melt may be represented by sub-

ordinate, but widely distributed, crystal-poor pumice clasts of low-silica (71%–74% SiO₂) rhyolite that yield FeTi oxide temperatures as high as 820 °C (Hildreth and Wilson, 2007).

Whereas some components (e.g., Ba, Sr, and Zr) added to the deepest-erupted magma likely originated by heating and partial dissolution of crystals in underlying crystal mush, the relatively high amounts of dissolved CO₂ in melt inclusions near rims of late-erupted quartz probably originated in the deeper mafic recharge melts. The CO₂-rich nature of eastern California basalts is evident: more than 100 t of magmatic CO₂ percolate upward near the western margin of Long Valley caldera daily (Sorey et al., 1998). Similar gases would have been released from basaltic melts added to the bowels of the pre-eruption magma system. As inferred for other systems (Bachmann and Bergantz, 2003), rising volatiles potentially served to transport heat.

The added CO₂ likely played another important role. Because of the near-eutectic nature of Bishop magma, partial dissolution of quartz followed by new growth at higher temperature requires an increase in solidus temperature. The simplest way to raise the solidus in a wet system is to reduce $a_{\text{H}_2\text{O}}$. In the Bishop magma reservoir, reduction of $a_{\text{H}_2\text{O}}$ would have resulted from the addition of CO₂. Diffusive transport of both H₂O (into CO₂-rich bubbles) and CO₂ (from bubbles into melt) is slower than heat conduction, perhaps explaining why partial dissolution took place before renewed, higher-temperature quartz growth.

Our observations show that once high-temperature rims on quartz started to grow, crystallization continued at high temperatures until eruption. That is, deep magma did not cool to pre-recharge conditions. This implies a relatively short time between the heating event and quenching by eruption. We can evaluate this possibility by analyzing the shape of the Ti concentration profile across a discordant boundary separating core from rim: the longer a phenocryst resided at high temperature, the shallower the profile, because gradients would be modified by diffusion. Our CL images (which reflect Ti concentration; Wark and Spear, 2005) and Ti analyses reveal that the profile is invariably steep (Fig. 3). In many late-erupted phenocrysts, Ti increases by ~40 ppm (a doubling of Ti content) across a distance of <10 μm. Based on measured diffusivities of Ti in quartz (Cherniak et al., 2006), this distance corresponds to the width of an interdiffusion zone that would develop in quartz at 800 °C in ~100 yr (FeTi oxides, in contrast, reequilibrate by diffusion on time scales of days to months [see Devine et al., 2003] and hence preserve no evidence of lower-temperature growth).

The upper limit (we assume an initial step-function profile, but it may have been less

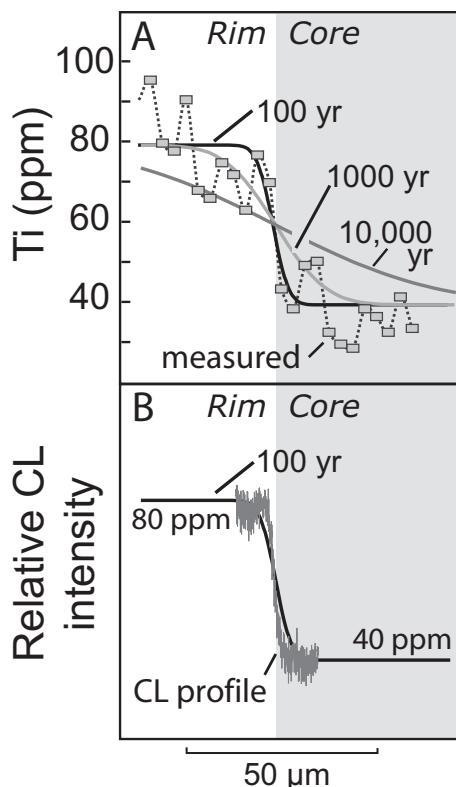


Figure 3. Ti concentration profiles in (A) and cathodoluminescence (CL) intensity in (B) across interface separating core from rim in representative quartz from package Ig2NWa. CL intensity serves as proxy for Ti concentration. Thick lines show model diffusion profiles assuming initial step function Ti concentration profile modified by diffusion for times of 100, 1000, and 10,000 yr at temperature of 800 °C, using diffusivity of 3×10^{-21} m²/s.

steep) for the time elapsed after onset of rim growth and eruption appears to be ~100 yr. That is, the high-temperature rims probably first started forming <100 yr before the 760 ka Bishop eruption, a short time compared with the ~100 k.y. history of the magma system (Reid and Coath, 2000; Simon and Reid, 2005). This close correspondence in time may not be a coincidence: large-volume, caldera-forming eruptions may be triggered by a sharp increase in the rate of mafic input, probably because it leads to overpressurization in response to volatile exsolution (e.g., Folch and Marti, 1998; Snyder, 2000).

We are not able to estimate the time elapsed between recharge and onset of crystal dissolution, or between onset of dissolution and growth of the high-temperature rims. Several variables, such as mass of recharge melts, depth of recharge, and mode of heat transport, are unknown. In any case, it is unlikely that there was a single recharge pulse. Evidence of multiple pulses appears to be recorded by bands of

different (but high) CL intensity and Ti content (e.g., Fig. 1C) in some quartz rims. Each recharge pulse likely resulted in some dissolution, thereby partially or completely erasing evidence of earlier thermal events.

We estimate that ~20–25 km³ of basalt would be required to heat 15%–20% of the erupted volume (650 km³) and to partially dissolve its phenocrysts (DR4; see footnote 1). However, the absence of mafic melt inclusions in erupted Bishop magma indicates that recharge took place at a depth greater than the deepest level erupted. This implies a greater volume of recharge melt simply because a larger mass of silicic magma (the more crystalline magma separating the mafic melts from the shallower volume later erupted) had to be heated. In comparison, only relatively small batches (most <1 km³) of mafic melt have reached the surface throughout the magmatic history at Long Valley, reinforcing the role played by intrusive (nonerupted) mafic melts in the generation and evolution of large-volume rhyolite magma systems (Hildreth, 1979, 2004).

CONCLUSIONS

Our results, summarized in Figure 4, are interpreted to indicate that the strong temperature and melt-compositional gradients present in the chamber at the time of eruption were transient features that were likely imposed <100 yr earlier. However, the overall zoning pattern in the Bishop magma system (cooler and more differentiated upward) was apparently a long-lived feature, as shown by changes with eruption sequence in (1) the uranium content of zircons with ages predating eruption by tens of thousands of years (Simon and Reid, 2005), (2) trace element contents of melt inclusions from the interiors of feldspar and quartz phenocrysts (Dunbar and Hervig, 1992; Wallace et al., 1999), and (3) the Ti contents of quartz phenocryst cores.

Reverse-zoned (bright CL, high-Ti rims) igneous quartz has recently been found in both volcanic (e.g., Bandelier Tuff, New Mexico; Wark and Wolff, 2006) and intrusive (Vinalhaven granite, Maine; work in progress by first author in collaboration with R. Wiebe) systems. In each case, the likely explanation is heating associated with mafic recharge. We suspect that growth of high-temperature quartz in each system, as in the Bishop system, can be explained by reduced water activity due to influx of CO₂. If mafic melts had instead been H₂O rich we would expect quartz dissolution, but not later reprecipitation at higher temperature (Wark and Bachmann, 2005). This raises the possibility that the response of quartz to a recharge event will be a function of tectonic setting, because H₂O-rich magmas are principally found at convergent plate margin settings.

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REFERENCES CITED

- Anderson, A.T., Davis, A.M., and Lu, F., 2000, Evolution of Bishop Tuff rhyolitic magma based on melt and magnetite inclusions and zoned phenocrysts: *Journal of Petrology*, v. 41, p. 449–473, doi: 10.1093/ptrology/41.3.449.
- Bachmann, O., and Bergantz, G.W., 2003, Rejuvenation of the Fish Canyon magma body; a window into the evolution of large-volume silicic magma systems: *Geology*, v. 31, p. 789–792, doi: 10.1130/G19764.1.
- Bindeman, I.N., and Valley, J.W., 2002, Oxygen isotope study of the Long Valley magma system, California; isotope thermometry and convection in large silicic magma bodies: *Contributions to Mineralogy and Petrology*, v. 144, p. 185–205.
- Cherniak, D.J., Watson, E.B., and Wark, D.A., 2006, Ti diffusion in quartz: *Chemical Geology*, v. 236, p. 65–74.
- Devine, J.D., Rutherford, M.J., Norton, G.E., and Young, S.R., 2003, Magma storage region processes inferred from geochemistry of Fe-Ti oxides in andesitic magma, Soufrière Hills Volcano, Montserrat, W.I: *Journal of Petrology*, v. 44, p. 1375–1400, doi: 10.1093/ptrology/44.8.1375.
- Dunbar, N.W., and Hervig, R.L., 1992, Petrogenesis and volatile stratigraphy of the Bishop Tuff—Evidence from melt inclusion analysis: *Journal of Geophysical Research*, v. 97, p. 15,129–15,150.
- Folch, A., and Marti, J., 1998, The generation of overpressure in felsic magma chambers by replenishment: *Earth and Planetary Science Letters*, v. 163, p. 301–314.
- Hayden, L.A., Watson, E.B., and Wark, D.A., 2005, Rutile saturation and TiO₂ diffusion in hydrous siliceous melts: *Eos (Transactions, American Geophysical Union)*, v. 86, Fall meeting supplement, abs. MR13A-0076.
- Hervig, R.L., and Dunbar, N.W., 1992, Cause of chemical zoning in the Bishop (California) and Banderli (New Mexico) magma chambers: *Earth and Planetary Science Letters*, v. 111, p. 97–108, doi: 10.1016/0012-821X(92)90172-R.
- Hildreth, W., 1979, The Bishop Tuff; Evidence for the origin of compositional zonation in silicic magma chambers, *in* Chapin, C.E. and Elston, W.E., eds., *Ash-flow tuffs*: Geological Society of America Special Paper 180, p. 43–75.
- Hildreth, W., 2004, Volcanological perspectives on Long Valley, Mammoth Mountain, and Mono Craters: Several contiguous but discrete systems: *Journal of Volcanology and Geothermal Research*, v. 136, p. 169–198, doi: 10.1016/j.jvolgeoes.2004.05.019.
- Hildreth, W., and Wilson, C.J.N., 2007, Compositional zoning of the Bishop Tuff: *Journal of Petrology* (in press).

- Lu, F., and Anderson, A.T., 1991, Mixing origins of volatile and thermal gradients in Bishop magma: *Eos (Transactions, American Geophysical Union)*, Spring meeting abstracts, p. 312.
- Mahood, G.A., 1990, Evidence for long residence times of rhyolitic magma in the Long Valley magmatic system: The isotopic record in the precaldera lavas of Glass Mountain: Reply: *Earth and Planetary Science Letters*, v. 99, p. 395–399, doi: 10.1016/0012-821X(90)90145-N.
- Peppard, B.T., Steele, I.M., Davis, A.M., Wallace, P.J., and Anderson, A.T., 2001, Zoned quartz phenocrysts from the rhyolitic Bishop Tuff: *American Mineralogist*, v. 86, p. 1034–1052.
- Reid, M.R., and Coath, C.D., 2000, In situ U-Pb ages of zircons from the Bishop Tuff; no evidence for long crystal residence times: *Geology*, v. 28, p. 443–446, doi: 10.1130/0091-7613(2000)028<0443:ISUPAO>2.3.CO;2.
- Simon, J.I., and Reid, M.R., 2005, The pace of rhyolite differentiation and storage in an ‘archetypal’ silicic magma system, Long Valley, California: *Earth and Planetary Science Letters*, v. 235, p. 123–140, doi: 10.1016/j.epsl.2005.03.013.
- Snyder, D., 2000, Thermal effects of the intrusion of basaltic magma into a more silicic magma chamber and implications for eruption triggering: *Earth and Planetary Science Letters*, v. 175, p. 257–273.
- Sorey, M.L., Evans, W.C., Kennedy, B.M., Farrar, C.D., Hainsworth, L.J., and Hausback, B., 1998, Carbon dioxide and helium emissions from a reservoir of magmatic gas beneath Mammoth Mountain, California, USA: *Journal of Geophysical Research*, v. 103, p. 15,303–15,323, doi: 10.1029/98JB01389.
- Wark, D.A., and Bachmann, O., 2005, Contrasting Ti zoning patterns in quartz phenocrysts from the Bishop and Fish Canyon Tuffs: An expression of volatile composition in recharge melts: *Eos (Transactions, American Geophysical Union)*, v. 86, Fall meeting supplement, abs. V13B-0523.
- Wark, D.A., and Spear, F.S., 2005, Ti in quartz: Cathodoluminescence and thermometry: *Geochimica et Cosmochimica Acta*, v. 69, supplement, p. A592.
- Wark, D.A., and Watson, E.B., 2006, TitaniQ: A titanium-in-quartz geothermometer: *Contributions to Mineralogy and Petrology*, v. 152, p. 743–754, doi: 10.1007/s00410-006-0132-3081.
- Wark, D.A., and Wolff, J.A., 2006, Mafic recharge eruption trigger for the Bishop and Banderli Tuffs: *Eos (Transactions, American Geophysical Union)*, v. 87, Fall Meeting Supplement, Abstract V33C-0682.
- Wallace, P.J., Anderson, A.T., Jr., and Davis, A.M., 1999, Gradients in H₂O, CO₂, and exsolved gas in a large-volume silicic magma system: *Journal of Geophysical Research*, v. 104, p. 20,097–20,122, doi: 10.1029/1999JB900207.
- Wilson, C.J.N., and Hildreth, W., 1997, The Bishop Tuff; new insights from eruptive stratigraphy: *Journal of Geology*, v. 105, p. 407–439.

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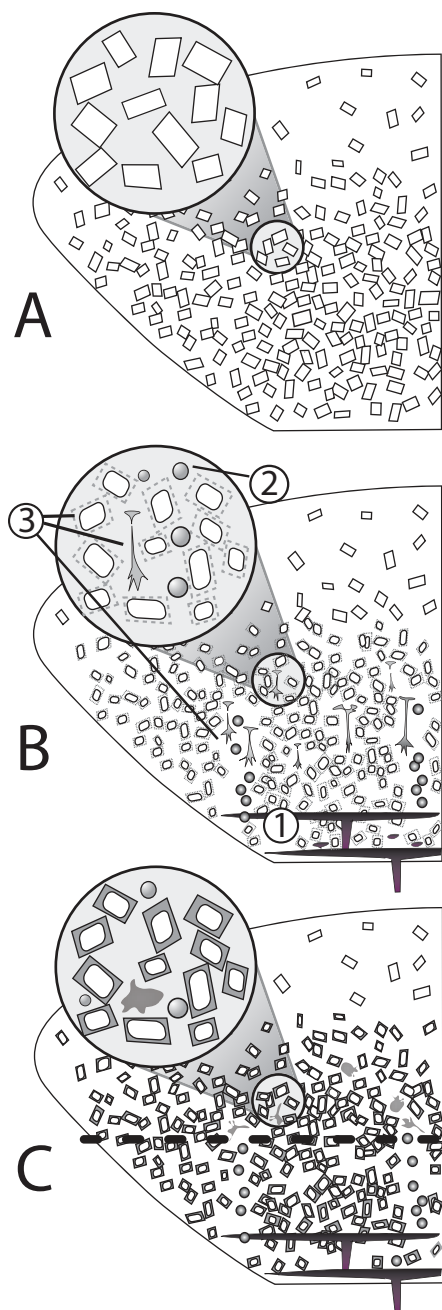


Figure 4. Three stages in development of Bishop magma chamber. **A:** Pre-recharge stage with normal, euhedral crystal growth. **B:** Recharge due to (1) deep injection of hot mafic melts that release (2) CO₂-rich volatiles and cause (3) partial resorption of deep crystals, producing Ba-, Sr-, and Zr-rich silicic melt that migrates upward. **C:** Renewed crystallization of deep phenocrysts at higher temperature due to lowering of water activity by addition of CO₂ (see text), followed within 100 yr by eruption to depth indicated by dashed line.