# Geology of the Precambrian Metamorphic Rocks Along South Hardscrabble Creek, Wet Mountains, Colorado[1]

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### ABSTRACT

*Proterozoic metamorphic rocks exposed along South Hardscrabble Creek are typical of those in the Wet Mountains on the east side of the Ilse fault, lacking the northeast trending, 1-mi (1.6 km) wavelength folds of rocks to the west. They are folded isoclinally implying that this is not a stratigraphic succession, but map units can be described and analyzed.*

*Three major units were recognized: 1) amphibolite, 2) biotite gneiss, and 3) granitic gneiss. Minor rock types include metagabbro and sillimanite-bearing quartzite. The amphibolite and metagabbro have compositions suggesting that they originated as tholeiitic basalts. The biotite gneiss probably had both shale and greywacke protoliths. The mineralogy, textures, and chemistry of the granitic gneisses indicate igneous origin, probably as late tectonic granitic intrusions of crustal derivation.*

## INTRODUCTION

The Wet Mountains are a northwest-southeast trending range which lies between the Front Range and the Sangre de Cristo Range in Central Colorado. They are a broad anticline with a core of Precambrian rocks flanked by deformed Mesozoic and Paleozoic sediments. The Precambrian core can be divided into several parts: the San Isabel Batholith, approximately 1360 Ma (Thomas et al, 1984), comprises the southern third of the core. The batholith is intrusive in amphibolite-grade metamorphic rocks. Plutons of both Boulder Creek age (1700 Ma) and Silver Plume age (1400 Ma) intrude similar metamorphic rocks in the northern portion of the Wet Mountains (Fig. 1). The lower Paleozoic Gem Park and McClure Mountain carbonatite complexes and lamprophyric or basaltic dikes also occur in the Wet Mountains.

The Precambrian rocks are cut by the northwest-southeast trending Ilse fault. Rocks west of the fault are best exposed in the Mount Tyndall quandrangle where the basement rocks include a variety of gneissic rocks, as well as granite and migmatites (Brock and Singewald, 1968). The gneisses are primarily of amphibolite grade, although locally they are of granulite grade as indicated by several small bodies of charnockite. All of these rocks have been deformed into folds with a wavelength of about 1 mi (1.6 km), trending northeast. This deformation contrasts markedly with deformation in rocks on the east side of the Ilse fault. There, a group of gneissic rocks lacks these northeast-trending folds but has been deformed several times.

This study focuses on the metamorphic rocks that are well-exposed along South Hardscrabble Creek at the north edge of the San Isabel Batholith east of the Ilse fault (Fig. 2). The rocks include granitic gneisses, biotite gneisses, and amphibolite as well as minor metagabbro, quartzite, and garnet biotite schist.

Previous work on the metamorphic rocks in the Wet Mountains is limited. Brock and Singewald (1968) described the petrography but provided no chemistry or interpretation of rocks west of the Ilse fault. The metamorphic rocks are grouped as undifferentiated gneisses on Pueblo 2° geologic map (Scott et al, 1978), and several reconnaissance maps (Taylor, 1974; Taylor and Scott, 1973). Several theses describe the geology of the eastern margin of the Wet Mountains (Logan, 1966; Martin, 1954), but these include no chemistry and provide no interpretation. This study divides the gneisses into mappable units and presents major and trace element chemistry. Similarity in appearance of the major units along South Hardscrabble Creek to rocks farther north (e.g., along North Hardscrabble Creek) suggest that the framework established here for discussing these rocks will be important in considering the origins of rocks throughout the Wet Mountains. Similarity between some of these units and rocks described in the Salida and Gunnison areas (Bickford and Boardman, 1984) suggests that understanding of these rocks will be useful in investigating the origin of Proterozoic rocks elsewhere in Colorado.

## ROCKS OF SOUTH HARDSCRABBLE CREEK

The oldest rocks along South Hardscrabble Creek are the metamorphic rocks which are the focus of this study. They are intruded by several types of igneous rocks. These include a few rhyodacitic sills dated at 1441 Ma (M. E. Bickford, 1986, personal communication); the San Isabel granites (dated at about 1360 Ma, Thomas et al, 1984); a large number of undated pegmatites, which may be related to the San Isabel granite or to known granite intrusions; and a number of small undated mafic dikes. Many of these dikes are intruded by the pegmatites, a relation not expected if the dikes were part of the lower Paleozoic alkalic complexes mentioned above. The igneous rocks are not discussed further in this paper.

The metamorphic rocks have been deformed several times. Reconnaissance maps (e.g., Taylor, 1974) suggested that rocks east of the Ilse fault show a strong foliation which was

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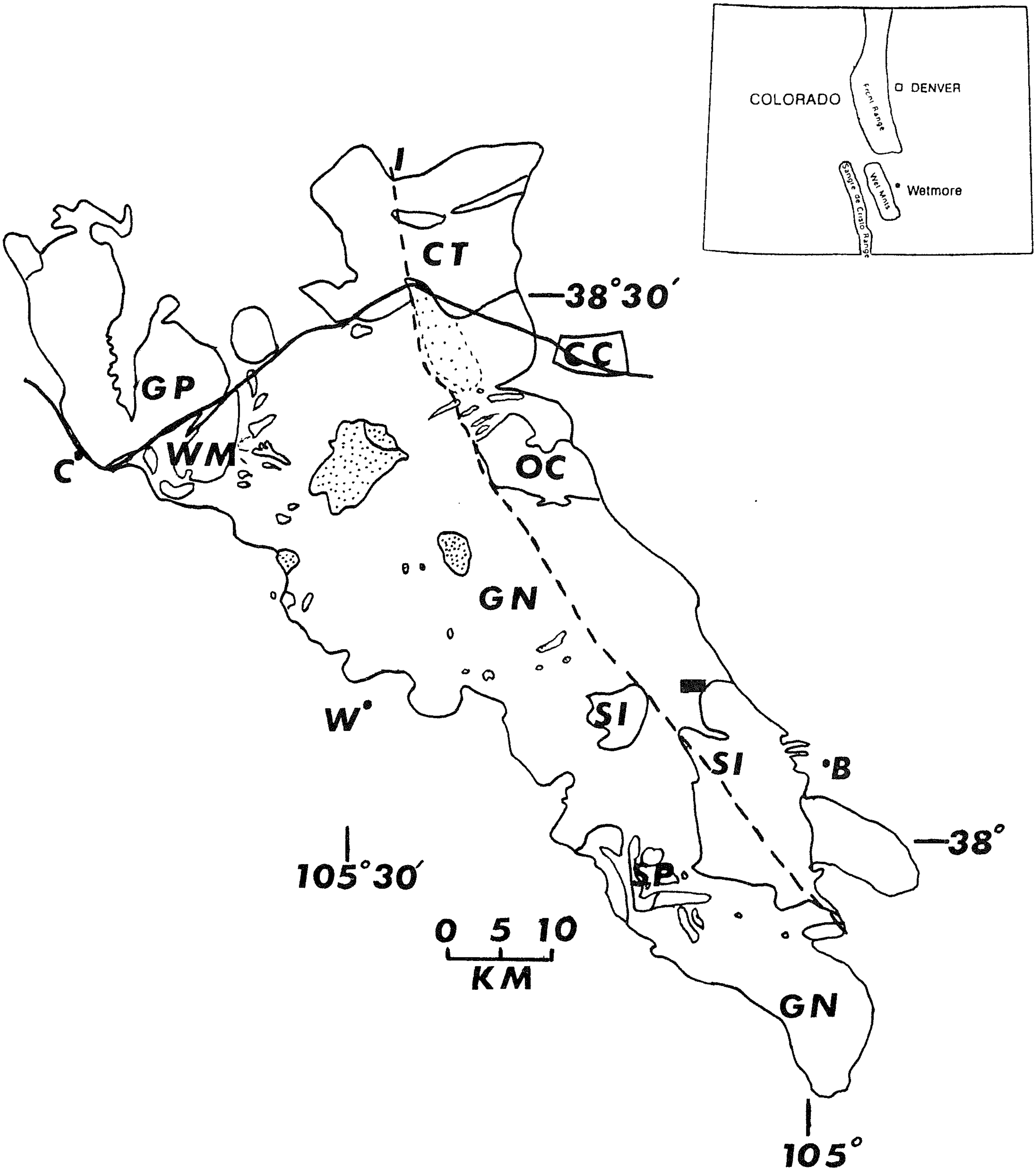

***Figure 1.*** *Geologic map of the Wet Mountains region. GN denotes several gneisses, presumably older than about 1700 Ma. Intrusions of the Boulder Creek event (about 1700 Ma) include the Crampton Mountain-Twin Mountain pluton (CT) and the Garrel Peak stock (GP). Intrusions of the Silver Plume event (1410 ± 50 Ma) include the West McCoy Gulch pluton (WM), Oak Creek pluton (OC), San Isabel batholith (SI) and several small intrusions (SP). Also shown is the trace of the Ilse fault (I). Geographic localities include Canon City (CC), Cotopaxi (C), Beulah (B), Westcliffe (W) and the Arkansas River (A). Dotted regions denote Phanerozoic rocks. The small black rectangle locates the study area.*

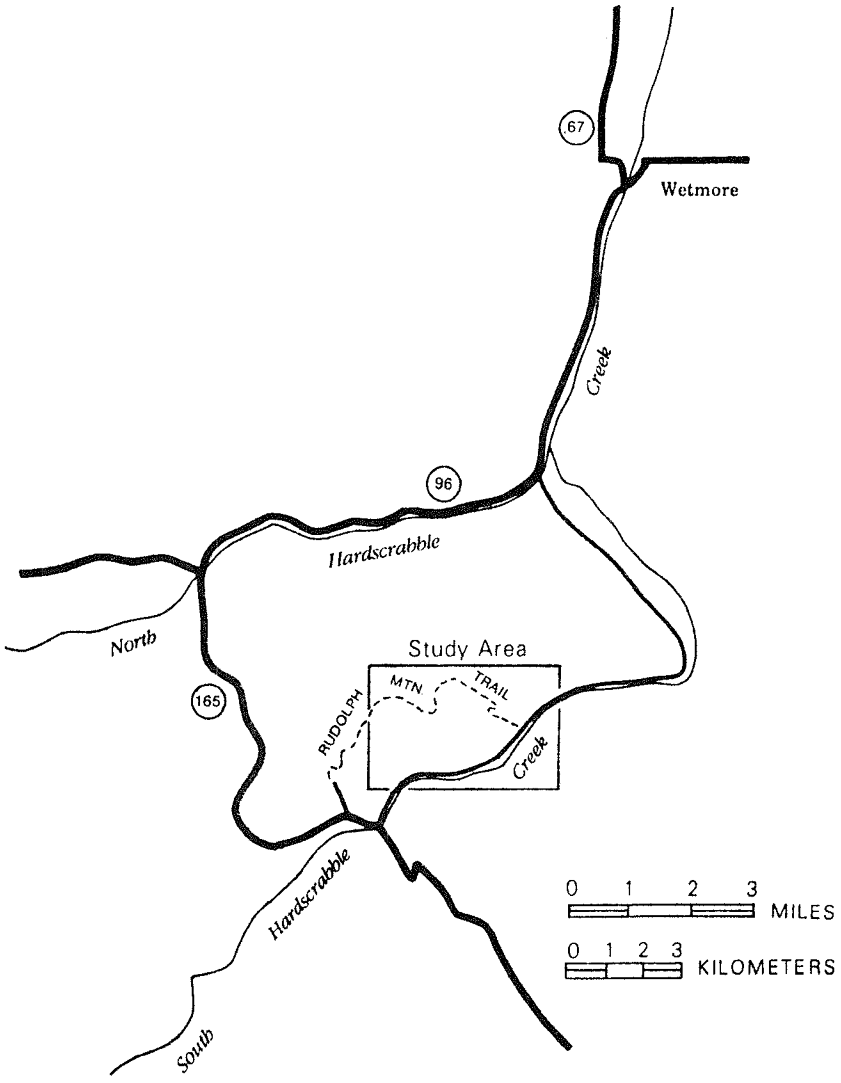

***Figure 2.*** *Location map for the South Hardscrabble Creek area, Wet Mountains, Colorado. The unlabelled road extending southeast from Highway 96 runs along the east margin of the Wet Mountains. Highway 165 is approximately located on the trace of Ilse Fault.*

folded into a large, gentle monocline covering most of the eastern half of the Wet Mountains. However, the rocks along South Hardscrabble Creek contain two foliations (the older of which is only rarely preserved) and show cataclastic deformation parallel to the second foliation. This second foliation is the result of isoclinal folding which was itself later deformed into small, open concentric folds. This is a similar history to the three periods of deformation of metamorphic rocks in portions of the northern Front Range (Braddock and Cole, 1979).

## METAMORPHIC ROCKS - OVERVIEW

Metamorphic rocks are well exposed in an area of about 3 sq mi (8 sq km) along South Hardscrabble Creek (Fig. 2). Approximately 17 percent of the exposed rocks are amphibolite, 50 percent are biotite gneiss, and 33 percent are granitic gneiss. Minor lenses of metagabbro, garnetiferous schist, sillimanitic gneiss, and sillimanite-bearing quartzite are also present. Isoclinal folding produced alternations among amphibolite, biotite gneiss, and granite gneiss (Fig. 3). These divisions were used to create units for detailed analysis. The contacts between units are sub-parallel to the primary foliation.

Most of the contacts are very sharp though parts of the biotite gneiss grade into surrounding granitic gneisses over an interval of approximately 3 ft (1 m).

## PETROGRAPHY OF THE METAMORPHIC ROCKS

### Amphibolites

Two units in the southwestern part of the study area are strongly foliated amphibolite (Fig. 3). Both show minor occurrences of cross-cutting foliations as evidence of an earlier deformation as well as cataclastic movement during the isoclinal folding event.

A modal analysis (Table 1) shows that these units consist almost entirely of hornblende and plagioclase. The plagioclase was determined petrographically to be andesine ($An_{40}$). Biotite is present, though it generally replaces hornblende. Quartz is a minor constituent present as tiny euhedral crystals. A trace of potassium feldspar is also present. The foliation is due to alignment of the mafic minerals (Fig. 4). This simple mineralogy is suggestive of igneous origin; a shale-dolomite protolith would more likely contain some calc-silicate or residual heavy minerals.

The presence of quartz and potassium feldspar in the amphibolite is important to interpretation of the granitic gneisses. Most of the amphibolites show distinct banding between mafic-rich and mafic-poor layers each about 0.1 to 0.2 in. (3 to 5 mm) thick. The presence of small undeformed quartz and potassium feldspar crystals indicates that these layers were formed in a partial melting event. This evidence supports the contention that the interlayered amphibolites and granitic gneisses did not originate through large-scale migmatization and that the granitic gneisses do represent a separate original rock type.

### Metagabbro

A concordant tablular body of metagabbro about 325 ft (100 m) in length by about 6 ft (2 m) thick crops out near the west edge of the field area (Fig. 3). Large clots of hornblende with clinopyroxene cores stand out from a more normally foliated background. A few of these spots enclose small plagioclase crystals and are therefore interpreted as relict ophitic texture. Only hornblende, clinopyroxene, and plagioclase are prominent, although a few trace minerals occur (Table 1). The plagioclase is andesine ($An_{43}$).

### Biotite Gneiss

The biotite-rich gneiss closely resembles the granitic gneisses except for greater abundance of biotite. One typical sample (Table 1) contains over 63 percent total feldspars along with 24 percent quartz. The plagioclase is andesine ($An_{38}$). The foliation results from the alignment of biotite which forms nearly 12 percent of the rock. Biotite appears to be a primary metamorphic mineral and shows no evidence of breaking down from amphibole. A trace of other minerals and myrmekite occur in this rock. One small lens contains almandine-rich garnet. On average, the unit shows a higher degree of mixing in which small stringers of granitic gneiss appear to cut across the foliation for a short distance of approximately

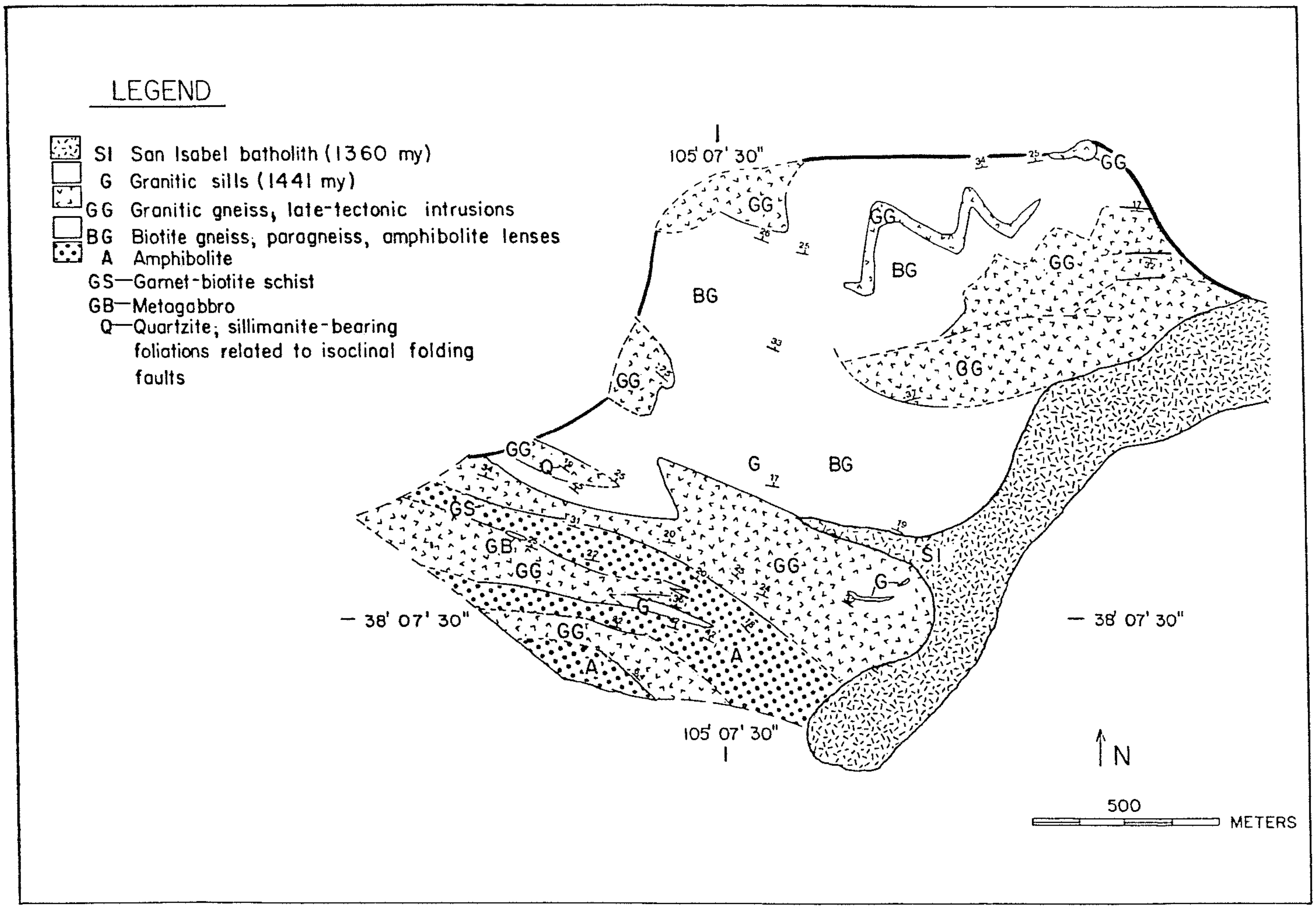

***Figure 3.*** *Geological map of the study area. Numerous small mafic dikes and pegmatities are not shown. The isoclinally folded sequence of amphibolite, biotite gneiss, and granitic gneiss is intruded by 1441 Ma granitic dikes (G) and by the 1360 Ma San Isabel batholith.*

3 ft (1 m) as opposed to the sharp boundaries which the amphibolites make with the gneisses.

## Granitic Gneiss

The granitic gneiss can be separated into six mappable parts (Fig. 3); variations in modal content and chemistry suggest that these are not a single homogeneous unit. Mineralogic and chemical features strongly imply that these were derived from a fractionating granitic magma.

These rocks (Table 1) are nearly void of mafic components. Without the biotite, parts of these units show no visible foliation. However, they are cut by the rhyodacite sills mentioned above and their contacts with the amphibolite units parallel the foliation suggesting that they are part of the metamorphic sequence. Approximately 40 percent of each unit is quartz that shows textures of annealing recrystallization. The proportion of feldspars (orthoclase, microcline, perthite, and plagioclase) is much more variable in the six units (Table 1). The plagioclase ranges from oligoclase ($An_{24}$) to andesine ($An_{35}$). Albite twinning is only partially developed in most specimens. Relict feldspar zonation is present. Large crystals of quartz and feldspar may represent relict phenocrysts. Muscovite occurs in most of the rocks. Myrmekite occurs in all of them. Sillimanite in three of the units places limits on some of the metamorphic conditions. In one unit, quartz,

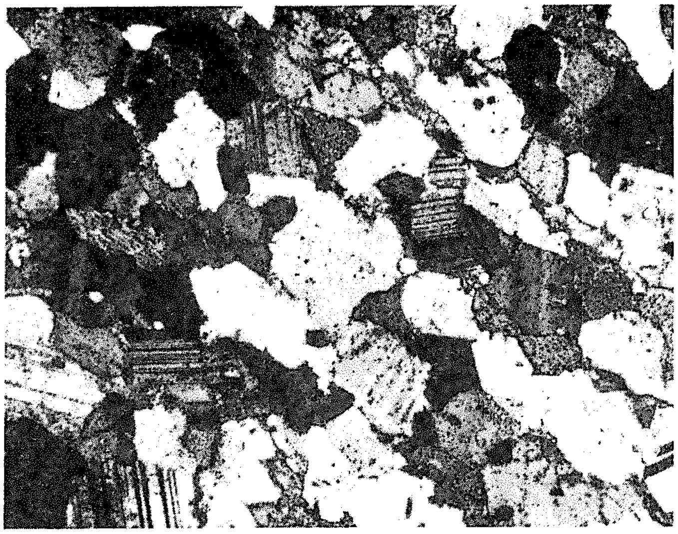

***Figure 4.*** *Photomicrograph (2 mm across) of amphibolite showing albite-twinned plagioclase and hornblende.*

## MODAL ANALYSIS

| | AMPHIBOLITE | | BIOTITE GNEISS | META-GABBRO | GRANITIC GNEISS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **UNIT:** | **B1** (32) | **B2** (9) | **B3** (39) | **MG** (25) | **R1** (31) | **R2** (24) | **R3** (27) | **R4** (18) | **R5** (40) | **R6** (46) |
| Quartz ......... | 2.5 | 2.3 | 24.0 | tr | 40.0 | 36.7 | 35.7 | 38.0 | 42.2 | 54.6 |
| Plagioclase ..... | 51.2 | 40.9 | 6.4 | 25.6 | 12.8 | 22.9 | 11.9 | 17.5 | 14.5 | 29.0 |
| Microcline ...... | 54. | | 13.4 | ± | 12.3 | 22.5 | 27.5 | 25.2 | 21.8 | |
| Perthite ........ | | | 43.5 | | 30.1 | 8.7 | 21.2 | 13.4 | 14.7 | |
| Orthoclase ..... | 1.0 | | | | | 1.5 | | | 1.8 | 12.8 |
| Clino-pyroxene ..... | | | | 22.9 | | | | | | |
| Amphibole ...... | 39.2 | 55.6 | | 50.9 | | | | | | |
| Biotite .......... | 6.0 | 1.2 | 11.8 | | 2.5 | 6.6 | | 2.0 | 2.8 | 2.6 |
| Muscovite ...... | | | | | | | 3.4 | 3.9 | 2.2 | 1.0 |
| Sillimanite ...... | | | | | | ± | tr | ± | | |
| Opaque (Mt) .... | ± | ± | ± | ± | 2.3 | tr | ± | | ± | |
| Epidote ........ | tr | | | ± | | ± | | | | ± |
| Zircon .......... | | ± | ± | | ± | | | | ± | |
| Sphene ........ | tr | ± | | ± | | | | | | |
| Apatite ......... | ± | | ± | | | | | | ± | |
| Rutile (Qtz) ..... | | | | | | | ± | ± | ± | ± |
| Myrmekite ...... | | | tr | | ± | ± | ± | ± | ± | ± |

***Table 1.*** *Modal analyses of a representative thin section for each of the major metamorphic units (B1, B2 are amphibolites, B3 is the biotite gneiss, MG is the metagabbro, R1-R6 are the granitic gneiss units).*

***Figure 5.*** *Photomicrograph (2 mm across) of granitic gneiss showing reaction boundaries of muscovite (m) + quartz (q) with kspar (k) + sillimanite (s).*

muscovite, sillimanite, and microcline have mutual reaction boundaries (Fig. 5) suggesting that metamorphic pressures and temperatures lay along the univariant reaction curve for muscovite and quartz with K-feldspar and sillimanite.

Though the micas suggest that there might have been a sedimentary component to these gneisses, the other textures and the chemistry (below) argue for an igneous origin. The presence of several blocks of amphibolite, resembling xenoliths, in one of the granitic gneiss units supports the conclusion that these rocks were originally two-mica granites.

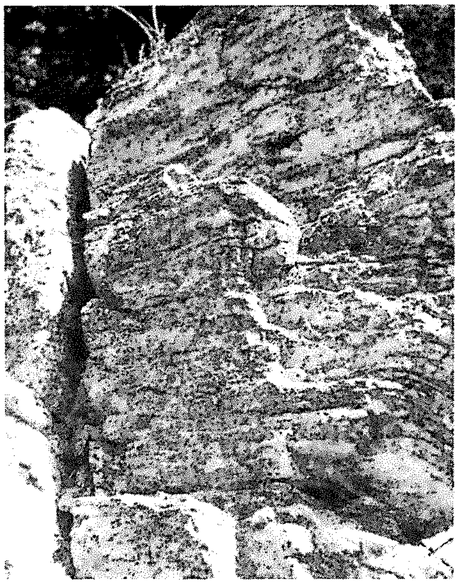

***Figure 6.*** *Outcrop of quartzite unit.*

### Quartzite

Perhaps the most interesting unit is the sillimanite-bearing quartzite outcrop found within one of the granitic gneiss units near the northwest edge of the field area. It is less than 10 ft (3 m) thick and slightly more than 325 ft (100 m) in exposed length (Fig. 6). The pink color is distinctive, but in hand specimen it is the banding of dark, discontinuous layers within the host rock which stands out (Fig. 7). The rock is composed almost entirely of interlocking, elongate crystals of quartz. Sillimanite and muscovite (retrograde from sillimanite) also occur. It is the dark bands that suggest an interpretation for this rock. Small rods of sillimanite are highly concentrated in the discontinuous dark areas of the rock (Fig. 7). This suggests that a quartz sandstone host received frequent but discontinuous input from a mud source forming pockets of mud within the sand, a texture common to flaser beds (Reinick and Singh, 1980). Although deformation may have produced this discontinuous pattern (and preservation of flaser beds would be unusual at this grade of metamorphism), the need for an environment capable of placing lenses of mud in a sandy regime does not change. The chemistry of this unit strongly supports this type of regime (Table 2). Flaser beds, in turn, are typically formed in shoreline or tidal flat types of environments. One other possibility is that the shale-sand layers formed in a turbidite sequence.

***Figure 7a.*** *Hand specimen of quartzite unit.*

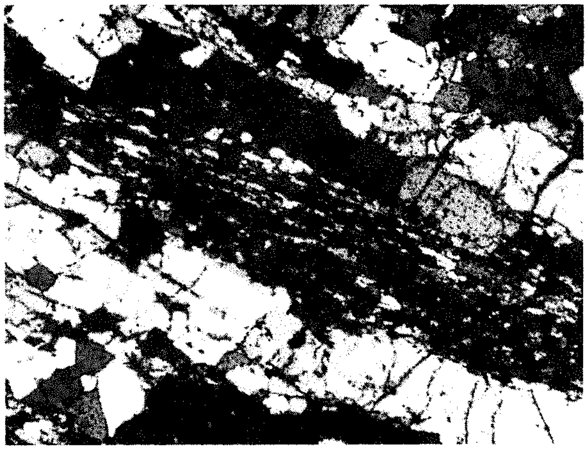

***Figure 7b.*** *Photomicrograph (2 mm across) showing concentration of small rods of sillimanite in the dark regions of the hand specimen.*

## PETROCHEMISTRY OF THE METAMORPHIC ROCKS

### Chemical Analyses

Forty samples from this field area were analyzed on an x-ray fluorescence spectrometer. Ten major and minor oxides and twelve trace elements were determined (Bower, 1985). $Fe^{2+}/Fe^{3+}$ ratios were determined by spectrophotometric analysis (Bower, 1984). The average values for each unit are given in Table 2. The chemical norms (CIPW) for the samples best representing each unit are given in Table 3.

### Amphibolites/Metagabbro

The amphibolite and metagabbro units appear to have originated as tholeiitic magmas. Besides the petrographic evidence discussed above, the chemistry of the rocks (Figs. 8a, 8b) support an igneous origin.

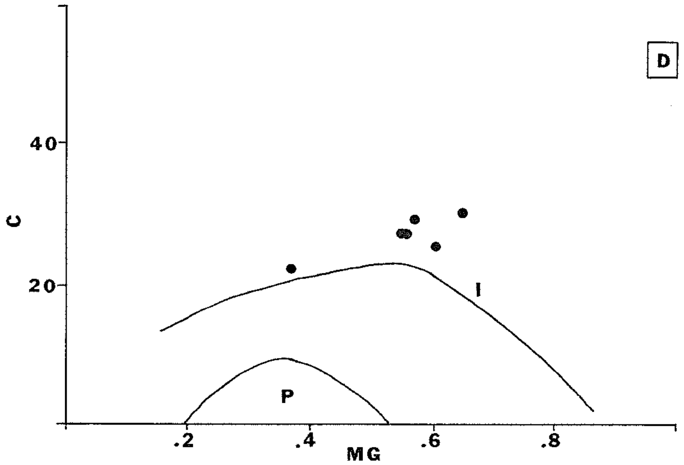

***Figure 8a.*** *Plot of Niggli C versus Niggli Mg values (after Leake, 1964). I: trend for igneous rocks; D and P: fields of dolomite and pelitic material respectively.*

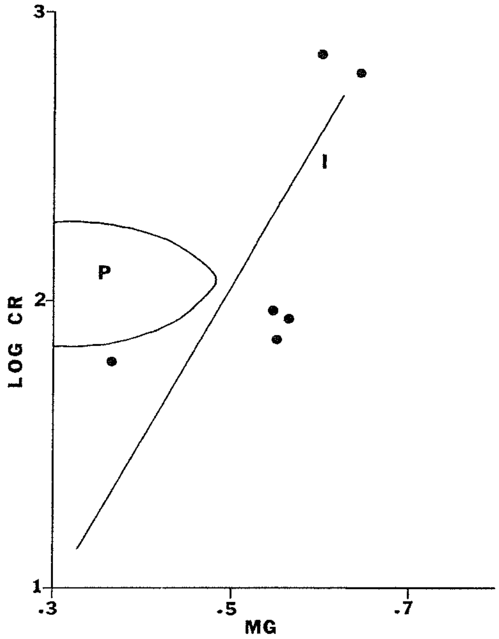

***Figure 8b.*** *Plot of Cr versus Niggli MG (after Leake, 1964). Symbols are the same as in Figure 8a.*

| | Amphibolite | | Biotite Gneiss | Metagabbro | Granitic Gneiss | | | | | | Quartzite |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **B1** (2) | **B2** (8) | **B3** (5) | **MG** (2) | **R1** (2) | **R2** (5) | **R3** (7) | **R4** (1) | **R5** (2) | **R6** (1) | HC-19-84 |
| $SiO_2$ ...... | 50.99 ± 1.68 | 50.26 ± 1.24 | 64.27 ± 7.53 | 49.61 ± .37 | 73.62 ± .24 | 74.78 ± 2.62 | 75.06 ± 1.44 | 76.11 | 75.24 ± 1.14 | 70.46 | 83.09 |
| $TiO_2$ ...... | 1.28 ± .47 | .90 ± .24 | .68 ± .32 | .67 ± .04 | .18 ± .10 | .19 ± .12 | .16 ± .09 | 0.24 | .10 ± .07 | 0.38 | 0.17 |
| $Al_2O_3$ ...... | 19.51 ± .76 | 15.82 ± 1.44 | 15.61 ± 3.71 | 10.02 ± .89 | 13.00 ± .19 | 12.90 ± .74 | 12.78 ± .55 | 13.32 | 13.46 ± .23 | 13.17 | 12.28 |
| $Fe_2O_3$ .. .. | 3.56 ± 1.30 | 2.65 ± 1.31 | 4.50 | 8.04 | 1.58 ± 1.05 | 1.01 ± .61 | 0.98 ± .36 | 1.08 | .93 ± .37 | 1.26 | 0.28 |
| FeO ... ... | 6.85 ± 1.75 | 6.71 ± .81 | 0.98 | 2.16 | 0.24 ± .23 | 0.64 ± .39 | 0.39 ± 0.25 | .53 | .18 ± .12 | 1.46 | |
| MnO . .. | .18 ± .01 | .19 ± .02 | .13 ± .06 | .34 ± .01 | .02 ± 0.0 | .02 ± .01 | .02 ± .01 | 0.01 | .02 ± .01 | 0.05 | 0.00 |
| MgO .. | 3.28 ± .18 | 6.24 ± 1.17 | 2.03 ± .98 | 10.75 ± 1.49 | .13 ± .09 | .59 ± .80 | .25 ± .23 | 0.24 | .11 ± .04 | 1.14 | 0.04 |
| CaO ... | 7.66 ± 3.37 | 9.96 ± 1.26 | 2.74 ± 1.81 | 13.52 ± .56 | .95 ± .29 | 1.11 ± .66 | .89 ± .70 | 1.98 | .58 ± .07 | 0.82 | 0.07 |
| $Na_2O$ | 2.50 ± .45 | 2.92 ± .61 | 2.81 ± 1.00 | 2.04 ± .36 | 3.08 ± .66 | 2.96 ± 1.11 | 2.76 ± .89 | 3.71 | 2.55 ± .48 | 2.00 | 0.01 |
| $K_2O$ ... .. | 2.30 ± 1.76 | 1.07 ± .40 | 4.04 ± 1.88 | .74 ± .01 | 4.61 ± .72 | 3.84 ± 1.39 | 4.45 ± 2.33 | 1.03 | 5.74 ± .28 | 6.62 | 0.06 |
| $P_2O_5$ . . | .42 ± .15 | .28 ± .13 | .17 ± .11 | .18 ± .06 | .03 ± .01 | .04 ± .03 | .36 ± .57 | 0.02 | .02 ± .01 | 0.02 | 0.00 |
| **Total** | **99.22** | **98.19** | **97.99** | **99.25** | **97.44** | **98.01** | **98.13** | **98.33** | **98.95** | **97.52** | **96.02**<br>**4.27** ($H_2O+$)<br>**100.00** |
| Rb (10) . . . | 65 ± 92 | (8) ± 7 | 129 ± 37 | 14 ± 9 | 176 ± 99 | 129 ± 97 | 152 ± 126 | 20 | 216 ± 138 | 154 | (0) |
| Sr (10) ... | 513 ± 230 | 399 ± 202 | 233 ± 136 | 180 ± 42 | 71 ± 17 | 162 ± 94 | 106 ± 69 | 195 | 117 ± 31 | 153 | (3) |
| Ba (100) .. | 532 ± 641 | 335 ± 158 | 1061 ± 750 | 142 ± 115 | 541 ± 658 | 755 ± 502 | 774 ± 712 | 185 | 553 ± 321 | 1748 | (0) |
| La (50) .. .. | (11) ± 16 | (20) ± 17 | (37) ± 27 | (16) ± 19 | (2) ± 2 | (27) ± 15 | (22) ± 31 | (19) | (19) ± 1 | (28) | 91 |
| Ce (50) .. | 127 ± 23 | (49) ± 30 | 59 ± 38 | (25) ± 18 | 85 ± 42 | 87 ± 21 | 85 ± 47 | 71 | 106 ± 47 | 92 | 96 |
| Y (10) ...... | (5) ± 6 | 32 ± 24 | (5) ± 4 | (6) ± 1 | (4) ± 1 | (5) ± 4 | (2) ± 3 | (10) | (0) ± | (5) | 25 |
| Zr (10) ..... | 131 ± 107 | 71 ± 19 | 166 ± 41 | 71 ± 36 | 149 ± 40 | 216 ± 53 | 154 ± 89 | 179 | 99 ± 5 | 197 | 123 |
| Ni (50) ..... | (0) ± 0 | (14) ± 20 | (6) ± 14 | 71 ± 100 | (15) ± 21 | (17) ± 35 | (17) ± 34 | (0) | (34) ± 48 | (0) | (0) |
| Co (10) .... | 34 ± 13 | 33 ± 1 | 17 ± 16 | 33 ± 39 | 18 ± 18 | 23 ± 25 | 23 ± 23 | 34 | 24 ± 26 | (5) | 25 |
| Cr (10) ..... | 61 ± 36 | 56 ± 25 | 11 ± 16 | 609 ± 70 | 15 ± 21 | (9) ± 14 | 12 ± 13 | 24 | 13 ± 15 | (0) | 24 |
| V (50) ...... | 245 ± 34 | 222 ± 32 | 92 ± 69 | 184 ± 42 | 23 ± 5 | 29 ± 11 | 26 ± 7 | (31) | 29 ± 11 | (51) | (17) |
| Zn (10) . | 89 ± 42 | 54 ± 33 | 125 ± 111 | 133 ± 16 | 14 ± 20 | 13 ± 14 | 24 ± 29 | (0) | 26 ± 36 | 78 | (0) |

***Table 2.*** *Average whole-rock chemical analyses for each of the major metamorphic units. Colorado College chemist Nathan Bower analyzed the samples at Los Alamos National Laboratory. Parentheses by unit name denote number of samples analyzed for each unit. Unit abbreviations are the same as in Table 1. Parentheses around the trace element values show analyses which were below detection limits of the x-ray fluorescence spectrometer. Ferric/Ferrous ratios were determined spectrophotometrically (Bower, 1984). For the units in which no standard deviation is shown, only the most representative sample of each unit was analyzed for the iron ratios.*

A plot of $Sio_2$ x $Zr/Tio_2$ (Fig. 9) places the amphibolites and metagabbro well within the tholeiitic field and all the amphibolites are hypersthene-normative (Table 3). Amphibolite from one unit is quartz-normative, but most other amphibolites are olivine-normative. One amphibolite lens in the biotite gneiss unit is also slightly quartz-normative. The metagabbro has the highest olivine content in the norm of any of the mafic rocks. Since the metagabbro also has a very high chromium content, it is likely to have formed through a cumulus process.

## Biotite Gneiss

The chemical analyses of this unit (Table 2) indicate that it lies halfway between the amphibolites and granitic gneisses in terms of silica content. It is not a completely homogeneous unit and contains at least one lens of amphibolite and one lens rich in magnetite porphyroblasts. Comparison with analyses of sedimentary rocks (Blatt et al, 1972) indicates that the biotite gneiss may have had several protoliths. The peraluminous rocks with silica contents less than 60 weight percent were probably shales, while the rocks which have about 65 weight percent silica and which are undersaturated in alumina were probably greywackes, and the high silica rocks (70-75 weight percent) resemble quartz wackes.

## Granitic Gneiss

The origin fo the granitic gneisses needs to be approached in two parts. First, the question of their possibly being large-scale migmatitic differentiates from an originally homogeneous pile needs to be discussed. Second, accepting that they actually represent a protolith interlayered and deformed with the other units, the question of igneous versus sedimentary origin can be addressed.

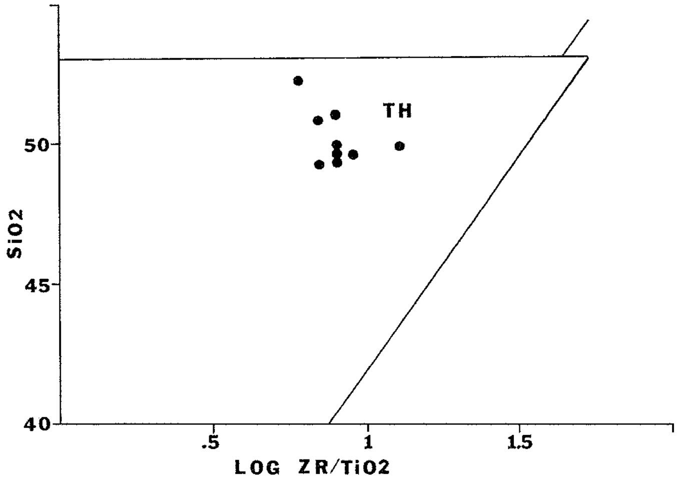

***Figure 9.*** *Weight percent $SiO_2$ versus log $Zr/TiO_2$ plot (Winchester and Floyd, 1977) showing that amphibolite and the metagabbro specimens plot within the tholeitte field (TH). Alkali basalts plot at higher $Zr/TiO_2$. Andesites plot at higher $SiO_2$.*

**CIPW NORM CALCULATIONS**

| | AMPHIBOLITE | | BIOTITE GNEISS | META-GABBRO | GRANITIC GNEISS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **UNIT:** | **B1** | **B2** | **B3** | **MG** | **R1** | **R2** | **R3** | **R4** | **R5** | **R6** |
| Quartz ......... | 3.89 | | 21.16 | | 35.85 | 39.59 | 40.62 | 45.99 | 37.02 | 29.40 |
| Corundum ...... | | | 1.94 | | 1.25 | 1.88 | 2.60 | 2.52 | 1.99 | 1.13 |
| Zircon .......... | 0.03 | 0.01 | 0.03 | .01 | 0.03 | 0.04 | 0.03 | 0.04 | 0.02 | 0.04 |
| Orthoclase ..... | 13.59 | 6.32 | 23.88 | 4.37 | 27.24 | 22.69 | 26.30 | 6.09 | 33.92 | 39.12 |
| Albite ........... | 21.15 | 24.71 | 23.78 | 17.26 | 26.06 | 25.05 | 23.35 | 31.39 | 21.58 | 16.92 |
| Anorthite ....... | 35.23 | 26.91 | 12.77 | 16.00 | 4.65 | 5.45 | 2.26 | 9.79 | 2.90 | 4.34 |
| Diopside ....... | 0.25 | 16.97 | | 40.43 | | | | | | |
| Hypersthene ... | 15.90 | 14.99 | 11.10 | 3.12 | 0.32 | 1.54 | 0.62 | 0.06 | 0.27 | 3.95 |
| Olivine ......... | | 0.94 | | 12.28 | | | | | | |
| Magnetite ...... | 5.16 | 3.84 | 1.32 | 3.26 | 0.32 | 1.46 | .86 | 1.04 | 0.40 | 1.83 |
| Chromite ....... | 0.01 | 0.01 | 0.002 | 0.13 | 0.003 | 0.002 | 0.003 | 0.005 | 0.003 | |
| Hematite ....... | | | | | 1.36 | | 0.39 | 0.94 | 0.66 | |
| Ilmenite ........ | 2.43 | 1.71 | 1.29 | 1.27 | 0.34 | 0.36 | 0.30 | 0.46 | 0.19 | 0.72 |
| Apatite ......... | 0.97 | 0.65 | 0.39 | 0.42 | 0.07 | 0.09 | 0.83 | 0.05 | 0.04 | 0.05 |
| **Solid Solutions** (mole %) | | | | | | | | | | |
| P1 (An) ....... | 61.1 | 50.7 | 34. | 47. | 14.4 | 17.0 | 8. | 23. | 11.2 | 20. |
| O1 (Fo) ....... | | 69.4 | | 73. | | | | | | |
| Hy (En) ....... | 57.8 | 69.4 | 52. | 73. | 100. | 96.6 | 100. | 100. | 100. | 77. |
| Di (En) ........ | 28.9 | 34.7 | | 37. | | | | | | |

***Table 3.*** *Normative calculations (CIPW) for each of the metamorphic units (abbreviations same as in Table 1).*

The outcrop pattern (Fig. 3) shows large, thick units of granitic-appearing material which could have formed through an extensive metamorphic-differentiation event. These units are cut by both the San Isabel batholith and the older rhyodacites, and their contacts are parallel to foliation in interleaved mafic units at contacts, indicating that they are part of the metamorphic package. The question of possible origin through migmatization can be approached through a series of observations. The granitic gneiss forms as discrete layers which have sharp contacts with the amphibolite layers and show only minor intermingling with the biotite gneiss. The sillimanite-bearing quartzite lies within these layers and shows no partial melting. The amphibolites are themselves differentiated. For the granitic gneisses to have formed through a similar event would require two episodes of metamorphic differentiation. In the first episode, plagioclase, quartz, and potassium feldspar would have been removed from some precursor which comprised all three of the rock types. The second episode would only have involved quartz and potassium feldspar, minerals with lower temperatures of fusion than plagioclase. Both a protolith which could have differentiated into amphibolite, biotite gneiss, and granite and a two episode process of differentiation seem improbable. Plagioclase compositions in the granitic gneiss of approximately $An_{30}$ would require a host material to have had compositions in the sodic bytownite ($An_{70}$) range for solidus and liquidus relations to match on a simple closed system two-phase Ab-An diagram. Texturally, there is a foliation present in the granitic gneiss units, the quartzo-feldspathic minerals show equilibrium triple junctions, plagioclase is only partially twinned, and quartz has undergone some annealing; all of which argue for metamorphic origin. Trends in Rb-Sr-Zr and K-C-N (Figs. 10 and 11) are more typical of igneous differentiation than of a eutectic melt. Also, the plots on the Q-Ab-Or diagram (Fig. 12) are not located at the minima for the pressure conditions which existed during metamorphism. Taken together, this is convincing evidence that the granitic gneisses existed as distinct units prior to the completion of metamorphism and did not form through migmatization.

The petrographic evidence discussed above favored an igneous origin, though the presence of minor biotite, muscovite, and sillimanite could suggest either an original clay component or a two-mica granite. Zoned plagioclase, possible relict quartz and feldspar phenocrysts, and modal values suggest an igneous origin. The xenoliths support granitic intrusion, though they could have been formed from blocks trapped in a rhyolitic ash-flow tuff.

The chemistry strongly supports igneous origin. Triangular plots of both K-C-N (Fig. 10) and Rb-Sr-Zr (Fig. 11) do not show a pattern that might arise from constant weathering of a source terrain. The linear patterns are typical of differentiation trends in igneous suites and could have been produced by eruption of rhyolitic ash from an evolving magma chamber or by injection of a differentiated granite. A plot on the Q-Ab-Or triangle (Fig. 12) shows that most of these rocks cluster around the low water pressure minima in the granite system.

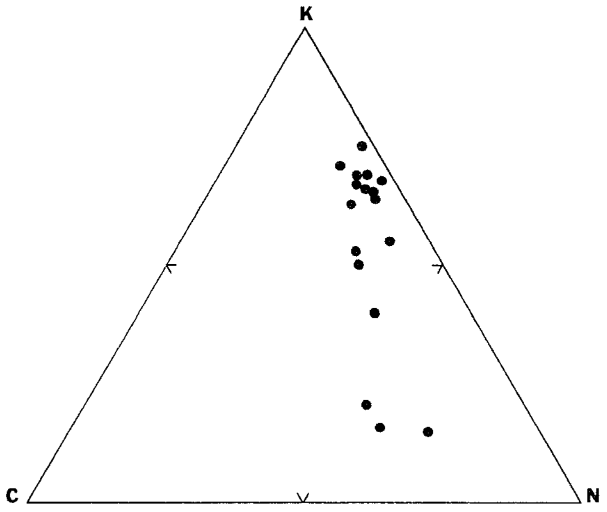

**Figure 10.** *K-C-N triangle for granitic gneiss samples showing linear relationship which suggests an igneous differentiation trend. Note, however, that isoclinal folding prevents any claims that these represent a temporal sequence.*

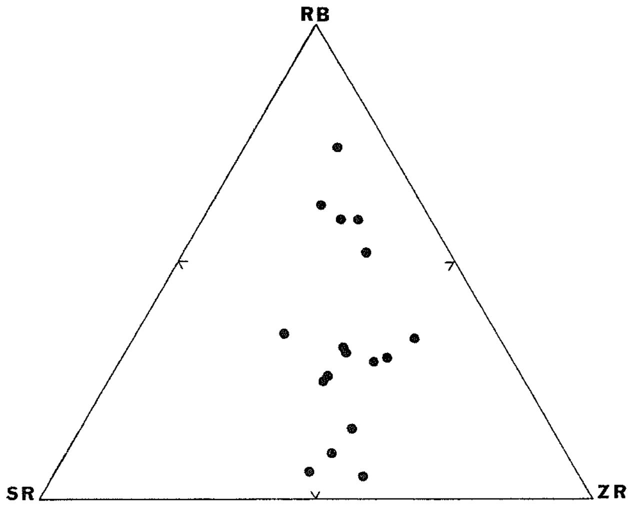

**Figure 11.** *Rb-Sr-Zr triangle for granitic gneiss samples (see Figure 10 also). Plot is more similar to igneous suites than to sediments produced through weathering of a source terrane.*

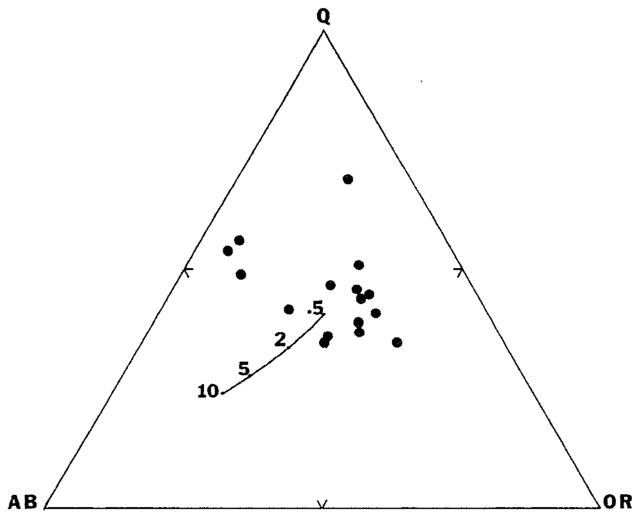

**Figure 12.** *Q-Ab-Or triangular plot for individual samples of granitic gneiss. The minima for the system are labelled for .5, 2, 5, and 10 kilobars. While the rocks plot near the minima for volcanism, they did not arise through partial melting under the higher pressure conditions of metamorphism (3 to 3.5 kb). The samples which plot near the Q-Ab sideline all showed unusually high biotite content while the sample which plotted closest to the Q-point was rich in sillimanite.*

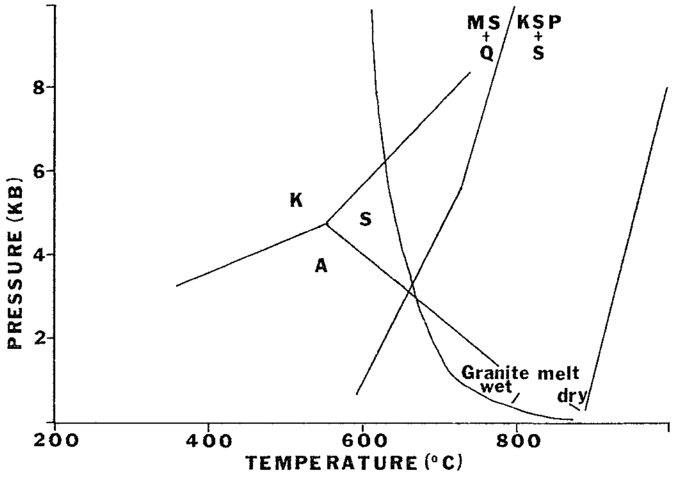

**Figure 13.** *Plot of andalusite(A)-kyanite(K)-sillimanite(S) system, the univariant quartz (Q) + muscovite (MS) = Kspar (KSP) + sillimanite (S), and melting of granite (wet and dry) curves used to determine probable conditions of metamorphism.*

Combining the chemical and petrographic evidence strongly suggests that large volumes of the granitic gneisses originated as melts. They are corundum-normative and contain two micas implying crustal derivation. The fact that the granitic gneisses are part of the deformed package but show less intense deformation is evidence that intrusion occurred during but late in the tectonic event.

## CONDITIONS OF METAMORPHISM

Several mineralogical observations make it possible to place reasonably narrow constraints on the pressure, temperature, and water conditions during metamorphism. The presence of abundant mica and amphibole indicate that water was present and that granulite facies conditions were not reached. However, these minerals do not constrain the activity of water since other fluids may have been present during metamorphism. The intense deformation, destruction of most relict features, and presence of sillimanite indicates that metamorphism occurred under high grade amphibolite conditions.

Conditions approached that of melting in a wet granite but were not sufficient to cause anything greater than local migmatiziation. The critical assemblage is the muscovite + quartz = sillimanite + Kspar univariant reaction in a granitic gneiss unit. A plot showing that curve with conditions under which a wet granite would melt covers an extremely limited region of P-T space (Fig. 13). This indicates that temperatures of metamorphism were about 1,200°F (650°C) and that pressures were about 3 to 3.5 kilobars (300,000 to 350,000 kPa). These estimates place these rocks in the uppermost amphibolite facies. These numbers are actually minimum conditions since the granite curve is based on albite-plagioclase, not the oligoclase found in these rocks. The intrusion of the San Isabel batholith may also have reset temperatures. Further studies involving the use of the garnet-biotite schist for geothermometry and searching for fluid inclusions which might constrain the fluid activities are underway.

## CONCLUSIONS

A sequence of metamorphic rocks of Proterozoic age is well exposed along South Hardscrabble Creek in the Wet Mountains. The presence of at least two foliations in rocks which were deformed into isoclinal folds and then refolded more gently suggests that this is not a stratigraphic sequence of rocks. The similarity of these rocks to rocks farther north in the Wet Mountains suggests that the units described in this study are important in defining and mapping other metamorphic rocks in the Wet Mountains.

Metamorphism reached peak conditions in the upper amphibolite facies. Minor migmatiziation suggests that partial melting under wet conditions was approached. The presence of the univariant reaction, muscovite + quartz = sillimanite + Kspar, helps to place the pressure at between 3 and 3.5 kilobars (300,000 and 350,000 kPa) and the temperature at about 1,200°F (650°C). Some retrograde reactions have occurred.

The sequence contains a variety of rock types. Amphibolites of tholeiitic basalt origin dominate the southwestern section of the field area. A metagabbro shows relict ophitic textures. The gneissic granites formed from two-mica, corundum-normative granitic intrusions probably derived from the crust. They intruded late in the tectonic event. The sillimanite-bearing quartzite is the best example of sedimentary material and argues for an environment capable of depositing pockets of mud in sand. The portion of the biotite gneiss which appears to have had a quartz wacke protolith requires a cratonic source of sediment input; the shale and graywacke protoliths suggest deep water deposition.

These studies are presently being extended north in the Wet Mountains in an effort to provide a firmer basis for interpretation of original tectonic setting through the use of discriminant diagrams. Comparisons of rocks on either side of the Ilse fault can then be made. On a still larger scale, the question of whether the Wet Mountains contain a suite of high-grade rocks equivalent to those which have been described farther west near Salida and Gunnison (Bickford and Boardman, 1984) or whether these are two separate terranes involved in the development of continental crust in Colorado may be addressed.

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