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TRACE ELEMENT AND MINERALOGICAL ALTERATION ASSOCIATED WITH MODERATE AND ADVANCED DEGREES OF K-METASOMATISM IN A RIFT BASIN AT SOCORRO, NEW MEXICO

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Abstract—Silicic ignimbrites (ash-flow tuffs) and interbedded mafic lavas of Oligocene age were altered by alkaline, saline brines beneath the Popotosa basin of the Rio Grande rift near Socorro, New Mexico. This alteration caused a variety of chemical and mineralogical changes in the affected rocks. The characteristic alteration mineralogy in highly metasomatized rock is adularia + hematite ± quartz ± clay minerals (Lindley, 1985), but we have determined, based on detailed mineralogical analysis of altered plagioclase, that the ratio of phases is highly variable, possibly as a function of degree of metasomatism. The relative proportion of adularia to clay minerals, and the composition of clay minerals is variable within the metasomatized rocks, possibly resulting from variations in fluid composition and temperature. During metasomatism, elements such as K, As, Rb, Sb, Ag, Cs, Au, Pb, Th and U were enriched in the altered rocks, whereas Na, Mg, Ca and Sr were depleted. Some trace elements, rather than varying smoothly with degree of rock alteration (estimated by K/Na ratio), change dramatically during either low or high degrees of alteration. These data suggest that the trace-element signature of alteration may be dependent on the mineralogical alteration assemblage, which may, in turn, depend on the composition of fluids that cause alteration. Dating of the metasomatic event by ⁴⁰Ar/³⁹Ar suggests that the alteration was active between 7.4 and 8.9 Ma. The estimated age range for deposition of playa clays suggests that metasomatism may have begun as early as 15 Ma, hence the metasomatism may have been active for many millions of years. The long duration of the metasomatic event and implied long time available for elements to be progressively scavenged from surrounding rocks may explain the lack of a distinctly depleted source area for elements enriched by the metasomatic alteration.

INTRODUCTION

Some areas of the western US, particularly in regions of Basin-and-Range extension, are characterized by surface enrichments of potassium (K) (Duval, 1990). In many areas, particularly one around Socorro, NM, this enrichment is thought to be caused by secondary enrichment of K by the process of K-metasomatism (Chapin and Lindley, 1986), in which K and other elements are concentrated in altered rocks by a K-rich fluid, while another set of elements are leached (depleted) from the altered rock. This type of fluid interaction with rocks has been associated with ore deposition in some areas (Roddy et al., 1988; Smith et al., 1991) and enrichment of some elements of economic interest has been observed in the Socorro area. However, the chemical nature of the altering fluid, the mineralogical reactions that occur during alteration, and the timing of alteration in the Socorro area are poorly understood. In this paper, we discuss results of ongoing research on the problem of K-metasomatism, particularly the chemical and mineralogical alter-

ation that occurred in several rhyolitic ignimbrites and basaltic andesites as a result of intermediate and advanced degrees of K-metasomatism. We also present preliminary ⁴⁰Ar/³⁹Ar dates for minerals that were produced during the alteration process.

BACKGROUND

Chemical and mineralogical alteration of rocks by interaction with fluids is a common process, especially associated with ore deposition (e.g., Barnes, 1979), but also common in diagenesis (Awwillter, 1993; Wintsch and Kvale, 1994). Enrichment of K by alteration fluids is a chemical signature observed in many places, associated both with hydrothermal/geothermal systems and lower temperature alkaline-saline brines (e.g., Saunders and Tuach, 1991; Turner and Fishman, 1991). A large area around Socorro shows evidence of K enrichment (Fig. 1; D'Andrea, 1981, Lindley, 1985 and Chapin and Lindley, 1986). This area of enrichment covers more than 1800 km² and is 1.5 km

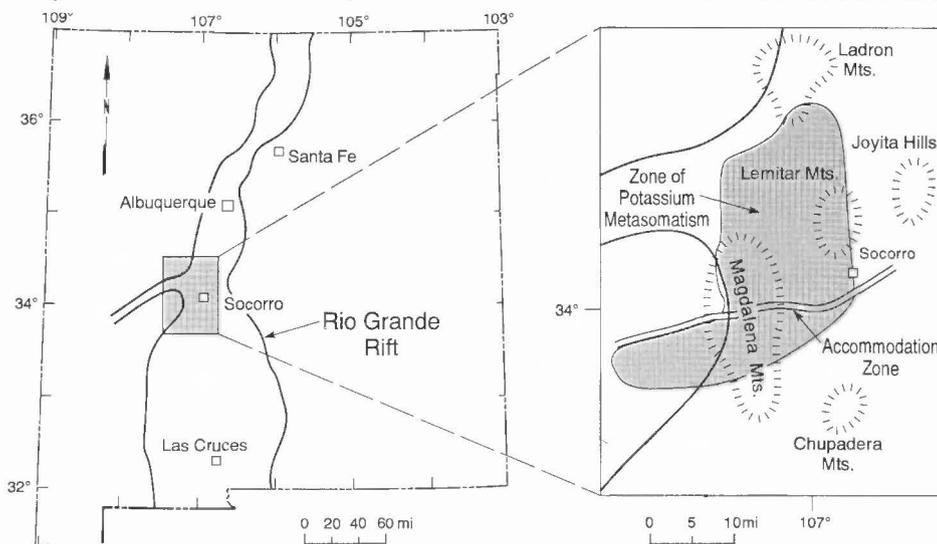


FIGURE 1. Map of the Socorro area, showing the extent of K-metasomatism, (after Lindley, 1985).

thick. The K_2O content of altered rocks can be as high as 13.5 wt % in rock that initially contained 4-5 wt %. Other components, such as Na_2O , CaO , and MgO , are removed during the alteration process (Chapin and Lindley, 1986).

Although chemical changes in metasomatized rocks are dramatic, the mineralogical effect of alteration is subtle (Lindley, 1985). The original rock textures, particularly in extrusive volcanic rocks, are preserved, even in rocks that have been highly altered. High-K phenocrysts in volcanic rocks, such as sanidine and biotite, are apparently unaffected by the metasomatic process, and remain fresh-looking even in a highly altered rock. However, low-K phases, such as plagioclase, and reactive phases, such as fine-grained groundmass, Fe-oxides and glass are strongly affected by the metasomatic process (Lindley, 1985). The alteration mineralogy typically consists of a mixture of K-feldspar (adularia) + hematite \pm quartz \pm clay minerals. Plagioclase phenocrysts in altered volcanic rocks typically are replaced by a fine-grained mixture of quartz + adularia + clay minerals (Lindley, 1985). Glass is also altered to a similar crystalline mixture. Pyroxene phenocrysts are hematized, as is groundmass magnetite (Lindley, 1985).

The fluids responsible for K-metasomatism could be derived from several geological environments. The chemical and mineralogical characteristics of alteration have been observed in intrusion-related hydrothermal systems (e.g., Saunders and Tuach, 1991), in rocks that have been altered by seawater at high water:rock ratios (Munhá et al., 1980), as well as in rocks altered by alkaline-saline brines (Sheppard and Gude, 1973; Duffin, 1989). The Socorro K anomaly was originally interpreted as an ancient geothermal system (D'Andrea et al., 1983), but was reinterpreted as widespread alteration by alkaline-saline brines derived from a large playa lake (Chapin and Lindley, 1986). This reinterpretation is based on three factors. First, the presence of thick playa mudstones in the Socorro area suggests that long-lived playas were present. Second, the size of the anomaly is large enough that if a hydrothermal system were responsible, it would have to be very large. The only magmatic systems in the area, which may have been large enough to cause a hydrothermal system of this magnitude, were active between about 27 and 32 Ma (McIntosh et al., 1992), and because rocks as young as 15 Ma are metasomatized (S. Cather, personal comm., 1994), the older, large magma chambers are ruled out as hydrothermal sources. Magmatism in the Socorro area younger than 15 Ma is very small-volume. Finally, altered rocks are enriched in $\delta^{18}O$ compared to fresh rocks, in contrast to the pattern expected in a hydrothermal system (Lindley, 1985). Basin-and-Range topography around the Socorro area, and a dry climate at the time of metasomatism are consistent with the presence of alkaline-saline playa brines; other K-metasomatized areas in the Western United States (Duval, 1990) may have formed by similar mechanisms.

Although ore deposits are associated with areas of K-metasomatism, in some cases associated with alkaline-saline brines (Roddy et al., 1988), the mobility of elements of economic interest in these systems is poorly understood. The objective of this research is to study the mobility of all elements, including elements of economic interest, in the Socorro K anomaly. This includes investigation of the mineralogy and chemistry that resulted from the alteration process, in order to better understand the fluid composition that was responsible for the alteration, and the location in the alteration assemblage in which different elements reside. The Socorro area is well suited to this type of study because of the presence of numerous regional ignimbrites, as well as basaltic-andesite lava flows, which are crosscut by the K anomaly. Therefore, it is possible to compare the chemical composition and mineralogy of altered rocks with their unaltered parent compositions, and obtain a clear picture of the changes caused by the metasomatic fluid.

ANALYTICAL METHODS

Whole rock geochemistry

Samples were taken of rhyolitic ignimbrites and basaltic-andesite flows at a wide range of locations in the K-metasomatized area. These samples have undergone varying degrees of metasomatism. Fresh samples from each of the ignimbrites and the basaltic-andesite lavas were

also collected, so that fresh and altered compositions could be directly compared. The samples were ground and sent to XRAL analytical services for analysis of major elements and a wide range of trace elements. Analyses were made by x-ray fluorescence, neutron activation analysis, and inductively-coupled mass spectrometry.

Mineralogy

In addition to whole-rock geochemical analysis, some detailed mineralogical analysis were made using x-ray diffraction. The instrument used was a Rigaku DMAX-I x-ray diffractometer with JADE software. In order to best characterize the mineralogical processes that took place during alteration, material was hand-picked from the interior of former plagioclase crystals, still recognizable in the samples of basaltic-andesite lavas or rhyolitic ignimbrites, but partially to completely replaced by an alteration assemblage. Samples were also taken of material that was likely to have been originally composed of glass. By using the technique of sampling a starting material of a known simple composition, the mineralogical changes as a function of degree of alteration could be better characterized. Also, the confusion of trying to differentiate between remnant unaltered mineral phases and alteration-produced phases was avoided (Lindley, 1985).

X-ray diffraction scans were run between 2 and 70° 2 θ using a Cu anode x-ray tube. The step width was 0.05° using a 0.5 second count time at 25 mA and 40 kV. Mineral phases were identified using standard peak search techniques, and approximate relative abundance of different phases was estimated using full-width, half-maximum measurements of peak size. Although it is not possible to exactly determine the ratio of mineral phases in a sample using XRD without a wide range of standards, the relative importance of different mineral phases within a group of mineralogically similar samples can be estimated based on XRD relative peak heights.

Age determinations

The age of K-metasomatic alteration in the Socorro area was determined by $^{40}Ar/^{39}Ar$ geochronology, using the New Mexico Geochronological Research Laboratory at the New Mexico Institute of Mining and Technology. The material dated was a mixture of adularia and quartz that replaced plagioclase feldspar during the alteration process. The samples were analysed with XRD prior to dating, in order to ascertain that no residual plagioclase, with an age signature representative of eruption age, rather than alteration age, remained in the hand-picked sample. The samples were repeatedly rinsed in deionized water, in order to remove as much secondary clay as possible. Although the clay would have formed during the alteration process, and would hence yield a useful age, the small crystal size of clay leads to recoil problems during irradiation, and is therefore undesirable (McDougal and Harrison, 1988). The presence of quartz mixed with adularia in the sample was not a problem, because the K and Ar content of quartz is negligible.

The $^{40}Ar/^{39}Ar$ dating facility at New Mexico Tech offers state-of-the-art equipment similar to that now operating in several other $^{40}Ar/^{39}Ar$ laboratories. The mass spectrometer is a MAP-215-50 instrument equipped with Faraday and electron multiplier collectors. The electrostatic filter and adjustable collector slit allow for a routine mass resolution of 600 at mass 40. The ^{40}Ar sensitivity is 7×10^{-4} A/Torr at normal source operating conditions (Trap Current = 200 μA , total emission 725 μA and 4 kV accelerating voltage). The instrument background at mass 36 is presently $\sim 7 \times 10^{-19}$ moles and the ^{40}Ar static rate of rise is $\sim 5 \times 10^{-13}$ cc/min.

RESULTS AND DISCUSSION

Mineralogical investigation

Other investigations have shown that the alteration mineralogy produced by K-metasomatism consists of adularia + quartz + hematite \pm clay minerals. However, in some studies, the mineralogy was studied using a bulk sample that contained original unaltered minerals as well as those produced by the alteration process (Lindley, 1985). Using this approach, it is difficult to quantify the relative abundances of phases

produced by alteration because of the number of interfering XRD peaks caused by primary minerals in the samples. However, by selectively sampling phases within an altered rock, such as a low-K phases (plagioclase) or reactive phases such as glass, the mineralogy caused by alteration can be better understood. Because the altered phases did not contain magnetite, this technique neglects analysis of the hematite phase of the alteration assemblage, but we feel it nevertheless expands our understanding of the mineralogical processes that occur during K-metasomatism.

Although previous studies have not reported major mineralogical variations between different K-metasomatized samples, our more detailed analysis suggests that wide mineralogical variations are present (Figs. 2 A-D). Some altered samples consist of a combination of quartz, adularia and clay minerals (Fig. 2A), but the proportions of these phases vary strongly between samples. In addition, some samples consist almost entirely of a single alteration phase such as clay minerals (Fig. 2B), or adularia + quartz (Fig. 2C). Several clay minerals have been observed in the samples, including mixed-layer illite-smectite (I/S) and kaolinite. Although some samples contain only one type of clay (either I/S or kaolinite) (Figs. 2A, D), others contain multiple clay mineral types in the same sample. Residual plagioclase (Fig. 2D, see peak at $\sim 22^\circ$) is observed in samples that have presumably undergone a lesser degree of alteration. Plagioclase coexists with adularia, clay minerals and quartz. In the samples that we analysed, residual plagioclase always co-exists with both clay minerals and adularia. Clay minerals in samples with residual plagioclase are dominantly kaolinitic, suggesting

that plagioclase first alters to quartz+kaolinite and then a progressive reaction occurs to form adularia with an increased addition of K^+ . This is consistent with mineralogical changes that can occur as a function of variable fluid composition, particularly the K^+/H^+ ratio (ratio of potassium ions to hydrogen ions), suggesting that adularia should form as the altering fluid becomes more concentrated with respect to K (Meyer and Hemley, 1967). Alternatively, the transition from clay minerals to adularia can be caused by increasing alteration temperatures at a constant fluid composition (Meyer and Hemley, 1967).

The starting material that undergoes alteration may also have an effect on the alteration mineralogy. Two samples, collected in close proximity to one another, one which appears to have been glassy before the alteration occurred (based on faintly preserved flow banding) and the other from which altered plagioclase was sampled, have very different alteration mineralogies. The sample that was originally glassy altered to dominantly adularia + quartz, whereas the other sample contains dominantly clay minerals, mostly of illitic composition. The variation in alteration products may be due to the low-K, high-Na and -Ca nature of the plagioclase crystal versus the higher K composition of the glass. A starting material higher in K might tend to alter to a more K-rich alteration product (adularia) whereas a lower-K mineral might tend to alter to a lower-K product, such as illite, smectite or kaolinite clay.

Geochemical analyses

Geochemical analyses of altered and unaltered samples of rhyolitic ignimbrites and basaltic andesite lavas show a wide range in composition.

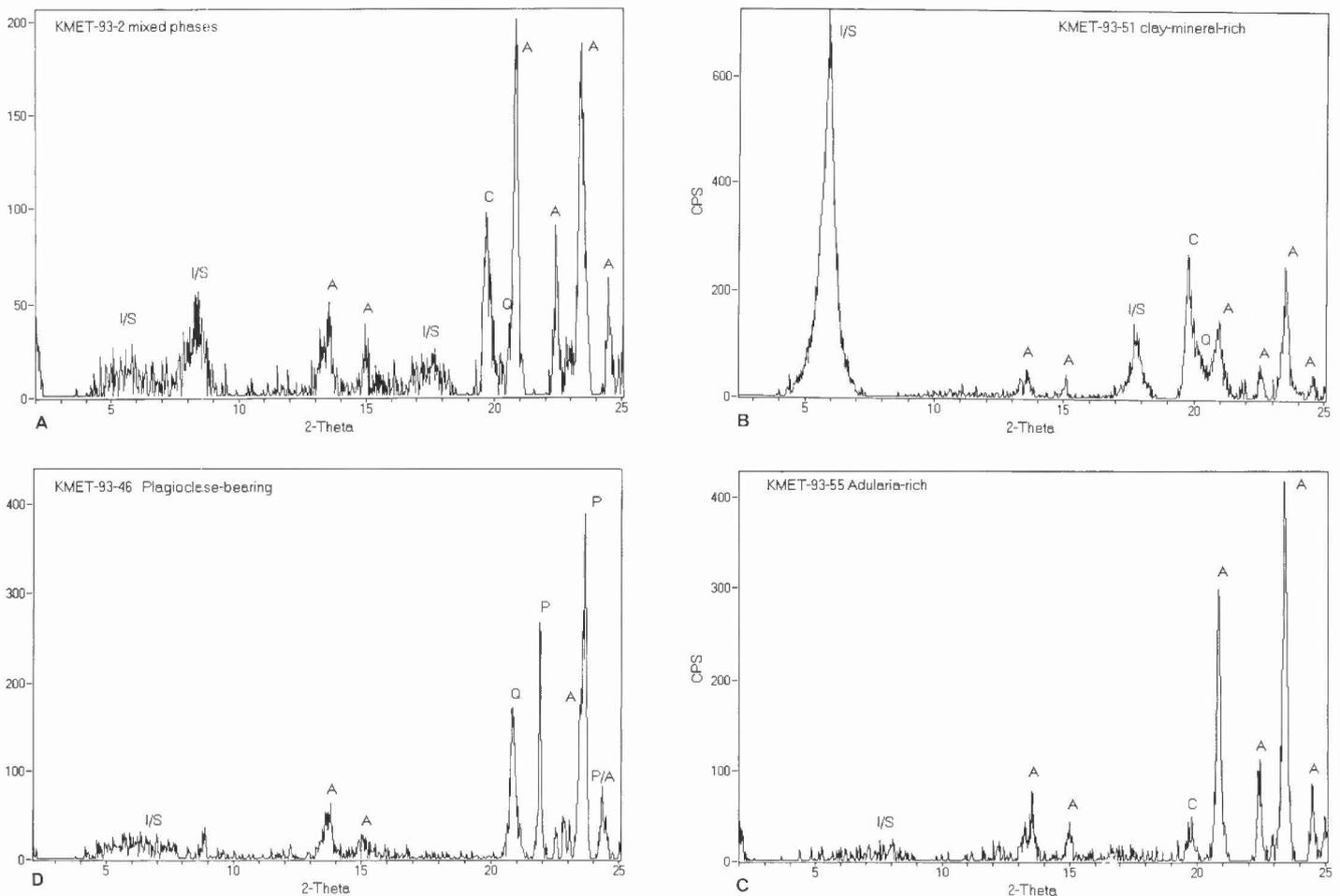


FIGURE 2. X-ray diffraction scans of alteration products of plagioclase showing peaks representative of different minerals. A, sample with mixed alteration phases, B, clay-mineral-rich sample, C, adularia-rich sample, and D, sample containing residual plagioclase. The letters marked on the scans identify main peaks for the different mineral phases. A = adularia; I/S = illite-smectite mixed layer clay minerals; C = clay minerals for which composition cannot be determined; Q = quartz; K = kaolinite; P = plagioclase. Quartz peaks occur as shoulders on adularia peaks, and adularia occurs as a shoulder on a plagioclase peak, hence the letters associated with these shoulders.

Five mafic altered-unaltered pairs of basaltic andesite samples were analysed, including the basaltic andesite of Silver Creek and the LaJara Peak basaltic andesite. Seven altered-unaltered pairs of rhyolitic ignimbrite samples were analysed, including the Hell's Mesa, LaJencia, Upper and Lower Lemitar and Upper and Lower South Canyon tuffs. In order to understand the processes of geochemical variations that occur as a result of K-metasomatism, enrichment or depletion factors (composition of altered rock/ composition of fresh rock) were calculated for elements in each altered/fresh rock pair. These enrichment/depletion factors were then averaged for the rhyolitic ignimbrite and the basaltic andesite samples (Fig. 3 A-C). Although there are some variations in the enrichment/depletion values for individual elements between samples, as should be expected in any geochemical alteration process by a fluid, we feel that averaging the behavior of elements in a number of samples of the same rock type yields the most representative chemical information about the alteration process.

Alteration of a rock by a fluid can lead to mass loss or gain in the original rock, by preferential removal of some phases or deposition of others. Mass gain as a result of K-metasomatism was reported by Glazner (1988), who noted a 14% increase in rock volume as a function of metasomatism. However, the volume of rocks in the Socorro area does not appear to have been changed by the metasomatic process. As can be seen from Fig. 3A, the abundance of Al, an element typically considered immobile during chemical alteration processes, is unchanged by K-metasomatism, in both the rhyolitic ignimbrite samples and the mafic flows. Si, which can be immobile in some types of alteration, is also unchanged. Finally, Ti, which is typically immobile in alteration processes involving fluids, is invariant in the rhyolitic ignimbrites but is slightly depleted in the more mafic flows. The depletion is probably due to alteration of magnetite to hematite, and removal of Ti in the magnetite mineral structure. Considered together, however, the lack of chemical variation of the three immobile elements, Al, Si and Ti, strongly suggest that no net mass gain occurred during the process of K-metasomatism.

Chemical enrichments and depletions

Although there was no net mass change during K-metasomatism, several elements underwent significant enrichments or depletions during the alteration process. Notably K and Rb were strongly enriched (Fig. 3A, 4), and Mg, Ca, Mn, Na and Sr were depleted (Fig. 3A), as was reported by Chapin and Lindley (1986), Glazner (1988) and Brooks (1986). The enrichment of K and depletion of Na and Ca are consistent with the alteration mineralogy observed. As plagioclase and glass in the samples are altered to some combination of adularia, quartz, hematite and clay minerals, Na and Ca are lost, and K is incorporated into the adularia structure, thereby increasing the K content of the sample. Rb will substitute for K in the feldspar structure (Deer, Howie and Zussmann, 1966) and will thereby also be enriched, whereas Sr, which tends to be concentrated in plagioclase and glass relative to potassic feldspar, will be progressively depleted as the plagioclase crystal structure or glass is replaced by potassic feldspar and clay minerals. Mg is probably lost largely through alteration of mafic silicate phases, but the mineralogical details of this alteration process are not well known because our investigation concentrated on alteration of plagioclase and glass. However, the relatively larger depletion of Mg from the basaltic-andesite as compared to rhyolitic ignimbrites favor this interpretation.

Elements of economic interest

In addition to the elements mentioned above, some elements of economic interest (Cu, Ag, Pt, Au, Sn, Pb), or elements that are indicator elements for elements of economic interest (As, Sb, Hg), are enriched in the K-metasomatized rocks (Fig. 3B). Although enrichments of some of these elements have been reported in other areas of K-metasomatism (Roddy et al., 1988, Brooks, 1986), they have not been measured before in the Socorro area. The absolute magnitude of enrichment is small in some cases (Fig. 4), but these elements are consistently enriched in the metasomatized rocks, suggesting that the fluid that caused K-alteration could produce economic ore deposits, if highly concentrated.

The location of these elements in the alteration assemblage (associated with, or incorporated into the structure of, which minerals) has not

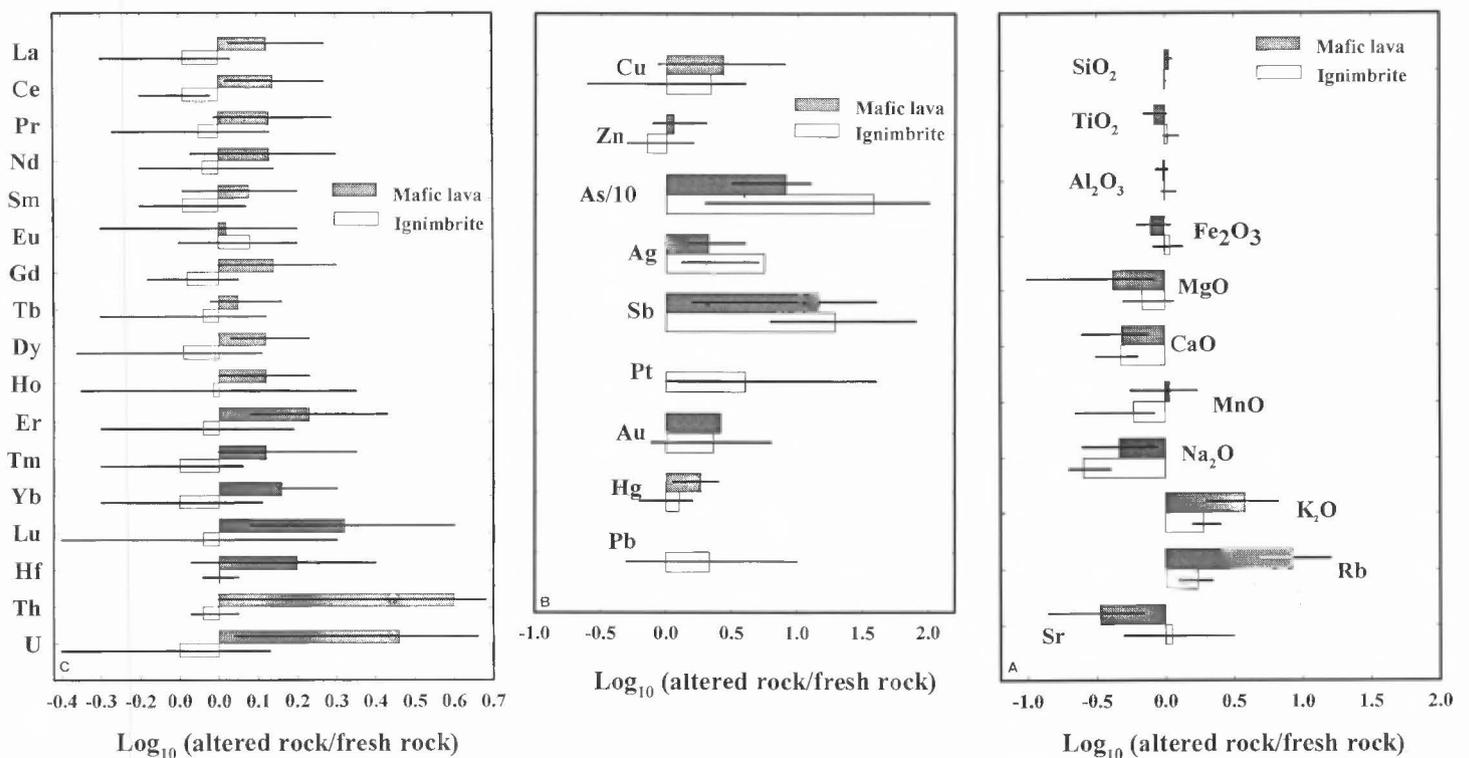


FIGURE 3. Enrichment/depletion diagrams for a variety of elements where the length of the bar represents the log_{10} of the altered rock/fresh rock composition. A, major elements plus Rb and Sr; B, elements of economic interest and indicator elements; and C, rare earth elements. The enrichment/depletion factors are based on averages of 5 and 7 altered/unaltered rock pairs for basaltic andesite and rhyolitic ignimbrites, respectively. The range of enrichment factors is shown by the black lines superimposed on the bars.

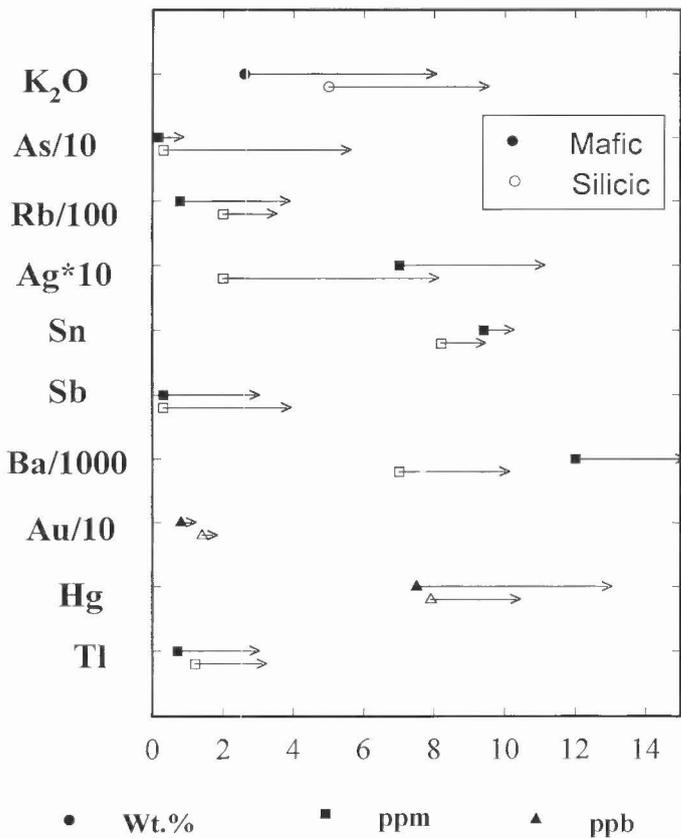


FIGURE 4. Average absolute enrichments of elements in silicic and mafic rocks. The symbols (circle for weight percent, square for ppm, and triangle for ppb) represent the unaltered rock composition. The length of the line shows the average absolute enrichment.

yet been determined, but studies to elucidate this problem are underway. The location and stability in the alteration assemblage for some elements, particularly As, are of interest because of the possible impact on the potability of local water supplies.

Rare-earth elements

Rare-earth elements (REE) have not been studied previously in K-metasomatized rocks. These were analysed in the rocks from the Socorro area, and were found to behave differently in the rhyolitic ignimbrites compared to the more mafic lavas. The REE are consistently enriched in the basaltic-andesite lavas, but are unchanged to slightly depleted in the rhyolitic ignimbrites (Fig. 3C). Although REE have not been determined for most areas of K-metasomatism, Glazner (1988) reported a lack of change in REE by the process of K-metasomatism in rhyolitic rocks from the Mojave Desert. However, subtle variations of REE may have been difficult to detect due to the interpreted mass increase of those rocks.

The strikingly regular variations of REE in the rhyolitic and mafic rocks in the Socorro area may be a function of the alteration mineralogy produced by the metasomatic process. Another possible explanation is that the metasomatic fluid composition plays a role in controlling the REE enrichments and depletions in the mafic and silicic rocks, respectively. However, this would imply that the fluid that altered the basaltic andesite rocks is chemically different than that which altered the rhyolitic rocks, and the close geographical proximity of these two rock types suggests that this is unlikely. Rare-earth elements are not compatible in quartz or adularia minerals produced by metasomatism, but are compatible to varying degrees in clay minerals, and these minerals can be important in controlling the REE composition of certain rocks (e.g., Cullers et al., 1977; Condie, 1991; Elliot, 1993). This leads to the suggestion that the enrichment or depletion of REE in K-metasomatized rocks may be a function of the composition and abundance of clay minerals produced during metasomatism. The clay minerals produced by alteration of a rhy-

olitic rock are likely to be different than those produced by a mafic rock, due to the different abundances of Na, Ca and K in the two rock types. This interpretation is speculative and more detailed chemical and mineralogical investigations are needed.

Chemical variations as a function of intermediate or advanced metasomatism

In addition to investigating the chemical composition of fresh and highly K-metasomatized mafic and rhyolitic rocks, several samples of rhyolitic rocks believed to be intermediately altered were also analysed. The rocks characterized by an intermediate degree of alteration contain K₂O contents intermediate between fresh rhyolite (~4-5 weight percent K₂O) and highly altered rhyolite (~13 weight percent K₂O). Other elements were analysed in the intermediately altered rocks: not all were found to vary in direct relationship to K₂O (Fig. 5). Some elements, such as Rb and Sr, vary strongly in the first alteration step (from fresh rock to intermediately altered), whereas others, such as Ba, As and Sb, are relatively invariant in the first step of alteration, but are strongly increased in the second step (intermediate to highly altered). The several possible explanations for this chemical behavior all relate to the alteration mineralogy. First, the marked decrease in Sr is likely due to progressive destruction of plagioclase in the host rock. As mentioned earlier, remnant plagioclase is found in some samples that have not undergone extensive alteration, and Sr is a compatible element in the plagioclase crystalline structure. Rb is apparently highly compatible in the phases that form in the early stages of alteration, and less so in the later phases. Our working model of mineralogical alteration involves clay minerals being formed early in the alteration process, and adularia being formed later (e.g., Meyer and Hemley, 1967), and although Rb is known to be compatible in the adularia structure, where it substitutes for K, it is probably more compatible in clay mineral structures and some is actually excluded during the clay mineral-adularia transition. Ba, As, Sb and La are apparently more compatible in the later-formed mineralogical assemblage. In contrast, Cu is highly enriched in the early alteration stages, but depleted later. Cu, and other metals, can be adsorbed onto the outside of mineral grains, rather than being incorporated into the actual chemical structure (Maynard, 1991). The larger surface area of clay minerals relative to other phases (Aagaard, 1974) may allow a greater amount of Cu to be adsorbed onto a clay mineral assemblage relative to an assemblage of adularia + quartz. Alternatively, the slightly different fluid composition or temperature responsible for deposition of adularia+quartz relative to clay may cause adsorbed Cu to be mobilized.

Age determinations and implications for source of enriched elements

⁴⁰Ar/³⁹Ar age determinations of 7.4 ± 0.1 and 8.7 ± 0.1 Ma have been

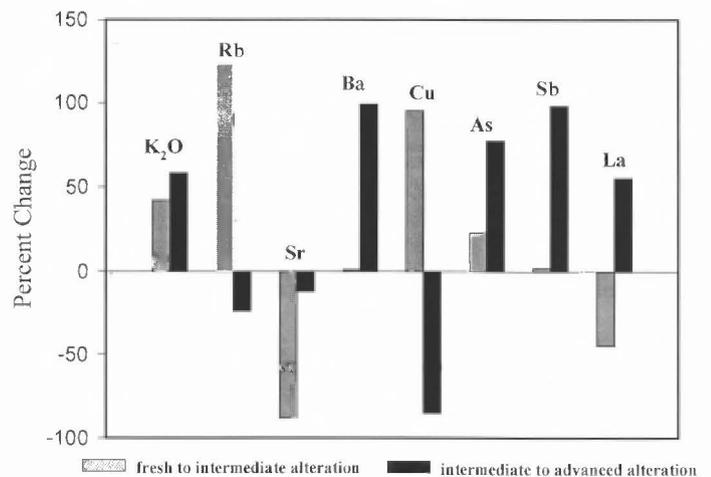


FIGURE 5. Percent change of elements as a function of intermediate and advanced degrees of alteration for a single rhyolitic ignimbrite. Length of the bar represents the percent change during each alteration step.

made on hand-picked adularia from two highly K-metasomatized samples (Fig. 6). The errors quoted are analytical errors to 1σ . Although we attempted to separate as much clay material as possible from the samples, the K/Ca ratio of between 10 and 100, determined as part of the $^{40}\text{Ar}/^{39}\text{Ar}$ analysis in the younger of the two samples, indicates that some clay minerals may have remained in the sample, and x-ray diffraction analyses confirms this idea. Although the clay minerals mixed in the sample are likely to have also formed by the metasomatic process, $^{40}\text{Ar}/^{39}\text{Ar}$ of clay minerals is hampered by recoil of ^{39}Ar out of the sample during irradiation, yielding an apparently old age. Thus, the younger of the two ages may be slightly older than the age of formation of adularia in that sample.

Even given that the younger age may be slightly too old, these dates, in conjunction with geological evidence, allow us to speculate about the timing and duration of K-metasomatism. In the northern part of the metasomatized area, playa clays are interbedded with 15 Ma volcanic ash (S. Cather, personal commun., 1994). The youngest known ash bed interbedded with playa clays is 7.85 Ma, but playa clays may have continued to be deposited until as recently as 4.1 Ma (R. Chamberlin, personal commun., 1994). Assuming that K-metasomatism could have occurred during the time when alkaline-saline brines were present, and that the alkaline-saline lake systems were the source of the playa clays, the above estimates of timing of playa clay deposition approximately bracket the time during which metasomatism may have occurred. The $^{40}\text{Ar}/^{39}\text{Ar}$ ages mentioned above are from one of the most highly metasomatized areas near Socorro and may have been among the latest material metasomatized at a time when the playa lake was smallest and the fluids were the most concentrated with respect to dissolved ions. Playa clay deposits are found near the sampling site for the two dated samples. However, metasomatism may have begun as early as 15 Ma, and may therefore have been an ongoing process for at least as long as 8 Ma. During this time, the playa lake in the enclosed basin or basins may have varied in size and alkalinity as a function of local climate, but nevertheless would have had continuous water input for a long time. The water fed into the basin would be derived from surrounding areas, and through chemical leaching of the rock through and over which the water travelled, would contain a small, but measurable quantity of a wide range of elements. These elements would be concentrated in the playa brines by evaporation, producing a dense fluid that could circulate through underlying rocks (Tyler et al., 1993; Leising et al., 1993). The possible long duration of the metasomatic event, and scavenging of elements from a wide geographical area over this long period could explain the lack of any discernable depleted source area for the elements that were enriched during metasomatism. The lack of a depleted source area has been puzzling, particularly for the element K, for which 6.4×10^{10} tons have been added to the rocks in the Socorro area during metasomatism (Chapin and Lindley, 1986).

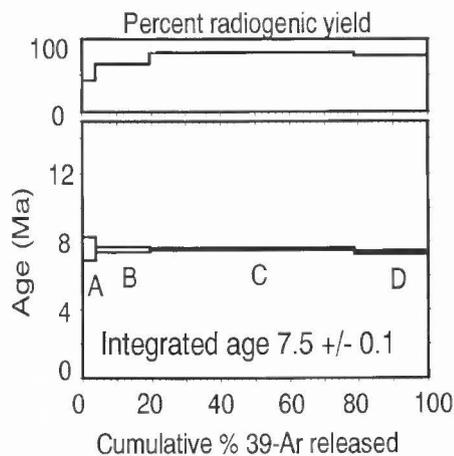


FIGURE 6. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum and percent radiogenic gas release for a step-heated adularia sample produced by K-metasomatism. The A, B, C and D steps represent heating steps during analysis.

CONCLUSIONS

K-metasomatism within an area of central New Mexico, a process caused by alkaline, saline brines in a playa lake environment, caused reactive phases, such as plagioclase phenocrysts and glass, to be altered to a range of secondary minerals, including quartz, adularia, and a range of clay mineral types. The mineralogy produced by alteration is complex, and may have been a function of fluid composition and fluid temperature, as well as composition of the altered rock. The metasomatism caused local rocks to be enriched in K and Rb, as well as other ore-forming or indicator elements, such as Au, Ag, Pt, Hg, As and Sb, but did not cause any net mass change in the altered rocks. During the alteration process, other elements, such as Mg, Ca, Na, Mn and Sr, were depleted. Although alteration of rhyolitic and basaltic-andesite rocks is chemically similar in many respects, some elements, particularly REE, behave differently, suggesting that the presence and composition of clay minerals in the alteration products may play a role in controlling alteration chemistry. The chemical enrichments and depletions of rocks appear to be a multi-step process, probably controlled by progressive mineralogical changes. Based on $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations on alteration phases, K-metasomatism appears to have been occurring between 7.4 and 8.7 Ma, but may have begun as early as 15 Ma, based on independent geological evidence. The long duration of the playa lake system may account for the lack of a discernable, depleted source area for elements enriched during metasomatism.

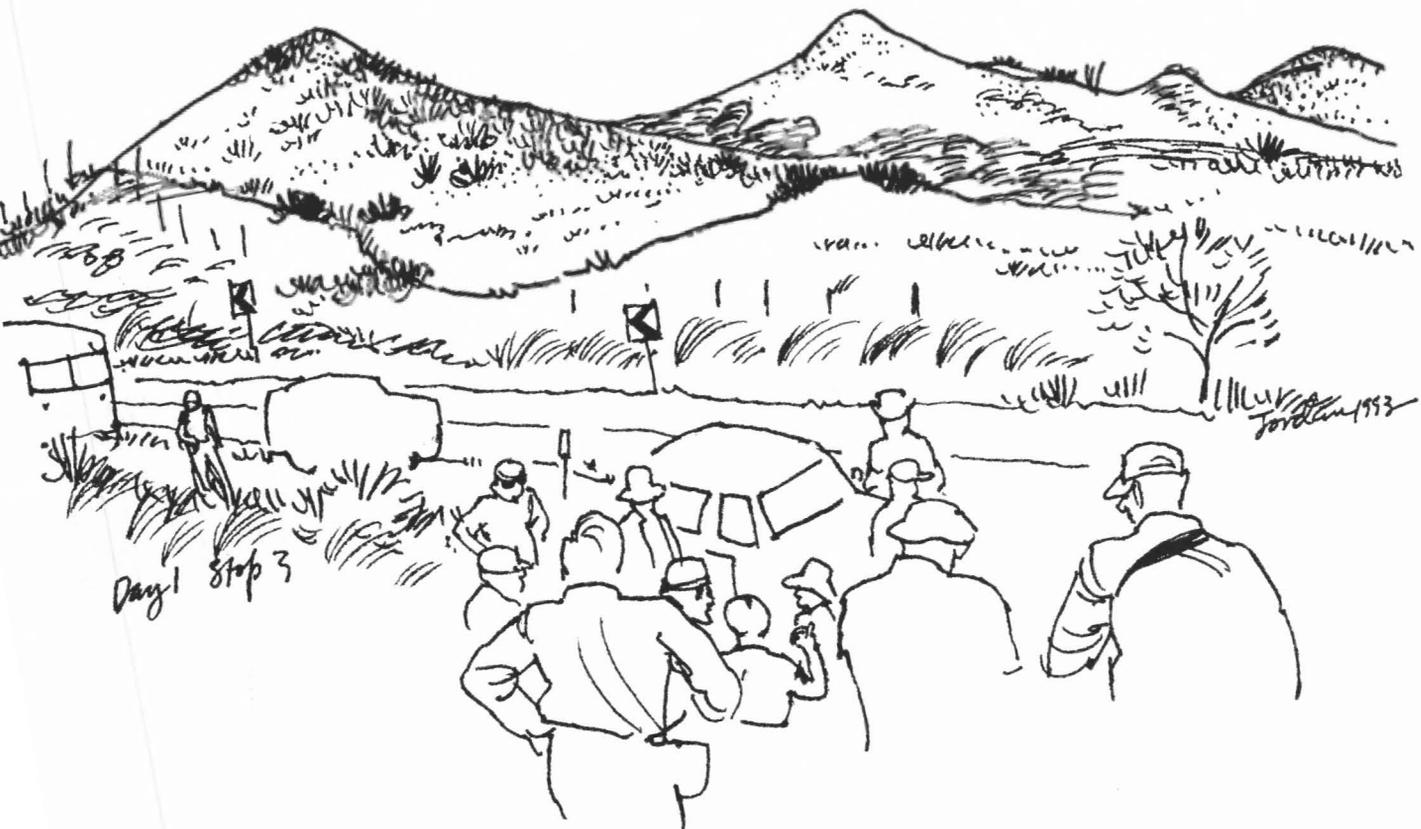
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