PRECAMBRIAN GEOLOGY OF CENTRAL COLORADO

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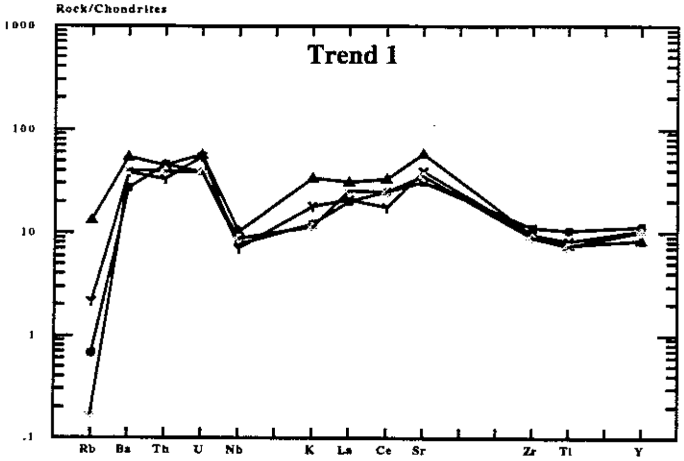

Fig. 3. Chondrite normalized spider diagram of Trend 1 showing Nb trough and high Ba/Rb ratio (after Sun, 1980).

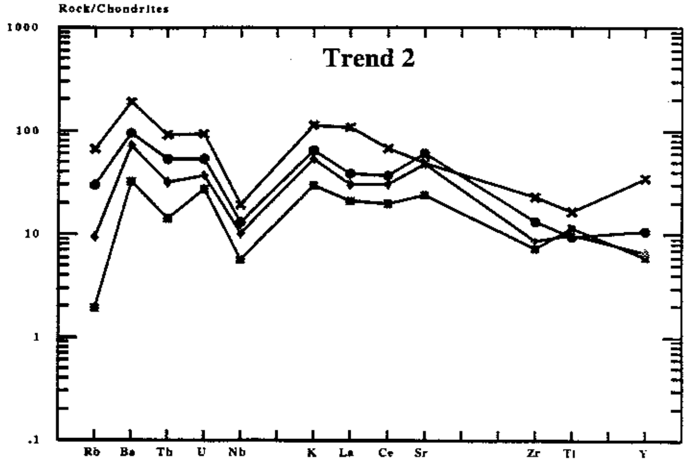

Fig. 4. Chondrite normalized spider diagram of Trend 2 showing Nb trough and high Ba/Rb ratio (after Sun, 1980).

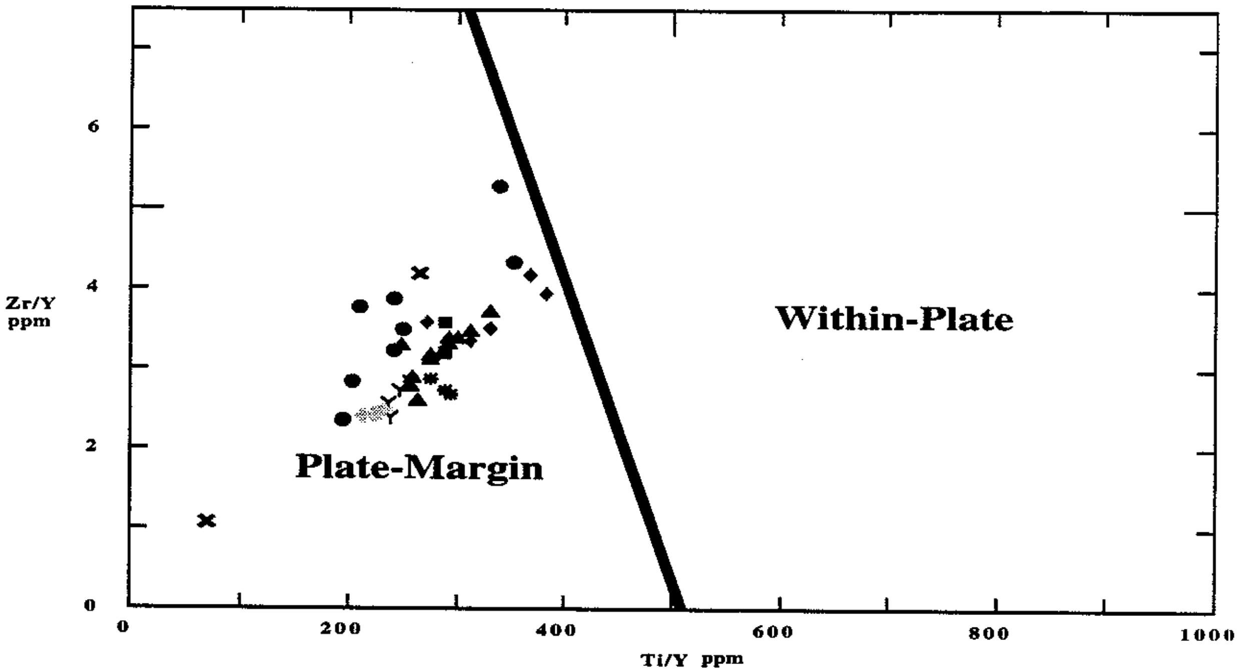

Fig. 5. Zr/Y-Ti/Y discrimination diagram indicating plate-margin nature of rocks of the study area (after Pearce and Gale, 1977).

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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 region west of the Wet Mountains has not been studied enough to determine how it is 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 Arkansas River Canyon, west of the McIntyre Hills and east of Salida, and then to relate that data to on-going debate over the assembly 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 and deformation (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 intrusion of trondjhemite accompanied by

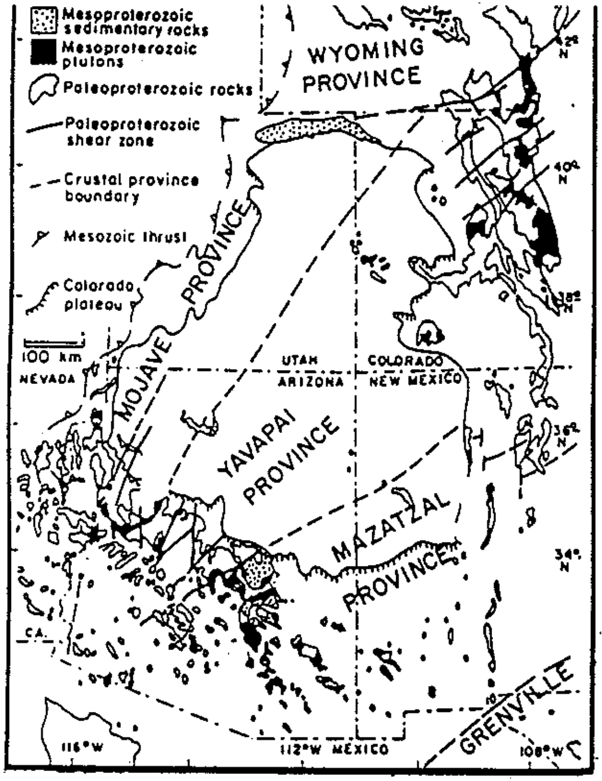

Figure 1. Outcrop map of Proterozoic rocks in the southwestern U.S. noting tentative boundaries of Yavapai and Mazatzal Terranes. Localities referred to in text include: 1 - Wet Mountains, 2 - southern Front Range, 3 - Cheyenne suture belt, 4 - Green Mountain, 5 - Idaho Springs, 6 - Dubois-Cochetopa-Salida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

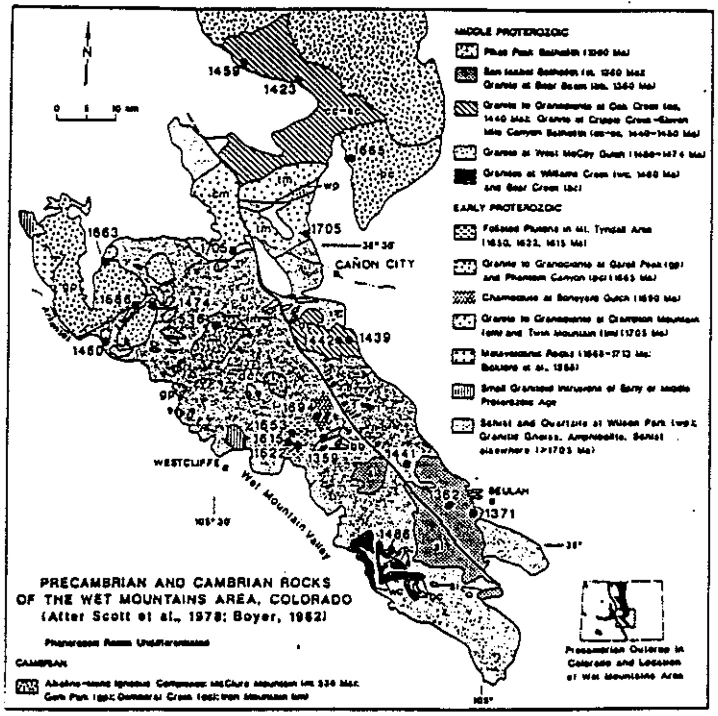

Figure 2. Geologic map of the Wet Mountains and southern Front Range, Colorado (modified after Boyer, 1962, and Scott and others, 1978) from Bickford and others, 1989.

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, to the east of this Keck project, were dated at 1694 ± 10 Ma (Bickford et al. 1989) and were tentatively correlated with the Mazatzal and with rocks in northern New Mexico by Karlstrom. Thus, the project area straddles a proposed major terrane boundary in Central Colorado.

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 Arkansas River Canyon is a critical area for evaluation of these models, because it lies across one proposed boundary between the Mazatzal and Yavapai rocks. Rocks to the west in Salida formed in a bimodal volcanic suite that is only weakly deformed. The bimodal volcanics do not occur in the Wet Mountains to the east, studied by the 1996 Colorado Keck Project.

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 central Colorado have yet been completed.

PROJECT OBJECTIVES

The primary objectives of the Colorado Keck project are to describe the lithologies, deformation, metamorphism and magmatism of Proterozoic age rocks in the Arkansas River Canyon. These rocks were mapped as undifferentiated gneisses and metavolcanics by the USGS, but no in-depth work has been done on them. 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 to which terranes the rocks of the Arkansas River Canyon are most closely related and whether they lie across an hypothesized terrane boundary. To accomplish this, the project focussed on defining lithologies, interpreting protoliths and depositional settings, recording kinematic indicators and collecting samples for petrographic and geochemical analyses.

STUDENT PROJECTS

The two sophomore students, **Sarah Stevens and Martha Wilson**, studied a lithologic unit of cordierite schist within the metasedimentary package. They mapped the contacts, carefully measured orientations of external schistosity and early fabrics preserved inside large cordierite porphyroblasts and worked out the metamorphic mineral sequence in the unit. They identified two fabrics preserved within the cordierite, one of which appears to be original bedding, crenulated prior to growth of the cordierite during metamorphism associated with the intrusion of Boulder Creek magmas. Late-stage unoriented overgrowths of sillimanite and biotite argue for a static recrystallization during the Silver Plume event.

Chris Bodle, David Gentry, Rima Givot and Eli Levitt were all involved in mapping south of the Arkansas River, east of Texas Creek. Chris and Rima identified amphibolite-grade bimodal metavolcanics with metasediments, while Eli and Dave, mapping a few miles farther south, found only metabasalts with metasediments in a region with a higher volume of plutonism. Predominant rock types are felsic gneiss and amphibolite. Other distinctive lithologies include: garnet-sillimanite-biotite gneiss, quartz-biotite gneiss, cordierite-biotite gneiss, cordierite schist and quartz-sillimanite "pod" gneiss. Eli and Chris compared the geochemistry of the metabasalts near Texas Creek and Road Gulch to samples previously studied in the Wet Mountains, southern Front Range and Salida areas. These samples best resemble Salida metabasalts, though they share similarities with all three regions. Details of the structural history of the region were studied by Rima, Chris and Dave. All the rocks showed evidence of at least two deformational events and a younger static thermal event. An early penetrative deformation involved isoclinal folding and transposition of primary layering. Foliation and axial surfaces of isoclinal folds strike E-W to SE-NW, with predominant N and NE dips in a lithologically varied sequence of felsic and mafic gneisses with interfoliated calcsilicate and cordierite schist, variably intruded by syn- or post-tectonic granitoids. Locally, high grade shear zones truncate these sequences; one major shear zone strikes ~N-S and records oblique strike-slip displacement. Open folding about NE axes warped the regional foliation into NE-plunging folds, apparently during emplacement of 1.4 Ga plutons. Growth of randomly oriented metamorphic minerals across foliation is also interpreted to have accompanied Silver Plume plutonism.

Erik Ekdahl and Kati Szramek mapped north of the Arkansas River near Howard. Kati worked on a region of lower-grade rocks which are very similar to the section described near Salida (Bickford and Boardman, 1984). Well-preserved tuffaceous and basaltic material are interlayered with metasediments. Litttle deformation and no partial melting have affected these rocks. The geochemistry of the amphibolites correlates well with metabasalts from the Salida area and southern Front Range, supporting an arc or back-arc setting for these rocks. Erik selected a small region in which mafic and felsic magmas have intermingled prior to regional metamorphism. The mingling is typical of arc magmas. Erik focussed on the geochemical variation across the contacts that characterized the mingling process.

Kate Wearn studied the bimodal metavolcanic rocks along a 50 km E-W traverse of the Arkansas River and its tributary canyons from near Howard to the Royal Gorge, emphasizing the previously unstudied felsic rocks. Many felsic samples preserve pyroclastic textures, and the distribution and abundance of these rocks was found to be far greater than previously believed. Her geochemical data show that most felsic rocks are metarhyolites with trace-element abundances very similar to those in the Salida area and to I-type, arc-related granitic rocks.

Laboratory support for student research came from the Oregon Sate University reactor Lab for INAA, from Actlabs for ICP analses and from the University of Massachusetts geochemical lab. We are grateful for all the support our students received.

PROJECT STATUS

Students in this project obtained the first detailed lithologic and structural data from the Arkansas River Canyon, constructed the first geological maps, and used geochemical analyses 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. Currently, debate exists over the possibility of a large terrane boundary separating Mazatzal and Yavapai rocks occurring in this region. These data will complement planned geophyscal projects which will explore the deeper crust.

Mapping north of Howard revealed a continuation of the low-grade, bimodal volcanic and sedimentary sequence described by Boardman for the Salida area. South of the Arkansas River, the rocks are somewhat higher grade and considerably injected by plutons of several ages. The bimodal volcanic sequence continues east possibly to the north end of the Wet Mountains, but is not observed in small exposures ten miles to the south. Extensive ductile deformation and at least two periods of metamorphism and plutonism have affected these rocks.

Preliminary results from the cordierite schist study, the structural study of rocks in the Five Point Gulch area and the magma-mingling projects will be presented at a GSA sectional meeting and we anticipate a project overview and details of the felsic volcanic and other structural studies will be presented at future GSA and AGU meetings.

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Structural and geochemical analysis of Proterozoic metamorphic rocks near Texas Creek, Colorado

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INTRODUCTION

All of the rocks in the study area are Proterozoic with the exception of younger intrusions and Tertiary-Quaternary alluvium. The area consists of a bimodal sequence with other rock units interlayered. These rocks are intruded by several different types of younger dikes, including pegmatitic, granitic, and mafic dikes that crosscut foliation. Most of the rocks have undergone amphibolite grade metamorphism, which is defined by the appearance of foliations and small and large scale folding within the rock units. Structural and geochemical analysis of these rocks will provide data for understanding the deformation that occurred in the area.

PETROGRAPHY

The analysis of 30 thin sections was conducted to determine the mineralogy of the rocks collected in the field. Identification of minerals along with microstructures and textures were noted. The major rock units found in the study area include amphibolite, felsic gneiss, and biotite gneiss and will be described below. The bimodal sequence is composed of the biotite gneiss and felsic gneiss. The other rock units that were distinguished in the field and through thin section analysis include Boulder Creek granodiorite, cordierite schist, quartzite, podrock, sillimanite schist, and epidosite.

Amphibolites in the study area have a unit thickness that varies from meters to tens of meters, are usually bounded by felsic gneiss or biotite gneiss, and occasionally are found in other units as large xenoliths. Rocks of the amphibolite units contain 25-50% xenoblastic to hypidioblastic amphibole (cummingtonite), 25-30% xenoblastic quartz, and varying amounts of plagioclase, microcline, chlorite, biotite, muscovite, epidote, sphene, zircon, hematite, and opaques. They are usually fine to medium grained, foliated rocks containing larger phenocrysts with inclusions, and some poikiloblastic minerals.

Felsic gneiss units vary from meters to hundreds of meters, are usually bounded by biotite gneiss or amphibolite and occasionally have amphibolite xenoliths. Felsic gneiss are fine to medium grained foliated rocks containing 15-40% xenoblastic to hypidioblastic microcline and/or plagioclase, 20-40% xenoblastic quartz, 15-20% hypidioblastic biotite, and varying amounts of muscovite, sphene, chlorite, epidote, garnet, zircon, hematite, apatite, and opaques.

Biotite gneiss units vary from meters to hundreds of meters and are usually bounded by felsic gneiss or amphibolite. These fine to medium grained rocks contain 20-40% hypidioblastic biotite, 15-25% xenoblastic to hypidioblastic microcline and/or plagioclase, 40% xenoblastic quartz, and varying amounts of muscovite, hematite, garnet, apatite, and zircon.

STRUCTURE

Structural measurements of foliations, lineations, and folds were taken. Field criteria and stereographic analysis of structures indicate that two generations of folding can be distinguished from the data.

First Generation Structures

The oldest structures in the study area are tight to isoclinal F_1 folds and are associated with S_1 layering, and a possible S_0 layering. S_1 is defined by the axial planar alignment of biotite and quartz. S_0 is defined as primary sedimentary or igneous layering. Thin section analysis has shown there is little or no preserved S_0 layering present in the rocks of the study area. The F_1 folds produced the prominent foliation and lineations associated with the rocks in the study area.