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DISTRIBUTION OF OXYGEN ISOTOPE VALUES IN THE BONITO LAKE STOCK AND SURROUNDING AREA, LINCOLN COUNTY, NEW MEXICO

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ABSTRACT—The Bonito Lake and Rialto stocks are two of the intrusions associated with the Sierra Blanca Volcanics in the Sierra Blanca region of New Mexico. This work, along with previous work in the area, has shown that isotopically-light meteoric water was the dominant fluid responsible for the mineralization and hydrothermal alteration of the volcanic and plutonic rocks in the Sierra Blanca region. Hydrothermal alteration of the stocks and the volcanics is widespread and ranges in intensity from mild to strong and is reflected in depleted oxygen isotope values relative to "normal" isotopic values. Whole-rock $\delta^{18}O$ values for the Bonito Lake stock range from 2.0 to 8.4‰ with a mean of 5.3 ±1.9‰ and 3.4 to 5.6‰ for the Rialto stock with a mean of 4.3 ±0.9‰. Oxygen isotope values for the Sierra Blanca Volcanics in the vicinity of the Bonito Lake and Rialto stocks range from 1.0 to 8.0‰ with a mean of 4.2 ±2.0‰. Quartz from gold veins located in the vicinity of the stocks yielded values of 4.9 to 15.3‰ with a mean of 10 ±2.9‰. Isotopic lows in the vicinity of the Bonito Lake stock are, in general, coincident with the location of mineralization in the this part of the Nogal-Bonito mining district. Water/rock ratios were likely low, ranging from less than one up to a high of 2.3. High $\delta^{18}O$ values for two Bonito Lake stock samples (8.1 and 8.4‰) are probably due to retrograde interaction with cool meteoric water at low water/rock ratios. A sample of the Sierra Blanca Volcanics collected in the vicinity of vein gold mineralization and containing void-filling quartz and calcite yielded a high value of 8.0‰.

INTRODUCTION

In the Sierra Blanca region, the Bonito Lake stock, the adjacent Rialto stock, and the associated Sierra Blanca Volcanics exhibit varying degrees of hydrothermal alteration ranging from mild to quite strong (Constantopoulos, 2007; Goff et al., 2011). The Bonito Lake stock covers an area of 19 km^2 and has been described as a hornblende-biotite syenite which is monzonitic along the western margin (Thompson, 1972), a syenite to quartz syenite (Allen and Foord, 1991), and a monzonite-syenite porphyry (Moore et al., 1991). Petrographic work (Constantopoulos, 2007) showed that the Bonito Lake stock consists of mainly biotite and hornblende syenite, with subordinate quartz syenite, and monzonite based on the IUGS classification scheme (LeMaitre, 1989). The samples plot in the syenite and syenodiorite fields (Constantopoulos, 2007) on an R1-R2 multicationic diagram (De La Roche et al., 1980). A K-Ar date of 26.6 ±1.4 Ma was reported by Thompson (1972). An $^{40}Ar/^{39}Ar$ date of 26.79 ±0.08 Ma and a U/Pb date of 27.3 ±0.4 Ma was recently obtained (Fraser Goff and William McIntosh, unpub. data, 2012). The area is host to a variety of mineral deposit types including placer gold, fissure veins, breccia pipes, and porphyry molybdenum-copper (Goff et al., 2011; McLemore et al., this volume).

Douglass and Campbell (1994) describe three forms of hydrothermal alteration in the region: early, widespread propylitic alteration of the volcanics; a similar propylitic alteration event associated with the Ag-Pb-Zn veins; and a later alteration event associated with the vein gold deposits. Alkali feldspars in the rocks of the Bonito Lake stock exhibit moderate to strong argillic alteration. The rims of plagioclase grains are moderately to strongly argillized and the cores generally exhibit mild to moderate sericitic alteration. Hornblende ranges from virtually unaltered to having strong chloritic alteration in which there is near total replacement of the hornblende. Biotite is iron-rich and mostly unaltered or only mildly altered to chlorite. In many samples, abundant secondary magnetite is common along biotite cleavages. Powder X-ray diffraction of one sample (NB-57) indicated that the biotite is the fluorannite variety.

Oxygen isotopes are a powerful tool for studying the interaction of hydrothermal waters and the affected rocks (Taylor, 1974; Campbell and Larson, 1998). A total of forty-one whole-rock and ten vein quartz samples were analyzed for their oxygen isotope composition. These samples were collected from the Bonito Lake and Rialto stocks, the Sierra Blanca Volcanics, and from several quartz veins with visible mineralization. The extractions were performed at Washington State University using chlorine trifluoride in a high-vacuum line similar to that described by Taylor and Epstein (1962). Results are reported in Table 1 in per mil (‰) deviation ($\delta^{18}O$) relative to VSMOW.

OXYGEN ISOTOPE RESULTS

The whole-rock $\delta^{18}O$ values for the Bonito Lake stock range from 2.0 to 8.4‰ with a mean of 5.3 ±1.9‰. This includes one dike sample from within the Bonito Lake stock, which yielded a $\delta^{18}O$ value of 5.4‰. The five Rialto stock samples yielded $\delta^{18}O$ values ranging from 3.4 to 4.3‰. Most of the Bonito Lake stock and all of the Rialto stock samples are depleted in ^{18}O relative to "normal" (i.e., unaltered) values for syenite (approximately 6 to 8‰) reported by Taylor (1968). These depleted values are consistent with hydrothermal alteration by ancient meteoric fluids and the evidence for this can be seen in thin section.

The volcanic rocks are slightly more depleted in ^{18}O than the plutonic rocks, likely a reflection of their more reactive nature to hydrothermal fluids. Greater permeability and finer grain size were probably equally important factors. The $\delta^{18}O$ values for the volcanic rocks range from 1.0 to 8.0‰ with a mean of 4.2 ±2.0‰ and are consistent with the values reported by Douglass and Campbell (1994). Most of these volcanic rocks are also depleted in ^{18}O relative to values for "normal" andesites reported by Taylor (1968) which range from 5.4 to 7.5‰.

TABLE 1. Oxygen isotope values for the Sierra Blanca Volcanics (SBV), Bonito Lake stock (BLS), Rialto stock (RS) and vein quartz (QTZ). Values are in per mil relative to VSMOW.

Number	Type	δO^{18}	General Location
NB-01	RS	3.5	Parsons Mine
NB-02	RS	3.4	Parsons Mine
NB-03	RS	4.1	Parsons Mine
NB-04	RS	4.7	Parsons Mine
NB-05	QTZ	4.9	Rockford Mine
NB-06	QTZ	9.8	Rockford Mine
NB-07	SBV	3.4	Rockford Mine
NB-08	QTZ	7.7	Rockford Mine
NB-09	QTZ	9.8	American Mine
NB-10	SBV	8.0	American South Mine
NB-11	SBV	4.2	American South Mine
NB-12	QTZ	12.1	American Mine
NB-13	QTZ	7.3	American Mine
NB-14	QTZ	10.5	American Mine
NB-15	QTZ	12.3	Helen Rae Mine
NB-15	QTZ	15.3	Helen Rae Mine
NB-16	QTZ	10.7	Helen Rae Mine
NB-17	SBV	5.6	American Mine
NB-18A	SBV	6.1	Rockford Mine
NB-18B	SBV	5.6	Rockford Mine
NB-19	BLS	5.2	Bonito Lake Dam
NB-20A	BLS	2.1	South Fork CG
NB-20B	BLS	2.6	South Fork CG
NB-21A	SBV	2.2	W of Betsy Cyn
NB-21B	SBV	1.4	W of Betsy Cyn
NB-22A	SBV	1.0	Between Robinson and Geo Wash. Cyn
NB-22B	SBV	1.8	Between Robinson and Geo Wash. Cyn
NB-23	BLS	3.3	Bear Creek Cyn
NB-24	BLS	4.0	Portal near Trail 36
NB-25	BLS	5.9	Portal near Trail 36
NB-26	BLS	4.4	Portal near Trail 37
NB-28A	SBV	4.4	Argentine Mine
NB-28B	SBV	3.0	Argentine Mine
NB-31	SBV	7.8	Turkey Cyn
NB-32	SBV	5.5	Tanbark Cyn
NB-33	SBV	4.4	Tanbark Cyn
NB-39	SBV	6.2	Tanbark Cyn
NB-40	RS	5.6	Tanbark Cyn
NB-41A	BLS	8.1	Indian Creek
NB-41B	BLS	8.4	Indian Creek
NB-42	BLS	5.7	Indian Creek
NB-43	SBV	3.5	Indian Creek
NB-45	SBV	3.3	Monjeau Pk Road
NB-46	SBV	2.7	Monjeau Pk Road
NB-49	BLS	4.7	Monjeau Pk Road
NB-53A	BLS	5.1	Bonito Lake Dam
NB-53C	BLS	6.2	Bonito Lake Dam
NB-54B	BLS	7.2	Between Kraut and Littleton Cyns
NB-55	BLS	7.0	Near S Fork CG
NB-57	BLS	2.0	Near S Fork CG
NB-53B	Dike	5.4	Bonito Lake Dam

Two of the Bonito Lake stock samples (NB-41A and NB-41B) yielded $\delta^{18}O$ values of 8.1 and 8.4‰, respectively; values above that for "normal" syenites (Taylor, 1968). These samples are finer-grained than the typical Bonito Lake stock samples and the alkali feldspars are strongly argillized. One possible mechanism to explain the elevated isotopic values in igneous rocks is the assimilation of higher $\delta^{18}O$ sedimentary country rock during differentiation (Taylor, 1968; Goff and Gardner, 1994). Another possible mechanism is retrograde alteration caused by an influx of relatively cool meteoric water at low water/rock ratios (Donoghue et al., 2010). The latter mechanism is preferred because there is no clear evidence of sedimentary country rock assimilation in the Bonito Lake stock. Two of the volcanic rocks also showed values above the "normal" values for andesites and trachytes (Taylor, 1968). The high value of 8.0‰ for sample NB-10 is due to the presence of abundant secondary comb quartz and calcite filling voids. This sample was collected at the Helen Rae mine. NB-31 ($\delta^{18}O$ = 7.8‰) is a porphyritic trachyte in which the mafic minerals are completely replaced by chlorite and calcite with abundant fine magnetite scattered throughout.

Vein quartz was collected from three gold mines, the American, Helen Rae-American and Rockford, located north of the Bonito Lake stock, yielding values of 4.9 to 15.3‰ with a mean of 10.0 ±2.9‰. These results are also consistent with those of Douglass and Campbell (1994), who obtained quartz $\delta^{18}O$ values as low as 3.9‰ for gold deposits and as low as 2.2‰ for silver base-metal deposits.

The range of values and means for the whole-rock and vein quartz samples are compared in Figure 1. While the means for the whole-rock samples are similar (4.2 to 5.1‰), the lower means for the Rialto stock and Sierra Blanca Volcanics reflect overall stronger alteration in these rocks. The mean $\delta^{18}O$ values for the vein quartz (10.0‰) is more than twice that for the plutonic and volcanic whole-rocks.

DISTRIBUTION OF ISOTOPIC VALUES AND WATER:ROCK RATIOS

Contoured $\delta^{18}O$ values are plotted Figure 2. Several of the plotted values represent the average of closely-spaced samples. The map shows a zone of ^{18}O depletion in the western half of the Bonito Lake stock. This low is located approximately where the Bonito fault crosses the stock and is also in an area of several mines and prospects. Higher $\delta^{18}O$ values in the eastern half of the Bonito Lake stock may reflect lower permeability

(Criss et al., 1984), consistent with the fact that there are fewer mines and prospects located in this area. Additionally, the locations of steeper $\delta^{18}O$ gradients roughly corresponds to areas of more numerous mines and prospects. This suggests higher permeability or higher water/rock ratios (Criss et al., 1984) in these areas. Douglass and Campbell (1994) found that alteration became more intense, from the fringes of the volcanic pile towards the center, where the stocks and most of the mineralization is located. In recent mapping of the Nogal Peak quadrangle, Goff et al. (2011) report that hydrothermal alteration in the area increases towards the south and east and "in particular near the margins and within the stocks."

To better understand the conditions under which hydrothermal alteration occurred, water/rock ratios were calculated using the equations of Taylor (1974; 1977). The results are plotted in Figure 3. For a closed system in which none of the hydrothermal fluid is lost, the effective water/rock ratio is given by:

$$\frac{\text{Water}}{\text{Rock}}(\text{closed}) = \frac{\delta^{18}O_{\text{rock}}^{\text{final}} - \delta^{18}O_{\text{rock}}^{\text{initial}}}{\delta^{18}O_{\text{water}}^{\text{initial}} - \left(\delta^{18}O_{\text{rock}}^{\text{final}} - \Delta\right)}$$

where $\Delta = \delta^{18}O_{rock}^{final} - \delta^{18}O_{\text{water}}^{\text{final}}$. This model assumes continuous recirculation of the water and re-equilibration with the rocks. The water/rock ratio for an open system was calculated using

$$\frac{\text{Water}}{\text{Rock}}(\text{open}) = \ln\left[\frac{\text{Water}}{\text{Rock}}(\text{closed}) + 1\right]$$

This model assumes that the water makes only a single pass through the system. While a perfectly closed and perfectly open system do not represent geologic reality, the actual water/rock ratios will likely lie between these two extremes.

Water/rock ratios were calculated using a $\delta^{18}O$ value of 8.4‰ for the initial unaltered rock composition (the least depleted whole-rock $\delta^{18}O$ value in this study); -13‰ for the initial meteoric water composition; alkali feldspar-water exchange values (A=2.91; B=-3.41) of O'Neil and Taylor (1967); and fluid inclusion homogenization temperatures of Douglass and Campbell (1994). Alkali feldspars (orthoclase and albite) dominate the mineralogy of the Bonito Lake stock (Constantopoulos, 2007) and feldspars generally exhibit the greatest isotopic exchange with hydrothermal fluid.

Figure 3 shows that at a constant water/rock ratio, higher temperature results in a lower value of $\delta^{18}O$ Also, at a given temperature, as the water/rock ratio increases, the value of $\delta^{18}O$ decreases. The results (Fig. 3) indicate that water/rock ratios varied from less than unity to approximately 2.3 for a closed system at 180° C. These are the extreme values; the actual water/rock ratios were likely somewhere in between.

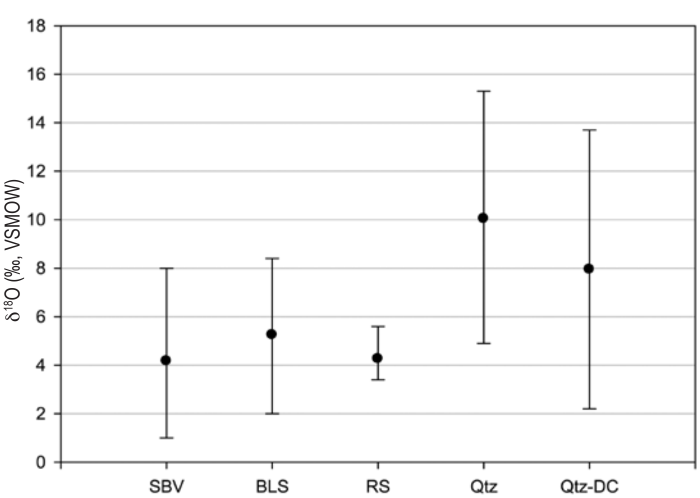

FIGURE 1. Range and means (dots) for oxygen isotope values in the Sierra Blanca Volcanics (SBV), Bonito Lake stock (BLS), Rialto stock (RS), vein quartz (Qtz) and vein quartz (Qtz-DC) of Douglass and Campbell (1994).

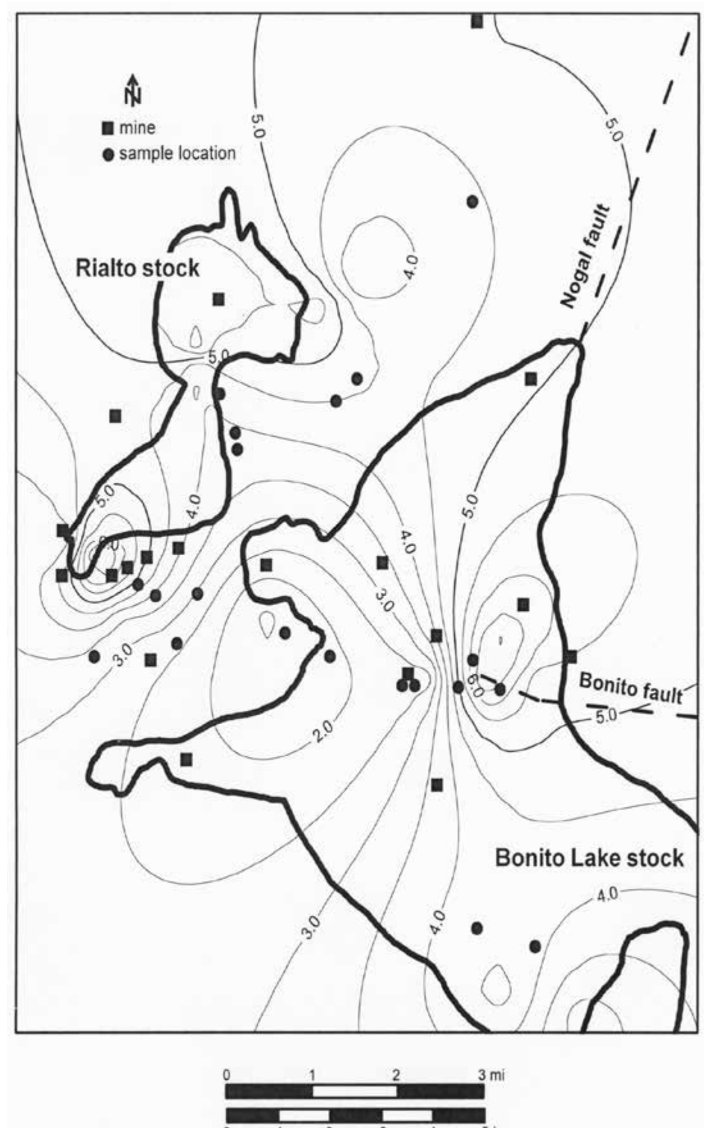

FIGURE 2. Map showing contoured $\delta^{18}O$ whole-rock values in per mil (‰) relative to VSMOW. Contour interval is 0.5‰. Outlines of the Bonito Lake and Rialto stocks are from Woodward (1991). Location of the Bonito and Nogal faults (dashed lines) from Thompson (1973).

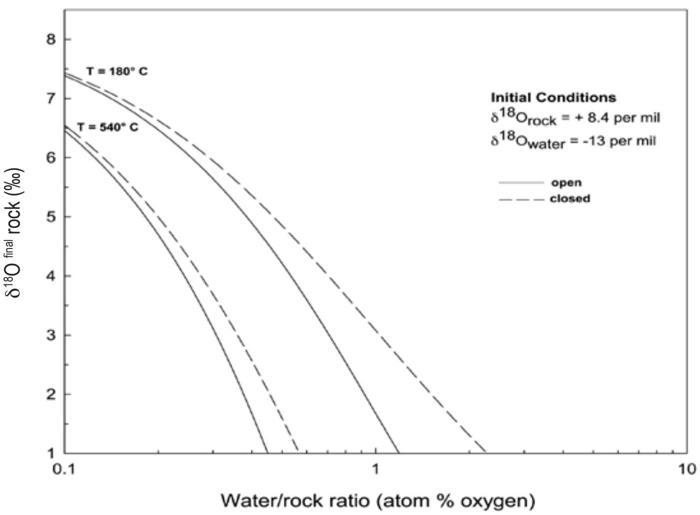

FIGURE 3. Water/rock ratios calculated using the equations of Taylor (1974; 1977). An initial $\delta^{18}O_{rock}$ value of +8.4‰ and an initial $\delta^{18}O_{water}$ value of -13‰ was assumed. The temperatures were selected on the basis of quartz fluid inclusion homogenization temperatures reported in Douglass and Campbell (1994) which range from 230° to 540° C for Au veins and 180° C to 350° C for Ag-Pb-Zn veins.

CONCLUSIONS

This work, along with previous work in the area, has shown that isotopically-light meteoric water was the dominant fluid responsible for the mineralization and hydrothermal alteration of the volcanic and plutonic rocks in the Sierra Blanca region. The whole-rock values range from 1.0 to 8.4‰ and vein quartz ranges from 4.9 to 15.3‰. The lower mean $\delta^{18}O$ value for the Sierra Blanca Volcanics (4.2‰) is consistent with their greater reactivity to the hydrothermal fluids. The mean $\delta^{18}O$ value for the Rialto stock (4.3‰) is similar to that for the Sierra Blanca Volcanics and both are lower than the mean $\delta^{18}O$ for the Bonito Lake stock (5.3‰). The Bonito Lake stock is not as intensely altered as the Rialto stock and two high values may reflect retrograde interaction with cool meteoric water at low water/rock ratios. Contoured $\delta^{18}O$ values show steeper gradients and lower isotopic values in the area of mineralization likely reflecting greater permeability. Water/rock ratios were low and this may explain why the area was not more strongly mineralized.

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Fraser Goff, Virginia McLemore, and Geoff Rawling provided thorough reviews which greatly improved the manuscript. Funding for the oxygen isotope analyses was provided by a Faculty Research Grant from Eastern New Mexico University.

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