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Lack of volatile gradient in the Taupo plinian-ignimbrite transition: Evidence from melt inclusion analysis

NELIA W. DUNBAR, PHILIP R. KYLE
Department of Geoscience, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801, U.S.A.

ABSTRACT

Ion and electron microprobe analyses of melt inclusions from the rhyolitic Taupo eruptive sequence of 1800 yr ago indicate that the 35-km³ preeruptive magma was homogeneous with respect to volatile, major, and trace elements at the time of crystallization and presumably at the time of eruption. The early-erupted Hatepe and Taupo plinian tephra both contain melt inclusions with an average of 4.3 wt% H_2O. Melt inclusions from an intraplinian ignimbrite contain 3.7 wt% H_2O, whereas melt inclusions in Taupo ignimbrite average 3.6 wt%. A sample from the latest-erupted part of the eruptive sequence has melt inclusions containing 4.4 wt% H_2O. The Cl and F content of melt inclusions from all samples range between ~1700 and 1900 ppm, and 400 and 600 ppm, respectively. The uniform H_2O content of the preeruptive magma suggests that whereas H_2O was almost certainly the main force behind this eruption, shifts in eruptive style from plinian to ultraplinian to ignimbrite were not controlled by variations in preeruptive H_2O contents. Vent configuration or the ability of the magma to degas passively may have played important roles in determining eruptive style.

INTRODUCTION

The volatile content of magma plays a critical role in driving explosive volcanic eruptions. However, it is not clear how magmatic volatile contents control the specific eruption styles, particularly in rhyolitic magmatic systems. Traditionally, the assumption has been made that the explosivity of the eruption is proportional to the H_2O content of the melt, implying that H_2O-rich rhyolitic magmas would produce explosive, tephra-producing eruptions, whereas H_2O-poor magmas would produce domes. However, Eichelberger et al. (1986) and Newman et al. (1988) showed that domes can be formed from a H_2O-rich melt, provided that the eruptive environment allows the magma to degas passively, rather than explosively. Another eruptive change that has been attributed to decreasing magmatic H_2O contents is the transition from a sustained plinian eruptive column to a collapsed, ignimbrite-producing column (Wilson, 1976). Column collapse can also be related to increasing vent diameter (Wilson et al., 1980). Such models are difficult to assess without detailed knowledge of the magmatic volatile contents in actual eruptive systems.

In this study, we examine variations in preeruptive volatile contents (particularly H_2O) during a major rhyolitic eruptive episode from the Taupo Volcanic Zone, New Zealand. The eruption underwent shifts among a number of different eruptive styles. Volatile contents of the magma were determined by ion and electron microprobe analyses of melt inclusions, small samples of melt trapped in phenocrysts during crystal growth (Roedder, 1984), which may be representative of preeruptive melt (e.g., Anderson, 1974; Hervig et al., 1989; Dunbar et al., 1989a). Trace-element contents of melt inclusions and trace-element contents and Sr isotopic content of pumice lumps from different eruptive phases were determined to gain a more complete understanding of the compositional structure and evolution of the Taupo magma chamber.

GEOLOGICAL BACKGROUND

The Taupo Volcanic Zone, located in the central North Island of New Zealand, has produced calc-alkaline volcanic rocks, composed dominantly of rhyolites with subordinate andesites and basalts, over the last 1 m.y. (Cole, 1979). A number of individual volcanic centers have been identified in the Taupo Volcanic Zone, including the Taupo Volcanic Center. The rhyolites are thought to be derived from partial melting of crustal graywackes driven by heat and volatiles supplied from subduction-related andesite (Reid, 1983; Cole, 1979). Although andesite is not abundant at the surface, large amounts may be present at depth. Eruption of andesite may have been inhibited by overlying rhyolitic magma bodies (Cole, 1979).

The rhyolitic Taupo eruptive episode 1800 yr ago is the most recent from the Taupo Volcanic Center. This episode produced the most powerful plinian (Taupo plinian pumice) and violent ignimbrite (Taupo ignimbrite) eruptions ever documented (Wilson and Walker, 1985). The total volume of in-situ tephra is ~18 km³ dry rock equivalent (D.R.E.), but as much as 35 km³ of magma may have been erupted (Wilson and Walker, 1985). Several other, less explosive, plinian and phreatoplinian eruptions also occurred as part of this sequence, all erupt-

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ed before the Taupo plinian pumice and Taupo ignimbrite (Wilson and Walker, 1985). Their deposits include the initial phreatoplinian ash, Hatepe plinian pumice, Hatepe phreatoplinian ash, and the Rotongaio phreatoplinian ash. Of these, the initial ash, Hatepe phreatoplinian ash, and Rotongaio phreatoplinian ash were influenced by external H_2O, and Hatepe plinian pumice was produced by a moderately explosive eruption driven solely by magmatic H_2O. The entire eruptive sequence was erupted over a period of ~2 weeks (Wilson and Walker, 1985). The final stages of the eruptive sequence involved passive vent filling or dome formation, which resulted in large blocks of pumice found in lake sediment. Many aspects of this unusual eruption have been well studied (Froggatt, 1981; Wilson, 1985; Wilson and Walker, 1985; Dunbar et al., 1989a, 1989b), and this, as well as the wide variation in eruptive styles, makes the Taupo eruptive sequence well suited to a study of the effect of magmatic volatile content on eruptive style.

The Taupo ignimbrite eruption (~10 km^3 D.R.E.) is unusual in its high emplacement velocities (~400 m/s) and widespread dispersal, reaching 80 ± 10 km in all directions from the source and covering an area of 20000 km^2 (Wilson, 1985). The flow was extremely energetic and was able to surmount obstacles 700 m high at ~45 km from the vent (Wilson, 1985). A substantial amount of lithic debris (2 km^3) is associated with the basal portion of the ignimbrite (Wilson and Walker, 1985).

In contrast to many large volume silicic eruptive products, the plinian and phreatoplinian precursors (8.2 km^3 of magma) of the Taupo ignimbrite show no evidence of major-, trace-, or volatile-element zonation (Dunbar et al., 1989a, 1989b). The precursor ashes, as well as the Taupo ignimbrite, contain 3–5 vol% crystals, mainly plagioclase and pyroxene, in which abundant, pristine melt inclusions are found.

ANALYTICAL METHODS

Melt inclusions in pyroxene and plagioclase were analyzed for major elements and Cl by a Jeol 8600 electron microprobe at Arizona State University, using standard ZAF matrix correction techniques. Analyses were made using a 20-μm beam size and a beam current of 15 nA in order to minimize Na migration and volatilization. Calibration, particularly for Cl, was checked using reference materials KN-18 and KE-12 (supplied by H. Sigurdsson). Analytical precision for Cl is ±100 ppm. Ion microprobe analyses of H_2O, F, Li, B, P, Ti, Rb, Sr, Y, Zr, Nb, Cs, Ba, Ce, and Th were made with a Cameca IMS 3f, following analytical procedures of Hervig et al. (1989). A 1–2 nA mass-analyzed primary beam of $^{16}O^-$ ions was focused to a spot 10–20 μm in diameter. The secondary ion intensity for H was calibrated using experimentally hydrated rhyolitic glasses analyzed by infrared spectroscopy, as well as hydrous rhyolitic glass synthesized at Sandia National Labs, Arizona State University, and California Institute of Technology (kindly provided by E. Stolper). Trace elements were calibrated against NIST SRM 610, a Na- and silica-rich glass containing varied abundances of 61 trace elements. Standards for F include both SRM 610 and KE-12, a comendite glass containing 4300 ppm F. Estimated error based on observed reproducibility of secondary reference materials suggests that the precision of analyses is ±15% for most trace elements, ±30% for F, and approximately ±0.5 wt% for H_2O.

TABLE 1. Average composition of matrix glass and melt inclusions

	Melt inclusions (n = 70)		Matrix glass** (n = 14)	
Element*	(wt%)	(1σ)	(wt%)	(1σ)
SiO_2	74.3	0.7	74.2	0.7
TiO_2	0.3	0.1	0.3	0.1
Al_2O_3	13.8	0.4	13.7	0.4
FeO	2.4	0.4	2.6	0.3
MnO	0.1	0.1	0.1	0.1
MgO	0.2	0.1	0.3	0.2
CaO	1.6	0.3	1.6	0.3
Na_2O	4.4	0.2	4.4	0.2
K_2O	2.7	0.1	2.7	0.1

Note: Analyses recalculated as volatile free.

* Analyzed by electron microprobe.

** Glass adhering to crystals, assumed to represent crystal-free melt composition.

Whole rock analyses were made on individual pumice lumps from a number of stratigraphic positions within all of the tephra units except the Rotongaio ash, where little pumice is present. Single pumice clasts were separated from bulk samples, crushed, and analyzed by X-ray fluorescence, following the method of Norrish and Chappell (1977).

RESULTS

Major- and trace-element composition of melt inclusions

Pristine melt inclusions are present in orthopyroxene and plagioclase phenocrysts from early phases of the Taupo eruption (Dunbar et al., 1989a), as well as in the Taupo ignimbrite. The plagioclase is An_{36} to An_{48} and is characterized by oscillatory zoning (Ewart, 1963). The melt inclusions, which are found predominantly in pyroxene, reach a maximum size of ~60 μm, are crack free, and appear to be uniformly distributed throughout the crystals. Some melt inclusions contain a small single bubble ($\ll$1% of melt-inclusion volume). No devitrified melt inclusions were observed, probably because of the rapid quenching of the magma during eruption. Major- and trace- element compositions of melt inclusions are indistinguishable from that of matrix glass (which represents crystal-free melt composition) both in terms of major- and trace-element composition (Table 1, Fig. 1). There are no systematic variations in trace-element contents of melt inclusions throughout the entire eruptive sequence.

Volatile composition of melt inclusions

The H_2O, F, and Cl contents of melt inclusions were determined from a number of stratigraphically controlled

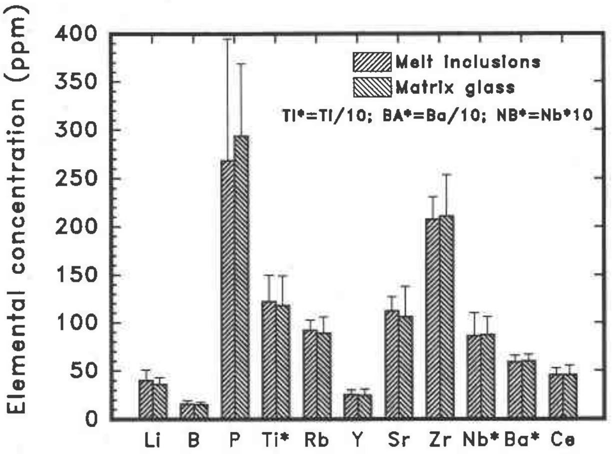

Fig. 1. Mean trace element composition of matrix glass and melt inclusions from the Taupo plinian tephra, as analyzed by ion microprobe. For melt inclusions, $n = 150$, for matrix glass, $n = 20$. Standard deviations for each data set are shown as error bars.

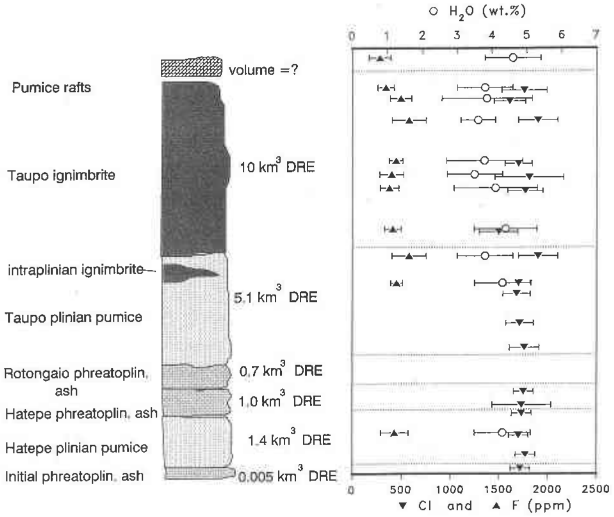

Fig. 2. H_2O, Cl, and F contents of melt inclusions in samples from the Taupo eruptive sequence, arranged in stratigraphic order. The standard deviation of each data set is shown as error bar. The number of analyses per data point ranges between approximately 10 and 20. Analytical errors for H_2O, F, and Cl are ±0.5 wt%, ±30 ppm, and ±100 ppm, respectively, based on counting statistics. Names and volumes of tephra units are from Wilson and Walker (1985).

samples through the Taupo eruptive sequence (Fig. 2). In addition to the elements listed above, attempts were made to analyze S by electron microprobe, but it was below detection limits in all cases (<200 ppm). Because of the greater ease of analysis, Cl was determined for samples from all eruptive units except the Rotongaio ash, whereas H_2O and F were only determined for the Hatepe and Taupo plinian tephras, the Taupo ignimbrite, and the late-stage pumice rafts, with greatest emphasis on the Taupo plinian and ignimbrite tephras. The most striking feature of the data set is the strong similarity among the volatile contents of all melt inclusions analyzed and the apparent lack of systematic increase or decrease in volatile contents throughout the eruptive sequence. The H_2O contents cluster around 4.0 wt%, F around 350 ppm, and Cl around 1700 ppm. Some variability exists within each data set (representative examples shown in Fig. 3), but the mean values of all samples for each component are similar.

Whole rock trace-element and isotope geochemistry

Published (Dunbar et al., 1989b) and new trace-element analyses show virtually no systematic variations within the Taupo eruptive sequence (Table 2). Some variations in Sr are likely to be due to varying crystal content of bulk samples. Slight variation in Rb is within analytical error. Sr isotope analyses of four samples representative of the eruptive sequence (Table 3) are uniform and show no evidence for isotopic gradients that might result from wall rock assimilation or magma chamber zonation.

DISCUSSION

Trace-element characteristics of the Taupo magma

The 18–35 km³ of magma erupted 1800 yr ago during the Taupo eruption was chemically homogeneous with respect to major and trace elements and Sr isotopic composition. The geochemical homogeneity of the early eruptive phases of this sequence was shown by Dunbar et al. (1989b). The current study shows that the final stages of the eruption were also homogeneous and identical to the early stages (Figs. 2, 4, Table 2). The magma was also homogeneous with respect to Sr isotopes (Table 3) and displays a strongly crustal signature. This observed chemical homogeneity is unlikely to be due to efficient syn-eruptive mixing of compositionally heterogeneous magma because melt inclusions, which should represent the magmatic composition at the time of crystallization, are also compositionally homogeneous throughout the eruptive sequence. If two initial magmatic compositions were thoroughly mixed during eruption, two populations of melt inclusions would be expected.

In order for 35 km³ of magma to be homogeneous, crystallization must have been minimal and convection is likely to have been vigorous. The crystal contents of the magma are low (3–5 vol%), suggesting that little crystallization took place during this time. The residence time of the magma in the chamber prior to eruption was short, <22000 yr, based on a marked change in magmatic composition following a 500-km³ tephra eruption 22590 yr ago (Wilson et al., 1988; Dunbar et al., 1989b). Bacon and Druitt (1988) and Druitt and Bacon (1989) report similar lack of compositional zonation within the rhyodacitic climactic eruption of Mount Mazama and ascribe the chemical homogeneity to continuous generation of silicic magma and associated vigorous convection caused by repeated injections of andesitic magma that fraction-

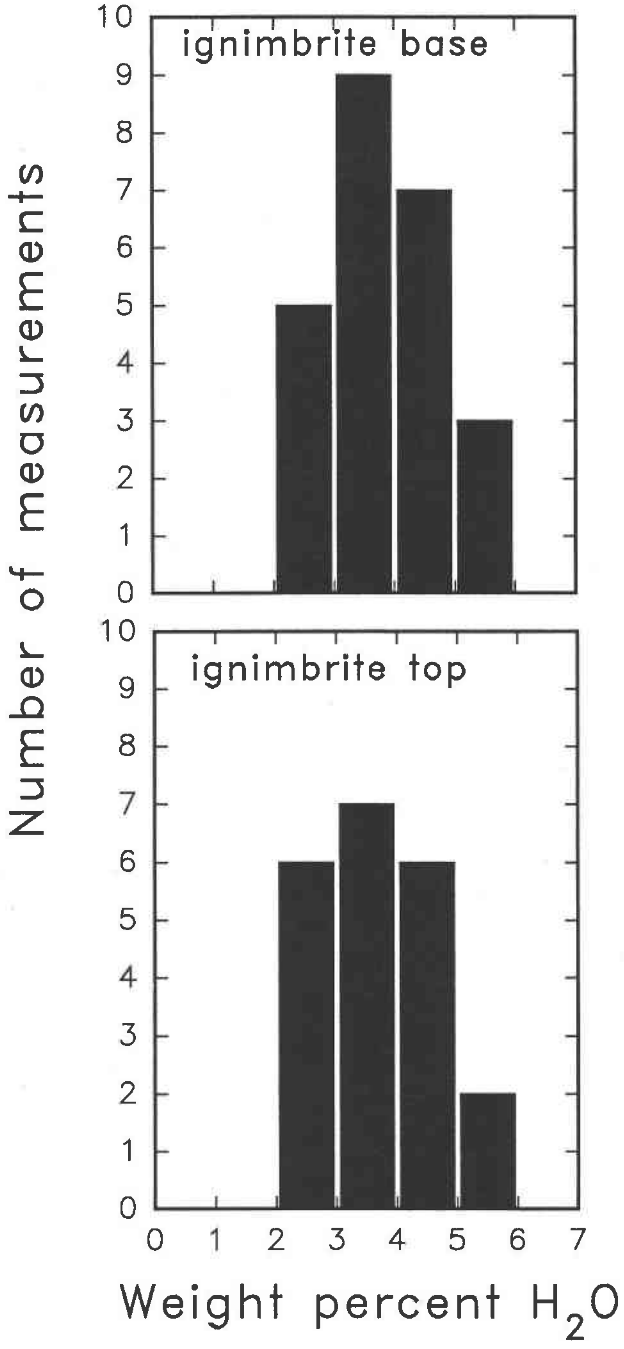

Fig. 3. Histograms of the H_2O contents of melt inclusion samples from the base and the top of the Taupo ignimbrite.

ally crystallized to produce the rhyodacitic magma over a period of ~25000 yr. Although the Taupo rhyolitic magma is thought to be derived mainly from partially melted crust rather than fractionally crystallized andesite, continuous underplating of andesitic magma batches may have provided the heat source to allow continuous partial melting of the overlying graywacke, as well as vigorous convection, leading to an unzoned magma body.

Table 2. XRF analyses of tephra from the Taupo eruptive sequence

Eruptive unit	Pb (ppm)	Th (ppm)	Rb (ppm)	Sr (ppm)	Y (ppm)	Zr (ppm)	Nb (ppm)	*n*
Taupo ignimbrite								
Top	20	11	96	160	35	221	8	6
Middle	19	12	97	160	35	221	8	7
Base	19	11	97	159	35	220	8	11
Taupo plinian	21	12	97	166	36	222	10	6
Hatepe phreato-plinian	21	12	99	156	36	222	10	4
Hatepe plinian	21	11	100	156	36	222	10	5
Initial ash	22	13	101	156	35	222	9	1

Note: n = number of analyses. Average error of analyses (1σ): Pb ± 3; Th ± 2; Rb ± 4; Sr ± 4; Y ± 2; Zr ± 4; Nb ± 1.

Magmatic volatile contents

The 35 km^3 of magma that produced the Taupo eruption from 1800 yr ago was not systematically zoned with respect to H_2O, Cl, and F, on the basis of the analysis of melt inclusions in pyroxene and plagioclase phenocrysts (Fig. 2). We believe that the melt inclusions are adequately representative of preeruptive Taupo melt due to their compositional similarity to matrix glass in both major and trace elements (Table 1, Fig. 1). No indication of postentrapment crystallization, crystal-growth edge effects, or devitrification are observed. Although no systematic variations are observed throughout the eruptive sequence, the scatter within any single sample is slightly greater than the analytical error, particularly for H_2O (Fig. 3). As can be seen in these histograms, which are representative of most analyzed samples from the Taupo plinian pumice and ignimbrite, most samples fall between 3 and 5 wt% H_2O, but some lower and higher values exist. This type of variation has been observed in virtually all studies of melt inclusions, regardless of analytical technique (Anderson et al., 1989; Dunbar et al., 1989a; Skirius et al., 1990). The low H_2O contents of some melt inclusions may be due to leaking of H_2O through undetected cracks in the host crystals (Skirius et al., 1990) and diffusive reequilibration of H_2O in the melt inclusions and the host magma, which would occur at different rates depending on the location of the melt inclusion in the crystal (Qin et al., 1992). Also, there may be small-scale heterogeneities within the magma with respect to H_2O as a result of local crystal growth, but this is difficult to demonstrate.

The volatile content of the Taupo magma is virtually identical to that of the magma that produced the climactic eruption of Mount Mazama 6845 ± 50 yr ago (3.9 wt% H_2O, 400 ppm F, 1880 ppm Cl, Bacon et al., 1992) and to the magma that produced the rhyolitic portion of the 1912 eruption in the Valley of Ten Thousand Smokes (VTTS) (3.8 wt% H_2O, 630 ppm F, and 1930 ppm Cl, Westrich et al., 1991). All three of these eruptions were produced from subduction-related systems, but the similarity of volatile contents cannot be directly attributed to source rock because the Taupo magma is attributed to partial melt, and the Mazama climactic magma and the

TABLE 3. Sr isotope analyses of whole rock pumice samples, Taupo Volcanic Center

Sample	Unit	Rb (ppm)	Sr (ppm)	^{87}Sr/^{86}Sr
15A	Taupo plinian	96	167	0.706031
27A	Hatepe plinian	99	156	0.706008
2A	Hatepe phreatoplinian	97	153	0.706023
44	Initial ash	101	154	0.706039

Note: Analyses made using VG354 mass spectrometer equipped with five multidynamic collectors. Internal precision on ^{87}Sr/^{86}Sr is 0.00001 (2 s.d.). Data are normalized to ^{86}Sr/^{88}Sr = 0.1194. During the period of analysis SRM 987 had ^{87}Sr/^{86}Sr = 0.710249 (2 sd, *n* = 36, Thirlwall, 1991). Rb and Sr analyses by XRF.

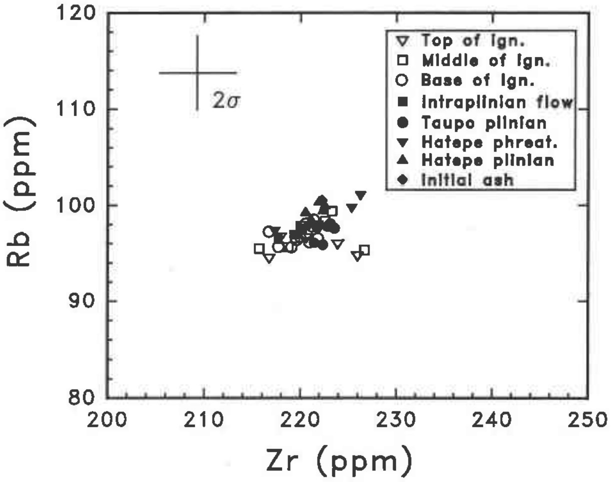

Fig. 4. Rb and Zr contents of bulk rock samples from the Taupo eruptive sequence, with different phases of the eruptive sequence shown in different symbols. Analytical error for both Rb and Zr is ±4 ppm.

rhyolitic portion of the VTTS 1912 eruption are thought to have evolved from fractional crystallization of more primitive magmas (Bacon and Druitt, 1988; Hildreth, 1987). One possibility is that both magmas inherited their volatile signatures from dehydration of a downgoing slab, rather than source rock, leading to similar volatile contents caused by a similar tectonic setting. However, although it is possible to envision that relative proportions of magmatic volatiles are related to a slab signature, it is difficult to attribute the similar absolute volatile contents of the three magmas to this mechanism. A final possibility could be that the magma chambers that produced these three eruptions all resided at similar depths in the crust, and that the similar volatile contents may be due to equilibration under fluid-saturated conditions. The H_2O contents of the three compositionally similar melts may be controlled by pressure, with excess H_2O forming a fluid phase, and the Cl contents may be controlled by fractionation between the melt and the H_2O-rich fluid phase. Westrich et al. (1991) suggest that the VTTS magma was undersaturated, but this suggestion was made because no evidence of magmatic vapor saturation, such as vapor-dominated melt inclusions, was observed. No evidence exists that unequivocally supports vapor undersaturation in the VTTS magma (H. Westich, personal communication, 1992). The magmatic F content, however, cannot be explained by this mechanism because of the high solubility of F in a rhyolitic melt (Webster, 1990).

Effect of magmatic volatile contents on eruptive style

Although the Taupo magma may have been saturated with respect to a vapor phase, the consistency of magmatic H_2O and the low crystal contents of the Taupo magma suggests that progressive oversaturation and vesiculation of the upper part of the magma chamber did not initiate eruption. Progressive oversaturation can be caused either by large-scale magmatic evolution due to fractional crystallization and upward concentration of volatiles (Blake, 1984) or by in-situ crystallization (Tait et al., 1989), causing large quantities of volatiles to exsolve from magma in the upper, lowest pressure, portions of the chamber. Neither of these scenarios can be applied to the Taupo magma because the crystal content is low, and there is no evidence of an increase in volatile contents toward the top of the magma chamber. The eruption, therefore, must have been initiated by some other factor, possibly tectonic depressurization or progressive upward migration of the magma body toward shallower crustal levels, promoting the type of widespread or catastrophic volatile exsolution that could initiate a major explosive eruption.

The Taupo eruption produced variably explosive plinian, ignimbrite-forming, and phreatoplinian deposits, yet it was derived from a magma that was homogeneous with respect to H_2O. Therefore, although magmatic H_2O was certainly the main force behind the eruptive events, the differences in eruptive style were not simply a function of the volatile content but were controlled by other factors. Interaction of meteoric H_2O and magma certainly had a strong influence on the phreatomagmatic stages of the eruption, but this explanation cannot be used to explain the differences among the parts of the eruptive sequence with no phreatic component. A lack of strong correlation between magmatic H_2O contents and eruptive style has been demonstrated directly and indirectly in a number of other cases. Hildreth and Drake (1992) suggested that the H_2O contents of explosive and effusive eruptions from Volcán Quizapu were similar and that the differences in eruptive style may have been due to pre-eruptive degassing. Hervig et al. (1989) determined that the H_2O content of the magma that produced low-explosivity plinian eruptions associated with Obsidian Dome, in California, was similar to that which produced the highly explosive Taupo plinian eruption. In contrast, Westrich et al. (1991) found that the H_2O content of a magma that produced a continuous plinian eruption zoned from rhyolite to andesite dropped from 3.8 to 1.0 wt%. Lowenstern and Mahood (1991) determined the preeruptive H_2O contents of a pantelleritic eruptive sequence and concluded that the decompression and degassing history of the magma are important in controlling eruption dynamics.

A number of factors may influence the nature of a volcanic eruption, including magmatic composition, volatile content, density of erupted material, mass flux, and diameter and configuration of the vent (Wilson et al., 1980; Woods and Caulfield, 1992). However, in an eruptive sequence such as the Taupo eruption of 1800 yr ago where magmatic major-element composition, volatile composition, and temperature remain constant (Dunbar et al., 1989b), the vent configuration is likely to be a dominant factor in controlling eruption style. The Taupo plinian eruption was highly explosive and had an extremely high eruption column of 50 km (Wilson and Walker, 1985). In contrast, the preceding Hatepe plinian eruption was much less explosive, although the volatile content was identical. However, by the time that the Taupo plinian eruption took place, the eruptive conduit may have already been well established, allowing unimpeded rapid upward movement of magma, leading to high eruption rates and a high column. Also, the conduit may have been wider during the Taupo plinian eruption, leading to a higher mass eruption rate, and consequently a higher eruption column (Wilson et al., 1980).

Because the H_2O content and major-element composition of the magma remained constant, the transition from the high plinian to collapsed ignimbrite eruption column is likely to have been caused by vent widening. Wilson et al. (1980) have modeled a similar scenario and suggest that progressive vent widening during eruption of magma with constant but elevated H_2O content can lead to a high plinian column followed by an ignimbrite eruption. On the basis of this model and with the assumption of a roughly circular vent, the vent radius during the Hatepe and Taupo plinian eruptions would have been several hundreds of meters but would have widened to 500 m or greater during the ignimbrite eruption. The presence of a large lithic layer within the basal portions of the Taupo ignimbrite suggests that vent widening occurred catastrophically rather than gradually, possibly as a result of withdrawal of magma from within the chamber (Wilson and Walker, 1985). Following ignimbrite eruption, passive eruption of late-stage pumice rafts occurred (Wilson and Walker, 1985). These pumice blocks, which are up to 12 m in length (Wilson and Walker, 1985), may represent material that filled the vent following ignimbrite eruption. This eruption style suggests that the vent system had been sufficiently disrupted by this point in the eruption to allow passive degassing, as suggested by Eichelberger et al. (1986), although without subsequent rewelding to form dense rhyolitic glass.

CONCLUSIONS

The Taupo eruption, consisting of a sequence of plinian, phreatoplinian, and ignimbrite eruptions, was derived from a magma body that was strikingly homogeneous with respect to trace elements, and isotopic and volatile components. The homogeneous nature of the magma may be due to the mechanism of magma generation, as well as active convection within the chamber. The consistency of magmatic volatile contents demonstrated for the magma that produced the 1800-yr-old Taupo eruption, plus that inferred or demonstrated for other small magmatic systems (<100 km^3 of magma) (e.g., Bacon and Druitt, 1988; Bacon et al., 1992; Eichelberger et al., 1986; Hildreth and Drake, 1992; Lowenstern and Mahood, 1991), suggests that the volatile content of the magma is not the dominant factor controlling eruptive explosivity or the point of plinian to ignimbrite transition. Rather, vent configuration, condition of the vent, and evolution of the vent throughout the eruption may play a more dominant role in controlling details of the eruptive nature.

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