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# Geochemistry and tectonic setting of Paleoproterozoic metavolcanic rocks of the southern Front Range, lower Arkansas River Canyon and northern Wet Mountains, central Colorado

**Reinhard A. Wobus[1], Martha J. Folley[2], Katherine M. Wearn[3], and Jeffrey B. Noblett[4]**

[1]*Department of Geosciences, Williams College, Williamstown, MA 01267, U.S.A.*

[2]*USA CRREL RS/GIS Center, 72 Lyme Road, Hanover, NH 03755, U.S.A.*

[3]*Department of Geological Sciences, University of Oregon, Eugene, OR 97403-4702, U.S.A.*

[4]*Department of Geology, Colorado College, Colorado Springs, CO 80903, U.S.A.*

## ABSTRACT

Across a 5000-km² area of central Colorado, previously unstudied Paleoproterozoic metabasalts (amphibolites) and metarhyolites (felsic gneisses) comprise a bimodal metavolcanic association within a dominantly metasedimentary terrain. Extending southward from about 39° N latitude in the southern Front Range to about 38° 15' N latitude in the Wet Mountains, and from the mountain front westward to the Wet Mountain Valley and Pleasant Valley fault system, this area includes the exceptional exposures within the lower Arkansas River Canyon from Howard downstream to Canon City. Regional metamorphism from garnet to sillimanite grade, pervasive deformation, and intrusion by three generations of Proterozoic plutons have largely obscured original stratigraphic relationships and primary structures within these metamorphic basement rocks, although a few pyroclastic features persist locally within the felsic members. These metavolcanic rocks are compositionally similar to the much better preserved bimodal section in the Salida area, dated at 1728 ±6 Ma by Bickford (1986), which emerges from beneath Paleozoic cover rocks about 15 km beyond the western edge of the area of this report.

Geochemical studies of 45 samples (30 amphibolites and 15 felsic gneisses) delineate two groups of metavolcanic rocks ranging in silica content from 45–55% in one group and from 65 to almost 80% in the other. Along a 100-km transect from north to south, metavolcanic rocks of the lower-silica group (amphibolites) show an increase in total alkalies (from 2% to 5–6%) and large ion lithophile trace elements as well as an increase in degree of enrichment in light rare earth elements (from $La_N/Lu_N < 2$ to $La_N/Lu_N \sim 5$). Rocks with higher silica content (felsic metavolcanic rocks) occur mostly in the Arkansas Canyon area and contain 6–8% total alkalies; they show strong fractionation between light and heavy rare earth elements with moderate to pronounced negative europium anomalies.

Tectonic discriminant diagrams using relatively immobile high-field-strength elements indicate volcanic arc settings for both mafic and felsic populations. Metavolcanic rocks from the northern Wet Mountains and Arkansas Canyon suggest a mature arc environment, possibly on an expanding continental margin. The isolated metabasalts to the north in the southern Front Range, where no felsic metavolcanic rocks have been identified, are more primitive island-arc tholeiites; they may represent pyroclastic rocks with a source beyond the study area.

These new data from a wide area of central Colorado reinforce results from the well-studied Paleoproterozoic bimodal arc assemblages to the west near Salida and Gunnison. They also allow the extension across a wider geographic area of previous tectonic models for the Paleoproterozoic evolution of the Colorado province (as defined by Bickford et al., 1986). These models (Condie, 1986; Reed et al., 1987; Karlstrom et al., 1987) portray the rapid addition of juvenile crust to the southern margin of the Wyoming province by accretion of individual volcanic arcs or larger, previously amalgamated arc terranes, resulting in the southward expansion of the craton by about 1300 km from 1800–1650 Ma.

**KEY WORDS:** Paleoproterozoic, central Colorado, bimodal metavolcanic rocks, tectonic setting, volcanic arcs.

## INTRODUCTION

The north-trending Front Range and Wet Mountain uplifts of central Colorado, and the east-west Arkansas River Canyon that separates them, include one of the largest continuous exposures of Proterozoic crystalline rocks in the Colorado province. The oldest of these basement rocks are metasedimentary and metavolcanic schists and gneisses which predate plutons of the Routt plutonic suite (Tweto, 1987), products of the earliest of three major Proterozoic intrusive episodes within the province (~1700 Ma). The Paleoproterozoic layered rocks are dominated by metasedimentary biotitic gneisses in an east–west belt through central Colorado, including most of the central and southern Front Range, whereas felsic and hornblendic gneisses largely derived from volcanic protoliths become more prominent to the north and south (Tweto, 1987).

Geochemical studies of metavolcanic rocks in the northern Front Range and southeastern Wyoming as well as in the Salida and Gunnison areas of central Colorado have led to a tectonic model of accreted volcanic arcs that were progressively added to the southern margin of the Archean Wyoming craton from about 1760–1650 Ma (e.g., reports summarized in Premo and Fanning, 2000). However, the metavolcanic rocks exposed within a 5000-km$^2$ (1800 mi$^2$) area in the southern Front Range, lower Arkansas River Canyon east of the Pleasant Valley fault, and northernmost Wet Mountains were not included in these studies. Some of these rocks had not been recognized as being of metavolcanic origin, because metamorphism, recrystallization, and deformation obscures many, but not all, of the primary volcanic features so well preserved in some other metavolcanic sections of Colorado, especially those near Gunnison and Salida (Boardman, 1976; Bickford and Boardman, 1984). In this report we provide the first petrologic and geochemical data for the generally unstudied metavolcanic rocks of this broad area and interpret them in the light of current tectonic models.

## GEOLOGIC SETTING

The Paleoproterozoic rocks of the study area comprise a thick series of metasedimentary and metavolcanic layered rocks and granitic plutons representing three extended episodes of intrusion between approximately 1700–1000 Ma (Fig. 1). These basement rocks appear today in the cores of fault-bounded uplifts of the Front Range and Wet Mountains produced during Laramide contraction and Neogene extension. The most continuous faults generally strike northwest and include, from east to west across the area, the Ute Pass, Currant Creek-Ilse, and Pleasant Valley-Westcliffe fault systems. Relief in the area is significant, ranging from 4300 m (14,110 ft) at the summit of Pikes Peak to about 1600 m (5400 ft) where the Arkansas River enters the Canon City embayment.

The layered metamorphic rocks in the southern Front Range at the northern edge of the study area (~39° N latitude) are dominantly biotitic and sillimanitic schists and gneisses derived from pelitic sedimentary protoliths. Calc-silicate gneiss, quartzite, and amphibolite are scarce, occurring only as thin concordant interlayers. Migmatites interpreted as anatectic, along with the common association of sillimanite and potash feldspar in metapelites, indicate regional metamorphic conditions of the upper amphibolite facies (Hawley and Wobus, 1977).

To the south and southwest, as noted by Tweto (1987), the metamorphic framework includes an increasing volume of metavolcanic rocks. In the northern and central Wet Mountains, metamorphic rocks are also dominated by biotite and quartzofeldspathic paragneisses which are locally

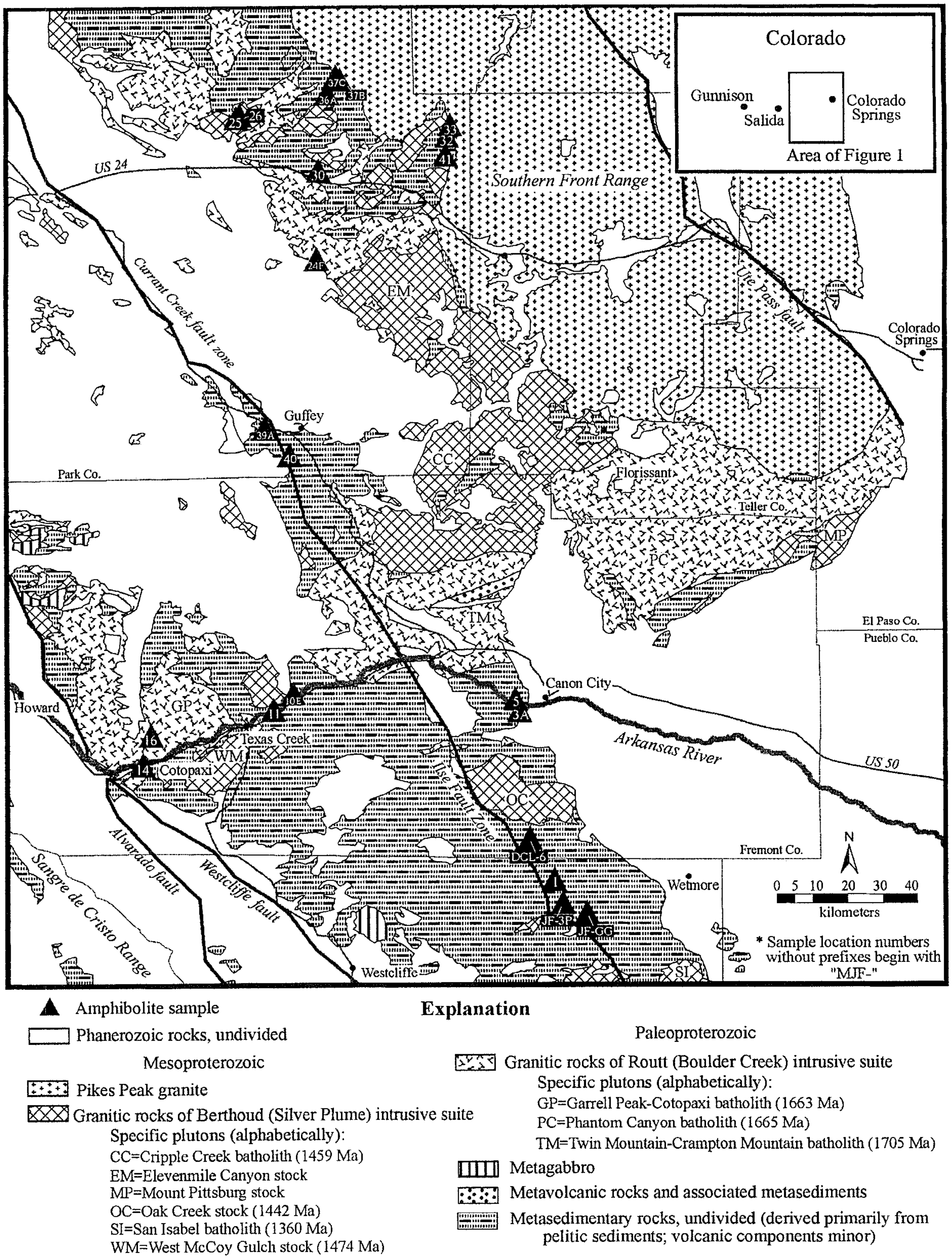


**Figure 1.** Regional geologic map of southern Front Range, Arkansas Canyon, and northern Wet Mountains, central Colorado (after Tweto, 1979), showing sample localities for mafic metavolcanic rocks (amphibolites) within area of this report.

sillimanite-bearing and migmatitic, but up to 20% of the section is amphibolite (Noblett et al., 1987, 1997). In the lower Arkansas River Canyon upstream from Canon City, interlayered felsic gneisses and amphibolites become progressively more common. These rocks appear to represent a bimodal metavolcanic association interspersed with feldspathic biotite gneisses and metapelites, locally cordierite- and/or sillimanite-bearing, where protoliths likely accumulated in basins along an active continental margin (Siddoway et al., 2000). Near the western edge of the study area just east of the Pleasant Valley fault, metamorphic grade and degree of deformation are slightly lower, allowing local preservation of primary volcanic and sedimentary features. This trend toward better preservation of original structures continues within the well-studied bimodal metavolcanic association northeast of Salida (Boardman, 1976, 1986), about 16 km (10 mi) west of the present study area and separated from it by a thick section of Paleozoic cover rocks.

Stratigraphic relations among the layered rocks within the broad area of this study can rarely be determined, and then only on a very local scale, due to the degree of deformation, the obliteration of most primary structures during metamorphic recrystallization, and the interruption of vertical and along-strike continuity by numerous plutons. No radiometric ages have been obtained for the metavolcanic rocks within this area. Bickford (1986) reported a zircon age of 1728 $\pm$6 Ma for a metadacite in the Salida section and an age of 1713 $\pm$14 Ma for a metarhyolite southwest of Howard and just beyond the western edge of the study area. However, some constraints on depositional ages are present. The oldest rocks anywhere in the Proterozoic Colorado province are ~1800-Ma metavolcanic rocks of the Green Mountain magmatic arc of southernmost Wyoming, with a gradual younging of arc-volcanic ages to the south through Colorado (Reed et al., 1987; Premo and Fanning, 2000). Minimum ages for the metamorphic sections are provided by intrusive rocks of the Routt plutonic suite, ~1700 Ma, many of which appear to be syntectonic with the most pervasive period of regional metamorphism and deformation within the Colorado province.

Plutons within the study area are mostly granitic (tonalite to granite) and represent three intrusive generations as recognized through much of central Colorado. The earliest plutons are I-type calc-alkaline rocks of the Routt plutonic series. They were emplaced during or near the end of the regional metamorphic episode and typically bear the imprint of that deformation. They range in age from ~1735 Ma in northern Colorado to ~1650 Ma, younging from north to south (Reed et al., 1987). Within the present study area, dated plutons of this earliest group include the Twin Mountain-Crampton Mountain batholith (1705 $\pm$8 Ma) and Phantom Canyon batholith (1665 $\pm$5 Ma) of the southernmost Front Range, and the Garrell Peak batholith (1663 $\pm$4 Ma) of the Arkansas Canyon just east of the Pleasant Valley fault (Bickford et al., 1989).

Plutons of the second Proterozoic intrusive episode (Berthoud plutonic series of Tweto, 1987; "Silver Plume intrusive event" in earlier literature) are metaluminous to peraluminous, commonly two-mica granites that typically either lack internal foliation or have a primary flow foliation subparallel to the margins of the pluton. Once considered anorogenic, their emplacement nevertheless imposed a local thermal or hydrothermal metamorphism on their wall rocks and in some cases reoriented the earlier regional metamorphic fabric within the older rocks (Hawley and Wobus, 1977; Siddoway et al., 2000). Dated plutons of this generation within the present study area are the Cripple Creek batholith, Oak Creek stock, and granite of West McCoy Gulch; they range in age from 1474–1442 Ma (Bickford et al., 1989).

The youngest plutons of central Colorado are the batholith of A-type Pikes Peak granite and its associated granitic to alkaline stocks in the southern Front Range. Dated at ~1080 Ma, this group of plutons is spatially, temporally, and geochemically unique within the Colorado province and was likely emplaced during a period of crustal extension, perhaps plume-induced (Smith et al., 1999).

## THIS STUDY

### Introduction

Many of the metavolcanic rocks which were collected for this study in the southern Front Range and lower Arkansas Canyon were first identified by the senior author during the course of regional geologic mapping for the U.S. Geological Survey (Taylor et al., 1975; Hawley and Wobus, 1977; Scott et al., 1978). Along with amphibolites of the northern Wet Mountains described by Noblett et al. (1987), they were sampled and analyzed petrographically and geochemically by participants in the Keck Geology Consortium (Folley, 1997; Wearn, 1998; Ekdahl, 1998; Szramek, 1998). The metavolcanic rocks are bimodal; no andesitic rocks have been found.

## Petrology and Petrography

### *Mafic Metavolcanic Rocks*

Metavolcanic rocks with basaltic protoliths now occur as amphibolites that are typically interlayered with other rock types in this generally high-grade metamorphic terrane. Samples from twenty amphibolite localities throughout the field area were chosen on the basis of their likely igneous protoliths and lack of alteration (Fig. 1). Amphibolites interlayered with calc-silicate gneisses (of presumed sedimentary protolith) were not included in this study, and most of those in close proximity to granitic or pegmatitic intrusions were also excluded.

Most of the amphibolites that were sampled in the southern Front Range form concordant layers in sharp contact with the far more voluminous pelitic schists and gneisses. They range in thickness from 1–10 m at most localities to an extreme example nearly 1 kilometer thick near the northern edge of the study area (Hawley and Wobus, 1977). Wahlstrom and Kim (1959) found that similar amphibolites in the northern Front Range are basaltic in composition and proposed that they were derived from tuffs, although no primary pyroclastic features were found. Such features are also absent at the localities studied for the present report. Amphibolites in the Buckhorn Creek shear zone of the northern Front Range were found to have tholeiitic compositions, and some contain relic pillow structures (Cavosie et al., 1999).

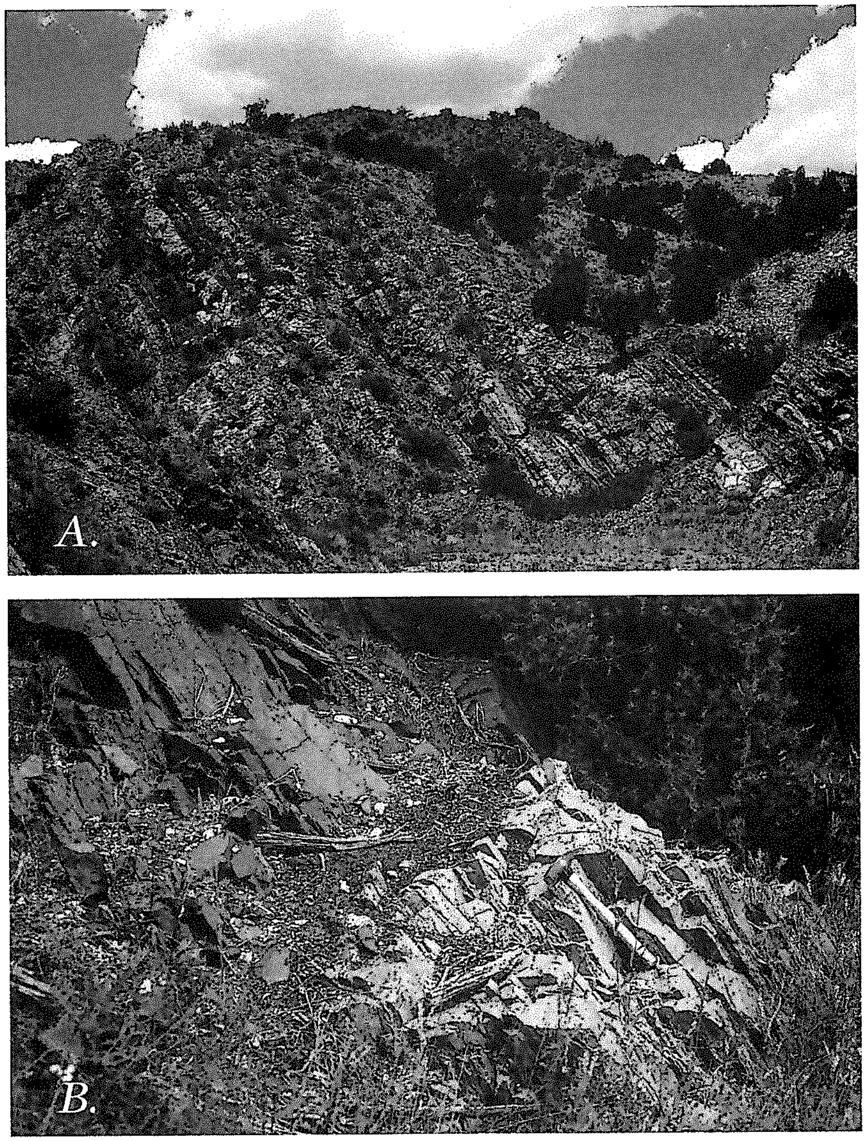


**Figure 2.** ***A***, Interlayered amphibolites (metabasalts) and felsic gneisses; roadcut exposure along Colorado Highway 96 at MacKenzie Junction, northern Wet Mountains (Hardscrabble Mountain 7 1/2-minute quadrangle). ***B***, Sharp conformable contact between amphibolite (metabasalt) and felsic metatuff in southern Five Points Gulch approximately 5.5 km east of village of Texas Creek, Colorado (Echo 7 1/2-minute quadrangle).

In the Arkansas Canyon, amphibolites are typically interlayered with felsic gneisses that are compositionally rhyolites and that locally retain primary pyroclastic fabrics. Associated rocks with sedimentary protoliths are relatively less abundant at the latitude of the canyon than farther north. Amphibolites in the northern Wet Mountains have the most complex lithologic relationships. Some form well-layered sequences (Fig. 2A), but others are deformed within felsic gneiss sections or occur as large xenoliths within granitic intrusions. These felsic gneisses are too highly recrystallized, however, to retain any primary structures, and some are migmatitic.

At hand-specimen scale most amphibolites are wholly dark or salt-and-pepper textured, fine- to medium-grained, and variably foliated. The least foliated varieties were preferentially selected during sample collection as the most likely to have igneous protoliths. Some varieties are

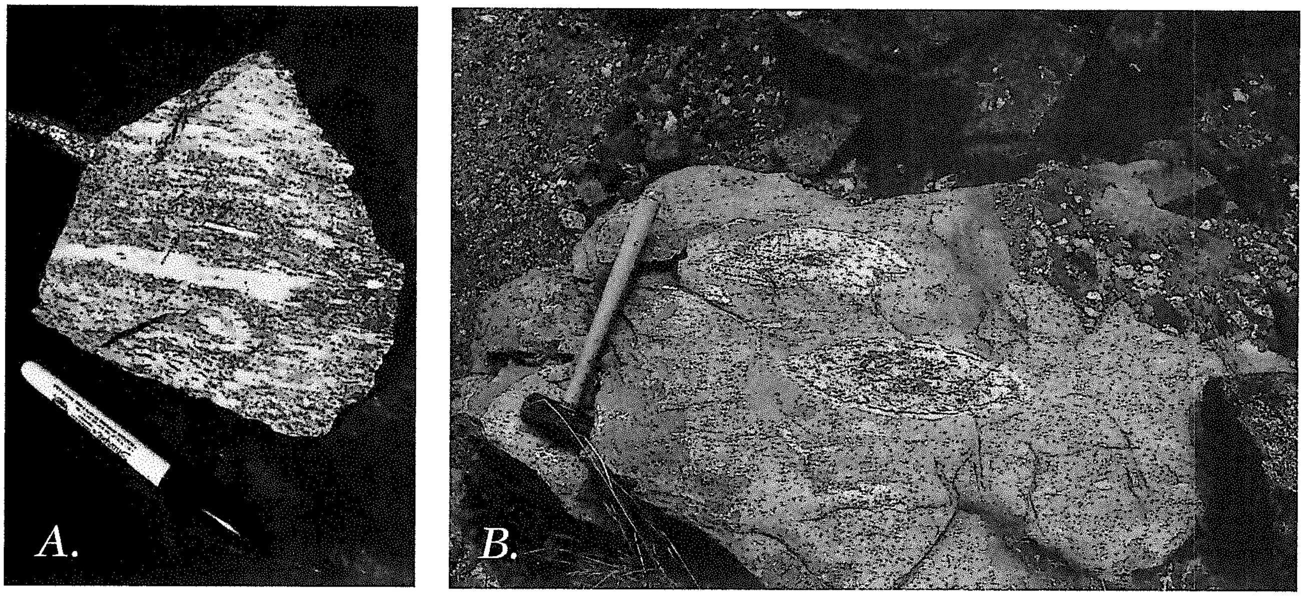


**Figure 3.** ***A***, Relict eutaxitic fabric (flattened pumice fragments) in felsic metatuff from upper Sand Gulch, approximately 0.7 km west of summit of Copper Mountain (Howard 7 1/2-minute quadrangle). ***B***, Possible volcanic bombs in aphyric groundmass of felsic metatuff, Texas Creek Gulch approximately 5 km NNW of Texas Creek (Echo 7 1/2-minute quadrangle).

porphyroblastic, with hornblende and/or plagioclase porphyroblasts that locally have been stretched within the plane of foliation. A few contain minor quartz. In thin section, they typically contain subequal amounts of hornblende and intermediate plagioclase (andesine or labradorite) in a wholly recrystallized crystalloblastic fabric. The amount of quartz ranges from zero to 20%; samples containing the higher amounts of quartz as well as diopside and/or epidote were interpreted as metasedimentary and were not included in the geochemical studies. Biotite, where present, appears secondary, as does some quartz, based on their habit as anhedral, interstitial grains. Accessory minerals are dominated by Fe- and Fe-Ti oxides; sphene is present in a few samples, with apatite still less common. Among the porphyroblastic varieties are several that show clusters of non-aligned coarser grained hornblende that resemble a glomeroporphyritic fabric in igneous rocks. Rarely, samples retain a relict intergranular fabric most indicative of an igneous protolith.

*Felsic Metavolcanic Rocks*

Felsic gneisses that were clearly derived from volcanic protoliths can be recognized in the field area only in the vicinity of the Arkansas Canyon. Rocks of similar mineral content to the north (Front Range) and south (Wet Mountains) are too highly recrystallized to preserve any primary volcanic structures or textures; some have even been partially melted and are migmatitic. In the lower Arkansas Canyon upstream from Royal Gorge, felsic gneisses (compositionally rhyolites) and amphibolites (compositionally basalts) are conformably interlayered on a scale of meters to tens of meters, with sharp contacts between the two rock types (Fig. 2B). Though metamorphosed from garnet to sillimanite grade (as indicated by pelitic metasedimentary interlayers), a few primary pyroclastic textures still remain in the felsic components, notably relict pumice fragments (fiammé) as shown in Figure 3A, lithic fragments, and remnant volcanic bombs up to 20 cm in length (Fig. 3B).

At the western edge of the study area, between the Garrell Peak granite batholith and Pleasant Valley fault (especially northeast of Howard in Sand Gulch and its tributary valleys), metamorphic grade is lower and degree of deformation is less than elsewhere in the study area. Felsic and mafic metavolcanic rocks and a few thin gabbroic sills here are interlayered with metasedimentary rocks dominated by micaceous quartzites and phyllites; some siliceous metasedimentary rocks (with probable volcaniclastic protoliths) even preserve graded beds and ripple marks (Szramek, 1998).

In this same section, in the valley of Little Badger Creek

**Figure 4.** Magma mingling locality, showing metabasalt enclaves in felsic groundmass; in valley of Little Badger Creek 0.5 km east of power line crossing and ~5 km north of Howard (Howard 7 1/2-minute quadrangle).

approximately 0.5 km east of the powerline crossing and about 5 km (3 mi) north of Howard, a small pluton ($<1$ km$^2$) contains numerous small mafic enclaves in a felsic host (Fig.4). The lobate or cuspate shape of the mafic enclaves, which comprise up to 80% of the total rock, suggests that mafic magma may have commingled with felsic magma, indicating that magmas of both compositions existed contemporaneously (Ekdahl, 1998). The mafic enclaves have been metamorphosed to amphibolite. The pluton itself is cut by the Garrell Peak batholith (1663 $\pm$4 Ma), so the age of the bimodal magmas in this small pluton is similar to that of the felsic and mafic metavolcanic rocks sampled throughout the field area.

Samples of felsic metavolcanic rocks were collected along a 50-km east–west transect of the Arkansas River and its tributary gulches and intervening ridges between Royal Gorge and Howard (Fig. 5). All of the felsic rocks are light colored (buff, gray, or pink) and thinly banded, with minor biotite defining foliation planes <1 mm thick. Many are fine grained and equigranular, but some have ellipsoidal clots of micas, K-feldspar, or quartz up to 1 cm long. A few preserve larger-scale pyroclastic features, as mentioned under field descriptions.

Petrographically, the felsic samples are a mosaic of very fine-grained anhedral quartz, microcline, oligoclase-andesine, and minor muscovite and/or biotite. Some show lenses of quartz and feldspar, best seen under uncrossed polars, that are interpreted as flattened and recrystallized pumice fragments. A few contain clusters of coarser quartz and feldspar grains that may represent lithic fragments incorporated within a pyroclastic deposit. Most samples are too fine grained for detailed modal analysis, but quartz and feldspar typically appear to comprise more than 90 per cent of these rocks.

# GEOCHEMISTRY

## Introduction

Analyses of 36 samples of metavolcanic rocks (21 mafic, 15 felsic) are reported in Tables 1 and 2. The samples were chosen to represent the least altered rocks thought to be derived from igneous protoliths and to provide the widest possible geographic coverage. All samples were crushed and pulverized in an alumina shatterbox dish at Williams College. Major and minor element

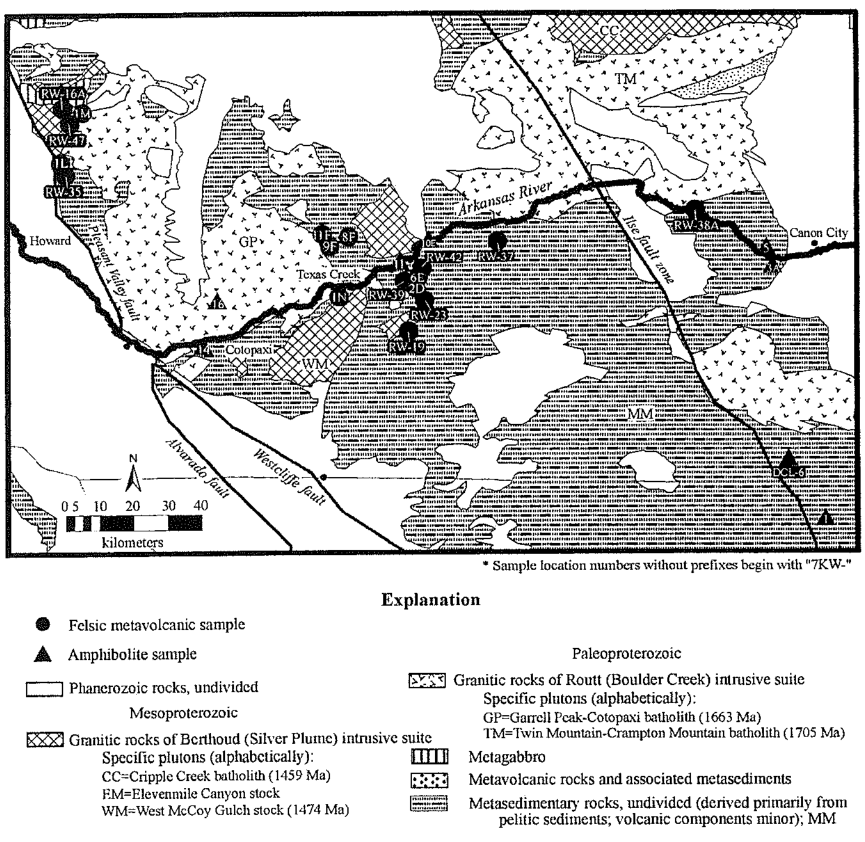


**Figure 5.** Map showing sample localities of felsic and mafic metavolcanic rocks in lower Arkansas River Canyon area.

determinations for all samples were obtained on fused discs by X-ray fluorescence (XRF) at the University of Massachusetts in Amherst. XRF trace element concentrations (for Sr, Rb, Ba, Nb, Zr, Y, Cr, Co, Ni, Zn, V, and Ga) for 34 samples were obtained from Activation Laboratories, Ltd., in Ontario, Canada. The reactor lab at Oregon State University was used for instrumental neutron activation analysis (INAA) of 24 samples for the trace elements: Th, Ta, Hf, Sc, and the rare earth elements La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu.

When plotted on a total alkalies vs. silica diagram (Fig. 6, after LeBas, 1986) the samples separate into two distinct populations, one between 45 and 55% silica and the other between 65 and 80% silica (with all but two in the latter group between 70 and 80% silica). This bimodal distribution, with the absence of andesitic compositions, has been noted by others who have studied the Paleoproterozoic metavolcanic rocks of the Colorado province (e.g., Boardman and Condie, 1986, in the Salida area; Condie and Nuter, 1981, in the Cochetopa succession south of Gunnison). A sizable gap between the two populations exists even when analytical results are expressed as ratios of elements thought to be immobile during metamorphism (e.g., $Zr/TiO_2$ vs. $SiO_2$ as in Winchester and Floyd, 1977). The geochemistry of the two groups will be discussed separately.

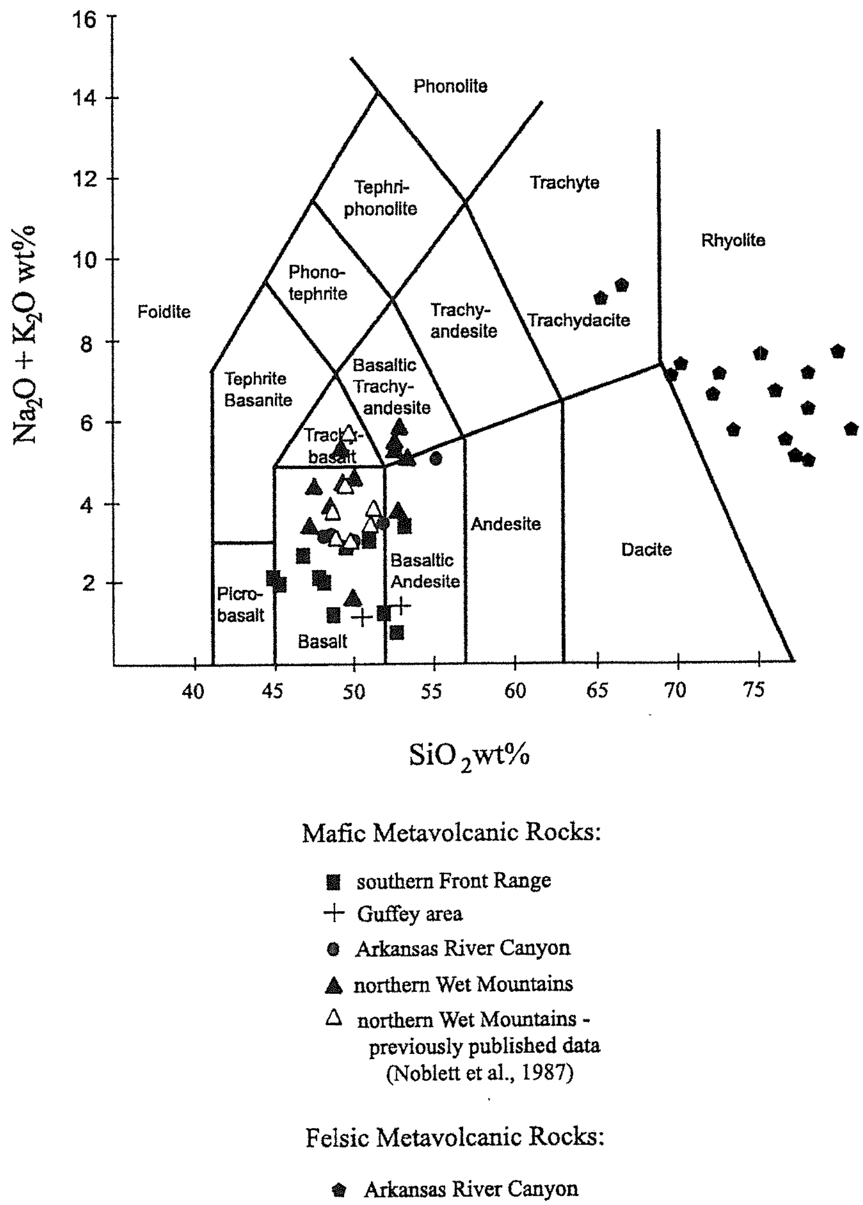


**Figure 6.** Total alkalies vs. silica diagram for metavolcanic samples from area of this report (after LeBas et al., 1986).

## Mafic Metavolcanic Rocks (Lower-Silica Group)

Amphibolites of the lower-silica group, compositionally basalt to basaltic andesite, vary in composition as a function of location along a 100-km N-S transect. The northernmost samples, from the southern Front Range and Guffey area, are lowest in total alkalies (most 2% with only two exceeding 3%), whereas those in the southern part of the area, of comparable metamorphic grade from the Arkansas Canyon and northern Wet Mountains, are as high as 5–6% total alkalies.

These compositional distinctions between northern and southern samples also appear in N-MORB-normalized spider diagrams (Fig. 7, after Pearce, 1983). All amphibolites show appreciable enrichment in large-ion lithophile elements (LILEs), but the magnitude of that enrichment is higher in the south than in the north (Fig. 7A vs. Fig. 7C). High-field-strength elements (HFSEs) generally plot at MORB values or slightly below, and Cr is notably depleted in several samples. The same trend of enrichment in the more incompatible elements appears in chondrite-normalized rare earth element (REE) diagrams (Fig. 8). REE diagrams for samples from all areas show smooth trends with very gentle negative slopes from light rare earth elements (LREEs) to heavy (HREEs), but samples from the southern Front Range show LREE enrichment of 10–30x chondrite ($La_N/Lu_N < 2$), whereas those from the northern Wet Mountains are enriched in LREEs at 30–100x chondrite ($La_N/Lu_N \sim 5$). These geochemical features suggest basaltic protoliths that were more "primitive" (tholeiitic) to the north and more highly evolved (calc-alkaline basalts and basaltic andesites) to the south.

### Felsic Metavolcanic Rocks (Higher-Silica Group)

All but two of the felsic metavolcanic samples from the Arkansas Canyon area contain between 70 and 80% $SiO_2$ and approximately 6–8% total alkalies; they plot as rhyolites on a total alkalies vs. silica diagram (Fig. 6). The other two samples, with 65–67% silica and slightly greater than 8% alkalies, are trachydacites in this terminology. A MORB-normalized spider diagram (Fig. 9) shows depletions, typical of felsic rocks, in Ti, P, and Sr, related to prior separation of Ti-oxides, apatite, and plagioclase, respectively. Rare earth element diagrams define two populations which may indicate more than one pyroclastic event, perhaps from different sources (Fig. 10). All samples show strong fractionation between LREEs and HREEs ($La_N/Lu_N \sim 5$), but about half the samples analyzed by INAA show a much more pronounced negative europium anomaly than the others. As expected, the strongest negative

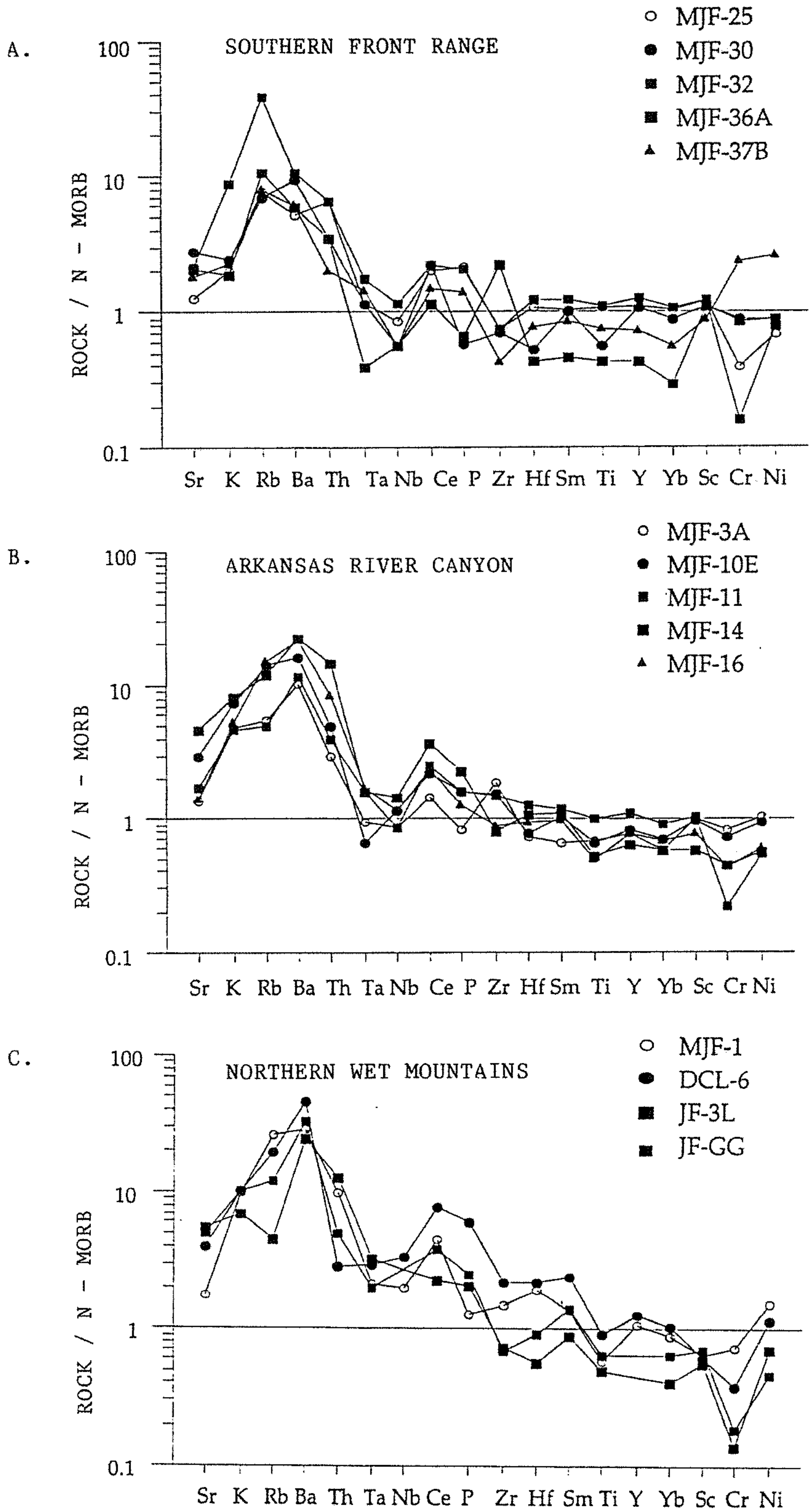


**Figure 7.** N-MORB-normalized trace element diagrams (after Pearce, 1983) comparing metabasalts from ***A***, southern Front Range in northern part of study area; ***B***, Arkansas River Canyon; and ***C***, northern Wet Mountains in southern part of study area.

**Table 1 (Continued on next page). Chemical analyses of ten samples of mafic metavolcanic rocks from the southern Front Range (numbers MJF-24F through -41), two from the Guffey area (MJF-39A and -40), four from the Arkansas River Canyon (MJF-3A through -14), and four from the northern Wet Mountains (MJF-1 through JF-GG). For sample locations see Figure 1.**

| (wt %) | MJF-24F | MJF-25 | MJF-26 | MJF-30 | MJF-32 | MJF-33 | MJF-36A | MJF-37B | MJF-37C | MJF-41 | MJF-39A |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 53.33 | 51.92 | 48.69 | 48.51 | 50.79 | 45.42 | 49.51 | 47.54 | 49.95 | 46.16 | 50.55 |
| $TiO_2$ | 0.79 | 1.6 | 0.73 | 0.83 | 1.68 | 1.4 | 0.66 | 1.13 | 1.76 | 2 | 0.92 |
| $Al_2O_3$ | 16 | 12.96 | 15.64 | 16.87 | 13.07 | 17.07 | 17.08 | 12.23 | 15.43 | 14.37 | 16.61 |
| $Fe_2O_3$ | 9.46 | 15.55 | 12.51 | 12.05 | 16.79 | 12.82 | 10.42 | 13.84 | 14.76 | 17.27 | 10.57 |
| MnO | 0.17 | 0.25 | 0.22 | 0.23 | 0.26 | 0.22 | 0.17 | 0.22 | 0.19 | 0.29 | 0.19 |
| MgO | 7.49 | 5.63 | 8.63 | 7.65 | 5.22 | 8.97 | 7.15 | 10.6 | 3.09 | 6.98 | 8 |
| CaO | 8.97 | 10.24 | 12.37 | 11.88 | 8.59 | 11.57 | 12.24 | 11.16 | 10.43 | 11.22 | 1.43 |
| $Na_2O$ | 1.93 | 1 | 1.1 | 1.78 | 1.61 | 1.43 | 2.53 | 2.36 | 2.71 | 1.05 | 0.64 |
| $K_2O$ | 1.54 | 0.3 | 0.19 | 0.36 | 1.29 | 0.67 | 0.28 | 0.34 | 1.34 | 1.18 | 0.42 |
| $P_2O_5$ | 0.11 | 0.26 | 0.54 | 0.07 | 0.25 | 0.14 | 0.08 | 0.17 | 0.37 | 0.34 | 0.14 |
| Total | 99.78 | 99.67 | 100.13 | 100.23 | 99.55 | 100.05 | 100.12 | 99.56 | 100.04 | 99.85 | 99.46 |
| (ppm) | | | | | | | | | | | |
| Rb | n.d. | 15 | n.d. | 14 | 77 | n.d. | 21 | 16 | n.d. | n.d. | 13 |
| Sr | n.d. | 150 | n.d. | 332 | 260 | n.d. | 248 | 220 | n.d. | n.d. | 456 |
| Zr | n.d. | 68 | n.d. | 64 | 67 | n.d. | 200 | 39 | n.d. | n.d. | 57 |
| Y | 27 | 33 | 18 | 32 | 38 | 30 | 13 | 22 | 25 | 41 | 19 |
| Nb | 4 | 3 | <2 | <2 | 4 | <2 | <2 | 2 | 7 | 4 | 4 |
| Ba | n.d. | 104 | n.d. | 185 | 209 | n.d. | 116 | 122 | n.d. | n.d. | 207 |
| Sc | n.d. | 49 | n.d. | 45.1 | 49.5 | n.d. | 44.3 | 35 | n.d. | n.d. | 33.8 |
| V | 178 | 378 | 250 | 267 | 394 | 294 | 243 | 196 | 334 | 395 | 253 |
| Cr | n.d. | 98 | n.d. | 220 | 39 | n.d. | 215 | 589 | n.d. | n.d. | 320 |
| Co | n.d. | 44.9 | n.d. | 43.3 | 46 | n.d. | 41.3 | 59.7 | n.d. | n.d. | 38.2 |
| Ni | n.d. | 62 | n.d. | 81 | 70 | n.d. | 81 | 235 | n.d. | n.d. | 85 |
| Cu | 52 | 44 | 75 | 15 | 45 | 93 | <5 | 50 | <5 | 36 | 135 |
| Zn | n.d. | 154 | n.d. | 143 | 164 | n.d. | 92 | 115 | n.d. | n.d. | 114 |
| Ga | 16 | 17 | 17 | 19 | 19 | 19 | 16 | 16 | 19 | 18 | 19 |
| La | n.d. | 8.1 | n.d. | 7.7 | 7.5 | n.d. | 4.6 | 5.8 | n.d. | n.d. | 8.5 |
| Ce | n.d. | 19.8 | n.d. | 22.1 | 21.9 | n.d. | 11.6 | 15.1 | n.d. | n.d. | 199.8 |
| Nd | n.d. | 10.5 | n.d. | 12 | 13.8 | n.d. | 25 | 9.4 | n.d. | n.d. | 11.5 |
| Sm | n.d. | 3.46 | n.d. | 3.34 | 4.02 | n.d. | 1.53 | 2.84 | n.d. | n.d. | 2.71 |
| Eu | n.d. | 1.31 | n.d. | 0.88 | 1.34 | n.d. | 0.67 | 0.99 | n.d. | n.d. | 1.38 |
| Tb | n.d. | 0.81 | n.d. | 0.71 | 0.85 | n.d. | 0.27 | 0.52 | n.d. | n.d. | 0.53 |
| Yb | n.d. | 3.5 | n.d. | 3 | 3.7 | n.d. | 1 | 1.9 | n.d. | n.d. | 1.7 |
| Lu | n.d. | 0.48 | n.d. | 0.45 | 0.57 | n.d. | 0.16 | 0.25 | n.d. | n.d. | 0.25 |
| Hf | n.d. | 2.63 | n.d. | 1.25 | 2.92 | n.d. | 1.03 | 1.84 | n.d. | n.d. | 1.63 |
| Ta | n.d. | 0.21 | n.d. | 0.21 | 0.32 | n.d. | 0.07 | 0.26 | n.d. | n.d. | 0.34 |
| Pb | 10 | 7 | 7 | <5 | 10 | <5 | 8 | <5 | 23 | 12 | 15 |
| Th | n.d. | 1.3 | n.d. | 0.69 | 1.3 | n.d. | 0.7 | 0.4 | n.d. | n.d. | 1.6 |
| U | n.d. | 2.5 | n.d. | 2.4 | 0.8 | n.d. | 2.7 | 2.4 | n.d. | n.d. | 2.5 |

Total iron as $Fe_2O_3$.
n.d. = no data.

**Table 1 (Continued).**

| (wt %) | MJF-40 | MJF-3A | MJF-10E | MJF-11 | MJF-14 | MJF-16 | MJF-1 | DCL-6 | JF-3L | JF-GG |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 52.86 | 48.59 | 48.03 | 51.83 | 54.86 | 49.79 | 52.9 | 50.29 | 53.22 | 49.4 |
| $TiO_2$ | 0.9 | 1.03 | 0.98 | 1.53 | 0.79 | 0.74 | 0.87 | 1.36 | 0.73 | 0.96 |
| $Al_2O_3$ | 13.19 | 15.84 | 17.12 | 13.92 | 16.7 | 1.75 | 16.15 | 15.77 | 19.48 | 17.43 |
| $Fe_2O_3$ | 9.56 | 11.09 | 12.57 | 14.03 | 8.67 | 11.69 | 9.46 | 11.43 | 8.8 | 12.93 |
| MnO | 0.42 | 0.21 | 0.22 | 0.23 | 0.16 | 0.33 | 0.19 | 0.24 | 0.14 | 0.16 |
| MgO | 8.73 | 8.18 | 7.53 | 5.51 | 4.75 | 7.85 | 6.27 | 6.23 | 3.55 | 4.42 |
| CaO | 11.78 | 11.71 | 10.54 | 9.61 | 8.69 | 13.53 | 8.39 | 8.75 | 9.36 | 8.95 |
| $Na_2O$ | 1 | 2.66 | 2.14 | 2.56 | 4.03 | 2.19 | 4.37 | 3.23 | 4.26 | 3.88 |
| $K_2O$ | 0.44 | 0.72 | 1.1 | 0.69 | 1.23 | 0.81 | 1.5 | 1.54 | 1.04 | 1.51 |
| $P_2O_5$ | 0.43 | 0.1 | 0.19 | 0.19 | 0.27 | 0.15 | 0.15 | 0.72 | 0.25 | 0.3 |
| Total | 99.32 | 100.12 | 100.42 | 100.08 | 100.15 | 99.82 | 100.23 | 99.56 | 100.83 | 99.95 |
| (ppm) | | | | | | | | | | |
| Rb | 20 | 11 | 28 | 10 | 24 | 30 | 53 | 39 | 9 | 24 |
| Sr | 1330 | 163 | 361 | 205 | 570 | 170 | 212 | 484 | 657 | 606 |
| Zr | 135 | 170 | 140 | 135 | 72 | 80 | 135 | 199 | 65 | 61 |
| Y | 24 | 23 | 25 | 33 | 19 | 23 | 32 | 38 | n.d. | n.d. |
| Nb | 9 | 3 | 4 | 3 | 5 | 4 | 7 | 12 | n.d. | n.d. |
| Ba | 300 | 202 | 318 | 233 | 451 | 433 | 581 | 901 | 494 | 650 |
| Sc | 27.4 | 40.2 | 39 | 42 | 23 | 31.2 | 25.8 | 24.7 | 22.7 | 27.8 |
| V | 196 | 247 | 268 | 348 | 183 | 210 | 153 | 184 | n.d. | n.d. |
| Cr | 451 | 207 | 185 | 54 | 111 | 110 | 181 | 95 | 35 | 47 |
| Co | 36.5 | 45 | 50.1 | 42.4 | 24.3 | 51.4 | 36.5 | 36.3 | 22.8 | 28.5 |
| Ni | 212 | 95 | 84 | 49 | 50 | 54 | 138 | 104 | 63 | 41 |
| Cu | 5 | 27 | 26 | 83 | 35 | 70 | 28 | 55 | n.d. | n.d. |
| Zn | 508 | 226 | 133 | 138 | 86 | 196 | 102 | 118 | 84 | 86 |
| Ga | 14 | 17 | 17 | 22 | 22 | 15 | 19 | 20 | n.d. | n.d. |
| La | 38 | 5.7 | 8.6 | 9.6 | 17.1 | 11 | 19.2 | 33.3 | 11.7 | 15.8 |
| Ce | 83.2 | 14.5 | 22 | 25.5 | 37.1 | 23.3 | 44.7 | 77.9 | 22.7 | 39 |
| Nd | 46.7 | 9.8 | 12.8 | 15.6 | 17.3 | 12.5 | 22.5 | 38.7 | 12.9 | 21 |
| Sm | 10.6 | 2.21 | 3.46 | 3.96 | 3.66 | 3.19 | 4.47 | 8.04 | 2.97 | 4.61 |
| Eu | 2.53 | 0.99 | 1.23 | 1.47 | 1.3 | 1.08 | 1.63 | 2.27 | 0.99 | 1.58 |
| Tb | 1.03 | 0.58 | 0.61 | 0.9 | 0.46 | 0.59 | 0.75 | 1.03 | 0.44 | 0.65 |
| Yb | 1.8 | 2 | 2.4 | 3.1 | 2 | 2.3 | 3 | 3.5 | 1.4 | 2.2 |
| Lu | 0.27 | 0.2 | 0.37 | 0.44 | 0.24 | 0.29 | 0.41 | 0.47 | 0.25 | 0.25 |
| Hf | 3.05 | 1.73 | 1.87 | 3.08 | 2.56 | 2.24 | 4.65 | 5.24 | 1.37 | 2.17 |
| Ta | 0.51 | 0.17 | 0.12 | 0.29 | 0.29 | 0.31 | 0.39 | 0.54 | 0.59 | 0.36 |
| Pb | 31 | 12 | 5 | 5 | 9 | 11 | 6 | 9 | n.d. | n.d. |
| Th | 5.9 | 0.6 | 1 | 0.8 | 2.9 | 1.7 | 2 | 0.57 | 2.6 | 1 |
| U | 2.9 | 2.9 | 2.7 | 2.8 | 1.9 | 1 | 1.4 | 3 | 2.2 | 2.4 |

Total iron as $Fe_2O_3$.
n.d. = no data.

**Table 2 (Continued on next page). Chemical analyses of 15 samples of felsic metavolcanic rocks from the Arkansas River Canyon area. For sample locations see Figure 5.**

| (wt %) | 7KW-6E | 7KW-8F | 7KW-9F | 7KW-11F | 7KW-1L | 7KW-1M | 7KW-1N | RW-16A | RW-19 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 65.14 | 70.79 | 70.19 | 77.5 | 76.42 | 66.28 | 72.65 | 77.43 | 74.96 |
| $TiO_2$ | 0.6 | 0.3 | 0.29 | 0.22 | 0.21 | 0.71 | 0.55 | 0.13 | 0.24 |
| $Al_2O_3$ | 15.8 | 15.14 | 15.5 | 13.67 | 12.58 | 15.42 | 13.03 | 12.21 | 12.72 |
| $Fe_2O_3$ | 6.08 | 3.89 | 3.75 | 1.59 | 2.38 | 5.18 | 4.75 | 1.51 | 3.12 |
| MnO | 0.18 | 0.14 | 0.12 | 0.05 | 0.08 | 0.11 | 0.13 | 0.06 | 0.08 |
| MgO | 1.8 | 0.58 | 0.55 | 0.29 | 1.74 | 0.75 | 0.69 | 0.38 | 0.61 |
| CaO | 1.53 | 1.85 | 1.92 | 0.39 | 0.58 | 2.63 | 1.09 | 0.65 | 0.48 |
| $Na_2O$ | 4.47 | 4.06 | 4.07 | 3.28 | 4.38 | 4.04 | 3.66 | 3.55 | 2.34 |
| $K_2O$ | 4.44 | 3.89 | 3.71 | 3.62 | 1.87 | 5.11 | 3.58 | 4.05 | 5.78 |
| $P_2O_5$ | 0.15 | 0.06 | 0.07 | 0.03 | 0.02 | 0.22 | 0.1 | 0.02 | 0.03 |
| Total | 100.19 | 100.71 | 100.17 | 100.64 | 100.26 | 100.45 | 100.23 | 99.99 | 100.36 |
| **(ppm)** | | | | | | | | | |
| Rb | 222 | 77 | 68 | 64 | 49 | 82 | 78 | 57 | 142 |
| Sr | 95 | 323 | 249 | 72 | 71 | 301 | 158 | 51 | 67 |
| Zr | 287 | 253 | 269 | 389 | 545 | 281 | 320 | 341 | 354 |
| Y | 56 | 43 | 47 | 65 | 111 | 42 | 59 | 67 | 75 |
| Nb | 21 | 14 | 15 | 21 | 28 | 18 | 19 | 24 | 18 |
| Ba | 1603 | 1069 | 1336 | 925 | 502 | 1291 | 1211 | 941 | 1324 |
| Sc | n.d. | 8.66 | 8.93 | 5.82 | 4.66 | 11.6 | 11.5 | n.d. | 5.64 |
| V | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Cr | n.d. | 5.6 | 5.5 | 5.9 | 3.1 | 4.4 | 7.3 | n.d. | 11.4 |
| Co | n.d. | 2.11 | 2.18 | 0.65 | 2.49 | 5.93 | 3.21 | n.d. | 2.6 |
| Ni | n.d. | 0 | 24 | 0 | 16 | 0 | 0 | n.d. | 0 |
| Cu | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Zn | n.d. | 87 | 92 | 38 | 32 | 97 | 88 | n.d. | 63 |
| Ga | 19 | 19 | 21 | 20 | 14 | 20 | 16 | 22 | 19 |
| La | n.d. | 36 | 39.6 | 48.3 | 19 | 28.5 | 30.1 | n.d. | 55.5 |
| Ce | n.d. | 65.8 | 72.4 | 85.6 | 37.4 | 65.4 | 64 | n.d. | 102 |
| Nd | n.d. | 30.6 | 34.7 | 44.4 | 20.9 | 35.5 | 31.1 | n.d. | 51 |
| Sm | n.d. | 7.4 | 7.95 | 10.4 | 5.45 | 7.73 | 6.55 | n.d. | 10.7 |
| Eu | n.d. | 2.15 | 2.31 | 1.33 | 1.27 | 1.9 | 1.22 | n.d. | 1.7 |
| Tb | n.d. | 1.2 | 1.25 | 1.74 | 2.03 | 1.15 | 1.39 | n.d. | 1.75 |
| Yb | n.d. | 4.8 | 4.8 | 6.9 | 11 | 4.3 | 6.2 | n.d. | 7.6 |
| Lu | n.d. | 0.66 | 0.72 | 0.93 | 1.79 | 0.54 | 0.92 | n.d. | 1.07 |
| Hf | n.d. | 6.15 | 6.63 | 9.32 | 13.1 | 6.6 | 8.38 | n.d. | 9.45 |
| Ta | n.d. | 0.82 | 0.86 | 1.23 | 1.45 | 0.85 | 1.14 | n.d. | |
| Pb | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Th | n.d. | 5.7 | 6.4 | 8 | 6.5 | 3.3 | 8 | n.d. | 11.6 |
| U | n.d. | 3.4 | 3.8 | 2.7 | 3.8 | 1.1 | 3.4 | n.d. | 2.7 |

Total iron as $Fe_2O_3$.
n.d. = no data.

**Table 2 (Continued).**

| (wt %) | RW-23 | RW-35 | RW-37 | RW-39 | RW-42 | RW-47 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 77.13 | 73.51 | 78.87 | 72.98 | 79.13 | 75.55 |
| $TiO_2$ | 0.15 | 0.19 | 0.13 | 0.31 | 0.21 | 0.27 |
| $Al_2O_3$ | 11.98 | 14.62 | 10.91 | 14.16 | 9.7 | 12.87 |
| $Fe_2O_3$ | 2.45 | 2.21 | 1.28 | 3.55 | 2.9 | 0.85 |
| MnO | 0.07 | 0.09 | 0.06 | 0.14 | 0.1 | 0.07 |
| MgO | 0.76 | 1.24 | 0.54 | 0.35 | 1.26 | 2.5 |
| CaO | 1.19 | 1.58 | 0.1 | 1.12 | 0.44 | 0.88 |
| $Na_2O$ | 3.76 | 5.24 | 1.07 | 4.67 | 1.2 | 4.5 |
| $K_2O$ | 2.05 | 1.2 | 7.01 | 3.11 | 5.08 | 2.7 |
| $P_2O_5$ | 0.01 | 0.01 | 0.02 | 0.06 | 0.06 | 0.04 |
| **Total** | 99.55 | 99.89 | 99.99 | 100.45 | 100.08 | 100.23 |
| **(ppm)** | | | | | | |
| Rb | 99 | 19 | 173 | 57 | 132 | 53 |
| Sr | 76 | 108 | 33 | 145 | 45 | 151 |
| Zr | 456 | 551 | 212 | 250 | 321 | 365 |
| Y | 58 | 66 | 60 | 51 | 78 | 38 |
| Nb | 27 | 26 | 17 | 14 | 18 | 7 |
| Ba | 535 | 543 | 1518 | 1179 | 451 | 1157 |
| Sc | 1.45 | n.d. | 11.4 | n.d. | 4.66 | 16.9 |
| V | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Cr | 9.2 | n.d. | 8 | n.d. | 5.6 | 5.4 |
| Co | 0.69 | n.d. | 0.66 | n.d. | 1.13 | 0.67 |
| Ni | 10 | n.d. | 0 | n.d. | 0 | 0 |
| Cu | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Zn | 99 | n.d. | 55 | n.d. | 94 | 43 |
| Ga | 26 | 22 | 16 | 24 | 17 | 23 |
| La | 38.1 | n.d. | 38.7 | n.d. | 42.4 | 43.4 |
| Ce | 73.7 | n.d. | 76.5 | n.d. | 81 | 74.2 |
| Nd | 36.7 | n.d. | 35.5 | n.d. | 44.4 | 30.5 |
| Sm | 7.41 | n.d. | 8.32 | n.d. | 10.5 | 6.06 |
| Eu | 1.97 | n.d. | 1.07 | n.d. | 1.65 | 1.73 |
| Tb | 1.32 | n.d. | 1.7 | n.d. | 2.09 | 1.12 |
| Yb | 6.2 | n.d. | 6.3 | n.d. | 8.3 | 4.2 |
| Lu | 0.93 | n.d. | 0.81 | n.d. | 1.13 | 0.52 |
| Hf | 12.2 | n.d. | 6.27 | n.d. | 8.19 | 8.57 |
| Ta | 1.2 | n.d. | 1.4 | n.d. | 1.08 | 1.18 |
| Pb | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Th | 6.8 | n.d. | 15.9 | n.d. | 6.9 | 9.9 |
| U | 9.4 | n.d. | 3.1 | n.d. | 3.4 | 2.8 |

Total iron as $Fe_2O_3$.
n.d. = no data.

europium anomalies are from the samples with the largest Sr depletion in Figure 9, both suggesting earlier plagioclase fractionation.

## GEOCHEMICAL INDICATORS OF TECTONIC SETTING

Petrologic and geochemical features of modern volcanic rocks have long been correlated directly with the tectonic environment in which these rocks are currently forming. The same criteria may also be applied to ancient volcanic rocks in order to recognize the tectonic signatures of such sequences. Caution must be exercised in interpreting the environments of ancient volcanic rocks, however, especially where regional metamorphic conditions have been pervasive enough to mobilize and redistribute some of the larger and lighter elements in these rocks. Large-ion lithophile elements may be especially susceptible to such remobilization, so that the geochemical discriminant diagrams most applicable to the tectonic interpretation of metamorphosed volcanic rocks rely on smaller high-field-strength elements or their ratios (Mullen, 1983; Pearce, 1983; Wood, 1980).

A widely used tectonic discriminant diagram for basalts is that of Mullen (1983), based on the small, highly charged minor elements Ti, Mn, and P, all of which can be determined by XRF analysis. The amphibolite analyses of this report are plotted on a Mullen diagram in Figure 11, along with nine analyses by Noblett (1987) of amphibolites from the Wet Mountains. All but one of the data points fall within fields representing basalts from volcanic arc environments. Samples from the Front Range are mostly in the field of island-arc

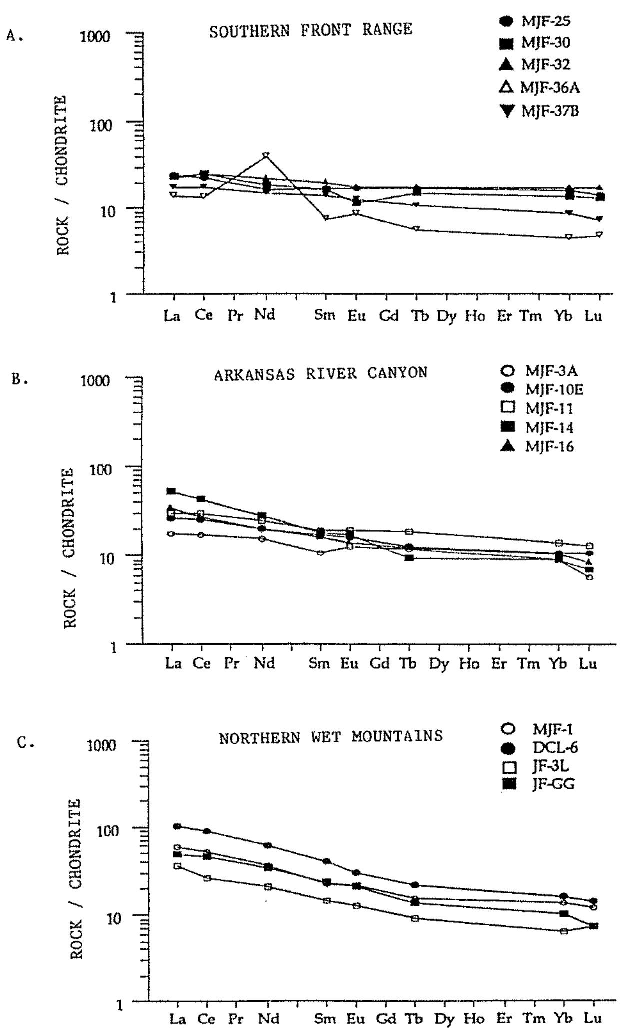


**Figure 8.** Chondrite-normalized rare earth element diagrams for metabasalts from ***A***, southern Front Range; ***B***, Arkansas River Canyon; and ***C***, northern Wet Mountains.

tholeiites, whereas those from the Wet Mountains are concentrated within the field of calc-alkaline basalts from more highly evolved arcs.

The trends described previously on N-MORB-normalized incompatible-element (spider) diagrams (Fig. 7) and REE diagrams (Fig. 8) are also consistent with volcanic arc settings. The lower degree of enrichment in LILEs and LREEs in amphibolites from the southern Front Range is similar to patterns found in tholeiitic basalts from immature oceanic arcs, whereas the greater enrichment in these trace element groups from samples to the south in the Wet Mountains is more indicative of calc-alkaline basalts from a more highly evolved island-arc or continental-margin arc setting (Pearce, 1983; Condie, 1989).

Another tectonic discriminant diagram (Paktunc, 1990) that uses trace element data for basaltic rocks portrays the domains of basalts from

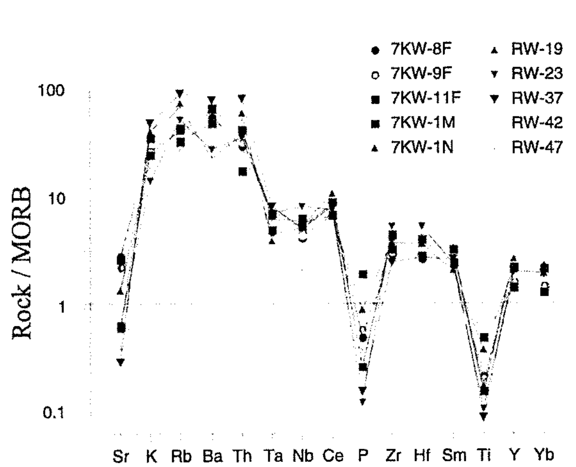


**Figure 9.** N-MORB-normalized trace element diagram (after Pearce, 1983) for felsic metavolcanic samples from Arkansas River Canyon area.

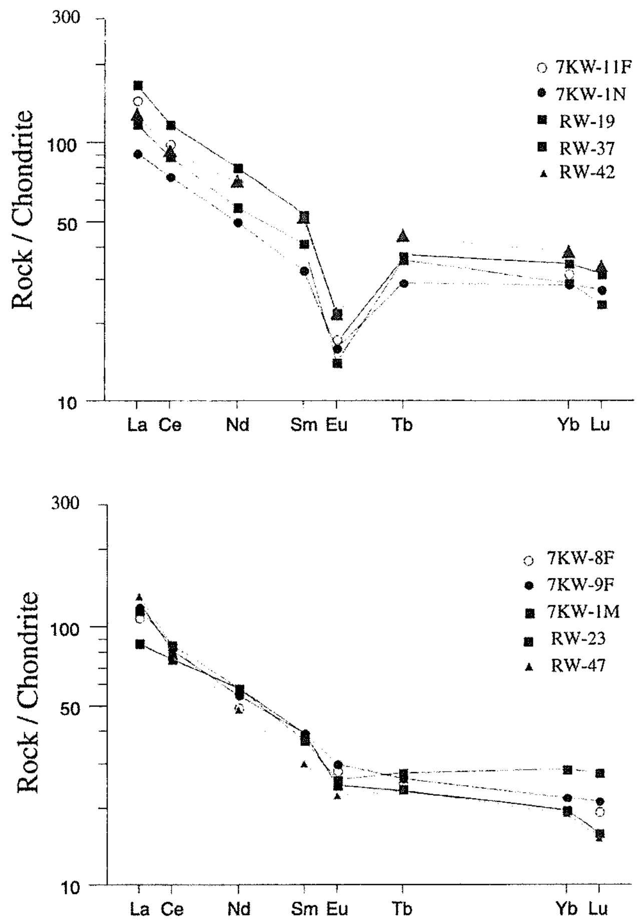


**Figure 10.** Chondrite-normalized rare earth element diagrams for two sets of felsic metavolcanic samples from Arkansas Canyon area.

mid-ocean ridges, back-arc basins, mid-plate oceanic islands, and island arcs as a function of Th/Nb vs. La/Hf. Of the thirteen mafic volcanic rocks from the present study for which sufficient trace element data are available, ten plot within the field of island-arc basalts, one appears in the field of ocean-island basalts, and two lie in undesignated areas. No analyses fall within the fields of ridge or back-arc basin basalts, both of which represent extensional tectonic environments.

Geochemical discriminants for the tectonic setting of felsic igneous rocks are generally less reliable (due especially to fractionation) than those for mafic rocks. However, some general comparisons are warranted, if only in terms of ruling out some tectonic environments. For example, chemical features of the felsic metavolcanic rocks from the Arkansas Canyon area most closely resemble those of I-type granites and rhyolites, typical of modern convergent-margin arc settings, rather than granitoids formed typically in extensional (A-type) or collisional (S-type) tectonic settings (Chappell and White, 1974; Loiselle and Wones, 1979; Whalen et al., 1987). At $SiO_2 > 70\%$, Arkansas Canyon metarhyolites show I-type properties such as very low FeO*/MgO, relatively high amounts of Ba and Sr, and relatively low values for Zr, Nb, Y, and Ce. These features contrast strongly with those of A-type granites of some extensional regimes. As pointed out by Eby (1990), considerable overlap occurs among the various types of granitic rocks in values for total alkalies and CaO at $SiO_2 > 70\%$; he regards the FeO*/MgO ratio for felsic rocks as a more reliable discriminant to distinguish granite types in regard to major element variation.

MacDonald et al. (1992) empirically determined the ranges and averages of major, minor, and trace element compositions for subalkalic silicic glasses (obsidians) of known tectonic origin from a variety of modern environments. They correlated specific geochemical signatures with four distinct tectonic settings: mature island arcs, active continental-margin arcs, continental interiors, and mid-ocean extensional zones. Comparison with this extensive data set shows that the ranges and average values for trace elements in the Arkansas Canyon felsic volcanic suite are most consistent with those for mature island arcs and arcs of active continental margins (Fig. 12).

The data for immobile trace elements in the felsic metavolcanic rocks from the Arkansas Canyon were also plotted on two widely used tectonic discriminant diagrams for high-silica rocks (Pearce et al., 1984; Harris et al., 1986). Both diagrams yielded

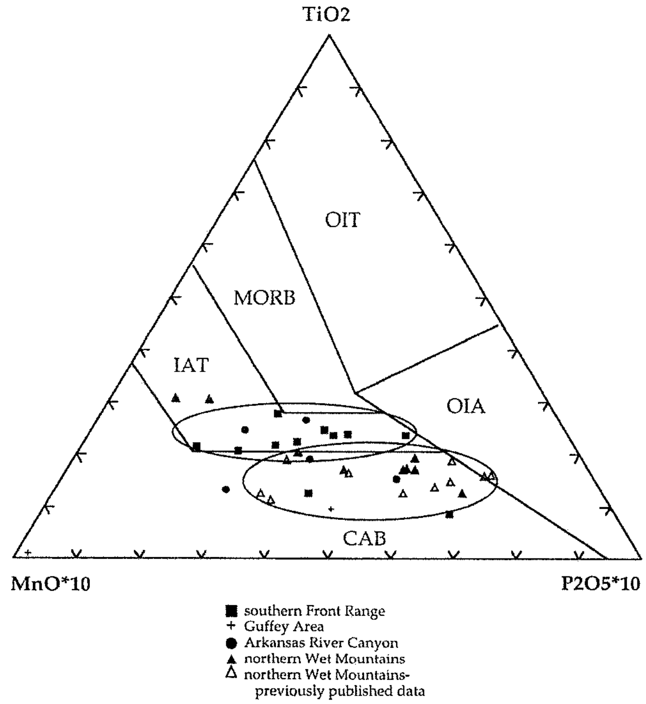


**Figure 11.** $MnO$-$TiO_2$-$P_2O_5$ tectonic discriminant diagram after Mullen (1983) showing distribution of metabasalt analyses. The fields are: OIT, ocean island (or seamount) tholeiite; OIA, ocean island (or seamount) alkali basalt; MORB, mid-ocean ridge basalt; IAT, island arc tholeiite; CAB, island arc calc-alkaline basalt. Oval fields show distribution of two possible groups of metabasalts for samples of this report.

non-definitive results, with the data points straddling the boundary between "volcanic arc" and "within plate" fields. These results may be noteworthy, however, in that they show exactly the same distribution as the data set for the oldest granitic plutons of the Arkansas Canyon area as presented by Anderson and Cullers (1999). In comparison with their work, trace element data for the Twin Mountain and Crampton Mountain batholiths (1705 $\pm 8$ Ma) also plot astride the boundary separating "volcanic arc granites" from "within plate granites," whereas those for the younger Garrell Peak batholith (1663 $\pm 4$ Ma) plot in the "within plate granite" field. Anderson and Cullers state that the trace element compositions for these earliest (~1.7 Ga) plutons most closely resemble those from magmatic arcs above subduction zones, and that the shift toward a "within plate" field by the time of emplacement of the Garrell Peak pluton represents an increasing crustal component associated with continental stabilization.

In summary, geochemical data for both the mafic and felsic volcanic rocks of the Arkansas Canyon area point uniformly toward derivation in con-

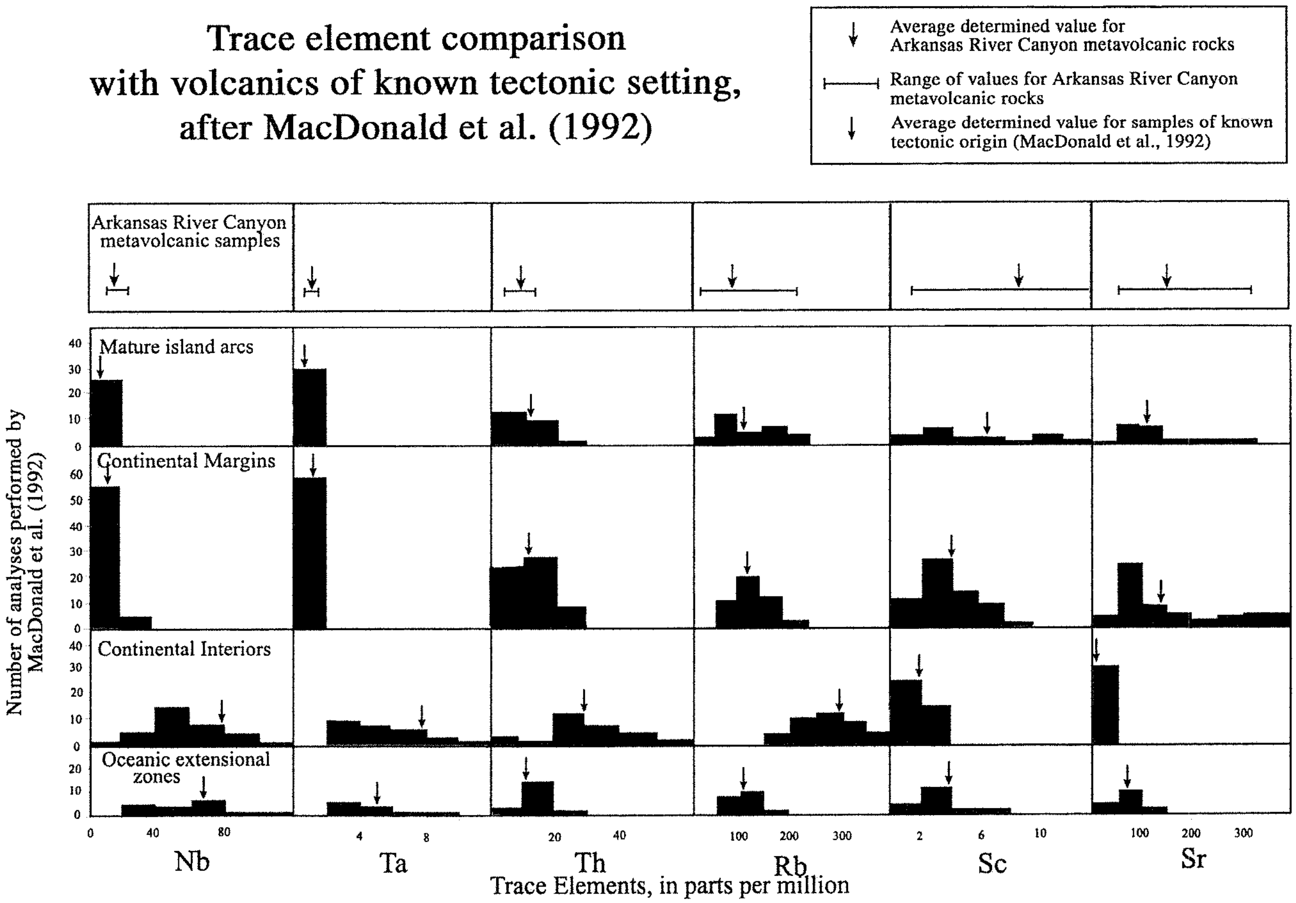


**Figure 12.** Comparison of ranges and means of selected trace elements in the Arkansas River Canyon felsic metavolcanic rocks with those of subalkalic silicic obsidians of known tectonic setting. (after MacDonald et al., 1992).

vergent-margin volcanic arc settings. No features of extensional environments, either ridge or back-arc, were recognized. The data for the metavolcanic rocks are also consistent with those for the oldest (~1.7 Ga) granitic plutons in the area, which are interpreted to have been emplaced along an active continental margin.

## REGIONAL COMPARISONS

The best studied sections of Paleoproterozoic metavolcanic rocks in central Colorado are those near Salida, 16 km west of the western boundary of the present study area, and the Cochetopa-Dubois successions south of Gunnison, approximately 130 km to the west. Both regions contain bimodal volcanic rocks that preserve primary volcanic structures and textures in areas where regional metamorphism and deformation have not been as pervasive as in the area of this report.

The Salida metavolcanic and associated metasedimentary rocks have been especially well studied (Boardman, 1976, 1986; Bickford and Boardman, 1984; Boardman and Condie, 1986). The section includes thick mafic flows and volcaniclastic units (breccias, pillow breccias), felsic tuffs and tuff breccias, and sedimentary units interpreted as products of near-source shallow water deposition. Gabbroic sills up to 300 m thick with relict ophitic texture intrude the volcanogenic layers; their compositions are distinctly tholeiitic and are similar to the metabasalts in the section, suggesting contemporaneity with them. To the east in the Badger Creek drainage, the section is characterized by felsic volcanic rocks and poorly foliated gabbroic sills, with only minor mafic volcanic rocks. A single U-Pb age of 1728 ±6 Ma was obtained on a metadacite from the Salida section (Bickford, 1986).

Geochemically, the felsic metavolcanic rocks of the Arkansas Canyon closely resemble some of those from the Salida area. While comparison of major element chemical compositions can be questioned at this metamorphic grade, the less mobile rare-earth element trends for most of the Arkansas

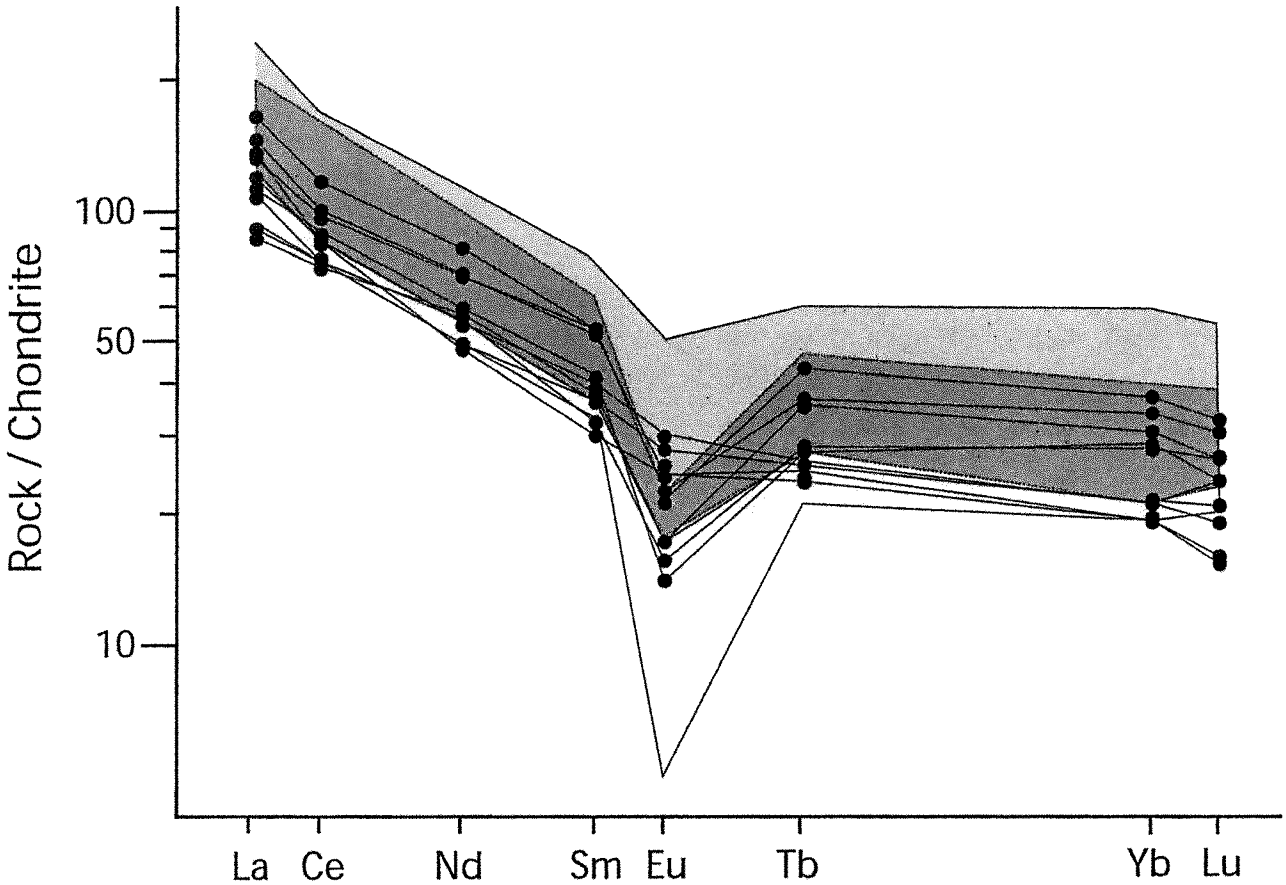


**Figure 13.** Comparison of chondrite-normalized rare earth element analyses of felsic metavolcanic rocks from Arkansas River Canyon area with ranges of those for aphyric felsic metavolcanic rocks from Salida area (Boardman and Condie, 1986), and for felsic metavolcanic rocks from the Dubois succession south of Gunnison (after Condie and Nuter, 1981). Lightest shading is for range of Salida samples, medium-gray shading is for range of Dubois samples, and darkest shading is region of overlap of ranges from Salida and Gunnison.

Canyon samples lie within the range of those for aphyric metarhyolites from Salida (Fig. 13; Boardman and Condie, 1986).

The metavolcanic successions south of Gunnison have been found to represent two separate bimodal assemblages based on U-Pb dating of zircons by Bickford (1986) and Bickford et al. (1989). The older group, known as the Dubois succession (or "Dubois greenstone"), contains moderately deformed metarhyolites within a thick section of metabasalts (some with pillow structures preserved) and metasedimentary rocks derived mostly from mafic igneous sources (Condie and Nuter, 1981; Knoper and Condie, 1988). Radiometric ages for the metarhyolites in this older sequence range from 1770–1760 Ma. A younger bimodal sequence, the Cochetopa succession, is made up of metavolcanic rocks that are tholeiitic basalt to basaltic andesite and rhyolite to dacite. These are interlayered with metasedimentary rocks most likely derived from turbidites, and the section has been intruded by gabbroic sills (Bickford et al., 1989). Remarkably well-preserved primary structures characterize the metavolcanic and metasedimentary rocks despite metamorphism to upper greenschist or lower amphibolite facies; pillow structures are found in the metabasalts, and eutaxitic fabrics from pyroclastic flows are common in the felsic metavolcanic rocks. U-Pb ages for metarhyolites in the Cochetopa succession range from 1740–1730 Ma (Bickford, 1986). Both groups of metavolcanic rocks south of Gunnison were intruded by tonalitic to granitic plutons within 15 m.y. of each volcanic episode.

Arkansas Canyon area metavolcanic rocks are similar to those south of Gunnison in their bimodal character, compositional ranges, and association with younger calc-alkaline granitic plutons. As shown by Knoper and Condie (1988), Dubois metabasalts are tholeiitic; their trace element patterns are similar to metabasalts in the southern

Front Range, with comparable enrichment in LIL elements up to 10x N-MORB and HFSE trends at or slightly below N-MORB values. Metabasalts in the Cochetopa succession are more calc-alkaline and resemble those in the northern Wet Mountains in their higher degree of LILE enrichment (10–30x N-MORB). Comparison of REE trends for felsic volcanic rocks of the Dubois succession with those from the Arkansas Canyon shows slightly greater enrichment in both LREEs and HREEs in the Dubois samples, but the shape of the plots is almost identical (Fig. 13).

## TECTONIC SYNTHESIS AND CONCLUSIONS

Boardman (1986) has characterized the Salida metavolcanic assemblage as a remnant of a young back-arc basin developed on or near continental crust of uncertain paleogeographic setting. Condie (1986) interpreted the Dubois succession near Gunnison as compositionally comparable to bimodal volcanic rocks formed in continental-margin arcs and associated back-arc basins, again without specifying the nature of the continental crust that would have been involved. In a later paper, Knoper and Condie (1988) proposed that all the Paleoproterozoic volcanic rocks of west-central Colorado were formed within or near arc systems and that the tectonic environment progressed through time from island arc to intra-arc and back-arc basin. Hill et al. (1999) and Hill and Bickford (2000) argued that a rift setting or continental-margin arc best fit the available data, the lack of andesites being incompatible with formation in offshore arcs. Furthermore, they noted that Sm-Nd data preclude the involvement of Archean crust, but that crust of Trans-Hudson and/or Penokean age (~1870 Ma) might have been available and could explain inherited cores of ~1870 Ma, which they have recently documented in zircons of the Dubois and Cochetopa successions near Gunnison.

Like the volcanic successions to the west near Salida and Gunnison, the Arkansas Canyon metavolcanic rocks are bimodal, with evidence (Fig. 4) that mafic and felsic magmas were concurrent. Although such basalt-rhyolite associations have commonly been used as "textbook" illustrations of extensional tectonic environments like back-arc basins (e.g. Condie, 1989), they are also a "relatively common characteristic of volcanism in continental magmatic arcs..." (Blatt and Tracy, 1996, p. 181). Several lines of evidence support a convergent-margin arc setting for the Arkansas Canyon rocks, where the mafic metavolcanic rocks have geochemical features that are strongly arc-related and that differ from those of MORBs, ocean-island (plume-generated), or back-arc basin basalts. The felsic metavolcanic rocks are I-type like those of the oldest granitic plutons of the area, indicative of magmatic arcs above subduction zones. In contrast, felsic igneous rocks of extensional tectonic settings are commonly A-type and enriched in alkalies, iron, and trace elements such as Zr, Nb, Y, and Ce, all of which are depleted in the felsic rocks of this study.

Though clearly more speculative, our data also suggest that the amphibolites in the northern part of the study area in the southern Front Range may represent mafic volcanic or volcaniclastic rocks from a more primitive arc system, judging from their relatively lower abundances of alkalies and large-ion lithophile trace elements (Figs. 6 and 7). Tectonic discriminant diagrams based on less mobile high-field-strength elements also show a distinction between island-arc tholeiite to the north and arc-type calc-alkaline basalt and basaltic andesite to the south through the field area (Fig. 11). There may thus be evidence in this region for contributions from two or more arc systems now juxtaposed after accretion. The more primitive tholeiitic compositions of amphibolites to the north, which lack any preserved flow features, could also have been derived from pyroclastic deposits with a source or sources outside of the present study area.

According to regional tectonic models for the growth of the Colorado province, the arc volcanism that produced these volcanic rocks would have been associated with the accretion of terranes against the rapidly expanding southern margin of the Wyoming craton late in Paleoproterozoic time. It is not possible to conclude from this study whether arcs accreted individually, joining with a succession of others to enlarge the craton one arc system at a time (Condie, 1986; Reed et al., 1987), or whether arcs may first have become amalgamated into a larger tectonic province prior to being joined to the growing craton (Karlstrom et al., 1987). The boundary between their older Yavapai province to the northwest and the younger Mazatzal province to the southeast projects from central Arizona, where it was originally recognized, northeastward into Colorado and approximately through the area of this report. Juxtaposition of these two large provinces may have involved thrusting as well as strike-slip movement along a series of shear zones (Karlstrom et al., 1987), though such a through-going tectonic boundary with appropriate trend has not been observed within the area of the present study. However, the identification of such a boundary at today's level of erosion could be complicated by nearly layer-parallel thrusting at the time these provinces were joined (Shaw and Karlstrom, 1999, p. 47).

Regardless of the nature or timing of accretion, the present study has shown that the widely distributed metavolcanic rocks of the large area of this report are similar to those of the well-studied sequences near Salida and Gunnison. Hitherto unassigned in terms of tectonic provenance, they appear to represent the products of volcanic arc environments which became components of the rapid continental expansion southward from the Wyoming craton late in Paleoproterozoic time, when as much as 1300 km of juvenile crust was added from the Cheyenne belt of southern Wyoming to northern Sonora.

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