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EARLY PROTEROZOIC VOLCANOGENIC SEQUENCES IN CENTRAL COLORADO

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INTRODUCTION[1]

Precambrian crystalline rocks exposed in the Laramide and post-Laramide uplifts in Colorado and southern Wyoming include Early Proterozoic metamorphic and plutonic rocks formed between 1655 and 1800 Ma and Middle Proterozoic intrusive rocks emplaced between 1450 and 1000 Ma. Most of the Early Proterozoic rocks are inferred to have been the products of magmatism and related sedimentation in magmatic arcs and related inter-arc basins that were accreted to the southern margin of the Wyoming craton during the Early Proterozoic. However, the extent and interrelationships of component tectonic units in this accretionary complex are too poorly established to recognize individual terranes in the modern tectonic sense (Hamilton, 1990). The Middle Proterozoic rocks post-date and may be entirely unrelated to the accretionary history.

Most of the older rocks probably represent juvenile additions to the continental crust; the Middle Proterozoic rocks are probably in large part the products of anatectic melting of pre-existing continental crust.

The region of accreted Early Proterozoic rocks are bounded on the north by the Cheyenne belt, a major northeast-trending shear zone that separates Archean rocks of the Wyoming craton on the north from arc-related Early Proterozoic rocks on the south. The belt is commonly interpreted as a suture along which rocks to the south were accreted to the craton along a southeast-dipping subjection zone (Duebendorfer and Houston, 1987).

The Proterozoic crystalline rocks of Colorado and Wyoming south of the Cheyenne belt have been referred to as the Colorado province by Bickford and others (1986) and as exposed parts of the Central Plains orogen (Bickford and others, 1986; Sims and Peterman, 1986). Those in southern Wyoming and northern Colorado are slightly older than rocks of the 1760-1700 Ma Yavapai province of Arizona; those in central and southern Colorado are probably in part equivalent to the Yavapai province, or part of a broad transition zone between the Yavapai province and the post-1700 Ma Mazatzal province to the south.

The Early Proterozoic metamorphic rocks are chiefly felsic and hornblendic gneisses, and biotitic gneisses and schists (Tweto, 1987). Many variants of each of the principal types and the different lithologies are commonly interlayered in various proportions. No coherent regional stratigraphic framework has been established, but in a general way the biotitic gneisses form a broad east-trending belt in central Colorado flanked by belts of felsic and hornblendic gneisses (Tweto, 1979). The metamorphic rocks are invaded by syn- and post-tectonic calc-alkaline plutons ranging in composition from gabbro to monzogranite and in size from small plugs and stocks to batholiths having outcrop areas of thousands of square kilometers.

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[1]Much of this material is abridged from a contribution to v. C-2 of the G.S.A. Decade of North American Geology on Precambrian rocks of the conterminous United States.

Most of the supracrustal rocks have been metamorphosed to middle- or upper-amphibolite facies. Sillimanite is widespread, cordierite is locally common, and andalusite and staurolite appear in rocks of slightly lower grade. Migmatites, at least in part produced by partial melting of pelitic gneisses, are very extensive, and granulite-facies pyroxene gneisses have been mapped in the Wet Mountains (Brock and Singewald, 1968) and are found locally elsewhere. The wide distribution of andalusite and cordierite and the very restricted occurrence of kyanite suggest that geothermal gradients were high (Reed and others, 1987). This is consistent with the fact that transitions from upper greenschist to upper amphibolite facies rocks commonly take place over distances of only a few kilometers. No systematic regional pattern to the metamorphism has been recognized, and isograds have been successfully mapped in only a few areas (Braddock and Cole, 1979; Nesse, 1984; Snyder, 1980).

Foliation in most amphibolite facies supracrustal rocks parallels compositional layering, even around hinges of isoclinal folds. Orientation of foliation in the metamorphic and syntectonic plutonic rocks displays no consistent regional pattern. Foliation patterns commonly form broad swirls a few tens of kilometers across that have no obvious relation to the trend of the lithologic belts. Elaborate chronologies of superimposed sets of folds in foliation and layering have been deduced in several areas, but none seems to have regional significance.

Metamorphism and deformation of the Early Proterozoic rocks were not synchronous throughout the region. For example, felsic volcanic rocks dated at 1790 Ma in southern Wyoming were deformed and metamorphosed during emplacement of plutons dated at 1780-1775 Ma. A pluton emplaced prior to the last stage of folding and prior to the principal regional metamorphism in the Big Thompson area in northern Colorado has been dated at about 1726 Ma. Quartzo-feldspathic gneiss dated at about 1697 Ma in the central Front Range was isoclinally folded and metamorphosed before or during emplacement of the Boulder Creek Granodiorite, dated at about 1670 Ma, and a post-tectonic pluton in the Arkansas Canyon east of Salida, dated at about 1705 Ma cuts metamorphosed and isoclinally folded volcanic rocks probably equivalent to those near Salida that have been dated at 1728 Ma. The disparate ages of regional metamorphism and deformation in various parts of the region and the close correspondence of these ages with ages of plutons in local areas suggests that rising magmas were the cause of much of the metamorphism and deformation (Reed and others, 1987). Such an inference is consistent with the high-T/low-P character of the metamorphism (Hamilton and Myers, 1967; Hamilton, 1981) and with the complex patterns of deformation.

Preservation of primary textures and structures is rare in most of the metamorphic rocks, but in several areas surprisingly well-preserved sequences of supracrustal rocks have survived metamorphism and deformation. These better-preserved sequences, which collectively probably comprise less than 10 percent of the exposed supracrustal rocks, provide important clues to the protoliths of the more recrystallized rocks, and to the tectonic settings in which they accumulated.

The sedimentary origin of some of the biotitic rocks has been confirmed in the Big Thompson area in the northern Front Range, where migmatitic gneisses can be traced through successive metamorphic zones into greenschist-facies phyllites and graywackes that display well-preserved graded bedding (Braddock and Cole, 1979; Nesse, 1984). Other well-preserved sequences, all of which contain significant proportions of volcanic and volcaniclastic rocks, include the Green Mountain-Hog Park area in southern Wyoming (Divis, 1976; Schmidt, 1983; Condie and Shadel, 1984), the Salida and Gunnison areas in central Colorado, and the Table Mountain-Vallecito Creek area in the Needle Mountains (Barker, 1969; Gonzales, 1988). The volcanic rocks in these sequences are generally bimodal, consisting of dacite, rhyodacite or rhyolite, and tholeiitic basalt. Andesites are minor or absent. The most easily accessible and the most intensively studied of these sequences are those in the Gunnison and Salida areas, and these are the foci for this field trip (figure 1).

GUNNISON AREA

Early Proterozoic rocks are extensively exposed along and south of the Gunnison River, especially in the valleys of the north-flowing tributaries between Cochetopa Creek (about 8 miles east of Gunnison) and the Lake Fork (about 20 miles west of Gunnison) (figure 2). The area lies near the axis of the late Paleozoic Uncompahgre uplift, and the Proterozoic rocks are disconformably overlain by the Junction Creek Sandstone of Jurassic age. Both the Proterozoic and the Mesozoic rocks are blanketed by Oligocene ash flow tuffs, laharic breccias, and related rocks derived both from the West Elk Mountains to the north and the San Juan Mountains to the south.

The general character of the Proterozoic rocks was recognized by Hunter (1925), but much of the knowledge of and interest in these rocks is based on the work by J.C. Olson, D.C. Hedlund and T.A. Steven, who produced a classic series of detailed geologic maps (Hedlund and Olson, 1973; Olson and Hedlund, 1973; Hedlund, 1974; Hedlund and Olson, 1975; Hedlund and Olson, 1974; Olson, Steven, and Hedlund, 1975; Olson, 1976; Olson and Steven, 1976). Equally classic maps cover the Proterozoic rocks exposed in the Black Canyon of the Gunnison to the west (Hansen, 1968, 1971). Although seldom adequately acknowledged by some later workers, these maps form the foundation for most of the subsequent studies of the stratigraphy, geochemistry, and geochronology of the Proterozoic rocks (Afifi, 1981a, 1981b; Bickford and Boardman, 1984; Bickford, Shuster, and Boardman, 1989; Condie and Knoper, 1986; Condie and Nuter, 1981; Knoper and Condie, 1988; Shonk, 1984).

Supracrustal rocks in the Gunnison area are all of Early Proterozoic age and consist of deformed and variably metamorphosed sedimentary, volcaniclastic, and felsic and mafic volcanic rocks, all complexly interlayered in various proportions. Much of the interlayering is clearly stratigraphic, but some may be due to tectonic shuffling. Metamorphism in much

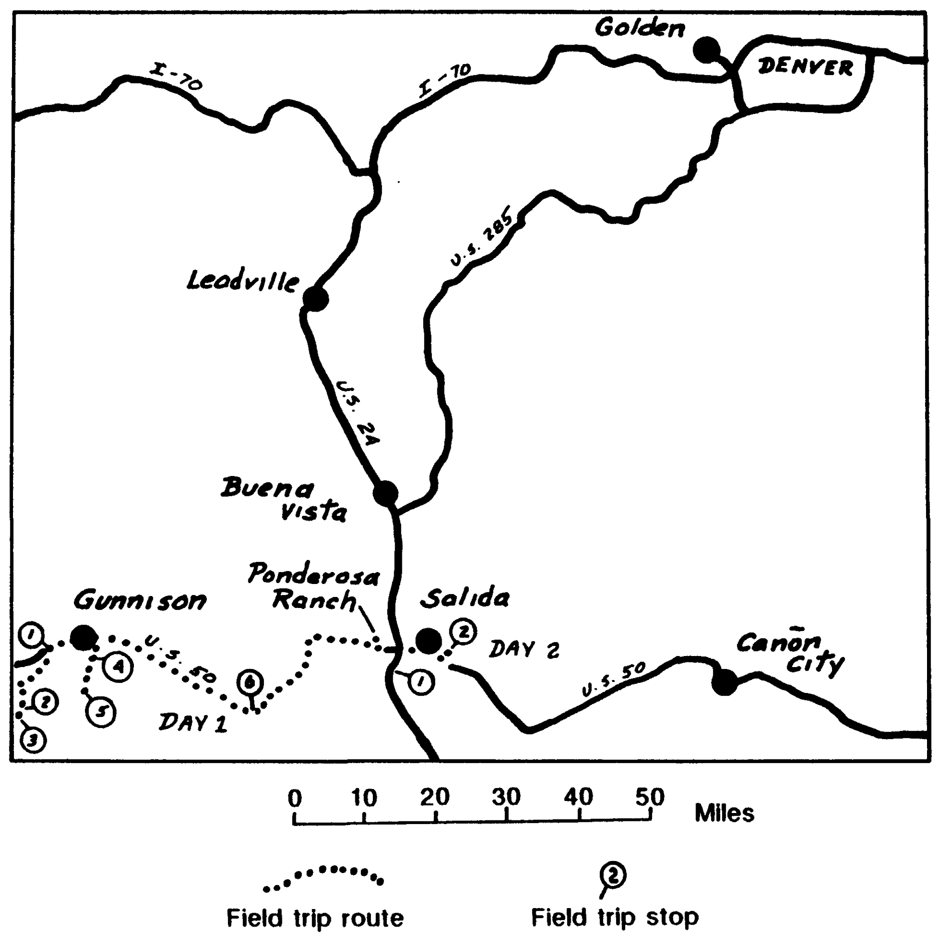

Figure 1. Index map showing route of field trip

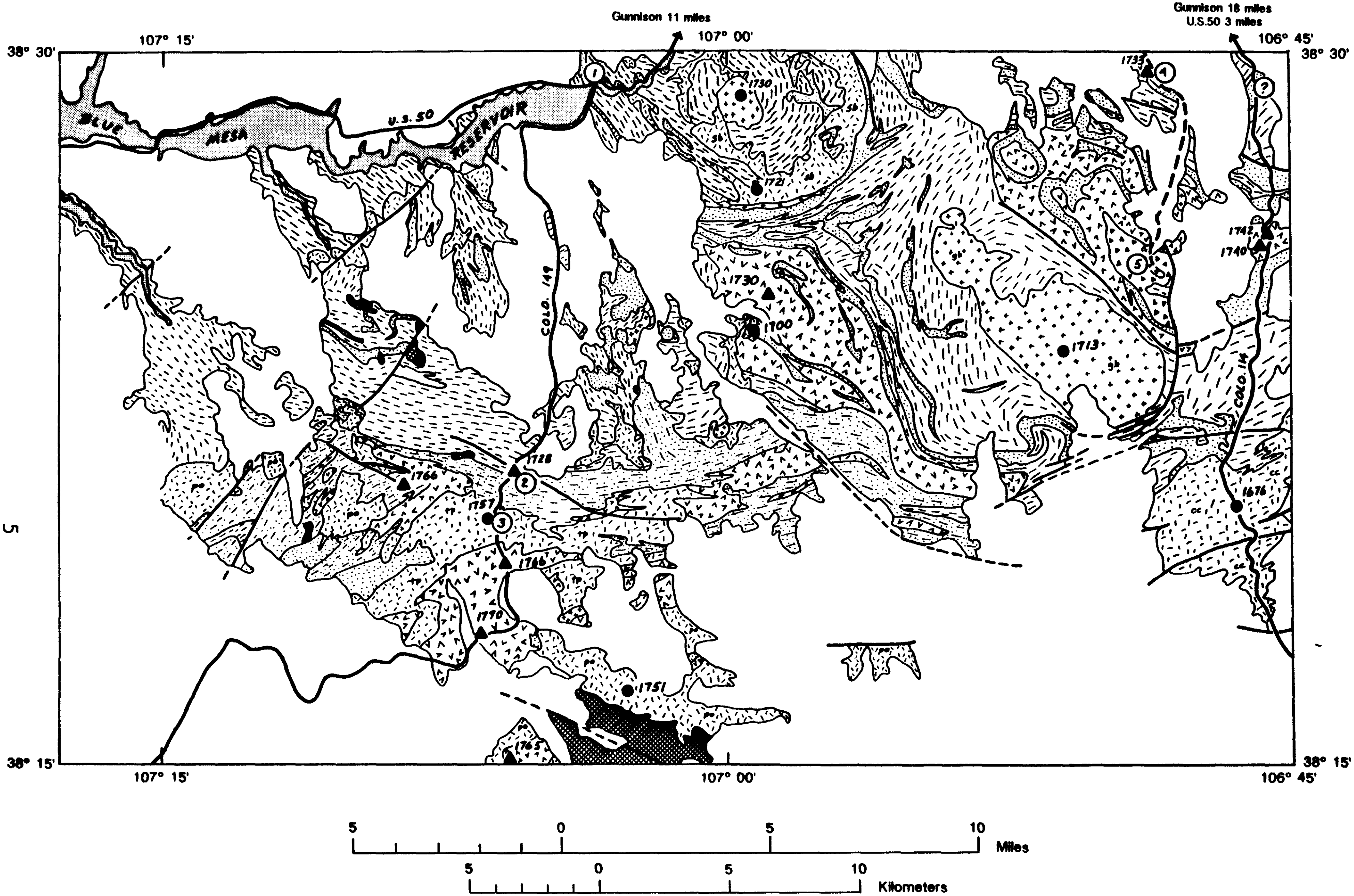

Figure 2. **Map of the Proterozoic Rocks of the Gunnison Area**

Compiled from Hedlund (1974), Hedlund and Olson (1973, 1974, 1975), Olson and Hedlund (1973), Olson (1976), Olson, Steven and Hedlund (1975), Olson and Steven (1976) and Hansen (1971)

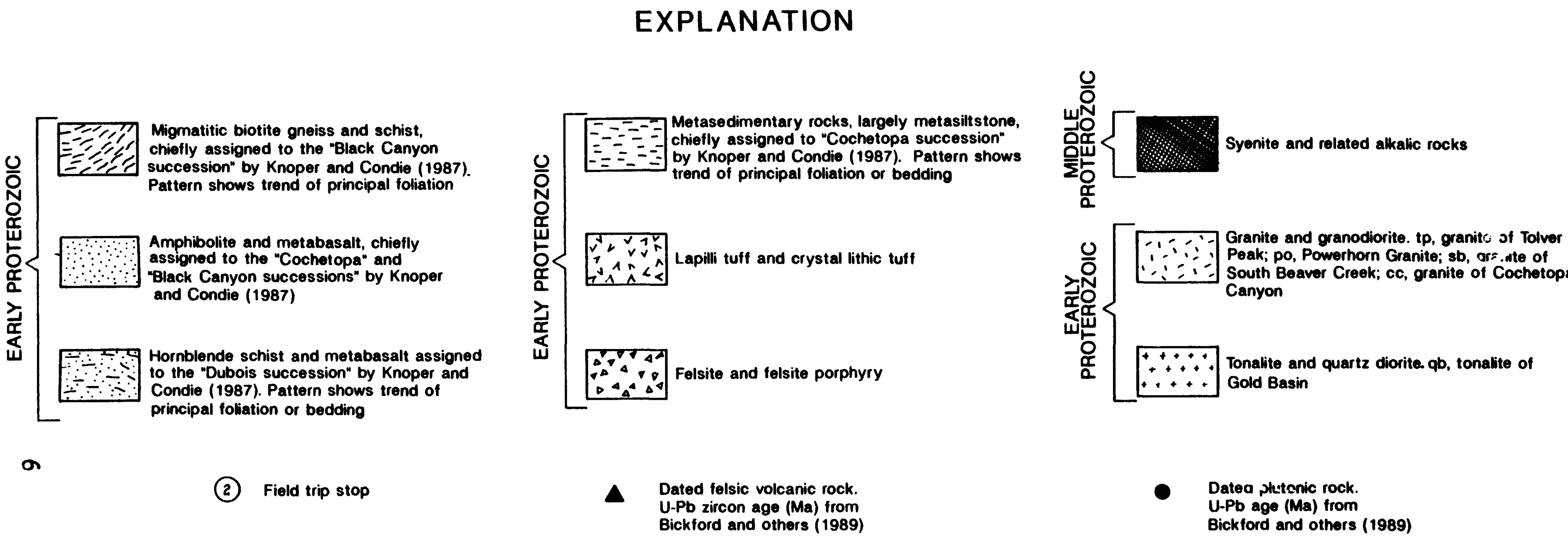

Figure 2.--Continued

of the area is lower amphibolite-facies, but ranges from upper amphibolite-facies (sillimanite-grade migmatites) in the northwest to epidote-amphibolite- or greenschist-facies in the east.

The Early Proterozoic supracrustal rocks are invaded by syntectonic and post-tectonic dikes, stocks, and irregular bodies of Early Proterozoic igneous rocks ranging in composition from quartz diorite and tonalite to monzogranite. They are also cut by dikes, plugs, and small stocks of syenite, carbonatite, and related alkalic rocks of Middle(?) Proterozoic age and by a swarm of generally northwest-trending diabase dikes of Cambrian or Ordovician (?) age.

Hunter (1925) recognized the mafic volcanic rocks and named them the Dubois Greenstone. Hedlund and Olson (1981) applied the name Dubois Greenstone to all of the predominantly metavolcanic rocks and the name Black Canyon Schist to the predominantly metasedimentary rocks. Condie and Nutter (1981) used the term "Dubois greenstone succession" to all of the metasedimentary and metavolcanic rocks in the Gunnison area. U-Pb zircon dating (Bickford and Boardman, 1984; Bickford, Shuster, and Boardman, 1989) subsequently showed that felsic volcanic rocks interlayered with the mafic rocks in the southwestern part of the area range in age from about 1770 to 1765 Ma, while those interlayered with metasedimentary rocks in the northeastern part of the area range in age from about 1740 to 1730 Ma. Condie and Knoper (1986) suggested calling the older rocks the "Dubois succession" and the younger rocks the "Cochetopa succession". Knoper and Condie (1988) apply the term "Black Canyon succession" to the migmatitic, predominantly metasedimentary rocks in the northern and northwestern parts of the area. The relations between these "successions" are unclear, partly, at least, because the "successions" themselves are nowhere clearly defined, and partly because no comprehensive structural synthesis of the entire area has been attempted. Condie and Knoper (1986) suggest that the "Dubois" and "Cochetopa successions" are separated by a major shear zone, but the detailed geologic maps (Olson and Hedlund, 1973; Hedlund and Olson, 1975) show no such zone. Knoper and Condie (1988) conclude that the "Cochetopa succession" rests unconformably or disconformably on the "Dubois succession" and that the "Cochetopa succession" overlies and interfingers with the "Black Canyon succession". However, detailed mapping and structural studies by Shonk (1984) and Shonk and Geissman (1984) show that at least part of the "Cochetopa succession" stratigraphically overlies the "Dubois"; they suggest that the two groups of rocks are time-stratigraphic equivalents.

According to Condie and Knoper (1986) and Knoper and Condie (1988) the "Dubois succession" consists mostly of basalt, volcaniclastic sediments, and felsic volcanic rocks, all of which are cut by mafic sills and dikes. It also contains subordinate sedimentary interbeds, including purple magnetite-quartzite (possibly representing ferruginous chert or cherty iron-formation) as well as other epiclastic and volcaniclastic rocks. Although the rocks have been variably sheared and metamorphosed to lower amphibolite-facies, pillows, pillow breccias, amygdules, and other volcanic textures and structures are locally preserved. Concordant syntectonic and post-tectonic plutons of monzogranite emplaced in the "Dubois succession" include the 1757 Ma granite of Tolvar Peak and the 1751 Ma Powderhorn Granite (Bickford and others, 1989), suggesting that the deformation took place within less than 10 m.y. of the eruption of the dated volcanic rocks.

The "Cochetopa succession" is comprised of fine-grained metasedimentary rocks interlayered with felsic and mafic volcanic rocks in a stratigraphic sequence that is at least 7 km thick (Afifi, 1981a, 1981b; Condie and Nuter, 1981; Shonk, 1984; Knoper and Condie, 1988). The rocks are metamorphosed to upper greenschist- or lower amphibolite-facies, but are less sheared than those of the "Dubois succession", so that primary textures and structures are remarkably well-preserved. Protoliths of the metasedimentary rocks were turbiditic wackes to siltstones. Carbonate rocks and metapelites are rare. The felsic rocks are chiefly dacites to alkali rhyolites and most were apparently derived from ash flow tuffs, fine-grained water-laid tuffs, lapilli tuffs, and tuff breccias. Some of the mafic volcanic rocks contain well preserved pillows and pillow breccias, indicating subaqueous extrusion. All of these rocks were intruded by thick sills of gabbro before folding and metamorphism. Early Proterozoic plutons emplaced in the "Cochetopa succession" include the 1730 Ma plug of quartz diorite that forms the core of the Gunnison plutonic complex, the 1721 Ma granite of South Beaver Creek that forms a series of inward dipping cone sheets surrounding the complex, the 1713 Ma tonalite of Gold Basin that forms a large pluton that is discordant in detail but whose emplacement may be related to the formation of some of the early steeply plunging folds, and the discordant post-tectonic 1676 Ma monzogranite pluton in Cochetopa Canyon (Bickford and others, 1989). Emplacement of the earlier of these plutons was apparently synchronous with deformation and metamorphism of the wall rocks, which thus must have taken place very shortly after eruption of the dated felsic volcanic rocks of the "Cochetopa succession"

The volcanic rocks of both the "Cochetopa" and "Dubois successions" are strongly bimodal. Mafic rocks are chiefly of basaltic compositions, while felsic rocks are rhyolite, quartz latite, or rhyodacite. Andesitic compositions are subordinate. Knoper and Condie (1988) have studied the chemistry of the mafic rocks and find that most of them maintained their basaltic major element compositions during metamorphism and deformation. They show a moderate iron enrichment trend similar to modern basalts in island arc or incipient back-arc basins, and most are relatively high in Al_2O_3 and CaO. Discrimination diagrams based on high-field-strength and rare-earth elements suggest that mafic rocks of the "Dubois succession" resemble basalts of modern immature island arcs, while those of the "Cochetopa succession" more closely resemble basalts of more evolved arcs, and those in the "Black Canyon succession" resemble back-arc basin basalts.

Felsic rocks in the "Dubois succession" have not been investigated geochemically, but those of the "Cochetopa succession" are similar to modern rhyolites, most resembling those of from bimodal suites in continental rift systems (Condie and Nuter, 1981).

SALIDA AREA

Well-preserved Early Proterozoic supracrustal rocks crop out beneath early Paleozoic strata on the northeastern flank of the Laramide Sawatch anticline. The Proterozoic rocks are well exposed in the drainages and low ridges immediately east and southeast of Salida. Similar rocks are also mapped by Scott, Taylor, Epis, and Wobus (1978) about 10 miles farther east, and in the Sangre de Cristo Range for as much as 10 miles to the south. The general character of the rocks near Salida was recognized by Cross (1895) and Van Alstine (1974), but Boardman (1976) provided the first detailed geologic map and detailed description of the stratigraphy and primary features. The description below is based largely on Boardman (1976, 1986a) and Bickford and Boardman (1984).

The sequence of supracrustal rocks in the Salida area is at least 4 km thick. The rocks are felsic submarine ash-flows and debris flows, typically grading upward into fine-grained volcaniclastic rocks. Mafic volcanic rocks occur chiefly in the bottom half of the section. Those at the base display textures indicating deposition from density flows, while those higher in the section include pillow lava, pillow breccia, and volcaniclastic debris. The section is extensively invaded by sheets of gabbro and diabase, some as much as 350 m thick. The rocks are all at amphibolite-facies, but the grade of metamorphism within the amphibolite-facies and degree of shearing increase toward the contact of the 1672 Ma Denny Creek batholith about eight miles north of Salida. Bickford and others (1989) report a U-Pb zircon age of 1728+/-6 Ma for dacite in the sequence near Salida, and 1668+/-18 Ma and 1713+/-14 Ma for rhyolites a few miles to the south that may be part of the same sequence.

Boardman and Condie (1986) studied the geochemistry of the volcanic rocks and the associated mafic sheets. They found that compositions of many of the rocks have been modified by pre-metamorphic processes, but that gabbro and diabase sheets and massive felsic tuffs are little modified either by diagenetic changes or metamorphism. The suite is strongly bimodal. Mafic rocks have compositions of subalkaline and tholeiitic basalts; felsic rocks fall in the calcalkaline to high-K rhyolite fields on K_2O vs. SiO_2 diagrams and in the rhyolite to dacite fields in normative Qtz-K-feldspar-plagioclase classification of Streckeisen (1980). Geochemical modeling by Boardman and Condie (1986) suggests that the mafic rocks were derived from fractional crystallization of high alumina olivine tholeiite. Field and major-element data support derivation of the felsic rocks by anatectic melting of deep crustal rocks, but trace-element modeling favors an origin by two-stage fractional crystallization of a basaltic liquid. Attempts to identify tectonic environments using trace element discrimination diagrams yield inconsistent results, but on the basis of field evidence and the weight of the geochemical data, Boardman and Condie (1986) conclude that the rocks all probably accumulated in shallow water in a back-arc basin on or near continental crust.

OUTLINE OF THE FIELD TRIP

Participants will assemble at 4 PM on Friday, September 6 at the 16th and Elm Street parking lot on the Colorado School of Mines Campus in Golden. We will drive to Salida via U.S. 285 and Colorado 291 for dinner. We then drive west on U.S. 50 to the Ponderosa Lodge, which will be the trip headquarters. Saturday we will drive west on U.S. 50 across Monarch Pass to the Gunnison area (figure 2). There we will spend the day examining exposures of the "Black Canyon", "Dubois" and "Cochetopa successions". The day will include several short traverses on foot.

We will spend Sunday on an all-day traverse east of Salida examining volcanic, volcaniclastic, and sedimentary rocks containing exceptionally well preserved primary features. The traverse will involve about 4.5 miles of walking and a climb of about 1600 feet with a little rock scrambling and some bushwacking. However, the quality of the outcrops and the array of primary features to be seen should justify the effort. We should be back to the vehicles by mid-afternoon and back to Golden in time for a late dinner.

TRAVERSE LOG

SATURDAY
September 7

MILEAGE

0.0 Leave lodge at Ponderosa Ranch
Till along North Fork of South Arkansas River contains abundant cobble of granite of the Mount Princeton batholith dated at about 37 Ma (E.H. DeWitt, pers. comm to Bruce Bryant, 1987).

0.9 Intersection of Chaffee Co. 240 and U.S. 50. Turn right.

1.9 Outcrop of amphibolite and felsic gneiss cut by pegmatite and fine-grained leucocratic dikes.

2.4 Conspicuous lateral and terminal moraines

5.9 Coarse-grained foliated granitic rocks containing amphibolite inclusions.

6.9 Monarch Lodge.
Outcrops above road on right are Leadville Limestone (Mississippian) and Belden Shale (Pennsylvanian) in a fault-bounded syncline mapped by Dings and Robinson (1957)

8.7 Large quarry in Leadville Limestone. Rock from here was once used as flux in steel mills at Pueblo.

Small amounts are now trucked to Salida and processed for use as in suppressing dust in coal mines, as additive to cattle feed, and for road metal.

8.9 Roadcut in Proterozoic granite mapped as Pikes Peak by Dings and Robinson (1957). Tweto (1979) maps granites in this area as Early or Middle Proterozoic.

10.7 Monarch Ski area

11.8 Roadcut in Proterozoic granite, much shattered and discolored along fault zone. Good views of Tabeguache (14,165 ft) and Shavano (14,225 ft) Peaks to north and east.

12.6 Monarch Pass on Continental Divide. High peak to the south is Mount Ouray (13,971 ft).

Monarch Pass is near the northeastern edge of the Late Paleozoic Uncompahgre uplift. To the east and north, Lower Paleozoic rocks rest on the Proterozoic basement. To the west and south, rocks as young as Jurassic directly overlie the basement.

Roadcuts on west side of pass are Proterozoic granite of uncertain age, much shattered and discolored.

18.4 Roadcuts in finer grained granite, less broken and discolored.

22.6 Sargents.
Junction of Marshall Pass road. Roadcuts to the west are amphibolite and felsic gneiss.

24.6 Roadcut in layered mafic-ultramafic rocks of Proterozoic age. If time permits, we will examine this outcrop on the return trip (Stop 6). Roadcuts for several miles to the west are amphibolite and felsic gneiss cut by abundant dikes of leucocratic granite.

30.4 View of Tomichi Dome to the north and west. The dome is underlain by a plug of granite porphyry of Middle Tertiary age.

35.6 Doyleville

36.8 Light-colored Junction Creek Sandstone (Upper Jurassic) rests on granite of Wood Gulch. The granite is post-tectonic, and has been dated at about 1700 Ma by Bickford, Shuster, and Boardman (1989).

43.0 Parlin. Proterozoic rocks in roadcuts here and to the west are chiefly tuffaceous metasedimentary rocks of the "Cochetopa succession". They are overlain by flat-lying Junction Creek Sandstone.

49.8 Volcanic breccia, probably part of the West Elk Breccia of Oligocene age, fills channel in Junction Creek Sandstone. Similar breccia is conspicuous in roadcuts between here and Gunnison.

55.3 Downtown Gunnison

62.2 Enter Curecanti National Recreation Area

65.0 Junction of U.S. 50 and Colo. 149.

STOP 1. BLACK CANYON SCHIST

Roadcut on north side of U.S. 50 (figure 2) exposes fine-grained, massive to rudely layered, biotite gneiss Identical to rocks mapped as Black Canyon Schist by Hansen (1971) and Hedlund and Olsen (1973) in quadrangles to the west. Rocks in this exposure were mapped by Hedlund (1974) as part of the unit he designated as "quartz-biotite schist and gneiss, and migmatite"; they are assigned to the "Black Canyon succession" by Knoper and Condie (1988).

The gneiss contains several boudined layers of fine-grained amphibolite and several layers of buff-colored marble which display greenish calc-silicate reaction rims. Some of the marble layers display complex folds which apparently plunge NW and are overturned SW, but axes are difficult to measure. The folds are cut by 5- to 10-cm thick undeformed dikes of granite, probably related to the granite of South Beaver Creek dated at 1721 Ma, which is exposed along U.S. Highway 50 to the east.

Near the W end of the outcrop is a 10 m thick pod or layer of foliated amphibolite, probably an intrusive. The amphibolite contains conspicuous wisps of quartzo-feldspathic material that seem to mark sheared fold hinges. At the E contact of the amphibolite is a 5-10 m body of fine-grained, sugary-textured, light-gray rock containing conspicuous 1-5 cm dark biotitic clots, probably inclusions, but possibly altered mafic phenocrysts. This rock seems to have intrusive relations to both the gneiss and the amphibolite, but is cut by granite dikes.

Turn south on Colo. 149 toward Lake City

66.7 Roadcuts in West Elk Breccia

76.8 Top of Nine Mile Hill

78.0 Milepost 105

78.2 Mail box on left labeled "Flying Raven". Turn left through wire gate on to dirt road.

78.8 Take left fork

79.1 Park in meadow and walk NW (downstream) about .25 mile around E side of stock pond.

STOP 2. DUBOIS GREENSTONE NEAR THE IRONCAP MINE

Rocks in this vicinity (figure 2) were mapped by Hedlund and Olsen (1975) as hornblende schist and gneiss interlayered with quartzite and quartz sericite schist, all part of the Dubois Greenstone. They are typical of the rocks assigned to the "Dubois succession" by Knoper and Condie (1987).

Rocks exposed include pillowed mafic metavolcanic rocks, mafic breccia, phyllite (probably derived from tuffaceous metasedimentary rocks), dark quartzite (probably metachert), and marble, which occurs between pillows and in layers in the metachert. The rocks are all strongly foliated and lineated. Lineation plunges down the dip of the foliation and is defined by elongated pillows and amygdules and alignment of hornblende needles.

Pillows are conspicuous in the outcrops at the E end of the dam. A shallow dozer cut about 100 m farther north exposes thinly layered mafic metasediments, mafic breccia, quartzite, and more pillow lava. An open stope about 50 m east (uphill) exposes a 2 m layer of quartzite with marble on both sides and in the center. The quartzite (metachert?) body is host to the ore at the Ironcap Mine, which consisted chiefly of sphalerite, pyrite, chalcopyrite, and galena. This metachert(?) body is typical of many in the Dubois Greenstone. Drobeck (1981 suggests that the chert and associated sulfides formed by exhalative processes on the sea floor.

Fine-grained felsic rocks, probably metavolcanics, are exposed along the jeep road 200-300 m east of the stock pond. Some of these display C/S planes that suggest that they are in part mylonitic.

Return to vehicles and retrace route to Colo. 149.

80.0 Colo. 149. Headframe of Anaconda Mine to N. Turn left.

80.5 View to the southeast of peaks in the La Garita Wilderness, including San Luis Peak (14014 ft). These peaks are composed of ash-flow tuffs and dacitic lavas of Oligocene age north of the Creede caldera.

STOP 3. GRANITE OF TOLVAR PEAK

Roadcut on east side of the highway (figure 2) exposes granite of Tolvar Peak. The rock is a medium-grained pink granite containing ovoid quartz phenocrysts as much as 5 mm long and biotite clots which define a good foliation. Granite from this outcrop has been dated by Bickford, Shuster, and Boardman (1989) at 1757+/-10 Ma. The granite is intrusive into the Dubois Greenstone, from which felsic volcanic rocks have been dated at 1765, 1766, 1766, and 1770 Ma. The quartz phenocrysts suggest that the granite may a hypabysal intrusive into the volcanic pile. The granite is probably syn- to post-tectonic with respect to the deformation in the Dubois Greenstone. If so, deformation of the volcanic package must have followed its deposition by only 10-15 million years.

A 10 M thick dike of undeformed diabase is exposed near the middle of the roadcut. This is one of an extensive NW-SE trending swarm of similar dikes, one of which has been dated by Hansen and Peterman (1968) at 499+/-60 Ma (Ordovician or Cambrian) [published figure adjusted for new constants].

Turn around (with great care!) and return north on Colo. 149.

94.1 Junction with U.S. 50. Turn right

97.8 Neversink Picnic Area. LUNCH STOP

Continue east on U.S. 50

107.5 Downtown Gunnison

113.2 Milepost 163

113.5 Junction County Road 42. Turn right

113.8 Cross Gunnison River

114.0 Take left fork

114.7 Cattle guard. Sign "No Winter Maintenance"

115.1 Take left fork--BLM Rt. 3072

116.4 Park and walk 200 M east to low brown outcrop on far side of drainage.

STOP 4. COCHETOPA SUCCESSION

The massive, fine-grained, siliceous rocks here were mapped by Olsen (1976) as part of his "felsite and felsite porphyry" unit; they are part of the "Cochetopa succession" of Knoper and Condie (1988). Few distinctive features are visible in most of the outcrop, but near the SE corner of the exposure are several 1-5 cm thick beds containing conspicuous detrital grains of quartz and feldspar, some showing possible graded bedding with tops to the south. Examples of possible cross-beds and ripple marks are visible nearby. These features suggest that some or all of the massive rocks in the rest of the outcrop may be metasiltstone, perhaps tuffaceous.

Metarhyolite interlayered with these rocks from the outcrop west of the road near where the vehicles are parked was dated by Bickford, Shuster, and Boardman (1989) at 1733+/-11 Ma

Continue south on BLM Rt. 3072

121.4 Milepost 5

123.8 Fenced spring on left

124.4 Milepost 8

124.6 Road junction. Continue south

125.1 View of West Elk Mountains to the NW and Elk Mountains to the N. Prominent peak that bears due N is Castle (14,265 ft); those that bear N10^{o}W are the Maroon Bells (14,014 ft and 14,156 ft)

We are on land recently donated to the Geology Department of the University of Florida for use as a geology field camp. We appreciate the permission of Tony Randazzo, Department Chairman, to enter the property and examine the outcrops. Park here and hike up the ridge to the W.

STOP 5. ASH FLOW TUFF AND VOLCANIC BRECCIA IN THE COCHETOPA SUCCESSION

Rocks in this ridge (figure 2) were mapped by Olson (1976) as part of his "lapilli tuff and crystal-lithic tuff" unit. Lowest outcrops on the ridge (about 100 ft above the vehicles) are light-gray crystal-lithic tuff containing conspicuous 2-3 mm plagioclase crystals, 1-2 cm lithic fragments, and some possible collapsed pumice fragments. A distinct steeply-dipping fracture cleavage trends approximately N-S and cuts a south-dipping foliation that trends approximately E-W. The foliation is apparently a primary compaction foliation accented by the growth of metamorphic biotite.

The most spectacular and photogenic outcrop is on the north side of the ridge a few feet below the crest and about 160 ft above the vehicles. Angular tabular chips and blocks of metasiltstone 1 cm to as much as 1 m in length lie in a matrix of felsic crystal tuff. Bedding is defined by the long dimensions of the larger blocks. Laminations in the blocks of metasiltstone are parallel, even to the extreme ends, suggesting that the blocks have not been significantly flattened. The breccia also contains fragments of blue or purple quartzite or metachert like that seen at Stop 2 in the Dubois Greenstone. Similar rock is exposed beneath the breccia in a small prospect pit to the north.

Rocks here have all been multiply deformed and metamorphosed to upper greenschist facies, so preservation of primary structures is remarkable. Detailed mapping and stratigraphic studies by Afifi (1981a; 1981b) show that these outcrops lie on the northwest limb of the Iris syncline, a major tight syncline that plunges steeply to SE (figure 3) and whose southwest limb is partly cut out by the Lulu fault. Both the fault and the syncline are folded by NE-trending open folds whose axial planes are approximately parallel to the fracture cleavage in some of these outcrops.

Map relations suggest that both formation of the Iris syncline and the later folding pre-dated emplacement of the tonalite of Gold Basin, dated at about 1713 Ma. Both deformations in this area must have post-dated deformation of the Dubois Greenstone seen at Stop 2. The youngest Early Proterozoic pluton in the region is the late post-tectonic granite of Cochetopa Canyon, dated at about 1676 Ma.

Return to vehicles and retrace route back to U.S. 50.

133.8 Junction with U.S. 50. Turn right

158.5 Park on south side of highway and <u>cross very carefully</u> to examine roadcut on north side.

STOP 6. MAFIC-ULTRAMAFIC COMPLEX
by John Pallister

Cumulus gabbro, melagabbro, and lherzolite are exposed in the roadcut. The "host" rock is layered cumulus gabbro composed of calcic plagioclase and clinopyroxene (which is variably replaced by late magmatic and subsolidus hornblende). The gabbro has adcumulus to heteradcumulus texture (with clinopyroxene and hornblende oikocrysts) and displays cumulus layering. Individual layers range in thickness from 1 cm to 1 m. Ratio layering (produced by variation in the modal ratio of cumulus phases) is locally displayed s cpx+hbl-rich melagabbro layers 5 to 10 cm-thick

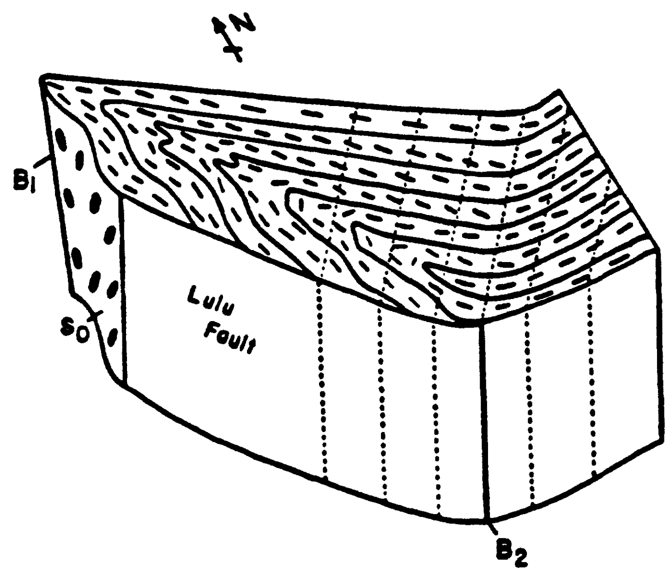

Figure 3. Schematic block diagram showing some principal structural features in the Iris area. The foreground is the surface of the Lulu fault. The Iris syncline (B_1) plunges steeply southeast within the Iris area. Second generation folding has resulted in open refolding of the Iris syncline and the Lulu fault about a steeply plunging axis (B_2). Solid lines represent bedding (S_0), dashed lines represent S_1, and the dotted lines represent fracture cleavage (S_2). The L_1 lineation is defined by elongated ellipsoidal fragments, the traces of which are shown on the S_0 surface. (from Afifi, 1981b)

alternating with more leucocratic 10 to 30 cm-thick planar laminated gabbro. (Planar lamination is a cumulus texture produced by the accumulation of crystals with long-axes distributed in planes, but with little or no lineation developed.) Some layers appear to be graded (normal and reverse). The layering is discontinuous (individual layers pinch out laterally) leading to a "gneissic" appearance, although the rocks have igneous textures and mineral assemblages. Low-angle cross laminations ("cross-beds") are preserved in the road outcrops. Although culmulus layering and cross laminations of the type described above have classically been attributed to crystal settling, similar layering is attributed to viscous flow (characterized by presence of interstitial melt and preservation of "igneous" textures) in the cumulus gabbros of ophiolites (Nicolas, 1989). These outcrops should be examined carefully for evidence of viscous deformation, including development of lineations and isoclinal folds that may have developed at high (super-solidus) temperatures, as well as evidence of filterpressing of interstitial melt to form layer parallel or crosscutting segregations.

The gabbro is intruded by several pegmatite dikes (exposed at the eastern end of the roadcut) and by diabase and hornblendite (or amphibolite?) dikes. The dikes are commonly at high angles to the cumulus layering. Near the western end of the outcrop, a 20 to 30 m-thick zone of orthocumulus biotite-bearing hornblende lherzolite is exposed. This zone appears to crosscut layering in the gabbro as a late magmatic dike, perhaps representing ultramafic cumulus mush mobilized from deeper levels of the intrusion. Similar intrusive ultramafic cumulates (typically wehrlites) are a common feature of ophiolites, where they are mobilized from ultramafic zones near the Moho (Pallister and Hopson, 1981; Nicolas, 1989).

We came across this gabbro body several years ago during a reconnaissance study of Proterozoic rocks in the Colorado Province. Aside from collecting a sample for possible Sm-Nd work, we have not done additional work, nor are we aware of any published studies or maps of this body. While having several characteristics of ophiolitic gabbros, the gabbro currently remains "out of context". The pluton may represent the cumulus substrate of the nearby Dubois greenstone belt; whether it is ophiolitic or part of a mafic arc pluton remains a matter of conjecture.

Glossary (supplied by JCR from AGI glossary):

adcumulus--formed by continuous growth of cumulus crystals from liquid of the same composition so that the crystals are unzoned.

heteradcumulus--formed by adcumulus growth of cumulus crystals and poikolitic crystals of the same composition.

lherzolite--a plutonic rock composed chiefly of olivene, orthopyroxene, and clinopyroxene.

melagabbro--gabbroic rock containing less than 35% plagioclase.

oikocryst--in poikolitic fabric, the enclosing crystal.

orthocumulus--cumulus texture characterized by one or more cumulus minerals plus the crystallization products of an intercumulus liquid.

wehrlite--peridotite composed of olivine and clinopyroxene.

Continue east on U.S. 50

182.2 Junction Chaffee Co. 240. Turn left

183.1 Ponderosa Ranch

SUNDAY
September 8

MILEAGE

0.0 Leave Lodge at Ponderosa Ranch

0.9 Junction with U.S. 50. Turn left.

7.4 Junction with U.S. 285 north of Poncha Springs. Follow U.S. 285 south.

10.6 Park on right side of highway

STOP 1. FELSIC GNEISS AND AMPHIBOLITE

Roadcut here exposes complexly interleaved and deformed felsic gneiss and fine-grained dark amphibolite, locally with discordant contacts. These rocks are typical of large expanses of Early Proterozoic rocks classed as "felsic gneiss and amphibolite" by Tweto (1979). No primary textures or structures can be recognized in this outcrop and such features are very rare elsewhere in similar rocks. The purpose of this stop is merely to invite comparison with rocks seen yesterday and with those that will be seen later today.

Return to vehicles, turn around with great care, and retrace route north on U.S. 285.

13.2 Junction with U.S. 50 in Poncha Springs. Follow U.S. 50 east toward Salida.

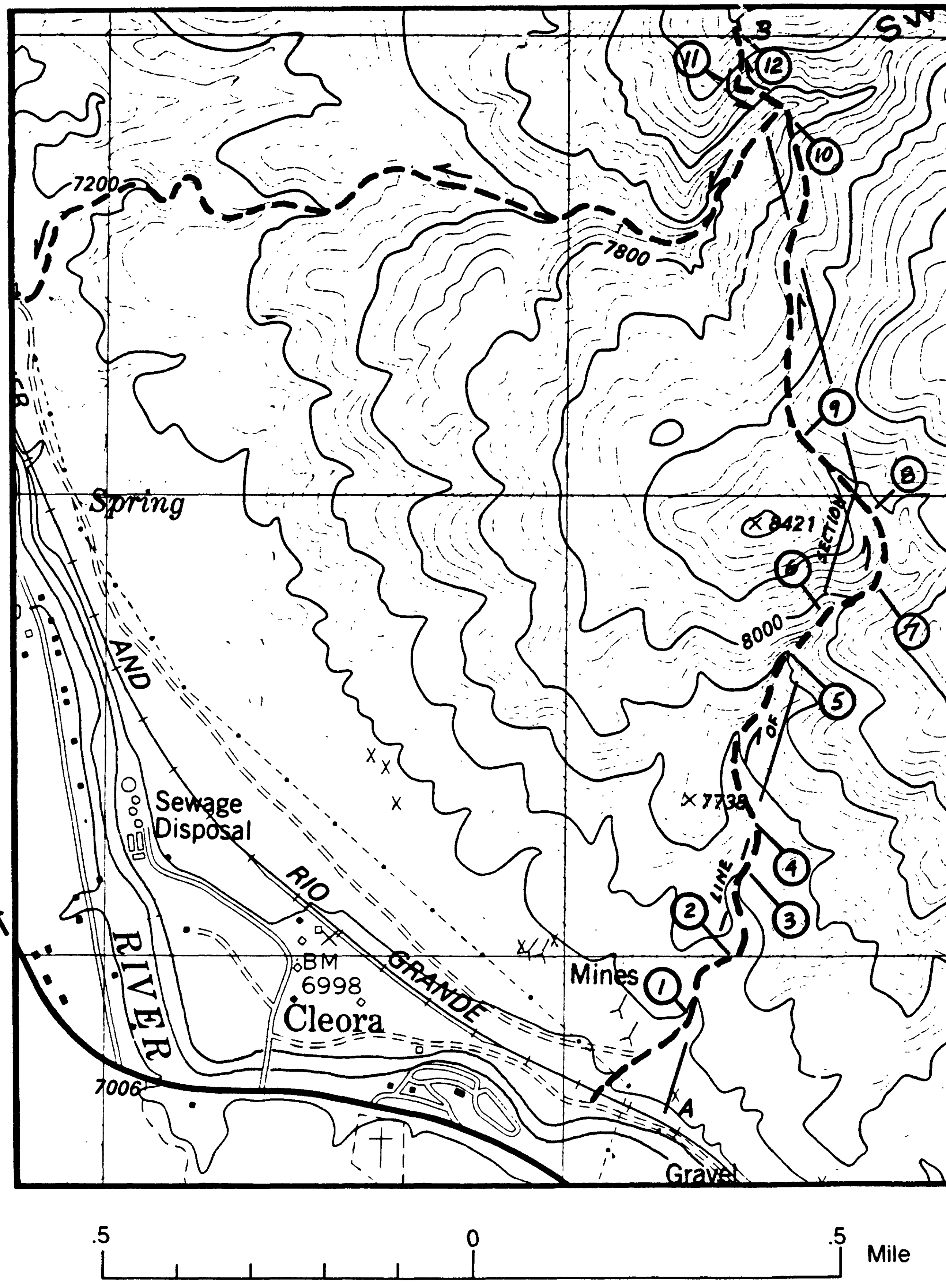

Figure 4. Map showing route of traverse near Salida

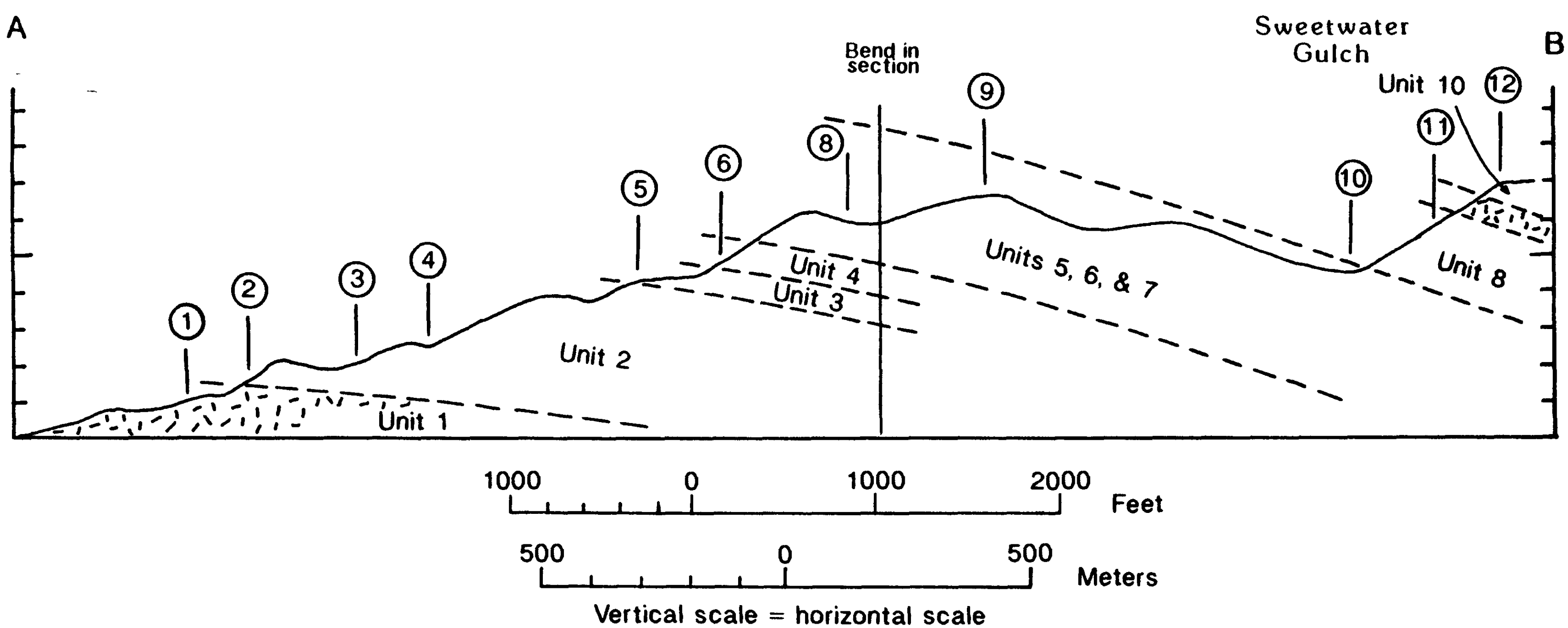

Figure 5. Cross section along traverse near Salida

16.8 Salida, west city limits.

18.2 Junction with Colo. 291 on E side of Salida. Continue on U.S. 50.

19.4 Turn left across bridge over Arkansas River

19.5 Turn right on rough dirt road just south of stock pens.

20.9 Park in fishing access area

STOP 2. FOOT TRAVERSE THROUGH EARLY PROTEROZOIC VOLCANOGENIC ROCKS

This traverse (figure 4) provides an opportunity to examine the sequence of volcanic and volcaniclastic rocks mapped and described by Boardman (1976, 1986A). The traverse is modified slightly from one described by Boardman (1986b). The units seen along the traverse (figure 5) are as follows:

Unit 1. Medium-to coarse-grained metagabbro with relict ophitic texture. Locally contains slabby xenoliths of metasediments as much as 2 m long. Chilled margin at upper contact, which is concordant with the overlying sediments.

Unit 2. Thin-bedded, fine-grained mafic and felsic metasediment. Most rocks are thin-bedded to laminated, and quartz-feldspathic or amphibolitic. Many beds display cross-laminations, and graded bedding. Some display scour, cut-and-fill, and soft-sediment deformation structures. A few contain lithic and crystal clasts as much as 2 cm long. Biotite is abundant, and hornblende needles have grown on some bedding surfaces.

Unit 3. Massive felsic crystal and lithic tuff in conspicuous cliff-forming unit. Crystal clasts, mostly feldspar, are distinct throughout; slabby lithic clasts as much as a meter long are abundant at the base. Lower half displays discontinuous banding on a scale of 3-5 cm.

Unit 4. Chiefly fine-grained metasediment rich in quartz, feldspar, and, locally, biotite. Massive to thinly bedded; locally displays soft-sediment deformation features. Coarse clastic beds in lower third of unit contains lensoidal clasts as much as 20 cm long, which appear to have been incorporated as unconsolidated sediment.

Unit 5. Massive crystal-lithic tuff (poorly exposed along the line of traverse). Fine-grained quartzo-feldspathic groundmass contains abundant lath-shaped feldspars as much as 5 mm long. Lithic clasts are mainly lensoidal volcaniclastic sediments.

Unit 6. Coarse, poorly-bedded, mafic volcaniclastic sediment (poorly exposed in line of traverse). Contains rounded mafic clasts as much as 25 cm long. Calcite-rich lenses and groundmass material are abundant.

Unit 7. Crystal-rich lapilli tuff. Lower 70% consists of massive to crudely layered feldspar-crystal clast-rich tuff. Lenticular biotite wisps are abundant at several horizons. Upper part is more equigranular, and contains fewer crystals or lithic clasts.

Unit 8. Mafic volcanic and volcaniclastic rocks. Lower and upper parts chiefly bedded basaltic lapillistone. Distinct bedding near top. Graded bedding and cross bedding conspicuous in some layers. Calcite is abundant in interstitial material. Middle of unit consists of pillow lava and pillow breccia. Interspersed throughout the unit are clastic layers rich in quartz, feldspar, and biotite, some of which are finely laminated, wavy-bedded, and cross-bedded.

Unit 9. Medium-grained gabbro, conformable to slightly cross-cutting.

Unit 10. Quartzo-feldspathic sediment. Lower half is very fine-grained and thinly bedded to laminated. Concentrically zoned ovoid structures resembling concretions are localized in a few horizons. Unit becomes coarser, thicker-bedded, and richer in feldspar toward top. Upper few meters contain abundant lithic and feldspar clasts.

[Descriptions abridged and paraphrased by JCR from Boardman, 1986b]

TRAVERSE MILEAGE
[ELEVATION IN FEET]

0.0 [6970] — Underpass beneath D&RG tracks

0.14 [7130] — Medium- to coarse-grained metagabbro containing 12 cm x 2 m slab of finely laminated metasediment. Gabbro has good relict texture. Plagioclase has labradorite cores overgrown by metamorphic andesine. Pyroxene is completely replaced by hornblende.

0.17 [7190] — Point 1. Gabbro pegmatite on W side of gulch

0.27 [7300] — Point 2. First outcrop above gabbro. About .5 m of gray cherty meta-ash(?) overlain by thinly-laminated greenish metasiltstone containing 1-2 mm dark prophyroblasts.

0.37 [7390] Float block of ash-flow tuff containing lithic fragments which display small euhedral garnet porphyroblasts.

0.44 [7500] Point 4. Thinly laminated dark green metasiltstone with graded beds and cross-beds. Pass up into light gray siliceous rock containing abundant green calc-silicate layers.

0.62 [7710] Base of ca. 10 m-thick gabbro sill exposed E of gulley.

0.70 [7820] Point 5. First outcrop of unit 3. Coarse-grained rudely layered felsic crystal tuff containing rip-up clasts of mafic and felsic metasediment. This is the base of a prominent rock step.

0.77 [7930] Point 6. Upper contact of unit 3. Felsic crystal tuff is overlain by thinly-laminated mafic metasediments.

0.85 [8015] Point 7. Gulley junction. Follow left (N) fork.

0.95 [8140] Point 8. Massive crystal tuff of unit 5.

1.09 [8250] Point 9. Saddle at head of draw. Follow yellow marker ribbons N into Sweetwater Gulch.

1.44 [8010] Outcrop of streaky welded tuff of unit 7.

1.54 [7920] Point 10. Large boulder in bed of Sweetwater Gulch is composed of mafic pillow breccia, presumably derived from unit 8. Laminated mafic tuff separates two breccia units

Traverse up slopes to NW and N is marked by yellow ribbons.

1.58 [8100] Mafic tuff and metasediments of unit 8, displaying conspicuous graded beds. Gabbro sill above.

1.63 [8160] Point 11. Thinly bedded mafic tuff breccia, coarser layers with 1-2 cm chips. Matrix is highly calcareous. Conspicuous graded bedding and cross-bedding.

1.69 [8300] Pass into gabbro sill (unit 9).

1.71 [8330] Point 12. Coarse-grained felsic metasediments of unit 10. Abundant white feldspar clasts and quartz eyes. One conspicuous layer contains dark highly calcareous clasts. Just below is mafic rock with relict igneous texture and amygdules, probably a thin flow.

Retrace route to Sweetwater Gulch

1.84 [7920]	Point 10. Follow stream SW and W down Sweetwater Gulch.
1.85- 2.15 [7900- 7720]	Good exposures of felsic crystal tuff of upper part of unit 7. Several 1-2 m sills of gabbro.
2.21 [7600]	Gabbro cut by dacite porphyry (probably Tertiary).
2.48 [7440]	Outcrops of tuff or tuffaceous metasediments.
2.90 [7200]	Thinly laminated feldspathic metasediments cut by dikes of gabbro.
3.17 [7040]	Powerline and jeep road. If we can arrange a shuttle, meet vehicles here. If not, follow road SE, parallel to railroad tracks and powerline.
4.50 [6970]	Starting point of traverse.

This concludes the field trip. Suggested return route is via Colo. 291 through downtown Salida to U.S. 285 and U.S. 285 back to the Denver area. Drive carefully!

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[2]Condie (pers. comm., 1986) points out that Knoper was inadvertently omitted in the listing of authorship in the original publication.

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