U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

A MODEL TO HELP EXPLAIN Sr-ISOTOPE DISEQUILIBRIUM BETWEEN FELDSPAR PHENOCRYSTS AND MELT IN LARGE-VOLUME SILICIC MAGMA SYSTEMS

by

Wendell A. Duffield[1]
Joaquin Ruiz[2]

Open-File Report 94-423

[1] U.S. Geological Survey
2255 North Gemini
Flagstaff, Arizona 86001

[2] Department of Geosciences
University of Arizona
Tucson, Arizona 85721

1994

INTRODUCTION

Geologists have long known that many silicic volcanic rocks contain feldspar phenocrysts in Sr-isotope disequilibrium with surrounding groundmass (Noble and Hedge, 1969; Stuckless and O'Neil, 1973; Futa and others, 1981; Halliday and others, 1984; Halliday and others, 1989; Johnson and Fridrich, 1990; Christensen and DePaolo, 1993). In some rocks, $^{87}Sr/^{86}Sr$ is greater in feldspar than in groundmass, while in others this Sr-isotopic ratio is less in feldspar (Table 1). Explanations for these relations include (1) sinking of phenocrysts into lower, less-radiogenic levels of a magma reservoir, coupled with eruption before equilibrium is attained (Noble and Hedge, 1969); (2) a higher rate of ^{87}Sr growth in melt versus crystals, coupled with eruption before equilibrium is attained (Christensen and DePaolo, 1993); and (3) post-eruptive interaction between rock groundmass and meteoric water, thus destroying a presumed preexisting equilibrium situation (Halliday and others, 1984). However, the applicability of these explanations is limited in that each is valid for one or the other disequilibrium relation between crystals and groundmass, but not for both. In this short note, we offer a model that can explain the presence of either disequilibrium relation, or of both, within a single eruptive unit of silicic volcanic rock. This model does not explain all cases of disequilibrium between feldspar-phenocrysts and groundmass of silicic volcanic rocks. Yet, it provides a broader and more versatile framework for explanation than previous models, and it may help explain some heretofore enigmatic Sr-isotope relations in volcanic deposits....silicic, intermediate and mafic alike.

THE MODEL

The model (Fig. 1) is an outgrowth of our work on the Taylor Creek Rhyolite of southwestern New Mexico. This rhyolite is a group of penecontemporaneous lava domes and flows formed through eruptions from a vertically-zoned magma reservoir (Duffield and Ruiz, 1992a,b). Sanidine phenocrysts in these lavas are systematically more radiogenic than surrounding groundmass, which represents the melt from which the crystals were growing just before eruption. A host of chemical data indicates that the Taylor Creek Rhyolite contains a minor (<1 wt%), albiet readily identifiable, component of country rock with highly radiogenic Sr (Reece and others, 1990; Duffield and Ruiz, 1992a,b). Thus the model is based on a magma reservoir open to chemical exchange with country rock. In addition, the model incorporates rate- and material-limited processes that produce an overall effect of dynamic disequilibrium within a body of magma; the particular disequilibrium relation preserved in a rock is a function of when eruption taps and quenches magma whose Sr-isotopic signature is constantly changing. Eruption early in the modelled system results in melt more radiogenic than growing feldspar crystals, whereas later eruption yields the opposite relation, or both, depending on vertical position in the reservoir (or stratigraphic position in the erupted products).

We illustrate these relations graphically in a plot of time versus $^{87}Sr/^{86}Sr$ for both melt and crystals growing from that melt (Fig 1). In order to relate the model to actual volcanic rocks, groundmass proxies for melt, and whole-rock provides a reference material of integrated groundmass and crystals. The modelled situation applies to any part of a magma body being contaminated by assimilation of country rock.

Rock Unit	Sample	Delta 87/86	Reference
Paintbrush Tuff	63L-17C	+0.0016	Noble and Hedge, 1969
	62L-50X	+0.0006	
Superstition Tuff	AP205	-0.00040	Stuckless and O'Neil, 1973
Clear Lake Volcanics	7	+0.00125	Futa and others, 1981
	9	+0.00054	
	12	+0.00102	
	22	+0.00020	
	27	-0.00049	
Bishop Tuff	B77	-0.00049	Halliday and others, 1984
	B94	-0.00041	
	B104	-0.00250	
	B107	-0.00076	
	B143	-0.00069	
Rhyolite of Glass Mountain	JM068	-0.00920	Halliday and others, 1989
	JM245	-0.00780	
	JM066	-0.00266	
Grizzly Peak Tuff	A1	-0.00033	Johnson and Fridrich, 1990
	AL7	-0.00126	
	T3	-0.00030	
Taylor Creek Rhyolite	WHC6	+0.00419	Reece and others, 1990; Duffield and Ruiz, 1992a; Duffield and Ruiz, unpub. data
	DGC1	+0.00808	
	KPM3	+0.00220	
	BRH1	+0.00520	
Bishop Tuff	BT6	-0.00173	Christensen and DePaolo, 1993
	BT39	-0.00026	
	BT29	-0.00031	
	BT27	-0.00015	
	BT24	-0.00052	

Table 1. Examples of Sr-isotope disequilibrium between feldspar phenocrysts and groundmass (or whole rock in some cases) of silicic volcanic rocks. These examples are tabulated only to show that such disequilibrium is common; whether or not examples other than the Taylor Creek Rhyolite resulted from the process modelled here is unknown at this time. Positive delta 87/86 indicates that feldspar is more radiogenic than groundmass.

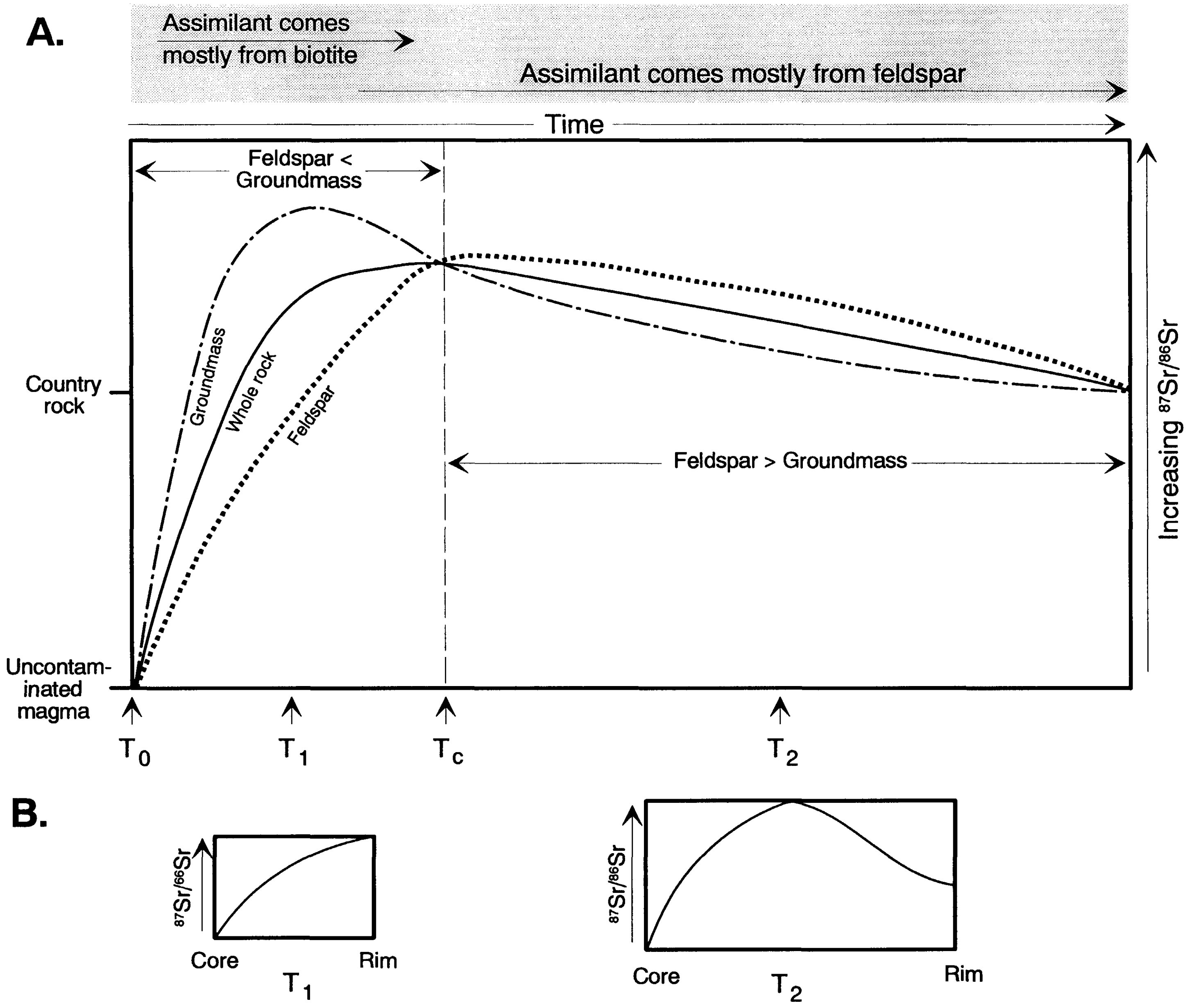

Figure 1. A. Schematic diagram illustrating how the ratio $^{87}Sr/^{86}Sr$ is changed in magma and phenocrysts by continuous assimilation of partial melt derived from biotite- and feldspar-bearing roof rocks. Because diffusion of Sr is faster in melt than in feldspar phenocrysts, the ratio in feldspar initially lags behind that of the melt from which crystals are growing. For the same reason, the ratio in feldspar overtakes that in melt after the contaminant from roof rocks starts to come mostly from country-rock feldspar instead of biotite. If eruption quenches the system at T_1 feldspar is less radiogenic than melt (rock groundmass). If eruption quenches the system at time T_2 the feldspar is more radiogenic than groundmass. **B**. Rim-to-core graphs show predicted $^{87}Sr/^{86}Sr$ profiles across feldspar grains at T_1 and T_2 stages in their growth, assuming little or no grain homogenization through diffusion.

The Y axis depicts $^{87}Sr/^{86}Sr$ without numerical scale. Contaminant from country rock is assumed to be more radiogenic than uncontaminated magma. The X axis depicts time with zero (T_0) defined as the instant before contamination first occurs. Sr-isotope equilibrium is assumed between magma and crystals at T_0. Ending time for the process of contamination is arbitrarily set at the moment the long-term effects of assimilation result in reestablishment of Sr-isotopic equilibrium at a value higher than that at T_0. Eruption may sample the contaminated magma at any intermediate time.

Country rock is assumed to contain biotite and feldspar as the main reservoirs of Sr. In addition, country rock is assumed to melt incongruently, such that biotite is initially the main contributor of Sr to the magma. As available biotite is consumed, feldspar becomes the principal contributor of Sr. This history of country-rock consumption gives rise to an initially high $^{87}Sr/^{86}Sr$ contaminant, much higher than bulk country rock, because the ratio of Rb to Sr is much greater in biotite than in feldspar. With time, the contaminant decreases progressively toward the $^{87}Sr/^{86}Sr$ value of country-rock feldspar, which might be somewhat higher in sanidine than in plagioclase.

At time zero (T_0), magma is a mixture of melt and growing feldspar crystals in isotopic equilibrium. However, by T_1 (Fig. 1) the melt is more radiogenic than the feldspar, because diffusion of Sr in melt is much faster than in feldspar. The rate-dependent lag effect maintains this crystal-melt isotope relation until T_c, a crossover to the opposite relation, whose onset is sometime after the Sr of the contaminant is coming mostly from country-rock feldspar. By T_2, the $^{87}Sr/^{86}Sr$ of feldspar phenocrysts is greater than that of surrounding melt, again because of the much faster diffusion of Sr in melt than in feldspar.

We emphasize that the outermost part of a growing phenocryst may be in Sr-isotope equilibrium (or nearly so) with melt at any time. However, before T_c the mean $^{87}Sr/^{86}Sr$ of a phenocryst is less than that of melt, whereas after T_c the mean is greater, because of the effect of inner crystal-growth zones. The crossover time (T_c) between more-radiogenic feldspar and less-radiogenic feldspar occurs when the mean value for a growing phenocryst is that of surrounding melt. This time presumably could vary for adjacent grains that nucleated at different times. The isotopic relations between feldspar phenocrysts and groundmass preserved in any particular rock depends on when the magma-crystal mixture is sampled by eruption.

VALIDITY OF ASSUMPTIONS

Assumptions built into the above model are reasonable within the framework of current understanding of large-volume reservoirs of silicic magma in the upper crust of continental settings. Many, if not most, reservoirs of this sort are interpreted to form at a few to several kilometers depth, and common crustal rocks at such depths contain biotite and feldspar. A broad range of schists, gneisses, and granitic and silicic volcanic rocks (sensu lato) fits this description.

The assumption of biotite being the principal early contributor of contaminant to the magma is in accord with the thermal stability of minerals that form common igneous and metamorphic rocks of the crust. Moreover, a field study of biotite-bearing granitic country rock partly melted by heat from an adjacent magma body indicates that biotite was the first phase to be totally consumed during the melting process (Kaczor and others, 1988). In some crustal rocks, hornblende may be more abundant than biotite, but the general features of the model are still valid should hornblende proxy for biotite.

The assumption of a contaminant more radiogenic than uncontaminated magma is tailored to suit our particular geologic situation. The reservoir of "uncontaminated" Taylor Creek Rhyolite magma had $^{87}Sr/^{86}Sr$ of about 0.705 and existed within Precambrian basement rocks whose $^{87}Sr/^{86}Sr$ was about 0.8 or even greater (Duffield and Ruiz, 1992a,b). As described in more detail later, the assumed initial Sr-isotope relations between magma and country rock can be adjusted to fit any field setting without invalidating the model.

The important role of diffusion of Sr in melt versus feldspar is justified by an orders-of-magnitude difference in diffusion rates in the two media (for example, see Baker, 1989 and Giletti, 1991). This difference is, in fact, the basis of an essentially closed-magma-system model proposed by Christensen and DePaolo (1993) to explain disequilibrium between feldspar and groundmass of the Bishop Tuff.

POSSIBLE TESTS OF THE MODEL

Unless diffusive redistribution homogenizes individual phenocrysts, zoning within a feldspar crystal should record a time-series change in $^{87}Sr/^{86}Sr$. For example, at T_1 a core-to-rim profile should range from the value of uncontaminated magma steadily upward toward a value limited by the $^{87}Sr/^{86}Sr$ of the contaminant (Fig. 1B). This profile is expected for a phenocryst less radiogenic than groundmass. In contrast, a core-to-rim profile for a crystal at T_2 should rise to a maximum value within an intermediate crystal zone and then decrease, toward the rim, to a value somewhat greater than that of uncontaminated magma (Fig. 1B). This profile is expected for a phenocryst more radiogenic than groundmass. If the rate of crystal growth is constant, then adjacent crystals of the same size should exhibit the same profile, whereas those of different sizes should exhibit different profiles; the largest crystals should contain the most nearly complete record of the contamination process.

The model also implies that the isotopic relation between feldspar phenocrysts and groundmass could change with stratigraphic position within an eruptive unit. The crossover time (Fig. 1, T_c) of the model would occur first at the margin of a magma reservoir and a crossover front would then migrate into the magma body with time. Thus, at any time after T_c migrated into a magma body, eruption could produce a deposit whose early-erupted part contains feldspar more radiogenic than groundmass and whose later-erupted part exhibits the opposite isotopic relation, if the magma body is simply tapped from the top down.

If the crossover time, T_c, is not recorded in an eruptive unit, yet evidence for contamination of the sort we describe is compelling, a qualitative estimate of duration of the contamination process is possible. For example, with one exception (sample B69, Table 1, and this is at the limit of analytical precision) feldspar phenocrysts in the Bishop Tuff are less Sr radiogenic than groundmass. Bulk country rocks around the Bishop Tuff reservoir probably were about as Sr radiogenic as, or slightly more Sr radiogenic than, uncontaminated magma (Halliday and others, 1984). Biotite of the country rocks would have been far more radiogenic than uncontaminated Bishop Tuff magma. Thus, if the Sr-isotope disequilibrium in the Bishop Tuff is a result of the process modelled by us, the crossover time, T_c, was not reached before eruption produced this ignimbrite. Christensen and DePaolo (1993) are the first to report that at least some biotite crystals in the Bishop Tuff are xenocrysts. This observation is consistent with the idea that magma for the Bishop Tuff assimilated some country-rock material.

VARIATIONS ON THE THEME

Boundary conditions for the model can be adjusted to fit different geologic settings, without affecting the applicability of the model. If, for example, a field setting indicates that bulk country rock is less radiogenic than uncontaminated magma, the initial disequilibrium relation (i.e., before T_c) could be one of feldspar more radiogenic than groundmass. If contaminant and magma are not measurably different in $^{87}Sr/^{86}Sr$, isotopic disequilibrium should not develop. However, if biotite (or hornblende) is in the country rock, contaminated magma may receive an initial spike of relatively high $^{87}Sr/^{86}Sr$, even though bulk-country-rock $^{87}Sr/^{86}Sr$ is the same as that of uncontaminated magma.

The relatively simple situation depicted by the model (Fig. 1) may become complicated when spatial variation in country rock exists around the margin of a magma reservoir. Spatial variations in both country-rock lithology and age could affect the degree and style of chemical imprint on magma due to contamination by the adjacent rocks. Such a complication may perhaps be evaluated best from detailed knowledge of the geology of a particular field setting. Time variations in the character of country rock also could complicate the simple picture; different types of country rock could be exposed at the magma-rock interface as assimilation proceeds.

The means by which contaminant enters and then penetrates into a body of magma are not explicitly addressed by the model. If contamination proceeds only by diffusion, penetration probably is limited to some meters or tens of meters over the probable range of life spans for large silicic magma reservoirs. If, however, the effect of Sr-isotope contamination is transmitted by convection, penetration is limited only by the dimensions of convection cells and the efficiency of chemical exchange across cell boundaries. The scale of vertically stacked convection cells thought to exist in some silicic magma bodies (for example, Fridrich and Mahood, 1987; Christensen and DePaolo, 1993) suggests that convectively-transported contamination could affect much of the rhyolitic part of a zoned reservoir of silicic magma. However, convection would tend to blur or homogenize magma composition within a convection cell, and thus any contamination-induced vertical change from feldspar phenocrysts more radiogenic to less radiogenic than melt (or vice versa) might not be preserved.

Contaminated magma might also be transmitted into progressively deeper levels of a reservoir if displaced downward by fractionated melt flowing to the top of the reservoir in response to side-wall crystallization (e.g., Christensen and DePaolo, 1993). This scenario also provides for a continuous or quasi-continuous supply of "uncontaminated" magma within the boundary zone between magma reservoir and roof rocks.

CONCLUSIONS

The model presented herein provides a means of producing various types of Sr-isotope relations between phenocrysts and melt and is testable through measurements of $^{87}Sr/^{86}Sr$ profiles for individual crystals. However, open magmatic systems are subject to contamination (sensu lato) from a variety of sources and a variety of ways, such that no model for Sr-isotope disequilibrium should be applied to a particular system without first evaluating geologic boundary conditions as completely as possible.

Highly evolved rhyolitic magma is perhaps the easiest to evaluate for possible contamination by country rocks through the process proposed herein, because such magma commonly exhibits extreme enrichments (e.g., Rb, Nb, and Th) and depletions (e.g., Sr and Ba) of many trace elements and accordingly is subject to easily detectable contamination by a very small proportion of material with average, or nearly average, crustal composition. For example, the uncontaminated Taylor Creek Rhyolite contains about 2-3 ppm Sr and low $^{87}Sr/^{86}Sr$ (Reece and others, 1990; Duffield and Ruiz, 1992a), whereas the Precambrian country rocks within which the magma reservoir resided contained 100's, if not 1000's, of ppm Sr and very high $^{87}Sr/^{86}Sr$. Such effective chemical leverage facilitates easy recognition of contamination and simultaneously casts doubt on explanations for Sr-isotope disequilibrium offered by models based on closed magma systems. In effect, our model can explain a variety of patterns of Sr-isotopic phenocryst-melt disequilibrium within a body of rhyolitic magma (and its erupted products), with minimal, yet essential, introduction of foreign material.

REFERENCES

Baker, D.R., 1989, Tracer versus trace element diffusion: Diffusional decoupling of Sr concentration from Sr isotope compositon: Geochimica et Cosmochimica Acta, v. 53, p. 3015-3023.

Christensen, J.N., and DePaolo, D.J., 1993, Time scales of large volume silicic magma systems: Sr isotopic systematics of phenocrysts and glass from the Bishop Tuff, Long Valley, California: Contributions to Minerology and Petrology, v. 113, p. 100-114.

Duffield, W.A., and Ruiz, J., 1992a, Compositional gradients in large reservoirs of silicic magma as evidenced by ignimbrites versus Taylor Creek Rhyolite lava domes: Contributions to Minerology and Petrology, v. 110, p. 192-210.

Duffield, W.A., and Ruiz, J., 1992b, Evidence for the reversal of gradients in the uppermost parts of silicic magma reservoirs: Geology, v. 20, p. 1115-1118.

Fridrich, C.J., and Mahood, G.A., 1987, Compositional layers in the zoned magma chamber of the Grizzly Peak Tuff: Geology, v. 15,p. 299-303.

Futa, K. Hedge, C.E., Hearn, B.C., Jr., and Donnelly-Nolan, J.M., 1981, Strontium isotopes in the Clear Lake volcanics: U.S. Geological Survey Professional Paper 1141, p. 61-66.

Giletti, B.J., 1991, Rb and Sr diffusion in alkali feldspars, with implications for cooling histories of rocks: Geochimica et Cosmochimica Acta, v. 55. p. 1331-1343.

Halliday, A.N., Fallick, A.E., Hutchinson, J., and Hildreth, W., 1984, A Nd, Sr and O isotopic investigation into the causes of chemical and isotopic zonation in the Bishop Tuff, California: Earth and Planetary Science Letters, v. 68, p. 379-391.

Halliday, A.N., Mahood, G.A., Holden, P., Metz, J.M., Dempster, T.J., and Davidson, J.P., 1989, Evidence for long residence times of rhyolitic magma in the Long Valley magmatic system: the isotopic record in precaldera lavas of Glass Mountain: Earth and Planetary Science Letters, v. 94, p. 274-290.

Johnson, C.M., and Fridrich, C.J., 1990, Non-monotonic chemical and O, Sr, Nd, and Pb isotope zonations and heterogeneity in the mafic- to silicic-composition magma chamber of the Grizzly Peak Tuff, Colorado: Contributions to Minerology and Petrology, v. 105, p. 677-690.

Kaczor, S.M., Hansen, G.N., and Perterman, Z.E., 1988, Disequilibrium melting of granite at the contact with a basic plug: A geochemical and petrographic study: Journal of Geology, v. 96, p. 61-78.

Noble, D.C., and Hedge, C.E., 1969, ^{87}Sr/^{86}Sr variations within individual ash-flow sheets: U.S. Geological Survey Professional Paper 650-C, p. C133-C139.

Reece, C., Ruiz, J., Duffield, W.A., and Patchett, P.J., 1990, Origin of Taylor Creek rhyolite magma, Black Range, New Mexico, based on Nd-Sr isotope studies: Geological Society of America Special Paper 246, p. 263-273.

Stuckless, J.S., and O'Neil, J.R., 1973, Petrogenesis of the Superstition-Superior volcanic area as inferred from strontium- and oxygen-isotope studies: Geological Society of America Bulletin, v. 84, p. 1987-1998.