PROTEROZOIC CRYSTALLINE ROCKS IN THE WET MOUNTAINS AND VICINITY, CENTRAL COLORADO

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Abstract—The oldest rocks in the Wet Mountains were metamorphosed about 1700 m.y. ago. They include biotite gneiss, granitic gneiss and amphibolite together with minor occurrences of charnockitic gneiss, quartzite and other units. The metamorphic rocks were intruded by late tectonic granitic rocks of the Crampton Mountain-Twin Mountain batholith and Garell Peak stock during the Boulder Creek intrusive event about 1700–1650 m.y. ago. A second major period of intrusion (Silver Plume event) occurred about 1400 m.y. ago and produced numerous granitic plutons including those at Williams Creek, Oak Creek and West McCoy Gulch. The youngest of these intrusions is the 1360 m.y. San Isabel batholith. Proterozoic rocks in the Wet Mountains were brought to the surface during Phanerozoic faulting and folding.

INTRODUCTION

The Wet Mountains are a northwest-southeast-trending range slightly more than 80 km long and averaging about 25–30 km in width in central Colorado (Fig. 1). At the north end they are about 2,100 m high, rising steadily to more than 3,600 m at Greenhorn Peak in the south. The crest of the range is a fairly flat erosional surface of mid-Tertiary age (Epis and Chapin, 1975).

The Wet Mountains are separated from the Sangre de Cristo Range to the west by the Wet Mountain Valley and Huerfano Park. To the northwest, the Arkansas River is usually chosen as the boundary between the Wet Mountains and the Front Range, although there is no abrupt change. They are separated from the southern tip of the Front Range by the Canon City Embayment, and the Colorado Piedmont Section of the Great Plains lies to the east and south.

Geologically, the Wet Mountains are a fault-bounded, south-plunging anticlinorium that exposes Proterozoic rocks at the surface (Fig. 2). Most of these rocks are amphibolite-grade gneisses and schists, many of which have been partially melted to produce migmatites. In the north, a number of granitic plutons have intruded these rocks, but the San Isabel batholith is the only large pluton in the south (Fig. 2). In this paper, we describe the petrology and geochemistry of the Precambrian rock units which occur in the Wet Mountains and then briefly summarize the results of geochronological investigations and the structural geology. Though a number of theses and other studies have been done in the Wet Mountains, portions of the range have not yet been described in the literature, and most of the older studies did not include geochemical analyses and interpretations.

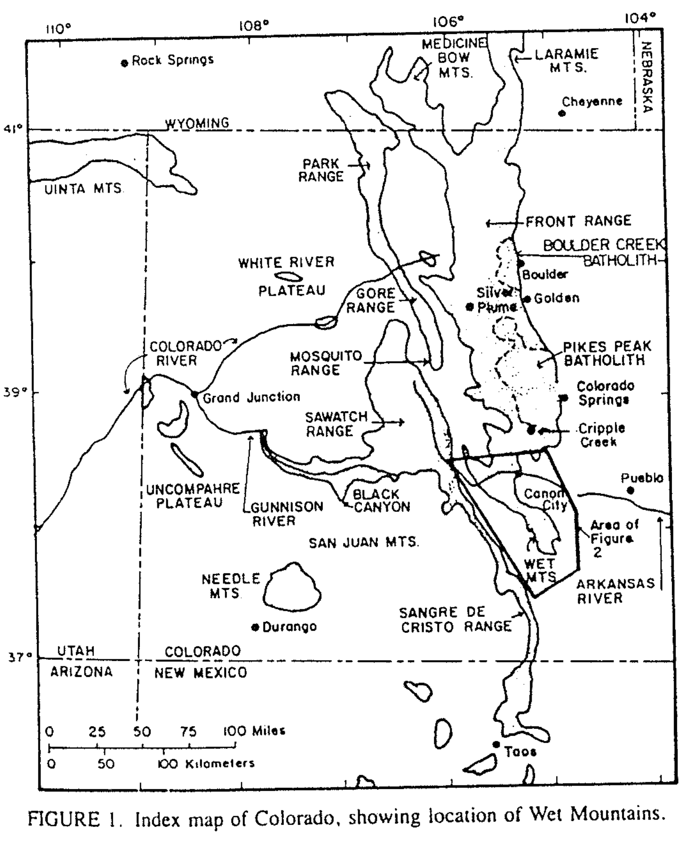

FIGURE 1. Index map of Colorado, showing location of Wet Mountains.

METAMORPHIC ROCKS OF THE WET MOUNTAINS

Introduction

The metamorphic rocks of the Wet Mountains are mostly mica schists, quartzo-feldspathic gneisses and amphibolites of sillimanite grade. Most

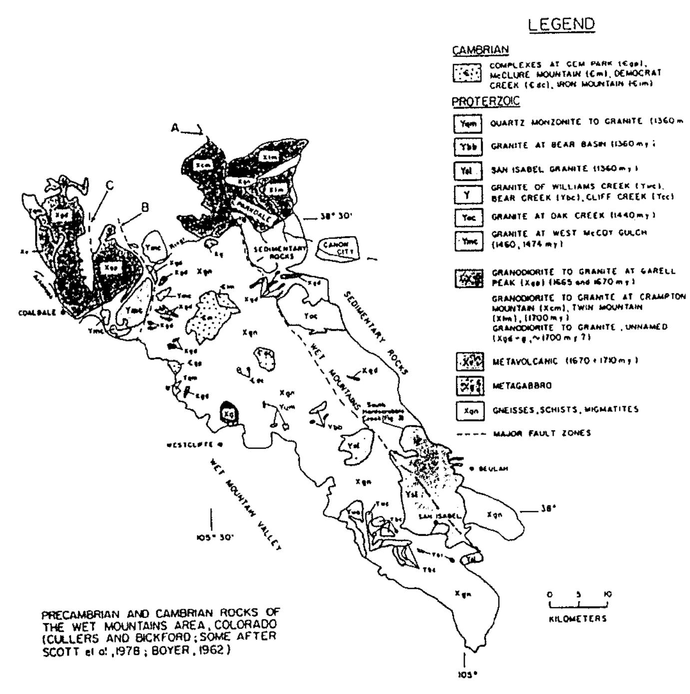

FIGURE 2. Geologic map of the Wet Mountains area. Faults drawn as dashed lines include: A – Ilse fault, B – Cotopaxi fault and C – Pleasant Valley fault.

of these rocks have been partially melted to form migmatites, some of which are quite contorted to the south. Most of the metamorphic section consists of paragneisses with intrusions of mafic materials. The lack of recognized volcanic protoliths, especially rhyolitic ash-flow tuffs and flows, distinguishes these metamorphic rocks from sequences immediately to the west in the Salida and Howard areas, though the higher grade of metamorphism in the Wet Mountains may have destroyed textural evidence of volcanic origins. Rare conformable lenses of calc-silicate gneiss and quartzite suggest that original bedding is nearly parallel to foliation. However, the presence of small, scattered isoclinal fold noses throughout the Wet Mountains suggests that much of the layering may instead be of tectonic origin. Several periods of deformation affected these rocks, and several ages of plutonism postdate the metamorphism and deformation.

The Ilse fault divides the metamorphic rocks into an eastern and a western portion. Incomplete studies preclude making any statements about whether these two portions were originally one terrane which has been faulted or whether the fault joins two distinct terranes. There is an obvious change in structural patterns across the fault as seen in the Pueblo $1 \times 2°$ sheet (Scott et al., 1978), and new studies have raised questions about the structural histories of the two regions. There are also some differences in protoliths of the rocks in the two regions, especially for rocks which are volumetrically minor (e.g., the charnockites and ultramafic rocks in the west and the sillimanite-bearing quartzite in the east). Nonetheless, the lack of detailed studies east of the Ilse fault makes it difficult to prove that these were originally two terranes.

Only two small regions of metamorphic rocks in the Wet Mountains have been studied in detail. These are the 7.5-minute Mount Tyndall quadrangle which is located west of the Ilse fault and a 12 km^2 area along South Hardscrabble Creek located east of the Ilse fault. Though preliminary investigations suggest that these two regions are representative of the metamorphic rocks in the Wet Mountains, results of the geochemical studies in these two regions should not necessarily be assumed to apply to the entire range.

Metamorphic rocks in the Mount Tyndall quadrangle

Early studies of these rocks occurred in the 1950's during thorium investigations (Christman et al., 1952, 1959). Brock and Singewald (1968) mapped the Mount Tyndall quadrangle and divided the metamorphic rocks into 27 units which they described petrographically. No geochemical studies were made, however, and work by Lanzirotti and Condie (1986a, b) and unpublished data by the authors of this paper represent the first attempts to place these rocks in their original tectonic setting.

The major rock types of the Mount Tyndall quadrangle include biotite gneiss, hornblende gneiss, alaskitic granite-gneiss and gabbroic gneiss. Smaller exposures of charnockitic gneiss (defined here as orthopyroxene-bearing gneiss), garnetiferous and iron-rich gneiss, sillimanitic gneiss, quartzite and calc-silicate also occur. Most of these rocks are interlayered with each other. Migmatites are common, and there are abundant dikes and sills of several granitic episodes in this quadrangle (Brock and Singewald, 1968).

The biotite gneiss (15–20% of the quadrangle) is a medium-grained, strongly foliated rock containing biotite, quartz, K-feldspar and oligoclase with local layers rich in garnet or sillimanite. The unit is generally migmatitic. Chemical analyses (Lanzirotti and Condie, 1986a) show a REE pattern similar to shale, with high concentrations of La, Th, U and Hf. They interpret the protolith as coarse-grained quartz-wacke derived from a granitic source, possibly deposited along a continental margin or in a cratonic basin.

The hornblende gneiss (about 50% of the quadrangle map) is a term used to encompass ortho-amphibolites as well as hornblende-bearing rocks with variable amounts of plagioclase, pyroxene, biotite and microcline, some of which are more likely to be sedimentary in origin and related to the biotite gneiss. The ortho-amphibolites appear to be relict mafic sills and dikes (Lanzirotti and Condie, 1986a). Exposures in the Bull Domingo Hills complex contain relict layering and cumulus textures suggestive of a layered gabbro sequence. Plots of rock chemistry on tectonic discriminant diagrams (e.g., Ti-Zr, Th-Hf-Ta and Th/Yb-Ta/Yb) suggest an island arc setting (Lanzirotti and Condie, 1986a).

The alaskitic granite-gneiss is a light-colored, medium- to fine-grained, two-feldspar granite with microcline more abundant than oligoclase. Magnetite and biotite comprise less than one percent of the rock. Though generally concordant to the metamorphic layering, the unit is locally cross-cutting. It is only weakly foliated in most places, although this varies proportionally with the mafic mineral content. The alaskitic gneiss is commonly associated with minor tonalitic gneiss and is intruded by quartz monzonite-gneiss. The granitic gneisses range in composition from tonalite through granite and seem to be syntectonic. Chemical analyses (Lanzirotti and Condie, 1986a) show that the granites have compositions near the minimum in the Q-Ab-Or-H_2O system at low water pressures and plot as within-plate granites on various discriminant diagrams (Y-Nb, Rb-Y+Nb and Ta-Yb).

The gabbroic gneiss and related ultramafic rocks crop out as tabular or elliptical bodies within the hornblende gneiss. The gabbroic gneiss is a hornblende-plagioclase rock with minor alkali feldspar, quartz and opaques. Ophitic textures support a plutonic origin for this rock. The ultramafic gneiss is only weakly foliated and appears to have been a websterite (hypersthene-bronzite and clinopyroxene with trace plagioclase and olivine). It presently contains abundant hornblende, possibly formed through reaction between the olivine and plagioclase.

The charnockitic gneiss is one of the most unusual metamorphic rocks in the region. The rock has a greasy, brown-green appearance and is composed of plagioclase (Ca-oligoclase), quartz, K-feldspar, amphibole, biotite and hypersthene. Anorthositic dikes cut through these charnockites. Lanzirotti and Condie (1986b) determined that the granulites were tonalitic in composition, with light REE enrichment and a mildly positive Eu anomaly. They are similar in composition to Archean charnockites of southern India. They are usually found as inclusions within the alaskitic granite and might be enormous fragments of lower crust transported during a partial melting event. Studies of fluid inclusions have not yet been made to test whether the charnockites, which lie almost entirely on a line within the Mount Tyndall quadrangle, might alternatively have formed through a dehydration process. It is certainly unlikely that they resulted from an abrupt, local rise in temperature and pressure during metamorphism.

Metamorphic rocks of South Hardscrabble Creek

Several theses (e.g., Martin, 1954; Logan, 1966) describe gneissic rocks within the eastern half of the Wet Mountains. Noblett (1986) investigated the petrography, geochemistry (major, minor, trace and rare-earth elements) and structure of rocks in a 12 km^2 area along South Hardscrabble Creek. Cullers (unpublished data) noted that exposures there are similar in appearance to rocks along North Hardscrabble Creek (Highway 96) and to the south near Beulah, suggesting that these results can perhaps be extended considerably along the eastern side of the range.

The most common rock types along South Hardscrabble Creek are amphibolite, biotite gneiss and granitic gneiss (Fig. 3). Minor units include metagabbro, biotite-garnet schist and sillimanite-bearing quartzite. These rocks have undergone at least two deformations and possibly a third earlier event. The earliest deformation is recorded only by a few outcrops of amphibolite which contain a weak foliation cross-cut by a more dominant foliation. The major deformation was an isoclinal folding event during which the primary foliation formed. No vestiges of original bedding have been identified. Boudinage, particularly of amphibolite lenses in the granitic gneiss, is abundant. Fold axes trend approximately north to northeast with a subhorizontal plunge. The last of the deformations bent these rocks into small concentric folds with fold axes trending northwest and also plunging subhorizontally.

Metamorphism occurred in the upper amphibolite facies, producing sillimanite-grade rocks along South Hardscrabble Creek. Reaction boundaries of muscovite and quartz against sillimanite and microcline are preserved in rocks which do not appear to have undergone partial melting. These observations constrain temperature and pressure con-

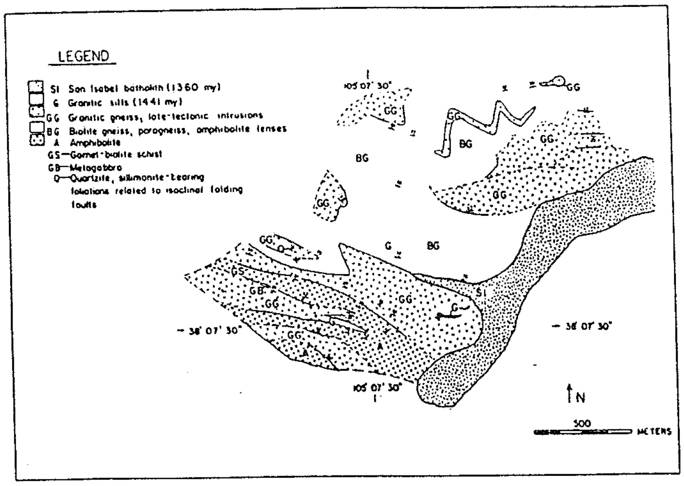

FIGURE 3. Geologic map along South Hardscrabble Creek.

ditions fairly tightly at about 650°C and 3.5 kb. Microprobe analysis of the garnet-biotite schist yielded a temperature of 560°C (assuming 3.5 kb pressure), although the garnet appears to have undergone some sub-solidus recrystallization.

The amphibolitic rocks are hornblende and andesine (An_{40}) with minor quartz and a trace of K-feldspar. The metagabbro contains clinopyroxene-cored hornblende in an ophitic relationship with plagioclase. Chemically (Table 1), these rocks are tholeiitic basalts which are similar to metabasalts from the Salida and Gunnison areas when plotted on a $SiO_2 \times Zr/TiO_2$ diagram. They are hypersthene normative with samples from one unit slightly quartz-normative, and those from another unit olivine-normative. Plots on a Ti-Zr discriminant suggest an ocean-floor basalt setting.

The biotite gneiss (Table 1) is a biotite-bearing microcline-andesine-quartz gneiss. Chemical analyses show that it could have been derived from several sedimentary protoliths including shale, graywacke and quartzwacke (Table 1). The REE analysis (Fig. 4) matches shale well, but the lack of alumino-silicate minerals suggests that most of the biotite gneiss originated as a graywacke.

TABLE 1. Chemistry of the three major metamorphic rock units along South Hardscrabble Creek. Number of analyses of each type is given in parentheses by the rock type. In the trace element portion of the table, () denote values recorded which were below the detection limit, and d.l. denotes elements below the detection limit for which values were not recorded. Analyses performed by x-ray fluorescence at Los Alamos National Laboratory by Nathan Bower. Column headings show C.I.P.W. norms for the amphibolites and assumed protoliths for the biotite gneiss.

	Amphibolites				Biotite Gneiss (5)		
	Gabbro (2)	Olivine-normative (3)	Quartz-normative (5)	Granitic Gneiss (18)	Shale (2)	Greywacke (1)	Quartzwacke (2)
SiO_2	49.61	49.98	50.68	74.65	56.99	64.28	71.53
TiO_2	0.67	0.88	1.01	0.18	0.97	0.78	0.34
Al_2O_3	10.02	16.00	16.66	12.97	18.01	15.77	13.13
Fe_2O_3	8.04	2.61	3.33	1.07	8.11	0.98	2.70
FeO	2.16	6.45	7.09	0.49	*	4.50	*
MnO	0.34	0.18	0.22	0.02	0.17	0.15	0.07
MgO	10.75	6.23	5.83	0.36	2.92	2.06	1.12
CaO	13.52	10.90	9.09	0.98	4.42	2.59	1.15
Na_2O	2.04	3.21	2.36	2.84	3.60	3.20	1.82
K_2O	0.74	0.95	1.56	4.37	2.76	2.58	6.05
P_2O_5	0.18	0.30	0.29	0.16	0.26	0.24	0.06
TOTAL	99.25	97.69	98.12	98.09	98.21	97.12	97.97
Rb (10)	14	17	40	148	148	89	132
Sr (10)	180	571	390	126	331	172	165
Ba (100)	142	312	376	740	392	869	1827
La (50)	(16)	(19)	(20)	(21)	(46)	(51)	(21)
Ce (50)	(25)	57	(28)	88	68	76	(41)
Y (10)	(6)	(d.l.)	13	(3)	(d.l.)	12	(d.l.)
Zr (10)	71	71	91	168	170	117	187
Ni (50)	71	(7)	(d.l.)	(17)	(d.l.)	(0)	(16)
Co (10)	33	(d.l.)	27	22	(d.l.)	31	19
Cr (10)	609	84	187	12	(10)	22	17
V (50)	184	218	236	(29)	155	104	43
Zn (10)	133	72	88	22	198	90	69

*total Fe as Fe_2O_3

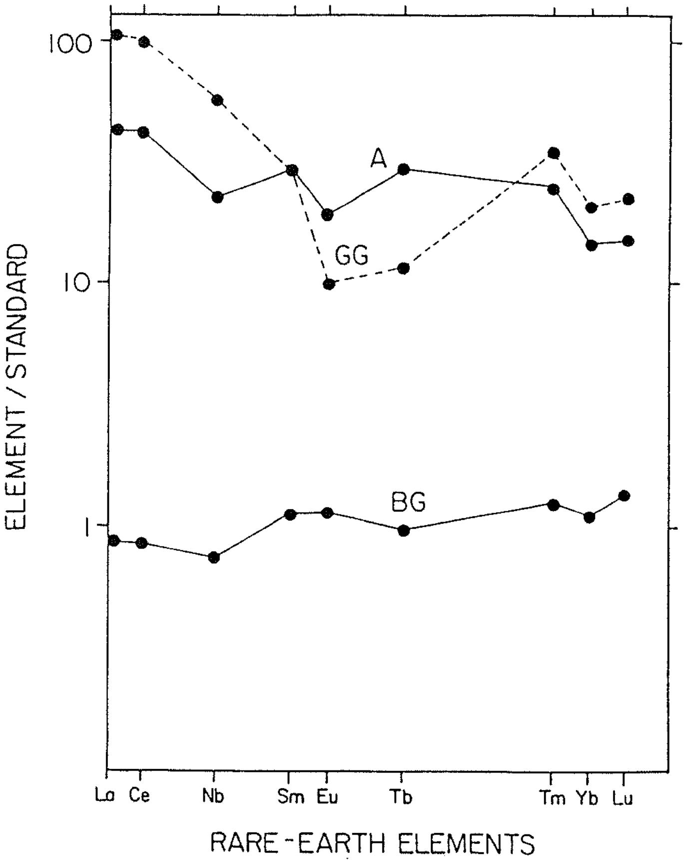

FIGURE 4. Rare earth element plot of the amphibolites (A, four samples), granitic gneiss (GG, six samples, dashed line) and biotite gneiss (BG, one sample). The amphibolite and granitic gneiss are plotted relative to a chondrite standard, whereas the biotite gneiss is plotted relative to the North American shale composite.

The granitic gneiss (Table 1) contains microcline, perthite, plagioclase (Ca-oligoclase) and quartz with minor amounts of biotite and muscovite and with traces of sillimanite, myrmekite, zircon and opaques. In one place, granitic gneiss contains xenoliths of amphibolite. The combination of metamorphic textures, sillimanite content, weak foliation and amphibolite xenoliths argues for the late stage intrusion of granite prior to the completion of the isoclinal folding. A variety of observations argues against the formation of the granite gneiss by an in situ anatexis process. Thus, the gneiss contains rotated xenoliths of amphibolite and zoned plagioclase and it encloses a sillimanitic quartzite unit which is entirely unmelted. It does not plot at the mininum on the Q-Ab-Or-H_2O diagram under the conditions inferred for metamorphism. The granite gneiss is corundum-normative and is enriched in light REE (Fig. 4), contains two micas and plots near the water-poor minimum in the Q-Ab-Or-H_2O system. This suggests that the original granites were derived from a crustal source. Their low Y + Nb content and high Rb content place them in the syn-collisional granite field.

One minor metasedimentary unit has some bearing on interpretations of the tectonic setting. The sillimanite-bearing quartzite is petrographically almost entirely quartz with small discontinuous lenses that are rich in sillimanite rods. Chemically, it is 83.1% SiO_2, 12.3% Al_2O_3 and 4.3% H_2O with only trace amounts of other elements. The sillimanite probably formed from small alumina-rich pockets of mud within a quartz sandstone. Such a texture is suggestive of shallow water, possibly tidal flat conditions.

These metamorphic rocks are broadly similar in mineralogy to rocks in the Mount Tyndall quadrangle. Chemically, however, rocks from the two areas formed in different settings: island-arc tholeiites, quartzwacke and tonalite in the Mount Tyndall quadrangle, whereas ocean floor basalts, graywacke and highly differentiated granites along South Hardscrabble Creek. Deformation produced isoclinal folding and later refolding of the rocks, but orientations and scale of folding are very dissimilar in the two regions. The lack of bimodal volcanic products distinguishes these two regions from the lower grade Proterozoic metamorphic rocks near Salida and Gunnison which were hypothesized to have formed in a primitive island arc (Bickford and Boardman, 1984) and immature back-arc basin (Condie, 1982), respectively. Though the differences between the two regions of metamorphic rocks within the Wet Mountains are not completely worked out, it is likely that the Wet Mountains themselves represent a terrane which is separate from Proterozoic rocks to the west in Colorado.

INTRUSIVE ROCKS OF THE WET MOUNTAINS

Introduction

Precambrian plutonic rocks of the Wet Mountains range in age from 1700 to 1360 m.y. and in general composition from tonalite to granite. The exceptions are small metagabbro and metadiorite sills, dikes and intrusions that have not been dated.

The plutonic rocks in Colorado were intruded in three major episodes at progressively shallower crustal levels: the Boulder Creek intrusive episode (about 1700 m.y.), the Silver Plume intrusive episode (about 1400 m.y.) and the Pikes Peak intrusive suite (about 1010 m.y.). The older two plutonic episodes are represented in the Wet Mountains; the younger Pikes Peak batholith is wholly contained within the Front Range.

Rocks of the oldest plutonic event (the Crampton Mountain-Twin Mountain batholith and the Garell Peak pluton of the Arkansas River canyon area on the north edge of the Wet Mountains: Fig. 2) are foliated parallel to foliations in their wall rocks as they are elsewhere in Colorado. Plutons of the Silver Plume episode in Colorado are generally unfoliated. However, the Oak Creek pluton is strongly foliated, and the San Isabel batholith is weakly foliated. These two plutons must represent a deeper-seated equivalent of other 1400-m.y. plutons that occur in a broad belt from Arizona to Labrador and are considered to be anorogenic (e.g., Anderson, 1983). Intrusions of all ages in the Wet Mountains plot in the within-plate granite fields in Rb-(Ta + Yb) and in Rb-(Nb + Yb) plots (Pearce et al., 1984). The discussion below is summarized in various abstracts (Cullers and Bickford, 1983; Griffin and Shaw, 1984; McCabe and Stone, 1984; Sassarini, 1984) as well as in Cullers and Wobus (1986).

Intrusions of the Boulder Creek intrusive event (~1700 m.y.)

General

Plutons of Boulder Creek age in Colorado typically contain early tonalite and granodiorite along their borders with more felsic rocks towards the interior. These tonalites and granodiorites are medium to coarse grained, often containing phenocrysts of alkali feldspar as much as several cm in size. Xenoliths of the metamorphic country rock are common along margins of the batholith. The interiors of the plutons contain more silicic hornblende-biotite granite, biotite granite and, rarely, muscovite-biotite granite.

Crampton Mountain-Twin Mountain batholith (1700 m.y.)

This intrusion (Fig. 5) is typical of the Boulder Creek plutons in Colorado. The rocks are subalkalic (Fig. 6) and are barely calc-alkaline in AFM diagrams; they contain biotite and magnetite-ilmenite. They tend, however, to be enriched in Fe relative to Mg more than most calc-alkaline intrusions (Table 2). In this respect, they are more similar to the younger intrusive rocks in this area.

The tonalites to granodiorites of the border zone are the least differentiated rocks (e.g., most metaluminous, low Sr, high Ba and REE; small, negative Eu anomaly) that are consistent with the melting of low-K sources in the crust with residual plagioclase and no alkali feldspar. In this respect, they are similar to source rocks that melted to form the younger Precambrian rocks in this region.

Differentiation toward the interior of the batholith resulted in in-

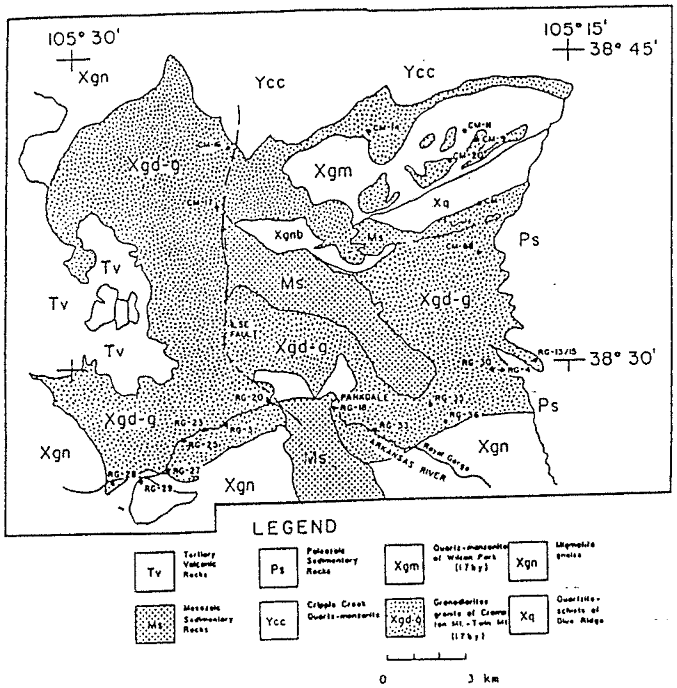

FIGURE 5. Geologic map of the Crampton Mountain-Twin Mountain pluton (from Taylor et al., 1975 and Wobus et al., 1979).

creasing alkali feldspar relative to plagioclase and increasing muscovite as the rocks become more peraluminous. The crystallization of plagioclase resulted in decreasing Sr and Eu/Sm ratios with increased silica. As the crystallization of alkali feldspar became more important, Ba and Eu/Sm ratios decreased more drastically with differentiation. One leucogranite sheet in the central portion of the intrusion has the highest silica content and contains as much as 15% muscovite, with little or no biotite.

Garell Peak pluton (1665 m.y.)

This pluton is subalkalic to alkalic (Fig. 6) and metaluminous to peraluminous (Fig. 7). It is enriched in Fe relative to Mg (Table 2). The Garell Peak pluton is more potassic and silicic than the older Crampton Mountain-Twin Mountain batholith, and it is more similar chemically to the younger (1400 m.y.) plutons in the Wet Mountains than to the older intrusive rocks.

The oldest and least differentiated facies in this pluton is coarse-grained monzogranite to syenogranite, and it contains hornblende (as much as 8%) and biotite (as much as 19%) (Fig. 8). Accessory minerals are magnetite, allanite, fluorite, sphene and zircon. The medium-grained facies is more highly differentiated, containing progressively more muscovite.

Little fractional crystallization of feldspar took place, as there are relatively small variations in Ba, Sr and Eu/Sm ratios within a given facies. In contrast, there are rather large variations in Rb. These unusual trends might result from a low but variable degree of melting of a crustal source with residual plagioclase, quartz and perhaps alkali feldspar. This model would produce the low Sr and Ba and large, negative

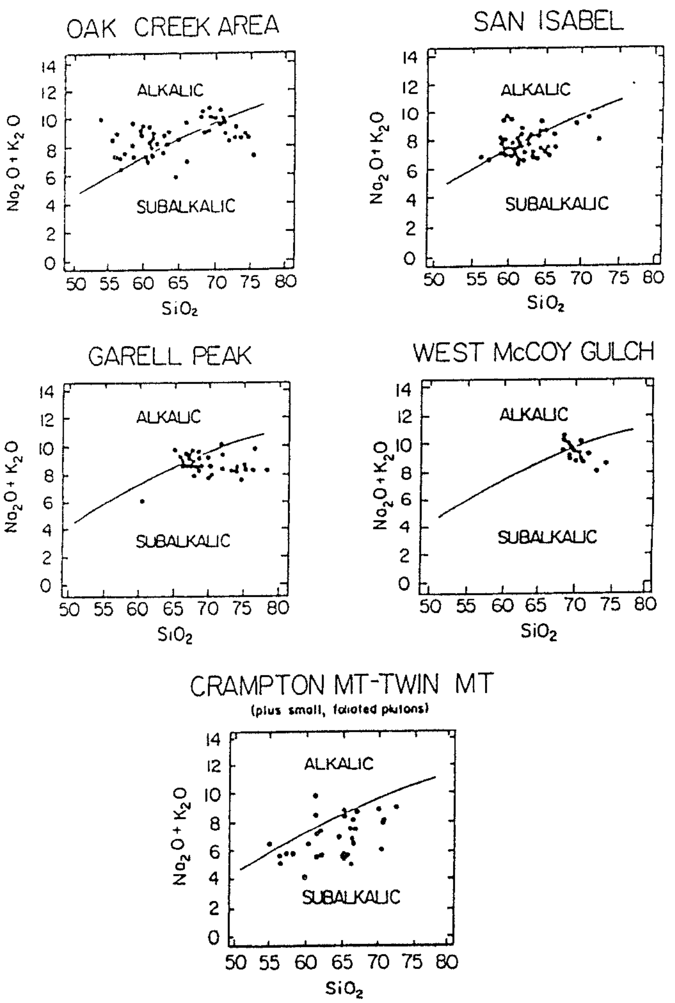

FIGURE 6. Alkalic indices of igneous plutons in the Wet Mountains.

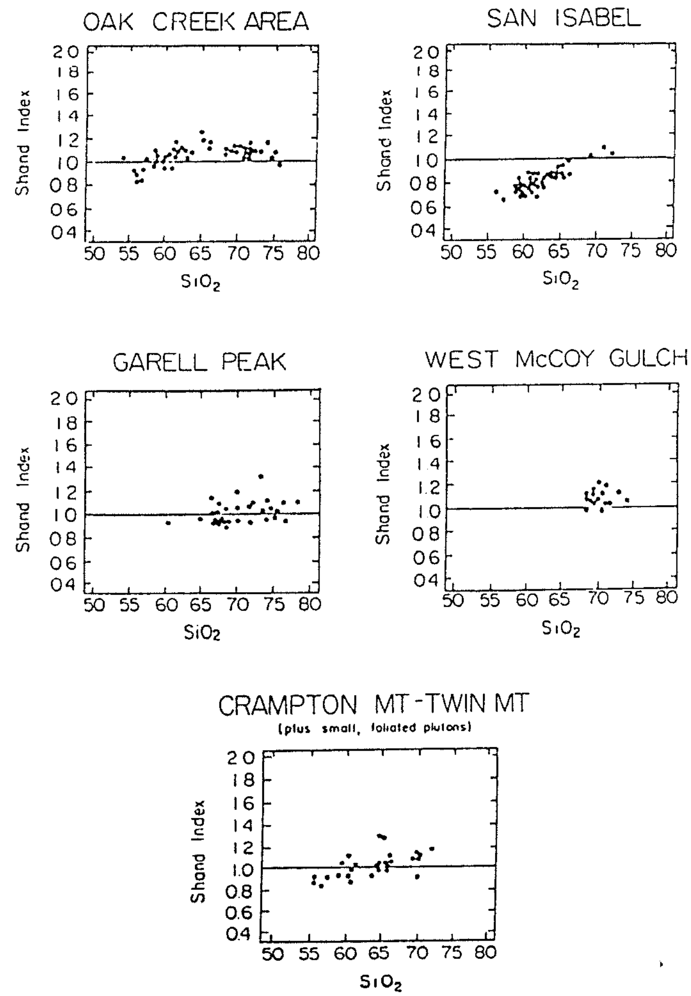

FIGURE 7. Plot of Shand index versus SiO_2 for plutons in the Wet Mountains.

TABLE 2. Range of chemical composition in igneous rocks of the Wet Mountains. Analyzed by Cullers and graduate students at Kansas State University. Major elements were determined by atomic absorption; minor and trace elements were determined by neutron activation.

	San Isabel Granite 1.36 by (57)	Granite at Bear Basin 1.36 by (57)	Oak Creek Granite 1.44 by (4)	West McCoy Gulch Granite 1.46-1.47 by (18)	Bear Creek, Williams Creek, Cliff Creek Granites (7)	Garell Peak Granite 1.66 by (39)	Crampton Mt.-Twin Mt. 1.7 by (22)
SiO_2	56.1-72.0	64.1-70.0	53.7-74.7	68.1-73.0	72.3-79	64.8-77	54.6-72.2
Al_2O_3	12.1-15.5	14.3-15.6	13.4-19.4	14.4-16.3	11.2-15.3	12.5-17.0	14.3-16.4
TiO_2	0.49-2.10	0.76-1.16	0.05-2.55	0.17-0.41	0.04-0.07	0.04-0.80	0.07-2.33
Fe_2O_3	2.17-11.6	3.26-5.53	0.73-8.57	1.89-3.70	0.36-0.94	0.62-6.24	1.18-11.6
MgO	0.34-3.0	0.62-1.22	0.04-2.74	0.31-0.69	0.01-0.12	0.02-0.88	0.21-3.03
CaO	0.53-6.1	0.83-2.32	0.49-5.44	0.94-1.72	0.86-1.22	0.38-2.39	0.60-6.06
Na_2O	2.47-4.35	2.72-3.11	2.62-4.75	2.73-3.89	2.16-2.76	2.79-6.17	1.81-3.84
K_2O	2.86-6.1	5.88-7.01	3.72-7.59	5.52-7.26	5.00-6.98	3.95-6.61	1.78-7.12
MnO	0.020-0.21	0.06-0.11	0.02-0.17	0.040-0.093	0.01-0.04	0.01-0.15	0.04-0.19
FeO/FeO+MgO	0.75-0.86	0.80-0.83	0.70-0.96	0.79-0.88	0.88-0.97	0.81-0.96	0.75-0.83
$\frac{Al_2O_3}{CaO+Na_2O+CaO}$	0.66-1.09	0.97-1.10	0.85-1.19	0.97-1.19	1.07	0.92-1.15	0.84-1.27
Rb	89-228	210-235	115-286	180-351	119-166	110-358	108-417
Sr	121-580	184-330	25-817	93-307	41-94	27-200	66-339
Ba	1420-2384	992-1480	139-3510	570-1380	116-1456	401-875	287-2300
La	86-236	125-347	11-841	58.5-180	2.7-138	0.05-153	24.1-570
Lu	0.8-2.2	1.37-2.38	0.20-2.0	0.38-1.40	0.045-1.0	n.d.-3.12	0.40-1.63
REE	434-1,090	688-1,500	38-2484	286-749	35-480	26-802	154-1,485
Eu/Sm	0.15-0.22	0.11-0.13	0.040-0.23	0.055-0.139	0.052-0.49	0.022-0.14	0.060-0.27
$(La/Lu)_{cn}$	6.0-17.3	9.0-19.3	1.2-255	7.2-38.5	0.26-35.6	2.1-12.0	2.2-60.8
Th	7.8-34	18.8-48.7	3.5-236	43-82	4.7-50.2	6-79	11.7-101
Hf	11.5-36	20-34	1.8-34.7	9.3-19	1.2-15.7	5.3-23	2.7-21.6
Sc	14-34	5.8-10.9	2.1-25.5	2.9-8.6	0.16-2.4	0.09-14	4.5-35.5
Cr	13-36	16-24	9.6-59	10-19	5-15.8	8-29.8	19-51

Eu anomalies that do not change much with differentiation, as well as the variable Rb content that is observed.

Intrusions of the Silver Plume intrusive episode (~1410±50 m.y.)

General

Rocks of Silver Plume age in Colorado are rarely foliated, and they are fine-to-medium grained, equigranular or porphyritic. Some, like the St. Vrain batholith in the northern Front Range, have few pegmatites (Anderson and Thomas, 1985), but the ones in the Wet Mountains have abundant pegmatites. Features such as the lack of metamorphic foliation and discordant contacts suggest most of these plutons are post-tectonic. Exceptions in the Wet Mountains are the extensively foliated Oak Creek pluton and the weakly foliated San Isabel batholith. These two intrusions were probably emplaced at mesozonal to catazonal depths.

Intrusions of Silver Plume age in the Wet Mountains are K-rich granites with high Fe relative to Mg (Table 2); they are thus similar in composition to other anorogenic granites that occur in a broad belt from Arizona to Labrador (Anderson, 1983). The intrusions in the Wet Mountains are marginally metaluminous to marginally peraluminous (Fig. 7). The San Isabel batholith is the most metaluminous, and the rest are mostly peraluminous. Magnetite is the only opaque mineral.

Granite of Williams Creek (~"1517 m.y.")

Leucogranites (granites of Williams Creek, Bear Creek and Cliff Creek) are intimately intermixed with intensely contorted migmatites near the top of Greenhorn Mountain in the southern Wet Mountains. One of these granites, the granite of Williams Creek, is composed almost entirely of alkali feldspar and quartz, with minor plagioclase and a trace of biotite, opaques and zircon. The zircon is euhedral, but it contains rounded cores very similar to the sedimentary zircons found in the metamorphic rocks. The age of all zircons is 1486 m.y., but the clear zircons are 1517 m.y. These granites probably formed by in situ melting of the metasedimentary country rocks.

Granite of West McCoy Gulch (1460 and 1474 m.y.)

The granite of West McCoy Gulch is a homogeneous, medium-grained leucogranite which ranges from monzogranite to syenogranite (Fig. 9). It contains 1.8 to 7.2% biotite and accessory muscovite, allanite, zircon, epidote, magnetite and apatite. The epidote may be primary, although this is somewhat uncertain.

Major and trace elements are fairly homogeneous throughout the pluton. The moderate Ba content, the large negative Eu anomaly and the low Sr content are consistent with the formation of the granite of West McCoy Gulch by melting of a plagioclase-rich crustal source with little or no residual alkali-feldspar left after melting.

South Hardscrabble Creek sills (1441 m.y.)

More than half-a-dozen sill-like bodies of very fine-grained granite intrude the metamorphic rocks along South Hardscrabble Creek. The largest of these bodies crops out in a cliff about 50 m thick and with 650 m of its length exposed. Smaller bodies may be as little as one m by 10 m.

The rock is a gray, holocrystalline, fine-grained, porphyritic granite. Phenocrysts include quartz, plagioclase (An_{31}), perthite, microcline and muscovite. Black pitted regions in the hand specimen are clots of biotite, magnetite and allanite. The groundmass is almost entirely quartz perthite and microcline with minor amounts of plagioclase, biotite and muscovite.

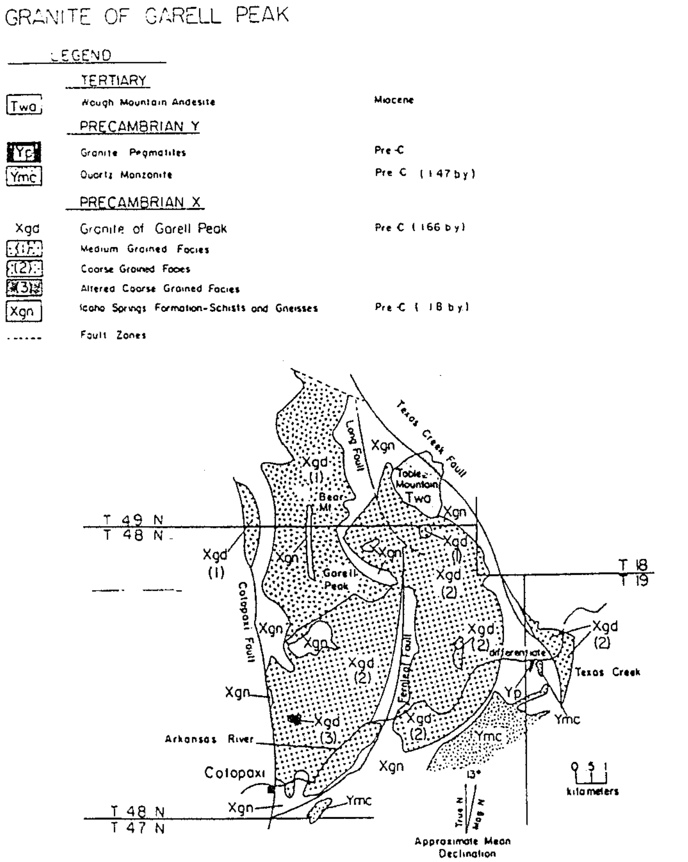

FIGURE 8. Geologic map of the Garell Peak pluton by Marc McCabe, Kansas State University.

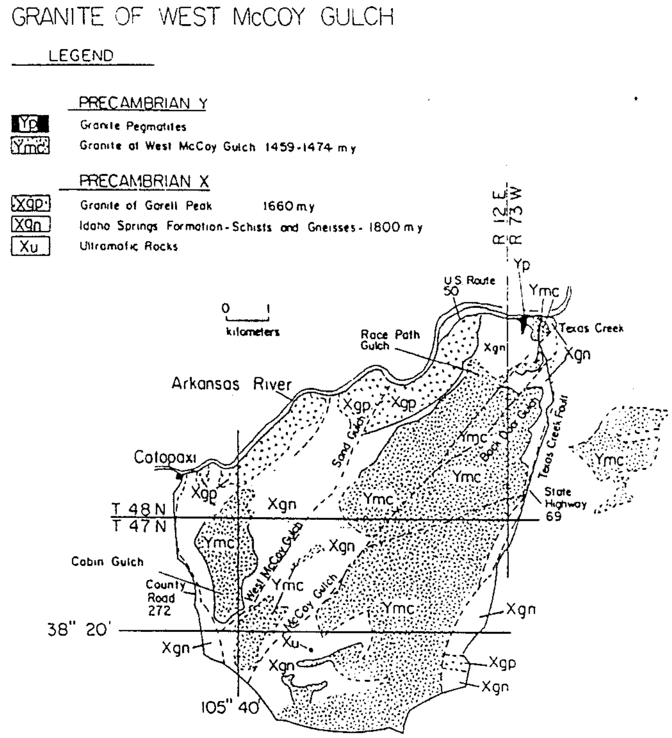

FIGURE 9. Geologic map of the West McCoy Gulch area by Nick Sassarini, Kansas State University.

Though the mineralogy fits that of a granitic liquid, the chemistry is quartz monzonitic on an $SiO_2 \times Zr/TiO_2$ diagram (Winchester and Floyd, 1977). The rock is peraluminous, high in Ba and Zr, low in Ni and enriched in the light REE with only a small negative Europium anomaly. It plots near, but not on the low pressure minimum in the Q-Ab-Or-H_2O system.

The two-mica composition, corundum-normative values and ratio of $Al/(Na + (Ca/2) + K)$ of 1.2 argue for the derivation of this granite from a crustal source. The fact that it does not plot on the minimum and that there is some variation in chemistry in one of the samples suggest some plagioclase fractionation.

There is an interesting association of mafic dikes with these sills. More than a dozen basaltic dikes cut the rocks along South Hardscrabble Creek including the granitic sills. These dikes are in turn cut by pegmatites. The pegmatites are most likely related to the San Isabel batholith which has its northern border exposed within tens of meters. If that relationship is valid, then the dikes intruded between 1441 and 1360 m.y.

Oak Creek pluton (1440 m.y.)

The Oak Creek pluton is composed of an early, foliated, coarse-grained facies intruded by small pods and dikes of a medium-grained leucogranite (Fig. 10). The coarse-grained facies is granodiorite to monzogranite porphyry with 5–65% phenocrysts of alkali feldspar and 0–26% phenocrysts of plagioclase. The groundmass consists of 4–30% quartz, 10–44% plagioclase, 0–16% alkali feldspar and 6–24% biotite. The accessory minerals are muscovite (2.2%), magnetite (4%), sphene (2.5%), apatite and zircon. The medium-grained leucogranite is equigranular; it consists of 16–43% alkali feldspar, 24–54% quartz, 20–49% plagioclase and 0–8% biotite. Accessory minerals are muscovite (0–2.1%), magnetite (trace to 1.6%), apatite, sphene and zircon.

There are fairly large variations in Si, Te, Mg, Fe, Ca, Mn, Sr, Ba, Eu/Sm ratios, REE, Cr, Sc and Th. Most variation diagrams are linear, suggesting that a physical separation of the feldspars and ferromagnesian minerals produced most of the variation within a facies.

San Isabel batholith (1360 m.y.)

The San Isabel batholith consists of two main facies: coarse grained and medium grained (Fig. 11). The coarse-grained facies, located mainly to the north and west, is monzogranite to syenogranite. It consists of alkali-feldspar phenocrysts in a medium-grained groundmass of quartz, alkali feldspar, plagioclase, biotite (20–30%), sphene and hornblende. The medium-grained facies is located to the south and east of the batholith, and it also ranges from monzogranite to syenogranite. It has the same range of minerals as the coarse-grained facies. Least differentiated portions of both facies are quite metaluminous, containing abundant hornblende. With increased differentiation, both facies become slightly peraluminous and may contain biotite with little or no hornblende.

The range in mafic minerals is large (15–35%), and they segregate in large zones. Physical accumulation of the ferromagnesian minerals (not feldspar and quartz) may account for much of the chemical variation in the batholith (e.g., large variation in Sc and Fe and small variations in Eu anomaly size, Ba and Sr).

Only rather complex models will explain the low initial Sr isotopic ratio, moderate Sr, Rb and REE contents, high Ba and small negative Eu anomalies. A tonalite or granodiorite originally derived from the mantle may have melted prior to the San Isabel melting event to produce a residuum with a low Rb/Sr ratio. Then this residuum could have melted to produce the least differentiated and hornblende-rich portions of the San Isabel magma.

GEOCHRONOLOGY

Work in recent years by Bickford (1986; also in preparation for the Geological Society of America "Tweto volume") has established a geochronological framework for the major Proterozoic events in the Wet Mountains, based on U-Pb dating of zircons. The geology and events discussed below are summarized in Figure 2.

The oldest rocks in the region are metamorphic rocks intruded by

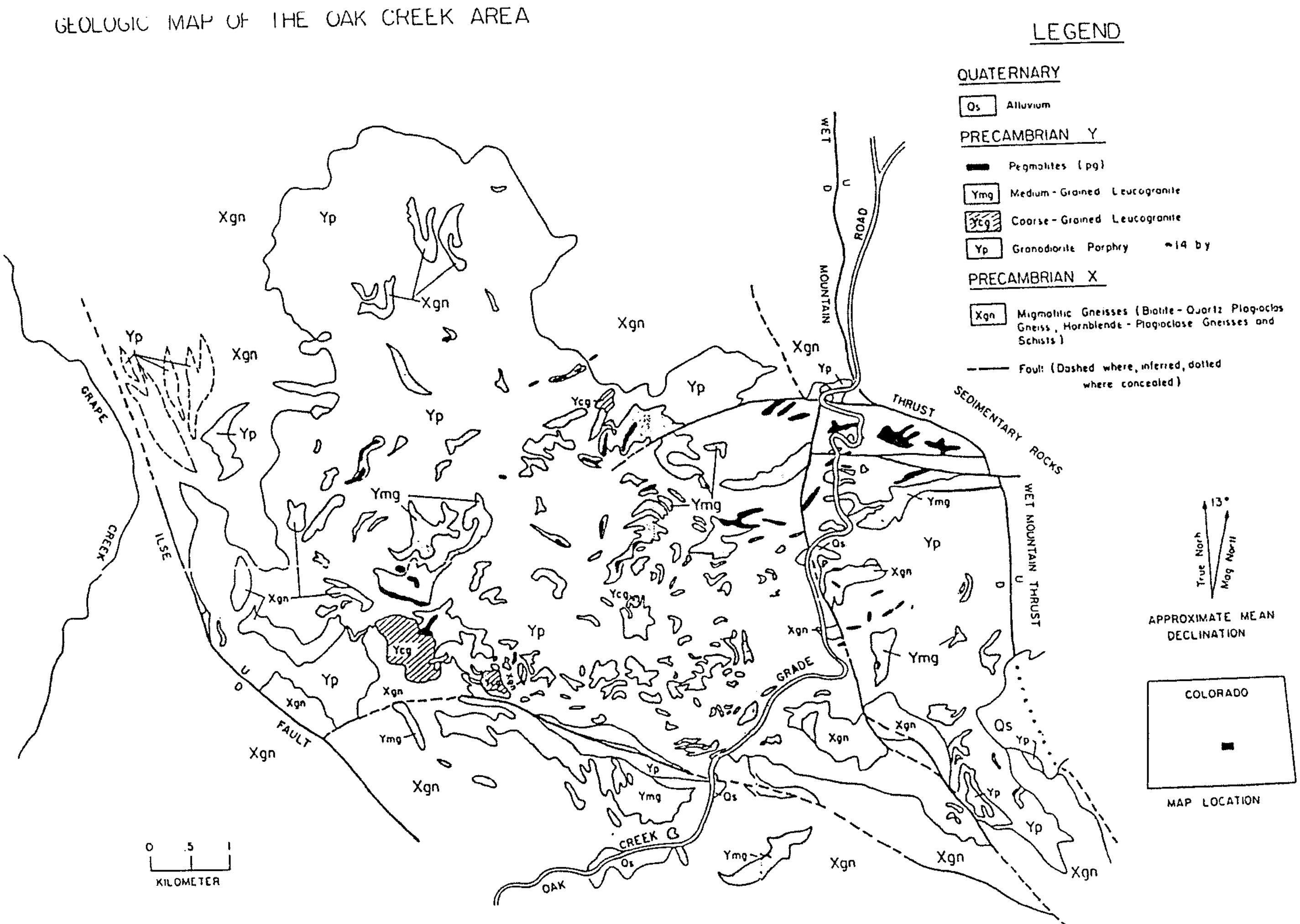

FIGURE 10. Geologic map of the Oak Creek pluton by Jim Stone, Kansas State University.

plutons about 1700 m.y. old. A small charnockite body within the otherwise amphibolite-grade metamorphic rocks was dated at 1694 ± 25 m.y. This date probably represents the time of granulite metamorphism, which normally resets zircons; because the emplacement of this body is problematical, as discussed previously, it is probably a lower limit on the age of metamorphism in the Wet Mountains. A slightly foliated granite which intruded metamorphic rocks east of the Ilse fault during the late stage of deformation is being dated to place a lower limit on the age of metamorphism of these rocks.

The oldest plutons in the Wet Mountains and vicinity have ages between 1600 and 1700 m.y. (Boulder Creek intrusive event). The pluton at Crampton Mountain-Twin Mountain at the northern edge of the Wet Mountains yielded ages of 1705 ± 8 m.y. and 1706 ± 5 m.y. Several ages determined for foliated granodiorite and tonalite yielded ages of 1665 ± 22 m.y. in the Garell Peak pluton and of 1621 ± 10 m.y. and 1610 ± 10 m.y. for tonalite and granite, respectively, in the Mount Tyndall quadrangle. Ages as young as 1620 m.y. have not been found elsewhere in Colorado.

A second plutonic episode represented by rocks in the Wet Mountains occurred in the 1410 ± 50 m.y. range (Silver Plume intrusive event). Three plutons and one group of sill-like bodies (South Hardscrabble Creek) were intruded between 1500 and 1430 m.y. The Bear Creek pluton (leucogranite), which occurs as sheets and dikes emplaced into migmatitic wall rocks, yields ages of 1517 ± 7 m.y. and 1486 ± 36 m.y. on different zircon fractions. The Oak Creek pluton, a foliated granite, was dated at 1434 ± 6 m.y. and at 1439 ± 8 m.y. The granite of West McCoy Gulch has been dated at 1460 ± 21 m.y. and 1474 ± 7 m.y. The fine-grained granitic sill-like body along South Hardscarbble Creek was dated at 1441 ± 23 m.y. A number of undated mafic dikes in the same area are also likely to be from this period, since they cut the sill-like bodies and are in turn cut by pegmatites which are probably part of the San Isabel batholith.

The youngest plutonic event in the Wet Mountains occurred at about 1360 m.y. Two zircon separates from granite of the San Isabel batholith dated at 1362 ± 3 m.y. and 1360 ± 5 m.y. The pluton at Bear Basin is 1349 ± 19 m.y. A Rb-Sr whole rock isochron of the San Isabel batholith, with an initial Sr isotopic ratio of 0.7030, gives an age identical to the U-Pb zircon age.

STRUCTURAL GEOLOGY OVERVIEW

At the southern end of the Wet Mountains, the south-plunging anticlinal structure of the range is evident where the prominent ridge of the Cretaceous Dakota Formation wraps around the uplifted portion of Greenhorn Mountain (Johnson, 1969). Steeply dipping sedimentary exposures along the east edge of the mountains also show this relationship. Most of the west limb of the Wet Mountains anticlinorium, however, is covered or in fault contact so the structure is less evident. Boyer (1962) determined that the dominant fracture pattern in the crystalline core of the southern part of the range trends N60°W and probably developed during emplacement of the San Isabel batholith (1360 m.y.). Two minor trends run N30°W and N40°E (Boyer, 1962).

The Wet Mountains are cut or bounded by a complex network of movement brought the Proterozoic metamorphic and plutonic rocks to the surface.

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