Compositional Changes Induced by Hydrothermal Alteration at the Red Mountain Alunite Deposit, Lake City, Colorado

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Compositional Changes Induced by Hydrothermal Alteration at the Red Mountain Alunite Deposit, Lake City, Colorado

By DANA J. BOVE and KEN HON

Sample analysis shows chemical changes in rocks
from hydrothermal alteration

U.S. GEOLOGICAL SURVEY BULLETIN 1936

DEPARTMENT OF THE INTERIOR
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Compositional Changes Induced by Hydrothermal Alteration at the Red Mountain Alunite Deposit, Lake City, Colorado

By Dana J. Bove *and* Ken Hon

Abstract

The Red Mountain alunite deposit, one of the largest in the United States (more than 70 million metric tons of alunite), formed on the eastern margin of the 23.1-Ma Lake City caldera, in southwestern Colorado. Several texturally and temporally distinct high-potassium dacite intrusions cut high-potassium dacite lavas that were erupted along the eastern ring fracture of the Lake City caldera after it collapsed. The majority of the dacite intrusions and lavas on Red Mountain were affected by hydrothermal brecciation and strong hydrothermal alteration, also dated at 23.1 Ma.

Alunitized rock occurs in two large, roughly conical centers with roots extending as much as 820 ft (feet) beneath the ground surface. The alunitized rock grades outward into argillized and weakly altered high-potassium dacitic rock and grades downward through argillic, sericitic, silicic, and potassic zones predominantly in dacite intrusions and hydrothermally brecciated rock.

Thirty-five altered and fresh rock samples from both the dacite intrusions and dacite lavas were analyzed for 10 major elements, 6 trace elements, sulfur, H_2O^+, H_2O^-, and CO_2, in order to evaluate the chemical changes that took place in the major altered zones during hydrothermal alteration. Mass-balance calculations indicate that large quantities of sulfur were introduced by the hydrothermal system. Sulfur is present primarily as SO_3 within alunitized rocks and as S_2 within pyrite-bearing potassic and argillic altered rocks. Al_2O_3 and K_2O were removed during alunitization, and PO_4 and strontium were enriched due to coupled substitution of PO_4^{3-} for SO_4^{2-} and Sr^{2+} for K^+ in the alunite structure. Water was added to all of the altered zones as hydrous alteration minerals. Both potassium and rubidium were added to the potassic zone, and a slight gain in Al_2O_3 was observed in kaolinite-altered rocks. An average gain of 15 weight percent SiO_2 took place in the zone of silicification. Zirconium, niobium, and TiO_2 remained relatively immobile in most of the alteration assemblages.

Manuscript approved for publication, March 9, 1990.

INTRODUCTION

Red Mountain, on the eastern margin of the 23.1-Ma Lake City caldera (Hon, 1987), Lake City, Colo. (fig. 1), hosts one of the largest replacement alunite deposits in the western United States (more than 70 million metric tons of alunite). Chemical analyses of 35 samples selected from both altered and fresh rocks from Red Mountain were analyzed to evaluate chemical changes within the major alteration assemblages. This paper briefly summarizes the geology of Red Mountain, presents the mass-balance data, and discusses the implications of these data with respect to mineralogic changes within the alteration assemblages.

Data from a 2,777-ft-deep drill hole and three relatively shallow holes (figs. 2, 3) indicate that the 23.1-Ma alunite deposit (Mehnert and others, 1979) is the upper level of a weakly mineralized, moderately high fluorine "porphyry-type system" characterized by multiple dacite intrusions, minor molybdenite, and strong potassic alteration (Bove, 1988; Bove and others, 1988).

Several temporally and texturally distinct high-potassium dacite intrusions (dacite porphyry of Red Mountain) cut older high-potassium dacite lavas (dacite lavas of Grassy Mountain) on Red Mountain that erupted after collapse of the Lake City caldera. Surface exposures of several irregular dacite porphyry intrusions are interpreted to be high-level apophyses either emplaced prior to, or were possibly fed from, a larger stock intercepted by a drill hole about 2,460 ft beneath the present ground surface (Bove, 1988; Bove and others, 1988).

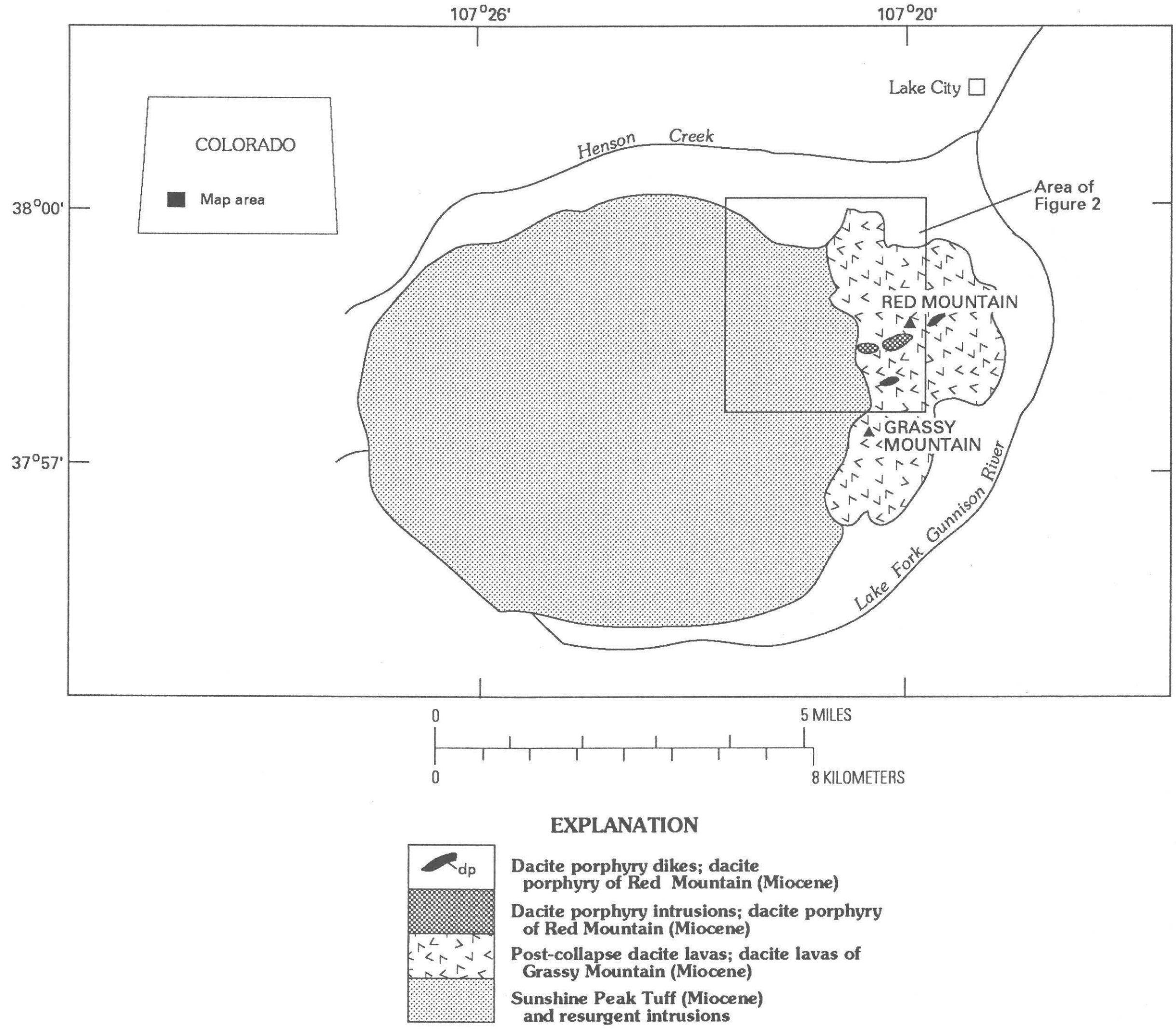

Figure 1. Generalized geology of the Red Mountain area, Lake City, Colo.

Alunitized rock occurs in two large, nearly conical centers whose roots extend as much as 820 ft below the surface (fig. 3) at Red Mountain. The alunite approaches end-member potassic composition. The alunite alteration assemblage is defined by the presence of alunite, quartz, and pyrite, with minor amounts of topaz, fluorite, pyrophyllite, and gypsum. Paragenetic relations within alunitized rock are complex; multiple stages of alunite include (1) early fine-grained alunite replacement of feldspar phenocrysts and quartz-pyrite-alunite alteration of the groundmass, (2) irregular alunite flooding of both groundmass and previously altered phenocrysts, (3) fine-grained, fracture-controlled alunite veinlets, and (4) localized veinlets of medium to coarse-grained translucent alunite.

Alunitized rocks grade outward into argillized (kaolinite predominant, plus sericite[1], pyrite and (or) minor smectite) and marginally altered rocks[2] and grade downward through argillic (kaolinite predominant and (or) sericite and (or) minor smectite), sericitic (sericite-pyrite predominant and (or) kaolinite and (or) minor smectite) and potassic (secondary potassium feldspar and biotite) altered zones (figs. 3, 4). The top part of the potassic alteration zone contains a silicification zone

[1]A term referring to a fine-grained (typically less than 10 micrometers), highly birefringent micaceous mineral. X-ray diffraction, electron microprobe, and geochemical data (Bove, 1988) indicate that sericite at Red Mountain is very fine grained high-magnesium muscovite or phengite (Srodon and Eberl, 1984).

[2]Rocks distinguished by the presence of smectite and sericite and containing relatively unaltered phenocrysts of sanidine and biotite. Some local variants of this assemblage resemble a typical propylitic assemblage. Marginal alteration occurs throughout most of the rocks on the periphery of Red Mountain.

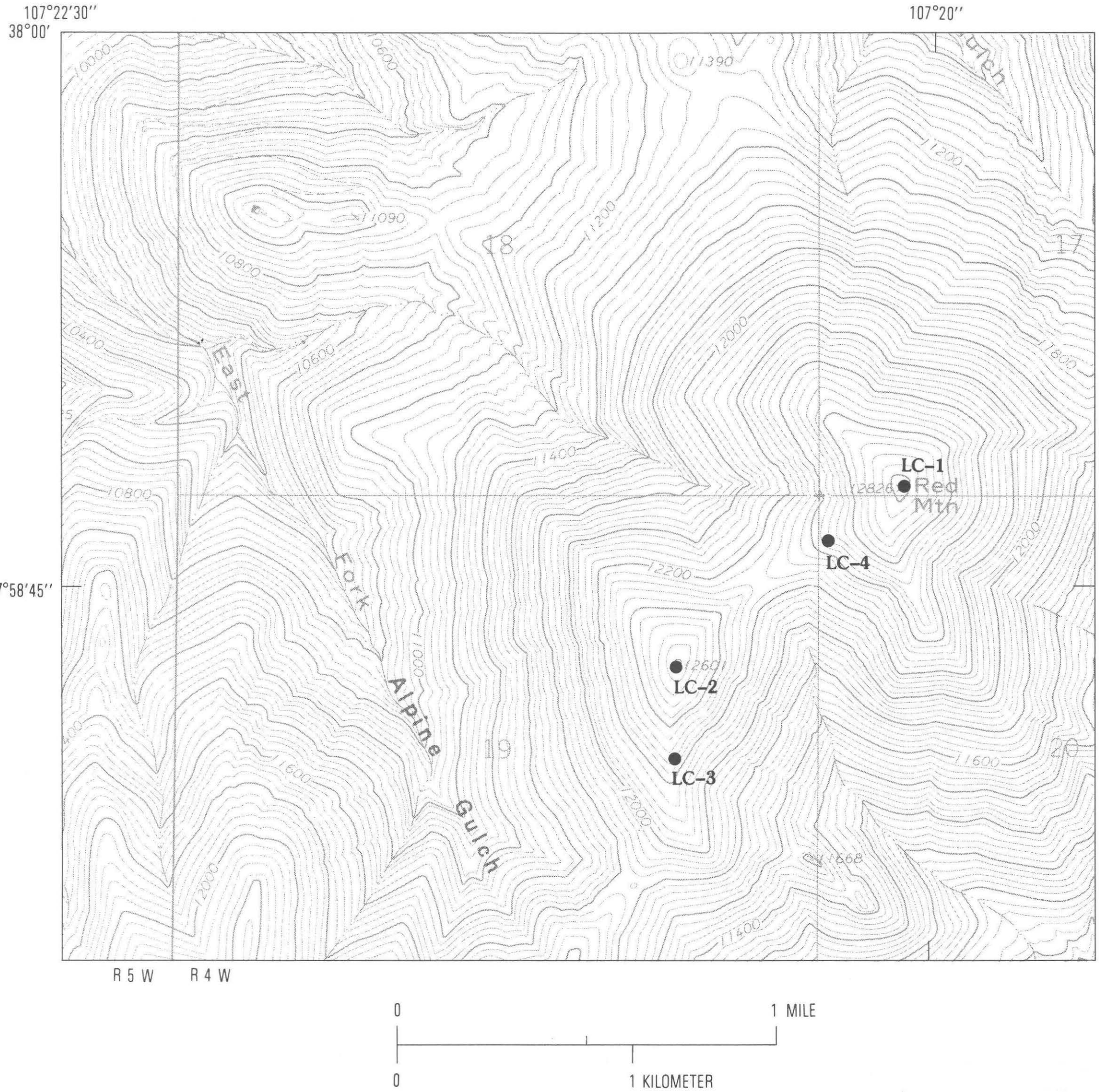

Figure 2. Drill-hole localities and topography, Red Mountain area. Dots are drill-hole localities with hole numbers.

characterized in drill core by intervals of microcrystalline quartz flooding and later stockwork veinlets of microcrystalline quartz. This drill core shows that argillic alteration overprinted earlier sericitic alteration, and the potassic zone was superimposed by sericitic and argillic alteration near the top of the zone (Bove, 1988; Bove and others, 1988) (fig. 3). Although the lateral and vertical transition from alunite altered rock into argillic and (or) sericitic altered rock was not directly observed, geologic data, which include potassium-argon dates on alunite and the fresh dacite lavas (Mehnert and others, 1973, 1979; Hon, 1987), detailed paragenetic studies, and stable isotope studies (Bove, 1988; Bove and others, 1988), indicate that the timing of alunitization was closely associated with stages of potassic and sericitic alteration.

Hydrogen-, oxygen-, and sulfur-isotope studies constrain the origin of alunite and the source of the fluids and sulfur (Bove, 1988; Bove and others, 1988). Each stage of alunite has distinctly different isotopic compositions, as do different generations of pyrite. Isotopic data suggest that sulfur in stages 1 and 2 alunite was derived from sulfate having a magmatic source at temperatures of 350 °C±25 °C and 200 °C±25 °C, respectively. Stage 3 and 4 alunite was formed from the local oxidation of H_2S from the magmatically derived hydrothermal plume as atmospheric oxygen was drawn into the upper levels of the late-stage hydrothermal system.

From detailed mineralogic, petrographic, and stable-isotope studies, alunite at Red Mountain was proposed (Bove and others, 1988) to have formed from a bouyant magmatic vapor plume that rose above the level of the meteoric-water-dominated fringe of a weakly mineralized molybdenum-porphyry hydrothermal system

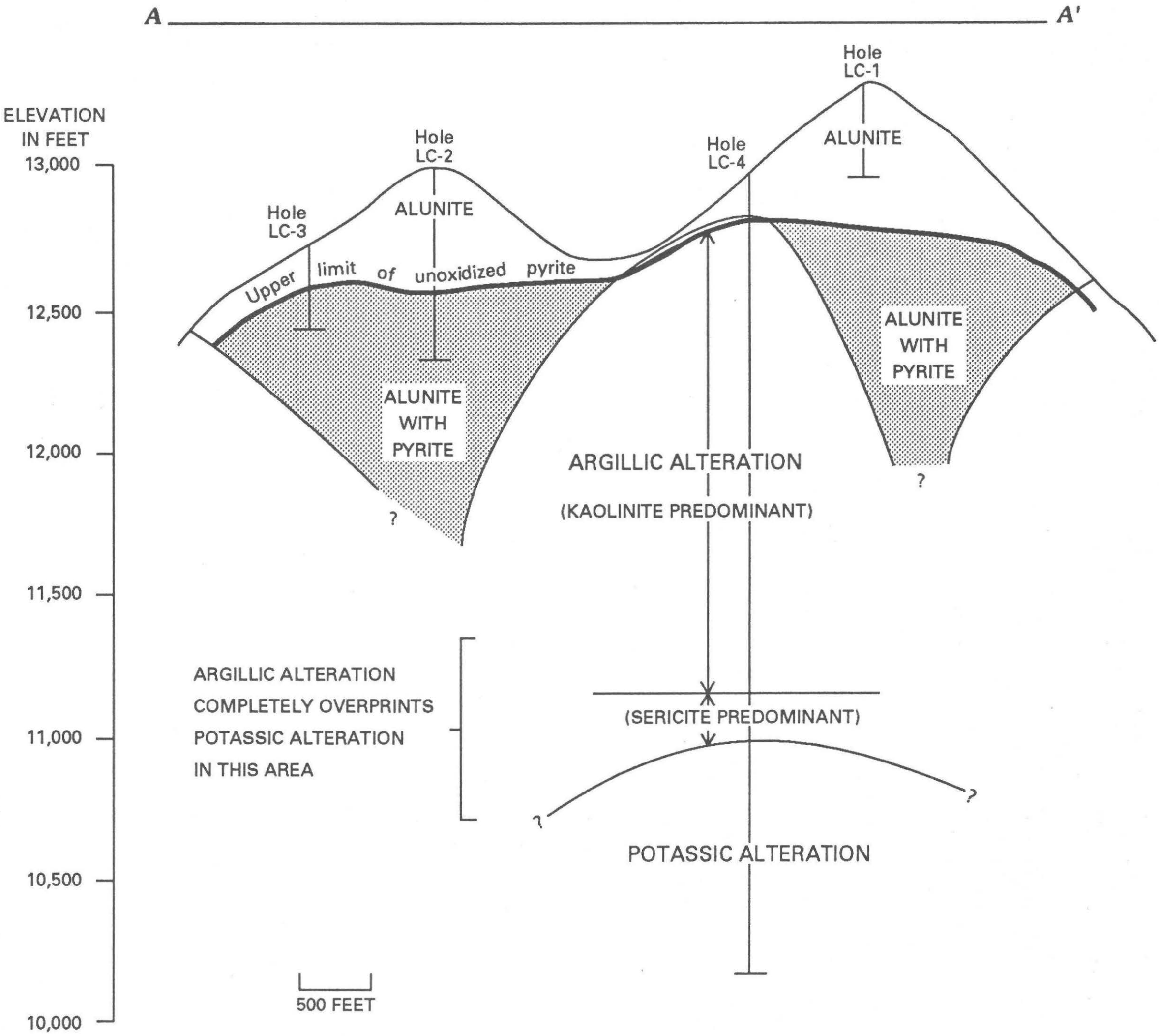

Figure 3. Cross section of hydrothermally altered area at Red Mountain, Lake City caldera, showing the profile of Red Mountain and the lower 12,601-ft peak. Cross section line *A–A′* is shown in figure 4.

Sulfur-isotope studies of the successive stages of alunite indicate a respective decrease in the oxidation state of the underlying magmas.

METHODS OF ANALYSIS

Thirty-five samples from the two predominant rock types at Red Mountain—the dacite lavas of Grassy Mountain and the dacite porphyry of Red Mountain (fig. 1)—were selected for a mass-balance study. Samples were analyzed for 10 major elements, 6 trace elements, sulfur, H_2O^+, H_2O^-, and CO_2. Major elements were analyzed for by wavelength-dispersive X-ray fluorescence (Taggart and others, 1987). Rubidium, strontium, zirconium, yttrium, niobium, and molybdenum were analyzed for by utilizing energy-dispersive X-ray fluorescence with an accuracy of +5–10 percent (Ludington, 1981). Total sulfur was determined using a Leco SR132 automated S analyser. One split (0.25 gram) of a sample was combusted with infrared detection of evolved SO_2 (Jackson and others, 1987). Total H_2O was calculated by combustion at 950 °C with Karl Fisher titration (Jackson and others, 1987) of H_2O; H_2O^- (moisture) was determined by the same procedure at 110 °C, and H_2O^+ was determined by difference (Jackson and others, 1987). Determination of carbonate carbon was by coulometric titration of acid-evolved CO_2 (Jackson and others, 1987).

In order to compare actual gains and losses of elements during alteration, the bulk rock density for each sample was determined by dividing the weight of the dry sample by its volume. As a result, the chemical compositions of the altered samples could be recalculated and compared to the equivalent fresh rock on the basis of weight per unit volume of rock (Gresens, 1966). Mass-balance calculations were made assuming constant volume, as indicated by the absence of phenocryst

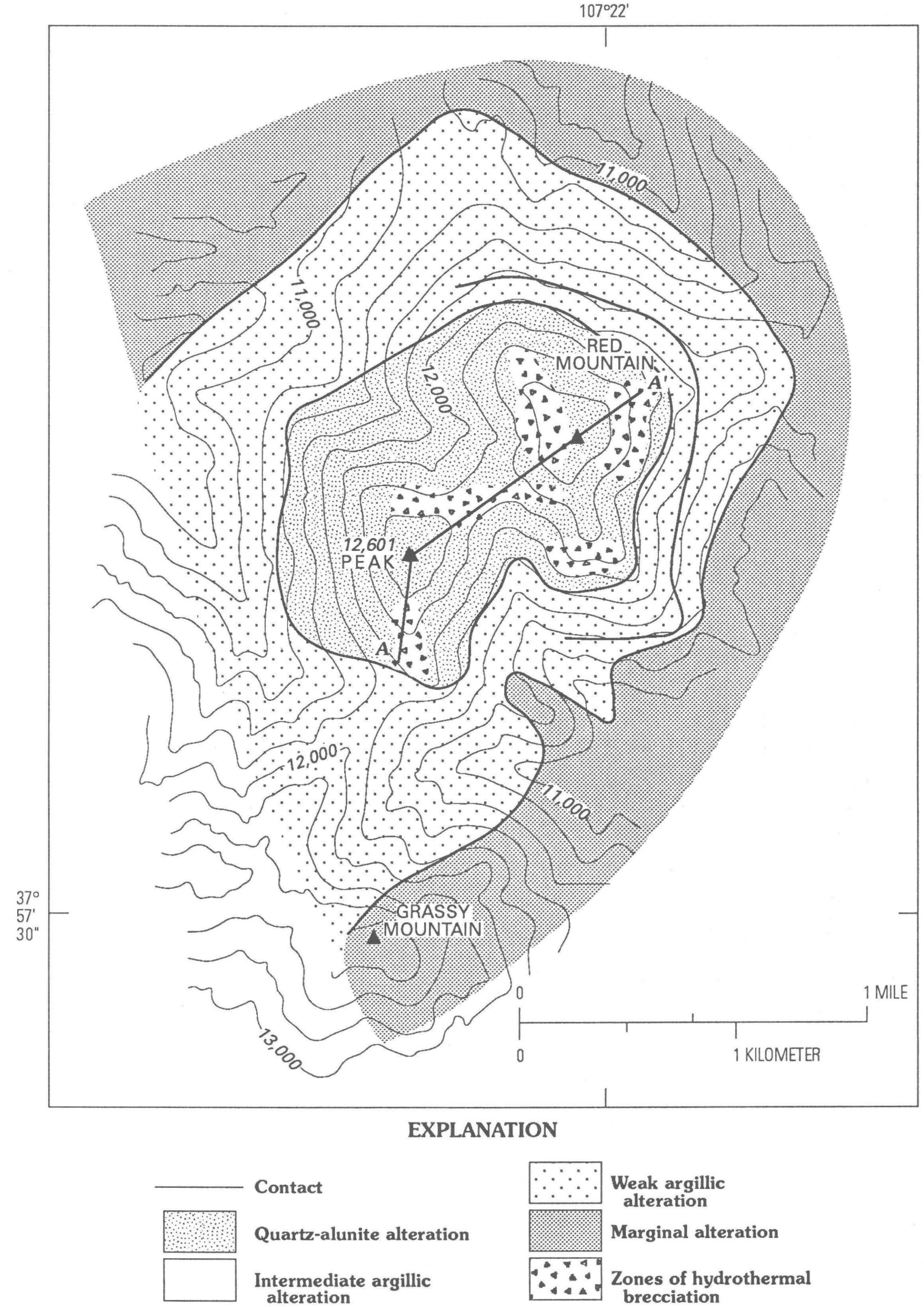

Figure 4. Plan view of hydrothermally altered area at Red Mountain. Cross section along line *A–A'* is shown in figure 3. Queried where extent of alteration is uncertain. Topographic base from U.S. Geological Survey Lake San Cristobal, scale 1:24,000. Contour interval 200 ft.

deformation, similarity in the volume percent of phenocrysts in fresh and altered rocks, and the preservation of the original rock texture.

Only samples of the dacite porphyry (rock unit Tdrp, tables 1–3) and the dacite lavas (unit Tldg) were included in the mass-balance study. This decision was made because of the abundance of these units both at the surface and in drill cores, the relative ease of differentiation of even the most altered of these rocks, and the availability of fresh samples of these rocks. Five fresh samples of the dacite lavas (1Tldg, 2Tldg, 3Tldg, 3aTldg, 4Tldg, tables 1 and 2) were collected from outcrops around the periphery of Red Mountain, and two fresh samples of dacite porphyry (1Tdrp and 2Tdrp, tables 1 and 2) were collected from dikes on the northeast and southeast flanks of Red Mountain (fig. 1). Two samples were collected from the marginal alteration assemblage (1TldgM and 2TldgM, tables 1 and 2), and two were collected from the quartz alunite zone (1aTldgA and 1bTldgA). All other samples were collected from drill holes LC1 through LC4 (figs. 2, 3). All of the fresh dacite lavas (unit Tldg, table 1) analyzed have essentially the same composition. Therefore, the most pristine of these samples, a vitrophyre, sample 3Tldg, was used as the reference fresh-rock sample to which altered samples of the dacite lavas were compared. Only two samples of fresh dacite porphyry (unit Tdrp) were analyzed. Both analyses were also quite similar and, having no geologic reason to prefer one sample over the other, we used the average of the two analyses as a reference to assess changes within altered dacite porphyry samples.

The increase or decrease of each component of the altered rocks compared with that of the parent rock (gains and losses), and the average relative percent of gain-loss (weight gain or loss of component (x) divided by the weight-percent component (y) of fresh rock) are illustrated in figures 5–14 and in table 3. Components are considered to be relatively immobile if the percent of a component gained or lost is within the range of variation of the fresh rock (table 2) or within the limits of experimental error of the related analytical technique.

The original geochemical data were adjusted during this study. Several nonstandard components such as FeS_2, SO_3, total sulfur (S TOT), and total iron (Fe TOT) were calculated (table 2). The derivation and meaning of these components, and all other manipulations and adjustments that were made to the samples, are documented below. All calculations are presented in the sequence in which they were made.

Adjustments and Calculations on Data

1. Petrographic data were used to characterize the mineralogy of the samples, allowing appropriate partitioning of sulfur and iron.

Sulfur in all alunitized samples devoid of pyrite was calculated as SO_3. Iron, which occurs predominantly in these samples as hematite, was calculated as Fe_2O_3.

Alunite-bearing unoxidized samples containing pyrite were treated as follows: Reduced sulfur was determined by a chromic ion treatment (Zhabina and Volkov, 1978; Westgate and Anderson, 1982) with all reduced sulfur calculated as FeS_2. Any remaining sulfur was calculated as SO_3. Excess iron was calculated as FeO.

Pyritized (alunite-free) samples were recalculated in the following manner: Initially, all sulfur was considered to be contained in FeS_2. If excess FeO was present (moles FeO more than one-half the moles of sulfur), the excess FeO was assigned to FeO or Fe_2O_3 depending on petrographic observations. Conversely, if one-half the moles of sulfur exceeded the moles of FeO, FeS_2 was calculated on the basis of analyzed FeO content, and excess sulfur was reported as sulfur. Therefore, all sulfur shown in tables 2 and 3 represents excess sulfur.

2. FeS_2-adjusted analyses were retotaled and normalized to totals before FeS_2 adjustment (original totals), correcting for a loss of one oxygen molecule during conversion from FeO to FeS_2. All analyses were normalized to 100 percent after the above adjustments were made.

3. Fe TOT (tables 2, 3) is total iron expressed as elemental iron and equals $0.699 \times Fe_2O_3 + 0.777 \times FeO + 0.465 \times FeS_2$. S TOT (tables 2, 3) is total sulfur expressed as elemental sulfur and equals $SO_3 \times 0.40 + FeS_2 \times 0.27 + S$ (excess sulfur).

4. Adjustments were made to fresh-rock analyses as follows: H_2O^+ (probably present in hydrated glass), H_2O^- (moisture), and CO_2 were subtracted from the fresh-rock analyses, as none of these components are present within the primary minerals. H_2O^+ in biotite is negligible and therefore was not considered (Bove, 1988).

First, H_2O^+ and H_2O^- were subtracted from the analyses of fresh rock samples, and analyses were normalized to 100 percent. The fresh-rock bulk densities were subsequently readjusted due to the loss of H_2O^+ and H_2O^- according to the following equation:

$$D_{adj} = \frac{Twt.}{Twt.-wt.H_2O} \times D^{org} - \frac{Twt.}{Twt.-wt.H_2O} \times D^{H_2O}$$

where

D_{adj} = bulk density adjusted,
Twt. = total weight of sample,
D^{org} = original bulk density,
wt.H_2O = weight percent total H_2O in sample,
D^{H_2O} = density of H_2O (1.00 gram per cubic centimeter).

Table 1. Original geochemical data for samples analyzed for the mass balance study, Red Mountain alunite deposit, Lake City, Colorado

[Elevation values are for samples obtained from drill core. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; S, silicified zone. NA, not applicable. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; density is reported in grams/cm^3; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
1Tldg[1]	NA	60.60	16.90	2.43	1.51	1.90	3.00	3.60	5.00
2Tldg[1]	NA	63.50	15.50	2.48	1.89	1.78	2.23	3.36	5.03
3aTldg[1]	NA	62.60	15.80	2.64	1.78	1.46	3.08	3.94	4.74
3Tldg[1]	NA	63.00	15.90	2.44	.92	1.19	2.66	3.13	5.24
4Tldg[1]	NA	63.00	16.10	2.54	1.87	1.29	2.74	3.92	5.23
1Tdrp[2]	NA	62.20	15.10	2.47	1.70	1.65	3.04	3.34	4.40
2Tdrp[2]	NA	60.70	15.50	3.84	1.89	2.23	2.46	4.12	4.66
1TldgM	NA	66.20	15.20	1.93	.86	.83	.79	2.68	5.94
2TldgM	NA	67.10	14.80	2.37	2.06	.86	.63	2.91	5.56
1aTldgA	NA	57.80	15.10	.36	0	.10	.10	.15	4.09
1bTldgA	NA	60.01	14.00	.32	0	.10	.17	.63	3.07
1TldgA	12,703	61.80	15.70	.18	0	.10	.10	.25	2.97
2TldgA	12,543	63.70	12.10	.99	0	.10	.02	.20	3.37
3TldgA	12,472	35.90	22.70	.64	0	.10	.05	.42	6.02
4TldgA	12,339	55.80	12.80	7.03	0	.10	.02	.34	3.32
5TldgA	12,318	54.70	14.50	1.86	0	.10	.10	.48	3.87
6TldgA[3]	12,168	50.00	15.60		3.56	.10	.08	.55	3.84
7TldgA	12,140	67.60	5.94	10.39	0	.10	.47	.15	1.62
8TldgA[3]	12,013	62.50	12.90	4.68	0	.10	.15	.15	1.29
1TdrpC	12,000	61.10	18.60	0	4.26	.33	.08	.67	4.22
2TdrpC	11,862	64.10	16.00	0	4.24	.63	.27	2.32	5.26
3TdrpC	11,190	60.60	20.40	0	4.71	.34	.02	.15	.84
4Tdrpc	11,140	60.10	21.80	0	3.64	.38	.02	.15	1.39
5TdrpC	11,106	67.70	16.60	0	3.52	.50	.04	.15	1.99
6TdrpC	11,090	59.40	24.50	0	1.63	.41	.04	.24	1.22
1TdrpK	10,494	63.10	15.10	0	3.90	1.49	.60	1.88	6.93
2TdrpK	10,450	62.40	13.10	0	3.41	5.25	.06	.95	8.96
3TdrpK	10,430	66.10	14.50	0	3.58	.19	.10	1.04	8.29
4TdrpK	10,210	66.80	13.50	0	1.40	2.68	.40	.95	9.77
5TdrpK	10,205	61.10	15.40	0	3.32	2.34	.59	1.27	10.60
6TdrpK	10,180	63.30	13.20	0	5.17	1.50	.44	1.08	9.01
7TdrpK	9,874	58.90	16.70	2.55	.87	2.93	.41	1.65	9.78
8TdrpK	9,774	62.30	14.50	2.31	2.11	1.90	1.94	2.70	7.99
1TdrpS	NA	89.40	1.81	0	3.87	.12	.08	.15	.34
2TdrpS	NA	73.10	11.50	0	2.39	1.44	.09	.79	5.98

[1]Unaltered dacite lavas of Grassy Mountain.

[2]Unaltered dacite porphyry.

[3]High totals are related to high sulfur determinations. Replicate analyses yielded similar high values. However, due to the large variations in chemical analyses for samples from the alunite zone, these samples do not significantly affect the average sample analyses and therefore were retained in the data set.

Table 1. Original geochemical data for samples analyzed for the mass balance study, Red Mountain alunite deposit, Lake City, Colorado—Continued

[Elevation values are for samples obtained from drill core. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; S, silicified zone. NA, not applicable. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; density is reported in grams/cm^3; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	H_2O	TiO_2	P_2O_5	MnO	CO_2	SO_3	S	H_2O^-	Total
1Tldg	NA	1.30	0.93	0.51	0.07	0.52	0	0	1.70	99.97
2Tldg	NA	1.03	.98	.30	.08	.28	0	0	.96	99.40
3aTldg	NA	1.26	1.02	.33	.11	.01	0	0	.54	99.31
3Tldg	NA	2.49	.94	.32	.06	.01	0	0	.14	98.43
4Tldg	NA	.64	1.04	.29	.09	.66	0	0	.16	99.57
1Tdrp	NA	1.28	.97	.37	.09	.91	0	0	.63	98.15
2Tdrp	NA	1.43	1.26	.43	.14	.23	0	0	.64	99.53
1TldgM	NA	1.34	.99	.18	.02	0	0	0	1.48	98.44
2TldgM	NA	1.31	.87	.30	.10	0	0	0	.37	99.24
laTldgA	NA	5.31	.75	.28	.02	.01	18.33	0	.28	102.68
lbTldgA	NA	5.23	.78	.37	.02	.01	17.70	0	.15	102.56
1TldgA	12,703	4.42	.99	.39	.02	0	12.38	0	.06	99.36
2TldgA	12,543	4.80	1.00	.12	.02	0	14.48	0	.08	100.98
3TldgA	12,472	8.13	.87	.48	.02	0	25.28	0	.08	100.69
4TldgA	12,339	4.87	1.12	.38	.02	0	15.30	0	.14	101.24
5TldgA	12,318	5.81	.92	.39	.02	0	17.89	0	.07	100.71
6TldgA	12,168	5.70	.63	.38	.02	0	21.80	2.90	.17	[3]105.33
7TldgA	12,140	3.74	2.35	1.00	.02	0	6.48	0	.23	100.09
8TldgA	12,013	5.36	1.28	.39	.02	0	15.77	0	1.45	[3]106.04
1TdrpC	12,000	4.46	1.01	.18	.02	0	0	4.21	.56	99.70
2TdrpC	11,862	1.70	.88	.20	.02	0	0	3.68	.27	99.57
3TdrpC	11,190	6.71	.97	.22	.02	0	0	4.66	.34	99.98
4Tdrpc	11,140	6.98	.87	.28	.02	0	0	3.76	.20	99.59
5TdrpC	11,106	4.60	.96	.18	.02	0	0	3.26	.27	99.79
6TdrpC	11,090	7.88	.95	.21	.02	0	0	1.89	.21	98.60
1TdrpK	10,494	1.44	.85	.32	.02	0	0	3.18	.52	99.33
2TdrpK	10,450	.63	.77	.20	.02	.82	0	2.78	.26	99.61
3TdrpK	10,430	1.37	.82	.22	.02	0	0	3.39	.26	99.88
4TdrpK	10,210	.52	.77	.29	.03	0	0	.90	.06	98.07
5TdrpK	10,205	.64	.93	.40	.02	0	0	2.77	.08	99.46
6TdrpK	10,180	.80	.84	.32	.14	0	0	2.38	.26	98.44
7TdrpK	9,874	1.54	1.05	.25	.07	.39	0	.85	.67	98.61
8TdrpK	9,774	.47	.81	.33	.30	.97	0	.45	.17	99.25
1TdrpS	NA	.52	.87	.23	.02	.01	0	3.22	.06	100.70
2TdrpS	NA	1.54	.87	.20	.02	.02	0	1.63	.26	99.83

After bulk densities were adjusted for H_2O subtraction, CO_2 was removed from the H_2O-adjusted samples, and analyses were normalized to 100 percent. Bulk densities were then recalculated to reflect CO_2 subtraction by using an equation similar to that above:

$$D_{adj} = \frac{Twt.}{Twt.-wt.CO_2} \times D^{org} - \frac{Twt.}{Twt.-wt.CO_2} \times D^{CO_2}$$

where

D_{adj} = bulk density adjusted,

Twt. = total weight of sample (100 grams),

D^{org} = original bulk density,

wt.CO_2 = weight percent CO_2 in sample,

D^{CO_2} = density of CO_2 (2.07 grams per cubic centimeter).

5. Adjustments were made to altered rock analyses as follows: H_2O^- and CO_2 were removed from the analyses

Table 1. Original geochemical data for samples analyzed for the mass balance study, Red Mountain alunite deposit, Lake City, Colorado—Continued

[Elevation values are for samples obtained from drill core. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; S, silicified zone. NA, not applicable. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; density is reported in grams/cm^3; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	Rb	Sr	Zr	Y	Nb	Mo	Density
1Tldg	NA	148	491	310	27	28	0	2.46
2Tldg	NA	165	406	265	25	35	0	2.50
3aTldg	NA	190	485	315	42	38	0	2.46
3Tldg	NA	209	497	271	56	32	0	2.46
4Tldg	NA	157	494	352	28	41	0	2.62
1Tdrp	NA	147	490	278	32	33	0	2.56
2Tdrp	NA	142	543	288	27	36	0	2.55
1TldgM	NA	187	337	287	16	36	0	2.12
2TldgM	NA	179	335	299	27	37	0	2.21
1aTldgA	NA	10	545	262	16	33	1	2.59
1bTldgA	NA	0	0	0	0	0	0	0
1TldgA	12,703	0	706	313	20	37	0	2.47
2TldgA	12,543	0	273	338	0	34	0	2.49
3TldgA	12,472	7	1,740	295	0	37	0	2.67
4TldgA	12,339	0	623	317	6	38	0	2.27
5TldgA	12,318	0	679	265	16	33	0	2.65
6TldgA	12,168	9	590	252	12	0	0	2.67
7TldgA	12,140	0	1,270	369	43	55	0	1.70
8TldgA	12,013	0	553	436	62	54	0	1.72
1TdrpC	12,000	133	313	301	26	40	0	2.34
2TdrpC	11,862	207	388	305	46	37	5	2.41
3TdrpC	11,190	48	193	358	30	37	76	2.09
4TdrpC	11,140	65	452	289	41	37	103	2.18
5TdrpC	11,106	104	276	309	44	44	130	2.43
6TdrpC	11,090	70	305	307	43	35	17	1.97
1TdrpK	10,494	283	219	303	31	39	134	2.55
2TdrpK	10,450	464	235	231	39	23	260	2.47
3TdrpK	10,430	283	408	293	62	42	157	2.37
4TdrpK	10,210	398	225	263	18	36	645	2.43
5TdrpK	10,205	408	203	315	24	41	146	2.51
6TdrpK	10,180	307	234	263	22	35	112	2.44
7TdrpK	9,874	435	330	369	19	43	73	2.50
8TdrpK	9,774	305	371	290	30	35	47	2.63
1TdrpS	10,350	5	371	303	11	42	238	2.55
2TdrpS	10,115	208	228	267	38	36	87	2.48

of the altered samples, the analyses were normalized to 100 percent, and the bulk densities were adjusted, as described in step 4. H_2O^+ was not subtracted from these samples because it is a structural component of many of the alteration minerals.

6. A volume factor was used to allow comparison of fresh and altered samples. Assuming constant volume (discussed previously), this factor indicates proportions of material lost during alteration and is defined as the density of the altered sample divided by the density of the fresh sample. Chemical components of the altered rock were multiplied by this volume factor (V) to normalize for the loss or gain of mass, thus allowing the fresh and altered samples to be compared directly. For example, it would be erroneous to compare weight percent SiO_2 in 100 grams of an altered, relatively low density sample to

Table 2. Adjusted geochemical data for samples from the Red Mountain alunite deposit, Lake City, Colorado

[Elevation values are for samples obtained from drill core. Adjustments to data are described in the section on "Methods" in the text. NA, not applicable; Std, one standard deviation; Avg, average of number of samples shown. Letters at end of sample numbers indicate: A, alunite zone;

Sample No.	Elevation (feet)	SiO_2	Al_2O_3	Fe_2O_3	FeO	FeS_2	Fe TOT	MgO	CaO
1Tldg[1]	NA	62.83	17.52	2.52	1.57	0	2.98	1.97	3.11
2Tldg[1]	NA	65.38	15.96	2.55	1.95	0	3.30	1.83	2.30
3aTldg[1]	NA	64.21	16.21	2.71	1.83	0	3.31	1.50	3.16
3Tldg[1]	NA	65.76	16.60	2.55	.96	0	2.53	1.24	2.78
4Tldg[1]	NA	64.21	16.41	2.59	1.91	0	3.29	1.31	2.79
Avg-Tldg	NA	64.48	16.54	2.58	1.64	0	2.92	1.57	2.83
Std	NA	1.03	.54	.07	.37	0	.39	.29	.31
1Tdrp[2]	NA	65.25	15.84	2.59	1.78	0	3.20	1.73	3.19
2Tdrp[2]	NA	62.45	15.95	3.91	1.94	0	4.24	2.29	2.53
Avg-Tdrp	NA	63.85	15.89	3.25	1.86	0	3.72	2.01	2.86
Std	NA	1.40	.05	.66	.08	0	.52	.28	.33
1TldgM	NA	68.23	15.67	1.94	.85	.15	2.09	.86	.81
2TldgM	NA	67.87	14.97	2.40	2.08	0	3.29	.87	.64
Avg-2	NA	68.05	15.32	2.17	1.47	.08	2.69	.86	.73
Std	NA	.18	.35	.23	.62	.08	.60	.01	.09
1aTldgA	NA	56.45	14.65	.35	0	0	.25	.10	.10
1TldgA	12,703	62.24	15.81	.18	0	0	.13	.10	.10
2TldgA	12,543	63.13	11.99	.98	0	0	.69	.10	.02
3TldgA	12,472	35.68	22.56	.64	0	0	.44	.10	.05
4TldgA	12,339	55.19	12.66	6.95	0	0	4.86	.10	.02
5TldgA	12,318	54.35	14.41	1.85	0	0	1.29	.10	.10
6TldgA	12,168	47.88	14.94	0	.30	5.20	2.65	.10	.08
7TldgA	12,140	67.69	5.95	10.40	0	0	7.27	.10	.47
8TldgA	12,013	59.76	12.33	4.47	0	0	3.13	.10	.14
Avg-9	NA	55.82	13.92	2.87	.03	0.58	2.30	.10	.12
Std	NA	8.96	4.10	3.45	.09	1.63	2.31	0	.13
1TdrpC	12,000	62.23	18.94	0	0	7.25	3.37	.34	.08
2TdrpC	11,862	65.14	16.25	0	.14	7.00	3.36	.64	.27
3TdrpC	11,190	61.47	20.69	0	0	7.98	3.71	.34	.02
4Tdrpc	11,140	60.97	22.11	0	0	6.17	2.87	.39	.02
5TdrpC	11,106	68.57	16.81	0	0	5.95	2.77	.50	.04
6TdrpC	11,090	60.59	24.99	0	0	2.78	1.29	.42	.04
Avg-6	NA	63.35	20.17	0	.03	5.98	2.80	.46	.08
Std	NA	2.84	3.03	0	.05	1.67	.78	.11	.09
2TdrpK	10,450	63.79	13.39	0	.29	5.32	2.70	5.37	.06
3TdrpK	10,430	66.89	14.67	0	0	6.05	2.81	.19	.10
4TdrpK	10,210	68.34	13.81	0	.37	1.72	1.09	2.74	.41
5TdrpK	10,205	61.91	15.60	0	.22	5.25	2.61	2.37	.60
6TdrpK	10,180	64.74	13.50	1.92	.85	4.55	4.12	1.54	.43
7TdrpK	9,874	60.54	17.12	2.52	0	1.64	2.52	3.01	.42
8TdrpK	9,774	63.43	14.77	4.16	0	.86	3.31	1.95	1.98
Avg-7	NA	64.23	14.69	1.23	.25	3.63	2.74	2.45	.57
Std	NA	2.51	1.23	1.55	.28	1.98	.85	1.47	.60
1TdrpS	10,350	89.56	1.81	0	.26	6.03	3.01	.12	.08
2TdrpS	10,115	73.73	11.60	0	.57	3.08	1.87	1.45	.09
Avg-2	NA	81.64	6.71	0	.42	4.56	2.44	.79	.09
Std	NA	7.91	4.89	0	.15	1.48	.57	.67	.01

[1]Unaltered dacite lavas of Grassy Mountain.

[2]Unaltered dacite porphyry.

[3]Excess sulfur (described in the section on "Methods" in the text).

M, marginal alteration zone; C, argillic zone; K, potassic zone; and S, silicified zone. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; adjusted density (see the section on "Methods of Analysis" in text) is reported in grams/cm[3]; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	Na_2O	K_2O	H_2O	TiO_2	P_2O_5	MnO	^{3}S	SO_3	^{3}S TOT
1Tldg	NA	3.73	5.18	0	0.96	0.53	0.07	0	0	0
3aTldg	NA	4.04	4.86	0	1.05	.34	.11	0	0	0
3Tldg	NA	3.27	5.47	0	.98	.33	.06	0	0	0
4Tldg	NA	4.00	5.33	0	1.06	.30	.09	0	0	0
Avg-Tldg	NA	3.70	5.20	0	1.01	.36	.08	0	0	0
Std	NA	.30	.20	0	.04	.09	.02	0	0	0
1Tdrp	NA	3.50	4.62	0	1.02	.39	.09	0	0	0
2Tdrp	NA	4.24	4.79	0	1.30	.44	.14	0	0	0
Avg-Tdrp	NA	3.87	4.71	0	1.16	.42	.12	0	0	0
Std	NA	.37	.09	0	.14	.03	.02	0	0	0
1TldgM	NA	2.76	6.13	1.38	1.02	.18	.02	0	0	.83
2TldgM	NA	2.94	5.62	1.32	.88	.30	.10	0	0	0
Avg-2	NA	2.85	5.87	1.35	.95	.24	.06	0	0	0
Std	NA	.09	.25	.03	.07	.06	.04	0	0	0
laTldgA	NA	.25	3.99	5.19	.73	.27	.02	0	17.90	7.17
1TldgA	12,703	.25	2.99	4.45	1.00	.39	.02	0	12.47	5.11
2TldgA	12,543	.20	3.34	4.76	.99	.12	.02	0	14.35	5.75
3TldgA	12,472	.42	5.98	8.08	.86	.48	.02	0	25.13	10.06
4TldgA	12,339	.34	3.28	4.82	1.11	.38	.02	0	15.13	6.06
5TldgA	12,318	.48	3.85	5.77	.91	.39	.02	0	17.78	7.12
6TldgA	12,168	.53	3.68	5.46	.60	.36	.02	0	20.86	11.13
7TldgA	12,140	.15	1.62	3.75	2.35	1.00	.02	0	6.49	2.60
8TldgA	12,013	.14	1.23	5.12	1.22	.37	.02	0	15.08	6.04
Avg-9	NA	.31	3.33	5.27	1.09	.42	.02	0	16.13	6.78
Std	NA	.13	1.30	1.14	.48	.23	0	0	4.95	2.41
1TdrpC	12,000	.68	4.30	4.54	1.03	.18	.02	.41	0	4.29
2TdrpC	11,862	2.36	5.35	1.73	.89	.20	.02	0	0	3.74
3TdrpC	11,190	.15	.85	6.81	.98	.22	.02	.46	0	4.73
4Tdrpc	11,140	.15	1.41	7.08	.88	.28	.02	.51	0	3.82
5TdrpC	11,106	.15	2.02	4.66	.97	.18	.02	.12	0	3.31
6TdrpC	11,090	.24	1.24	8.04	.97	.21	.02	.45	0	1.94
Avg-6	NA	.61	2.17	5.66	.94	.22	.02	.31	0	3.64
Std	NA	.80	1.69	2.10	.05	.03	0	.19	0	.88
2TdrpK	10,450	.97	9.16	.64	.79	.20	.02	0	0	2.85
3TdrpK	10,430	1.05	8.39	1.39	.83	.22	.02	.20	0	3.44
4TdrpK	10,210	.97	9.99	.53	.79	.30	.03	0	0	.92
5TdrpK	10,205	1.29	10.74	.65	.94	.41	.02	0	0	2.81
6TdrpK	10,180	1.11	9.21	.82	.86	.33	.14	0	0	2.44
7TdrpK	9,874	1.69	10.06	1.59	1.08	.26	.07	0	0	.88
8TdrpK	9,774	2.76	8.14	.48	.83	.34	.31	0	0	.46
Avg-7	NA	1.41	9.39	.87	.87	.29	.09	.03	0	2.03
Std	NA	.60	.87	.41	.10	.07	.10	.07	0	1.03
1TdrpS	10,350	.15	.34	.52	.87	.23	.02	0	0	3.23
2TdrpS	10,115	.80	6.03	1.55	.88	.20	.02	0	0	1.65
Avg-2	NA	.47	3.19	1.04	.87	.22	.02	0	0	2.44
Std	NA	.32	2.85	.52	0	.01	0	0	0	.79

Table 2. Adjusted geochemical data for samples from the Red Mountain alunite deposit, Lake City, Colorado—Continued

[Elevation values are for samples obtained from drill core. Adjustments to data are described in the section on "Methods" in the text. NA, not applicable; Std, one standard deviation; Avg, average of number of samples shown. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; and S, silicified zone. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; adjusted density (see the section on "Methods of Analysis" in text) is reported in grams/cm^3; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	Rb	Sr	Zr	Y	Nb	Mo	Density adj
1Tldg	NA	148	491	310	27	28	0	2.51
2Tldg	NA	165	406	265	25	35	0	2.54
3aTldg	NA	190	485	315	42	38	0	2.58
3Tldg	NA	209	497	271	56	32	0	2.50
4Tldg	NA	157	494	352	28	41	0	2.63
Avg-Tldg	NA	174	475	303	36	35	0	2.55
Std	NA	22	34	31	11	4	0	0
1Tdrp	NA	147	490	278	32	33	0	2.59
2Tdrp	NA	142	543	288	27	36	0	2.58
Avg-Tdrp	NA	145	517	283	30	35	0	2.59
Std	NA	2	26	5	2	1	0	0
1TldgM	NA	187	337	287	16	36	0	2.14
2TldgM	NA	179	335	299	27	37	0	2.21
Avg-2	NA	183	336	293	22	37	0	2.18
Std	NA	4	1	6	5	0	0	0
laTldgA	NA	10	45	262	16	33	1	2.59
1TldgA	12,703	0	706	313	20	37	0	2.47
2TldgA	12,543	0	273	338	0	34	0	2.49
3TldgA	12,472	7	1,740	295	0	37	0	2.67
4TldgA	12,339	0	623	317	6	38	0	2.27
5TldgA	12,318	0	679	265	16	33	0	2.65
6TldgA	12,168	9	590	252	12	0	0	2.67
7TldgA	12,140	0	1,270	369	43	55	0	1.70
8TldgA	12,013	0	553	436	62	54	0	1.73
Avg-9	NA	2	804	323	20	36	0	2.36
Std	NA	4	477	55	19	14	0	0
1TdrpC	12,000	133	313	301	26	40	0	2.35
2TdrpC	11,862	207	388	305	46	37	5	2.41
3TdrpC	11,190	48	193	358	30	37	76	2.09
4Tdrpc	11,140	65	452	289	41	37	103	2.18
5TdrpC	11,106	104	276	309	44	44	130	2.43
6TdrpC	11,090	70	305	307	43	35	17	1.97
Avg-6	NA	99	323	314	41	38	66	2.22
Std	NA	53	82	21	7	2	50	0
2TdrpK	10,450	464	235	231	39	23	260	2.47
3TdrpK	10,430	283	408	293	62	42	157	2.37
4TdrpK	10,210	398	225	263	18	36	645	2.43
5TdrpK	10,205	408	203	315	24	41	146	2.51
6TdrpK	10,180	307	234	263	22	35	112	2.44
7TdrpK	9,874	435	330	369	19	43	73	2.51
8TdrpK	9,774	305	371	290	30	35	47	2.63
Avg-7	NA	371	287	289	31	36	206	2.48
Std	NA	66	75	41	14	6	190	0
1TdrpS	10,350	5	371	303	11	42	238	2.55
2TdrpS	10,115	208	228	267	38	36	87	2.49
Avg-2	NA	107	300	285	25	39	163	2.52
Std	NA	101	71	18	13	3	75	0

Table 3. Geochemical data showing gains and losses from major alteration zones, Red Mountain alunite deposit, Lake City, Colorado

[Elevation values are for samples obtained from drill core. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; S, silicified zone. NA, not applicable. Tldg represents samples of dacite lavas of Grassy Mountain. Tdrp represents samples of dacite porphyry. Note that S represents excess sulfur (see "Methods" section in the text); n.m., not a meaningful value. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; density is reported in grams/cm^3; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	SiO_2	Al_2O_3	Fe_2O_3	FeO	FeS_2	Fe TOT	MgO	CaO
1TldgM	NA	-7.36	-3.19	-0.89	-0.23	0.13	-0.74	-0.51	-2.08
2TldgM	NA	-5.77	-3.36	-.43	.88	0	.39	-.47	-2.21
Avg-2	NA	-6.56	-3.27	-.66	.32	.07	-.18	-.49	-2.15
Avg Rel[1]	NA	-9.98	-19.71	-25.94	33.01	n.m.	-7.31	-39.56	-77.25
1aTldgA	NA	-7.28	-1.42	-2.18	-.96	0	-2.27	-1.14	-2.68
1TldgA	12,703	-4.27	-.98	-2.37	-.96	0	-2.40	-1.14	-2.68
2TldgA	12,543	-2.88	-4.65	-1.57	-.96	0	-1.84	-1.14	-2.76
3TldgA	12,472	-27.65	7.50	-1.87	-.96	0	-2.05	-1.14	-2.72
4TldgA	12,339	-15.65	-5.10	3.77	-.96	0	1.89	-1.15	-2.76
5TldgA	12,318	-8.15	-1.32	-.59	-.96	0	-1.16	-1.14	-2.67
6TldgA	12,168	-14.62	-.65	-2.55	-.64	5.55	.30	-1.13	-2.69
7TldgA	12,140	-19.73	-12.55	4.53	-.96	0	2.42	-1.17	-2.46
8TldgA	12,013	-24.41	-8.06	.55	-.96	0	-.36	-1.18	-2.68
Avg-9	NA	-13.07	-3.45	.16	-.93	.55	-.35	-1.15	-2.66
Avg Rel	NA	-19.87	-20.81	6.38	-96.72	n.m.	-14.03	-92.47	-95.91
1TdrpC	12,000	-7.28	1.33	-3.25	-1.86	6.59	-.66	-1.71	-2.79
2TdrpC	11,862	-3.12	-.74	-3.25	-1.73	6.52	-.58	-1.42	-2.60
3TdrpC	11,190	-14.16	.84	-3.25	-1.86	6.45	-.72	-1.73	-2.84
4Tdrpc	11,140	-12.44	2.76	-3.25	-1.86	5.21	-1.30	-1.69	-2.84
5TdrpC	11,106	.60	-.09	-3.25	-1.86	5.60	-1.12	-1.54	-2.82
6TdrpC	11,090	-17.68	3.15	-3.25	-1.86	2.12	-2.74	-1.69	-2.83
Avg-6	NA	-9.55	1.40	-3.25	-1.84	5.12	-1.32	-1.62	-2.79
Avg Rel	NA	-14.95	8.81	-100	-98.71	n.m.	-35.46	-80.49	-97.62
2TdrpK	10,450	-2.90	-3.10	-3.25	-1.58	5.08	-1.14	3.11	-2.80
3TdrpK	10,430	-2.53	-2.44	-3.25	-1.86	5.55	-1.14	-1.84	-2.77
4TdrpK	10,210	.39	-2.92	-3.25	-1.52	1.62	-2.70	.56	-2.48
5TdrpK	10,205	-3.74	-.74	-3.25	-1.65	5.10	-1.18	.29	-2.28
6TdrpK	10,180	-2.74	-3.16	-1.44	-1.06	4.30	.17	-.56	-2.45
7TdrpK	9,874	-5.07	.73	-.81	-1.86	1.59	-1.27	.91	-2.45
8TdrpK	9,774	.68	-.87	.98	-1.86	.87	-.36	-.03	-.85
Avg-7	NA	-2.23	-1.80	-2.07	-1.63	3.48	-1.09	.34	-2.31
Avg Rel	NA	-3.49	-11.30	-63.78	-87.24	n.m.	-29.41	16.92	-80.83
1TdrpS	10,350	24.49	-14.11	-3.25	-1.60	5.95	-.75	-1.89	-2.78
2TdrpS	10,115	7.17	-4.72	-3.25	-1.32	2.96	-1.92	-.61	-2.77
Avg-2	NA	15.74	-9.36	-3.25	-1.46	4.44	-1.34	-1.25	-2.78
Avg Rel	NA	24.65	-58.87	-100	-78.25	n.m.	-36.02	-61.91	-97.09

[1]Avg Rel is average relative percent gained or lost (see "Methods" section in text).

the SiO_2 content present in 100 grams of its fresh and significantly more dense counterpart. Adjusted analyses for altered samples were multiplied by the volume factor, using the corrected bulk densities derived in steps 4 and 5, and subtracted from the corresponding density-adjusted fresh-rock analyses, resulting in the weight percent gained or lost per unit volume of rock during hydrothermal alteration.

DISCUSSION OF RESULTS

Mass-balance data (table 3), as determined by the methods discussed in the previous section of this report, are discussed in this section. Average compositional gains and losses, and average relative weight percent gain or loss within the major alteration zones are graphically portrayed in figures 5–14.

Table 3. Geochemical data showing gains and losses from major alteration zones, Red Mountain alunite deposit, Lake City, Colorado—Continued

[Elevation values are for samples obtained from drill core. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; S, silicified zone. NA, not applicable. Tldg represents samples of dacite lavas of Grassy Mountain. Tdrp represents samples of dacite porphyry. Note that S represents excess sulfur (see "Methods" section in the text); n.m., not a meaningful value. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; density is reported in grams/cm³; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	Na_2O	K_2O	H_2O	TiO_2	P_2O_5	MnO	S	SO_3	S TOT
1TldgM	NA	-0.90	-0.23	1.18	-0.11	-0.18	-0.04	0	0	0.08
2TldgM	NA	-.67	-.50	1.17	-.20	-.07	.03	0	0	.00
Avg-2	NA	-.78	-.36	1.18	-.15	-.12	-.01	0	0	.04
Avg Rel	NA	-24.01	-6.56	n.m.	-15.72	-36.69	-15.42	n.m.	n.m.	n.m.
laTldgA	NA	-3.01	-1.33	5.37	-.22	-.05	-.04	0	18.54	7.43
1TldgA	12,703	-3.02	-2.51	4.40	.00	.05	-.04	0	12.32	5.05
2TldgA	12,543	-3.07	-2.14	4.74	.01	-.22	-.04	0	14.29	5.73
3TldgA	12,472	-2.82	.92	8.63	-.06	.18	-.04	0	26.84	10.74
4TldgA	12,339	-2.96	-2.49	4.37	.02	.01	-.04	0	13.74	5.55
5TldgA	12,318	-2.76	-1.39	6.12	-.01	.08	-.04	0	18.84	7.55
6TldgA	12,168	-2.70	-1.54	5.83	-.34	.05	-.04	0	22.27	11.89
7TldgA	12,140	-3.17	-4.37	2.55	.62	.35	-.05	0	4.41	1.77
8TldgA	12,013	-3.17	-4.62	3.55	-.13	-.08	-.05	0	10.43	4.18
Avg-9	NA	-2.98	-2.33	4.97	.05	.06	-.04	0	15.23	6.65
Avg Rel	NA	-91.15	-42.53	n.m.	4.60	18	-70.13	n.m.	n.m.	n.m.
1TdrpC	12,000	-3.25	-.80	2.72	-.22	-.25	-.10	.37	0	3.89
2TdrpC	11,862	-1.67	.28	.20	-.32	-.23	-.10	0	0	3.48
3TdrpC	11,190	-3.75	-4.02	4.10	-.36	-.23	-.10	.37	0	3.82
4Tdrpc	11,140	-3.74	-3.52	4.56	-.41	-.18	-.10	.43	0	3.22
5TdrpC	11,106	-3.73	-2.81	2.97	-.24	-.24	-.10	.11	0	3.11
6TdrpC	11,090	-3.68	-3.76	4.72	-.42	-.25	-.10	.34	0	1.48
Avg-6	NA	-3.35	-2.84	3.45	-.35	-.23	-.10	.26	0	3.17
Avg Rel	NA	-86.45	-60.40	n.m.	-30.31	-54.30	-85.40	n.m.	n.m.	n.m.
2TdrpK	10,450	-2.94	4.05	-.79	-.40	-.22	-.10	0	0	2.72
3TdrpK	10,430	-2.91	2.99	-.14	-.40	-.21	-.10	0.18	0	3.15
4TdrpK	10,210	-2.96	4.69	-.91	-.42	-.14	-.09	0	0	.86
5TdrpK	10,205	-2.62	5.72	-.78	-.24	-.02	-.10	0	0	2.72
6TdrpK	10,180	-2.83	3.99	-.63	-.34	-.11	.02	0	0	2.30
7TdrpK	9,874	-2.23	5.06	.13	-.11	-.17	-.05	0	0	.85
8TdrpK	9,774	-1.07	3.58	-.92	-.32	-.07	.19	0	0	.47
Avg-7	NA	-2.52	4.30	-.57	-.32	-.13	-.04	.03	0	1.87
Avg Rel	NA	-65.17	91.36	-100	-27.59	-32.33	-29.52	n.m.	n.m.	n.m.
1TdrpS	10,350	-3.72	-4.37	-.89	-.30	-.19	-.10	0	0	3.18
2TdrpS	10,115	-3.10	1.10	.09	-.31	-.22	-.10	0	0	1.59
Avg-2	NA	-3.41	-1.60	-.40	-.30	-.20	-.10	0	0	2.39
Avg Rel	NA	-88.08	-33.99	n.m.	-26.31	-49.28	-83.56	n.m.	n.m.	n.m.

Alunite Alteration Zone

Average gains and losses and average relative weight percent gains and losses within alunitized samples are shown in figures 5 and 10, respectively. Mass-balance data from individual samples from the alunite zone are presented in table 3.

Mass-balance calculations show large additions of sulfur, which is present primarily as SO_3, to the alunitized rocks (table 3, fig. 5). Additions of SO_3 average 15 weight percent and range from 4 to 27 percent. Pyrite (reported as FeS_2 in tables 2 and 3), which is unoxidized in the deeper levels of the alunite zone, shows an addition of 5.2 percent sulfur in the only alunitized and pyrite-bearing sample analyzed (6TldgA). Alunite alteration produced average gains of roughly 5 percent H_2O^+ and 262 ppm (parts per million) strontium (53 relative percent strontium enrichment). In addition, all samples enriched in strontium correspondingly gained P_2O_5. The correlative enrichment of P_2O_5 and strontium within

Table 3. Geochemical data showing gains and losses from major alteration zones, Red Mountain alunite deposit, Lake City, Colorado–Continued

[Elevation values are for samples obtained from drill core. Letters at end of sample numbers indicate: A, alunite zone; M, marginal alteration zone; C, argillic zone; K, potassic zone; S, silicified zone. NA, not applicable. Tldg represents samples of dacite lavas of Grassy Mountain. Tdrp represents samples of dacite porphyry. Note that S represents excess sulfur (see "Methods" section in the text); n.m., not a meaningful value. Rb, Sr, Zr, Y, Nb, and Mo are reported in parts per million; density is reported in grams/cm^3; remainder of analyses are in weight percent]

Sample No.	Elevation (feet)	Rb	Sr	Zr	Y	Nb	Mo
1TldgM	NA	-49	-209	-25	-42	-1	0
2TldgM	NA	-51	-201	-7	-32	1	0
Avg-2	NA	-50	-205	-16	-37	0	0
Avg Rel	NA	-23.82	-41.18	-5.94	-66.60	-.77	n.m.
laTldgA	NA	-199	-450	0	-39	2	1
1TldgA	12,703	-209	201	38	-36	5	0
2TldgA	12,543	-209	-225	66	-56	2	0
3TldgA	12,472	-202	1361	44	-56	8	0
4TldgA	12,339	-209	69	17	-51	3	0
5TldgA	12,318	-209	223	10	-39	3	0
6TldgA	12,168	-199	133	-2	-43	-32	0
7TldgA	12,140	-209	367	-20	-27	5	0
8TldgA	12,013	-209	-114	31	-13	5	0
Avg-9	NA	-207	262	34	-37	2	0
Avg Rel	NA	-99.10	52.76	12.56	-66.50	6.20	n.m.
1TdrpC	12,000	-26	-205	-4	-8	3	0
2TdrpC	11,862	46	-128	6	11	1	5
3TdrpC	11,190	-108	-334	11	-8	-3	61
4Tdrpc	11,140	-92	-109	-34	3	-2	87
5TdrpC	11,106	-49	-231	12	9	8	122
6TdrpC	11,090	-94	-258	-44	1	-6	13
Avg-6	NA	-62	-213	-9	3	0	57
Avg Rel	NA	-43.12	-41.29	-3.24	10.09	-1.23	n.m.
2TdrpK	10,450	296	-265	-57	5	-11	248
3TdrpK	10,430	112	-116	-9	25	6	144
4TdrpK	10,210	227	-278	-31	-15	1	606
5TdrpK	10,205	249	-293	28	-9	7	142
6TdrpK	10,180	143	-269	-30	-11	0	106
7TdrpK	9,874	275	-170	80	-14	9	71
8TdrpK	9,774	163	-113	17	-1	3	48
Avg-7	NA	209	-215	-1	-3	2	197
Avg Rel	NA	144.87	-41.64	-.21	-9.05	5.65	n.m.
1TdrpS	10,350	-142	-124	21	-21	8	235
2TdrpS	10,115	53	-270	-21	5	2	84
Avg-2	NA	-43	-198	0	-8	5	158
Avg Rel	NA	-29.88	-38.34	-.06	-27.51	14.55	n.m.

alunitized rocks can be explained by replacement of $(SO_4)^{-2}$ in alunite by trivalent $(PO_4)^{-3}$; this replacement was accompanied by substitution of divalent strontium cations for monovalent potassium in alunite, which offsets the charge imbalance (Scott, 1987; Botinelly, 1976; Stoffregen and Alpers, 1987). Electron microprobe and SEM (scanning electron microscope) analyses of samples enriched in P_2O_5 and strontium show no evidence of a discrete mineral phase such as svanbergite [(Sr,Ca) $Al_3(SO)_4(PO)_4(OH)_6$], which is common in the alunite assemblage at Summitville, Colo., and elsewhere (Stoffregen, 1985; Stoffregen and Alpers, 1987). Substitution of P_2O_5 and strontium in alunite is probably the result of the destruction of primary apatite, which releases H_3PO_4 into solution, and the liberation of strontium from the alteration of primary plagioclase (Stoffregen and Alpers, 1987).

With the exception of zirconium, titanium, and niobium, which remained relatively immobile, substantial amounts of most other components, including SiO_2 (average 13 percent, 20 relative percent), Al_2O_3 (average 3.5 percent, 21 relative percent), K_2O (average 2.3 per-

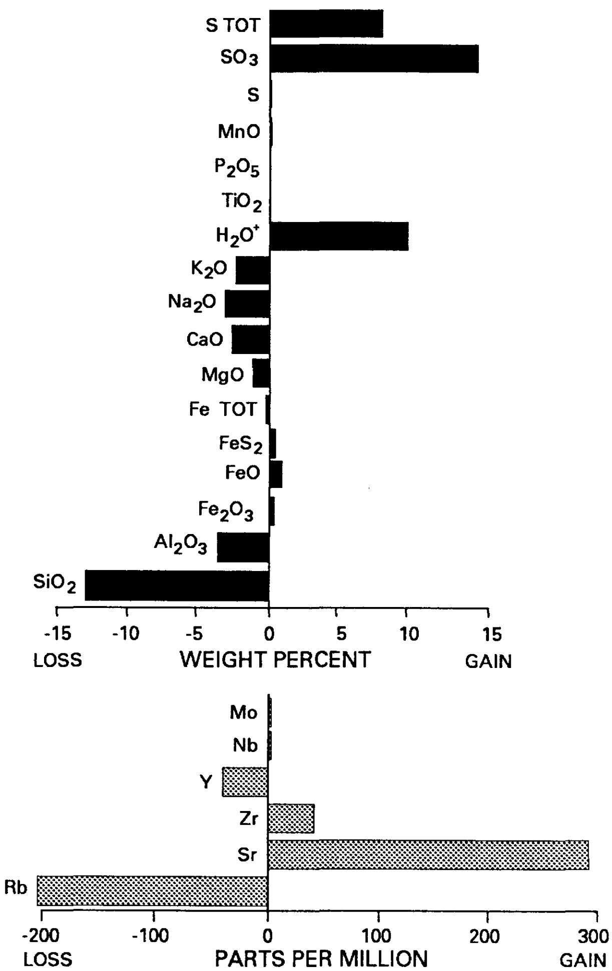

Figure 5. Average gains and losses from alunite alteration assemblage, Red Mountain. S TOT is total sulfur calculated as S, and Fe TOT is total Fe calculated as Fe. S is excess sulfur.

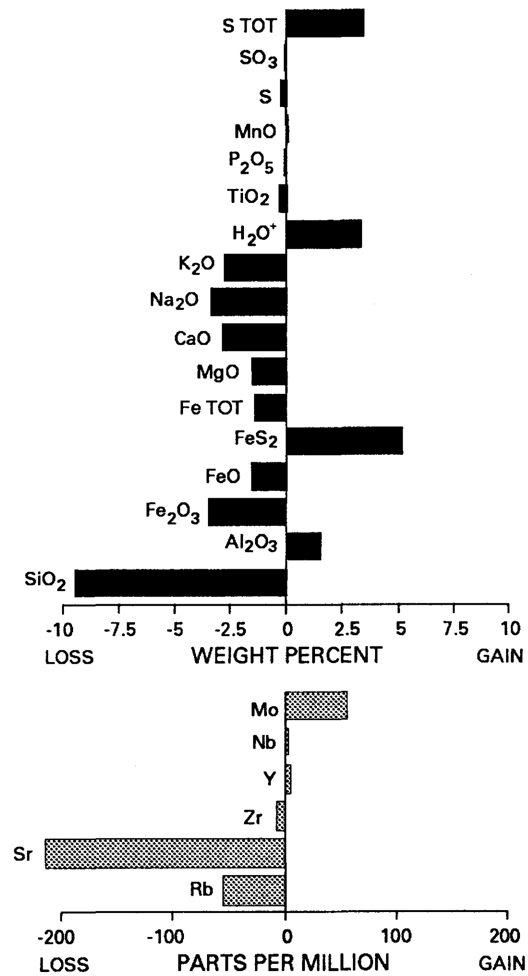

Figure 6. Average gains and losses from argillic alteration assemblage, Red Mountain. S TOT is total sulfur calculated as S, and Fe TOT is total Fe calculated as Fe. S is excess sulfur.

cent, 42.5 relative percent), and almost all rubidium, were leached from the alunitized rocks.

In general, most gains and losses of elements can be attributed to acid-sulfate alteration (Hemley and others, 1969), which is indicated by the breakdown of all the primary mineral constituents, except for zircon, and the replacement by alunite of predominantly feldspar.

As shown in table 3, Al_2O_3 has been depleted in all but one sample (6TldgA), with losses ranging from 0.7 to 12.6 percent and averaging 3.5 percent. However, upon close inspection of these data, a direct correlation was noted between the stage of alunite predominant in a sample and the extent of Al_2O_3 depletion; minor to insignificant losses of Al_2O_3 were from samples containing predominantly stage 1 alunite (1aTldgA, 1TldgA, and 6TldgA), and appreciably higher depletions were from samples in which stage 2 alunite predominates. These variations are consistent with petrographic data, which show that partial dissolution of stage 1 alunite took place prior to stage 2 alunite crystallization. Stage 1 is composed of dense, fine-grained alunite pseudomorphous after feldspar, whereas stage 2 alunite, which is characterized by low crystal density and moderate microporosity, occurs in intricately connected microfractures and in microscopic void space created by the dissolution of stage 1 alunite. Leaching of stage 1 alunite prior to stage 2 would account for the greater Al_2O_3 loss in stage 2 relative to stage 1 samples. Containment of alunite-saturated fluids within a relatively closed system (at the scale of the whole alunite zone) after interim stage 1 and 2 dissolution, and nonhomogeneous reprecipitation, could explain the extreme variations in Al_2O_3 mobility in stage 2 samples (2TldgA, 3TldgA, 4TldgA, 5TldgA, 7TldgA, and 8TldgA, table 3).

Considering the mobility of iron, all but two samples, one of which contained unoxidized pyrite (6TldgA), showed either substantial enrichment (1.9–2.4 percent) or depletion (–1.2–2.4 percent) in total iron

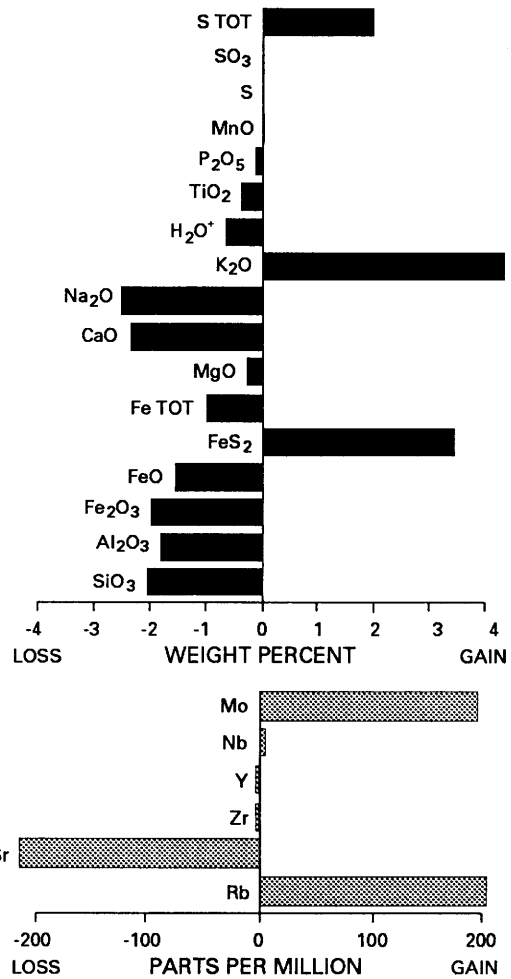

Figure 7. Average gains and losses from potassic alteration assemblage, Red Mountain. S TOT is total sulfur calculated as S, and Fe TOT is total Fe calculated as Fe. S is excess sulfur.

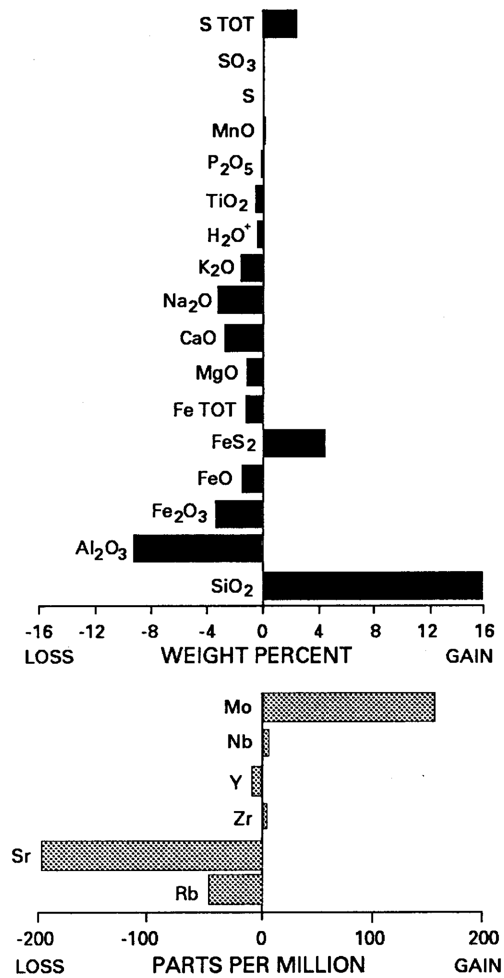

Figure 8. Average gains and losses from silicic alteration assemblage, Red Mountain. S TOT is total sulfur calculated as S, and Fe TOT is total Fe calculated as Fe. S is excess sulfur.

(Fe TOT, table 3). The relative immobility of Fe TOT, as noted in pyrite-bearing sample 6TldgA, may indicate that Fe TOT was relatively constant in all alunitized rocks prior to supergene alteration of pyrite. Hematite and (or) limonite, which formed during this alteration of pyrite, is present in the group of samples where Fe TOT fluctuates.

Argillic Alteration Assemblage

Compositional gains and losses and relative percent gains and losses for argillized samples are shown in table 3. Figure 6 portrays average gains and losses, whereas average relative percent gains and losses from argillic altered samples are illustrated in figure 11.

The argillic alteration assemblage is characterized by substantial gains in sulfur present primarily as FeS_2 (average 5.1 percent), H_2O^+ (average 3.4 percent), molybdenum (average 57 ppm), and relatively minor additions of Al_2O_3 (average 1.4 percent) (table 3, fig. 6). The most substantial losses were of MgO (average 1.6 percent), CaO (average 2.8 percent), and Na_2O (average 3.4 percent), for which average relative losses amount to 80–98 percent of the equivalent fresh-rock abundances. Lesser, though still significant, losses (less than or equal to 60 percent relative loss) were in SiO_2 (average 9.5 percent), total iron (Fe TOT) (average 1.32 percent), K_2O (0–4 percent), TiO_2 (average 0.35 percent), P_2O_5 (average 0.23 percent), and rubidium and strontium (average 62 and 213 ppm, respectively). Apparent mobility of zirconium, yttrium, and niobium was probably insignificant and may indicate anomalous trace-element homogeneity in the two fresh samples analyzed (table 2). Enrichment of FeS_2, H_2O^+, Al_2O_3, and molybdenum in the argillic alteration zone is easily explained by the presence of as much as 5 volume percent pyrite, an abundance of clay minerals (pre-

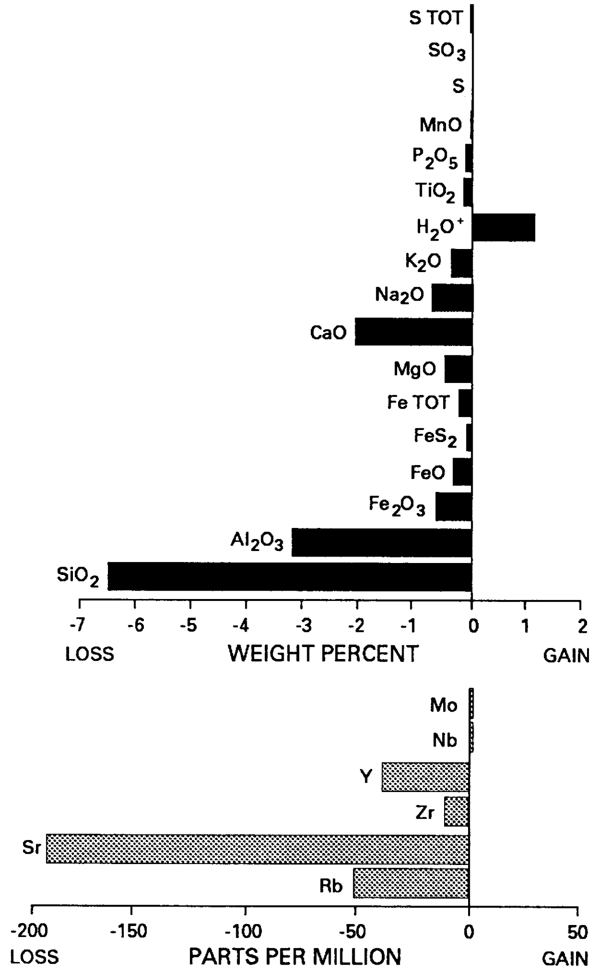

Figure 9. Average gains and losses from marginal alteration assemblage, Red Mountain. S TOT is total sulfur calculated as S, and Fe TOT is total Fe calculated as Fe. S is excess sulfur.

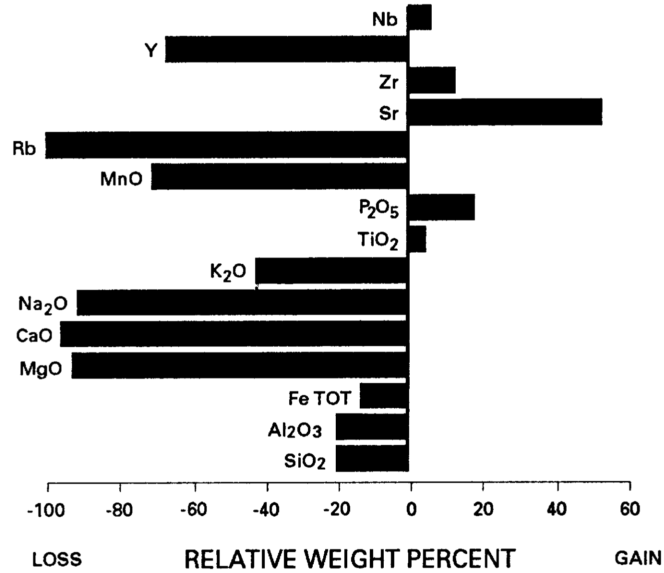

Figure 10. Average relative percent gains and losses from alunite alteration assemblage, Red Mountain. Note gains in SO_3, S TOT, and H_2O^+ in figure 5.

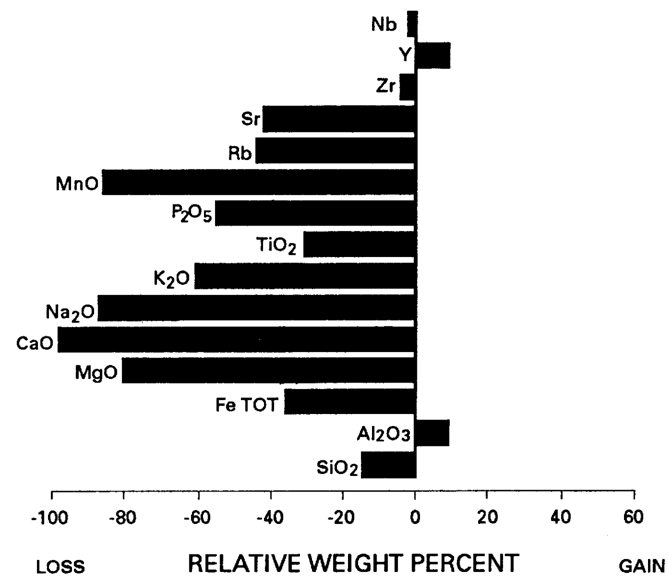

Figure 11. Average relative percent gains and losses from argillic alteration assemblage, Red Mountain. Gains in S TOT, H_2O^+, and FeS_2 are shown in figure 6.

dominantly kaolinite) that account for gains in H_2O^+ and Al_2O_3, and sporadic late pyrite-sericite and (or) molybdenite-bearing fracture fillings. Variable alteration of feldspars and biotite, and complete destruction of clinopyroxene, primary opaque minerals, and apatite account for the observed losses in the elements discussed above. Loss of TiO_2, which is considered relatively immobile in most hydrothermal environments (Gresens, 1966), is substantiated by the presence of leucoxene within local pyrite-sericite and (or) quartz veinlets. As in the alunitized rocks, zircon appears unaltered, which substantiates zirconium immobility.

Potassic Alteration Assemblage

Average gains and losses and average relative weight percent gains and losses within potassically altered samples are shown in figures 7 and 12, respectively. Gains and losses and relative enrichment or depletions within individual samples are shown in table 3.

Potassically altered rocks show greater than 80 percent (197 ppm average gain) average relative enrichment in FeS_2 (3.5 percent average gain), K_2O (4.3 percent average gain), rubidium (209 ppm average gain), and molybdenum (table 3, fig. 7). Less significant amounts of MgO (average 17 relative percent) were added to the rocks, resulting in an average gain of 0.34 percent but as much as 3 percent in one sample.

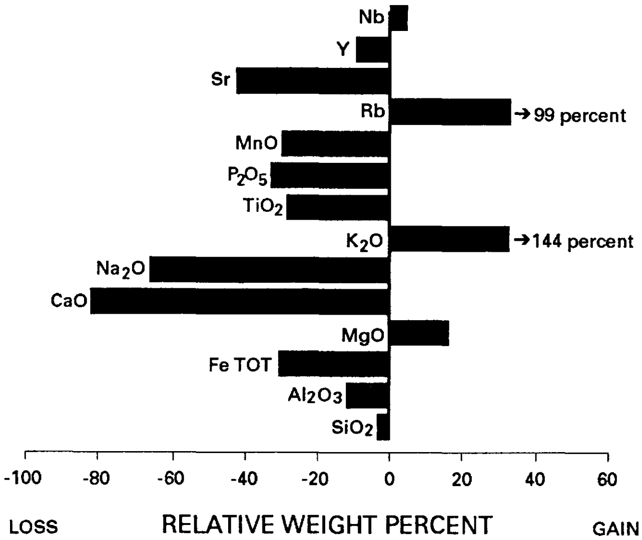

Figure 12. Average relative percent gains and losses from potassic alteration assemblage, Red Mountain. Gains in S TOT, K_2O, and FeS_2 are shown in figure 7.

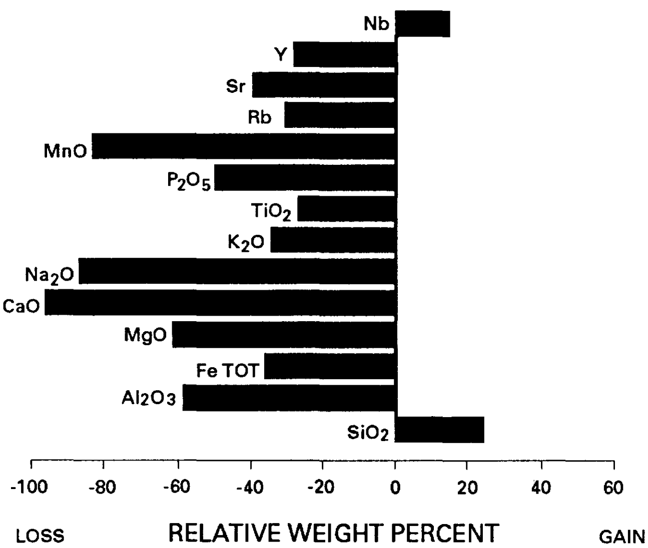

Figure 13. Average relative percent gains and losses from silicic alteration assemblage, Red Mountain. Note that gains in S TOT, SiO_2, and FeS_2 are shown in figure 8.

The components most substantially depleted are CaO (2.3 percent average loss) and Na_2O (2.5 percent average loss), with average relative losses greater than 65 percent. Total iron (Fe TOT), TiO_2, P_2O_5, strontium, and MnO were removed from the rocks, resulting in an average relative loss ranging from 28 to 42 percent, whereas losses in Al_2O_3 are less significant, averaging 11 relative percent. As in the argillic alteration zone, zirconium, niobium, and yttrium appear to have been slightly mobile; however, this apparent mobility may reflect the extreme similarity in the trace-element content of the two fresh rocks sampled (table 2).

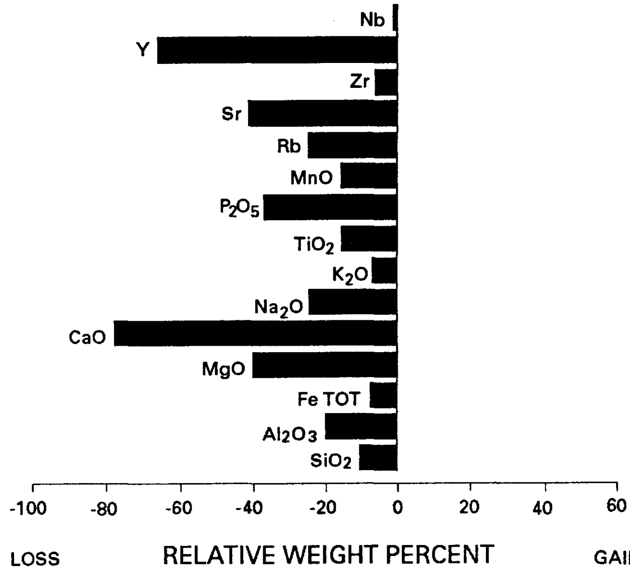

Figure 14. Average relative percent gains and losses from marginal alteration assemblage, Red Mountain. Gain in H_2O^+ is shown in figure 9.

K_2O and rubidium enrichment and substantially lower potassium-rubidium ratios in altered (potassium: rubidium 215) versus fresh rocks (potassium:rubidium 330) are characteristic of rocks that have undergone potassium metasomatism (Scherkenbach and Noble, 1984). The presence of anomalous molybdenum (occurring as minor molybdenite), averaging about 350 ppm in a 900-ft interval in the potassic zone (Bove and others, 1990), accounts for the observed molybdenum enrichment. The presence of secondary potassium feldspar and biotite adequately explains anomalous potassium and rubidium enrichments, whereas the high phlogopitic component of the secondary biotites (as much as 23 percent MgO) (Bove, 1988) undoubtedly is the source of MgO enrichment.

The amount of pyrite (FeS_2) added to potassically altered rocks (average 3.5 percent) is similar to the enrichment in all of the altered zones, excepting the marginal alteration assemblage, which contains no pyrite. As noted in the "Introduction," pyrite in potassically altered rocks is paragenetically related to postpotassic sericite and (or) quartz alteration.

Silicification Zone

Compositional gains and losses and relative percent gains and losses for silicic altered samples are shown in table 3. Figure 8 portrays average gains and losses within silicic altered samples, whereas average relative percent gains and losses are illustrated in figure 13.

Analyses of the two silicified dacite porphyry samples are considered to represent high (sample 1TdrpS) and low (sample 2TdrpS) ranges of silicification. Both samples show gains of SiO_2 (7.2 and 24.5 percent), averaging 15.7 percent, which equates to 24.7 relative percent SiO_2. Aside from large gains in SiO_2 (25 percent), FeS_2 (6 percent), and molybdenum (235 ppm), most components of sample 1TdrpS (high-range silicification) have been removed.

In contrast to sample 1TdrpS (high-range silicification), sample 2TdrpS contained a significantly greater proportion of sericitized secondary potassium feldspar relative to microcrystalline quartz. A smaller net gain in SiO_2 (7.2 percent), coupled with enrichment in K_2O (1.1 percent) and rubidium (53 ppm), reflects the mineralogical differences between these samples. Enrichment in FeS_2 (3 percent) and molybdenum (84 ppm) is considerably less in sample 2TdrpS than in sample 1TdrpS (6 percent FeS_2, 235 ppm molybdenum). This difference appears to be related to higher fracture densities within rocks containing abundant fracture-filling quartz veinlets, which would allow greater infiltration of sulfide-bearing hydrothermal fluids.

Relatively small losses of TiO_2 (0.3 percent or 26 relative percent) occurred in the average silicified sample (Avg–2); the losses are consistent with TiO_2 mobility within argillic and potassic altered rocks. Apparent losses in zirconium, yttrium, and niobium may be insignificant and may result from anomalous trace-element homogeneity in the two fresh samples analyzed (table 2).

Marginal Alteration Assemblage

Of the 23 analyzed components of rocks from the marginal alteration assemblage, 15 were relatively immobile during alteration (table 3, figs. 9, 14). Of the eight mobile components of these rocks, only H_2O^+ was gained (average 1.2 percent) (table 3, fig. 9). Losses, for the most part, were relatively minor compared to the alteration assemblages previously discussed and include depletions in SiO_2 (average 6.6 percent or 10 relative percent), Al_2O_3 (average 3.3 percent or 20 relative percent), CaO (average 2.2 percent or 77 relative percent), Na_2O (average 0.8 percent or 24 relative percent), strontium (average 205 ppm or 41 relative percent), and yttrium (average 37 ppm or 67 relative percent) (table 3, figs. 9, 14). The losses primarily represent alteration of plagioclase and clinopyroxene, whereas H_2O^+ was incorporated primarily in kaolinite, smectite, and sericite. Rubidium, zirconium, and niobium were relatively immobile (table 3, figs. 9 and 14).

SUMMARY

Seven major alteration assemblages from the 23.1-Ma Red Mountain alunite deposit were studied to assess geochemical and accompanying mineralogical changes that occurred during hydrothermal alteration. Thirty-five samples selected from both altered and fresh rocks were analyzed for 10 major elements, 6 trace elements, sulfur, CO_2, H_2O^+, and H_2O^-. Mass-balance calculations show large additions of sulfur, which was derived from the hydrothermal system. This sulfur is present primarily as SO_3 within alunitized rocks and FeS_2 within the potassic and argillic alteration zones. Al_2O_3 and K_2O were removed during alunitization, and PO_4 and strontium were enriched due to coupled substitution of PO_4^{3-} for SO_4^{2-} and Sr^{2+} for K^+ in the alunite structure. Water was added to all of the altered zones as secondary hydrous alteration minerals. Both potassium and rubidium were added to the potassic zone, and a slight gain in Al_2O_3 was observed in kaolinite-altered rocks. An average gain of 15 weight percent SiO_2 took place in the silicification zone. Zirconium, niobium, and TiO_2 remained relatively immobile in most of the alteration assemblages.

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