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Roof-rock contamination of Taylor Creek Rhyolite, New Mexico, as recorded in hornblende phenocrysts and biotite xenocrysts

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ABSTRACT

The Taylor Creek Rhyolite, a group of coeval, mid-Tertiary, silica-rich rhyolite lava domes in southwestern New Mexico, is notable for recording bulk-rock evidence of minor, yet easily measurable, contamination of its source magma reservoir resulting from assimilation of Proterozoic roof rock. Most of the evidence is recorded in trace element concentrations and $^{87}Sr/^{86}Sr_i$ ratios, which are far different in uncontaminated magma and roof rocks. Hornblende phenocrysts and biotite xenocrysts also record the effects of contamination. Electron microprobe analyses show that all hornblende grains are zoned to Mg-rich and Fe- and Mn-poor rims. Rim MgO content is typically about 10 wt% greater than core MgO content. Other hornblende constituents are not measurably variable. Biotite xenocrysts, trace mineral constituents, are present only in the domes that are most contaminated, as judged by bulk-rock variations in trace element concentrations and $^{87}Sr/^{86}Sr_i$. Biotite grains are invariably partly to almost completely altered. Microprobe analyses of the cores of the least-altered grains show that large variations in Fe and Mg and that biotite contains 2–20 times as much Mg as fresh biotite phenocrysts in other silica-rich rhyolite lavas. Fe and Mg are negatively correlated in hornblende and biotite, consistent with mixing two end-member compositions. The mass ratio of contaminant to magma was probably less than 1:100, and major constituents, including Al, were not measurably affected in hornblende. Al-in-hornblende barometry yields essentially a constant calculated pressure of about 1.5 kbar, which is consistent with the interpretation that all contamination occurred in a boundary zone about 300 m thick at the top of the magma reservoir.

INTRODUCTION

The Taylor Creek Rhyolite comprises 20 lava domes and related pyroclastic deposits that are part of the middle-Tertiary, Mogollon-Datil volcanic field of southwestern New Mexico (Fig. 1). These volcanic rocks were emplaced during a period of about 1500 yr (Champion et al. 1991) at 27.92 Ma (Duffield and Dalrymple 1990) and represent the eruption of 100 km^3 of magma from a chemically zoned boundary layer 300 m thick along the top of a reservoir 1000 km^2 in plan view (Duffield and Ruiz 1992a, 1992b). The rhyolite is of uniform silica-rich composition in terms of major constituents but exhibits considerable variations in trace elements and $^{87}Sr/^{86}Sr_i$, which indicate variable contamination by radiogenic, granitic (*sensu lato*) roof rocks (Duffield and Ruiz 1992a, 1992b). Early-erupted domes exhibit the greatest degree of contamination, presumably because they were fed by magma closest to the roof-rock source of contaminant.

Because silica-rich rhyolite magma typically has evolved far beyond the average composition of continental crust, especially with regard to the concentration or depletion of many trace elements, considerable chemical leverage exists for minor contamination to produce large and easily measurable effects. For example, the least contaminated (uncontaminated?) Taylor Creek Rhyolite contains about 2 ppm Sr and 2 ppm Ba, whereas average upper continental crust contains about 2 orders of magnitude more of each. The maximum degree of contamination documented produced Taylor Creek Rhyolite with about 20 ppm Sr and 40 ppm Ba, roughly equivalent to the bulk assimilation of <1 wt% of Precambrian rocks (Duffield and Ruiz 1992a), assuming compositions like those of Precambrian rocks common in the Taylor Creek region (Condie and Budding 1979; Condie and McCrink 1982; Condie et al. 1985).

To date, evidence for contamination of Taylor Creek Rhyolite magma has been derived principally from chemical analyses of bulk-rock and sanidine phenocrysts. We here report additional evidence of contamination expressed as Mg-rich biotite xenocrysts, recognized as such for the first time, and as core-to-rim enrichment of Mg in hornblende phenocrysts. The least contaminated Taylor Creek Rhyolite contains so little Mg (<0.1 wt% MgO by XRF analyses) that this element behaved essentially

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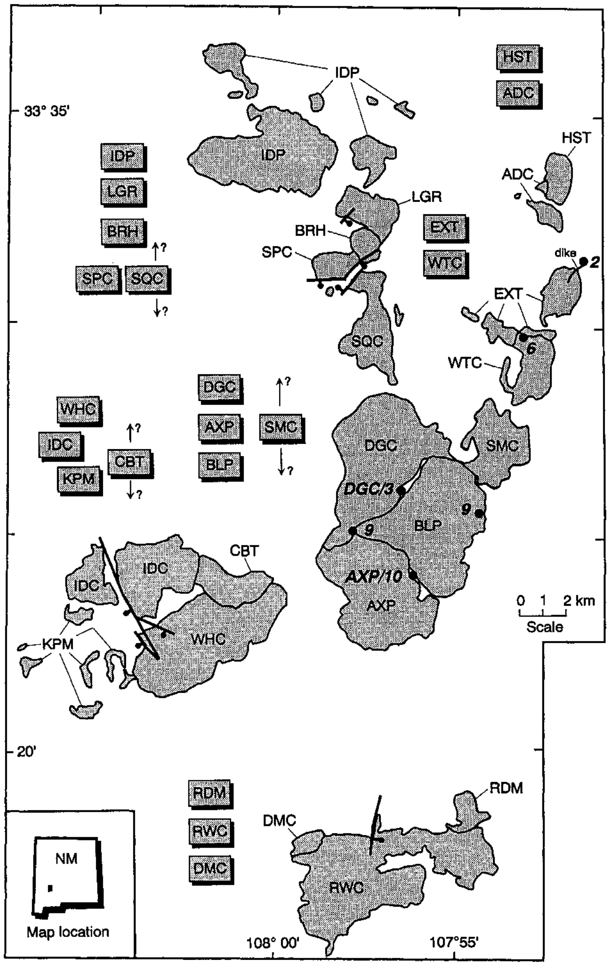

Figure 1. Domes of Taylor Creek Rhyolite, with samples indicated by numbers. Boxes show local stratigraphic relationships.

as a trace constituent of high chemical leverage as the magma body assimilated roof-rock material.

Hornblende

Taylor Creek Rhyolite contains between 15 and 35 vol% phenocrysts (Duffield and Dalrymple 1990). At least 98% of the phenocrysts are quartz and sanidine, in roughly equal amounts; <2% are potassic oligoclase and a mafic phase, also in nearly equal proportions. Unambiguous identification of the mafic phase is commonly impossible because of the considerable alteration that occurred simultaneously with groundmass devitrification during cooling of the eruptive units immediately after emplacement. Nonetheless, partly altered hornblende grains, biotite grains, or both are identifiable in some devitrified rocks, and fresh grains of hornblende are present in vitrophyres.

Although virtually all groundmass is devitrified, about one dozen vitrophyre localities were discovered during mapping. Six vitrophyre samples were large enough for polished thin sections, enabling electron microprobe analysis of fresh hornblende grains. Most hornblende grains are ~0.5–1.0 mm in maximum dimension, somewhat smaller than the coexisting quartz and feldspar phenocrysts. The area of a polished section, approximately 25 × 45 mm, always includes at least one grain of hornblende but rarely more than three. The hornblende is typically subhedral and pleochroic in shades of pale green and brown. Zoning is not apparent optically.

Hornblende is fundamentally uniform in composition in all elements except Fe, Mn, and Mg (Table 1); other coexisting phenocrysts are comparably homogeneous (Duffield and du Bray 1990). The hornblende is edenite, according to the classification of Hawthorne (1981). Standard deviations of the mean for all hornblende analyses are less than or equal to analytical uncertainty for all

Table 1. Average compositions of amphibole phenocrysts and biotite xenocrysts of the Taylor Creek Rhyolite

	DGC/9 core $n = 7$	DGC/9 rim $n = 7$	BLP/9 core $n = 12$	BLP/9 rim $n = 6$	WTC/6 core $n = 7$	WTC/6 rim $n = 9$
SiO_2	43.83 ± 0.36	44.39 ± 0.28	44.52 ± 0.44	44.76 ± 0.44	45.92 ± 0.92	45.32 ± 0.64
TiO_2	1.28 ± 0.11	1.21 ± 0.05	1.23 ± 0.11	1.26 ± 0.07	1.44 ± 0.15	1.38 ± 0.17
Al_2O_3	7.28 ± 0.22	7.02 ± 0.26	6.78 ± 0.16	6.74 ± 0.26	6.69 ± 0.36	6.77 ± 0.22
FeO_{tot}	22.61 ± 0.53	21.74 ± 0.38	21.11 ± 0.63	20.94 ± 0.44	18.14 ± 0.96	18.32 ± 0.89
MnO	1.41 ± 0.08	1.34 ± 0.08	1.18 ± 0.08	1.16 ± 0.12	0.94 ± 0.09	0.99 ± 0.12
MgO	8.87 ± 0.36	9.34 ± 0.26	9.90 ± 0.23	9.99 ± 0.07	11.92 ± 0.70	11.66 ± 0.59
CaO	10.29 ± 0.15	10.28 ± 0.23	10.53 ± 0.10	10.53 ± 0.08	10.68 ± 0.17	10.56 ± 0.36
Na_2O	2.26 ± 0.08	2.19 ± 0.10	2.26 ± 0.16	2.24 ± 0.12	2.30 ± 0.19	2.19 ± 0.19
K_2O	1.14 ± 0.08	1.09 ± 0.08	0.97 ± 0.04	0.97 ± 0.05	0.88 ± 0.06	0.94 ± 0.06
F	2.23	2.21	1.74	1.73	2.50	2.54
Cl	0.22	0.22	0.20	0.20	0.16	0.17
Subtotal	101.41	101.02	100.40	100.51	101.13	100.85
O = (F + Cl)	−0.99	−0.98	−0.77	−0.77	−1.09	−1.11
H_2O calc.	0.84	0.85	1.09	1.09	0.77	0.74
Total	101.26	100.89	100.72	100.83	100.81	100.48
Mg′	41.1	43.4	45.5	46.0	54.0	53.0
$^{[4]}Al$	1.27	1.20	1.19	1.17	1.16	1.16
Na + K	0.90	0.86	0.86	0.85	0.84	0.82
P (kbar)	1.9	1.6	1.6	1.5	1.4	1.4

Note: Microprobe operating conditions: 15 keV accelerating voltage, 30 nA current, 5 mm spot diameter. F and Cl determined on ARL microprobe at U.S. Geological Survey, Menlo Park, California. Bence-Albee data reduction. H_2O and $^{[4]}Al$ calculated assuming 23 O atoms for amphiboles and 22 O atoms for biotite. Mg′ = 100Mg/(Mg + Fe). Pressures calculated using Johnson and Rutherford (1989).

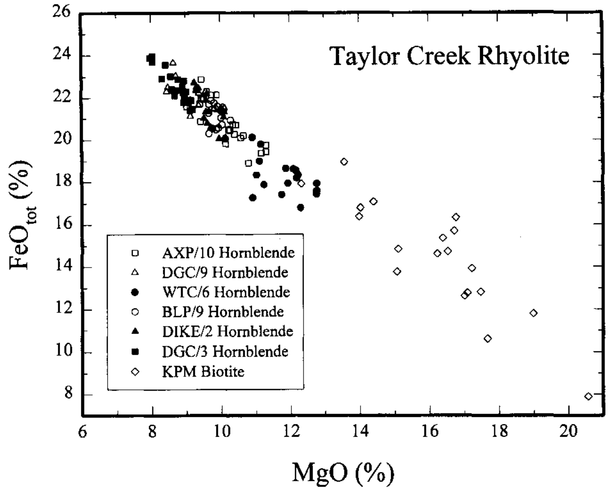

FIGURE 2. FeO$_{tot}$-MgO covariation in hornblende and biotite from the Taylor Creek Rhyolite. The approximately linear array is interpreted to reflect mixing of an MgO-rich contaminant (xenocrystic biotite) with MgO-poor magma. Sample WTC/6 is from the most contaminated dome, on the basis of trace element and isotopic results, and has the most MgO-rich amphiboles. Within-sample chemical variations in hornblendes reflect crystal zoning.

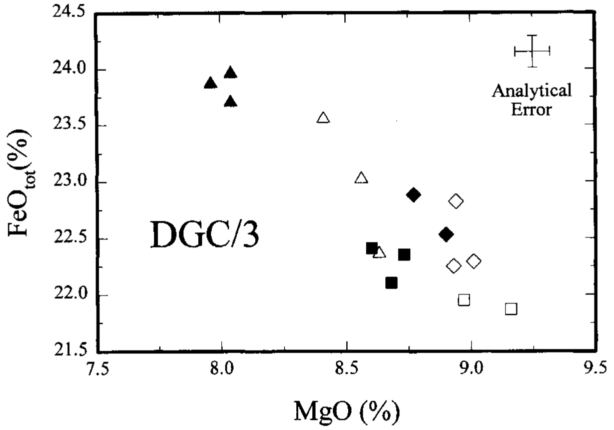

FIGURE 3. Representative core-rim compositional variations in hornblende phenocrysts of Taylor Creek Rhyolite. Profiles across individual grains reveal systematic MgO enrichment of the rims. Different grains are represented by different symbols (solid = core, open = rim).

constituents except Fe, Mn, and Mg. Fe and Mn correlate negatively with Mg (Fig. 2), and rims of grains are systematically enriched in Mg and depleted in Fe, relative to cores (Fig. 3).

In general, core and rim compositions vary somewhat from grain to grain within a polished section. In one section, the core composition of one hornblende grain is about the same as the rim composition of another (Fig. 3). Apparent variation of core (or rim) composition within a single grain probably is an artifact of the subjectivity in selecting multiple core (or rim) spots to analyze in grains that typically are subhedral and partly resorbed. Further ambiguity in locating the core of a grain is unavoidable in studies using planar sections; in an extreme situation, a grain might have only its rim exposed, whereas the core position would be above or below the plane of the section. Nonetheless, our pairs of core and rim analyses show that rims systematically are relatively Mg rich.

The shape of zoning profiles within grains was defined by closely spaced spot analyses along linear traverses across the most nearly euhedral grains. Because of the ambiguities of grain analyses noted above, the shapes of the profiles differ somewhat from grain to grain. Most

TABLE 1.—*Continued*

	DIKE/2 core $n = 7$	DIKE/2 rim $n = 8$	AXP/10 core $n = 15$	AXP/10 rim $n = 11$	DGC/3 core $n = 10$	DGC/3 rim $n = 10$	KPM biotite $n = 20$
SiO_2	44.49 ± 0.49	44.73 ± 0.45	44.67 ± 0.33	45.11 ± 0.65	44.33 ± 0.31	44.19 ± 0.46	39.10 ± 1.24
TiO_2	1.29 ± 0.08	1.23 ± 0.15	1.27 ± 0.07	1.23 ± 0.10	1.23 ± 0.11	1.21 ± 0.10	3.06 ± 0.42
Al_2O_3	6.79 ± 0.31	7.03 ± 0.30	6.66 ± 0.18	6.65 ± 0.35	6.67 ± 0.39	6.86 ± 0.25	12.45 ± 0.55
FeO_{tot}	21.84 ± 0.79	20.91 ± 0.59	20.90 ± 0.91	20.49 ± 1.34	22.81 ± 0.83	22.32 ± 0.64	14.65 ± 2.73
MnO	1.18 ± 0.11	1.09 ± 0.11	1.19 ± 0.13	1.17 ± 0.07	1.32 ± 0.10	1.32 ± 0.07	0.69 ± 0.29
MgO	9.46 ± 0.16	9.97 ± 0.18	10.10 ± 0.45	10.42 ± 0.92	8.52 ± 0.40	8.88 ± 0.26	16.11 ± 1.95
CaO	10.55 ± 0.05	10.56 ± 0.15	10.60 ± 0.13	10.63 ± 0.14	10.33 ± 0.25	10.42 ± 0.18	0.05 ± 0.05
Na_2O	2.09 ± 0.09	2.09 ± 0.11	2.27 ± 0.10	2.24 ± 0.11	2.17 ± 0.09	2.23 ± 0.08	0.25 ± 0.16
K_2O	0.94 ± 0.05	1.02 ± 0.05	0.96 ± 0.03	0.94 ± 0.04	0.94 ± 0.08	1.00 ± 0.06	9.26 ± 0.29
F	2.08	2.08	2.01	1.99	1.80	1.82	2.72
Cl	0.22	0.22	0.18	0.18	0.22	0.22	0.14
Subtotal	100.94	100.92	100.81	101.06	100.32	100.48	98.47
O = (F + Cl)	−0.93	−0.93	−0.88	−0.88	−0.81	−0.82	−1.18
H_2O calc.	0.92	0.92	0.97	0.99	1.03	1.03	2.70
Total	100.93	100.91	100.89	101.16	100.55	100.69	100.00
Mg′	43.6	46.0	46.8	47.6	40.0	41.5	66.2
$^{[4]}Al$	1.19	1.19	1.17	1.16	1.15	1.19	2.18
Na + K	0.81	0.82	0.85	0.84	0.84	0.86	1.83
P (kbar)	1.6	1.6	1.5	1.4	1.4	1.6	—

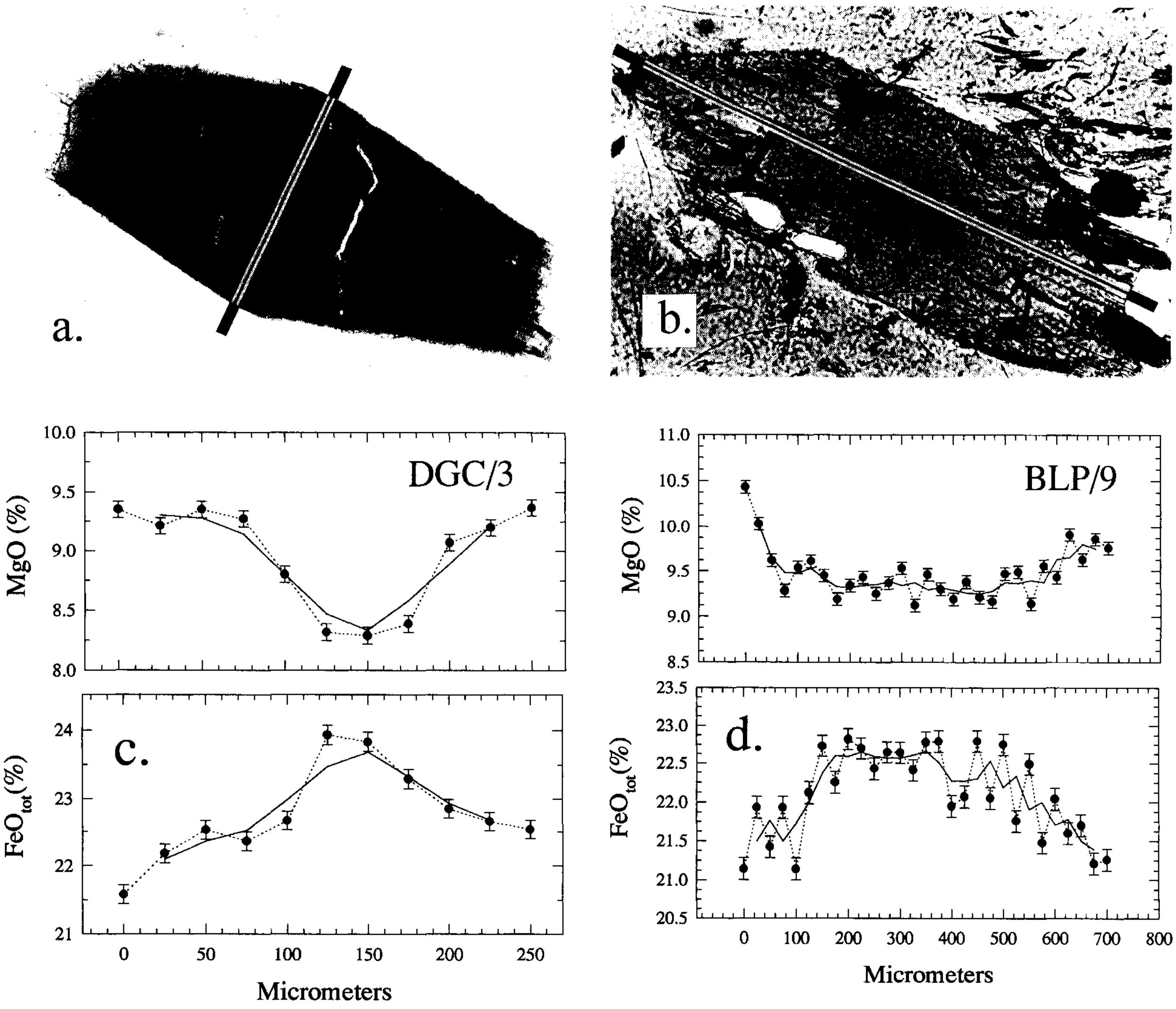

FIGURE 4. Representative zoning profiles across hornblende phenocrysts of the Taylor Creek Rhyolite. Microphotographs **a** and **b** show lines of traverse and are paired with graphs **c** and **d**, respectively. Individual data points with error bars are connected by dotted lines; running averages are shown with solid lines.

measured profiles are not bilaterally symmetrical, presumably because a typical subhedral grain is missing part of its rim. Nonetheless, all profiles are broadly U shaped and show a maximum Mg/Fe at the rim and minimum Mg/Fe at the core (Fig. 4).

BIOTITE

Biotite occurs as partly to completely altered grains ~0.5–1 mm wide. Biotite makes up much less than 1 vol% of the rhyolite and is sparse enough to be considered a trace mineral. It is conspicuously absent from Taylor Creek Rhyolite vitrophyre. The few known vitrophyre localities are associated with domes the melt of which was produced farthest from the magma–roof-rock interface and which lie near the uncontaminated end of the bulk-rock spectrum. The bulk compositions of domes that contain biotite represent magma most contaminated by melt from the magma–roof-rock interface, as defined by several independent criteria (Duffield and Ruiz 1992a, 1992b). These characteristics first prompted us to hypothesize that biotite grains are xenocrysts. All previous studies of the Taylor Creek Rhyolite (for example, Lufkin 1972; Eggleston 1987; Maxwell et al. 1986) reported biotite as a phenocryst. Our microprobe analyses are consistent with interpretation of biotite as xenocrystic.

Biotite grains were hand-picked from a crushed sample of the dome richest in biotite (map unit KPM of Duffield et al. 1987). The central parts of the grains were analyzed to avoid, as much as possible, the corroded margins typical of even the least-altered biotite. As with the hornblende phenocrysts, the greatest compositional variations in the biotite are in Mg and Fe. The biotite is also notable for MgO content as high as 20.6 wt% (Table 1, Fig. 2).

DISCUSSION

Almost all compositional variation in hornblende and biotite grains of the Taylor Creek Rhyolite is in the Mg and Fe contents, which are negatively correlated, with the biotite field at relatively high Mg and low Fe (Fig. 2). These relations are compatible with variable proportions of mixing between two end-member compositions.

The concentration of MgO in fresh biotite phenocrysts from other silica-rich rhyolites and their intrusive equivalents typically is in the range of 1–10 wt% (Nash and Crecraft 1985; Mahood and Hildreth 1983; Hildreth 1977; du Bray 1994). Thus, the biotite from the Taylor Creek Rhyolite, with up to 20.6 wt% MgO, is anomalously magnesian or "primitive." Silica-rich rhyolite, including the Taylor Creek Rhyolite, typically contains <0.1 wt% MgO (Bacon et al. 1981; Hildreth 1981; Duffield and Ruiz 1992a).

The generally corroded condition of biotite grains in the Taylor Creek Rhyolite, in conjunction with their anomalously high Mg content, indicates that the biotite was far out of equilibrium with surrounding melt just prior to an eruption-induced quench of the melt-crystal mix. Biotite alteration might have occurred during groundmass devitrification when the hornblende phenocrysts were partially to completely altered. However, fresh hornblende phenocrysts are present in all Taylor Creek Rhyolite vitrophyre, whereas biotite is conspicuously absent. Moreover, the hornblende zoning to Mg-rich and Fe-poor rims is opposite what one would expect if zoning were the result of crystal growth from silicic melt evolving in a closed magma body. There is no evidence that the Mg-rich rims were produced by oxidation just prior to eruption; the hornblendes are deep green, not red-brown as would be the case for oxyhornblende, and iron titanium oxides phases are unzoned and indicate conditions near the FMQ-buffer curve (800 °C, $f_{O_2} = -14$; Duffield and du Bray 1990). Finally, the rims most enriched in Mg (Fig. 2) are on phenocrysts from the vitrophyre-containing dome that is most contaminated, as indicated by other independent criteria, including high $^{87}Sr/^{86}Sr_i$, high Sr, and high Ba (Duffield and Ruiz 1992a, 1992b). We interpret all these features to reflect minor and variable degrees of assimilation of Mg-rich biotite from roof rocks.

We infer that biotite-derived Mg was incorporated into growing hornblende phenocrysts. Corroded crystals of biotite are present in the most-contaminated domes because eruption quenched an ongoing assimilation process. The chemical imprint of completely dissolved biotite is measurable in hornblende of some of the less-contaminated domes, even though biotite grains are absent from these domes, perhaps simply because the biotite dissolved completely before the effects of the contamination process had propagated to the relatively deeper magma-reservoir levels that fed these domes. We reemphasize that maximum reservoir drawdown was only about 300 m (Duffield and Ruiz 1992a, 1992b); the entire contamination effect apparently was restricted to this thin boundary layer along the top of the reservoir.

Abundant evidence consistent with this contamination scenario is seen in trace element and Sr isotopic variations in bulk-rock samples and sanidine-phenocryst concentrates (Duffield and Ruiz 1992a, 1992b). Assimilation of highly radiogenic Proterozoic biotite from roof rocks also is a key to explaining Sr isotopic disequilibrium between sanidine phenocrysts of Taylor Creek Rhyolite and the melt (rock groundmass) from which they grew (Duffield and Ruiz 1992a, 1992b, 1994; Ruiz and Duffield 1994).

Magma contamination apparently was minor both in the volume affected and in the volume fraction of contaminant, which was almost certainly <1 vol%. However, extreme chemical leverage associated with typical silica-rich rhyolite compositions permits easy recognition of even such minor contamination for many trace constituents. The contamination process is recorded in the Mg-enriched rims of the hornblende phenocrysts because this phenocryst phase was the principal sink for Mg introduced by the biotite xenocrysts. Magnetite and ilmenite, the only other mafic phases in the Taylor Creek Rhyolite, have MgO contents of <0.35 and <0.79 wt%, respectively (Duffield and du Bray 1990), far less than the 10 wt% typical of the hornblende (Table 1). The relatively constant Mg and Fe concentrations across much of the width of grain BLP/9 and the relatively abrupt steepening of Mg and Fe compositional gradients near the grain rim (Fig. 4d) are consistent with a contamination process that began after the phenocryst had nucleated and grown for some time in an uncontaminated magma body.

Because so little contaminant was added, major constituents, including Al, of the Taylor Creek Rhyolite magma were not measurably affected. Thus, application of the hornblende geobarometer seems valid. The bulk composition and mineral phases present (quartz, sanidine, plagioclase, hornblende, ilmenite, and magnetite) are appropriate to Al-in-hornblende barometry as developed from studies of several natural and experimental granitic systems, and a uniform 800 °C temperature of phenocryst growth calculated from two-feldspar and iron titanium oxide geothermometers (Duffield and du Bray 1990) eliminates any concern of temperature variation affecting calculated pressures. We know of five published formulations for calculating pressure from Al content in hornblende (Hammarstrom and Zen 1986; Hollister et al. 1987; Rutter et al. 1989; Johnson and Rutherford 1989; Schmidt 1992). For a given formulation, all pressures calculated for the Taylor Creek Rhyolite are equal within established uncertainties. Pressure varies somewhat from formulation to formulation, although all pressures indicate crystal growth at upper-crustal depths of a few kilometers. Constant pressure, whatever the actual value may be, is consistent with the conclusion noted above of Duffield and Ruiz (1992a, 1992b) that magma for all eruptions came from a relatively thin zone at the top of the Taylor Creek Rhyolite reservoir. The Johnson and Rutherford (1989) barometer yields a mean of about 1.5 kbar (Table 1), equivalent to about 5 km of lithostatic load.

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