PRECAMBRIAN GEOLOGY OF THE JAWBONE MOUNTAIN AREA, RIO ARRIBA COUNTY, NEW MEXICO

by

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Dedicated to my loving wife,

Jill

ABSTRACT

The Precambrian rocks in the Jawbone Mountain area can be grouped into three packages of supracrustal rocks, one of which is intruded by plutonic rocks. The oldest package comprises the Moppin Metavolcanic Series which contains a suite of calc-alkaline volcanic and volcaniclastic rocks. Moppin lithologies include biotite schist, chlorite schist, and amphibole schist. Volcanic protoliths represented include basalt, andesite, and dacite. This suite is interpreted as having accumulated in a volcanic arc setting. The Moppin Metavolcanic Series is intruded by the Maquinita granodiorite and the granite of Hopewell Lake.

The next younger package of supracrustal rocks is the Burned Mountain metarhyolite. This metarhyolite, with well-preserved eutaxitic textures and clasts resembling flattened pumice fragments, is interpreted to be a sub-aerial ash-flow tuff. Trace element geochemistry compares favorably with continental rhyolites associated with crustal extension.

A thick sequence of siliciclastic sediments is the youngest package of Precambrian rocks in the study area. The base of this package, containing metaconglomerate, arkose, and micaceous quartzite, marks the transition from rhyolite accumulation to clean sandstone deposition. The sandstone, now vitreous quartzite more than 1 km thick, was deposited on an inner shelf and exhibits bedforms produced by tidal and storm processes.

Regional metamorphism to the upper greenschist facies has occurred in all the Precambrian rocks in the study area.

Foliations of two main types occur. A bedding-parallel cleavage is related to early deformation events which produced tight to isoclinal folding. An axial-planar cleavage associated with a later, broad, upright folding is seen on a more limited basis.

Preliminary U-Pb dates exist for the Maquinita granodiorite (1755 Ma) and the Burned Mountain metarhyolite (1700 Ma).

Briefly, the geologic history is as follows: Moppin Series deposited in a volcanic arc; syntectonic intrusion of granodiorite as arc is being accreted to a craton; uplift and erosion of Moppin; continental extension and extrusion of Burned Mountain metarhyolite; marine transgression with basin development and deposition of immature sediments followed by sandstone deposition; entire Precambrian sequence buried, metamorphosed, and multiply deformed.

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TABLE OF CONTENTS

LIST OF PLATES

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

PURPOSE

This study is part of an ongoing project on the Precambrian geology of the northern Tusas Mountains. Specific goals in the Jawbone Mountain study area were:

1) to delineate and map the major Precambrian units at a scale of 1:12,000, paying particular attention to stratigraphy and the relation of the plutonic rocks to the supracrustal rocks;

2) to document Precambrian structural fabrics and relate them to local and regional structural history;

3) to determine the nature and grade of metamorphism;

4) to chemically characterize the major supracrustal and plutonic units;

5) to consider possible depositional environments and tectonic settings that may have prevailed during the early Proterozoic in northern New Mexico.

LOCATION

The Jawbone Mountain study area is located in the Tusas Mountains of north-central New Mexico, 20 miles west of Tres Piedras. The 28 square-mile area is mostly within the Carson National Forest (Figure 1). The west side of

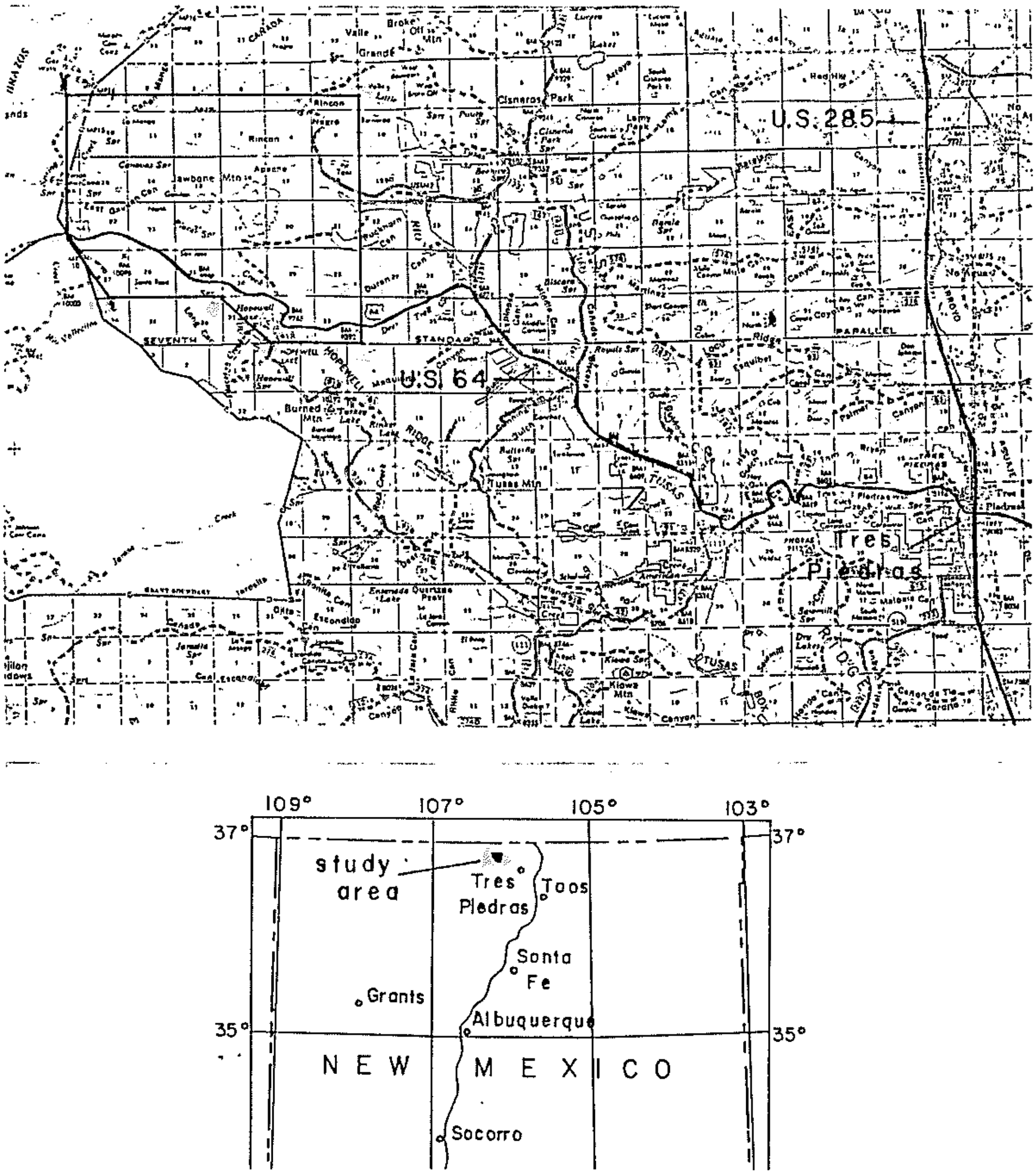

Figure 1. Location map of Jawbone Mountain study area.

the area extends onto private land. The study area falls on four 7.5-minute quadrangles: Burned Mountain, Broke Off Mountain, East Gavilan Canyon, and Lagunitas Creek. It lies between north latitudes 36° 42' and 36° 46' and west longitudes 106° 12' and 106° 19'.

Main access into the area is via US 64 from Tres Piedras. Numerous ranch roads and official Forest Roads provide additional access.

METHODS OF INVESTIGATION

Field mapping was performed during the summer months of 1983 and 1984. The area was mapped at a scale of 1:12,000. Fifty-eight thin-sections were studied. Eleven samples were analyzed by x-ray fluorescence at the New Mexico Bureau of Mines and Mineral Resources for ten major elements and thirteen trace elements.

PREVIOUS INVESTIGATIONS

The study area was first mapped by Just (1937) as part of his study of pegmatites in the Petaca and Picuris areas. He named the major units in the area. These included the Hopewell Series (principally of hornblende-chlorite schists which Just interpreted as metabasalts and meta-andesites), the Ortega quartzite, the Vallecitos rhyolite, and the Tusas granite.

Barker (1958) mapped the Las Tablas (15-minute) quadrangle which includes the Burned Mountain (7.5-minute) quadrangle of this study. Barker renamed the Hopewell Series the Moppin Metavolcanic Series. He divided the quartzite into two major units: an older Ortega quartzite that lay stratigraphically below the Moppin Series, and a younger Kiowa Mountain Formation that overlay the Moppin. Barker changed the name of the Vallecitos rhyolite to the Burned Mountain metarhyolite, and suggested that the Burned Mountain consisted mainly of a series of hypabyssal intrusives rather than flows. Barker also subdivided the Tusas granite of Just into the Maquinita granodiorite and the Tres Piedras granite.

Bingler (1965) mapped the La Madera (7.5-minute) quadrangle, 25 km southeast of the Jawbone study area. His report emphasized the structural complexities and metamorphism of the Precambrian rocks. He presented evidence for three periods of deformation. Bingler described the Precambrian rocks using only metamorphic rock names and did not discuss possible protoliths. Bingler's (1968) map of Rio Arriba County covers the entire study area at a scale of 1:120,000.

Two other maps published in the late 1960's covered parts of the study area. Muehlberger (1968) mapped the Brazos Peak (15-minute) quadrangle which covers the high quartzite ridge in the northwest portion of the study area. Doney's (1968) map of the Cebolla (15-minute) quadrangle covers the southwest part of the study area, which is underlain mostly by quartzite and Tertiary rocks.

Recently, R. Wobus has been studying the Precambrian rocks of the Tusas Mountains in conjunction with a USGS project to map the Aztec 2° sheet (in preparation). Reconnaissance maps of the Burned Mountain (7.5-minute) quadrangle (Wobus and Manley, 1982) and several other quadrangles were produced from this study. Wobus (1985) proposes a revised stratigraphy for the Proterozoic supracrustals of the Tusas Mountains. He assigns all of the quartzite to the Ortega quartzite which he considers the youngest Precambrian supracrustal exposed.

This study of Jawbone Mountain is the third in a series of Master's theses by students at New Mexico Institute of Mining and Technology. Kent (1980) mapped the area around Tusas Mountain. The Burned Mountain area was mapped by Gibson (1981). The northwestern part of Gibson's area overlaps slightly with the southeastern portion of the present Jawbone Mountain study area.

GENERAL GEOLOGIC SETTING

REGIONAL TECTONIC SETTING

The Tusas Mountains are the present topographic expression of the Brazos uplift. The uplift trends north-northwest from Ojo Caliente to north of the Colorado border (Figure 2). The Needle Mountains of Colorado lie on the trend of the Brazos uplift and contain Precambrian rocks that share a similar tectonic history. To the west of the Brazos uplift is the Chama Basin, which Muehlberger (1967) describes as an elevated terrace separating the large San Juan Basin from the Brazos uplift. The eastern margin of the Brazos uplift is less distinct than its western margin. Baltz (1978) says that the east-tilted Brazos uplift merges into the east-tilted San Luis Basin. He arbitrarily picks the boundary as the western outcrops of basin-fill sediments and Taos Plateau basalts. At its southern end, the Brazos uplift is bounded by the Española Basin.

The Brazos uplift has been an emergent area through much of Phanerozoic time. The only Paleozoic rocks in the area are a small exposure of middle Pennsylvanian sediments in the southwest corner of the Brazos Peak quadrangle. Whatever other Paleozoic sediments were deposited in the Tusas Mountains region have been removed by erosion.

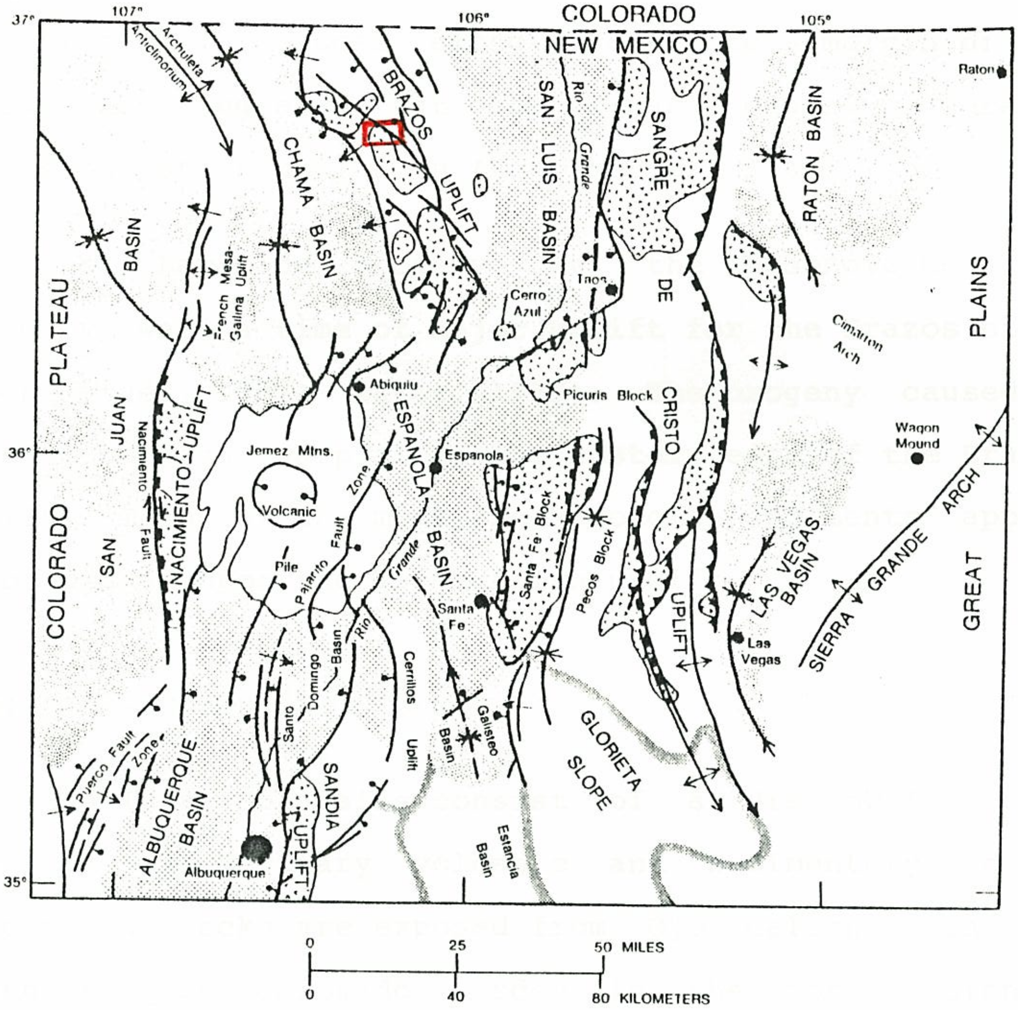

Figure 2. Map showing major tectonic elements in north-central New Mexico (from Baltz, 1978). Red outline shows location of Jawbone Mountain area.

The Mesozoic record in the region is more complete. This era is represented by rocks of the Chinle, Entrada, and Morrison Formations. These rocks pinch out against the Precambrian rocks along the western margin of the uplift and suggest that the Tusas Mountains were a persistent structural high (Muehlberger, 1967).

The Laramide orogeny at the Mesozoic-Cenozoic boundary was a time of major uplift for the Brazos block (Muehlberger, 1967; Baltz, 1978). The orogeny caused a large monoclinal warp along the western edge of the Brazos uplift. This warping made the Mesozoic sediments appear to be draped upon the Precambrian uplift.

REGIONAL PRECAMBRIAN GEOLOGY

The Tusas Mountains consist of a Precambrian core mantled by Tertiary volcanic and sedimentary rocks. Precambrian rocks are exposed from Ojo Caliente in the south to the Colorado border in the north, along a north-northwesterly trend.

The Precambrian stratigraphy of the Tusas Mountains has been the subject of some disagreement since Just's original mapping in 1937. Various rock names and proposed stratigraphic relationships are presented in Table 1. Those listed represent changes and/or refinements in the understanding of the stratigraphy.

TABLE 1

General Precambrian Stratigraphy in the Tusas Mountains

Just 1937	Barker 1958	Gresens & Stensrud 1974	Wobus 1985	This study
Ortega quartzite	Kiawa Mountain Formation	Ortega quartzite	Ortega quartzite	vitreous quartzite
				micaceous metasediments (transitional package)
Vallecitos rhyolite		metavolcanic-metasedimentary complex	Burned Mountain metarhyolite	Burned Mountain metarhyolite
Hopewell Series	Moppin Metavolcanic Series		Moppin Metavolcanics	Moppin Metavolcanic Series
	Ortega quartzite			

The following summary incorporates the ideas and mapping of Gresens and Stensrud (1974), Williams and Wobus (1984), and Wobus (1985), and represents the current version of Precambrian stratigraphy in the Tusas Mountains.

The oldest Precambrian supracrustal unit exposed in the Tusas Mountains is a package of metamorphosed volcanic, volcaniclastic, and related sedimentary rocks. The package is dominated by mafic to intermediate composition rocks with minor quartz-rich layers and has been called the Moppin Metavolcanic Series by Barker (1958). Moppin rocks are restricted to the northern part of the Tusas range. An amphibolite layer cropping out around Kiowa Mountain in the central Tusas Mountains, and recently assigned to the Moppin by Wobus (1985), is the southernmost exposure of the Moppin Metavolcanic Series.

In the northern Tusas Mountains, the Moppin is unconformably overlain by the Burned Mountain metarhyolite. This metarhyolite, named by Barker (1958), has eutaxitic textures and contains abundant phenocrysts of quartz and alkali feldspars. South of Kiowa Mountain, the metarhyolite is the oldest exposed unit. Much of this area was originally mapped as a quartz-muscovite schist (Petaca schist of Just, 1937). Gresens and Stensrud (1974) did detailed field, petrographic, and chemical work in and around the Las Tablas (15-minute) quadrangle and determined that most of the quartz-muscovite schists there were metarhyolites which have been changed by recrystallization and/or metasomatic alteration. Wobus (1985) includes these southern metarhyolites with intercalated conglomerates and quartz-rich sediments as part of an expanded Burned Mountain metarhyolite.

Lying above the Burned Mountain metarhyolite in the northern part of the range is a group of sediments which mark a transition from volcanic-dominated rocks to clean quartzites. This transition group contains metaconglomerate, arkose, micaceous quartzite, and quartz-muscovite schist. In the south, these rocks have not been formally described, although recent mapping by M. Williams (personal communication, 1985) shows this transition group to be present. He reports that the package is thinner than in the north, is dominantly micaceous quartzite, and contains no metaconglomerate.

The Ortega quartzite is the youngest Precambrian supracrustal rock in the Tusas Mountains. It is a clean, vitreous quartzite with minor quartz-pebble conglomerate layers. Cross-bedding is well-preserved in many places and generally marked by hematite layers with or without alumino-silicates. From exposures in the northern Tusas Mountains the quartzite is estimated to be over 1 km thick.

Several felsic plutons of Precambrian age intrude the supracrustal succession. The exact genetic and chronologic relationships among these plutons, and their relation to regional metamorphic events, are not yet known. Radiometric ages on some plutons are not easily interpretable, and other plutons have not been dated. Several plutons contain xenoliths of Moppin rocks but have no exposed contacts with units higher in the section. Among these are the Maquinita granodiorite, the granite of Hopewell Lake, and the Tusas Mountain granite as defined by Wobus and Hedge (1982). Barker (1958) maps a septum of metarhyolite within the Tres Piedras granite on the northeast side of Tusas Canyon. Contacts between the Ortega quartzite and plutonic rocks are not known.

There have been three periods of deformation on a regional scale (Bingler, 1965). M. Williams (personal communication, 1985) has documented a fourth deformation on a local scale in the southern Tusas Mountains. The first two periods of deformation produced isoclinal folds, intense foliation, small scale transposition of layering, and repetition of stratigraphy. According to Bingler, fold axes of D_1 folds trend roughly northeast whereas those of D_2 folds trend northwest. The third deformation produced large scale, open folds which generally trend east-west. The Jawbone Syncline and Hopewell Anticline, which pass through the Jawbone study area, are products of this third deformation. The orientation of the fabrics observed by Bingler in the La Madera (7.5-minute) quadrangle are not consistent throughout the range. This is because the physical parameters of the rocks which are exposed today were not uniform at the time of deformation. Such parameters include lithology, thickness of beds, and metamorphic temperature.

Rocks in the Tusas Mountains are variably metamorphosed from lower greenschist to lower amphibolite grade. Metamorphic grade seems to increase to the southeast (Barker, 1958; Kent, 1980). Chlorite-epidote-muscovite is a typical assemblage within rocks of the Moppin Metavolcanic Series in the northern part of the range. In the southern part of the range the typical Moppin assemblage is biotite + hornblende. Garnet and staurolite also occur in rocks of appropriate composition in the southern Moppin exposures. Aluminous rocks and layers throughout the range contain kyanite. In addition, andalusite can be found in the northern part and kyanite + sillimanite in the southern part.

TERTIARY AND QUATERNARY GEOLOGY

The Tusas Mountains region began the Tertiary as an uplifted block, but by late Eocene time, parts of the region were again submergent or low-lying and receiving sediments. Where Precambrian rocks are not now exposed, they are covered by coarse sediments and thin volcanics ranging in age from Eocene to mid-Miocene (Wobus and Manley, 1982). The basal Tertiary unit is the El Rito Formation and is composed of coarse sandstone and boulder conglomerate. The boulders are mostly Precambrian rocks, with quartzite being the dominant clast in the Jawbone study area. Thus, abundant Precambrian quartzite float in an area is not always a reliable sign that quartzite constitutes the immediately underlying bedrock. The Tertiary sediments do not crop out well because they are poorly cemented and form erosional profiles. Tertiary volcanic flows form ledges or cappings on small mesas.

Baltz (1978) postulates that the present position and orientation of basins in northern New Mexico is due to tectonism from late Miocene through Pleistocene time. Muehlberger (1967) documents Miocene down-to-the-west faulting in the Brazos Peak quadrangle with up to 1000 feet of throw on the major faults.

The study area appears to have been glaciated some time during the Quaternary. Some streams flow in wide valleys that are stepped with benches of hummocky material believed to be terminal moraines. Creek beds are poorly defined and whole valley floors are marshy. Other valleys contain quartzite boulder fields with angular pieces of rock averaging 40-70 cm in diameter. Muehlberger (1968, p. 5) describes these as "quartzite boulder fields of ground moraine from which the fine material has been washed out."

MINERALIZATION

Known economic mineralization within the study area occurs in the southeastern quadrant where it constitutes part of the Hopewell mining district. The major portion of the Hopewell district lies outside this study area and is the subject of a detailed study by Boadi (1986) as part of a Master's thesis at New Mexico Tech. The Hopewell district is a gold district with silver and copper credits. Bingler (1968) has reviewed the mining history of the area.

The Jawbone Mine is located in the southeastern part of Section 19. A shaft was sunk and drifts driven on a quartz vein which strikes northwestward and dips 65° NE. The vein reportedly contained pyrite, chalcopyrite, and specularite, with tourmaline alteration along its margins. Gold and copper were produced from the mine prior to 1905 (Lindgren et al., 1910).

Iron-formation is exposed along the top of Iron Mountain in the northeastern part of Section 30 where it consists of a one-meter-thick horizon of magnetite-rich chlorite-quartz phyllite. A shaft was sunk on this occurrence, but no production is reported. The iron-formation is discussed in more detail in a following section on the Moppin Metavolcanic Series.

PRECAMBRIAN GEOLOGY

NOMENCLATURE

Rock names used in this study are metamorphic names, unless there is little doubt as to the protolith. Rock names are assigned with major minerals listed in increasing abundance. A carbonate-chlorite-quartz schist thus has more chlorite than carbonate, and more quartz than chlorite.

OVERVIEW OF JAWBONE MOUNTAIN AREA

The Jawbone Mountain study area contains many but not all of the units which occur in the Tusas Mountains. Table 2 lists the Precambrian units shown on Plate 1 and gives the relative percentage of each unit when compared to the total exposed Precambrian in the study area.

TABLE 2

Moppin Metavolcanic Series	15%
Burned Mountain metarhyolite	5%
Micaceous metasediments	10%
Vitreous quartzite	40%
Maquinita granodiorite	25%
granite of Hopewell Lake	5%

SUPRACRUSTAL ROCKS

Moppin Metavolcanic Series

The oldest supracrustal unit in the study area is the Moppin Metavolcanic Series. It is composed of metamorphosed, primarily mafic volcanics and volcaniclastics and other metasedimentary rocks. Rocks of the Moppin Series crop out as a largely contiguous block in the east-central portion of the map. Most of Section 28, the northern half of Section 29, and the northeast quarter of Section 30 are underlain by Moppin rocks. Moppin rocks are also found as inclusions in surrounding plutonic rocks.

In general the Moppin does not form good outcrops. Most outcrops are less than one meter high and cover an area less than 3 meters square. The fine-grained, well-foliated rocks crop out as small, vertical fins. Following units along strike is difficult because of lack of outcrop.

The Moppin Series is composed of four major lithologies and at least two minor rock types. A biotite-quartz schist is the most common rock type within the Moppin Series. The next most common lithology is a chlorite-quartz phyllite which ranges to a quartz-chlorite phyllite. The other major units are a chlorite-plagioclase schist and a biotite-quartz-amphibole schist.

Minor rock types are iron-formation and various felsic schists.

A biotite-quartz schist comprises about 40% of the Moppin Series in the Jawbone Mountain area. This rock type extends from the northeastern part of Section 29 through the same part of Section 28, cropping out along the major ridge there. Outcrops parallel the main foliation. This schist ranges from dark gray to black in hand specimen.

Composition is somewhat variable, but in general the biotite-quartz schist contains 60-75% quartz, 25-30% biotite, about 5% muscovite, and minor epidote. The quartz and biotite are segregated into fine bands which define the foliation. Biotite-rich bands are 0.1-0.2 mm thick. Quartz is recrystallized and has an average grain diameter of 0.08 mm. Epidote appears to be replacing subhedral plagioclase grains. Some layers of biotite-quartz schist contain small euhedra of magnetite, a common constituent in many Moppin rocks.

Chlorite-quartz phyllite makes up about 25% of the Moppin and is the major lithology on Iron Mountain. Many of the Moppin inclusions in the plutonic rocks are of this type. The texture of this lithology varies and in places it is coarse enough to be called a schist. Chlorite and quartz in sub-equal amounts comprise 70-80% of the rock. Feldspars make up another 15-20%, with plagioclase dominant over K-spar. The rock also contains about 5% epidote and up to 2-3% magnetite. Epidote commonly occurs as aggregates with roughly rectangular outlines. The magnetite usually occurs as euhedra.

Plagioclase grains fall within the albite-oligoclase range and appear to be largely detrital, showing rounding and fracturing. But within the same thin-sections there are feldspars which appear subhedral to almost euhedral. Most feldspars are partially altered to sericite or epidote, or both.

Finer-grained varieties of quartz-chlorite phyllite have chlorite dominant over quartz. Feldspars are a minor constituent. Plagioclase grains are <0.5 mm long and riddled with epidote. These rocks contain 15-20% epidote which is evenly distributed and may contain 2-4% carbonate minerals.

Foliation is defined by the alignment of chlorite grains. Some rocks show a fine banding which parallels the chlorite alignment. Bands of fine quartz and feldspar alternate with a mixture of chlorite and epidote. Magnetite is concentrated in the chlorite-epidote layers but not exclusively.

At the top of Iron Mountain the phyllite becomes finer-grained and more siliceous. This rock is composed of quartz, chlorite, biotite, and magnetite euhedra. The biotite is concentrated in bands 1-2 mm thick. The rock is finely layered and in places shows well-developed graded bedding. The graded bedding is defined by an upward fining of quartz grains. The younging direction is to the north, a direction consistent with the regional structures as defined by Barker (1958).

Chlorite-plagioclase schist makes up about 15% of the Moppin and is extensively exposed along the southern flanks of Iron Mountain where it alternates with chlorite-quartz phyllite and, toward the top of the hill, iron-formations. Some phyllite contains abundant plagioclase fragments and bears a striking resemblance to the chlorite-plagioclase schist. The chlorite-plagioclase schist is distinctive in the field. On a weathered, lichen-free surface, abundant feldspar phenocrysts stand out against a green, quartz-chlorite matrix. In places, the feldspars have been stretched and now parallel the dominant foliation.

The euhedral to subhedral plagioclase grains are oligoclase in composition and comprise 50% of the rock. The average size of the laths is 3 x 2 mm. They have been extensively altered to sericite with a component of sausserite. The centers of larger plagioclase grains are preserved.

The remainder of the rock is a fine matrix of chlorite and quartz in sub-equal amounts with minor epidote and magnetite. Chlorite forms a rim around many plagioclase phenocrysts. A foliation is defined by the alignment of chlorite grains in the matrix and lenses of quartz grains. Even larger single quartz grains and some plagioclase laths show a preferred orientation. Quartz has been recrystallized and shows well-developed triple-point boundaries.

The fourth major lithology in the Moppin is a biotite-quartz-amphibole schist with actinolitic hornblende megacrysts. It crops out mainly in the central part of Section 28 and comprises about 10% of the Moppin. A small outcrop of amphibole schist is found in south-central Section 5. This outcrop may be an inclusion in a large body of granodiorite.

The rock is composed of 40-50% blue-green actinolitic hornblende, 30-40% quartz, and 10-15% biotite. Some units have up to 7% chlorite and all contain minor epidote, magnetite and/or ilmenite, and plagioclase.

The amphibole porphyroblasts exhibit sieve texture and are riddled with quartz and epidote inclusions. Laths of actinolitic hornblende average 1.5-2.0 mm in length and 0.3 mm in width. Many longer laths are curved (Figure 3).

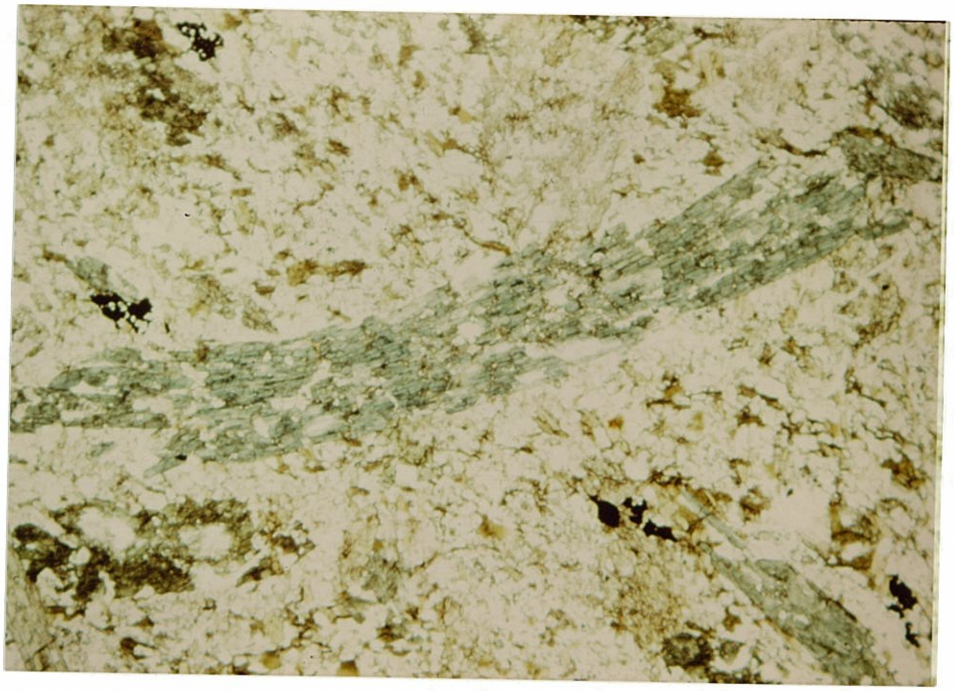

Figure 3. Photomicrograph of biotite-quartz-amphibole schist showing curvature of a large actinolitic hornblende lath. Note poikiloblastic texture of the actinolitic hornblende. Frame length is 4 mm. Polars uncrossed.

The matrix is composed of fine-grained quartz, biotite, and even finer epidote. Average quartz grain size is 0.05 mm in diameter. Biotite grains average 0.1 mm long. In some rocks, biotite appears as porphyroblasts as well as a matrix mineral.

One particular outcrop of amphibole schist is an actinolite schist containing megacrysts of uralitic actinolite which have replaced pyroxene grains. These grains exhibit relict twinning, crystal outline, and fracture patterns inherited from clinopyroxene. The megacrysts average 1.5 x 0.8 mm. Whether the megacrysts were originally phenocrysts or porphyroblasts is not certain, though it is probable that they were phenocrysts in a mafic volcanic source rock. The matrix has been recrystallized and now contains quartz, small amphiboles, and chlorite.

The iron-formation exposed along the ridge of Iron Mountain is a thin unit and not very extensive along strike. The best exposure is in a shaft on top of Iron Mountain. The shaft was sunk directly on the iron-formation which parallels foliation and dips steeply to the north. The rock is purplish-black with abundant iron staining. The entire exposure of iron-formation is 1 m thick which includes some interbeds of very fine-grained, tan phyllite. The thickest bed of pure iron-formation is 30-40 cm thick. In thin-section the rock is composed of 40-50% magnetite, 30-40% quartz, and 15-20% chlorite, with minor hematite. There is no mineral banding evident at the thin-section scale. In hand specimen a crude cm-scale banding is seen which appears to reflect a change in the mica content. Foliation is defined by the parallel alignment of planes of chlorite.

Several small outcrops of felsic schists are present in the central and eastern parts of Section 28. They are gray to pinkish-tan in color and mainly sericite-quartz schists. They contain 30-70% quartz, 20-25% sericite, 15-40% feldspars, with minor epidote, biotite, and magnetite. The feldspar component is roughly equal amounts of plagioclase and K-spar. At least one rock preserves an igneous texture with interlocking subhedral plagioclase laths about 0.1 mm long.

These felsic schists are all well-foliated although the fabric is not obvious in the quartz-rich varieties. The foliation is conformable to that developed in nearby Moppin units. The strike of these felsic units, where measurable, parallels the dominant foliation.

At the west end of Iron Mountain there is a felsic dike which cuts the volcaniclastic units at a low angle. The dike is 1.5 m wide and is exposed over a strike length of 3-5 m. In subcrop the dike can be traced 60 m to the east along a trend 085°. The foliation in the adjacent Moppin rocks trends 065° and dips 70° north. This fine-grained dike is tan with pink to brown iron staining. In hand specimen it appears nonfoliated but in thin-section muscovite shows a well-developed foliation. From orientation data, the foliation trends roughly east-west, but it cannot be determined whether the foliation parallels the dike margins or the regional foliation. Quartz grains show moderate undulatory extinction. The presence of both a strained quartz and a foliation indicates the dike has seen a deformational event and is most likely Proterozoic in age.

Sodic plagioclase and quartz each constitute 30-40% of the dike with muscovite comprising about 20%. Microcline is present at 5% along with accessory magnetite, chlorite, and epidote.

The Moppin Metavolcanic Series is interpreted as a package of mafic to intermediate volcanics and volcaniclastics with minor felsic igneous rocks and sediments. Two rock types closely resemble primary volcanic rocks. One is the hornblende schist with hornblende megacrysts which appears to have originally been a porphyritic basalt with pyroxene phenocrysts. The other is the chlorite-plagioclase schist. The high proportion of plagioclase phenocrysts and lack of ferromagnesian phenocrysts suggest that this unit may have originally been an andesite. The chemical data on these rocks, which is presented in the section on geochemistry, are inconclusive in terms of identifying a protolith.

The chlorite-quartz phyllites are interpreted as reworked volcanic rocks of two types. The first type, the rocks with a significant feldspar component, are more proximal to their source. Alternatively, they may represent a volcaniclastic rock in which the feldspars were abraded before lithification. The second type is more distal and feldspars have been broken down. The rectangular aggregates of epidote may have replaced ferromagnesian phenocrysts.

Lithologies found at the top of Iron Mountain represent a hiatus in volcanic activity. The fine-grained, siliceous phyllite with graded bedding was deposited in a low energy environment. The iron-formation and cherty bands in the phyllite are probably chemical sediments.

The protoliths of the sericite-quartz schists are probably felsic igneous rocks. The apparent narrow exposures of these rocks and their fine-grained nature may favor an origin as aplite dikes. The quartz-rich varieties may represent a feldspathic sediment.

Burned Mountain Metarhyolite

The Burned Mountain metarhyolite unconformably overlies rocks of the Moppin Series, although it is not present everywhere in the stratigraphy. There are two lines of evidence which suggest that this contact is an unconformity. One is the field relationship between the two units. It appears that the Burned Mountain metarhyolite was deposited on a Moppin surface with topographic relief. There is at least one place where the Moppin rocks are overlain by a coarse conglomerate that constitutes the basal unit of a 1-km-thick metasedimentary package that normally overlies the Burned Mountain. The other evidence is from radiometric dates. The Burned Mountain metarhyolite has a date of ca. 1700 Ma (Silver, in Robertson et al., in prep). The Moppin Series is intruded by the Maquinita granodiorite which is dated at ca. 1755 Ma (Silver, in Robertson et al., in prep). Thus the Moppin - Burned Mountain contact may represent a gap of 55 Ma, suggesting an unconformity.

Metarhyolite exposures define a layer 35-40 m thick which wraps around the nose of the Jawbone Syncline. This layer starts in SE Section 19, T29N, R7E and trends northeast into Section 20. As it approaches Section 17 it turns north then slightly northwest before disappearing beneath unconsolidated material of probable glacial origin. In Section 19, about 125 m northwest of the Jawbone Shaft, the contact between Moppin and Burned Mountain rocks is exposed in a small prospect pit. The contact zone has been intensely altered by silicification and carbonatization.

The color and textures of the Burned Mountain metarhyolite are variable in the study area, just as they are throughout its exposures in the northern Tusas Mountains. Rock color varies from deep red through pinkish-gray along with shades of purple and a dull orange. Phenocrysts of microcline are very common and may be as large as 7-8 mm in length. Quartz phenocrysts (or "eyes") are ubiquitous and the most distinctive feature of this rock (Figure 4). These quartz eyes display a variety of pale colors ranging from purple to red to blue. They vary in size from 0.3 mm to 1.5 mm, averaging 0.8 mm. Larger quartz phenocrysts are elliptical in shape and have dimensions up to 2 x 1 mm. This elliptical shape is probably due to stretching and rotation during metamorphism. Most are still single quartz grains which have considerable undulatory extinction. A few have developed numerous sub-grains which also show strain and have curved boundaries.

The matrix of the metarhyolite is very fine-grained, composed mainly of quartz (60%) and sericite (40%) with minor opaques. Matrix quartz grain size averages 0.02 mm. There are also clasts of fine-grained material about 4 x 1 mm. Sericite is the dominant component of the clasts observed in thin-section. Some contain sericite with opaques and no quartz whereas others may contain 10-20% quartz. One clast with fine laminae of sericite and quartz contains phenocrysts of altered microcline.

Figure 4. Photomicrograph of Burned Mountain metarhyolite. Shows euhedral quartz phenocrysts, fine-grained clasts interpreted as pumice fragments (brownish), and sericite-quartz matrix. Note the unsorted texture of this rock. Frame length is 9 mm. Polars crossed.

As mapped on Plate 1, the Burned Mountain metarhyolite includes a lithology in which original igneous textures are less well-preserved. This rock is basically a sericite-quartz schist with relict quartz phenocrysts. Many of these quartz eyes have been elongated in the plane of foliation causing sub-grain development, fracturing, and intense undulosity. Feldspars are generally gone from this unit, having broken down to sericite and quartz. A few angular K-spar grains are present in one thin-section. Euhedral grains of magnetite, zircon, and colorless spinel were observed in at least one thin-section. The fine-grained matrix quartz shows a preferred orientation as do the sericite/muscovite grains. The quartz phenocrysts have been deformed into rods, visible in hand specimen, which define a predominant extension lineation.

Samples 84 and 84B represent another variety of metarhyolite. They are from one moderate-sized outcrop in southeastern Section 19. This rock is a banded, sericite-kyanite-quartz schist containing relict quartz eyes. The pelitic layers are gray, 0.5 to 2.0 cm thick, and give the rock a definite banded appearance in hand specimen. The rock is mottled with a purplish iron staining. A spaced crenulation cleavage is visible in hand specimen as well as in thin-section (Figure 5). Quartz makes up 60-85% of this rock, with relict quartz eyes being 10% of the quartz. It is these characteristic

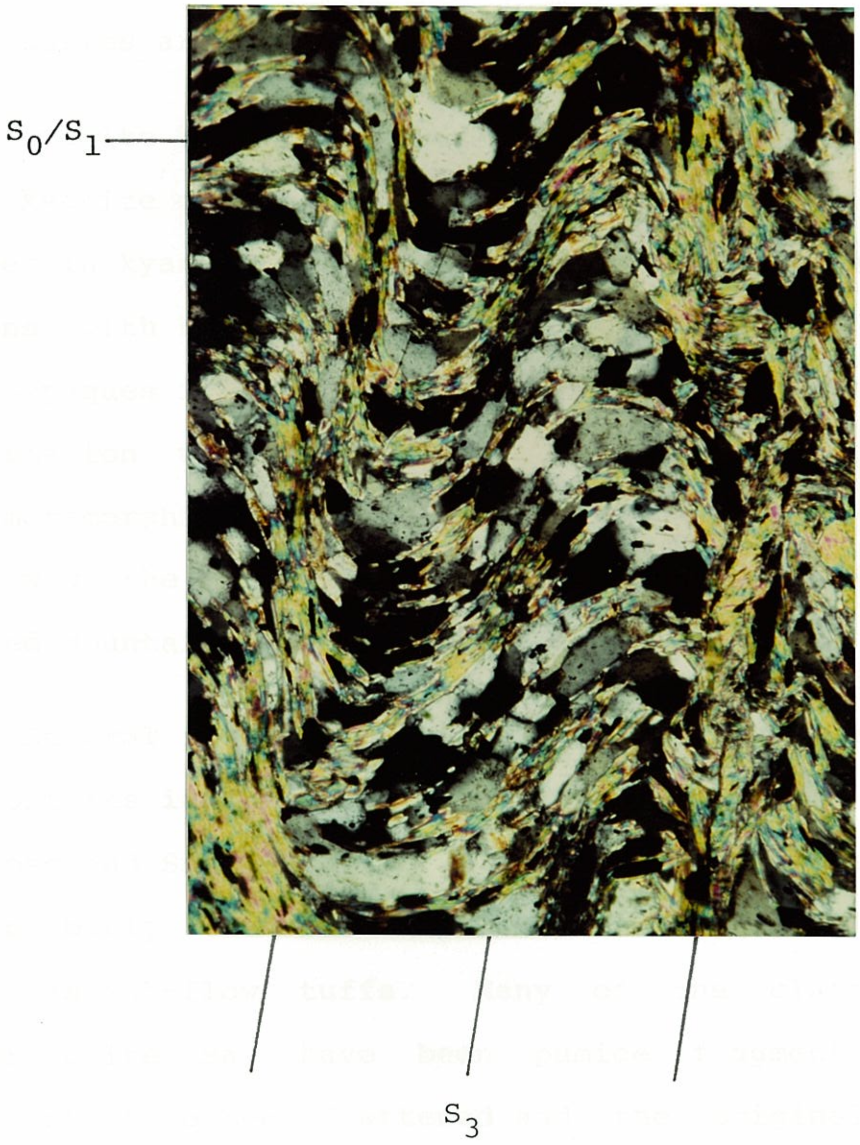

Figure 5. Photomicrograph showing crenulation cleavage in S84B, a sericite-kyanite-quartz schist. Frame length is 1 mm. Polars crossed. S-surfaces are described in the structure section.

quartz eyes which allow this rock to be grouped in the metarhyolite unit. The pelitic layers are composed of kyanite, sericite, and minor chloritoid. Kyanite comprises 10-25% of the rock and sericite another 5-15%. Sericite occurs in both quartz and clay layers. Accessories are opaques and piemontite.

Kyanite has replaced crenulated sericite grains, yet the kyanite grains themselves are not deformed. Cleavage traces in kyanite are straight and continuous even in grains with highly curved outlines (Figure 6). Trains of fine opaques in kyanite preserve a record of an earlier deformation which the kyanite did not see. Thus the peak of metamorphism, represented by kyanite formation, followed the deformational (fabric-forming) events in the Burned Mountain metarhyolite.

Several features of the Burned Mountain metarhyolite support its interpretation as an ash-flow tuff. According to Ross and Smith (1961), the presence of pumice fragments is probably the most important criteria for identifying rocks as ash-flow tuffs. Many of the clasts in the metarhyolite may have been pumice fragments but the fragments have been flattened and the original material has totally recrystallized. No internal pumice structure remains. The shapes of some clasts do resemble fiamme with flared ends as shown in Ross and Smith (1961) (Figure 4). Other workers in the Tusas Mountains have also

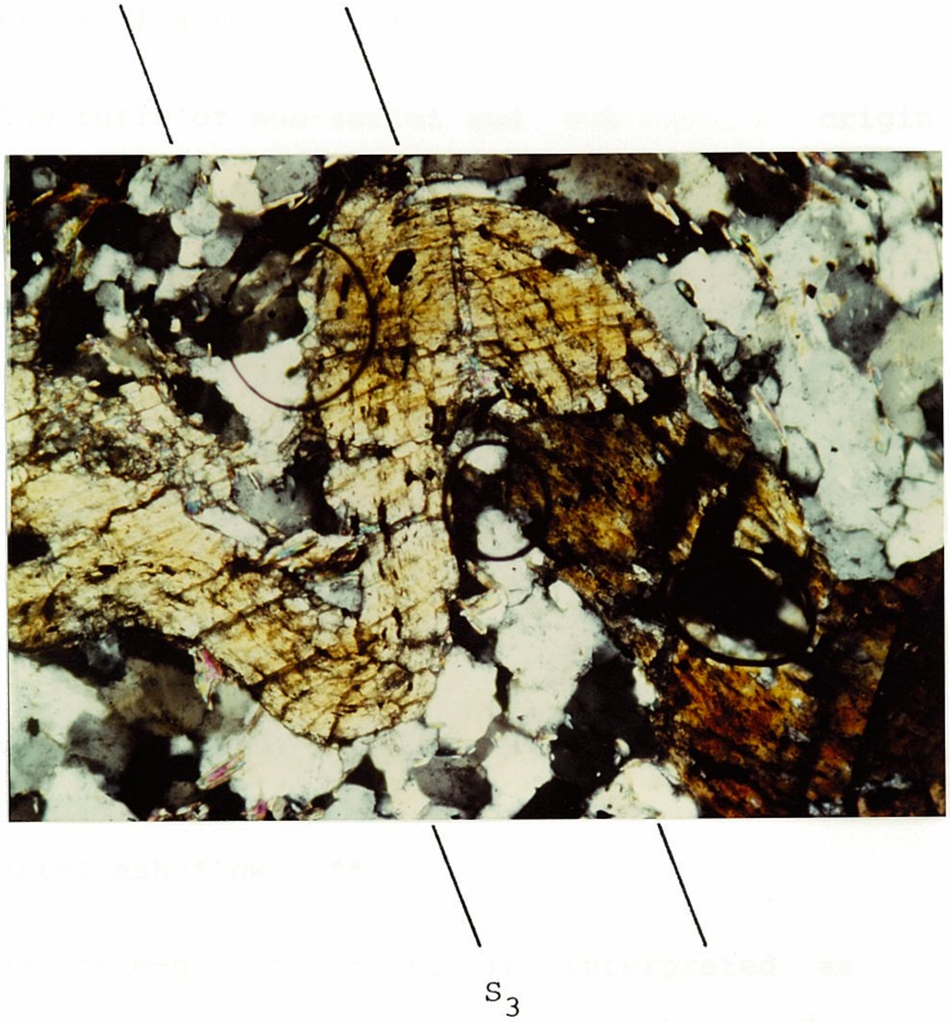

Figure 6. Photomicrograph showing kyanite overgrowing a fold in S84B, a sericite-kyanite-quartz schist. Material in fold was originally sericite. Frame length is 1 mm. Polars crossed.

interpreted these clasts to be pumice fragments (Kent, 1980; Gibson, 1981). Phenocrysts of quartz and K-spar, broken or angular, in a fine matrix are also characteristics of ash-flow tuffs.

Ash-flow tuffs of sub-aerial and sub-aqueous origin can have many common features. Among these are great areal extent and a general unsorted nature. It has even been suggested that sub-aqueous ash-flows can be welded as easily as sub-aerial ash-flows (Sparks et al., 1980). A feature of sub-aqueous ash-flows which is distinct from sub-aerial ash-flows is the presence of interbedded marine sediments. There are no marine sediments within or around the Burned Mountain metarhyolite. In addition, the Burned Mountain metarhyolite was deposited on an erosional Moppin-Maquinita surface. These last two factors support the interpretation of the Burned Mountain metarhyolite as a sub-aerial ash-flow tuff.

The sericite-quartz schist is interpreted as a portion of the metarhyolite which has undergone metasomatism and some recrystallization. Feldspar phenocrysts have completely broken down yet quartz phenocrysts remain. Gresens and Stensrud (1974) report that such alteration produces a quartz/sericite ratio of 60/38. The ratio of schists in the Jawbone study area varies from 60/40 to 50/50.

The kyanite-bearing schists are thought to have undergone reworking in addition to some alteration. The kyanite-rich layers were probably deposited as clayey interbeds. This lithology does occur at the stratigraphic top of the metarhyolite, a feasible position for reworking to occur after rhyolite extrusion.

Micaceous Metasediments

Overlying the Burned Mountain metarhyolite is a package of mixed metasediments which in general are more micaceous than the vitreous quartzite at the top of the Precambrian section in the study area. This package contains coarse metaconglomerate, fine-grained quartz-sericite schist, and micaceous quartzite. The major area of exposure for this unit is around the Jawbone Syncline axis. Micaceous quartzite underlies most of east-central Section 19, northwest Section 20, and southwest Section 17. A smaller exposure occurs along the boundary between Sections 25 and 26, T29N, R6E. Structural data for this site is taken from Gibson's (1981) map. The micaceous metasediments package of rocks is analagous to the feldspathic metasediments of Gibson (1981), but the feldspathic component is minor or absent in rocks from the Jawbone study area and thus the package name has been changed to more accurately reflect the local lithologies.

The lithology at the base of the micaceous metasediments package and immediately overlying the Burned Mountain metarhyolite in most places is a metaconglomerate. It does not crop out anywhere in the study area, but is very abundant in float. The unit ranges from 5-20 m in thickness. The rock is 30-40% clasts in a gray, phyllitic matrix of fine to medium-grained sericite and quartz. Phyllitic rock fragments are the dominant clast type. They are extremely flattened in the plane of foliation, undergoing elongation in the process. The phyllite clasts are mostly cream to tan in color, but pink, light green, and gray are also common. Clast size is quite variable, with an average phyllite clast being 4 x 2 cm, ranging up to 8-10 cm in length. Other common clasts are vein quartz and chert, usually black or red. These clasts tend to be more rounded or blocky, and were clearly more resistant to the deformation which flattened the phyllite clasts. One unusual clast was collected in central Section 19. It is a large clast with the third dimension visible, and measures 11 x 6 x 5 cm. The clast appears to be an iron-rich siliceous sediment. There are two bands of deep purple iron-dominant material alternating with light purple silica-dominant bands. The dark bands show some small-scale faulting which occurred after lithification of the original sediment and presumably prior to its erosion. This clast does not resemble the iron-formation seen on

Iron Mountain but rather the banded ironstone described by Kent (1980) in the Tusas Mountain area.

Some clasts of metarhyolite are found in float pieces of metaconglomerate just above the Burned Mountain metarhyolite (Figure 7). These are not common, but help to establish that the Burned Mountain metarhyolite was being eroded and was contributing debris to the conglomerate.

In at least two localities, the rock overlying the metarhyolite is a fine-grained quartz-sericite schist. At these locales the metaconglomerate does not crop out and the section passes into a micaceous quartzite. The rock is tan to gray and shows compositional layering with bands of heavy minerals. Foliation is well-developed in this rock, and a crenulation cleavage can be seen in hand specimen as well as thin-section. Sericite predominates over quartz in this schist. Opaques comprise at least 5% of the rock. Fine, detrital epidote makes up 3-5%, and is evenly distributed throughout the rock.

This schist may be more closely linked, genetically, to the altered metarhyolite beneath it than to the conglomerate and micaceous quartzite above it. The components of the schist are in roughly the same proportion as the matrix of the altered metarhyolite. A sample of metarhyolite collected 60 m from the quartz-sericite schist contains fine, disseminated epidote just

Figure 7. Photograph of float boulder of metaconglomerate with clasts of metarhyolite. SE 1/4 section 19.

as the schist does. The schist is uniformly fine-grained and contains neither relict quartz eyes nor other large grains.

Outcrops of micaceous quartzite are adjacent to areas of abundant metaconglomerate float. These outcrops are generally low and linear, following a foliation trend and/or a primary bedding feature. The rocks are gray to light brown with minor iron staining. Cross-bedding is visible in some outcrops, although it may be distorted due to folding. The rock is fine to medium-grained. There are layers dominated by coarse quartz grains in which sericite is a minor component. A few clasts of phyllite and chert are present. Although it can not be proven in the field, the metaconglomerate may grade into the micaceous quartzite.

Quartz comprises 70-80% of the micaceous quartzite; sericite makes up the remaining 20-30% of the rock. Some of the sericite is coarse enough to be called muscovite, but for simplicity all the white mica will be referred to as sericite. Accessory opaques and epidote are generally present. Grains of zircon and spinel were observed. Some of the quartz in this rock is contained in clasts of sandstone. These clasts are generally larger than the matrix quartz grains. Clasts and large quartz grains average 0.7 mm in long dimension. The smaller quartz grains are by far the dominant group and range from 0.08

to 0.35 mm, averaging 0.2 mm. The micaceous quartzite is moderately to well-foliated. Well-foliated rocks show persistent lines of sericite which flow around quartz grains. Most quartz grains and quartzose clasts are elongated or ovoid and show parallel alignment. Quartz grains show undulose extinction, fractures, and have curved boundaries. Triple-point junctions with straight boundaries are present but are not especially common.

Vitreous Quartzite

The youngest Precambrian supracrustal unit in the study area is vitreous quartzite. All quartzites in the Tusas Mountains were named Ortega quartzite by Just (1937). Barker (1958), on the other hand, thought there were two quartzites in the region. The older one he called Ortega quartzite and placed it stratigraphically below the Moppin. He placed the younger quartzite above the Moppin and called it the Kiowa Mountain Formation. He mapped the rocks on the east end of Jawbone Ridge as a part of the Kiowa Mountain Formation. Current workers in the Tusas Mountains consider the quartzites to be a single stratigraphic unit (Wobus, 1985; M. Williams, personal communication, 1985). The quartzites on Jawbone Ridge are specifically referred to as Ortega quartzite by Soegaard and Eriksson (1985) in their study of the Ortega Group. The lithologic name "vitreous quartzite" is used here because correlation of all the quartzites in the Tusas

Mountains is beyond the scope of this thesis.

Vitreous quartzite is the most widely exposed Precambrian unit in the study area. Vitreous quartzite makes up Jawbone Mountain and Jawbone Ridge, the major topographic features in the study area. Outliers of quartzite crop out south of Jawbone Ridge in Sections 14, 15, and 23, T29N, R6E. Another large body of quartzite is present in southwestern Section 22, northern Section 27, and southeastern Section 27.

The vitreous quartzite is folded by the Jawbone Syncline, whose axis trends west-northwest through the study area. Outcrops representing both limbs of the fold as well as the axial region are exposed. In southeastern Section 14, a 700 m thick section of quartzite is exposed along a rib protruding from Jawbone Ridge. The bottom of the quartzite is not exposed here, but it is estimated from exposures immediately to the northwest in the Brazos Box that this quartzite is over 1 km thick.

Outcrops of vitreous quartzite are generally very large and fairly continuous. They may be as much as 6 to 10 m high with very steep and smooth sides. Glaciation has enhanced the smoothness of many quartzite outcrops.

In outcrop, especially from a distance, the quartzite appears to be a uniform battleship gray. Upon a closer look, a number of textural and color variations are seen.

This rock commonly has a light purple color rather than gray. It is a medium to coarse-grained, very pure quartzite. Cross-bedding is well-preserved and provides clear evidence of stratigraphic facing (Figure 8). Cross-beds are defined mostly by accumulations of hematite. Detailed descriptions of sedimentary structures found in these rocks are given in Soegaard and Eriksson (1985).

Pebbly conglomerate forms a minor but distinctive lithology within the vitreous quartzite. Clasts are almost entirely milky quartz and comprise 60-75% of these layers. Within a single layer of conglomerate, clasts are roughly equal in size, but between layers there can be a significant difference in clast size. Clast size ranges from 4 mm to 3 cm. The layers themselves vary from 5 cm to 1 m thick. They are interbedded with the vitreous quartzite and in places appear to be just a very coarse component of it.

Fine-grained, aluminum-rich interbeds are present in numerous places in the vitreous quartzite. These may appear as thick cross-beds (up to 1 cm) or may form a thin layer 5-8 cm thick. These dark gray to black layers were originally clay-rich and are now composed of quartz, kyanite, sericite, and hematite.

Quartz comprises 95-99% of the vitreous quartzite. Sericite, kyanite, and hematite occur as accessories. Thin-section examination shows the quartz to have a

Figure 8. Photograph of cross-bedding in vitreous quartzite. Stratigraphic up is toward the upper right. Frame length is 60 cm.

bimodal size distribution. Small grains constitute a slight majority of the quartz. Diameter of small quartz grains averages 0.2 mm with a range from 0.09 to 0.35 mm. The larger grains have an average diameter of 1.0 mm and range from 0.5 to 3.0 mm. Most quartz grains show undulatory extinction. Many larger grains have sutured-lobate boundaries, whereas triple-point boundaries are common among small grains. In addition to quartz grains, the vitreous quartzite also contains quartz pebble clasts which average 1 x 0.5 cm. One such clast seen in thin-section was composed of very fine quartz with sericite and opaques. Quartz grain size was on the order of 0.05 mm.

In the southwest part of the study area there are outcrops of vitreous quartzite which contain the mineral viridine. Viridine is manganese-bearing andalusite and has a deep green color distinct from epidote. The occurrence of viridine seems to be restricted to the basal part of the vitreous quartzite. The viridine occurs mainly on cross-beds along with sericite and kyanite. In places the viridine appears to have been remobilized from cross-beds onto cleavage planes. One such place is in northern Section 27 where bedding measurements suggest proximity to the axial region of a fold. The viridine which occurs in this study area is part of a more extensive occurrence which Williams (1984) has traced throughout the Tusas range.

The bimodality of quartz grain size in the vitreous quartzite is interpreted to be an original sedimentary feature. This means that at least some parts of the sandstone protolith were poorly sorted. The population of smaller grains exhibits many triple-point boundaries, indicating that they have recrystallized. Larger grains do not show signs of recrystallization. Most large grains are surrounded by smaller grains. The smaller grains apparently took up the stress during metamorphism.

M. Williams (personal communication, 1985) has discussed possible origins for the viridine horizon. Because of the position of viridine on cross-beds and not as an interlayer within the quartzite, he discounts the idea that the Mn-enrichment was caused by a weathering process in the original sediments. Instead, he favors the idea of an anomalous concentration of manganese being introduced to the siliciclastic sediments. This could be achieved by the addition of clay-sized, Mn-rich detritus to the predominantly sandy sediments. The clay could be deposited on cross-beds, where the viridine is observed today.

PLUTONIC ROCKS

Two varieties of plutonic rocks have been distinguished in the present study area. The more abundant rock-type is a granodiorite (the Maquinita granodiorite of Barker, 1958). The other plutonic rock is the granite of Hopewell Lake, informally named after an exposure south and southwest of Hopewell Lake (Gibson, 1981). This granite and granodiorite may be separate plutons, or chemical variants of a single composite body. North and east of Hopewell Lake, there is a gradational zone between the two intrusive rocks in which some features of each rock-type are present. The following descriptions, however, come from samples well away from this gradational zone. The only occurrence of plutonic rocks is in the eastern half of the study area.

Maquinita Granodiorite

Maquinita granodiorite occurs in two large areas and several isolated smaller areas. Most of Section 8, T29N, R7E is underlain by granodiorite. This granodiorite continues south, covering eastern Section 17 and parts of Sections 16 and 20. The majority of Section 20 is a thick aspen forest on a moderate east-facing slope. Outcrops are very scarce and even float is uncommon. The rare outcrop areas on this hillside are outlined with dotted lines on the geologic map. Most of Section 20 is probably underlain by granodiorite, but it is covered by a veneer of Tertiary sediments, and glacial and/or colluvial material. The other significant area of granodiorite is in the southeast part of the study area. It covers large portions of Sections 29 and 32 and extends into Sections 28, 30, and 33. The northern and southern areas of granodiorite are separated by rocks of the Moppin Metavolcanic Series.

Outcrops of granodiorite are usually large and fairly continuous. Outcrops are commonly 2-4 m high. In sections 8 and 17, granodiorite forms prominent steep ridges and several cliffs which overlook the upper Rio Tusas. In outcrop, rock color ranges from light to dark gray. In hand specimen, weathered surfaces are dominantly gray but may appear mottled or banded due to black biotite.

The Maquinita granodiorite is medium to coarse-grained with good idiomorphic texture and is moderately to well-foliated. Foliation planes are defined by lines and knots of biotite. Foliation development ranges from outcrops that are massive and only weakly foliated to exposures that are intensely foliated resulting in a schistose granodiorite.

Euhedral plagioclase crystals make up 40-65% of the Maquinita granodiorite. Alteration to sericite plus epidote is generally extensive, commonly obliterating even ghost albite twins. Lath size ranges from 0.5 x 0.2 mm to

5 x 3 mm, averaging 1.5 x 0.7 mm. Several thin-sections show evidence of deformation with bent and/or shattered plagioclase grains (Figure 9).

The remainder of the rock is 20-30% quartz, 10-25% microcline, and 5-20% biotite. Accessory minerals are chlorite, sphene, magnetite, muscovite, and zircon. Some areas of granodiorite have experienced mild carbonate alteration and now contain a few percent carbonate minerals.

The relationship between Maquinita granodiorite and the Moppin *Series is not clearly understood. The* prevailing idea in the literature is that the granodiorite intrudes the Moppin. Within this study area, the main evidence supporting an intrusive relationship is the presence of xenoliths of Moppin rock in the granodiorite. The inclusions are usually quartz-chlorite phyllite and are more common in the southern area of granodiorite than in the northern block. Moppin xenoliths range in size from tens of centimeters to 5-6 m. Near larger inclusions the granodiorite commonly contains abundant chlorite, suggesting that some assimilation of Moppin material has occurred. In the southwestern part of Section 29, there are numerous Moppin xenoliths. At one outcrop, it appears that Moppin and granodiorite have been folded together. Contacts between granodiorite and the main body of Moppin rocks are not exposed.

Figure 9. Photomicrograph of Maquinita granodiorite with broken plagioclase crystals. Fractures are filled with sericite. Frame length is 4 mm. Polars crossed.

Granite of Hopewell Lake

Outcrops of the granite of Hopewell Lake are located in Sections 31 and 32, mostly south and east of Hopewell Lake. Granite outcrops are generally small, low, and discontinuous. The granite exhibits more deformation and alteration than the granodiorite and as a result is also more weathered. Weathered surfaces are tan to brown with iron staining. The most prominent feature in hand specimen is the presence of quartz megacrysts which tend to stand out on weathered faces. The megacrysts are about 4 mm in diameter but may get as large as 1 cm. Xenoliths of Moppin rocks are found in most outcrops of this granite.

In thin-section the granite contains 30-40% plagioclase, 30% quartz, and 20-25% microcline. Biotite, chlorite, and muscovite combined represent about 2-3% of the rock. Magnetite and tourmaline occur as accessories. Plagioclase is albite-oligoclase and is sericitized with minor epidote. Quartz occurs mostly as subhedral phenocrysts, 1-4 mm in diameter. Smaller grains of quartz occur interstitially between plagioclase grains. Quartz phenocrysts are recrystallized and strained. Microclines commonly fill interstices between plagioclase and quartz phenocrysts, but some have subhedral outlines. Larger microcline grains may contain several small euhedral plagioclases as inclusions.

The granite of Hopewell Lake has also been subjected to carbonate alteration. The carbonate, probably siderite, formed small rhombehedra, 0.1 to 0.5 mm long, which are now mostly limonite. These grains are disseminated through the rock but seem to occur most commonly within plagioclase grains. Sphene euhedra were replaced by carbonate and are now limonite. Carbonate/limonite may be present in up to 10% of the rock. Plutonic rocks with carbonate alteration are restricted to the southeastern part of the study area and fall within a 1.6 km radius of Hopewell Lake.

Transition Zone Rocks

Contacts between the granite and granodiorite are not exposed, but they appear to be gradational. In the field, the features used to classify a rock as the granite of Hopewell Lake were the presence of quartz megacrysts and the lack of ferromagnesian minerals. Maquinita granodiorite, on the other hand, lacked large quartz grains and contained abundant biotite, making it a darker rock than the granite.

Thin-section examination revealed that some plutonic rocks did not match their field classification. Rocks with quartz megacrysts and <5% biotite from 800 m north of the Hopewell Lake spillway contain 50% plagioclase and plot well into the granodiorite field on the Q-A-P ternary of Streckeisen (1976) (Figure 10). There are also rocks

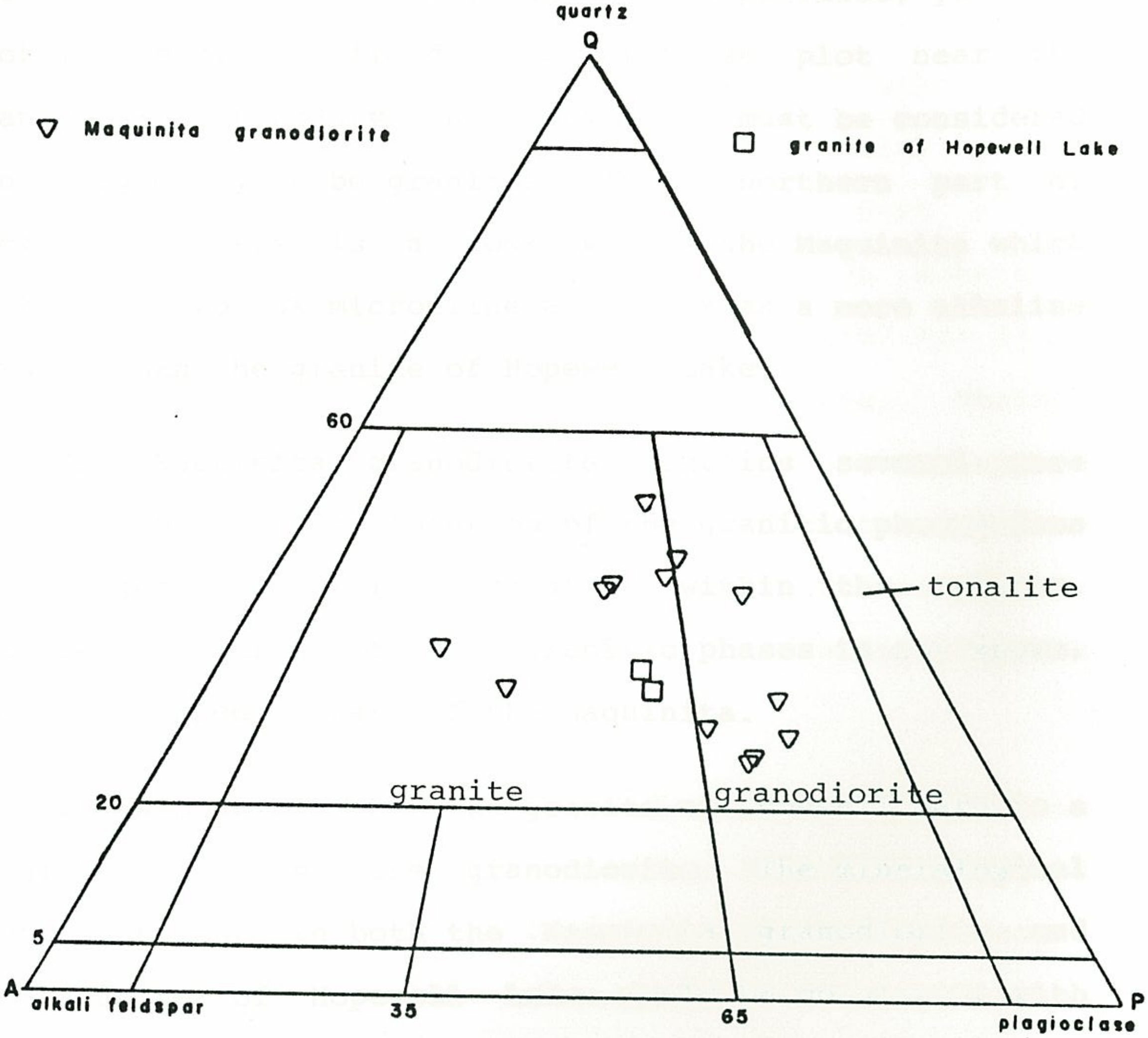

Figure 10. Modal composition plot of fifteen plutonic rocks from Jawbone Mountain study area (after Streckeisen, 1976).

in both areas of granodiorite which contain 15-20% biotite and have a typical gray Maquinita appearance, yet they plot in the granite field. Most of these plot near the granodiorite boundary but they still must be considered mineralogically to be granites. In the northern part of Section 8 there is a rock within the Maquinita which contains up to 35% microcline and plots as a more alkaline granite than the granite of Hopewell Lake.

The Maquinita granodiorite contains several more granitic phases. The location of the granitic phases does not suggest a vertical zonation within the pluton. Because the extent of these granitic phases is not known, they are mapped as part of the Maquinita.

It is possible that the granite of Hopewell Lake is a granitic phase of the granodiorite. The mineralogical variations found in both the Maquinita granodiorite and the granite of Hopewell Lake would be consistent with those of a single, large, heterogeneous granitic pluton. Inclusions of Moppin rocks in both the granite and the granodiorite suggest that they are parts of the same intrusive. But for several reasons the granite of Hopewell Lake has been mapped as a separate lithology. One reason is that the mineralogical differences make it possible to distinguish between the granite and the granodiorite, and so they can be mapped as separate lithologies. Another reason is that the granite is large enough, over 0.6 sq. km., and well-enough exposed.

There is some question as to whether these two lithologies were intruded at the same time, or whether the granite of Hopewell Lake was emplaced later. The Maquinita granodiorite has a preliminary U-Pb zircon crystallization age of ca. 1755 Ma (Silver, in Robertson et al., in prep). Boadi (1986) reports a 1467 +/- 43 Ma Rb-Sr isochron for the granite of Hopewell Lake. Whether the 1460 Ma date represents the actual emplacement age of the granite or merely a later metamorphic event remains to be tested. Additional U-Pb zircon geochronology is clearly needed to determine the relationships between these plutonic rocks.

Both plutonic rocks in the study area are medium to coarse-grained and are interpreted to have been emplaced at depth. The mesozone of Buddington (1959), which ranges from depths of 8-16 km, is a probable setting for the emplacement of these plutonic rocks. This implies that part of the Moppin Metavolcanic Series was buried to a depth of at least 8 km by 1755 Ma.

STRUCTURE

Structural Overview of the Tusas Mountains

A brief summary of the deformational fabrics seen in the Tusas Mountains is presented in Table 3. Not all of these fabrics are observed in the Jawbone Mountain study area.

TABLE 3

DEFORMATIONAL FABRICS IN THE TUSAS MOUNTAINS

D_1: strong bedding-parallel foliation (orientation varies from N to NW)

extension lineation

isoclinal folding; microscopic and mesoscopic folds only

D_2: foliation - trends NW and crosscuts S_1 in places where observed; not well-documented in the northern Tusas Mountains

intersection lineation

folds - from microscopic to map-scale

D_3: axial-planar foliation (east-west orientation)

intersection lineation

folds - from microscopic to map-scale including a strong crenulation cleavage

D_4: weak north-south crenulation cleavage

Faults

The Tusas Mountains are part of the Brazos Uplift, which is a large block bounded by major faults and cored with Precambrian rocks. No direct evidence of major faulting was observed in the exposed Precambrian rocks of the Jawbone Mountain study area. Faults shown on Plate 1 are taken from maps by Barker (1958), Doney (1968), and Muehlberger (1968) and are probably related to mid- to late-Tertiary extension. Minor faulting is evidenced by displacement along quartz veins on the order of 1-5 cm.

Tectonite Fabrics

FOLIATIONS. All rock units in the study area show some development of tectonite foliation. The foliations are of two types: a strong bedding-parallel cleavage (S_1), and a more limited axial-planar cleavage (S_3). Both types of foliation are usually defined by an alignment of micas and/or chlorite: biotite in the granodiorite, chlorite and/or biotite in the Moppin rocks, and muscovite/sericite in the metarhyolite and micaceous metasediments. The quartzite shows the least foliation, but it does contain an S_3 fracture cleavage near the axial region of the two major folds. Kyanite, formed in pelitic layers within the quartzite, commonly shows a preferred orientation roughly parallel to bedding.

The S_1 foliation is generally parallel to compositional layering in rocks of the Moppin Metavolcanic Series. It is also well-developed in the plutonic rocks. The dominant trend of the S_1 foliation is northwest to north-northwest, with steep dips to either side (Figure 11). An exception to this is in the northern block of Maquinita granodiorite where the foliation trends north-south.

A bedding-parallel cleavage is also developed in rocks younger than the Moppin. Compositional layering (S_0) in the Burned Mountain metarhyolite is not always clearly defined, but where it is, there is a foliation which parallels it. Whether this foliation is S_1 or S_2 is not clearly understood. S_2 foliations have been described for other parts of the Tusas Range (Bingler, 1965; M. Williams, personal communication, 1985) but are not well documented within the Jawbone study area.

The S_3 foliation trends west-northwest and roughly parallels the axis of the Jawbone Syncline. The axial-planar nature of the S_3 foliation can be observed in the micaceous metasediments. In the noses of minor folds, the S_3 foliation is perpendicular to bedding. On the limbs of these folds, bedding and foliation are roughly parallel. At least one overturned limb was recorded where bedding dips more steeply than the S_3 foliation. In some mica-rich rocks, the S_3 foliation is expressed as a

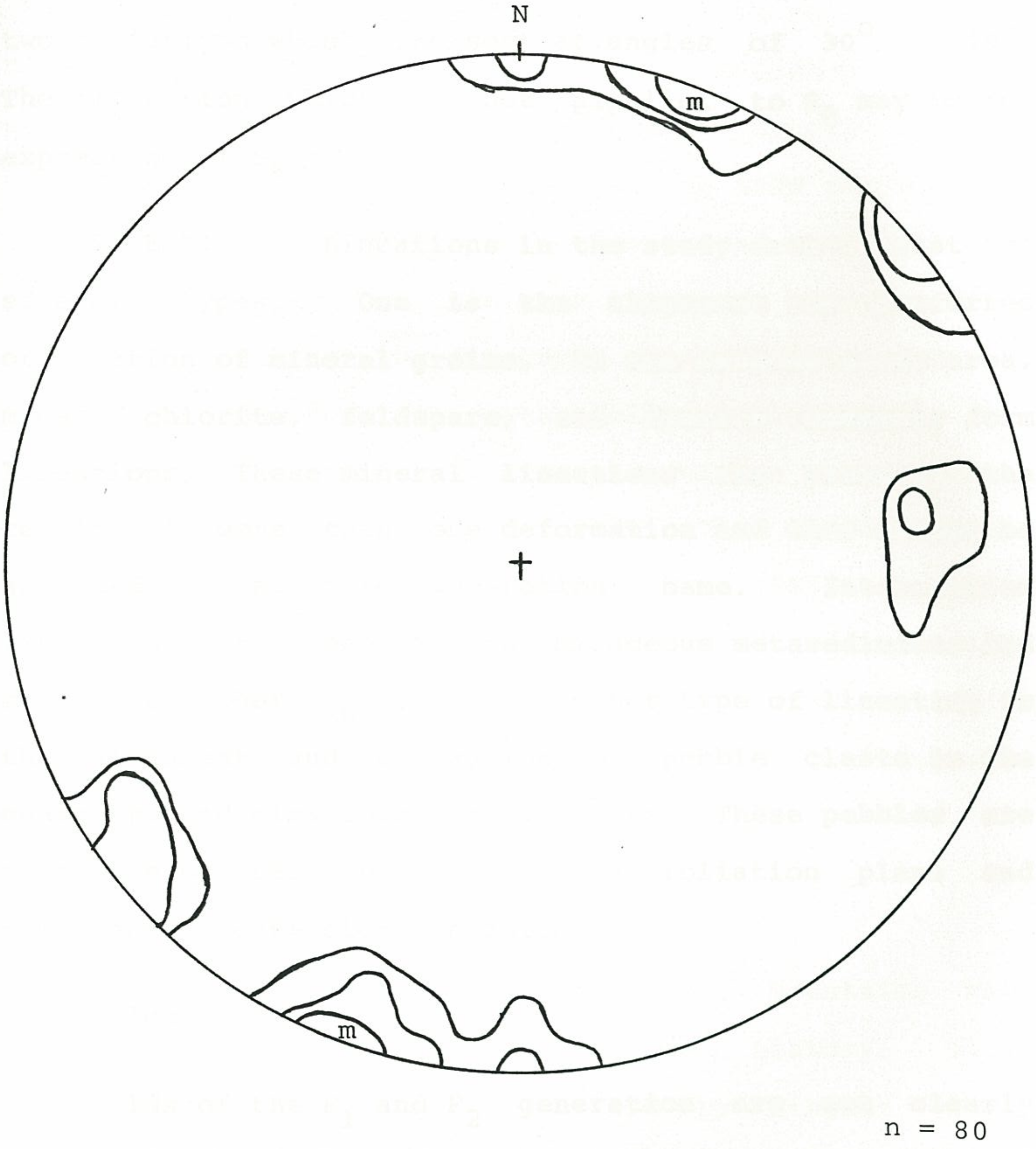

Figure 11. Contoured, lower hemisphere, equal-area plot of poles to S_1 foliation in the Moppin Metavolcanic Series and the Maquinita granodiorite. Contour intervals are 5%, 8%, and 10% of 1% area; maximum (m) is 11%.

crenulation cleavage (Figure 5). Some fine-grained lithologies within the Moppin Metavolcanic Series exhibit two foliations which intersect at angles of $30^{\circ} - 40^{\circ}$. The foliation which is not parallel to S_0 may be an expression of S_3.

LINEATIONS. Lineations in the study area consist of several types. One is the alignment or preferred orientation of mineral grains. In the Jawbone study area, micas, chlorite, feldspars, and kyanite commonly form lineations. These mineral lineations are probably the result of more than one deformation and thus cannot be assigned an accurate generation name. Intersection lineations are seen in the micaceous metasediments and represent either L_{20} or L_{30}. Another type of lineation is the alignment and elongation of pebble clasts in the quartzite and micaceous metasediments. These pebbles are often elongated parallel to a foliation plane and represent an extension lineation.

Folds

Folds of the F_1 and F_2 generation are not clearly present in the Jawbone Mountain study area. Some units of the Moppin Metavolcanic Series contain thin (0.5 to 2.0 cm), discontinuous quartzose layers which exhibit hooks or closures but cannot be traced as folds. These may represent transposition caused by an isoclinal folding event. Tight interfolding of Moppin and Maquinita rocks is suggested at an outcrop in southwestern Section 29.

The prominent folds of this study area belong to the F_3 generation. The biggest folds are the Jawbone Syncline and the Hopewell Anticline. The Jawbone Syncline is an open to close fold which plunges 22° to N80W (Figure 12). The closure of this fold can be seen around the east end of Jawbone Ridge. In this area there are numerous minor F_3 folds in rocks of the micaceous metasediments and the altered Burned Mountain metarhyolite (Figure 13). The Hopewell Anticline is an F_3 structure with a much steeper plunge, approximately 70° to N50W. This difference has led M. Williams (personal communication, 1985) to think that there is an F_2 component to this fold. Additionally, the fault shown in the southwestern part of the map (Plate 1) may have played a part in rotating the Hopewell Anticline into its steeper orientation.

Deformations

The Precambrian rocks in the Tusas Mountains have experienced a complex deformational history. Three periods of deformation were described by Bingler (1965) for the La Madera (7.5-minute) quadrangle in the southern part of the range. M. Williams (personal communication, 1985) believes that there is evidence for four periods of deformation in some parts of the Tusas range. Recognizable effects of all three major deformations are not observed together in any one place or rock unit in the

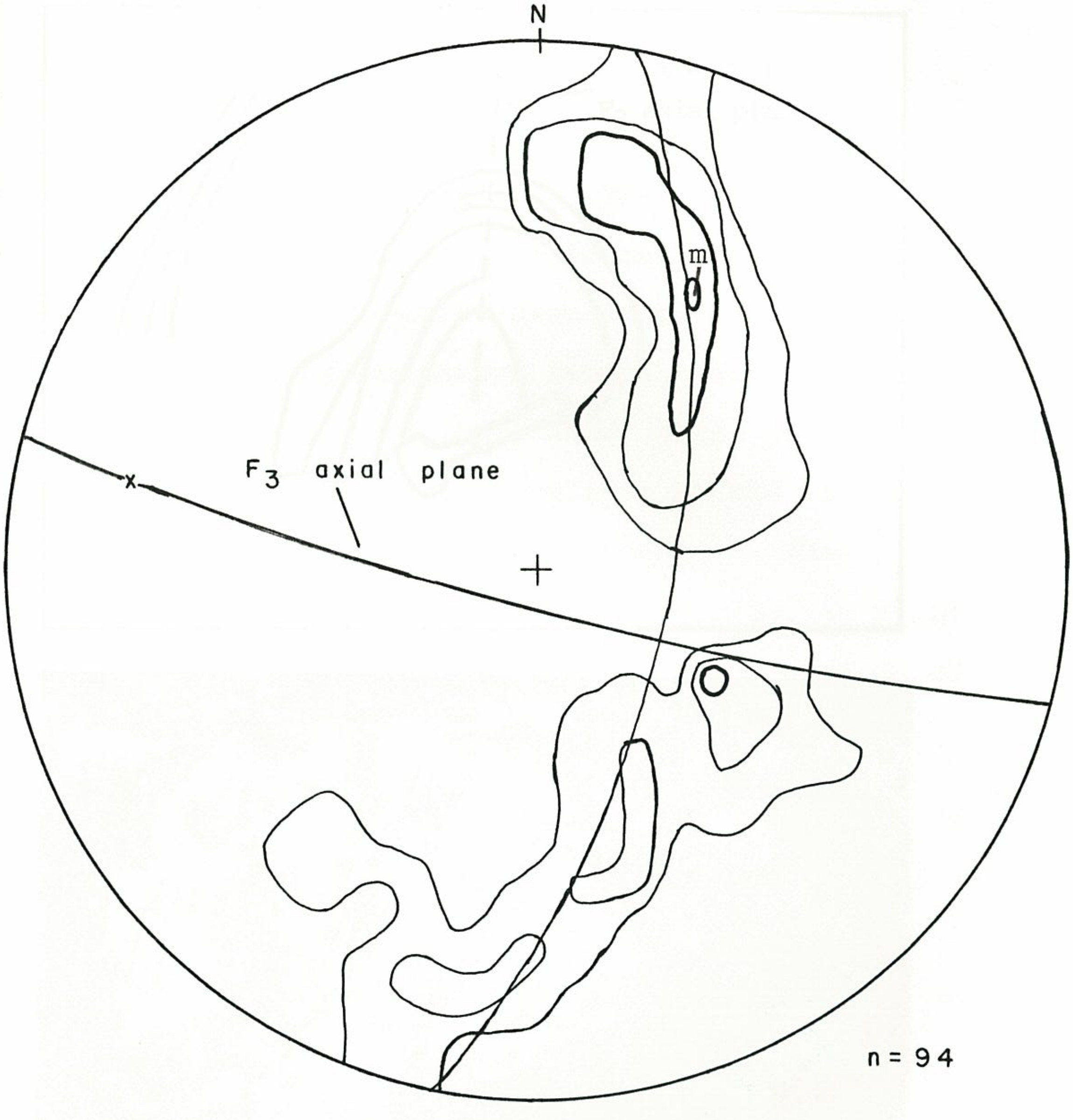

Figure 12. Contoured, lower hemisphere, equal-area plot of poles to bedding in the vitreous quartzite and the micaceous metasediments. A pole which represents the Jawbone Syncline axis is marked by "x' and plunges 22° to N80W. Contour intervals are 2%, 4%, 6%, and 8% of 1% area; maximum (m) is 8%.

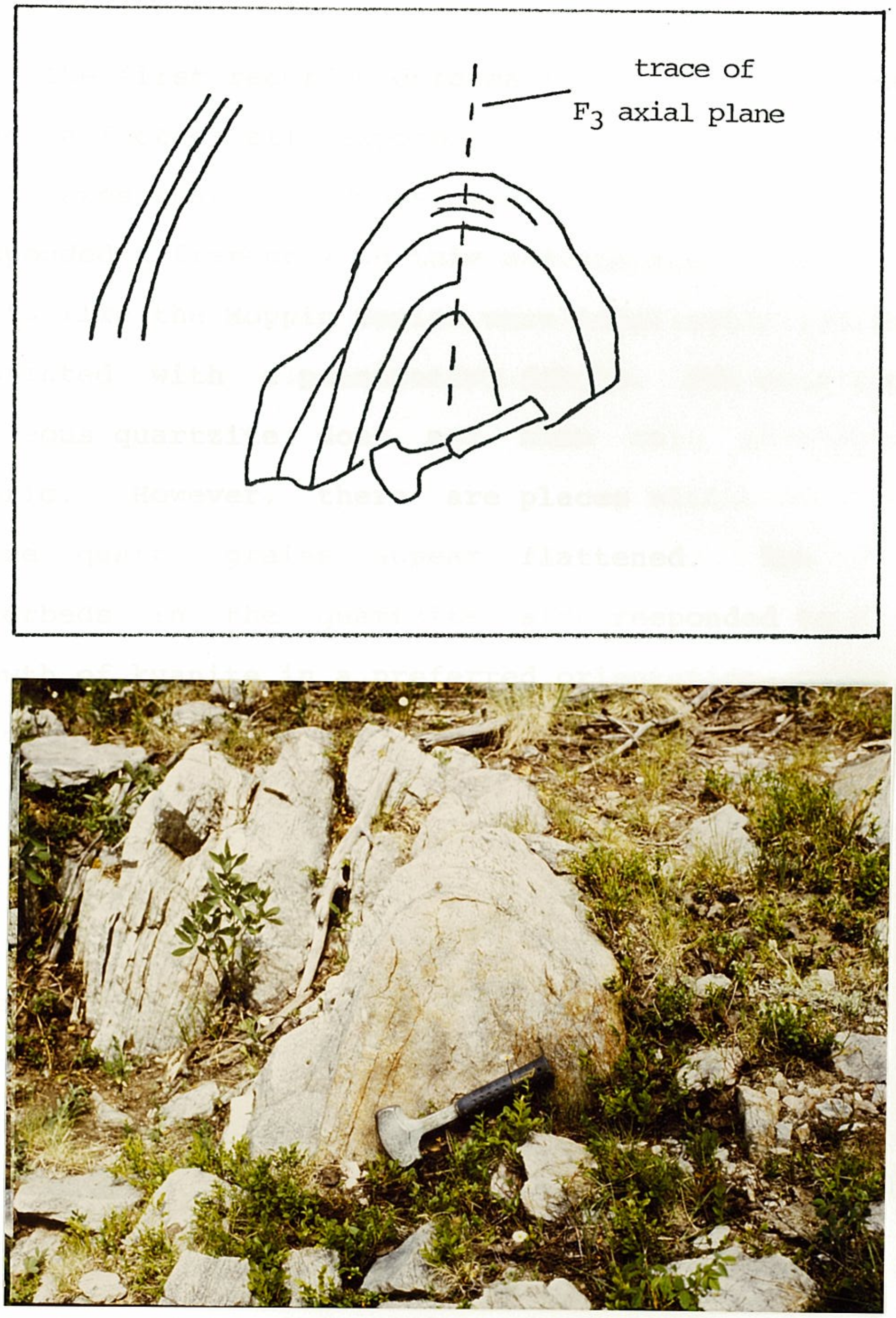

Figure 13. Photograph and sketch of minor F_3 fold in micaceous metasediment unit. This minor fold is associated with the larger Jawbone Syncline structure. View looking west.

study area. Usually only one or sometimes two events have left a clear-cut record within a rock unit.

The first recorded deformation in the area seems to have affected all exposed Precambrian units and thus post-dates quartzite deposition. The various lithologies responded differently to this deformation. Less competent units like the Moppin Series were isoclinally folded and imprinted with a penetrative fabric. The more competent vitreous quartzite does not show this penetrative D_1 fabric. However, there are places within the quartzite where quartz grains appear flattened. The clay-rich interbeds in the quartzite also responded to D_1 by the growth of kyanite in a preferred orientation parallel to bedding.

The nature of the D_2 event is not well understood. The effects of D_2 are not consistent across the Tusas Range. In the central Tusas Mountains, around Kiowa Mountain, there is a clear cross-cutting relationship between D_1 and D_2 fabrics (M. Williams, personal communication, 1986). In the Jawbone Mountain and other areas where D_2 is not observed, the relationship between the two deformations may be co-axial.

The third deformation also affects all the Precambrian units in the region. The thick, competent quartzite acted as an enveloping surface during D_3 folding. Less competent rocks, such as some fine-grained micaceous metasediments, deformed more plastically than the quartzite. In some units, D_3 is expressed as a pervasive crenulation cleavage which overprints an earlier (S_1, or possibly S_2) foliation (Figure 5).

A D_4 fabric has been observed south of the Jawbone Mountain area (M. Williams, personal communication, 1985). This fabric is a weak crenulation cleavage oriented north-south and seen only in muscovite schists.

METAMORPHISM

Precambrian rocks in the Tusas Mountains have undergone varying degrees of regional metamorphism. Regionally, metamorphic grade increases from greenschist facies in the northwest to amphibolite facies in the southeast (Barker, 1958; Bingler, 1968).

Rocks of the Moppin Metavolcanic Series contain the best mineral assemblages for assessing metamorphic grade. This is because many of the Moppin rocks started as fine-grained volcaniclastics with variable compositions, as opposed to the largely monomineralic quartzite. Scattered pelitic interlayers in the quartzite and altered metarhyolite contain the best concentrations of alumino-silicates, which may also be used to assess metamorphic grade. In the Jawbone Mountain study area, most rocks are in the greenschist facies, either in the chlorite zone or the biotite zone.

Based on metamorphic mineral assemblages, the Moppin rocks in this study area can be divided into three groups. The group representing the largest area has the simple assemblage of quartz + biotite +/- epidote. These rocks are found in NE Section 29 and the northern third of Section 28. The second group is a chlorite-dominated group which covers the western third of the Moppin unit. The relative mineral percentages are variable, but the general assemblage is chlorite + quartz + albite/

oligoclase + epidote. The third group is dominated by amphiboles, typically blue-green actinolitic hornblendes. A typical assemblage is actinolitic hornblende + quartz + biotite +/- chlorite. This group is located in the southeastern part of the Moppin unit. All three groups of mineral assemblages fall within the low-grade metamorphic division of Winkler (1976).

Some of the aluminous metasediments also provide constraints on metamorphic conditions. Samples of reworked metarhyolite contain kyanite with minor chloritoid. Kyanite is also found in pelitic layers within the vitreous quartzite. The occurrence of chloritoid is limited to the greenschist facies. The upper temperature limit of this facies is about 500°C, which would be a maximum temperature for rocks in the area.

Kyanite by itself occurs over a wide range of temperatures and pressures. Kyanite plus one other alumino-silicate will constrain metamorphic conditions to a known reaction curve on a P-T diagram. Just south of this study area, along southern Placer Creek, there is a layer in quartzite which contains kyanite and viridine (Mn-andalusite) in equilibrium. M. Williams (personal communication, 1985) has performed microprobe analyses to study the partitioning of iron between these minerals. From his analyses he has estimated metamorphic conditions of 425°-450°C and 3Kb (Figure 14).

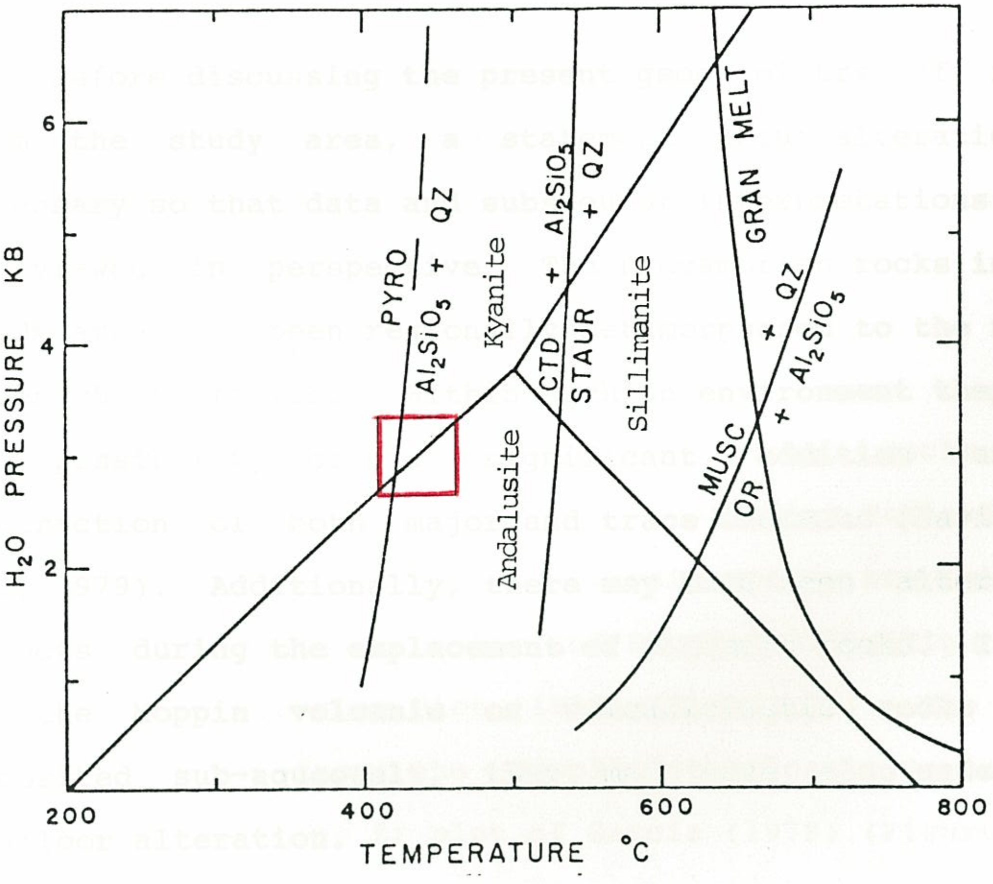

Figure 14. Aluminum silicate phase diagram with other equilibria curves (Holdaway, 1971). Red box outlines P-T conditions represented by rocks in the Jawbone study area.

GEOCHEMISTRY

Eleven rock samples were analyzed for ten major elements and thirteen trace elements using x-ray fluorescence techniques at the New Mexico Bureau of Mines and Mineral Resources. Methodology and precision are briefly described in Appendix I. The eleven samples consisted of 7 plutonic rocks, 2 Moppin Series rocks, and 2 Burned Mountain metarhyolites.

Alteration

Before discussing the present geochemistry of rocks from the study area, a statement about alteration is necessary so that data and subsequent interpretations may be viewed in perspective. The Precambrian rocks in the study area have been regionally metamorphosed to the upper greenschist facies. Within such an environment there is the possibility of a significant addition and/or subtraction of both major and trace elements (Davies et al., 1979). Additionally, there may have been alteration effects during the emplacement of plutonic rocks. If any of the Moppin volcanic or volcaniclastic rocks were deposited sub-aqueously, they may have also undergone seafloor alteration.

Carbonate alteration has occurred in several places in the southeastern quarter of the Jawbone study area, particularly in the vicinity of Hopewell Lake and the

Hopewell mining district. Rocks within this district are extensively carbonatized as well as silicified. These alteration events may have affected rocks in other parts of the study area.

While collecting rocks for geochemical analysis, those which appeared thoroughly altered were avoided. But truly fresh-looking rocks were not always available for sampling. Outcrops of metarhyolite were scarce and so rocks which were visibly altered were collected. Plutonic rock samples were collected to investigate chemical variation between the granite and the granodiorite. Some of these rocks were visibly altered, but they were collected because their field location was important in the sampling scheme.

Supracrustal rocks

Analytical data for the supracrustal rocks are presented in Table 4. Immediately following Table 4 is a series of geochemical plots. Volcanic rocks are plotted on a diagram of Winchester and Floyd (1977) (Figure 15) and on Jensen's Cation Plot (1976) (Figure 16). The mafic volcanic rocks from the Moppin Metavolcanic Series are plotted on the Ti vs Zr plot of Garcia (1978) (Figure 17).

The two Moppin rocks analyzed are a chlorite-plagioclase schist and a quartz-chlorite phyllite. Petrographic evidence suggests that these and other Moppin

TABLE 4

CHEMICAL ANALYSES OF VOLCANIC ROCKS IN JAWBONE MOUNTAIN AREA

	* S21A	* S73X	+	** S73	** S96	++
SiO_2	54.55	56.69	57.94	79.72	78.00	72.82
TiO_2	0.73	0.55	0.87	0.17	0.15	0.28
Al_2O_3	20.58	17.39	17.02	11.32	11.63	13.27
Fe_2O_3 (T)	7.17	8.31	3.27	2.57	2.53	1.48
FeO	-	-	4.04	-	-	1.11
MgO	2.49	5.59	3.33	0.12	0.03	0.39
CaO	4.24	4.26	6.79	0.02	0.80	1.14
Na_2O	4.68	3.67	3.48	1.17	2.87	3.55
K_2O	1.44	0.56	1.62	4.74	3.92	4.30
MnO	0.08	0.10	0.14	0.02	0.07	0.06
P_2O_5	0.18	0.12	0.21	0.05	0.04	0.07
LOI	3.23	2.57	0.83	0.78	0.21	1.10
TOTAL	99.37	99.81	99.54	100.68	100.25	99.57
V	170	128		14	<5	
Cr	72	102		50	51	
Ni	11	137		8	7	
Cu	72	<20		<20	24	
Zn	81	125		157	164	
Ga	17	17		20	22	
Rb	31	33		124	91	
Sr	516	427		65	155	
Y	18	29		84	81	
Zr	120	80		281	308	
Nb	10	15		31	31	
Ba	565	132		357	279	
Pb	24	23		39	51	

CIPW MINERAL NORMS (WT%)

	* S21A	* S73X	+	** S73	** S96	++
Q	5.76	11.45	12.37	53.25	43.23	32.87
C	4.06	3.32	-	4.38	1.35	1.02
Or	8.49	3.29	9.60	28.00	23.15	25.44
Ab	39.26	30.75	29.44	9.86	24.17	30.07
An	19.99	20.43	26.02	0.00	3.67	4.76
Hy	14.88	24.49	9.49	3.56	3.38	1.34
Mt	1.24	1.43	4.74	0.44	0.44	2.14
Il	1.38	1.05	1.65	0.32	0.28	0.54
Ap	0.42	0.28	0.50	0.11	0.10	0.17
Di	-	-	4.84	-	-	-

* Moppin metavolcanic rocks
\+ average andesite of LeMaitre (1976)
** Burned Mountain metarhyolite
++ average rhyolite of LeMaitre (1976)

trace element values in PPM

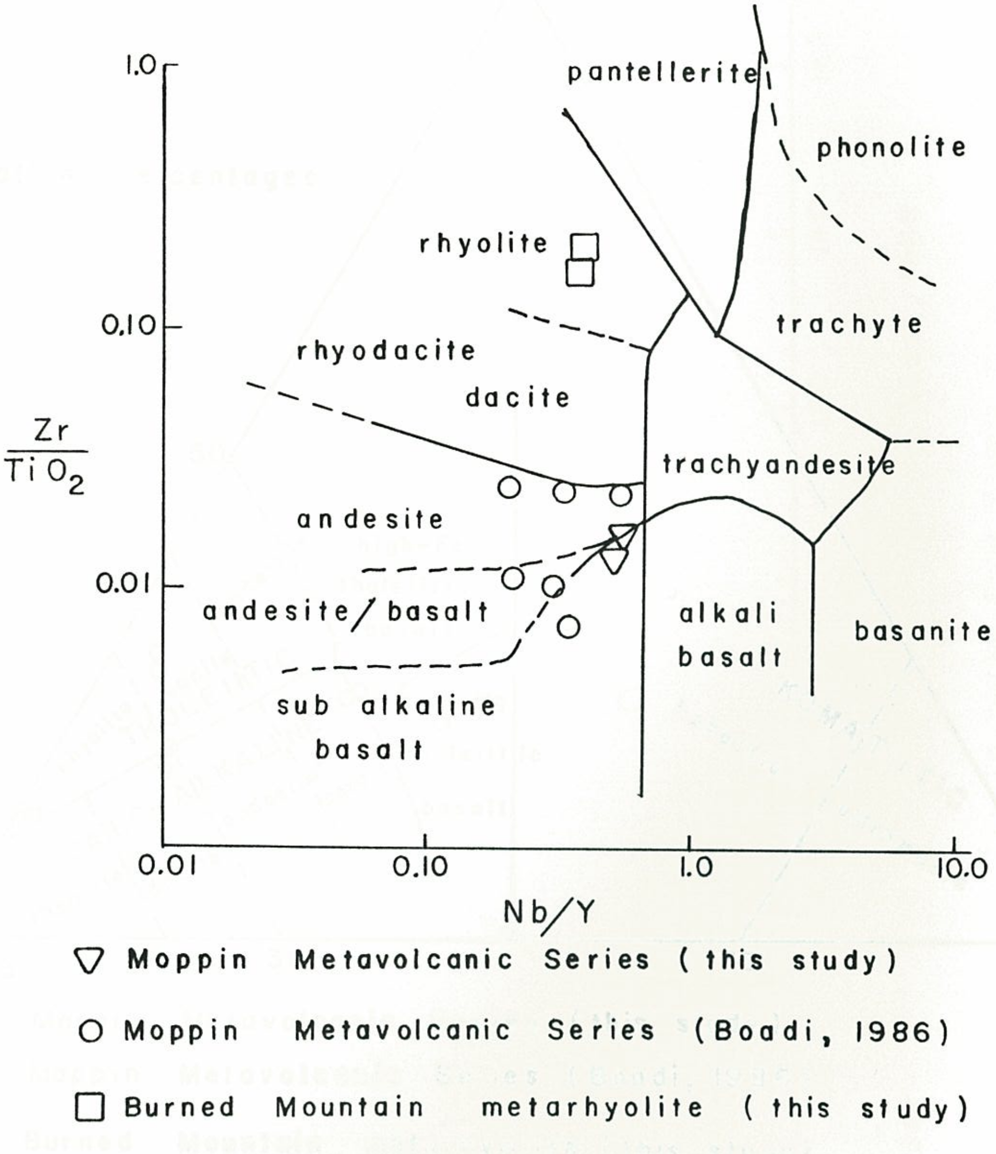

Figure 15. Plot of volcanic rocks from Jawbone and adjacent areas on diagram of Winchester and Floyd (1977).

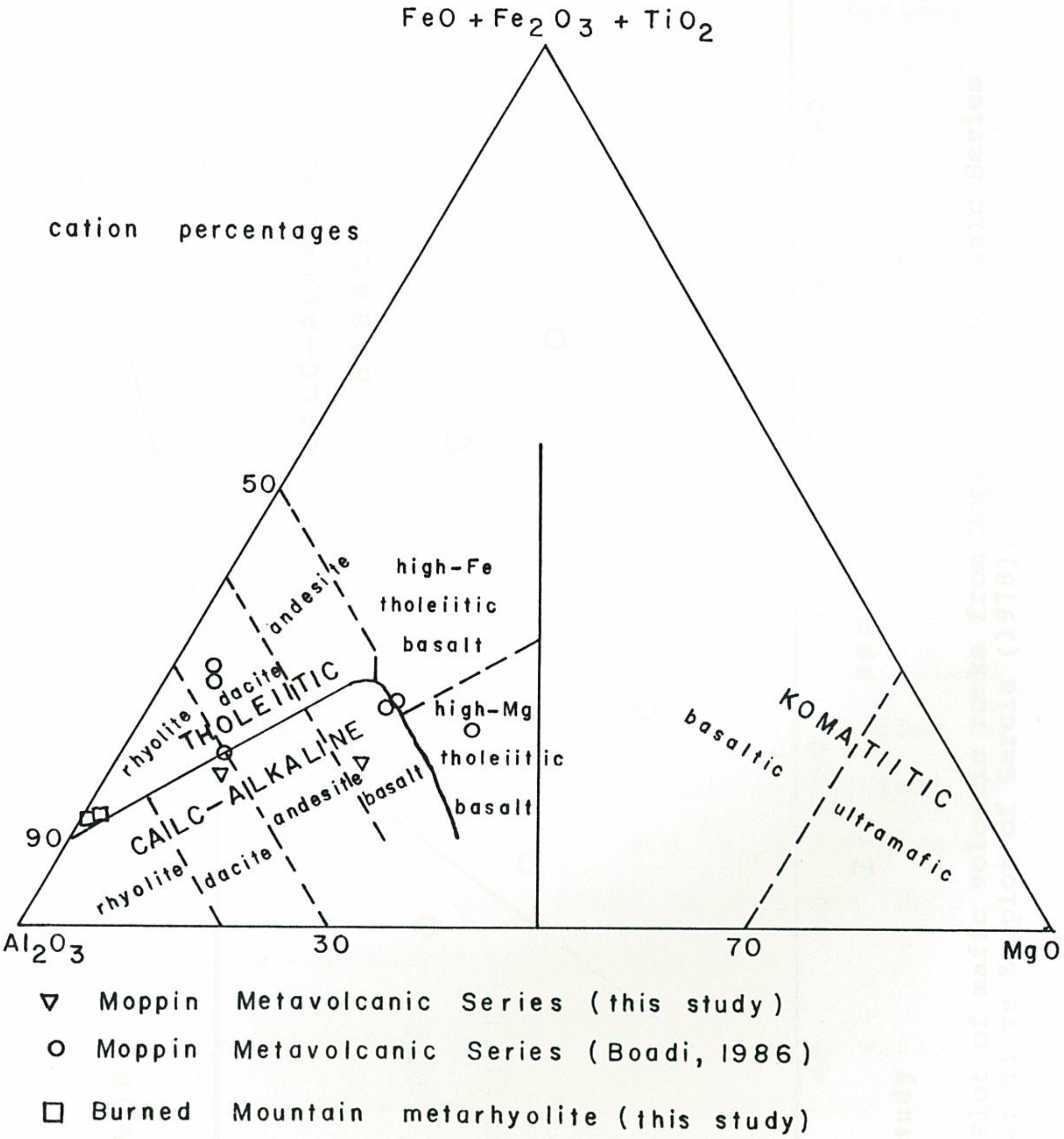

Figure 16. Plot of volcanic rocks from Jawbone and adjacent areas on Jensen's (1976) Cation Plot. Note that cation percentages are used, not weight percentages.

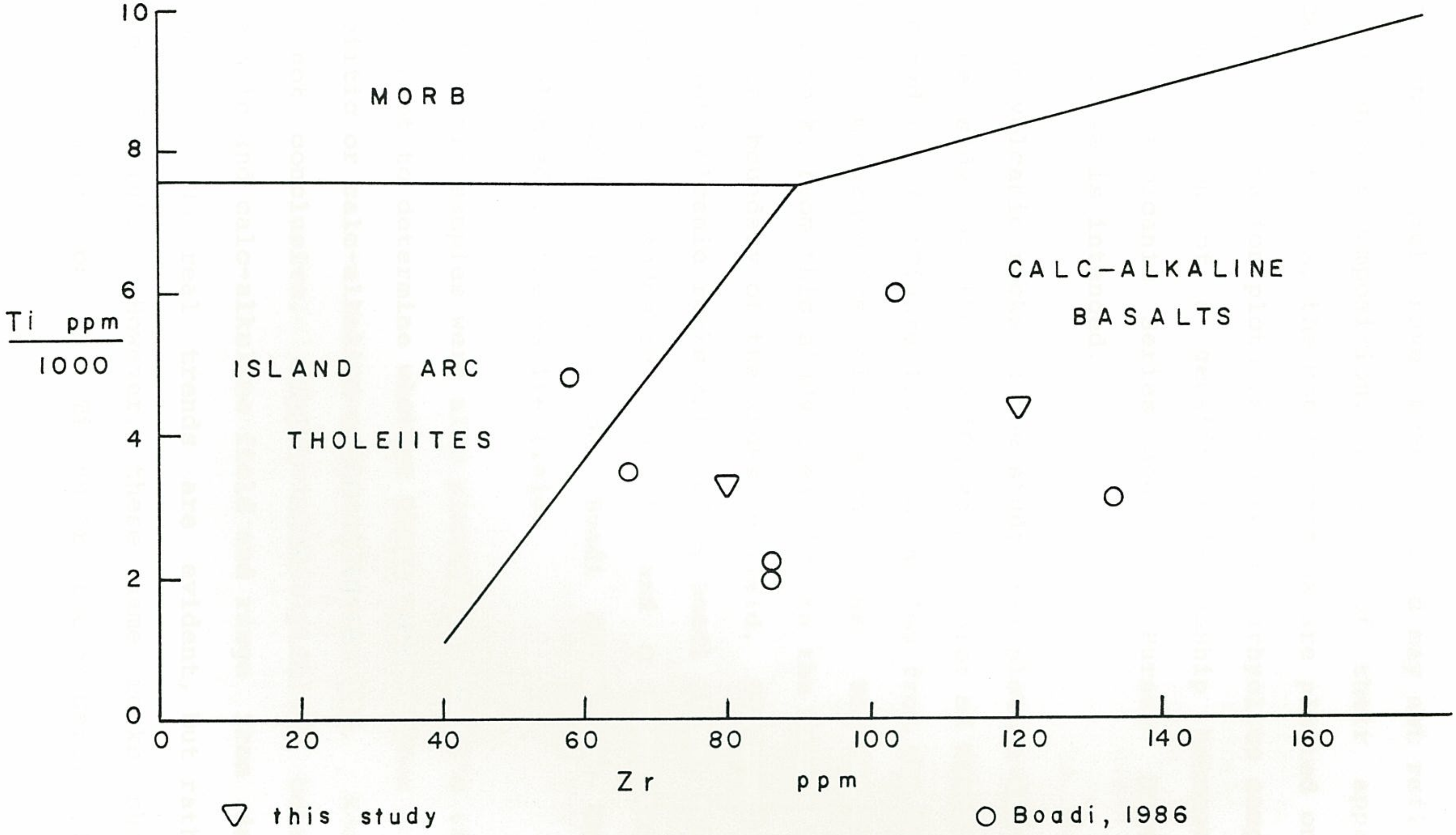

Figure 17. Plot of mafic volcanic rocks from Moppin Metavolcanic Series on Ti vs Zr plot of Garcia (1978).

rocks are volcanics and volcaniclastics. The chemistry of those rocks which have been reworked may not reflect a primary igneous composition. Because of their apparent volcanic affinities, the Moppin samples are plotted on the same classification plots as the two metarhyolite samples. No implication of a genetic relationship between the Moppin Metavolcanic Series and the Burned Mountain metarhyolite is intended.

The volcanic rocks in the study area plot on the sub-alkaline side of the Zr/TiO_2 vs Nb/Y plot of Winchester and Floyd (1977) (Figure 15). The samples from the Burned Mountain metarhyolite plot as rhyolites. The samples of Moppin rocks from this study area plot in the basalt field near the boundary of the andesite field. Six samples of Moppin metavolcanic rocks analyzed by Boadi (1986) fall in the fields of andesite, basalt, and a mixed basalt-andesite field. In addition, Boadi shows one Moppin sample plotted in the dacite field.

Volcanic samples were also plotted on Jensen's (1976) Cation Plot to determine whether these rocks belong to the tholeiitic or calc-alkaline suite (Figure 16). Results were not conclusive. Moppin rocks plot in both the tholeiitic and calc-alkaline field and range from dacite to basalt. No real trends are evident, but rather a scatter of points. However, these same rocks show a better grouping on the Ti vs Zr plot of Garcia (1978)

(Figure 17). All samples but one fall within the field of calc-alkaline basalts. Garcia interprets calc-alkaline basalts as representing volcanic arcs.

The Moppin Metavolcanic Series is interpreted to be a mixed suite of basalts and andesites plus several minor rock types. The presence of andesites is shown by the geochemical data obtained by Boadi (1986). Boadi also indicates that some dacite is present. Thus the Moppin seems to range from mafic to intermediate without a compositional gap.

The trace element chemistry of the Burned Mountain metarhyolite is consistent with an origin as a continental rhyolite associated with crustal extension. Data from this study were compared to those published by Ewart (1979) for Tertiary rhyolites which are part of bimodal basalt-rhyolite associations. Values for Zr, Sr, V, Y, and Zn compare favorably with Ewart's data, as do CaO and MgO values.

Plutonic rocks

Analytical data for the plutonic rocks are presented in Table 5. Immediately following Table 5 is a normative feldspar plot of seven plutonic rocks from the Jawbone Mountain study area (Figure 18).

TABLE 5

CHEMICAL ANALYSES OF INTRUSIVE ROCKS IN JAWBONE MOUNTAIN AREA

	Granite of Hopewell Lake			-----Maquinita Granodiorite-----					
	S111	S100	+	S131	S112A	S112B	S12A	S24C	++
SiO_2	68.56	69.94	71.30	73.20	71.16	68.87	69.46	68.39	66.09
TiO_2	0.48	0.26	0.31	0.09	0.27	0.28	0.26	0.29	0.54
Al_2O_3	16.96	16.43	14.32	14.12	15.38	16.99	15.40	15.52	15.73
Fe_2O_3 (T)	4.44	2.81	1.21	2.68	2.61	2.80	3.96	3.05	1.38
FeO	-	-	1.64	-	-	-	-	-	2.73
MgO	0.30	0.86	0.71	0.39	0.96	0.66	1.27	1.19	1.74
CaO	0.38	1.35	1.84	1.58	1.74	2.61	2.56	1.53	3.83
Na_2O	5.11	5.59	3.68	3.22	5.19	6.76	3.73	4.60	3.75
K_2O	2.24	1.64	4.07	4.26	1.37	0.63	2.17	3.84	2.73
MnO	0.03	0.04	0.05	0.05	0.03	0.05	0.06	0.05	0.08
P_2O_5	0.16	0.11	0.12	0.07	0.11	0.10	0.11	0.12	0.18
LOI	1.67	1.67	0.64	0.32	1.13	0.87	1.04	0.85	0.85
TOTAL	100.33	100.70	99.89	99.98	99.95	100.62	100.02	99.43	99.63
V	94	40		22	45	49	56	56	
Cr	93	66		51	66	83	68	74	
Ni	8	10		<5	11	10	7	12	
Cu	44	<20		<20	<20	<20	<20	<20	
Zn	44	43		35	48	44	40	41	
Ga	19	17		10	15	16	12	14	
Rb	46	32		66	32	12	50	68	
Sr	534	804		291	556	1219	485	728	
Y	5	2		11	4	0	9	8	
Zr	110	122		136	106	145	101	162	
Nb	9	7		10	6	7	8	11	
Ba	1420	935		922	784	411	931	1606	
Pb	16	16		<15	<15	<15	<15	17	
CIPW MINERAL NORMS (WT%)									
Q	27.23	25.68	29.06	33.08	29.63	19.72	30.38	20.52	22.36
C	5.83	3.26	0.92	1.55	2.47	0.72	2.55	1.31	0.26
Or	13.22	9.68	24.50	25.17	8.11	3.71	12.82	22.66	16.11
Ab	42.85	47.34	31.13	26.68	43.50	56.33	30.98	38.95	31.73
An	1.03	6.00	8.04	7.56	8.09	12.66	12.22	6.79	17.34
Hy	6.04	5.61	3.37	4.56	5.55	5.07	8.23	6.72	7.40
Mt	0.77	0.48	1.75	0.46	0.45	0.48	0.68	0.52	2.00
Il	0.91	0.50	0.58	0.18	0.52	0.54	0.50	0.54	1.03
Ap	0.36	0.25	0.28	0.16	0.25	0.24	0.25	0.28	0.42

+ average granite of LeMaitre (1976)
++ average granodiorite of LeMaitre (1976)

trace element values in PPM

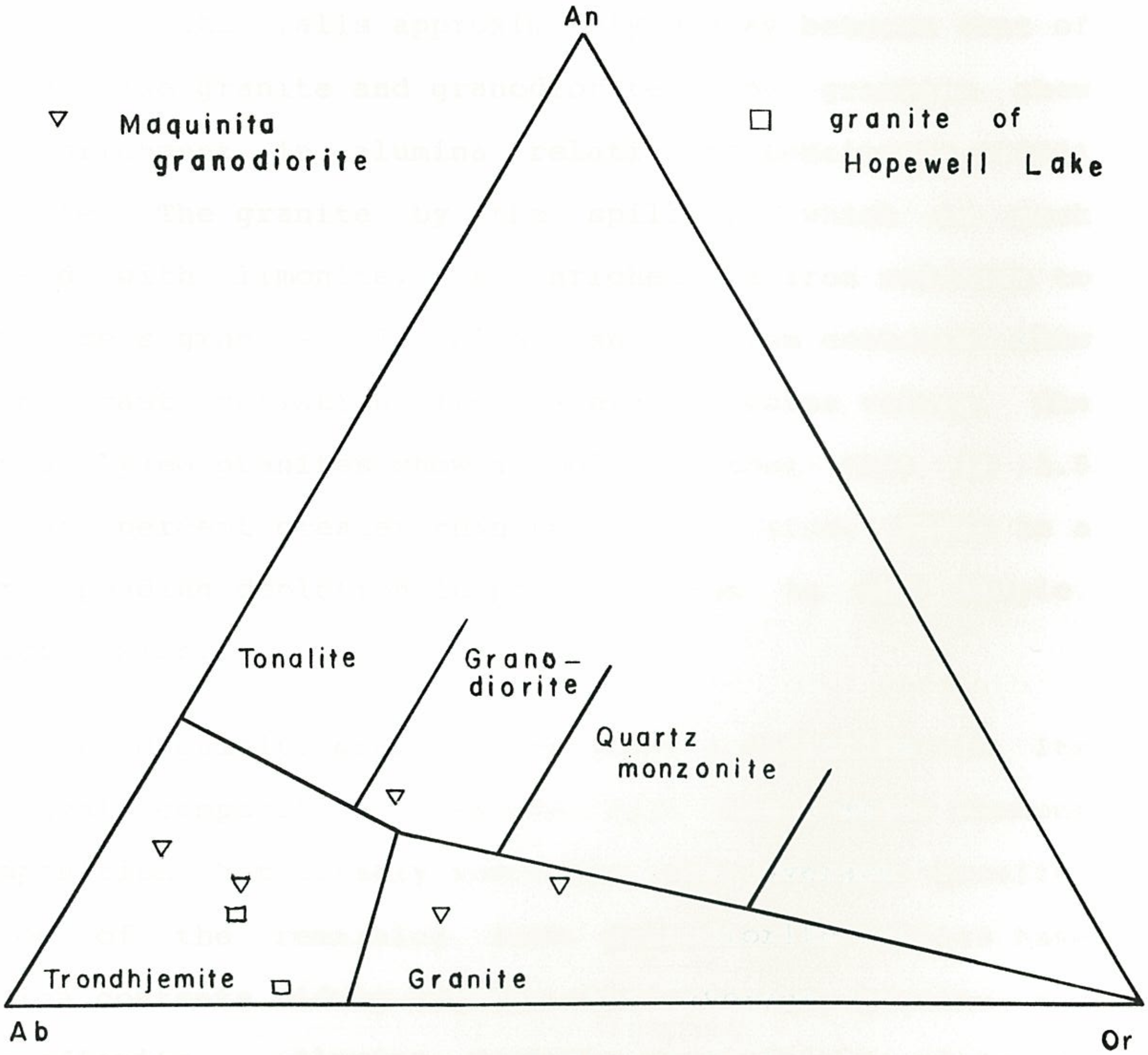

Figure 18. Normative feldspar plot (after O'Connor, 1965; modified by Barker, 1979) of seven plutonic rocks from Jawbone Mountain study area.

Of the seven plutonic rocks analyzed, two samples are from the granite of Hopewell Lake and the other five from the Maquinita granodiorite. All seven rocks were compared to both the granite and granodiorite of LeMaitre (1976).

Silica content in the two samples of the granite of Hopewell Lake falls approximately midway between that of the average granite and granodiorite. The granites show an enrichment in alumina relative to LeMaitre's (1976) granite. The granite by the spillway, which is pock marked with limonite, is enriched in iron relative to LeMaitre's granite. The alkali and calcium contents show significant variation from average granite values. The two analyzed granites show a sodium content that is 1.5 weight percent greater than LeMaitre's value. There is a corresponding depletion in potassium and, in one sample, calcium also.

The Maquinita granodiorite shows a variation in its chemical composition. Sample S131 has a major element composition that closely resembles the average granite. Three of the remaining four granodiorite samples have silica contents midway between the average granite and granodiorite. Alumina contents are fairly close to average values. The alkali and calcium contents of the granodiorites (except S131) show patterns similar to those seen in the samples of the granite of Hopewell Lake; sodium is enriched and potassium and calcium are depleted relative to LeMaitre's (1976) granodiorite. In an overall view of the chemistry, the Maquinita ranges from a granite to a slightly siliceous granodiorite.

Of the seven plutonic rocks analyzed, the four which exhibit the greatest departure from published average values are all within an 800 m radius of Hopewell Lake. Evidence from the field and thin-sections may help explain why these rocks are more altered than plutonic rocks farther north. Rocks in this area contain numerous shear zones which parallel the dominant foliation. Even rocks away from the shear zones show evidence of deformation by broken plagioclase phenocrysts (Figure 9). The deformation may have opened up conduits in the rock through which altering fluids could pass.

All seven plutonic samples were plotted on Barker's (1979) An-Ab-Or plot using normative feldspar percentages (Figure 18). The three least-altered plutonic rocks from this study plot in the same fields on the An-Ab-Or plot as they do on the Q-A-P modal mineralogy plot (Figure 10). The four most-altered samples mentioned above plot as trondhjemites, athough two are from the granite of Hopewell Lake and two are from the Maquinita granodiorite. Mineralogically and chemically, they do have some characteristics common to trondhjemites. However, the definition of a trondhjemite, as presented in Barker (1979), requires alkali feldspar to constitute 10% or less of the total feldspar. Plutonic rocks in the Jawbone study area contain 10-30% alkali feldspar, significantly more than the amount for trondhjemites. In addition, the Maquinita granodiorite contains 10-20% biotite. This is in the permissible range for trondhjemite but well above some trondhjemites reported in the literature (Barker et al., 1974; Williams et al., 1982).

The reason that some rocks from the study area plot as trondhjemites is due to a chemical alteration which has enriched the rocks in sodium at the expense of potassium, thus inflating the normative Ab value. Gibson (1981) plots similar rocks on the same plot and has two of the four in the trondhjemite field. Gibson's chemical data show that these two have the same sodium enrichment and potassium depletion seen in this study. Apparently, some time after the plutons were crystallized, a sodium-rich fluid was flushed through the rocks. Sodium replaced potassium in the alkali feldspars to a significant extent but not enough to change the mineralogy of the rock. This alteration event was probably related to regional metamorphism and possibly related to the event(s) which mineralized the Hopewell mining district.

DISCUSSION

RELATION TO REGIONAL PRECAMBRIAN ROCKS

There are numerous other occurrences of Proterozoic rocks across southern Colorado and northern New Mexico. Several of these occurrences have features similar to the Proterozoic of the northern Tusas Mountains. Proterozoic terranes near Gunnison and Salida, Colorado, and Pecos, New Mexico, have been described as greenstone belts (Robertson and Moench, 1979; Condie and Nuter, 1981; Bickford and Boardman, 1984). The Needle Mountains of southwestern Colorado contain the Irving Formation which has also been described as a greenstone (Barker, 1969). Another similar terrane is the Gold Hill-Wheeler Peak area near Taos, New Mexico, but this has not been labelled a greenstone (Condie and McCrink, 1982). In general these terranes are composed of a mixture of metavolcanics and metasediments intruded by felsic plutons. Mafic volcanics dominate over felsic volcanics. Pillow basalts occur in the Salida, Gunnison, and Pecos areas. Volcaniclastic rocks make up a significant proportion of the metavolcanics in several areas. Within the volcaniclastics at Pecos, Gold Hill, and in the Needle Mountains are thin iron-formations which are analagous to the iron-formation described by Kent (1980) in the Tusas Mountains.

The age of most of these terranes is constrained only by the age of an intruding pluton. There are, however, a few dates for volcanic rocks within the greenstones. Bickford and Boardman (1984) report two periods of volcanism in the Gunnison area. The earlier period ranges from 1770 to 1760 Ma and the later from 1740 to 1730 Ma. A large granitic pluton was intruded around 1750 Ma. In the Salida area, Bickford and Boardman report a date of 1730 Ma from a dacite. The age of the Pecos greenstone is not well known. Robertson and Moench (1979) suggest that a model lead age of 1720 to 1710 Ma is permissible for the massive sulfide deposit which is hosted in volcanic rocks.

All of these terranes are intruded by at least one pluton. Compositions of plutons are reported as diorite, granodiorite, granite, and tonalite. Reported U-Pb ages on these plutons range from 1650-1750 Ma. The preliminary 1755 Ma date of the Maquinita granodiorite is close to this range. In the Gold Hill area, the volcanic pile is intruded by a tonalite dated at 1750 Ma (S. Bowring and R. VanSchmus cited in Condie and McCrink, 1982).

These Proterozoic terranes have been metamorphosed to greenschist and/or amphibolite facies, and all areas record at least two and probably three periods of deformation.

The Gold Hill and Pecos areas have another similarity to the Tusas Mountains in that the metavolcanic package is overlain by mature sediments analagous to the Ortega Group.

Ortega Group rocks themselves crop out in several areas east of the Tusas Mountains. These areas are the Picuris range, the Truchas range, and the Rio Mora area. In these areas, the Ortega Group is underlain by the Vadito Group, a volcanic-dominated assemblage with metaclastics and metavolcaniclastics (Bauer, 1984). The Vadito, however, is not mafic volcanic dominated and is more likely correlative with the Burned Mountain metarhyolite than with the Moppin Metavolcanic Series. The presence of the Ortega Group across all these ranges helps to establish the regional extent of the continental shelf and slope on which the Ortega accumulated.

PRECAMBRIAN DEPOSITIONAL AND TECTONIC SETTINGS

The Precambrian rocks in the Tusas Mountains are a lithologically and chronologically diverse group that does not fit neatly into any single tectonic setting. To identify probable settings in which these rocks originated, one must consider the major supracrustal packages with related plutonic rocks individually, considering the constraints provided by each package. Defined on the basis of lithologies, chemistry, geology, and limited age data, the three major rock packages, from oldest to youngest, are: 1) Moppin metavolcanics, 2) Burned Mountain metarhyolite, and 3) vitreous quartzite. Micaceous metasediments represent a transitional package between the Burned Mountain metarhyolite and the vitreous quartzite.

The constraints on the Moppin metavolcanics package include the following:

The volcanic rocks in this package do not make up a classical bimodal assemblage of basalts and rhyolites. Within the Moppin Metavolcanic Series, basalts are apparently dominant but rocks of andesitic and dacitic composition are present. Kent (1980) reports that three of her amphibolite units geochemically resemble Nockold's (1954) average andesite. Gibson (1981) also has rocks which plot as andesites on several discrimination diagrams. Intermediate volcanics occur along Placer Creek and plots of their immobile trace elements show these rocks to be andesites and dacites (Boadi, 1986). Moppin metavolcanics exhibit rather consistent calc-alkaline affinities on most geochemical discrimination diagrams.

There is no direct evidence that the Moppin volcanics were extruded sub-aqueously, although pillow-like structures have been observed in Moppin rocks that crop out in the Brazos Box (J. Robertson, personal communication, 1985). Within this package a number of lithologies are viewed as being volcaniclastics or reworked volcanics. There are also fine-grained, graded sediments and iron-formations like those exposed along the top of Iron Mountain. Some of these lithologies are certainly water-laid. This implies that Moppin volcanism occurred close to or in a body of water.

At about 1755 Ma, the Moppin package was intruded by the Maquinita granodiorite. The coarse grain size of the granodiorite suggests it may have been emplaced within the mesozone. Volcanism may have continued simultaneously with emplacement but at least part of the volcanic pile was at about 8 km depth.

A likely tectonic setting for the deposition of the Moppin Metavolcanic Series is a volcanic arc. An arc setting is suggested by both the calc-alkaline nature of the volcanics and by the presence of a compositional continuum from basalt to dacite. Whether it is a continental margin arc or an island arc is not clear from data collected.

The Burned Mountain metarhyolite has a number of constraints. These constraints include:

The Burned Mountain metarhyolite is interpreted to be an ash-flow tuff. This is based largely on the interpretation of fine-grained clasts as flattened, recrystallized pumice fragments. Abundant unsorted, subhedral to sub-rounded phenocrysts of quartz and microcline provide supporting textural evidence. Other evidence that suggests the metarhyolite was deposited as an ash-flow comes from its areal extent. The general map pattern of the metarhyolite in the northern Tusas Mountains is that of a thin unit (30-100 m thick) which extends for 20 km or more along a complexly-folded strike length.

Many of the above features are common to both sub-aerial and sub-aqueous ash-flows. Even welding, which the Burned Mountain metarhyolite exhibits in places, is thought to be possible in an underwater as well as in a sub-aerial environment. Two features of the metarhyolite, however, seem to indicate sub-aerial deposition. One is the absence of interbedded or encompassing marine sediments. The other feature is that the Burned Mountain metarhyolite rests with angular unconformity on an erosional Moppin-Maquinita surface.

Trace element geochemistry suggests an origin as continental rhyolites associated with crustal extension or rifting.

There is a preliminary U-Pb date of 1700 Ma (Silver, in Robertson et al., in prep) for the Burned Mountain metarhyolite. This age constrains the termination of Moppin volcanism since the metarhyolite was deposited on an erosional surface of the Moppin which had some topographic relief.

The metarhyolite was erupted and accumulated in a continental extensional environment. Eruption probably took place sub-aerially from one or more volcanic centers.

The constraints for the vitreous quartzite include the following:

A recent, detailed sedimentologic study of the Ortega Group in northern New Mexico (including the Ortega quartzite) is described by Soegaard and Eriksson (1985). The Ortega quartzite is the lowest stratigraphic unit in the Ortega Group. Large-scale trough cross-beds, large to medium-scale tabular planar cross-beds, and reactivation surfaces with mudstone veneers are documented in quartzite from the present study area along Jawbone Ridge. Many trough cross-beds contain coarse, pebbly lags at the top and bottom of the bed. The bottom layer is a normal lag deposited as the new bed begins to be deposited. The top layer is thought to be a winnowed lag left behind as storm waves winnowed away the finer material. The mudstone veneers are the layers which now contain kyanite.

Soegaard and Eriksson (1985) interpret the depositional environment of the quartzite to be an inner shelf setting. This shelf slopes shallowly to the south and southeast, receiving sediments from the north and northwest. Tidal processes dominated this environment, forming the several types of bedding features. Based on thickness of trough cross-beds, Soegaard and Eriksson infer a minimum water depth of 3-4 m for the inner shelf during deposition.

Thick successions of quartzite are normally interpreted as being deposited in a stable environment. This is certainly true of the depositional environment for the vitreous quartzite. Depositional environment seems to have remained nearly constant throughout the deposition of this clean and very thick (>1 km) quartzite. In order to accumulate such a thickness and keep water depth nearly constant during deposition, subsidence must have been taking place at the same rate as deposition. This subsidence implies a degree of tectonic instability. A suggested setting for vitreous quartzite deposition would be on the inner part of a continental shelf within a subsiding basin.

There is a major difference between the setting of the oldest package and that of the two younger packages. The Moppin package represents an arc setting and the younger two require the presence of a continental mass. The unconformity between the Moppin Metavolcanic Series and the Burned Mountain metarhyolite encompasses an event during which the volcanic arc was joined to an existing continent. This event was probably a compressive event and was perhaps synchronous with the intrusion of the Maquinita granodiorite.

PRECAMBRIAN GEOLOGIC HISTORY

prior to 1755 Ma: submarine extrusion and deposition of Moppin volcanics and volcaniclastics in a volcanic arc setting. Volcanic arc situated on a plate moving toward a continent.

1755 Ma: syntectonic intrusion of pluton(s) into Moppin as volcanic arc is being accreted onto a continent. One pluton, the Maquinita granodiorite, is mostly a granodiorite with granitic phases. The granite of Hopewell Lake may also have been intruded at this time.

1755 - 1700 Ma: Moppin deposition may have continued during part of this interval, but by 1700 Ma the Moppin was exposed and being actively eroded.

1700 Ma: extrusion of Burned Mountain metarhyolite as a primarily sub-aerial ash-flow tuff in a continental extensional setting.

after 1700 Ma (probably soon after): upper portions of metarhyolite were reworked locally into fine-grained sediments some of which were aluminum-rich (now kyanite-bearing).

Marine transgression onto an extensional lowland produces a sedimentary basin. Coarse detritus contributed from both the Moppin Series and the Burned Mountain metarhyolite.

Continued transgression enlarges basin and allows development of a continental shelf. Source area to the north and northwest provides a constant supply of siliciclastic material resulting in deposition of 1 km of sandstone. Subsidence must have occurred at about the same rate as deposition.

1650 - 1300? Ma: subsequent to sandstone deposition, the entire Precambrian package is buried to a depth of 8-12 km. Rocks experience three or more periods of deformation and regional metamorphism to greenschist facies.

SUMMARY

The Moppin Metavolcanic Series is the oldest unit in the Tusas Mountains. It consists of metavolcanic rocks and intercalated volcaniclastics and sediments. The volcanics range from basalt to dacite, with mafic volcanics more abundant. The volcaniclastics are derived principally from mafic volcanics. The minor sediments include siltstone and iron-formation. The Moppin unit is intruded by two plutonic rocks within the Jawbone study area. These are the Maquinita granodiorite and the granite of Hopewell Lake.

Unconformably overlying the Moppin Metavolcanic Series is the Burned Mountain metarhyolite, an ash-flow tuff which accumulated on a Moppin erosional surface. Overlying the metarhyolite is a transitional package of sediments, here called micaceous metasediments. This package includes metaconglomerate, micaceous quartzite, and quartz-sericite schist. These sediments grade upwards into a clean quartzite which is the youngest Precambrian supracrustal unit in the Tusas. The term "vitreous quartzite" is used here as the unit name for the quartzite.

Three periods of deformation are recorded in rocks of the Tusas Mountains although the timing of these events is not well known. Extension lineation and tight to isoclinal folds were produced by D_1 and possibly by D_2. The D_3 deformation produced large-scale, open folds and a well-developed axial-plane foliation. Rocks in the study area have undergone regional metamorphism to the greenschist facies.

Geochemical analysis of Moppin volcanics shows them to be largely calc-alkaline. The calc-alkaline affinity of these rocks is suggestive of an arc setting for their extrusion and deposition. Other greenstone successions in northern New Mexico and southern Colorado, which have lithologies similar to the Moppin, have been described as accumulating in volcanic arcs.

Moppin rocks formed within a compressional tectonic environment, specifically within an arc setting. The basement upon which the Moppin was extruded is not known. Plutonic intrusion into the Moppin occurred, probably as the volcanic arc was being accreted to a continental mass. By 1700 Ma, the stress regime had changed to extensional. In this regime the rhyolitic ash-flow tuffs of the Burned Mountain unit were extruded. Marine transgression formed a sedimentary basin. Eventually a shelf developed within the basin and the vitreous quartzite was deposited on this shelf.

The micaceous metasediments unit of this study is interpreted as a transitional unit between the environment of ash-flow tuff extrusion and clean quartzite deposition. The conglomerate is an early, basin-filling sediment. The sediments generally fine upward into the vitreous quartzite.

The northern Tusas Mountains represent an evolution of tectonic settings. The oldest known rocks represent a volcanic arc. This arc was accreted to an existing continent and syntectonically intruded by one or more felsic plutons. Extension occurred within this newly enlarged continent, producing sheets of ash-flow tuffs. Continued extension combined with marine transgression formed a basin in which continental clastic material accumulated. This whole package of Proterozoic rocks became the basement for the subsequent Phanerozoic sedimentary and tectonic activity.

APPENDIX I: GEOCHEMICAL METHODS

All analyses were performed on the Rigaku 3064 X-ray Fluorescence Spectrometer at the New Mexico Bureau of Mines and Mineral Resources. Major elements were determined using fused discs containing 0.5 grams of sample and 2.7 grams of Spectroflux 105. This flux contains lithium carbonate, lithium tetraborate, and lanthanum oxide. Trace elements were determined using pressed pellets containing 7 grams of sample and 7 drops of polyvinyl alcohol as a binder.

Several USGS rock standards were analyzed along with the samples from this study to check precision and drift in the spectrometer. These standards included G-2, SY-3, BCR-1, BHVO-1, and QLO.

All major element data is presented on a dry basis. Precision of the values for the major elements and some trace elements is given in Table 6.

TABLE 6

PRECISION OF XRF SPECTROMETER FOR MAJOR ELEMENT OXIDES AND SELECTED TRACE ELEMENTS

SiO_2	±0.4%
TiO_2	±0.4%
Al_2O_3	±0.3%
Fe_2O_3(total)	±0.7%
MnO	±2.0%
MgO	±1.6%
CaO	±0.3%
Na_2O	±1.5%
K_2O	±0.6%
P_2O_5	±1.0%
Rb,Sr,Y,Zr,Nb	±10% at >10ppm
Cu,Zn,Ba	±10% at >20ppm
V,Cr,Ni,Ga	±10% at > 5ppm
Pb	±10% at >15ppm

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