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Genetic Implications of Minor-Element and Sr-Isotope Geochemistry of Alkaline Rock Complexes in the Wet Mountains Area, Fremont and Custer Counties, Colorado

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Abstract. Concentrations of Rb, Sr, and REE (rare earth elements), and Sr-isotopic ratios in rocks of the Cambrian alkaline complexes in the Wet Mountains area, Colorado, show that rocks formed as end-products of a variety of magmas generated from different source materials. The complexes generally contain a bimodal suite of cumulus mafic-ultramafic rocks and younger leucocratic rocks that include nepheline syenite and hornblende-biotite syenite in the McClure Mountain Complex, nepheline syenite pegmatite in the Gem Park Complex, and quartz syenite in the complex at Democrat Creek. The nepheline syenite and hornblende-biotite syenite at McClure Mountain (535 ± 5 m.y.) are older than the syenitic rocks at Democrat Creek (511 ± 8 m.y.). REE concentrations indicate that the nepheline syenite at McClure Mountain cannot be derived from the hornblende-biotite syenite, which it intrudes, or from the associated mafic-ultramafic rocks. REE also indicate that mafic-ultramafic rocks at McClure Mountain have a source distinct from that of the mafic-ultramafic rocks at Democrat Creek.

In the McClure Mountain Complex, initial $^{87}Sr/^{86}Sr$ ratios for mafic-ultramafic rocks (0.7046 ± 0.0002) are similar to those of hornblende-biotite syenite (0.7045 ± 0.0002), suggesting a similar magmatic source, whereas ratios for carbonatites (0.7038 ± 0.0002) are similar to those of nepheline syenite (0.7038 ± 0.0002). At Democrat Creek, initial ratios of syenitic rocks (0.7032 ± 0.0002) and mafic-ultramafic rocks (0.7028 ± 0.0002) are different from those of corresponding rocks at McClure Mountain.

Introduction

Three alkaline igneous complexes in the Wet Mountains area, the McClure Mountain Complex, the Gem Park Complex, and the complex at Democrat Creek, have been tacitly assumed by earlier workers to be genetically related. Until this study, ages of rocks of the different complexes have been assumed to be essentially the same, even though the intrusive sequence of the different rock types has been fairly well established. Data presented here resolve some of the absolute age differences of the rock units. This study also attempts to resolve the apparent inconsistency of the association of calcic plagioclase-bearing rocks and carbonatites (Rock 1976) in the alkaline intrusive complexes through a discussion of their Rb, Sr, and REE (rare-earth elements) distributions and their Sr-isotope systematics. These data show that rocks of the complexes did not form through fractionation of a single magma but instead formed as end-products of several magmas generated from different source materials. Thus the association of calcic plagioclase-bearing rocks and carbonatites is fortuitous. Analytical methods are similar to those discussed by Simmons and Hedge (1978).

Geologic Setting

The Wet Mountains area is about 20 km southwest of Canon City, Colorado, just east of the Sangre de Cristo Range and south of the Arkansas River (Fig. 1).

The McClure Mountain and Gem Park Complexes and the complex at Democrat Creek, which Olson and others (1977) considered to be of Cambrian age, intrude Proterozoic X (1.6–2.5 b.y.) metamorphic rocks – chiefly layered granitic gneisses, hornblende gneisses, and amphibolites – and granitic rocks of Boulder Creek age (1.72 b.y.) and Silver Plume age (1.45 b.y.) (Taylor and others 1975a, b). The western edge of the Gem Park Complex is bordered by Tertiary welded tuffs, boulder gravels, and water-laid tuffs (Parker and Sharp 1970). Both the rocks of the complexes and the Precambrian host rocks are intruded by a variety of dikes and veins, especially carbonatites (Armbrustmacher 1979), lamprophyres (Heinrich and Dahlem 1969), red syenites, and quartz-barite-thorite veins (Armbrustmacher 1976; Christman and others 1959). The relative ages of intrusion of the various dikes are not consistent.

The host rocks adjacent to the alkaline intrusive complexes, carbonatite dikes, and thorium deposits, and parts of the complexes themselves, are generally fenitized. Quartzo-feldspathic host rocks typically show loss of quartz, have had their feldspars replaced by potassic feldspar that contains abundant ferric oxide inclusions, have had their mafic minerals destroyed or replaced by blue and green sodic amphiboles and pyroxenes, and have fractures lined with similar minerals or with epidote. Where mafic-ultramafic host rocks are fenitized, the most conspicuous result is the replacement of mafic minerals by vermiculite, which at some places is in near-economic concentrations.

Rocks of the Complexes

McClure Mountain Complex

The McClure Mountain Complex, named and defined by Shawe and Parker (1967), is the largest complex and con-

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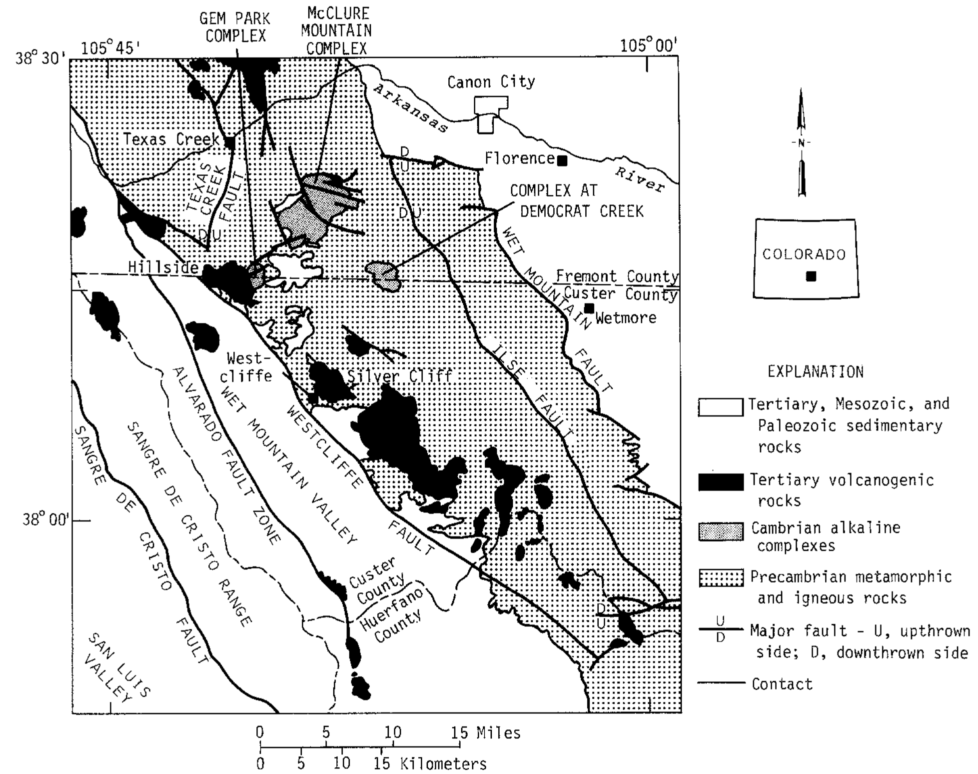

Fig. 1. Map of Wet Mountains area showing location of alkaline complexes, Fremont and Custer Counties, Colorado. Geology modified from Scott and others (1976)

tains the greatest variety of rock types. The distribution of various rock types has been interpreted by Heinrich and Alexander (1979) as representing a mafic-alkalic ring complex. The complex consists of a series of mafic-ultramafic rocks centered around Iron Mountain in the northeast part of the complex, mafic nepheline-clinopyroxene rocks termed ijolite by Heinrich (1966), and two types of syenite, hornblende-biotite syenite and nepheline syenite. These rocks in turn are intruded by a variety of alkaline dikes including carbonatites. The mafic-ultramafic part of the complex at Iron Mountain has been described by Shawe and Parker (1967).

Mafic and ultramafic rocks of the Iron Mountain part of the McClure Mountain Complex form a funnel-shaped stratified intrusion that is intruded by small, discordant masses of similar rocks, as well as by dikes of carbonatite and syenite. The stratified part of the complex consists of igneous cumulates comprising essentially five cumulus minerals in various proportions. They are plagioclase, Ca-rich clinopyroxene, olivine, magnetite, and spinel. All of these minerals except spinel also occur as intercumulus material, along with reddish-brown sodic amphibole and red biotite. Euhedral apatite appears to have coprecipitated with magnetite. Considerable variations in mineral proportions and in grain size occur over a few centimeters distance, although rock types tend to be more homogeneous along rather than across the strike of the stratification. These characteristics are typical of igneous cumulates (Jackson 1961). The most abundant rock types include clinopyroxene adcumulates, plagioclase adcumulates, magnetite adcumulates, and orthocumulates consisting of the cumulus minerals in various combinations and in various proportions.

The discordant masses that intrude the stratiform rocks are recognized in the field by their crosscutting relationship to the stratiform rocks, by the presence of xenoliths of rocks of the layered part of the complex near contacts, and by a lack of layering (Shawe and Parker 1967). Rocks of the discordant intrusions consist chiefly of anorthosite and pyroxenite and contain minerals that are optically indistinguishable from those of the stratiform rocks.

Most of the norms for both stratiform and discordant intrusions (Shawe and Parker 1967) show the presence of normative olivine and normative nepheline with or without normative leucite but tend to lack normative hypersthene and totally lack normative quartz. According to Wilkinson (1974), basaltic rocks containing normative nepheline and normative olivine are alkali basalt types. Plots of weight-percent alkalies versus weight-percent SiO_2 (Fig. 2) show that the mafic-ultramafic rocks plot near the boundary line conventionally used to partition alkaline basalts from subalkaline basalts. Anorthositic and gabbroic rocks plot as members of the alkali basalt family; pyroxenitic rocks plot as subalkaline rocks because of their relative deficiency in Na_2O and K_2O due to differences in plagioclase abundance.

The next younger rock in the sequence at the McClure Mountain Complex is the mafic nepheline-clinopyroxene rock (ijolite of Heinrich and Dahlem 1966). Modal analyses of six samples of this rock show considerable variation in components, but they have average values of 26.8 volume-percent nepheline, 30.4 percent sodic pyroxene, 25.5 percent brown biotite, 2.8 percent sphene, 1.8 percent magnetite, and 1.6 percent apatite. Some samples contain potassic feldspar, but none of the samples contain plagioclase. Plots of the mafic nepheline-clinopyroxene rocks on a nepheline-mafic mineral-potassic feldspar diagram (Fig. 3), modified from Sorensen (1974), show these rocks to have the modal compositions of ijolite and melteigite, with the feldspar-rich variety falling in the malignite field. Chemical analyses of three samples of these rocks show 38–47 percent SiO_2 and 6–11 percent alkalies. The rocks average more than 27 per-

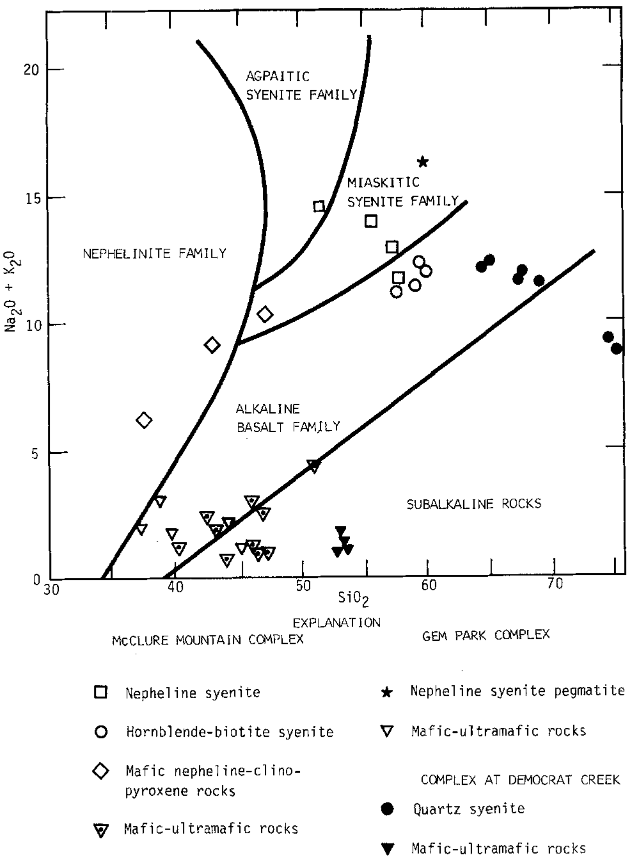

Fig. 2. Plots of weight-percent alkalies versus weight-percent silica for samples from the McClure Mountain Complex, Gem Park Complex and complex at Democrat Creek (modified from Currie 1976, Fig. 1)

cent normative nepheline and 25 percent normative diopside. Plots of these rocks on an alkalies versus SiO_2 diagram (Fig. 2) show these to be the only rocks to fall in the nephelinite family field.

Two varieties of syenite occur as part of the McClure Mountain Complex, hornblende-biotite syenite and relatively younger nepheline syenite. Modal analyses of 11 samples of hornblende-biotite syenite, which is homogeneous appearing in outcrop, show averages of more than 75 percent by volume microperthite, 4 percent sodic amphibole, 5.7 percent brown biotite, and 1 percent or less sphene, magnetite, and apatite. Nepheline was identified in three samples; sodic pyroxene, which has a reaction relationship with sodic amphibole, occurs as remanents in 6 samples; sodic plagioclase has an irregular distribution and occurs in amounts ranging from 0 to nearly 34 percent. No potassic feldspar, exclusive of that contained in microperthite, has been identified. Plots of modal hornblende-biotite syenite on a QAPF diagram (Fig. 4) show the dominance of the feldspar components; most of the samples fall in the alkali syenite, syenite, and monzonite fields, depending on the abundance of plagioclase. Chemical analyses of four samples of hornblende-biotite syenite average 59 percent SiO_2 and 11.5 percent alkalies. All samples contain normative nepheline and normative olivine and lack normative quartz, normative diopside, and normative hypersthene. The normative feldspars show the relationship Ab > Or > An for all samples. Plots of $Na_2O + K_2O$ versus SiO_2 (Fig. 2) place the samples in the alkali basalt family. It should be noted that the hornblende-biotite syenites are characteristically homogeneous in their modal and normative mineral content.

The nepheline syenites show a wide diversity in modal mineral content. Twenty-four samples average 15.8 percent

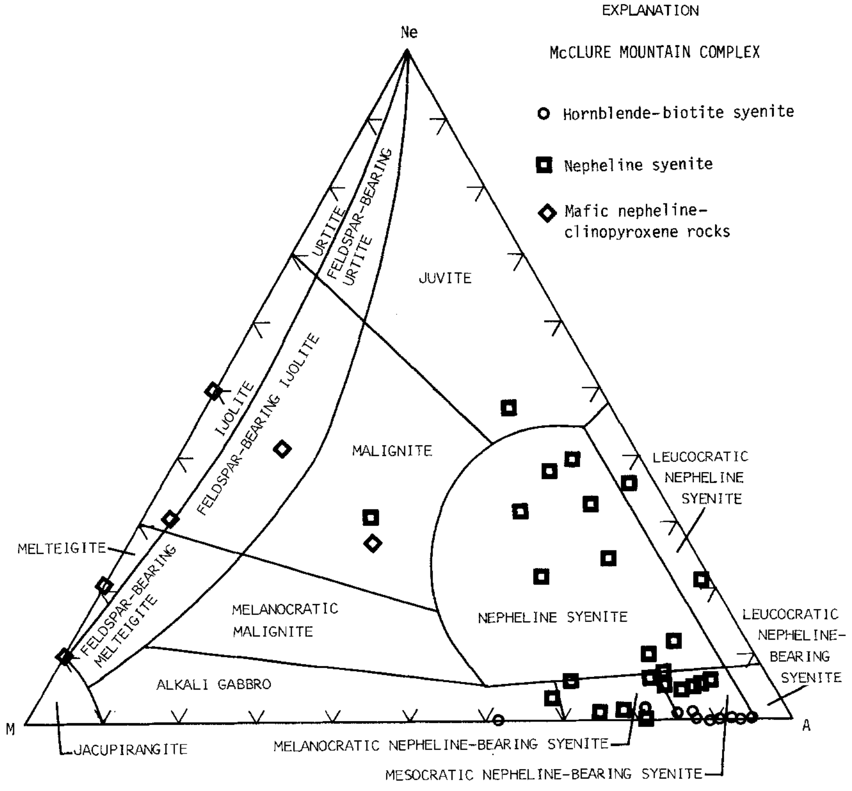

Fig. 3. Modal variation in nepheline (*Ne*), mafic minerals (*M*), and potassic feldspar (*A*) of rocks from the McClure Mountain Complex (from Sorensen 1974a, p. 17)

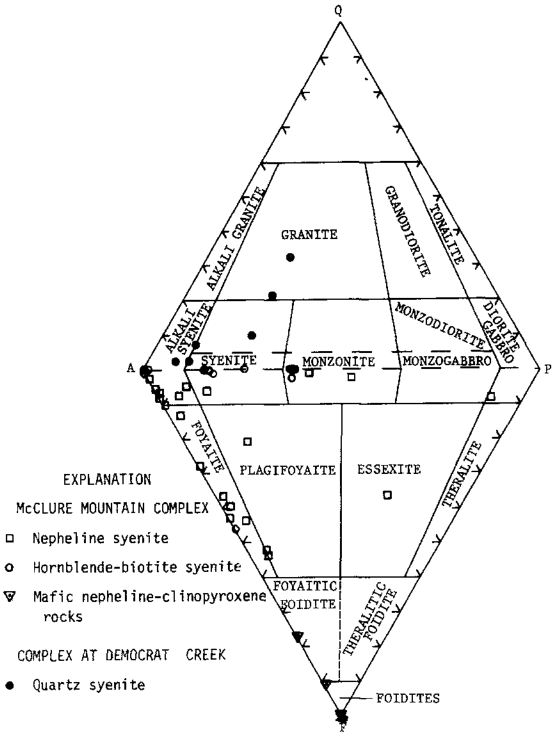

Fig. 4. Modal variation in quartz (Q), alkali feldspar and plagioclase (An_{0-5}) (A), plagioclase $(\mathrm{An}_{>5})$ (P), and feldspathoid (F) of syenites from the McClure Mountain Complex and the complex at Democrat Creek (modified from Sorensen 1974a, p. 16). Values are in percent by volume

nepheline, ranging from less than 1 to 36 percent. Nearly every sample contains sodic amphibole, which averages 10 percent; many samples contain sodic pyroxene, which averages about 4 percent when present. Biotite is ubiquitous and averages 2.5 percent. Microperthite averages 62.7 percent; plagioclase, which is present in 70 percent of the samples studied, averages more than 13 percent when present; potassic feldspar is present in one-third of the samples but averages nearly 28 percent where present. Sphene, magnetite, and apatite are present as accessory minerals and sodalite has been found at one locality. Plots of modal nepheline-mafic minerals-potassic feldspar (Fig. 3) show that most of the samples occupy nepheline syenite fields. One sample plots in the juvite field, and one sample plots in the malignite field. Plots of modal constituents on the QAPF diagram (Fig. 4) show that most of the samples plot parallel to the alkali feldspar-feldspathoid base in the alkali syenite and foyaite fields. Several other plots scatter into other fields. Chemical analyses of three samples of nepheline syenite average more than 55 percent SiO_2 and 13.5 percent alkalies, with $Na_2O > K_2O$. Normative nepheline averages more than 17 percent, and normative olivine is also present. Normative feldspars show the relationship $Or > Ab > An$. Plots of $Na_2O + K_2O$ versus SiO_2 (Fig. 2) show a spread of points more or less centered around the miaskitic syenite family field. Relative to the hornblende-biotite syenites, the nepheline syenites are considerably more heterogeneous in modal and normative mineral content.

Gem Park Complex

The Gem Park Complex is southwest of the McClure Mountain Complex (Fig. 1). It was first mentioned by Parker and others (1962) and the outline and extent of the complex was first illustrated by Parker and Hildebrand (1963). Parker and Sharp (1970) have formally defined and described the rocks of the Gem Park Complex and much of this discussion is based on their work. The complex consists mainly of mafic-ultramafic rocks intruded by carbonatites and other types of dikes, and one exposure of nepheline syenite pegmatite.

The mafic-ultramafic rocks of the Gem Park Complex appear to also form a funnel-shaped stratiform body, as indicated by the concentric distribution of rock types and the dip of mineral layering toward the center of the complex. The rocks are offset by several northeast-trending high-angle normal faults that also offset the Tertiary volcanic rocks immediately west of the complex. The mafic-ultramafic rocks consist of igneous cumulates comprising the cumulus minerals plagioclase, clinopyroxene, and magnetite. The most abundant rocks are plagioclase-clinopyroxene orthocumulates and clinopyroxene adcumulates. Locally, plagioclase adcumulates and magnetite orthocumulates are interlayered with the other lithologies. Plagioclase, clinopyroxene, and magnetite, along with reddish-brown sodic amphibole and reddish-brown biotite, occur as intercumulus material. Anhedral apatite containing two-phase fluid inclusions is also intercumulus, and euhedral sphene is an uncommon accessory mineral. Drill core from the northern part of the complex intersects coarse-grained clinopyroxene adcumulate containing abundant iron and iron-copper sulfide minerals. The Gem Park rocks appear to contain smaller amounts of olivine than McClure Mountain mafic-ultramafic rocks.

Norms for Gem Park mafic-ultramafic rocks (Parker and Sharp 1970, p. 4) lack quartz and hypersthene but contain nepheline and olivine. Plots of alkalies versus SiO_2 (Fig. 2) show that the majority of Gem Park rocks fall in the alkali basalt family field and overlap plots of mafic-ultramafic rocks from the McClure Mountain Complex.

Near the center of the Gem Park Complex a small pit exposes nepheline syenite pegmatite that most likely intrudes the mafic-ultramafic rocks (Parker and Sharp 1970). This rock consists of untwinned and microperthitic potassic feldspar, nepheline, aegirine-augite, sodic amphibole, sphene, muscovite, apatite, magnetite, albite, and sodalite(?). Parker and Sharp (1970) also noted the presence of natrolite and analcite. One chemical analysis of nepheline syenite pegmatite (Roden 1977), which may not be representative, is very high in total alkalies and plots in the miaskitic syenite family field in the alkalies versus SiO_2 diagram (Fig. 2).

For the most part, the layered mafic-ultramafic rocks at Gem Park are quite similar to those occurring in the McClure Mountain Complex at Iron Mountain. Differences include the greater abundance of olivine and the greater diversity of rock types at Iron Mountain. Nevertheless, the mafic-ultramafic cumulates at the Gem Park and the McClure Mountain Complexes are believed to share a common origin.

Complex at Democrat Creek

The complex at Democrat Creek is southeast of the McClure Mountain Complex (Fig. 1). Rocks of this complex have been partly mapped and described by Christman and others (1954), Singewald and Brock (1956), Parker and

Hildebrand (1963), and Heinrich and Dahlem (1966). As mentioned in an earlier report (Armbrustmacher 1979), close examination of rocks of the complex at Democrat Creek show them to be quite unlike rocks of the other complexes.

The bulk of the complex at Democrat Creek consists of leucocratic rocks; mafic-ultramafic rocks are essentially restricted to the southern part of the complex. The contact of the leucocratic rocks with the Precambrian host rocks is marked by a breccia zone in some places. Several satellitic intrusions of syenitic rocks surround the main part of the complex. Rocks of the complex are cut by quartz-barite-thorite veins and by a variety of syenitic dikes, but no carbonatite or red syenite dikes have yet been found.

The mafic-ultramafic rocks at Democrat Creek do not show obvious layering, although the distribution of rock types does not rule out that possibility. The most abundant rock types are gabbros and pyroxenites that contain both Ca-rich clinopyroxenes and Ca-poor orthopyroxenes, a characteristic of tholeiitic rocks. These rocks also contain yellowish-green, pleochroic amphibole that occurs interstitial to the pyroxenes. Small amounts of biotite, variable amounts of plagioclase as much as about 25 percent by volume, and accessory magnetite, sphene, quartz, and apatite constitute these rocks. Calculations of norms show the presence of diopside and abundant hypersthene. Normative nepheline is absent. These are characteristics of saturated tholeiitic basalts (Wilkinson 1974). Plots of alkalies versus SiO_2 (Fig. 2) for two gabbros and two pyroxenites show that Democrat Creek rocks have limited variability in these components and that the rocks are subalkaline.

The most abundant rock type in the complex at Democrat Creek is quartz syenite. Samples of these rocks average nearly 15 percent modal quartz by volume. Microperthite averages 62 percent, albite averages 13 percent, and microcline occurs in variable amounts between 0 and 20 percent. Sodic amphibole is the chief mafic mineral but is absent from some samples; biotite occurs in most samples but does not exceed 3 percent. Fluorite and zircon occur as accessories in nearly every sample; magnetite and perovskite(?) are sparse. Plots of modal data on the QAPF diagram (Fig. 4) show that the quartz syenites are the only rocks from the alkaline complexes to plot on the quartz side of the diagram; samples are in the alkali syenite, syenite, and granite fields, depending on the amount of quartz. Chemical analyses of quartz syenites show an average SiO_2 content of 68.7 percent for seven samples and an average alkali content of 11 percent with $Na_2O > K_2O$. The CaO content of these rocks does not exceed 1.1 percent. Plots of alkalies versus SiO_2 (Fig. 2) show the rocks are within the fields of the alkaline basalt family and subalkaline rocks.

To summarize, the mafic-ultramafic rocks found in the McClure Mountain and Gem Park Complexes are structurally, lithologically, and chemically quite similar to one another, and therefore it is assumed that they share a common origin. The mafic-ultramafic rocks at Democrat Creek are structurally, lithologically, mineralogically, and chemically unlike the rocks of the other complexes although the distribution of rock types leaves open the possibility that they may also be igneous cumulates. However, the parent magma of Democrat Creek rocks almost certainly had more tholeiitic affinities than that of the mafic-ultramafic rocks of the other complexes. The only leucocratic rock at Gem Park, other than various dikes, is the small exposure of nepheline syenite pegmatite that is unlike any other rock within the other alkaline complexes. In the McClure Mountain Complex, there are two nepheline-rich rocks, the mafic nepheline-clinopyroxene rock (or ijolite) and the nepheline syenite, both of which are characteristically heterogeneous in regard to modal mineralogy and whole-rock chemistry. The hornblende-biotite syenite at McClure Mountain contains only scattered grains of nepheline and tends to be quite homogeneous in regard to modal mineralogy and whole-rock chemistry. The quartz syenite at Democrat Creek shows practically no mineralogical or chemical similarities with the McClure Mountain syenites.

Ages of the Complexes

Radiometric age determinations of Wet Mountains alkaline rocks have been summarized by Olson and others (1977). Their data for rocks from the McClure Mountain Complex are: 520 m.y. (average hornblende K – Ar age), 521 m.y. (Rb – Sr isochron), 508 m.y. (average biotite K – Ar ages), and 506 m.y. (sphene fission-track age); the quartz syenite in the complex at Democrat Creek has average K – Ar ages of 512 m.y. (biotite), and 534 m.y. (hornblende). Their data show that red syenite dikes associated with rocks of the complexes have an age of 495 m.y. (Rb – Sr isochron). Their attempts to date rocks from the Gem Park Complex gave unsuitable results (Olson and others 1977, p. 683).

In the present study, whole-rock isochrons were determined for leucocratic rocks from the McClure Mountain Complex and for the complex at Democrat Creek. The hornblende-biotite syenites and nepheline syenites from the McClure Mountain Complex lie along the same whole-rock isochron (Fig. 5), and, although field relationships indicate that the nepheline syenite is younger than hornblende-biotite syenite, these differences cannot be resolved with these data. The age of these syenites is 535 ± 5 m.y.; the initial $^{87}Sr/^{86}Sr$ ratio is 0.7045 ± 0.0002. The quartz syenites from the complex at Democrat Creek show a greater variation in Rb – Sr ratios, and the whole-rock isochron gives an age of 511 ± 8 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7032 ± 0.0002 (Fig. 6). Thus, an age difference of about 24 m.y. exists between the syenites in the McClure Mountain Complex and the quartz syenite in the complex at Democrat Creek. The relative and absolute age relationships of the rocks of the Wet Mountains area are given in Table 1.

Rare-Earth Elements

Abundance of rare-earth elements (REE) in rocks from the McClure Mountain Complex and the complex at Democrat Creek are given in Table 2. The rocks tend to contain more abundant total REE than igneous rocks of the upper continental crust (Wedepohl 1971, Table 7.3), but somewhat less abundant total REE than comparable rocks of other alkaline complexes (Gerasimovsky 1974; Moller and others 1980; Eby 1975). Rocks from the Fen alkaline complex have total REE abundances (Mitchell and Brunfelt 1975) similar to those in rocks from the McClure Mountain Complex and the complex at Democrat Creek. The distributions of REE in rocks from the McClure Mountain Complex and the complex at Democrat Creek (Figs. 7–11) show a more or less continuous decrease in abundance with increased atomic number, due to enrichment of light REE, a characteristic of alkaline undersaturated rocks (Moller and others 1980).

Table 1. Relative and absolute age relationships of rocks of the Wet Mountains area, Colorado

Geologic ages	Rock types	Absolute ages
Tertiary	Volcaniclastic rocks	
Cambrian	Quartz-barite-thorite veins; various leucocratic dikes	
	Complex at Democrat Creek:	
	quartz syenite	511 m.y.
	breccia	
	mafic-ultramafic rocks	
	Carbonatites, red syenites, lamprophyres (?)	
	McClure Mountain Complex:	
	nepheline syenite	535 m.y.
	hornblende-biotite syenite	535 m.y.
	mafic nepheline-clinopyroxene rock	
	Gem Park Complex:	
	nepheline syenite pegmatite	
	Gem Park and McClure Mountain cumulates	
Precambrian	Silver Plume or Proterozoic Y age:	
	granitic intrusive rocks	1,450 m.y.
	Boulder Creek or Proterozoic X age: granitic intrusive rocks	1,720 m.y.
	Proterozoic X metamorphic rocks	

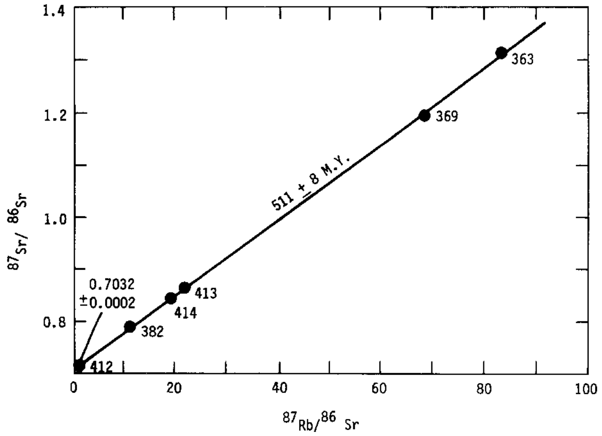

Fig. 6. Whole-rock isochron of quartz syenites of the complex at Democrat Creek, Colorado

Chondrite-normalized rare-earth element (REE) data for mafic rocks from the complex at Democrat Creek and the McClure Mountain Complex are plotted on Fig. 7, along with data for tholeiitic mid-ocean ridge basalt, alkali basalt, and nephelinite taken from Kay and Gast (1973). The gabbroic rock from Democrat Creek contains less total REE than the various types of basalts, and it shows some increase in the light- to heavy-REE ratio relative to the tholeiitic basalt. The mafic cumulate rocks from the McClure Mountain Complex contain total amounts of REE comparable to tholeiitic basalt, but the light rare earths are enriched and the heavy rare earths depleted relative to the tholeiitic basalt. Total REE content of cumulus rocks from the McClure Mountain Complex is greater than that in the Democrat Creek mafic rock. The McClure Mountain cumulates contain less abundant REE than the alkali basalt and the nephelinite.

Using the modal analyses of the mafic-ultramafic rocks and published crystal-to-liquid distribution coefficients for the component minerals it is possible to calculate the REE patterns for the liquids which would have been in equilibrium with these cumulate mafic rocks. These patterns are shown with the REE pattern for alkali basalt on Fig. 8. The close similarity of these REE patterns suggest that the liquids from which the gabbro at Democrat Creek and the cumulus mafic rocks at McClure Mountain Complex crystallized are similar in REE composition to a normal alkali basalt magma. Just as the REE content of the basalts increases in the order tholeiite-alkali basalt-nephelinite, perhaps the liquid from which the McClure Mountain cumulates crystallized had a slightly higher alkali content than the liquid from which the gabbros at Democrat Creek crystallized, and the more tholeiitic composition of the Democrat Creek rocks is reflected.

Chondrite-normalized REE data for the various syenites (Table 2) are plotted on the diagrams shown in Figs. 9–11.

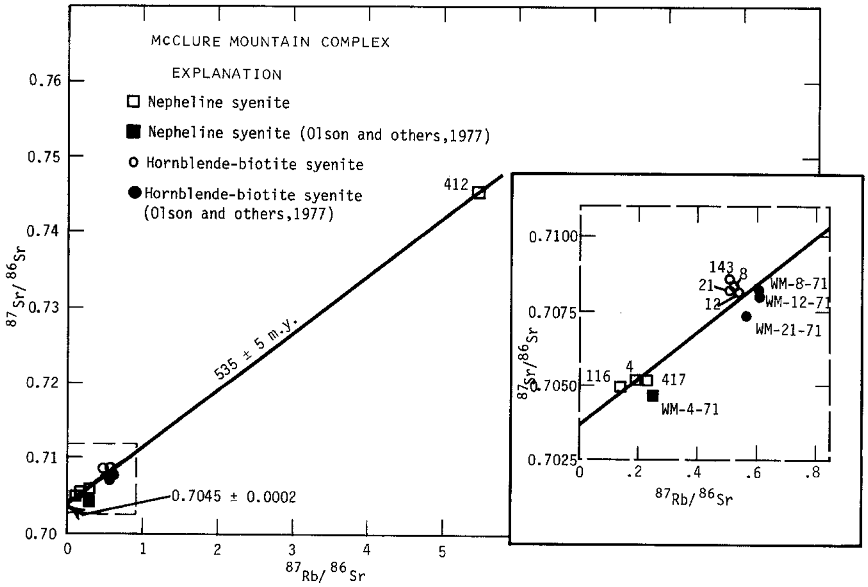

Fig. 5. Whole-rock isochron of nepheline syenites of McClure Mountain Complex, Colorado

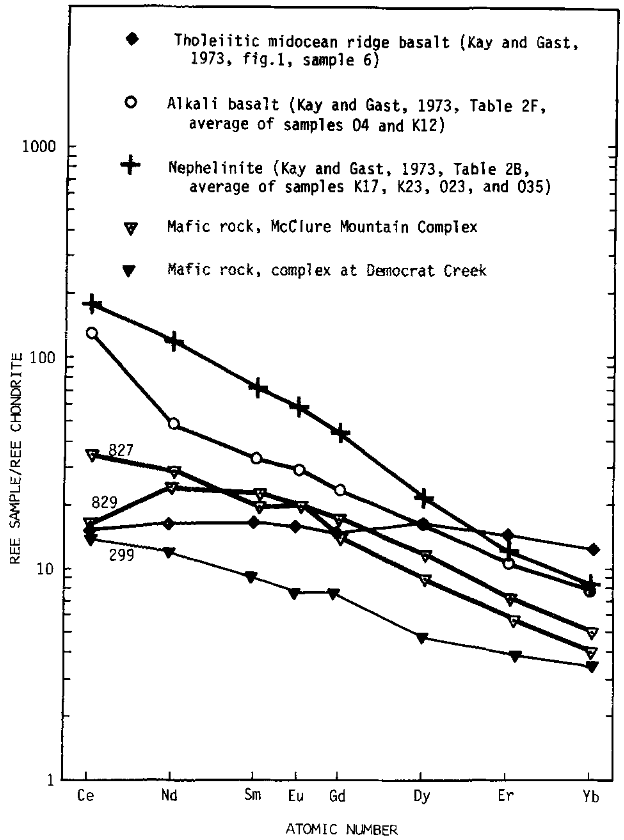

Fig. 7. Chondrite-normalized rare-earth-element data from mafic rocks from McClure Mountain Complex, complex at Democrat Creek, and other basalt samples (from Kay and Gast 1973)

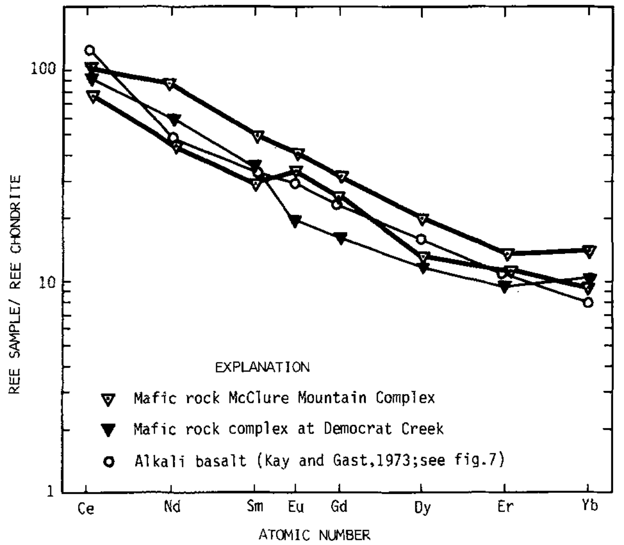

Fig. 8. Chondrite-normalized rare-earth-element data for liquids from which mafic rocks of McClure Mountain Complex and complex at Democrat Creek crystallized. Data are calculated from published crystal/liquid distribution coefficients

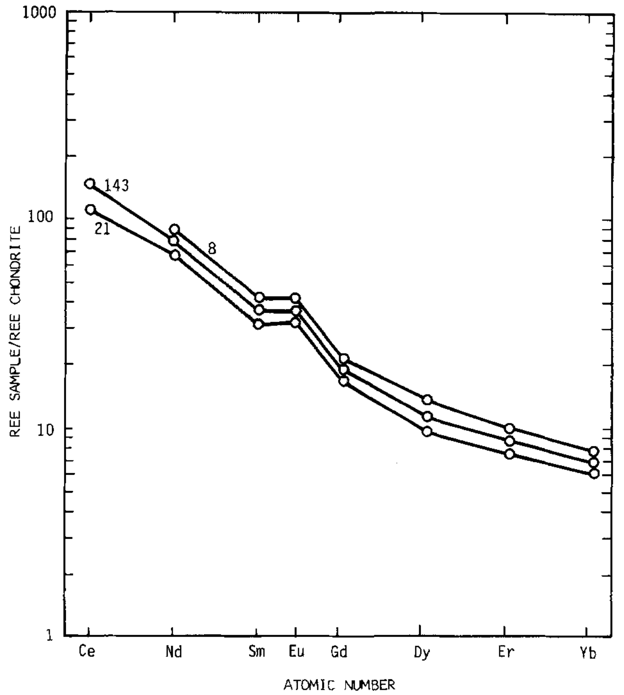

Fig. 9. Chondrite-normalized rare-earth-element data for hornblende-biotite syenite samples from the McClure Mountain Complex

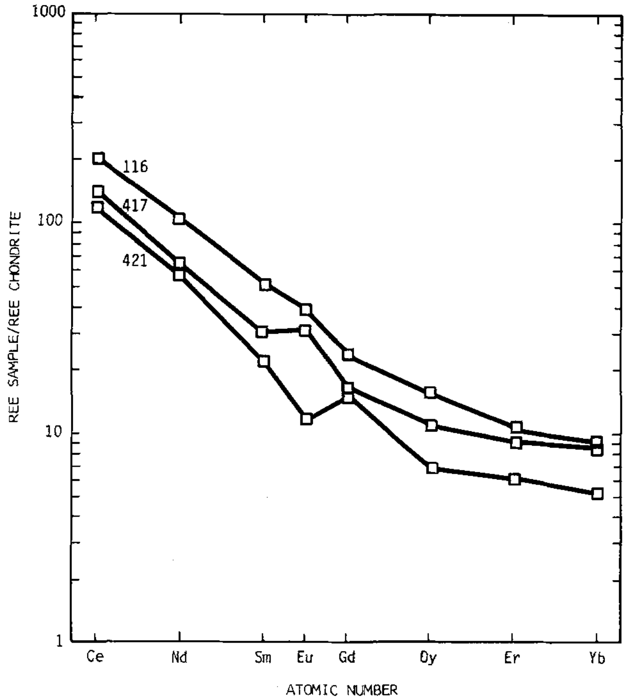

Fig. 10. Chondrite-normalized rare-earth-element data for nepheline-syenite samples from the McClure Mountain complex

The REE patterns of the hornblende-biotite syenites in the McClure Mountain Complex cover a fairly narrow range (Fig. 9). This small variation correlates with their small variation in modal mineralogy, normative mineralogy, and major-element abundances. Their small positive europium anomalies are due to the presence of sodic plagioclase. The REE patterns of nepheline syenites (Fig. 10) show small positive and negative europium anomalies, which again correlate respectively with more and less modal plagioclase. These patterns again point out the variability in modal mineralogy of these rocks. The REE patterns of the quartz syenites of the complex at Democrat Creek (Fig. 11) show considerable variation. One pattern has a fairly large negative europium anomaly that reflects corresponding low CaO

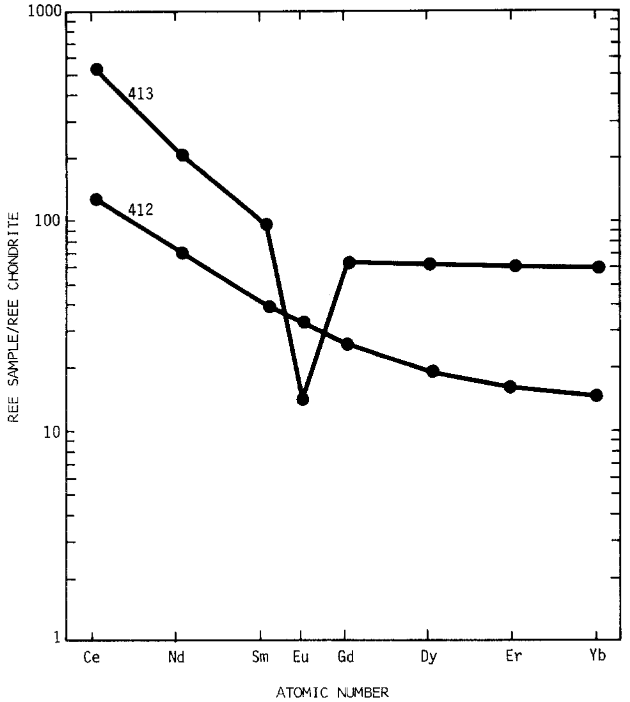

Fig. 11. Chondrite-normalized rare-earth-element data for quartz syenite samples from the complex at Democrat Creek

(<1.0 percent) and low Sr contents (34 parts per million). These data suggest that this rock crystallized from a melt from which plagioclase had been removed.

In summary, the REE data show that the Democrat Creek mafic rocks are slightly but significantly different from the McClure Mountain Complex cumulates. The liquids from which the Democrat Creek mafic rocks crystallized appear to have been less alkaline than the liquids from which the McClure Mountain Complex cumulates crystallized. The REE patterns for the syenites reflect the homogeneity and apparent lack of evidence of fractionation of the hornblende-biotite syenite, the variation in plagioclase content due to some fractionation in the nepheline syenites, and the strong evidence of fractionation due to loss of plagioclase in the quartz syenites at Democrat Creek.

Initial $^{87}Sr/^{86}Sr$ Ratios

Initial $^{87}Sr/^{86}Sr$ ratios for alkaline rocks of the Wet Mountains area range in value from 0.7025 to 0.7048 (Table 3). Uncertainty of these ratios is less than ±0.0001. Mafic-ultramafic rocks from the complex at Democrat Creek have initial values that range from 0.7025 to 0.7034, and one sample of quartz syenite has a value of 0.7032. Mafic-ultramafic rocks from the McClure Mountain Complex have values of 0.7044 and 0.7048, nepheline syenites range from 0.7036 to 0.7040, hornblende-biotite syenites range from 0.7041 to 0.7048, mafic nepheline-clinopyroxene rocks have values of 0.7036 and 0.7038, and six carbonatites, including four analyzed by Roden (1977), have values of 0.7036 to 0.7041. The Democrat Creek rocks appear to form a coherent group characterized by relatively low initial $^{87}Sr/^{86}Sr$ values (Fig. 12). At the McClure Mountain Complex, hornblende-biotite syenite has initial $^{87}Sr/^{86}Sr$ ratios similar to those of the mafic-ultramafic cumulate rocks but different from the nepheline syenites, mafic nepheline-clinopyroxene rocks, and the carbonatites, which constitute a separate group having similar values. The carbonatites that intrude the Gem Park Complex have ratios (Roden 1977) similar to carbonatites that intrude the McClure Mountain Complex.

A summary of strontium isotopic contents of alkaline rocks from Australia, Spain, and the western United States by Powell and Bell (1970) shows initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7034 to 0.7169. Some of the values are similar to those of oceanic basaltic rocks but values for rocks from the western United States with ratios ranging from 0.703 to 0.709 suggested to Powell and Bell that those rocks may have formed by partial melting of deep crustal rocks that have lower Rb/Sr ratios than those of average crust. Bell and Powell (1970) showed a range of initial $^{87}Sr/^{86}Sr$ ratios between 0.7029 and 0.7061 for carbonatites and alka-

Table 2. Rare-earth element abundances (in parts per million) in rocks from the complex at Democrat Creek and the McClure Mountain Complex

Sample number	Rock type	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb
Complex at Democrat Creek									
299	Gabbro	10.8	6.64	1.71	0.521	2.03	1.43	0.787	0.722
412	Quartz syenite	116	45.6	8.26	2.58	7.05	6.32	3.52	3.40
413	Quartz syenite	470	122	18.8	0.966	17.5	19.4	12.9	14.1
McClure Mountain Complex									
827	Plagioclase-clinopyroxene cumulate	25.0	15.7	3.71	1.36	5.28	2.71	1.20	0.860
829	Clinopyroxene-plagioclase cumulate	12.6	13.0	3.97	1.36	5.33	3.57	1.57	1.06
417	Nepheline syenite	108	37.8	5.74	2.34	4.34	3.52	1.98	1.90
116	Nepheline syenite	159	60.5	9.38	2.78	6.39	4.98	2.37	1.95
421	Nepheline syenite	104	32.7	4.58	0.871	4.02	2.30	1.32	1.19
143	Hornblende-biotite syenite	119	46.2	7.29	2.64	5.37	3.95	2.25	1.65
21	Hornblende-biotite syenite	104	39.0	6.11	2.54	4.67	3.34	1.69	1.41
8	Hornblende-biotite syenite	–	50.0	7.95	2.87	5.93	4.38	2.05	1.64
420	Red syenite dike	–	91.4	20.0	0.384	17.8	26.2	21.9	30.1
419	Carbonatite	3,308	1,346	177	51.1	–	116	51.3	38.5
419X	Carbonatite	648	220	34.9	10.3	–	22.9	13.2	13.9

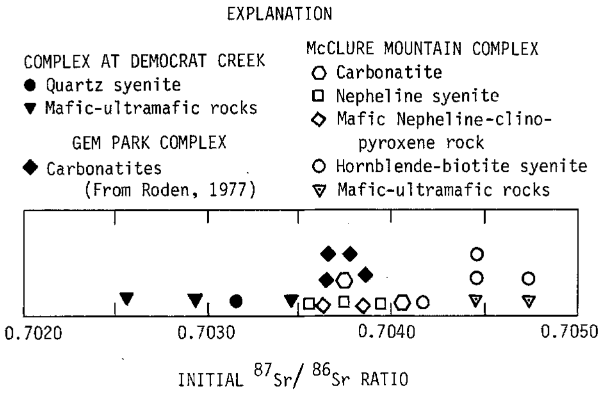

Fig. 12. Distribution of initial $^{87}Sr/^{86}Sr$ ratios for alkaline rocks of the Wet Mountains area, Colorado

line rocks from eastern Uganda. The carbonatites average 0.7034 and the associated alkaline rocks average 0.7045. These differences indicate to them that the rocks are not related solely by magmatic differentiation from a single parent magma. Compared with these data, the Wet Mountains rocks have a considerably narrower range in initial $^{87}Sr/^{86}Sr$ ratios, and the carbonatites have ratios comparable with those of nepheline syenite and mafic nepheline-clinopyroxene rock.

Initial $^{87}Sr/^{86}Sr$ ratios for carbonatites and plutonic rocks from the core of the Alnö alkaline complex, Sweden (Brueckner and Rex 1980), are similar to ratios of rocks from the McClure Mountain Complex and the complex at Democrat Creek. Brueckner and Rex suggest that these low initial $^{87}Sr/^{86}Sr$ ratios show that most of the Alnö magmas were not contaminated by crustal rocks (p. 116), but are characteristic of magmas having a primitive or mantle origin.

The relatively high initial $^{87}Sr/^{86}Sr$ ratios (0.7096 ± 0.0022) for agpaitic syenites at Ilimaussaq, Greenland (Blaxland and others 1976), are interpreted to show contamination by reaction with crustal wall rock. The same interpretation has been made for the Kangerdlugssuaq alkaline intrusion of East Greenland (Pankhurst and others 1976), certain complexes of the Gardar province of south Greenland (Blaxland and others 1978), shallow intrusions of syenite, trachyte, and phonolite in the Diablo Plateau of Texas and New Mexico (Barker and others 1977), and other localities (Powell and Bell 1974).

To summarize the initial $^{87}Sr/^{86}Sr$ ratios, samples from the complex at Democrat Creek have distinctly lower values than those from the McClure Mountain Complex. Within the McClure Mountain Complex, the mafic-ultramafic cumulates and the hornblende-biotite syenites have initial $^{87}Sr/^{86}Sr$ ratios similar to one another, and the nepheline syenites, mafic nepheline-clinopyroxene rocks, and carbonatites all have ratios similar to one another. These data suggest that at least three separate magmatic sources, originating in the upper mantle or lower crust, are responsible for the Wet Mountains alkaline rocks.

Rb/Sr Ratios

Rubidium and strontium concentrations and Rb/Sr ratios (Table 3) suggest additional petrologic aspects of these

Table 3. Rb and Sr, in parts per million, and Sr isotopic data for rocks of the complex at Democrat Creek and the McClure Mountain Complex

Sample number	Rock type	Rb	Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Initial $^{87}Sr/^{86}Sr$
Complex at Democrat Creek							
299	Gabbro	5.25	285	0.0184	0.0535	0.70290	0.70252
302	Gabbro	1.32	208	0.0063	0.0183	0.70309	0.70296
359	Pyroxenite	3.42	162	0.0211	0.0609	0.70384	0.70340
412	Quartz syenite	96.9	474	0.2044	0.5923	0.70746	0.70315
413	Quartz syenite	251	34.1	7.361	21.61	0.86059	–
414	Quartz syenite	174	26.1	6.667	19.54	0.84414	–
363	Quartz syenite	297	11.0	27.00	82.47	1.3146	–
369	Quartz syenite	233	10.4	22.40	67.84	1.1893	–
382	Quartz syenite	172	41.9	4.105	12.00	0.79088	–
McClure Mountain Complex							
827	Plagioclase-clinopyroxene cumulate	3.17	1,010	0.0031	0.0091	0.70484	0.70477
829	Clinopyroxene-plagioclase cumulate	1.69	370	0.0046	0.0132	0.70454	0.70444
417	Nepheline syenite	126	1,725	0.0730	0.2113	0.70519	0.70359
116	Nepheline syenite	134	2,939	0.0456	0.1318	0.70497	0.70397
4	Nepheline syenite	161	2,266	0.0711	0.1890	0.70515	0.70372
421	Nepheline syenite	194	103	1.883	5.470	0.74548	–
143	Hornblende-biotite syenite	94.6	542	0.1745	0.5048	0.70856	0.70475
8	Hornblende-biotite syenite	86.9	487	0.1784	0.5166	0.70831	0.70441
12	Hornblende-biotite syenite	98.4	530	0.1857	0.5371	0.70819	0.70413
21	Hornblende-biotite syenite	92.0	531	0.1733	0.5019	0.70821	0.70442
420	Red syenite dike	375	20.8	18.03	54.04	1.0914	–
419	Carbonatite	0.3	4,997	0.00006	0.00020	0.70378	0.70378
419X	Carbonatite	0.6	11,632	0.00008	0.00016	0.70406	0.70406
496	Mafic nepheline-clinopyroxene rock	97.1	1,582	0.0614	0.1775	0.70502	0.70367
498A	Mafic nepheline-clinopyroxene rock	78.6	1,370	0.0574	0.1660	0.70510	0.70384

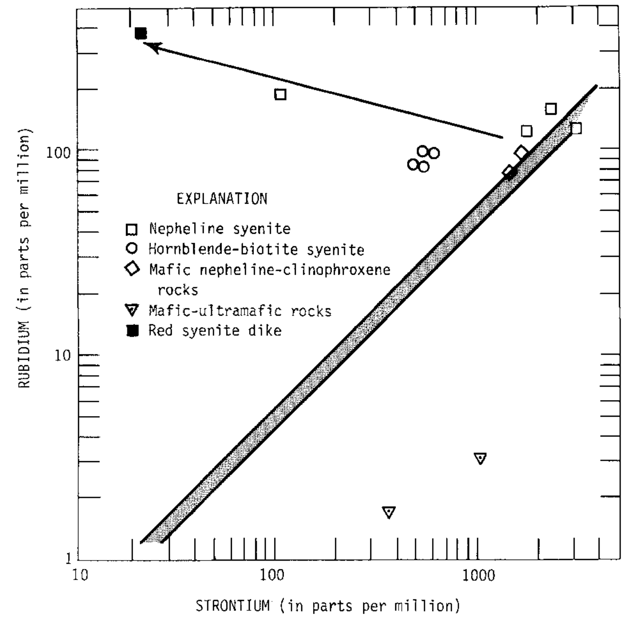

Fig. 13. Rubidium/strontium ratios of rocks from the McClure Mountain Complex. Patterned area represents approximate Rb/Sr ratios required to yield observed $^{87}Sr/^{86}Sr$ ratios

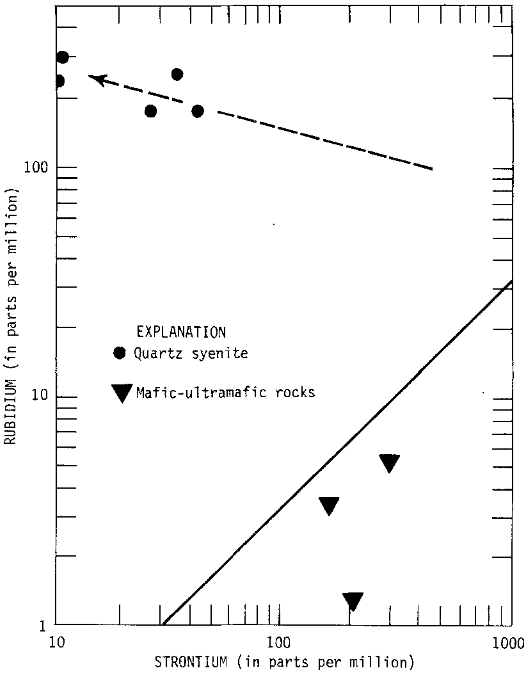

Fig. 14. Rubidium/strontium ratios of rocks from the complex at Democrat Creek. *Solid line* indicates approximate Rb/Sr ratios required to yield observed $^{87}Sr/^{86}Sr$ ratios. Dashed line indicates fractionation

rocks. The Rb contents of the mafic-ultramafic rocks from the McClure Mountain Complex and the complex at Democrat Creek are very low. Values range from 1.3 to 5.3 ppm. These low values are consistent with a cumulus origin for the mafic-ultramafic rocks at Democrat Creek as well as those from the McClure Mountain Complex because Rb tends to be depleted in plagioclase and pyroxene, the major minerals in these rocks, and is concentrated in the residual melt. The Rb/Sr ratios in quartz syenites in the complex at Democrat Creek are highly variable, ranging from 4.1 to 27. This wide range reflects the highly fractionated nature of these rocks. The Rb/Sr ratios of the hornblende-biotite syenites in the McClure Mountain Complex are very consistent, ranging from 0.17 to 0.18, and suggest that these rocks are not fractionated. The Rb/Sr ratios of nepheline syenite and mafic nepheline-clinopyroxene rocks also tend to be somewhat variable.

Figure 13 shows the distribution of Rb and Sr values for rocks of the McClure Mountain Complex. The diagonal field represents the approximate Rb/Sr ratios that would be required to produce the observed $^{87}Sr/^{86}Sr$ ratios for these rocks. The plotting of the mafic rocks below the Rb/Sr diagonal is a consequence of their cumulus origin – the liquid remaining after the removal of pyroxenes and plagioclase would contain proportionately more Rb than the resulting cumulus rocks. Figure 13 also shows that three of the nepheline syenites and the mafic nepheline-clinopyroxene rocks lie on or very near the Rb–Sr diagonal, indicating that the Rb/Sr ratios of these rocks are close to those of the material from which they were derived. The fourth nepheline syenite and a sample of red syenite lie on a line that is a trend of Rb–Sr values best developed by fractionation of nepheline-bearing rocks. The hornblende-biotite syenites homogeneously possess higher Rb/Sr ratios than their calculated parent and do not lie on the Rb–Sr diagonal.

Figure 14 shows the Rb/Sr ratios of rocks from the complex at Democrat Creek; the diagonal line represents the Rb/Sr ratios required to yield the observed $^{87}Sr/^{86}Sr$ ratios. The fact that the mafic-ultramafic rocks again plot below the Rb–Sr diagonal suggests a cumulus origin for these rocks also. No rocks have Rb/Sr ratios that plot near the Rb/Sr diagonal and thus a complicated process is required to increase the Rb/Sr ratios of the quartz syenites over the calculated parent magma – rocks reflecting this process have not been identified in this study if they are present. The distribution of Rb/Sr ratios in the quartz syenites shows a more or less progressive decrease in Sr which suggests fractionation through removal of plagioclase. This fractionation was also suggested by the REE data (Fig. 11).

Conclusions

The significant differences in age, mineralogy, chemistry, and initial $^{87}Sr/^{86}Sr$ ratios between the McClure Mountain Complex and the complex at Democrat Creek require fundamental genetic differences between the two complexes.

It is not known how much time might have been involved in the emplacement of the various rock types of the McClure Mountain Complex, but the differences in initial $^{87}Sr/^{86}Sr$ and minor element geochemistry require at least two source materials. The nepheline syenites and the carbonatites have similar initial $^{87}Sr/^{86}Sr$ rocks, and therefore they possibly were derived from the same source and their profound differences in chemistry and mineralogy are possibly due to some process such as liquid immiscibility.

Initial $^{87}Sr/^{86}Sr$ ratios of the hornblende-biotite syenites and the mafic-ultramafic rocks are similar but distinct from those of the nepheline syenites. A genetic relationship between the hornblende-biotite syenites and the mafic-ultramafic rocks is possible, but such a hypothesis cannot be tested rigorously because the necessary intermediate rocks

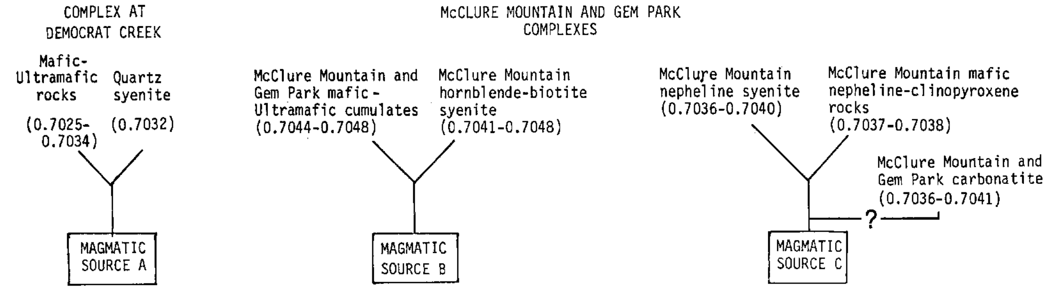

Fig. 15. Grouping according to their initial $^{87}Sr/^{86}Sr$ ratios (values in parentheses) of rock types of alkaline complexes in the Wet Mountains area, Colorado

are not available for study. It is known that the mafic-ultramafic rocks are cumulates. Their extremely mafic mineralogy and their trace-element geochemistry indicate that they are cumulates of a more mafic magma than the hornblende-biotite syenites. Possibly the hornblende-biotite syenites could have fractionated from this mafic magma. The relatively high Rb/Sr ratios of the hornblende-biotite syenites would be consistent with such a process, but the positive Eu anomalies are not.

The hornblende-biotite syenites have lower Sr contents than the nepheline syenites but higher initial $^{87}Sr/^{86}Sr$ ratios. We must therefore consider the possibility that the hornblende-biotite syenites were derived from the nepheline syenites with the addition of radiogenic ^{87}Sr from the Precambrian wall rocks. This hypothesis could only explain the data, however, if significant fractional crystallization, which lowered the Sr content, occurred together with the assimilation that raised the $^{87}Sr/^{86}Sr$ ratio. Fractional crystallization that would greatly lower the Sr content would have to involve plagioclase, and plagioclase removal would produce negative Eu anomalies, whereas the hornblende-biotite syenites actually have positive Eu anomalies.

The only mechanism, which we can envision for the genesis of the hornblende-biotite syenites, which would be compatible with their high Rb/Sr ratios and positive Eu anomalies, is that they represent essentially primary magmas formed by a partial melting process that left a residue rich in pyroxene. The pyroxene would retain significant Sr but does not have a relative preference for Eu.

It therefore seems that a minimum of three distinct source materials and a variety of geologic processes were necessary to produce the major alkaline rock types observed in the Wet Mountains. This complicated situation is diagrammed in Fig. 15. Only one source material is necessary for the rocks of the complex at Democrat Creek, and the various rock types there might be fairly simply related as products of fractional crystallization. The hornblende-biotite syenites of the McClure Mountain Complex and the mafic-ultramafic rocks of the McClure Mountain and Gem Park Complexes may have ultimately been derived from the same source material, but mafic-ultramafic rocks are cumulates from a basaltic magma that was probably not directly related to the hornblende-biotite syenite magma. Similarly the nepheline syenites and the carbonatites might have been derived from the same source material.

A suggestion for the possible nature of these respective source materials might be that they were rocks differing in basaltic compositions. A gabbro of tholeiitic composition would be a suitable source material for the rocks of the complex at Democrat Creek. A more alkaline gabbro might be a suitable source for the hornblende-biotite syenites of the McClure Mountain Complex, whereas a gabbro of nepheline basalt composition may have been the source of the nepheline syenites. Although this narrative is admittedly speculative, some history at least this complicated is necessary to account for such a diversity of rocks so closely related spatially.

References

Armbrustmacher TJ (1976) Thorium deposits in the Wet Mountains area, Fremont and Custer Counties, Colorado. US Geol Surv Open-File Rept 76–284: 18 pp

Armbrustmacher TJ (1979) Replacement and primary magmatic carbonatites from the Wet Mountains area, Fremont and Custer Counties, Colorado. Economic Geology 74: 888–901

Barker DS, Long LE, Hoops GK, Hodges FN (1977) Petrology and Rb–Sr isotope geochemistry of intrusions in the Diablo Plateau, northern Trans-Pecos magmatic province, Texas and New Mexico. Geol Soc Am Bull 88: 1437–1446

Bell, Keith, Powell, JL (1970) Strontium isotopic studies of alkalic rocks: The alkalic complexes of eastern Uganda. Geol Soc Am Bull 81: 3481–3490

Blaxland AB, van Breemen O, Emeleus CH, Anderson JG (1978) Age and origin of the major syenite centers in the Gardar province of south Greenland: Rb–Sr studies. Geol Soc Am Bull 89: 231–244

Blaxland AB, van Breemen O, Steenfelt A (1976) Age and origin of agpaitic magmatism at Ilimaussaq, south Greenland: Rb–Sr study. Lithos 9: 31–38

Brock MR, Singewald QD (1968) Geologic map of the Mount Tyndall quadrangle, Custer County, Colorado. US Geol Surv Geol Quadr Map GQ-596

Christman RA, Brock MR, Pearson RC, Singewald QD (1954) Wet Mountains, Colorado, thorium investigations, 1952–1954. US Geol Surv Trace Elements Investigations Rep 354: 52 pp

Christman RA, Brock MR, Pearson RC, Singewald WD (1959) Geology and thorium deposits of the Wet Mountains, Colorado: A progress report. US Geol Surv Bull 1072-H: 491–535

Currie KL (1976) The alkaline rocks of Canada. Geol Surv Canada Bull 239: 228 pp

Eby GN (1975) Abundance and distribution of the rare-earth elements and yttrium in the rocks and minerals of the Oka carbonatite complex, Quebec. Geochim Cosmochim Acta 39: 597–620

Fenton MD, Faure G (1970) Rb–Sr whole-rock age determinations of the Iron Hill and McClure Mountain carbonatite-alkalic complexes, Colorado. Mountain Geol 7: 269–275

Gerasimovsky VI (1974) Trace elements in selected groups of alkaline rocks. In: H Sorensen (ed) The alkaline rocks, pp 402–412. New York, John Wiley and Sons

Heinrich EW (1966) The geology of carbonatites. Chicago, Rand McNally and Company, 555 pp

Heinrich EW, Alexander DH (1979) Geology and petrogenesis of the dike retinue of the McClure Mountain mafic-alkalic complex, Colorado, USA [abstr]. Geological Association of Canada-Mineralogical Association of Canada annual meeting, Program with Abstracts 4:56

Heinrich EW, Dahlem DH (1966) Carbonatites and alkalic rocks of the Arkansas River area, Fremont County, Colorado. In: PRJ Naidu (ed) International Mineral Assoc. volume, pp 37–44. Mineralogical Society of India

Heinrich EW, Dahlem DH (1967) Carbonatites and alkalic rocks of the Arkansas River area, Fremont County, Colorado. 4. The Pinon Peak breccia pipes. Am Mineral 52:817–831

Heinrich EW, Dahlem DH (1969) Dikes of the McClure Mountain-Iron Mountain alkalic complex. Fremont County, Colorado, USA. Bull Volcanol 33:960–976

Jackson ED (1961) Primary textures and mineral associations in the ultramafic zone of the Stillwater Complex, Montana. US Geol Surv Prof Pap 358:106 pp

Jaffe HW, Gottfried D, Waring CL, Worthing HW (1959) Lead-alpha age determinations of accessory minerals of igneous rocks (1953–1957). US Geol Surv Bull 1097-B:65–148

Kay RW, Gast PW (1973) The rare earth content and origin of alkali-rock basalts. J Geol 81:653–682

Larson ES Jr (1942) Alkalic rocks at Iron Hill, Gunnison County, Colorado. US Geol Surv Prof Pap 197-A:1–64

Mitchell RH, Brunfelt AO (1975) Rare earth element geochemistry of the Fen alkaline complex, Norway. Contrib Mineral Petrol 52:247–259

Moller P, Morteani G, Schley F (1980) Discussion of REE distribution patterns of carbonatites and alkalic rocks. Lithos 13:171–179

Olson JC, Marvin RF, Parker RL, Mehnert HH (1977) Age and tectonic setting of lower Paleozoic alkalic and mafic rocks, carbonatites, and thorium veins in south-central Colorado. US Geol Surv J Res 5:673–687

Parker RL, Adams JW, Hildebrand FA (1962) A rare sodium niobate mineral from Colorado. In: Geological Survey research 1962. US Geol Surv Prof Pap 450-C:C4–C6

Parker RL, Hildebrand FA (1963) Preliminary report on alkalic intrusive rocks in the northern Wet Mountains, Colorado. In: Geological Survey research 1962. US Surv Prof Pap 450-E:E8–E10

Parker RL, Sharp WN (1970) Mafic-ultramafic igneous rocks and associated carbonatites of the Gem Park Complex, Custer and Fremont Counties, Colorado. US Geol Surv Prof Pap 649:24 pp

Powell JL, Bell K (1970) Strontium isotopic studies of alkalic rocks: Localities from Australia, Spain and the western United States. Contrib Mineral Petrol 27:1–10

Powell JL, Bell K (1974) Isotopic composition of strontium in alkalic rocks. In: H. Sorensen (ed) The alkaline rocks, pp 412–423, New York, John Wiley and Sons

Rock NMS (1976) The role of CO_2 in alkali rock genesis. Geol Mag 113:97–113

Roden MK (1977) Rare earth element distributions and strontium isotope data from the Gem Park igneous complex, Colorado. Manhattan, Kansas State University, unpublished MS thesis, 103 pp

Scott GR, Taylor RB (1975) Post-Paleocene Tertiary rocks and Quaternary volcanic ash of the Wet Mountains Valley, Colorado. US Geol Surv Prof Pap 868:15 pp

Scott GR, Taylor RB, Epis RC, Wobus RA (1976) Geologic map of the Pueblo 1° × 2° quadrangle, south-central Colorado. US Geol Surv Miscellaneous Field Studies Map MF-775

Shawe DR, Parker RL (1967) Mafic-ultramafic layered intrusion at Iron Mountain, Fremont County, Colorado, US Geol Surv Bull 1251-A:A1–A28

Simmons EC, Hedge CE (1978) Minor-element and Sr-isotope geochemistry of Tertiary stocks, Colorado Mineral belt. Contrib Mineral Petrol 67:379–396

Singewald QD, Brock MR (1956) Thorium deposits in the Wet Mountains, Colorado. US Geological Survey Professional Paper 300, 581–585

Sorensen H (1974) Introduction. In: H. Sorensen (ed) The alkaline rocks, pp 15–22. New York, John Wiley and Sons

Taylor RB, Scott GR, Wobus RA, Epis RC (1975a) Reconnaissance geologic map of the Cotopaxi 15-minute quadrangle, Fremont and Custer Counties, Colorado. US Geol Surv Miscellaneous Investigations Map I-900

Taylor RB, Scott GR, Wobus RA, Epis RC (1975b) Reconnaissance geologic map of the Royal Gorge quadrangle, Fremont and Custer Counties, Colorado. US Geol Surv Miscellaneous Investigations Map I-869

Wilkinson JFG (1974) The mineralogy and petrography of alkali basaltic rocks. In: Sorensen H (ed) The alkaline rocks, pp 67–95. New York, John Wiley and Sons

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