Precambrian Geology of Central Colorado

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INTRODUCTION

The Precambrian rocks of Colorado consist of greenschist-to amphibolite facies (minor granulite) metamorphic rocks (1792 to 1694 Ma) intruded by granitic plutons at roughly 1700 Ma, 1400 Ma and 1080 Ma. Nd-Sm determinations show that the source of these rocks separated from the mantle at approximately 1800 Ma, from a widespread, homogeneous, depleted-mantle reservoir similar to that found beneath modern magmatic arcs (Nelson and DePaolo, 1985). The Colorado rocks are part of a 1300-km-wide Proterozoic orogenic belt in the southwestern U.S. Within roughly 200-m.y., a region twice the width of the Appalachian or Cordilleran mountain belts formed from juvenile crust and was accreted to the Archean Wyoming craton terrane by terrane. This amounts to assembly of more than 50% of the present crust of North America between 2000 Ma and 1600 Ma. The significance of the Keck project in Colorado lies in understanding the history and mechanism of continental growth (Karlstrom and Bowring, 1988). The Wet Mountains and Southern Front Range have not been studied enough to determine how they are connected to nearby metasedimentary rocks of the Idaho Springs region or bimodal metavolcanic terranes of central Colorado. The Colorado project was designed to describe the petrology and kinematic history of rocks in the Wet Mountains and Southern Front Range, and then to relate that data to on-going debate over the assemblage of crustal rocks in the Southwest.

REGIONAL GEOLOGY

The Cheyenne belt of southern Wyoming is a 200-km-long, up to 7-km-wide mylonite zone interpreted to be the suture zone between the Archaean Wyoming province and Proterozoic rocks accreted to the south (Karlstrom and Bowring, 1988). North of the suture, the early Proterozoic Snowy Pass Quartzite Supergroup was deposited on Archean basement. The Snowy Pass metasediments include quartz-pebble conglomerates, arkosic units, marine siliciclastic rocks, black slate and dolomites formed on a stable cratonic margin with a hint of an approaching arc in the uppermost volcanogenic units (Karlstrom and others, 1983). Subduction was directed southward beneath that arc. None of the rocks in the Wyoming Province appears to have been the source for the voluminous metasediments of the Colorado Proterozoic (Condie and Martell, 1983).

Early descriptions of the Proterozoic rocks of Colorado focussed on a metamorphic complex of metasedimentary biotite gneisses and schists, and metavolcanic hornblende-rich and felsic gneisses (Tweto, 1980). Research west of Denver led to the definition of the Idaho Springs Formation as a series of interbedded metamorphic rocks, presumably of sedimentary origin, which are typically exposed in the hills surrounding Idaho Springs. The rocks are dominantly interlayered biotite gneiss, granite gneiss, and microcline-quartz-plagioclase-biotite gneiss (Moench, 1964). The use of the term "Idaho Springs" Formation for metamorphic rocks in Colorado became obsolete in the 1980's as numerous workers identified more distinctive lithologic packages that comprise specific terranes.

In southern Wyoming, the Green Mountain Formation (1792 Ma) is a bimodal metavolcanic (pillow basalt and rhyolite) calc-alkaline sequence interlayered with sillimanite gneiss, marble and calcareous schist (Condie and Shadel, 1984). These rocks formed within the southern arc terrane. The Wyoming craton collided with the arc, leading to a reversal in subduction direction toward the north beneath the Wyoming craton. To its south, the Idaho Springs terrane of the northern Front Range consists largely of metasediments ranging from chlorite-phyllite to sillimanite grade. Recent work suggests that these rocks experienced two episodes of metamorphism (e.g. Selverstone; 1995, Nyman and others, 1994). The earlier metamorphic event involved deep burial of a sedimentary pile, possibly related to the collision with the Wyoming craton at ~1700 Ma, erosion to shallower depth, and

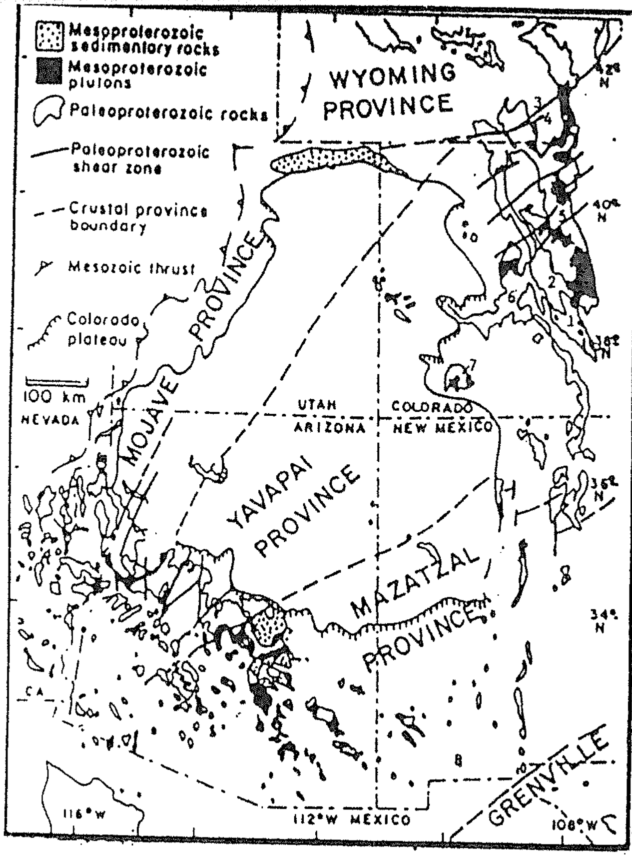

Figure 1. Outcrop map of Proterozoic rocks in the southwestern U.S. noting tentative boundaries of Yavapai and Mazatzal Terranes. Localities referred to in text include: 1 - Wet Mountains, 2 - southern Front Range, 3 - Cheyenne suture belt, 4 - Green Mountain, 5 - Idaho Springs, 6 - Dubois-Cochetopa-Salida and 7 - Irving formations. Modified from Nyman and others, 1994.

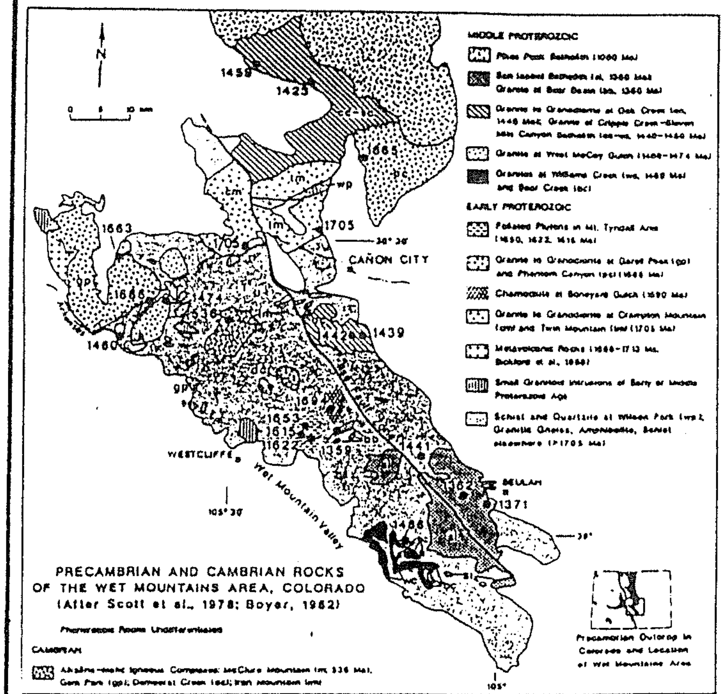

Figure 2. Geologic map of the Wet Mountains and southern Front Range, Colorado (modified after Boyer, 1962, and Scott and others, 1978) from Bickford and others, 1989.

intrusion of trondjhemite accompanied by further transpressional deformation. A second regional heating and metamorphism driven by widespread plutonism at ~1400 Ma is supported by Ar-Ar data and by growth of new cordierite, staurolite and andalusite in response to the regional reheating at lower pressures .

In west-central Colorado, three other terranes have been studied primarily by geochemical techniques (e.g. Bickford and Boardman, 1984; Boardman and Condie, 1986; Knoper and Condie, 1988) and were the focus of the 1987 Colorado Keck Project. The Dubois Greenstone, near Gunnison, contains bimodal metavolcanics (1770-1760 Ma) with a subordinate amount of volcaniclastic metasediments. Various geochemical discriminant diagrams suggest an origin in an immature island-arc setting. The adjacent Cochetopa succession (1745-1730 Ma) contains primarily volcaniclastic metasediments with bimodal felsic and mafic volcanics. Geochemistry of mafic rocks suggests a more evolved arc or possibly an intra-arc basin setting. Near Salida a similar bimodal volcanic succession (1740-1730 Ma) occurs with shallow-water volcaniclastic sediments.

Further to the southwest, in northern Arizona, other workers have identified two superterranes overlapping slightly in age (e.g. Karlstrom and others, 1987). The Yavapai supergroup (1800-1696 Ma) is a greenstone belt containing greenschist to amphibolite-facies, volcanogenic sediments (greywacke, chert, iron formation) and basaltic-to-rhyolitic lavas, all intruded by calc-alkaline plutons, presumably developed as an oceanic island arc. The Yavapai terrane has undergone polyphase, ductile deformation evidenced by an isoclinal recumbent fold phase, overprinted by a subvertical foliation, and later by local fabrics related to strike-slip zones. Deformation may have taken place both at 1740 and 1700 Ma. The Mazatzal terrane is slightly younger (1738-1630 Ma) and developed in a more stable continental setting. It consists primarily of quartzite and shale with felsic lava and pyroclastic flows. Deformation between 1692 and 1650 Ma was more brittle and occurred at lower temperature than Yavapai events, resulting in a fold-and-thrust belt with ductile shear zones. Karlstrom and Bowring (1987) have correlated the two Arizona superterranes into Colorado, with the Yavapai incorporating the Dubois, Cochetopa, Salida, Green Mountain and

Idaho Springs "terranes" The Wet Mountains, the focus of this project, were dated at 1694 ± 10 Ma (Bickford et al. 1989) and would be tentatively correlated with the Mazatzal and with rocks in northern New Mexico.

This correlation has led to a significant debate over the mechanism of development of the continental crust in the southwestern U.S. Two contrasting models call for successive accretion of thin terrane belts, progressively to the south (Condie, 1986; Reed et al., 1987) or for addition of material already consolidated in two superterranes (Karlstrom et al. 1987). Condie (1986) and Reed and others (1987) used geochemistry and geochronology to identify discrete terranes accreted to the Wyoming craton, younging to the south as follows: Green Mountain at 1790 Ma; the Irving Formation in the Needle Mountains of Colorado, at 1780 Ma, Dubois at 1740 Ma; Cochetopa and Salida at 1740 to 1715 Ma; northern New Mexico (Pecos) at about 1720 Ma; numerous terranes in New Mexico and Arizona at ~1680-1700 Ma; and several small terranes in central New Mexico at 1650 Ma. Their model would relate all the Proterozoic rocks to a single style of accretion involving southward-jumping subduction and successive collisions. Karlstrom and others (1987) were disturbed by the width and rapid emplacement of these terranes and proposed an alternative model in which the larger composite Yavapai and Mazatzal terranes developed independently. The older Yavapai island-arc rocks were accreted about 1710 Ma and the younger Mazatzal continental rocks are likely to be allochthonous relative to the Yavapai, although they may have been deposited unconformably on the Yavapai crust.

The Wet Mountains and southern Front Range are critical areas for evaluation of these models, because they are not readily explained by in either model. Rocks in the Wet Mountains lie slightly east of the Salida sequence but are higher-grade and lack bimodal volcanics (Noblett and others, 1987). The southern Front Range is almost entirely underlain by meta-pelites with minor amphibolite and calc-silicate (Hawley and Wobus, 1977) and with no clear relationship to either Idaho Springs to the north or Wet Mountain rocks to the south. Any model of terrane evolution in the southwestern U.S. must be consistent with geologic relationships in the Wet Mountains and southern Front Range.

The metamorphic rocks in Colorado have been intruded by several generations of granitoids. The Boulder Creek intrusive event (about 1700 Ma) includes many granodiorite to tonalite plutons, which are generally foliated parallel to their wall rocks. Two plutons in the Wet Mountains intruded at 1705 and 1665 Ma, and are syn-to-late tectonic in the Boulder Creek episode. After a long hiatus, renewed plutonism occurred between 1517 Ma and 1360 Ma in the Wet Mountains and Front Range. Granitic plutons from this interval are sometimes slightly foliated but have been correlated with the anorogenic magmatism of North America. Recent work (e.g. Selverstone, 1995, Nyman and others, 1994) suggests that a regional transpressional orogeny affected the Southwest, coincident with a thermal event in the region which imposed temperatures of about 500°C. Ar-Ar ages, textural overprints by metamorphic minerals and regional foliation support this new interpretation. No studies on rocks from the Wet Mountains and central Colorado have yet been completed.

PROJECT OBJECTIVES

The primary objectives of Colorado Keck project are to describe the lithologies, deformation, metamorphism and magmatism of Proterozoic age in the northeastern Wet Mountains and in addition, to sample rocks from the southern Front Range which might constrain P-T-t conditions and provide correlations among Colorado terranes by means of geochemistry of mafic rocks. In light of the controversy just described over the mechanism of crustal evolution in Colorado and the significance of 1400 Ma events, we hope to use our findings to determine whether the Wet Mountain 'terrane' is most closely related to the Idaho Springs, Salida, Yavapai or Mazatzal terranes; or whether it constitutes a terrane in its own right. To accomplish this, the project focussed on a region which has not been mapped in detail before, defining lithologies, recording kinematic indicators and collecting samples for petrographic and geochemical analyses.

STUDENT PROJECTS

We began the research with a week-long overview of Colorado Proterozoic rocks before selecting individual projects. John Goodge (SMU) and Karl Karlstrom (University of New Mexico) provided phenomenal support in the field identifying features and helping to teach students how to work in high-grade metamorphic regions. Goodge also presented his research on amphibolites from Antarctica and showed the students the steps involved in research like ours. Karlstrom focussed on problems in the Southwest and convinced the students of the significance of our work in light of crustal evolution. John Shallow, formerly with American Copper and Nickel, led us on an examination of a Proterozoic volcanic massive sulfide deposit. Yoshihide Ogasawara (Waseda University) joined us for two weeks, and was especially helpful in explaining how he determines P-T conditions from calc-silicate rocks like those we were collecting in the Front Range. Visiting faculty John Brady (Smith), Tekla Harms (Amherst) and Shelby Boardman (Carleton) all added significantly to the success of their students and our project.

Five of the students chose to map in fairly rugged terrain in the northeastern Wet Mountains. Josh Feinberg worked along South Hardscrabble Creek; Amanda Ash and Lindsey Quackenbush worked north of North Hardscrabble Creek; and David Cuevas and Dorothy Metcalf mapped in the Newlin Creek drainage. Each of the mappers produced a field map including lithology and structures. They were able to show that the oldest rocks are metasediments (formerly shale, quartzwacke, or graywacke) and metabasalt, isoclinally folded, metamorphosed and injected by several generations of granite. Their work was presented at the combined South-Central Rocky Mountain GSA meeting, and at the Northeastern section meeting.

Two of the students (Layla Stiles on granites and Martha Folley on amphibolites) focussed their studies on variations of a single lithology across the region from the Wet Mountains to the southern Front Range. Layla and the mappers were able to demonstrate at least three distinct phases of granitoid and characterize them in the field. The earliest recognized granite in the Wet Mountains intruded the mixed gneisses before completion of isoclinal folding and has been tentatively dated at ~1720 Ma (U-Pb, by M.E. Bickford at Syracuse University), providing an intrusive age significantly older than any obtained by previous work. Layla's geochemical work (XRF and INAA) should help us to distinguish between syn-to-late tectonic (ca. 1.7 Ga Boulder Creek?) granites and post-tectonic (ca. 1.4 Ga Silver Plume) granite. Martha collected amphibolites (mostly meta-basalts) along a 100-km N-S transect for geochemical analysis by XRF and INAA. Her results, when plotted on various classification and tectonic discriminant diagrams should help to compare the Wet Mountain and southern Front Range with other terranes, and with each other.

Two of the students (Kate McCloskey and Sara Rosenzweig) studied the metamorphic pressure-temperature history of the region. Kate worked on rocks in the Wet Mountains, employing mostly garnet-biotite geothermometers but also studying one calc-silicate and an unusual pyroxene-bearing granulite occurrence. Sara worked on gneisses in the southern Front Range including a variety of wollastonite-bearing calc-silicates, cordierite-anthophyllite gneiss and garnet-biotite-staurolite metasediments.

Numerous labs provided facilities for our research. The University of Massachusetts provided microprobe and XRF support. Oregon State provided INAA data. Pat Bickford at Syracuse University obtained the U-Pb age determination. Waseda University performed P-T calculations for calcsilicate rocks. The University of New Mexico and the Colorado College Natural Sciences Division supported Ar-Ar analyses. We, the project faculty, are deeply grateful for all the support received and for our students' tremendous commitment to this project.

PROJECT STATUS

Students in this project obtained the first detailed lithologic and structural data from the eastern Wet Mountains, constructed the first geological maps, and used geochemical analyses of rocks from the Wet Mountains and southern Front Range to model rock origins. Their work will be used in coming years to constrain models of crustal growth in the region because existing tectonic models have not incorporated findings from these study areas. Thus, the fundamental field and laboratory data are the most significant aspect of the project. Further vital contributions will come from the 1997 Keck project in the northern Wet Mountains and Arkansas River Canyon.

Dark, close-layered gneisses appear to be primarily metasediments of continental or arc derivation with minor basalts (now amphibolites). The isoclinally folded gneisses have NW- to WSW-striking foliations, with mineral lineations, where present, plunging generally downdip to the NE or NNE. Sparse kinematic indications give top-to-SW shear sense, with possible late, down-to-NE extension crenulation. Static mineral recrystallization textures overprinted the gneissic fabrics throughout the study area. Isoclinal folding and polyphase deformation are considered typical of Yavapai terrane rocks. The new U-Pb age obtained this summer indicates that the Wet Mountains are slightly older than previously recognized. The P-T determinations should allow these rocks to be considered in terms of the looping P-T paths recognized in the Southwest (Williams and Karlstrom, 1996). The mineral recrystallization may have developed during regional re-heating at 1.4 Ga, subject to verification by ongoing Ar-Ar work. These significant findings from the student projects have enabled us to introduce the Wet Mountains and southern Front Range in the discussion of Proterozoic crustal growth in the Southwest.

Preliminary structural results have been presented at two GSA sectional meetings and we anticipate a project overview and details of the P-T and lithologic studies to be presented at future GSA and AGU meetings. The work will continue in summer 1997 in the northern Wet Mountains and west into the McIntyre Hills and Arkansas River Canyon as we try to characterize the geology in that area. This new work will further test the terrane model by extending the study towards a known terrane in Salida. It will also address issues concerning the origin of economic volcanic massive sulfide deposits in the Proterozoic.

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