Characterization of the Basement Rocks in the Mescalero 1 Well, Gudalupe County, New Mexico

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By

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ABSTRACT

The well Mescalero 1, drilled by Labrador Oil Company in 1996 in the Tucumcari Basin of east central New Mexico, penetrated 2652 meters of basement rocks. Three major intrusive rock types (gabbro, quartz syenite, granite) and a metasedimentary-metavolcanic sequence compose this basement section. The metasedimentary-metavolcanic sequence fits the description of the Debaca sequence, a package of Proterozoic metasediments that occurs mainly in the subsurface west Texas and southeastern New Mexico. The most abundant mafic rock in the basement section is gabbro which yielded a biotite $^{40}Ar/^{39}Ar$ age of 1090 $\pm$ 4 Ma. Because the gabbro caused contact metamorphism in other Mesoproterozoic rock units, it appears to be the youngest unit within the basement. The quartz syenite, which underlies the Debaca sequence, yielded a SHRIMP U-Pb zircon age of 1334 ± 52 Ma. On the basis of the ages of the gabbro and quartz syenite, the age of the Debaca Terrane can be reasonably constrained to be between 1.09 and 1.33 Ga.

The metasedimentary-metavolcanic sequence includes volcaniclastic metasediment, tuffaceous metasediment, meta-arkose, metarhyolite, arkosic metasediment, quartzose dolomite and dolomitic quartzite. This package is similar to the metasedimentary-metavolcanic rocks observed elsewhere in the Debaca terrane. Here, the Debaca sequence rests on weathered quartz syenite of the underlying granite-rhyolite Panhandle Terrane. This

nonconformity is a distinctive marker horizon on seismic reflection lines across the Tucumcari Basin.

Each rock unit encountered in Mescalero 1 has a characteristic geophysical well log signature that is useful in tying the observed lithologies in this well to other basement wells with geophysical logs. For example, the gabbro has a density of about 3 gm/cc and low gamma values and the predominately dolomitic sediments have densities of ~2.75 and low gamma values. On the basis of natural gamma-ray spectral log analysis, most of the horizons of volcaniclastic metasediment and some dolomitic quartzite units containing smoky quartz have elevated uranium content and correspondingly high gamma ray values.

INTRODUCTION

Mescalero 1 is a deep well, drilled by Labrador Oil Company in 1996 as part of an exploration program for petroleum in Guadalupe County, east-central New Mexico. The well is located in section 1, Township 6N, and Range 22E (Figures 1 and 2) within the Tucumcari Basin, a basin that developed during late Pennsylvanian to early Permian time (Broadhead and King, 1988). The well penetrated ~1768 meters of Paleozoic to Mesozoic sediments and ~2652 meters of basement rocks, totaling 4420 meters. The drill cuttings are on file at the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), Socorro, New Mexico. No basement rocks crop out near Mescalero 1, and the nearest outcrop is in the Pedernal Hills, about 100 km west of the Mescalero 1. In addition to Mescalero 1, several wells have been drilled in the Tucumcari Basin that intersect basement consisting of granite, rhyolite, quartzite, dolomitic marble, diorite, and schist (Foster and Stipp, 1961; Figure 2). Previous work, summarized by Barnes et al. (1999a), has identified a number of distinct provinces in the basement of Texas and eastern New Mexico (Figure 1). There are three specific objectives of this report:

a) To characterize Proterozoic rocks in Mescalero 1 on the basis of petrological and mineralogical associations, complemented by geochemical analysis.

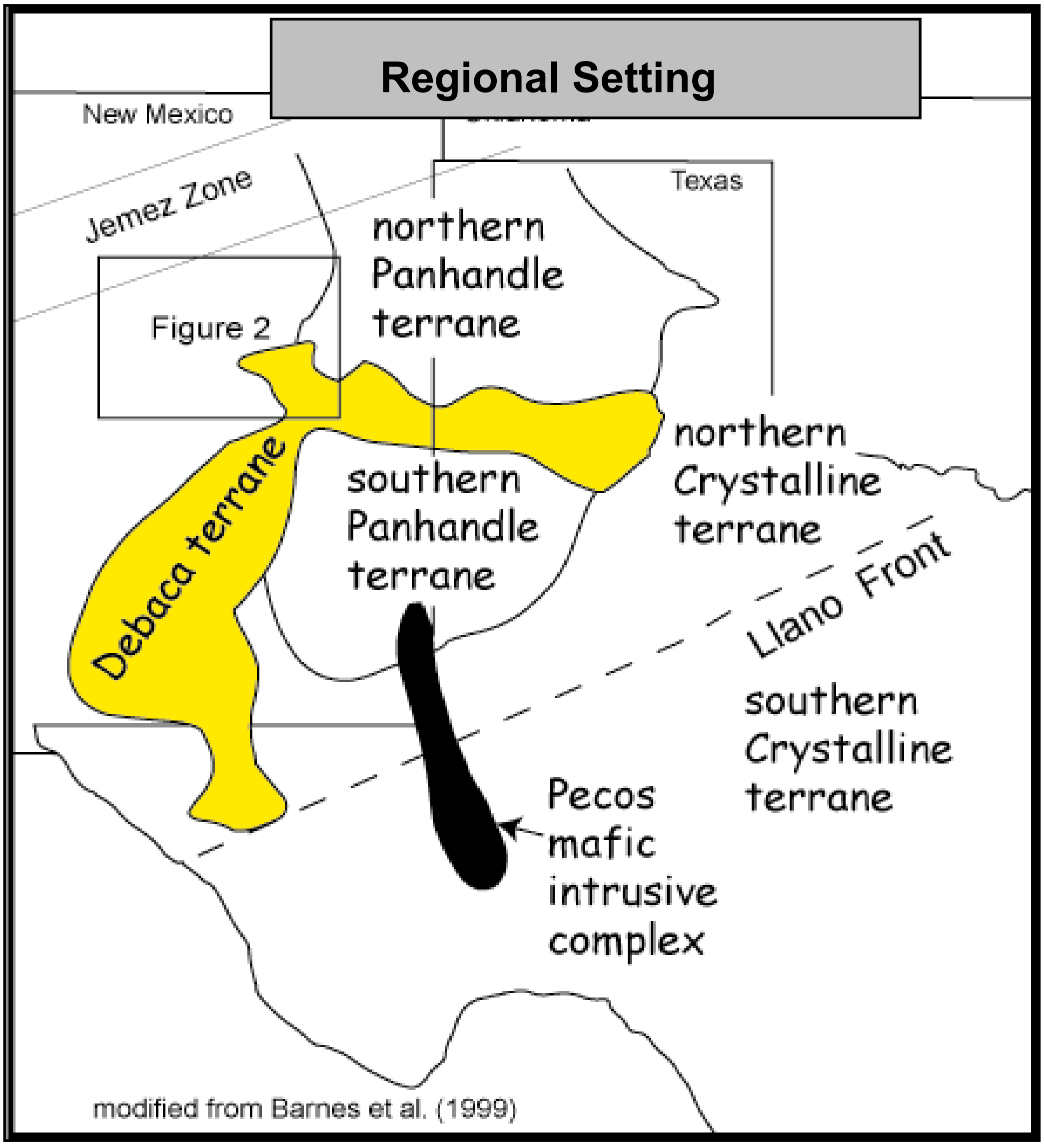


Figure 1. Generalized map showing the location of the Tucumcari Basin with respect to the Proterozoic terrenes: the Panhandle Terrane, the Crystalline Terrane, the Pecos Mafic Intrusive Complex, the Llano Front, and the Debaca Terrane.

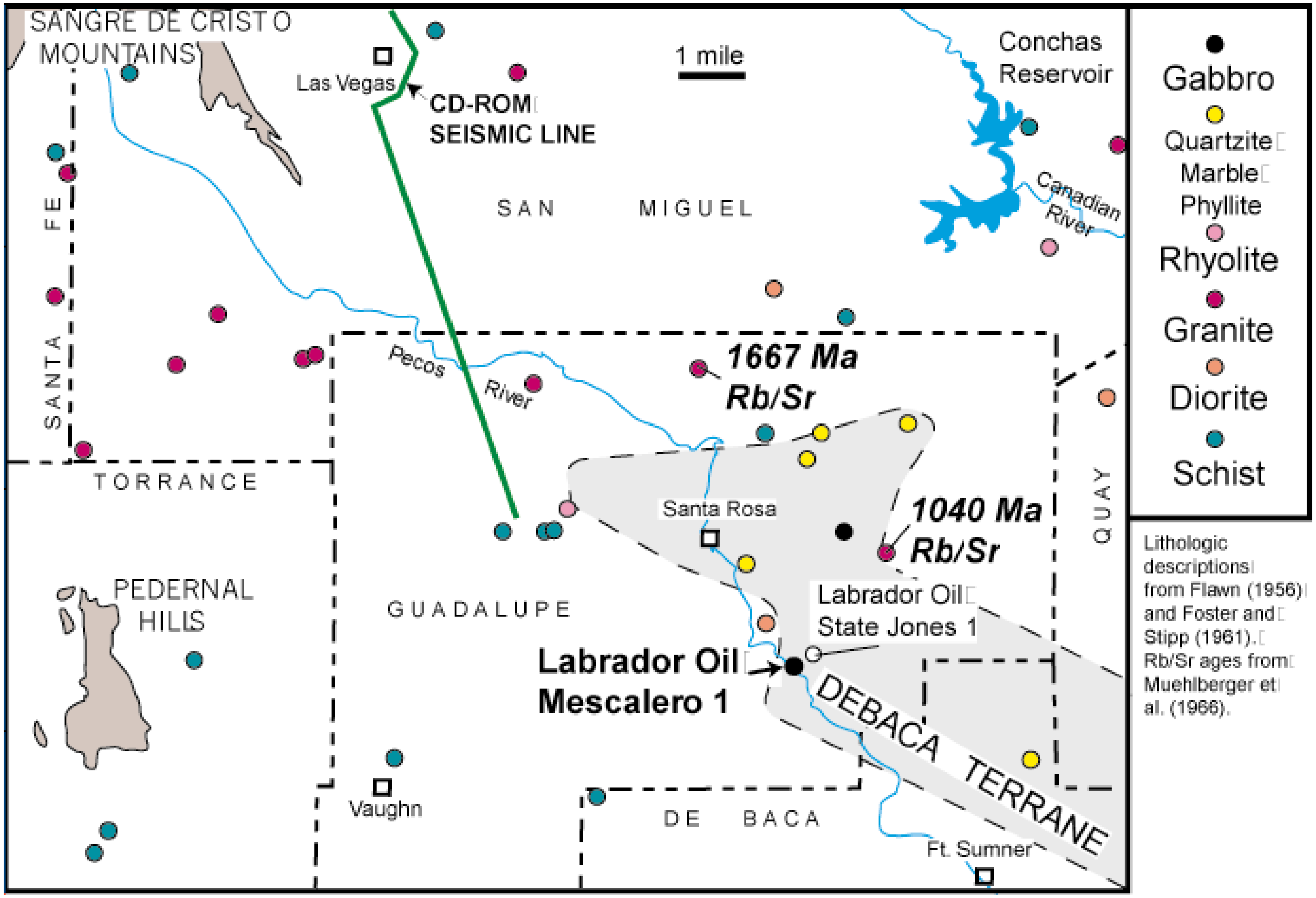


Figure 2. Map showing the location of the Labrador Oil Mescalero No. 1, and other wells drilled in the Tucumcari Basin region. Brown areas are exposed Proterozoic rocks and gray area highlights the Debaca Terrane.

b) To determine the ages of minerals from the basement intrusive rocks using $^{40}Ar/^{39}Ar$ and U-Pb methods to determine their age of emplacement and to bracket the age of deposition of the metasediments.

c) To calibrate geophysical well logs with petrologic data.

Analysis of these rocks is important for (1) understanding the nature of deep basement reflectors on seismic lines in eastern New Mexico, and (2) constraining the Mesoproterozoic history of eastern New Mexico.

PREVIOUS WORK

Flawn (1956), in examining well cuttings and core from Precambrian basement terranes in the subsurface of Texas and southeastern New Mexico, defined the Swisher Gabbroic Terrane in the Texas panhandle and eastern New Mexico. This terrane is composed by carbonates and arkosic siltstone interbedded with diabases and gabbroic intrusions. Although contact metamorphism adjacent to the mafic intrusions is locally important, these rocks do not appear to have experienced significant regional metamorphism. Flawn (1956) noted that the Swisher Terrane sits on the Panhandle Volcanic Terrane, a sequence of rhyolite tuffs and granite intrusions. Flawn (1956) also recognized that the Precambrian sedimentary rocks in the Franklin Mountains of west Texas share similarities with rocks encountered in the subsurface of southeastern New Mexico. He simply called this sequence of rocks in southeastern New Mexico the “Metasedimentary and Metavolcanic Terrane”. Subsequent work by Foster and Stipp (1961), Muehlberger et al., (1966; 1967), Denison and Hetherington, (1969), and Denison et al. (1984) have added lithologic and new geochronologic data to establish age relationships and further refine the identity of the subsurface terranes. Muehlberger et al. (1967) defined the Debaca Terrane based on well samples from De Baca County, New Mexico. This terrrane is composed of weakly metamorphosed quartzite, siltstone and sandy carbonates with diabase and gabbro intrusions. They note that the lithologies in the De Baca are quite similar to those in the Swisher Terrane and that the two units occupy the same stratigraphic position, although the amount of diabase is greater in the latter. Dennison et al. (1984) combined the two names into the Debaca-Swisher terrane and Barnes et al. (1999a) simply call the entire area the Debaca Terrane (Figure 1).

REGIONAL SETTING

Regional geologic and tectonic settings of the Proterozoic basement rocks of southeastern New Mexico and west Texas have been documented by several investigators, including Flawn (1956), Foster and Stipp (1961), Muehlberger et al., (1966; 1967), Denison and Hetherington, (1969), Denison et al. (1984), Mosher (1998), Barnes et al. (1999 and 1999a), and Bickford et al. (2000). This section gives a brief summary of the regional setting, and readers are referred to the above publications for additional background information. Figure 1 shows the location of the Mesoproterozoic Debaca Terrane with respect to other Proterozoic basement features including the

Crystalline Terrane, the Panhandle Terrane, the Pecos mafic intrusive complex, and the Llano Front. The oldest rocks (1.7-1.6 Ga) are represented by the Crystalline Terrane. The term Crystalline Terrane was designated by Barnes et al. (1999a) to include various Proterozoic terranes such as the Chaves granite terrane of Muehlberger et al. (1967), and the Red River mobile belt, Fisher metasedimentary terrane, Texas craton, and the Llano Province of Flawn (1956). The northern and southern Panhandle Terranes are underlain by 1.4 Ga A-type granite and rhyolite. The Debaca Terrane consists of metasedimentary and metavolcanic rock units deposited in a shallow basin on the Panhandle Terrane, and later intruded by gabbro. The Pecos mafic complex is a 1.1 Ga layered intrusion interpreted to be related to extension during the 1.1 Ga Grenville Orogeny (Barnes et al., 1999). The Llano front, which is defined by a gravity and magnetic anomaly (Mosher, 1998),separates basement affected by Grenville contractional deformation from undeformed basement.

METHODS

Binocular scope observation of cuttings

Drill cuttings were laid out on a table in petri dishes in sequential 100 ft intervals in order to identify major changes in color, texture, and luster. Then, drill cuttings were examined under a SM-80 SWIFT binocular microscope using 10X magnification. Emphasis was put on determining the hardness, shape of the chips (blocky, rounded or flat), color, luster, matrix, grain size, texture (clastic, crystalline etc.), structure (foliation, bedding etc.) and composition. Great care was used in identifying and removing cuttings that had caved from uphole.

Optical-mineral petrography

Twenty-two representative samples were collected from different rock types for preparation of polished thin sections. Drill cuttings were picked using a SM-80 SWIFT binocular scope, and tweezers, bent-tip picks, and spoons. Thin sections were prepared by Caprock Laboratories Inc., located in Midland, Texas. Six additional polished thin sections from the NMBMMR were also examined.

Geochronologic analysis

In an attempt to determine the age of emplacement of some of the basement rocks penetrated by the Mescalero 1 well, age determinations using $^{40}Ar/^{39}Ar$ and SHRIMP U-Pb zircon age methods were made on samples of biotite from gabbro, and of zircon from meta-arkose and syenite. Granite and metarhyolite were evaluated as potential geochronology candidates, but insufficient datable material was recovered from these rocks. Samples for U-Pb geochronology were milled and a heavy mineral concentrate was obtained using a Wilfley table, a Frantz magnetic separator, and heavy liquids. The $^{40}Ar/^{39}Ar$ age was determined in the geochronology laboratory of the New Mexico Tech by Matthew Heizler. SHRIMP U-Pb zircon analyses were performed in the geochronology laboratory of Australia National University by Melanie Barnes.

Electron microprobe

Electron microprobe analyses were performed to identify a suite of minerals from the quartz syenite and dolomitic quartzite. All electron microprobe studies were performed at the New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico, using a Cameca SX-681 Electron microprobe.

Geochemistry

Seven representative samples from selected rock units were identified for major and trace-element chemical analyses. Approximately 25 grams of chips were collected for each sample. Each sample represents a composite of approximately 100 feet. Samples for both thin sections and chemical analysis were collected picking up representative chips one by one using tweezers, bent-tip picks, and spoons. Care was taken to avoid exotic material (contamination) in these samples. Samples were analyzed for 10 major element oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. Samples were also analyzed for 11 trace elements: Sr, Ba, Zr, Y, Sc, V, Cr, Cu, Zn, Nb, and Be. Major element suites were determined through X-ray fluorescence (XRF) using a fused disk. Trace element suites were determined through X-ray fluorescence (XRF) using pressed powder pellets.

Analyses were conducted in the XRF laboratory of the Texas Tech University, Texas.

Well log analysis

In addition to the well preserved set of cutting samples from Mescalero 1, an excellent suite of modern geophysical logs was run in the well, including gamma ray, neutron porosity, density porosity, resistivity, and sonic velocity logs. This suit of logs provides a rare opportunity for detailed characterization of the rocks. The observations made for this well can be applied to similar rocks/well log signatures/seismic reflections elsewhere in the region.

The complete suite of logs was examined and the sonic, density, and gamma logs were digitized. Kate Miller at UTEP used the digitized sonic log to produce a synthetic seismogram. The digitized logs were correlated with the petrographic analyses and average values of sonic velocity, density, and gamma response were determined for each rock type. The average values were plotted on cross-plots to determine which physical properties were most diagnostic for determining lithology.

RESULTS

This section shows the results of petrography, geochemistry, geochronology, well log analysis, and seismic analysis for the basement rocks in Mescalero 1.

Petrography

Petrographic study made on a suite of 22 thin sections led to identification of` three major intrusive rock types (gabbro, quartz syenite, and granite), and a metasedimentary-metavolcanic sequence, with localized contact metamorphism (hornfels and marble) adjacent to the intrusive bodies (Figure 3). A detailed microscopic description for each rock type is presented in Tables 1 and 2.

The metasedimentary-metavolcanic sequence is composed of tuffaceous metasediment, metarhyolite, volcaniclastic metasediment, dolomitic quartzite, quartzose dolomite, arkosic metasediment, and meta-arkose (Figure 4) This metasedimentary-metavolcanic sequence matches the description of the Debaca Terrane that exists primarily in the subsurface of the west Texas Panhandle and southeastern New Mexico (Denison and Hetherington, 1969).

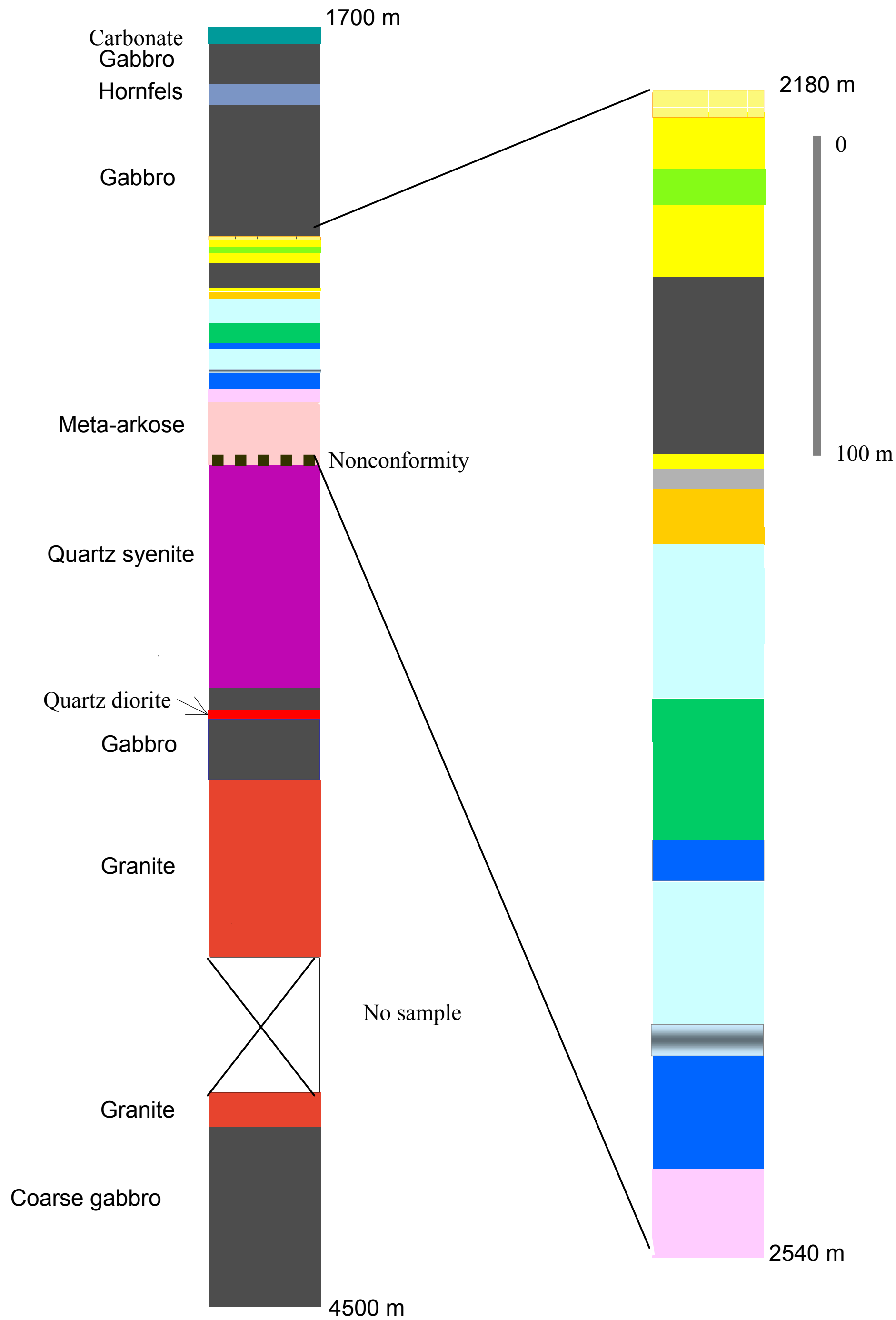


Figure 3. Stratigraphic column of the basement rocks in Mescalero No. 1.

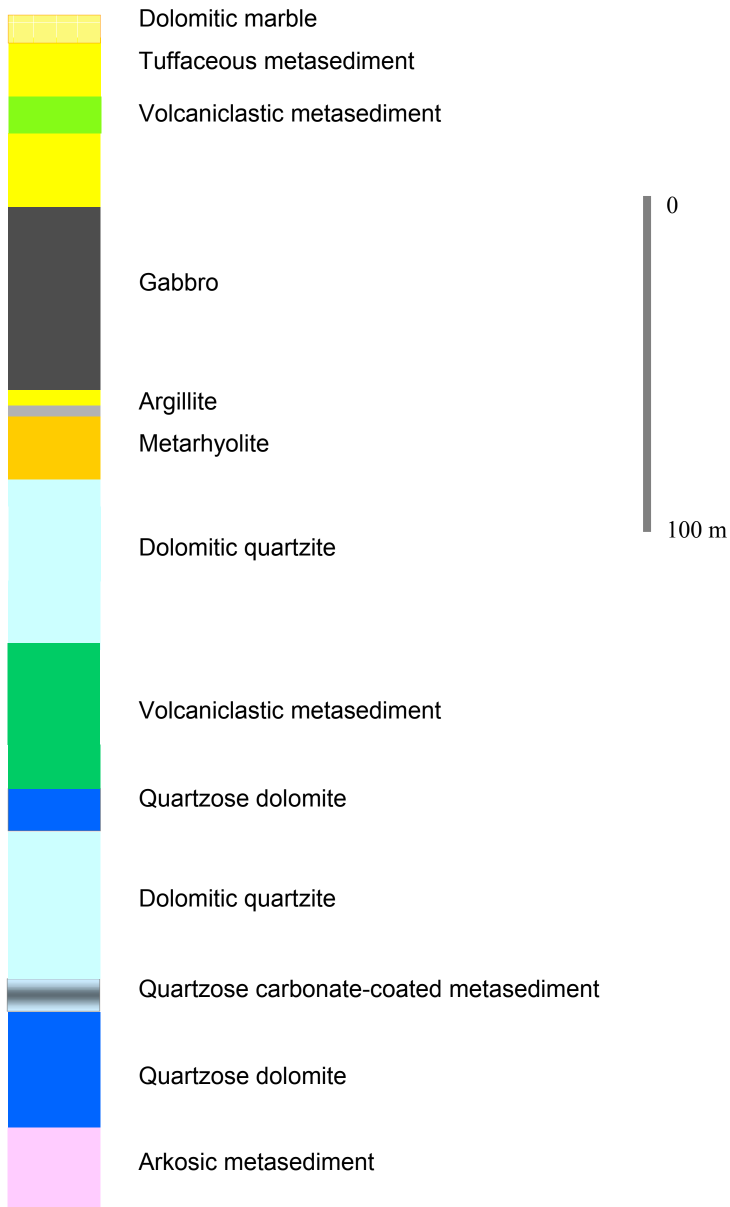


Figure 4. Expansion of the metasedimentary-metavolcanic stratigraphic column.

The following is a description of the major rock units encountered downhole in the well, keyed to Figure 3.

1) Gabbro is a medium to coarse crystalline rock, with a cumulate to sub-ophitic texture (Figure 5). Subhedral crystals of olivine are embedded within large crystals of pyroxene and interlocked between plagioclase crystals. Plagioclase feldspar is the dominant mineral species, followed by pyroxene, olivine and lesser amounts of amphibole. In general, plagioclase feldspars are tabular and may display a sub-parallel orientation suggesting flow structure. Biotite and magnetite are very important accessory minerals in this rock. Books of biotite showing cores of magnetite are commonly observed. Other accessory minerals present are apatite, rutile and titanite. Chlorite, hematite, epidote and carbonate (calcite) may be present as product of alteration of former minerals. Chlorite, the most abundant alteration mineral, occurs as a result of alteration of mafic minerals (hornblende and biotite). Hematite of supergene origin is a result of oxidation of magnetite. Epidote and carbonate locally replace plagioclase.

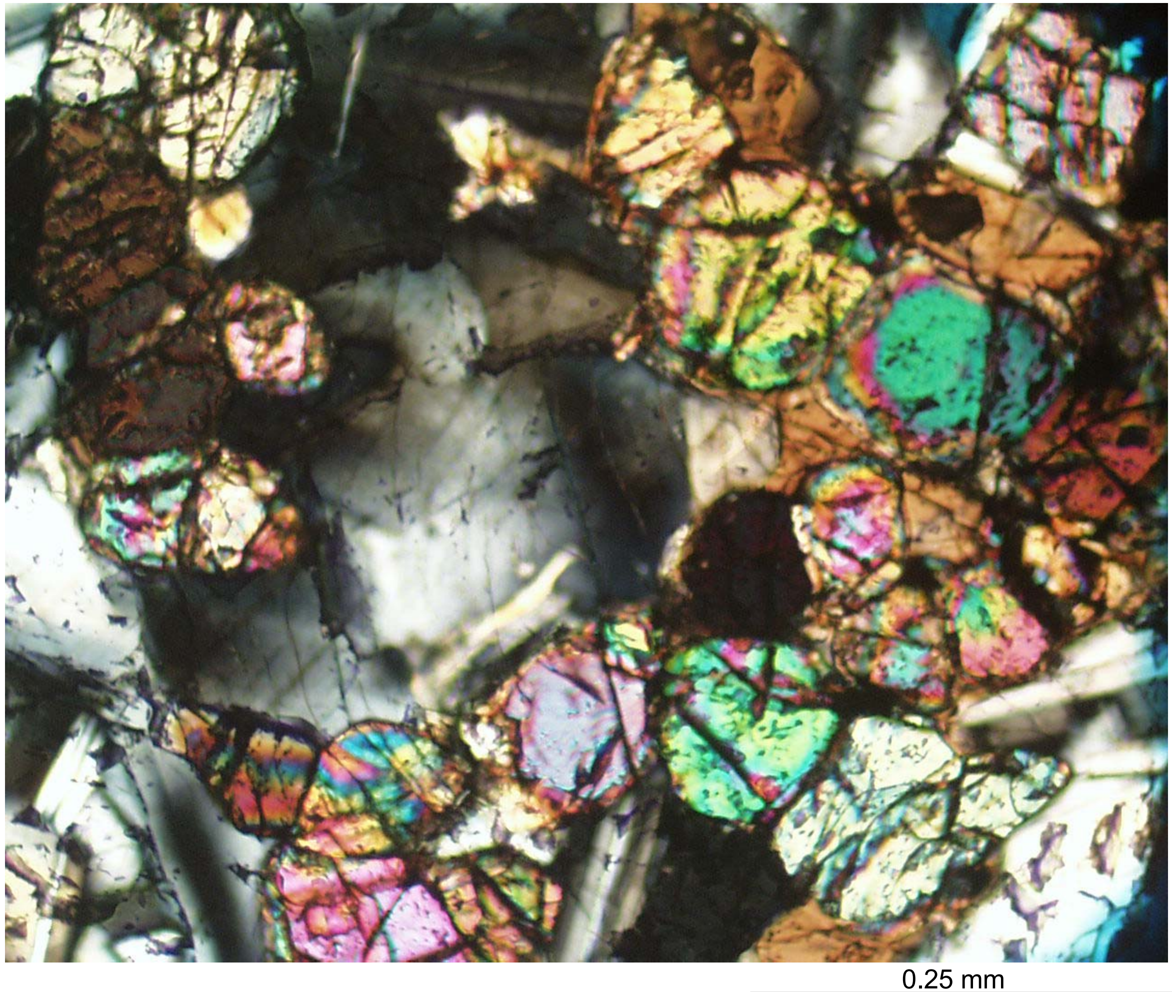
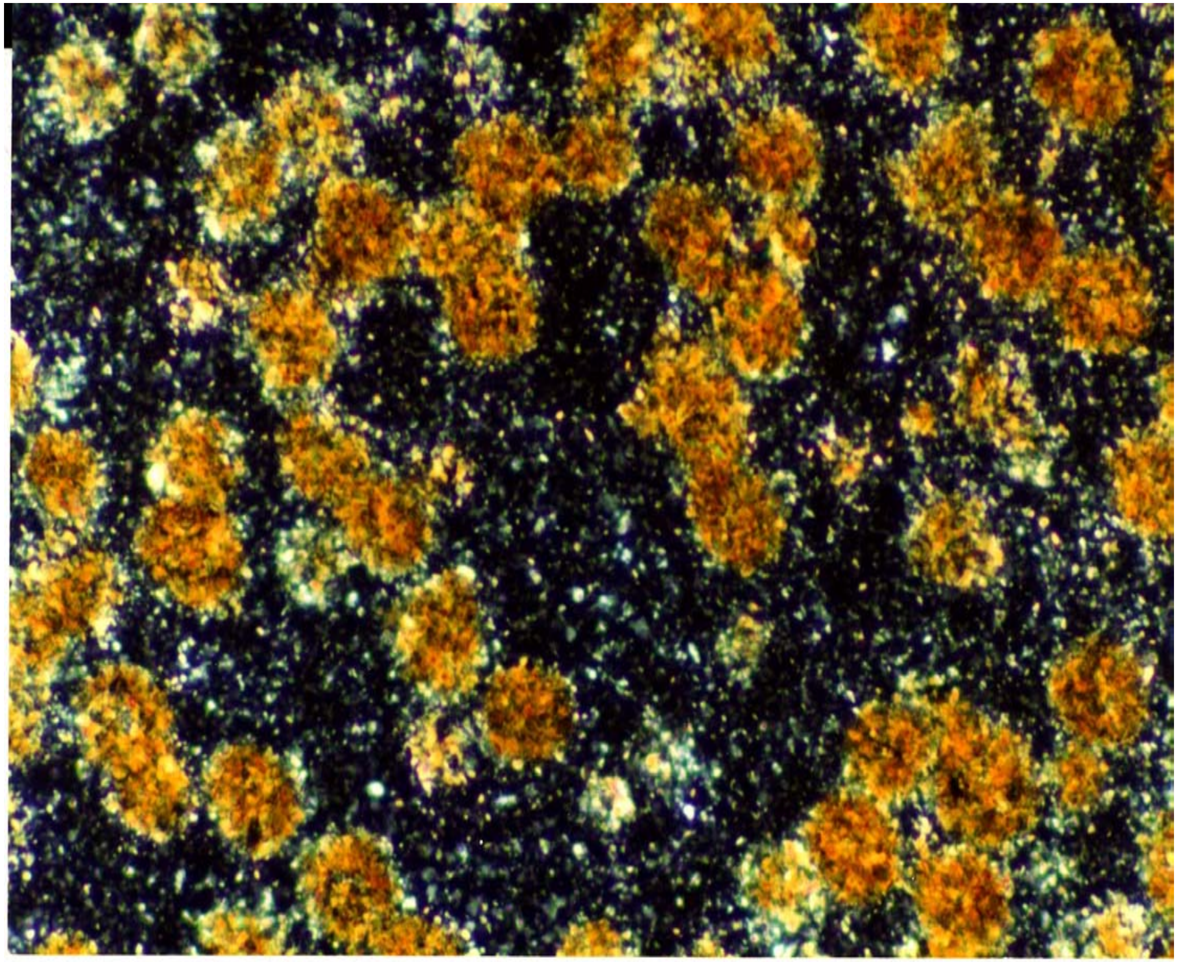


Figure 5. Photomicrograph of gabbro exhibiting a cumulate to subophitic intergrowth texture in which anhedral pyroxene crystals (brown) occupy the spaces between crystals of feldspar, and olivine crystals (greenish, bluish to reddish) of fairly uniform size are developed within the largest crystals of pyroxene.

The two largest bodies are at depths of 1759-1859 m and 1905-2155 m. A number of small dikes are inferred in the lower part of the well. The gabbro appears to be the youngest rock unit within the basement, since it causes metamorphism in other Proterozoic rock units.

2) Hornfels is fine-grained, with a spotted texture developed by very fine-grained and reddish-brown biotite suggesting contact metamorphism (Figure 6). The groundmass is cryptocrystalline and dominated almost entirely by very fine-grained microlites of quartz. Accessory minerals are pyrite and rutile. Pyrite is disseminated as small cubic crystals throughout the groundmass. Rutile, which is dark brown under cross-nicols, commonly occurs as aggregates of small and rounded grains. Ghosts of quartz and feldspar phenocrysts are present locally. The rock has been strongly altered and the dominant alteration minerals include muscovite, sericite, carbonate, and lesser amounts of chlorite. Laths of randomly-oriented muscovite and sericite occur in feldspar sites. Late micro-veinlets of micro-crystalline quartz are observed. The occurrence of this unit is very limited in the Proterozoic section. The hornfels is approximately 46 m thick and is located between two bodies of gabbro close to the top of the Proterozoic section (Figure 3).



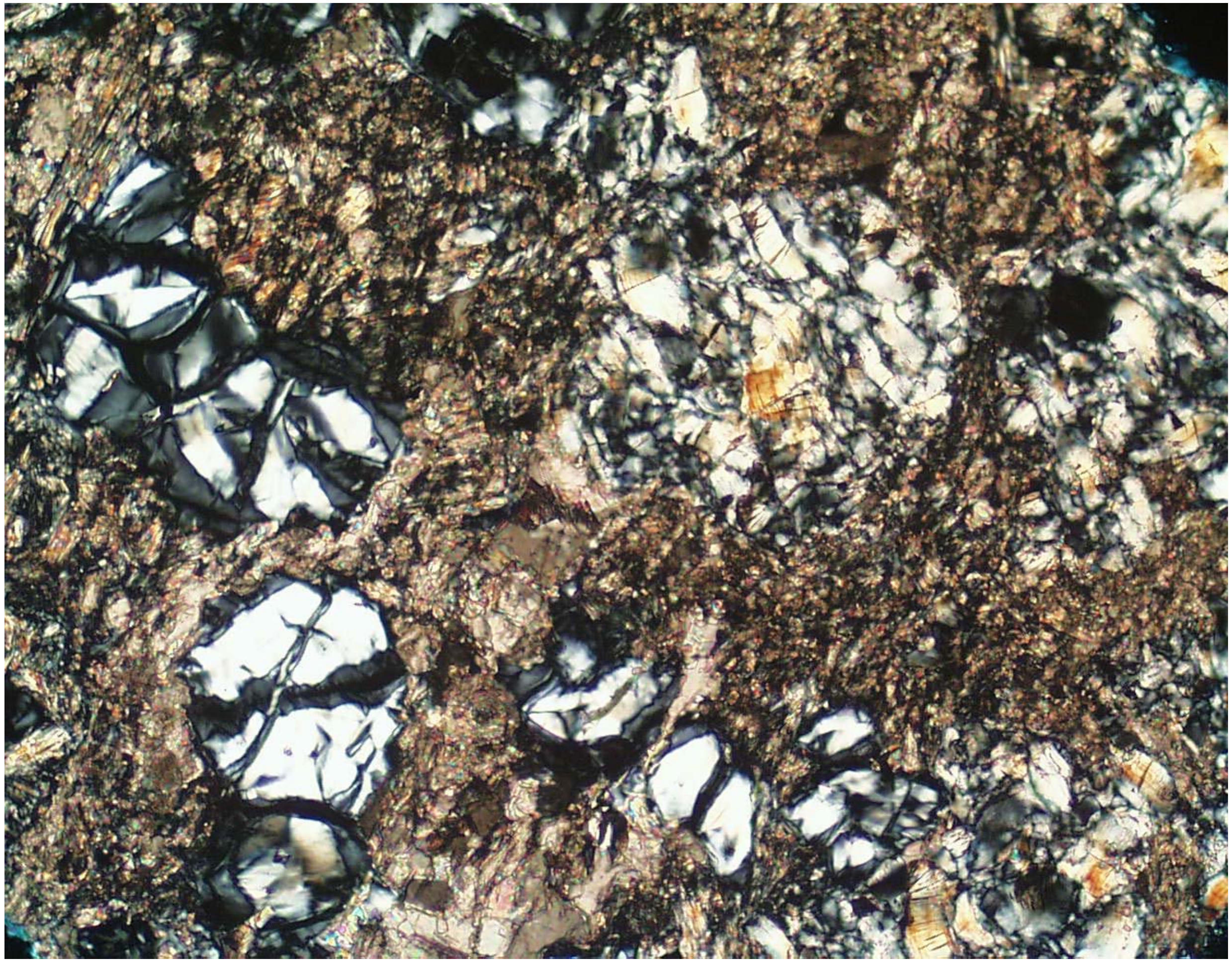
0.2 mm

Figure 6- Photomicrograph showing well-developed spotted texture on hornfels suggesting contact metamorphism. Locally, this rock may show relics of plagioclase and re-crystallized quartz crystals. This unit occurs as a thin horizon truncated by two bodies of gabbro at the upper portion of the basement.

3) Metasedimentary-metavolcanic sequence (2155-2664 m):

A) The volcaniclastic metasediment consists of angular to sub-angular fragments of quartz, feldspar, and lithic fragments . The lithic fragments are from at least three different sources, plutonic, sedimentary and volcanic rocks, and are within a fine- to medium-grained groundmass. Potassium feldspar, commonly exhibiting a well-developed “tartan” twinning, indicates the immature character of this lithology. The presence of K-feldspar may indicate that the sediment was relatively proximal to its igneous source, and that little chemical weathering occurred. Fragments of volcanic rocks are generally strongly altered to white phyllosilicates, kaolinite, and carbonate. Fragments of quartz containing abundant fluid inclusions are common. The matrix is dominated by microlites of feldspar, quartz, mafic minerals, clay and carbonates, which occur as irregular patches. Fragments of igneous intrusive rocks are composed mostly of potassium feldspar, plagioclase and quartz. Accessory minerals include apatite (15-30 microns), zircon (10-20 microns), pyrite, and dark brown rutile.

B) The tuffaceous metasediment is fine-grained, light green to milky white, is soft, and is poorly reactive with cold dilute hydrochloric acid. Quartz, feldspar, and fragments of devitrified glass-shards dominate the rock. Carbonate, zeolite and randomly oriented muscovite are also observed (Figure 7).



0.3 mm

Figure 7- Photomicrograph of tuffaceous metasediment showing zeolitic spherulites (left hand side of the field of view) within a fine-grained groundmass composed mostly by calcite, white phyllosilicate, silica, and clay.

C) The metarhyolite is commonly aphanitic. Portions of the unit are porphyritic with light green, dark green, to brown color. The rock exhibits an incipient spotted texture that is only observed at high magnification. It locally shows flow structure and contains remnants of phenocrysts such as biotite, hornblende, titanite, and feldspar, which are totally replaced by one or more of the following minerals: chlorite, carbonate, and white phyllosilicates (Figure 8). Ghosts of biotite (up to 300 microns) show cores of pyrite and an alteration halo of chlorite. Relicts of tabular-shaped amphibole are completely replaced by chlorite and carbonate (calcite). Feldspar relicts are commonly superimposed by aggregates of randomly oriented grains of muscovite. Skeletons of titanite, preserving distinctive twinning, are pseudomorphed by carbonate. Pyrite and magnetite are common in this rock. Pyrite is euhedral and may occur disseminated in the groundmass and filling microfractures. Hematite, after pyrite, is observed in microfractures. Magnetite occurs as sporadic small crystals also disseminated in the groundmass. Rutile occurs as small, rounded, reddish to light brown grains, which are disseminated in the groundmass. Late veinlets of plagioclase and quartz cross-cut the rhyolite.

D) The quartzose dolomite is fine-to coarse grained, white to light gray or dark gray in color and has a clastic texture. Quartz, dolomite and calcite dominate this rock type. Quartz represents about 50 percent by volume of the rock, whereas dolomite and calcite make up the remaining 50 percent.

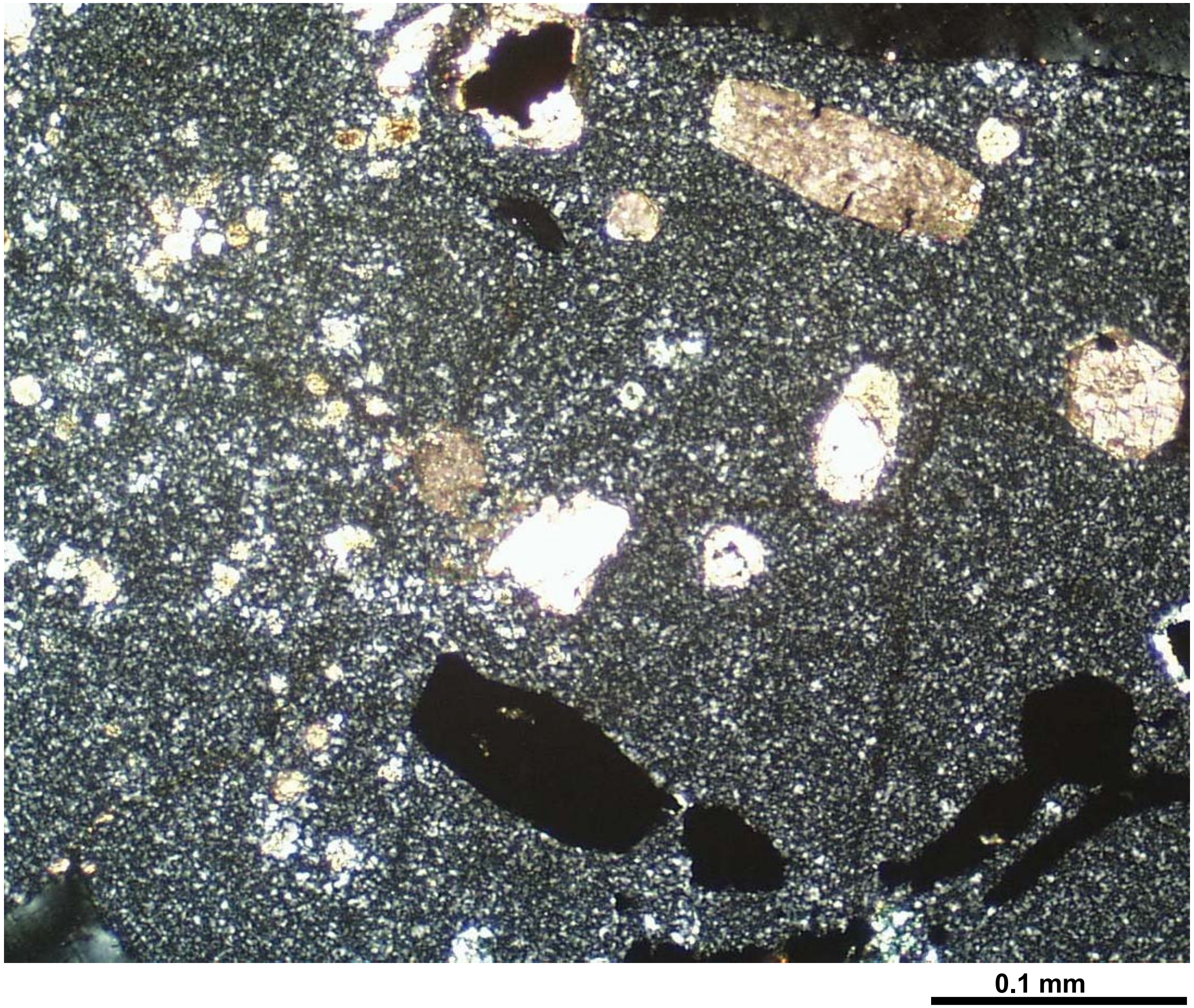


Figure 8- Photomicrograph of meta-rhyolite exhibiting a porphyritic texture in which euhedral hornblende phenocrysts are embedded within a aphanitic groundmass. Note amphibole (upper right) partially replaced by calcite.

This rock is very friable and effervesces selectively with cold dilute hydrochloric acid.

E) The dolomitic quartzite is fine-to coarse grained, light gray, white, or black in color. It has a sugary texture, dominated by quartz, dolomite, and calcite. Quartz grains commonly are smoky and occur in incipient dark-colored bands intercalated with light colored bands, which include dolomite and calcite. Smoky quartz grains impart a dark color to this rock. Dolomite crystals are well developed and generally fill pore spaces between quartz grains suggesting that dolomite is paragenetically later than quartz. Calcite commonly is fine crystalline and also exists coating quartz grains.

F) The meta-arkose is fine to medium-grained and pink to orange in color. The rock is made up quartz, potassium feldspar, plagioclase, and lithic fragments of igneous rock (syenite), and chert (Figure 9). The matrix is predominantely composed of smaller grains of quartz and feldspar cemented by calcite and iron oxide. Quartz fragments rich in fluid inclusions are abundant in this rock; however, fragments of clean quartz are also present, suggesting at least two sources for quartz fragments. Potassium-feldspar grains are partially replaced by undifferentiated clay-size minerals, and plagioclase may be replaced by carbonate and white phyllosilicate. In its lower portion, the meta-arkose contains abundant fragments of the underlying quartz syenite (Figure 10).

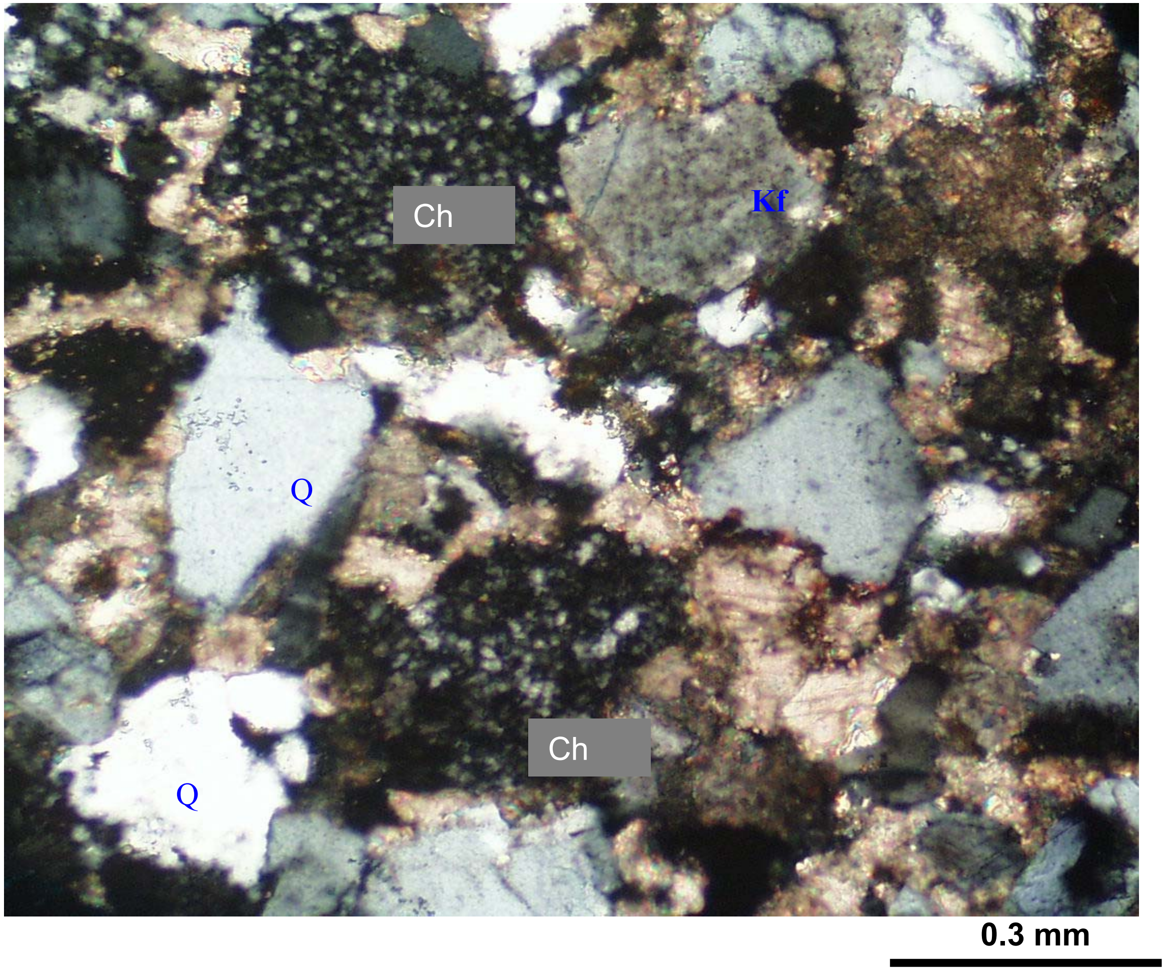


Figure 9. Photomicrograph of meta-arkose. Framework grains consist of quartz (Q), potassium feldspar (Kf) and fragments of chert (Ch). Matrix is composed of mixed carbonate (calcite) and clay. Locally, this unit is rich in fragments of syenite.

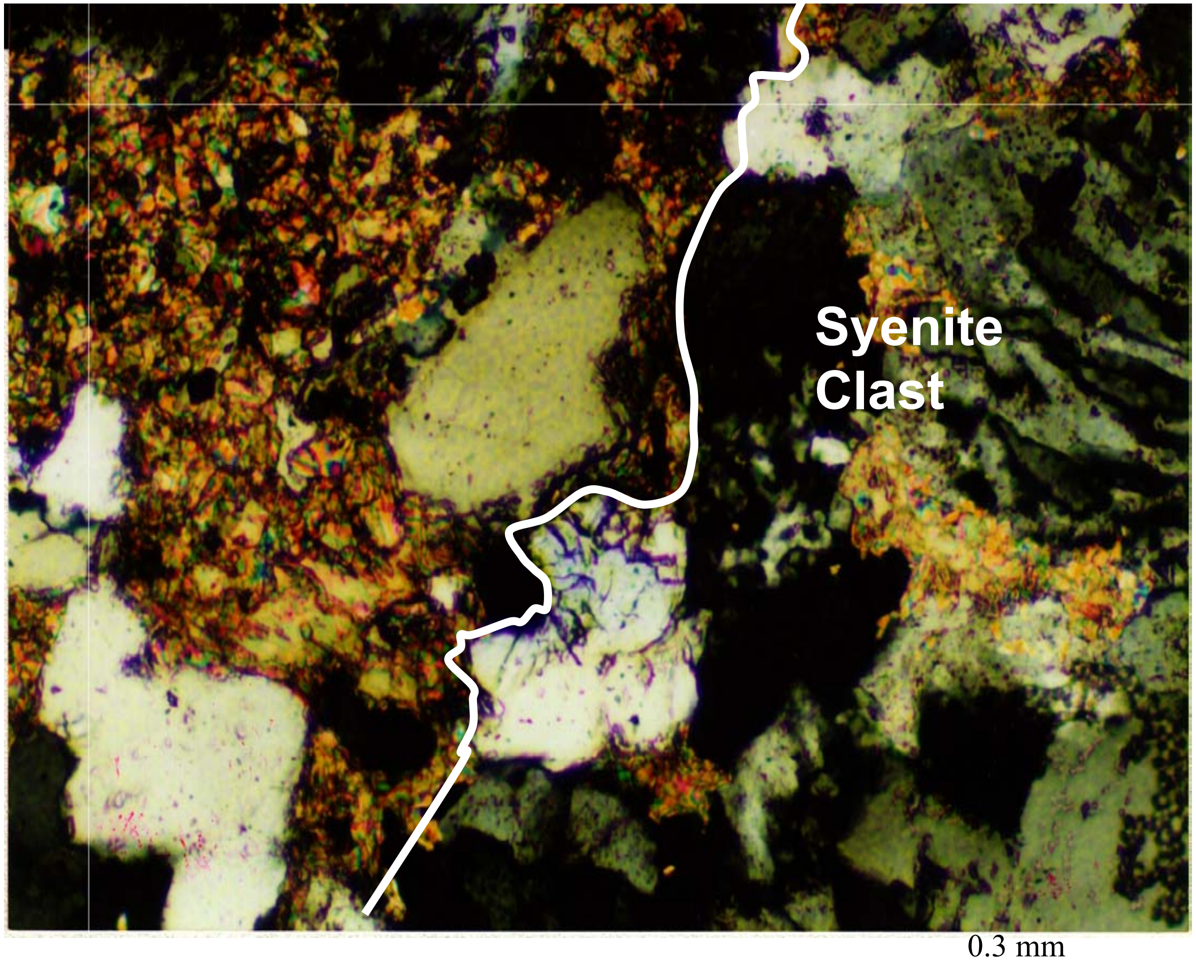
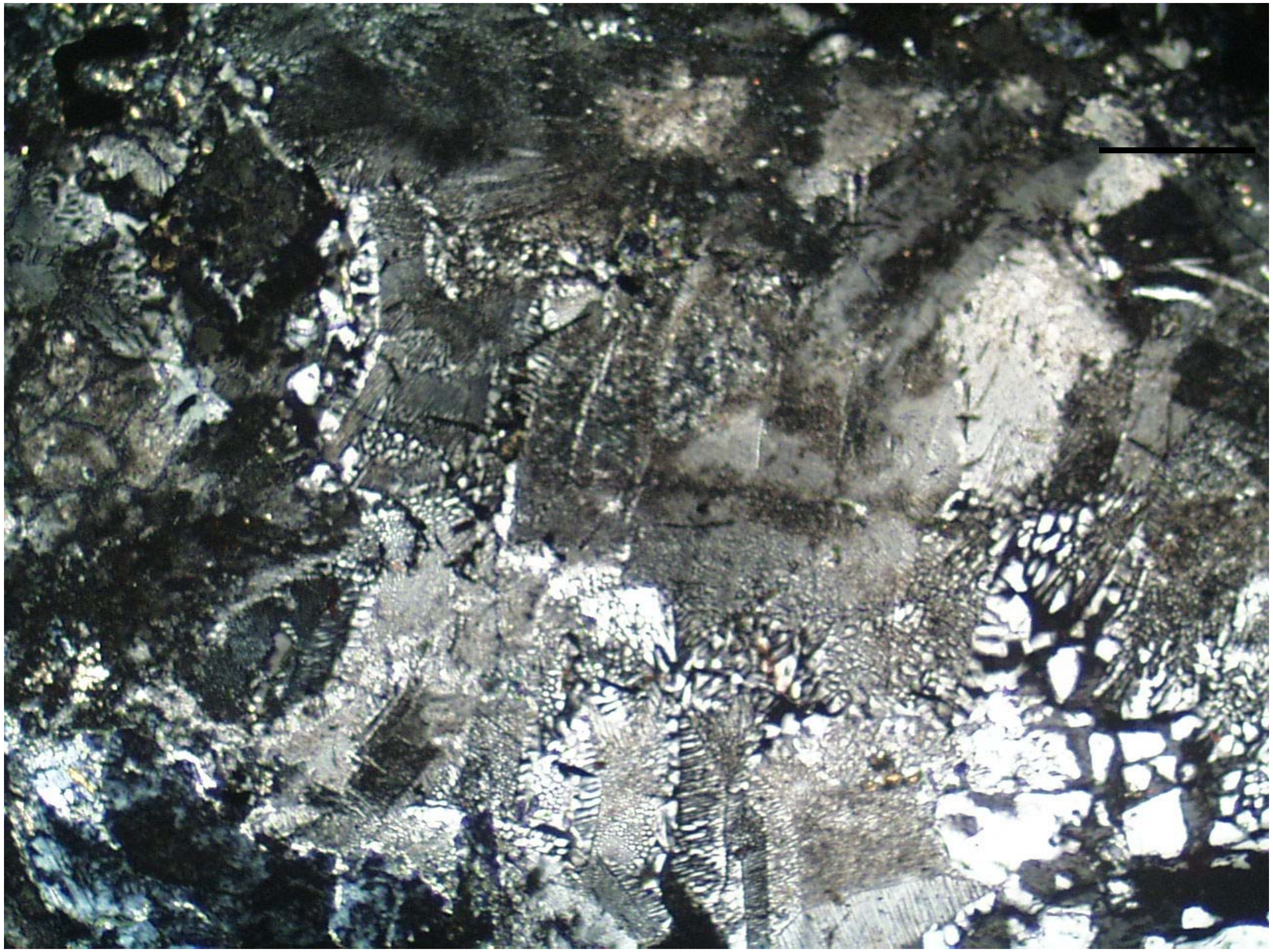


Figure 10. Photomicrograph of meta-arkose showing a clast of quartz syenite (right hand side of the photograph).

4) Quartz syenite is medium to coarse-crystalline, is pink, light orange to light gray, and is dominated by potassium feldspar. This rock exhibits some variation in composition, passing from syenite to quartz syenite downhole. Near its top, the syenite is strongly altered and exhibits a well-developed weathering profile (red due to oxidation of iron-bearing minerals), indicating an disconformable contact between the quartz syenite and overlying meta-arkose. This zone shows up as a strong reflector on a seismic line in the Tucumcari basin. Microscopically, the rock shows a hypidiomorphic granular texture that is locally granophyric or myrmekitic, with intergrowths of potassium feldspar and quartz (Figure 11). The rock is made up of K-feldspar, plagioclase and lesser amounts of biotite, hornblende and quartz. Magnetite is an important accessory mineral in this rock. Potassium feldspar is euhedral to sub-hedral, equant, with size ranging between 1 and 2 mm. Quartz commonly forms wormy or cuneiform blebs within potassium feldspar. In addition, it commonly exists as large crystals showing sinuous contacts at the boundaries with K-feldspar. This sinuous contact may be developed under low-grade metamorphism where minerals grow in rocks that are already solid and compete for space with other minerals. Plagioclase, when not altered, occurs as laths with size varying between 0.5 to 1.5 mm. Accessory minerals are magnetite, amphibole, biotite, ilmenite, apatite, zircon and rutile. Alteration minerals are sericite, muscovite, and chlorite. Sericite and muscovite replace feldspar, and chlorite commonly replaces amphibole and biotite.



0.1 mm

Figure 11. Photomicrograph of quartz syenite showing a granular to granophyric texture with myrmekitic intergrowths of potassium feldspar (gray) and quartz (light-colored) in which quartz forms a wormy texture within the potassium feldspar.

This rock shows a remarkable increase in quartz content with depth passing transitionally from syenite to quartz syenite. Near its basal contact, quartz syenite grades to quartz diorite.

5) Granite (3740 to 4100 m) has a porphyritic texture comprising large phenocrysts of plagioclase (1.2-2.0 mm), potassium feldspar and quartz, in a matrix composed mostly by quartz, feldspar and mafic minerals (hornblende and biotite), in decreasing order. Accessory minerals are magnetite, apatite, and ilmenite. White phyllosilicates may occur as replacement of feldspar. The age relationship between the granite and the other basement units is unknown.

Well log analysis

The total gamma activity and bulk density for each rock type in the well are shown in Figures 12 and 13. Figure 12 shows the detailed variation of gamma ray activity and density with respect to rock type. This diagram shows a strong correlation between lithology and gamma ray activity. For example, gabbro in the upper portion of the diagram, shows very consistent and low gamma ray values (~20 GAPI), and very high values of density (~3.0 gm/cc). The volcaniclastic metasediment, in the middle of the diagram, shows very variable values of gamma ray activity and density. This variability is attributed to wash out (excessive borehole diameter) during drilling, which is discernible on the caliper log; therefore, these parameters

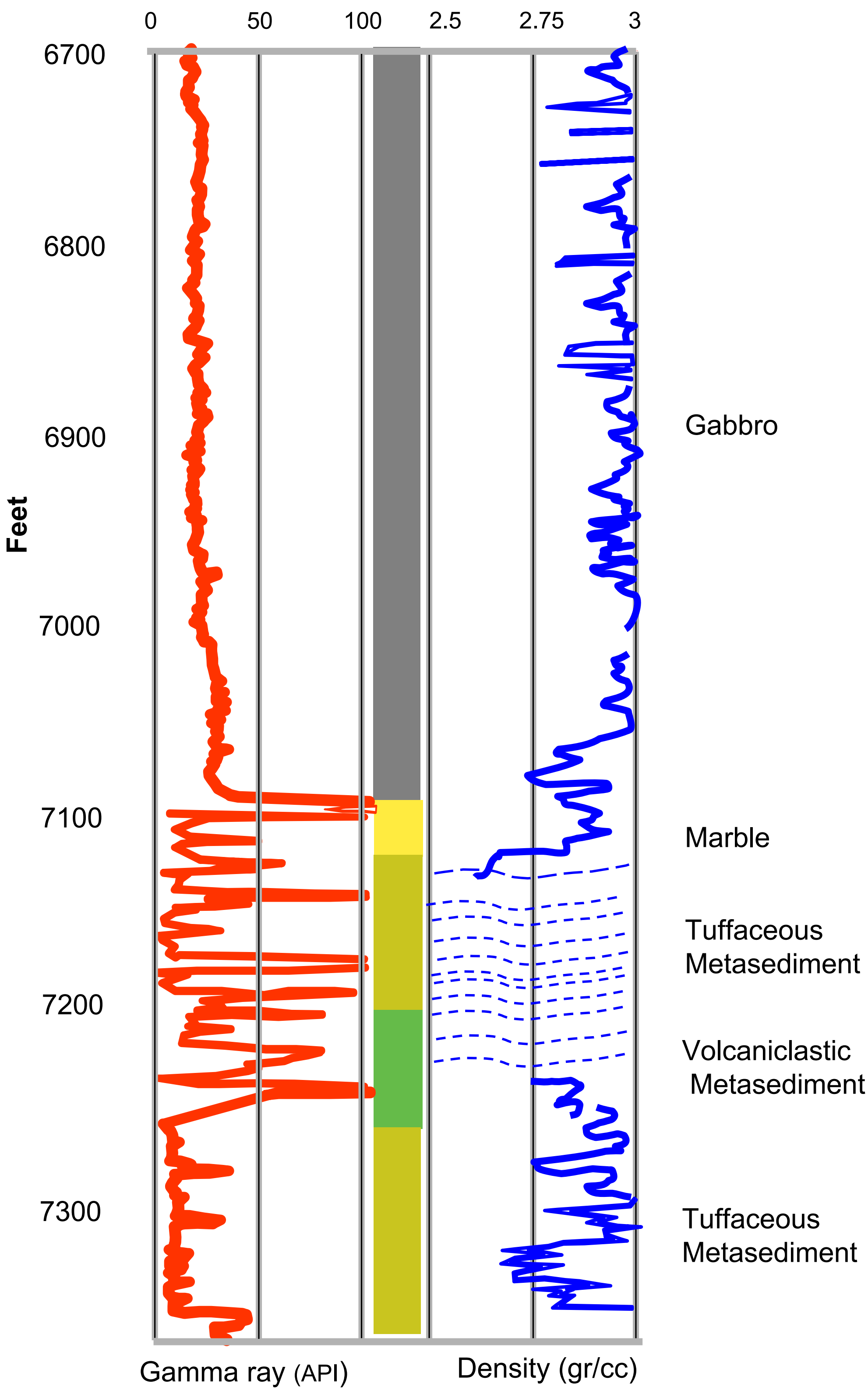


Figure 12. Relationship between lithology, gamma ray activity and density. Keys: The red line represents total gamma ray activity. The blue line on the right side of the diagram represents density. The variability of the density line (wavy shape near the bottom of the diagram) may be an indication of wash out (excessive borehole diameter during drilling) in this interval.

are not reliable. The lower portion of the diagram shows tuffaceous metasediment exhibiting very consistent and low values of gamma ray activity (~10 GAPI), and relatively high values of density (> 2.75 gm/cc).

Geophysical signatures for dolomitic quartzite, volcaniclastic metasediment, quartzose dolomite, arkosic metasediment and meta-arkose are presented in Figure 13. This diagram indicates identical geophysical features for dolomitic quartzite, quartzose dolomite, and the volcaniclastic metasediment. The average values of total gamma ray and density for these units are approximately 40 GAPI and the values of densities varying from 2.75 to 2.8 gm/cc. The arkosic metasediment and meta-arkose, at the bottom of the diagram, show different geophysical signatures. The meta-arkose shows high gamma ray activity (~100 GAPI), and values of delta gamma ray are almost zero. On the other hand, the arkosic metasediment, overlying the meta-arkose, is characterized by moderate values of gamma ray activity (between 75 and 100 GAPI), and high values of delta gamma ray (see arkosic metasediment by the bottom of Figure 13), suggesting relatively high amounts of uranium.

The average density and total gamma ray values for almost the entire suite of rocks characterized in this study were plotted in a cross-plot diagram (Figure 14). The diagram shows two clearly identifiable populations. The upper clusters of points have been designated population one and the lower cluster population two.

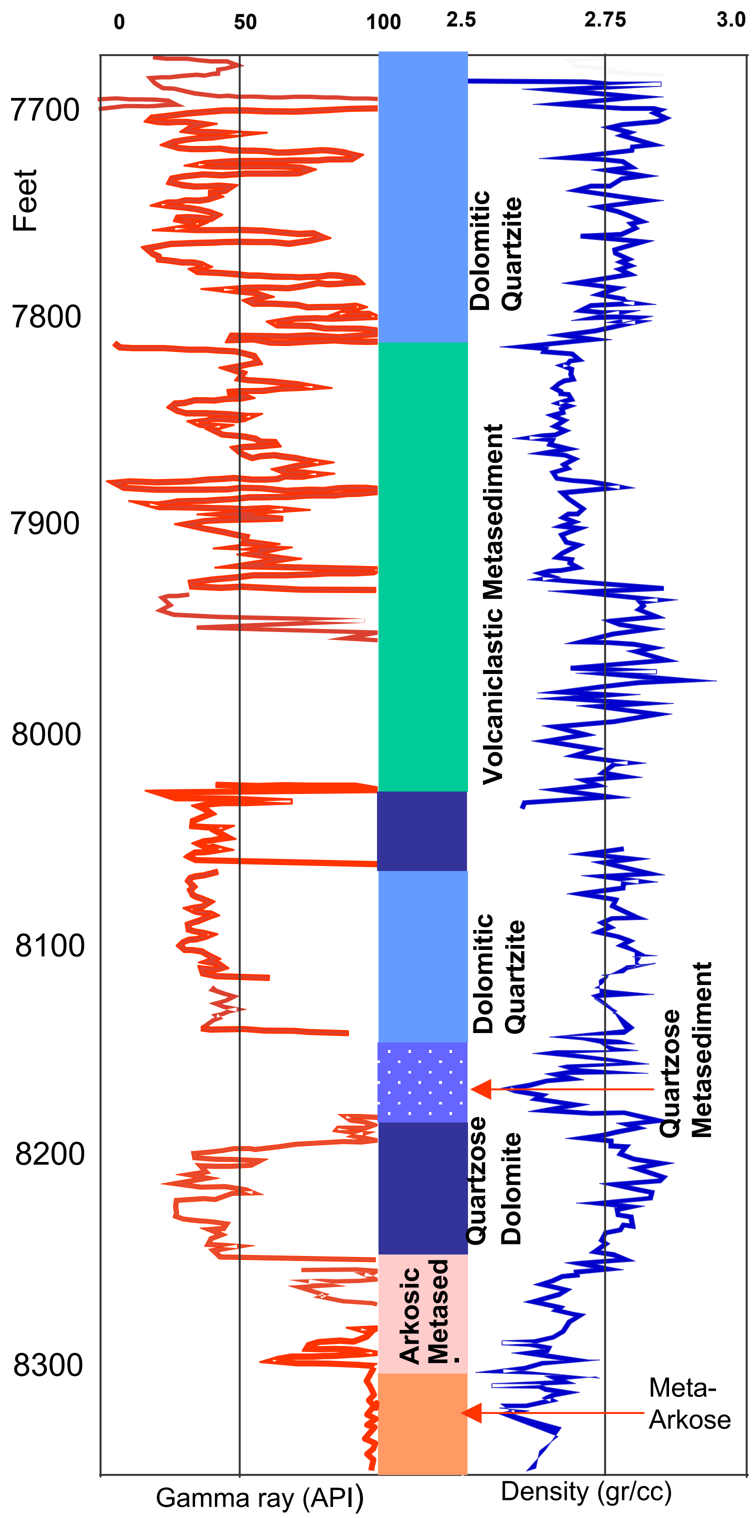


Figure 13. Correlation between lithology, gamma ray activity and density. Keys: The red line represents total gamma ray activity. The blue line on the right side of the diagram represents density. The orange arrows point out two rock types: quartzose metasediment and meta-arkose.

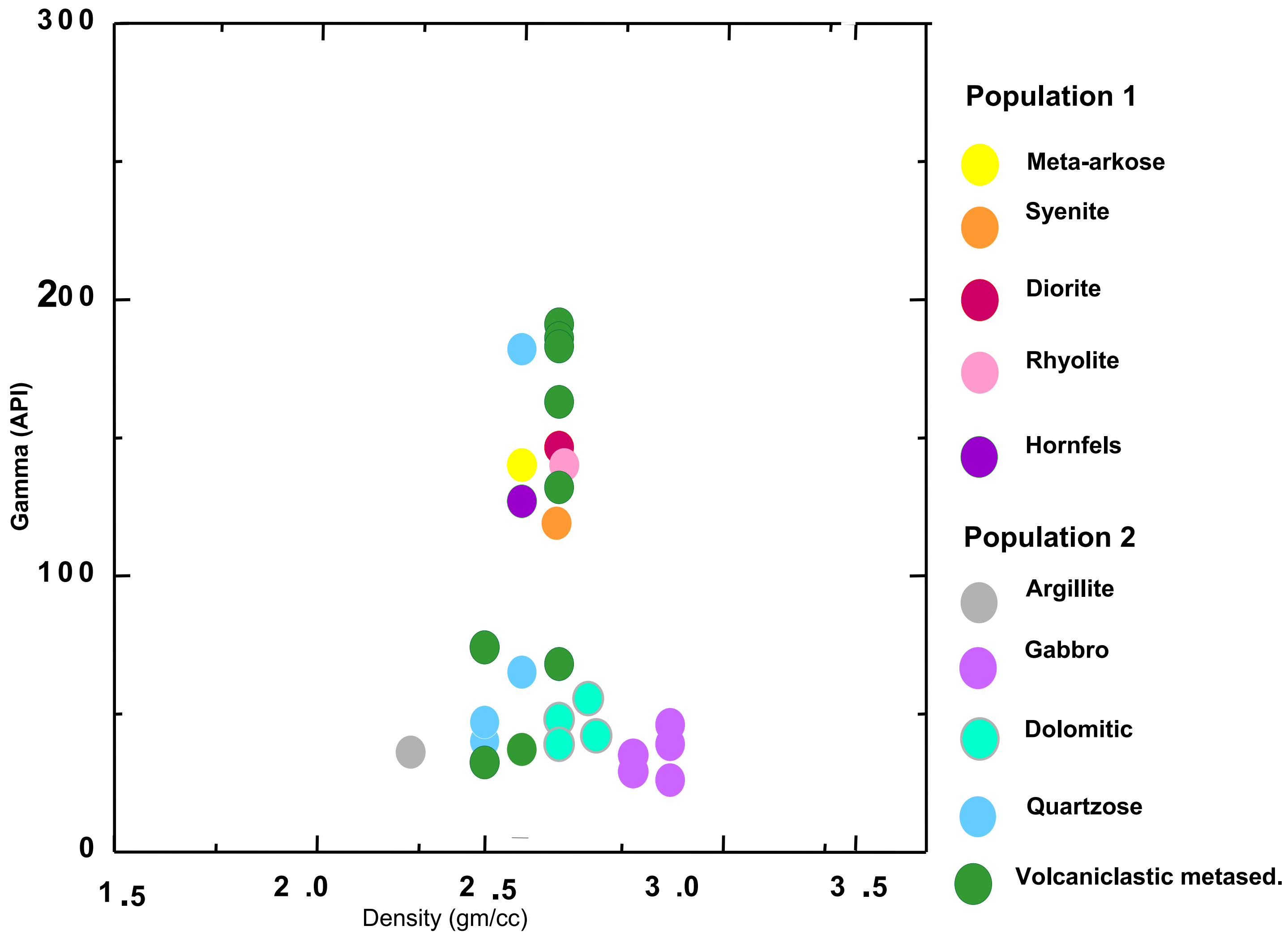


Figure 14. Cross-plot diagram showing the relationship between gamma ray activity and density for different rock types. Values on the Y-axis represent total gamma ray (GAPI) and the values on the X-axis represent density (gm/cc)

The population one, which is composed of meta-arkose, quartz syenite, diorite, rhyolite, and hornfels, is characterized by high total gamma activity (between 125 and 200 GAPI) and constant values of density averaging 2.6 gm/cc. In contrast, population two shows lower values of gamma activity (~50 GAPI). The values of density for this population are very variable, ranging from 2.3 to 3.0 gm/cc. The lowest values of density correspond to argillite, and the highest values correspond to gabbro.

The above paragraphs indicate that each rock type penetrated by the well Mescalero 1 exhibits a characteristic geophysical signature. In general, the felsic units exhibit high values of gamma ray activity, suggesting that the gamma ray activity are related to potassium feldspar. On the other hand, the more mafic units are characterized by low gamma ray values. These results indicate that cross-plot diagrams are useful in characterizing the basement rocks penetrated by the well Mescalero 1 on the basis of their gamma ray activity and density. Indeed, these results should be helpful in interpreting the geophysical logs from the nearby State Jones 1, another deep well drilled by Labrador Oil for which there are no cuttings. Sonic log data was not as diagnostic as the gamma ray and density data, but the sonic log was used to create a synthetic seismogram for comparison to the seismic line available for this area (see Figure 20).

Geochemistry

The igneous rocks penetrated by the well Mescalero 1 vary from gabbro, quartz diorite, and quartz syenite to granite. The samples fall into three compositional groups: 1) mafic samples (43.27 to 49.35 wt. SiO_2); 2) intermediate samples (52.28 to 65.15 wt. SiO_2); and 3) one felsic sample (71.64 wt. SiO_2); (Table 3 and Table 3A). Figure 15 is a plot of FeO_T / (FeO_T + MgO) versus SiO_2 weight percent for mafic rocks from Mescalero 1 compared to mafic rocks from the E-W arm of Debaca Terrane (see Figure 1 for location), and mafic rocks from the Nellie intrusion (the Pecos Mafic Intrusive Complex), west Texas (Barnes et al. 1999a). The entire suite of rocks plots in the diagram exhibit FeO_T / (FeO_T +MgO) ratios < 0.8, suggesting I-type magma signatures (Anderson, 1983). The diagram clearly indicates that the mafic rocks of Debaca Terrane in Mescalero 1 and the mafic rocks in the E-W arm of the Debaca Terrane have similar FeO_T / (FeO_T +MgO) ratios, ranging from 0.66 to 0.73. Similarly, the diagram indicate that one sample of gabbro from the Northern Panhandle Terrane has FeO_T / (FeO_T +MgO ratio = 0.63. In contrast, the mafic rocks of the Nellie intrusion have very low FeO_T / (FeO_T +MgO) ratio (ranging from 0.41 to 0.43). Based on the FeO_T / (FeO_T +MgO) ratio, the volumetrically larger, layered Pecos Mafic Intrusive Complex (PMIC) follows a tholeiitic trend, while the volumetric smaller intrusions in the Debaca Terrane are transitional mafic rocks.

Table 3. Major and Trace Element Geochemistry. Key: Total Iron Oxide (FeO_T) represents Fe_2O_3 and FeO.

SAMPLE	6100-6230	6770-80	7000-80	7870-80	7880-7950
	Hornfels	Gabbro	Gabbro	Rhyolite	Metasediment
SiO[2]	53.65	45.67	43.27	71.64	52.63
TiO[2]	0.78	1.95	2.48	0.34	0.61
Al[2]O[3]	18.40	18.35	16.90	12.22	9.31
Fe[2]O[3]	6.78	12.32	13.44	2.01	3.14
MnO	0.09	0.17	0.19	0.05	0.05
MgO	2.51	4.75	5.23	0.73	6.63
CaO	2.14	7.83	7.75	2.14	5.94
Na[2]O	0.45	3.54	3.57	3.16	1.17
K[2]O	10.79	0.89	1.27	3.23	7.05
P[2]O[5]	0.08	0.27	0.59	0.04	0.04
Total	**95.67**	**95.74**	**94.69**	**95.56**	**86.57**
Sr	247	459	472	121	340
Ba	644	325	421	683	263
Zr	174	175	233	328	289
Y	35.2	19.1	34.1	81.4	18.8
Sc	20.0	15.7	19.2	10.5	8.9
V	103	187	185	13	60
Cr	68	128	42	2	39
Cu	49	78	35	1	27
Zn	58	152	151	28	21
Nb	12	15	18	16	14
Be	1.5	0.6	0.8	1.5	1.0

SAMPLE	10300-400	10400-1050	10530-70	6310	7820
	Quartz Diorite	Diorite	Diorite	Gabbro	Metasediment
SiO[2]	52.28	47.89	49.35	47.03	53.39
TiO[2]	1.90	2.21	2.15	2.41	0.61
Al[2]O[3]	16.02	14.93	14.51	17.06	9.84
Fe[2]O[3]	11.06	10.95	10.43	14.21	3.39
MnO	0.16	0.17	0.16	0.22	0.06
MgO	4.30	4.29	3.62	5.67	7.04
CaO	6.76	6.66	5.56	7.59	6.65
Na[2]O	3.56	3.47	3.81	3.82	1.17
K[2]O	2.15	2.15	2.50	1.29	7.51
P[2]O[5]	0.62	0.72	0.71	0.47	0.04
Total	**98.83**	**93.43**	**92.80**	**101.04**	**100.39**
Sr	305	273	236	400	429
Ba	815	732	720	139	496
Zr	285	284	324	183	202
Y	47.7	54.2	58.6	24.6	26.6
Sc	23.2	23.8	22.9	31.9	19.6
V	153	165	172	322	181
Cr	24	25	26	292	57
Cu	32	30	29	137	36
Zn	106	112	134	112	236
Nb	19	19	20	24	15
Be	1.2	1.4	1.3	1.1	1.4

Table 3- Cont'n.

SAMPLE	8240 Arkose	8320 Arkose	8740 Quartz Syenite	8800 Quartz Syenite	9800 Quartz Syenite
SiO_2	55.18	56.90	64.52	64.96	65.15
TiO_2	0.55	0.28	0.81	0.89	0.84
Al_2O_3	9.15	8.68	14.17	14.32	14.40
Fe_2O_3	3.15	1.91	4.83	5.43	5.17
MnO	0.08	0.09	0.07	0.10	0.10
MgO	4.78	3.85	1.55	1.41	1.41
CaO	7.32	8.58	2.32	2.13	3.18
Na_2O	1.15	1.15	3.78	3.78	3.63
K_2O	7.73	6.74	5.07	4.71	4.08
P_2O_5	0.09	0.13	0.28	0.31	0.31
Total	**100.10**	**99.31**	**99.62**	**99.59**	**100.29**
Sr	736	417	118	270	572
Ba	888	286	850	244	302
Zr	170	203	222	204	160
Y	18.6	19.9	22.1	29.8	15.5
Sc	19.0	9.1	4.7	7.6	13.2
V	126	56	12	49	93
Cr	132	38	2	27	30
Cu	52	27	7	33	20
Zn	79	24	30	69	68
Nb	25	13	7	13	12
Be	1.5	1.6	2.3	1.7	1.3

Table 3A. Comparison of selected major element analyses of mafic rocks in Mescalero with mafic rocks from the Nellie Intrusion, Northern Penhandle Terrane (NPT) and Debaca Terrane (DT).

Sample	Rock Type	MgO	FeOT	FeOT +MgO	FeOT/FeOT +MgO
6770-81	Gabbro	4.75	12.32	17.07	0.72
7000-80	Gabbro	5.23	13.44	18.67	0.72
6310-20	Gabbro	5.67	14.21	19.88	0.71
10300-400	Quartz Diorite	4.30	11.06	15.37	0.72
10400-1050	Diorite	4.29	10.95	15.24	0.72
10530-70	Diorite	3.62	10.43	14.05	0.74
DT-473*	Gabbro	8.42	16.14	24.56	0.66
DT-474*	Gabbro	6.45	14.6	21.05	0.69
DT-477*	Gabbro	6.66	17.66	24.32	0.73
Nellie 1**	Norite	8.49	6.45	14.94	0.43
Nellie 2**	Norite	9.77	7.12	16.89	0.42
Nellie 3**	Norite	9.52	7.34	16.86	0.44
NPT***	Gabbro	6.18	11.85	18.03	0.657

Keys: (*) represents samples of gabbro from the Debaca Terrane (from Barnes at el. 1999a); (**) is samples of Norite from the Nellie Intrusion in west Texas (Barnes at el. 1999); and (***) is sample of gabbro from Northern Panhandle Terrane. FeOT represents total iron oxides (Fe_2O_3 and FeO)

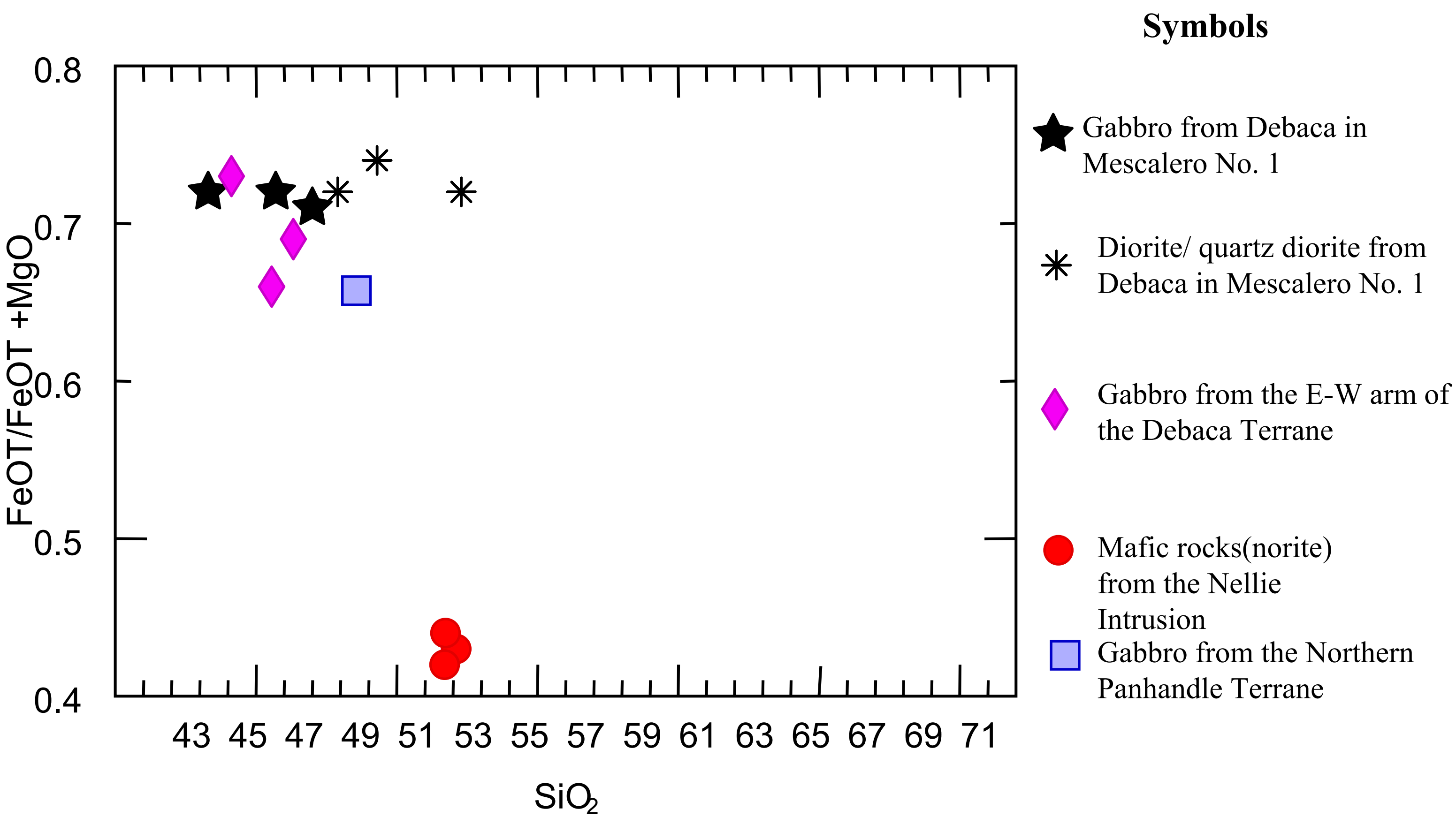


Figure 15. FeO_T / FeO_T + MgO versus SiO_2 plot for samples of mafic rocks from the E- W arm of the Debaca Terrane in Mescalero 1, Nellie Intrusion, and Northern Panhandle Terrane.

The K_2O/ Na_2O ratio for discriminating intermediate to felsic rocks, including quartz syenite and rhyolite in Mescalero 1, is shown in Table 3B. The quartz syenite and rhyolite samples have K_2O/ Na_2O ratios greater than 1 (ranging between 1.02 and 1.34), suggesting A-type felsic rocks (Barnes at el., 1999a). Therefore, the igneous rocks in Mescalero 1 can be subdivided on the basis of their geochemistry into two groups: 1) rocks with K_2O/ Na_2O ratios > 1, designated as A-type felsic rocks; and 2) rocks with FeO_T / (FeO_T +MgO) ratios < than 0.8, which have been designated as I-type mafic rocks.

The tectonic setting of intermediate and felsic igneous rocks can be determined by using Nb versus Y discrimination diagrams (Pearce et al.,1984) as presented in Figure 15A. The quartz syenite lies within the syn-collisional granite field; the rhyolite lies within the ocean-ridge granite field, and the quartz diorite plot within plate granite field. The tectonic setting of these felsic rocks is not clear, based on our limited data set.

Microprobe analysis

Microprobe analysis was performed to two samples: one from quartz syenite and the other from dolomitic quartzite. Figures 16 is a microprobe image of a grain titanite from quartz syenite. A close up of Figure 16 is presented in Figure 17.

Table 3B. Whole-rock major and trace element analyses of quartz syenite in the well Mescalero 1.

SAMPLE	8740	8800	9800
	Quartz Syenite	Quartz Syenite	Quartz Syenite
SiO_2	64.52	64.96	65.15
TiO_2	0.81	0.89	0.84
Al_2O_3	14.17	14.32	14.40
FeOT	4.83	5.43	5.17
MnO	0.07	0.10	0.10
MgO	1.55	1.41	1.41
CaO	2.32	2.13	3.18
Na_2O	3.78	3.78	3.63
K_2O	5.07	4.71	4.08
P_2O_5	0.28	0.31	0.31
Total	**99.62**	**99.59**	**100.29**
K_2O/Na_2O	1.34	1.25	1.12
Sr	118.28	270.11	572.15
Ba	849.84	244.04	301.97
Zr	222.07	204.34	160.22
Y	22.14	29.81	15.53
Sc	4.74	7.59	13.16
V	11.68	49.08	92.82
Cr	2.12	26.76	30.40
Cu	6.79	33.11	20.00
Zn	29.99	69.01	67.77
Nb	6.65	12.66	11.52
Be	2.29	1.72	1.27

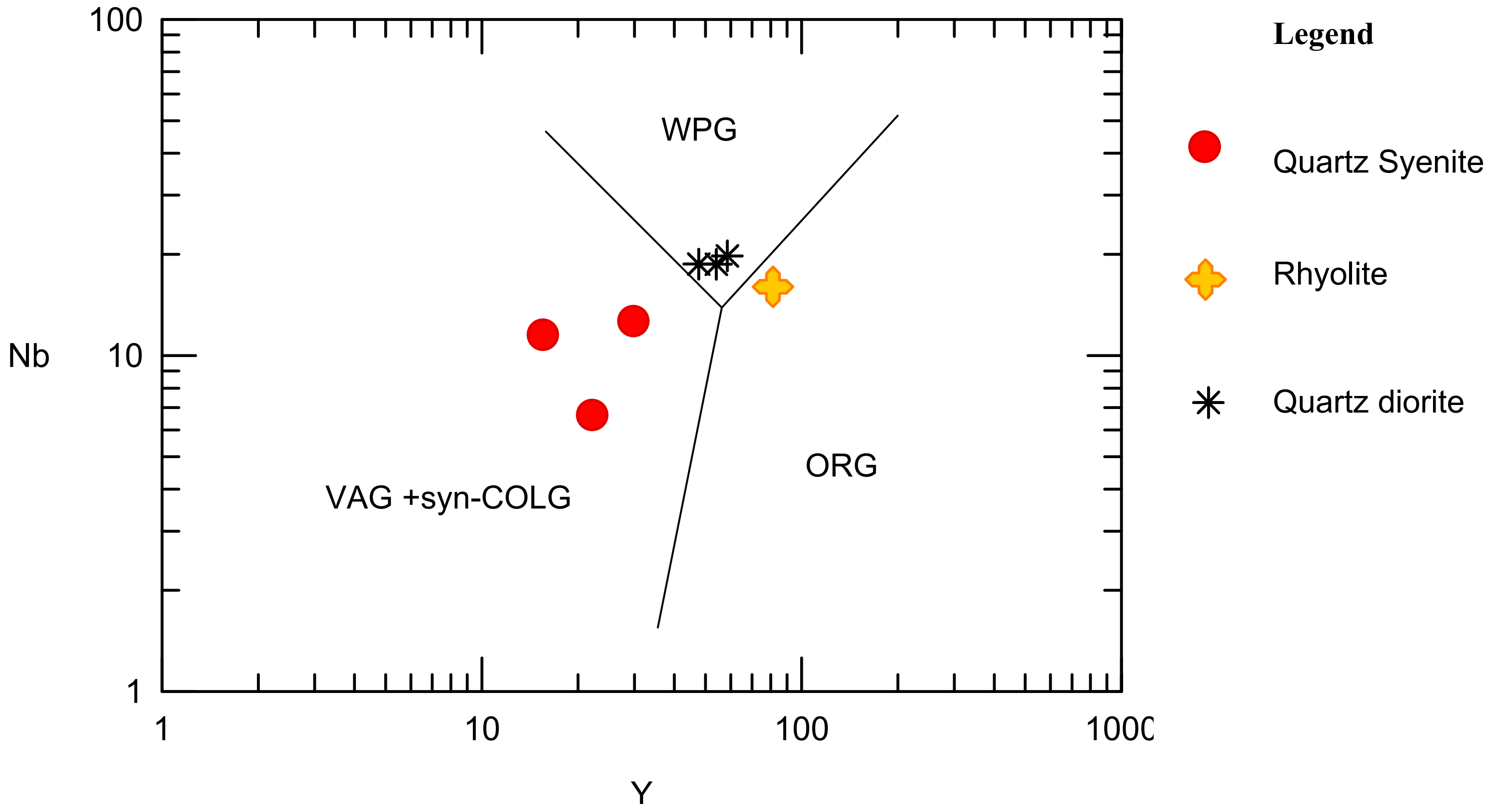


Figure 15A. Nb versus Y discrimination diagram for intermediate and felsic rocks in Mescalero 1. Keys: Syn-COLG is syn-collisional granite; VAG is volcanic-arc granite; WPG represents within plate granite; and, ORG indicates ocean-ridge granite (after Pearce et al., 1984). Values in X and Y axes are expressed in part per million (ppm).

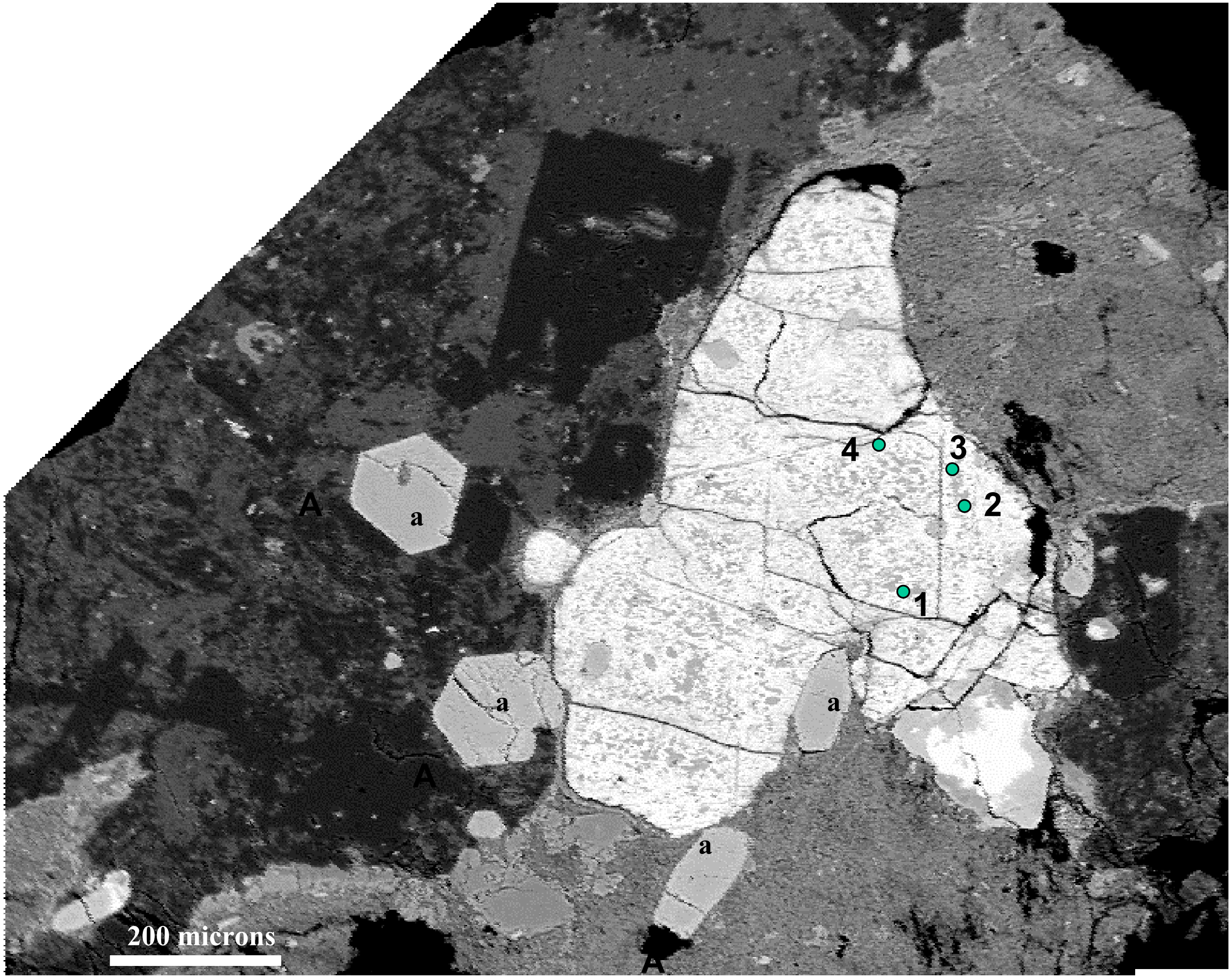


Figure 16. Microprobe image of the quartz zyenite. The grain at center is titanite intergrowths with ilmenite. The euhedral crystals surrounding the titanite are apatite (a).

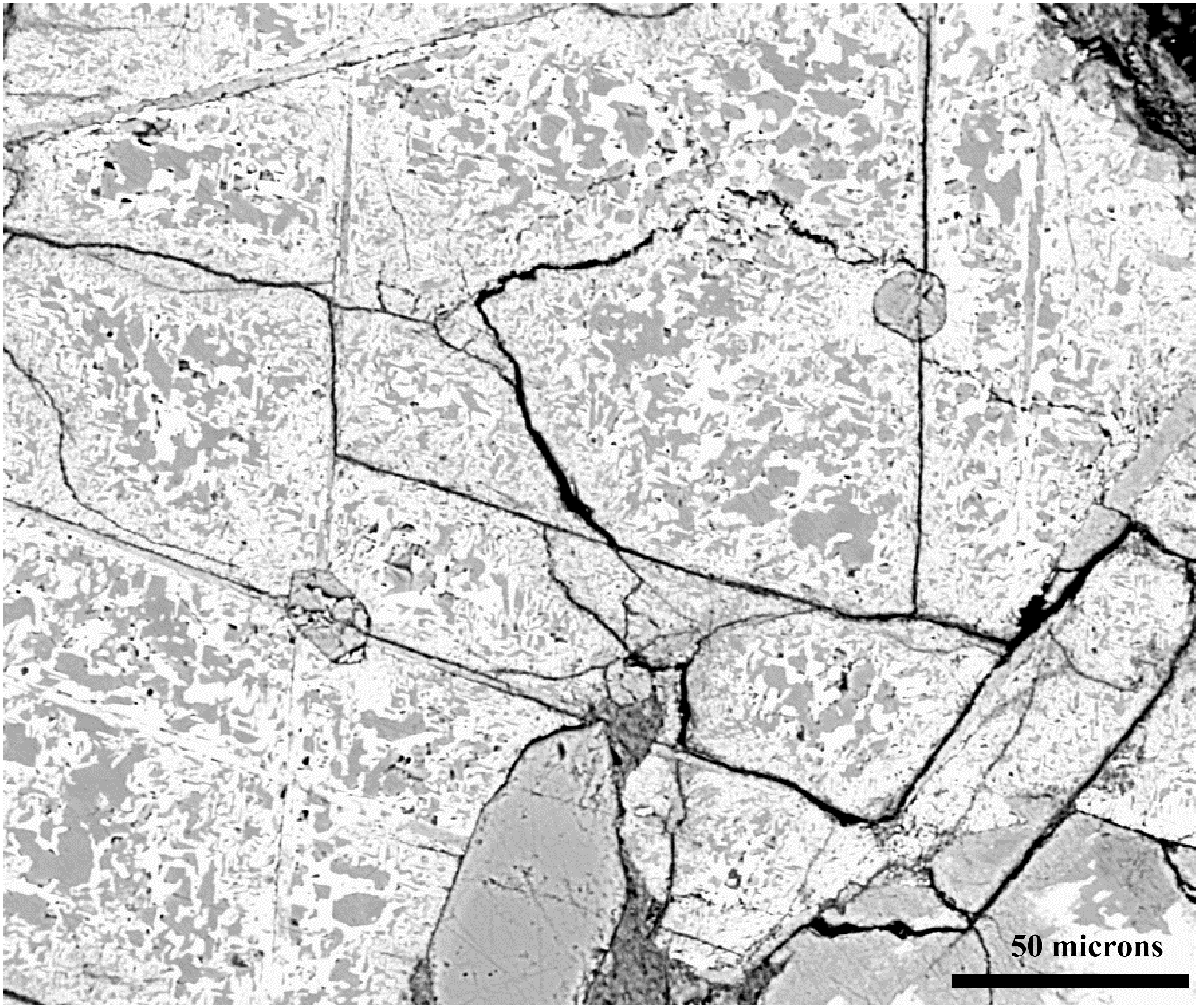


Figure 17. Close up of Figure 16 showing an expanded view of the titanite

Four points were analyzed on this grain, and results indicate two minerals phases: titanite (light gray) and ilmenite (white). The intergrowth between titanite and ilmenite is surrounded by a halo of apatite, suggesting that a possible deuteric alteration has occurred, in which calcium has been leached from titanite-ilmenite resulting in the developing of apatite. This is in agreement with petrographic observations that indicate that apatite is spatially and geochemically associated to titanite in the quartz syenite.

Figure 18 shows a distinctive graphic texture developed by potassium feldspar(gray) and quartz (dark to black). This texture is a characteristic feature of the quartz syenite. It is clearly identifiable under standard microscopic examination.

Geochronologic analysis

Results of geochronologic analyses are presented in Figure 19. Gabbro that intrudes the Debaca sequence yields a biotite $^{40}Ar/^{39}Ar$ age of 1090 ± 4 Ma. Because gabbro intrudes the other Proterozoic rock units it appears to be the youngest unit within the basement. The quartz syenite, which underlies the Debaca sequence, yields SHRIMP U-Pb zircon age of 1334 ±52 Ma. On the basis of the ages of the gabbro and the quartz syenite, the age of the Debaca Terrane can be reasonably constrained to be between 1090 and 1334 Ma. This range of ages is in coincidence with the period during

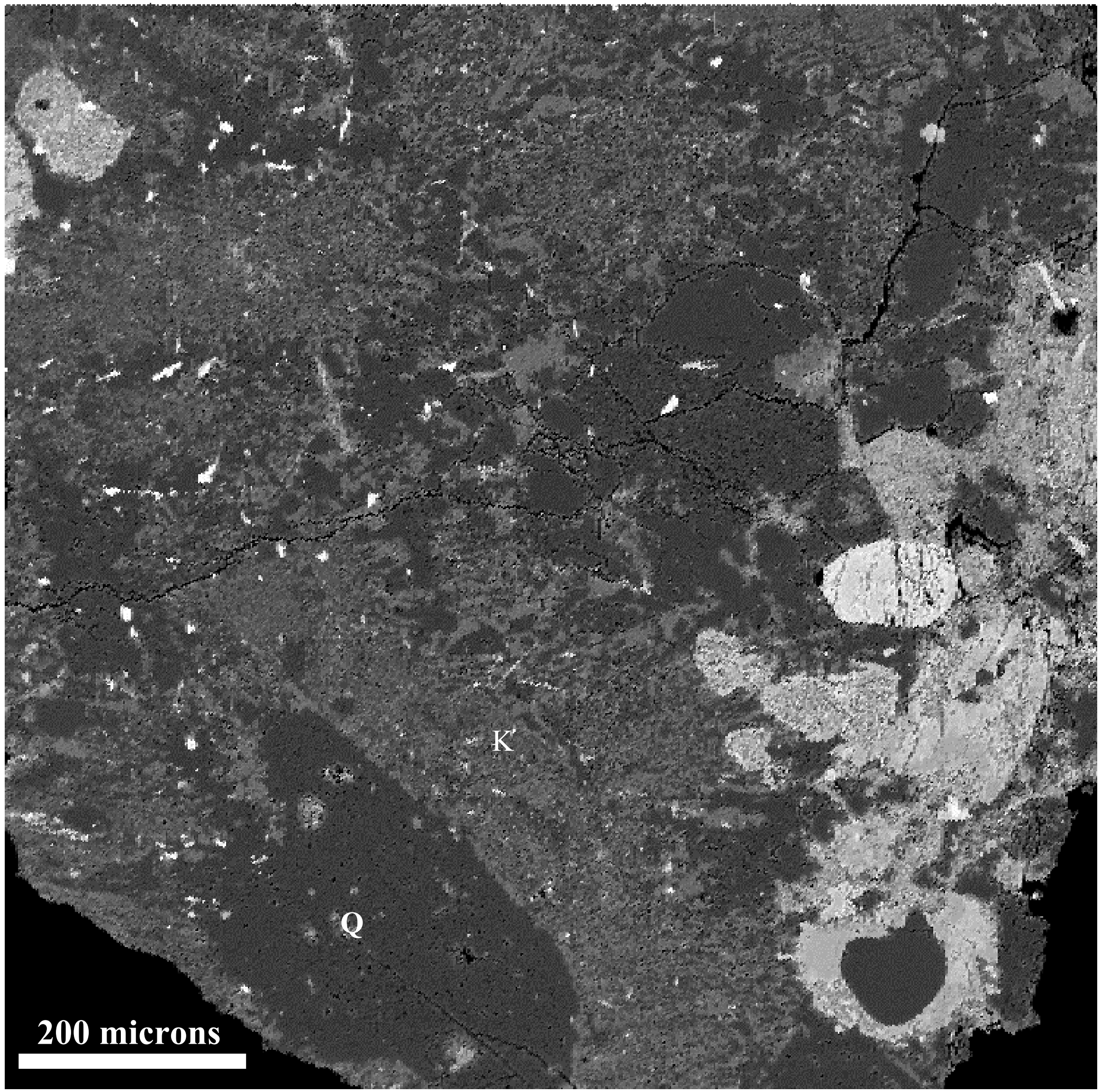


Figure 18. Microprobe Image of quartz syenite showing a graphic texture developed by quartz (Q) and potassium feldspar (K)

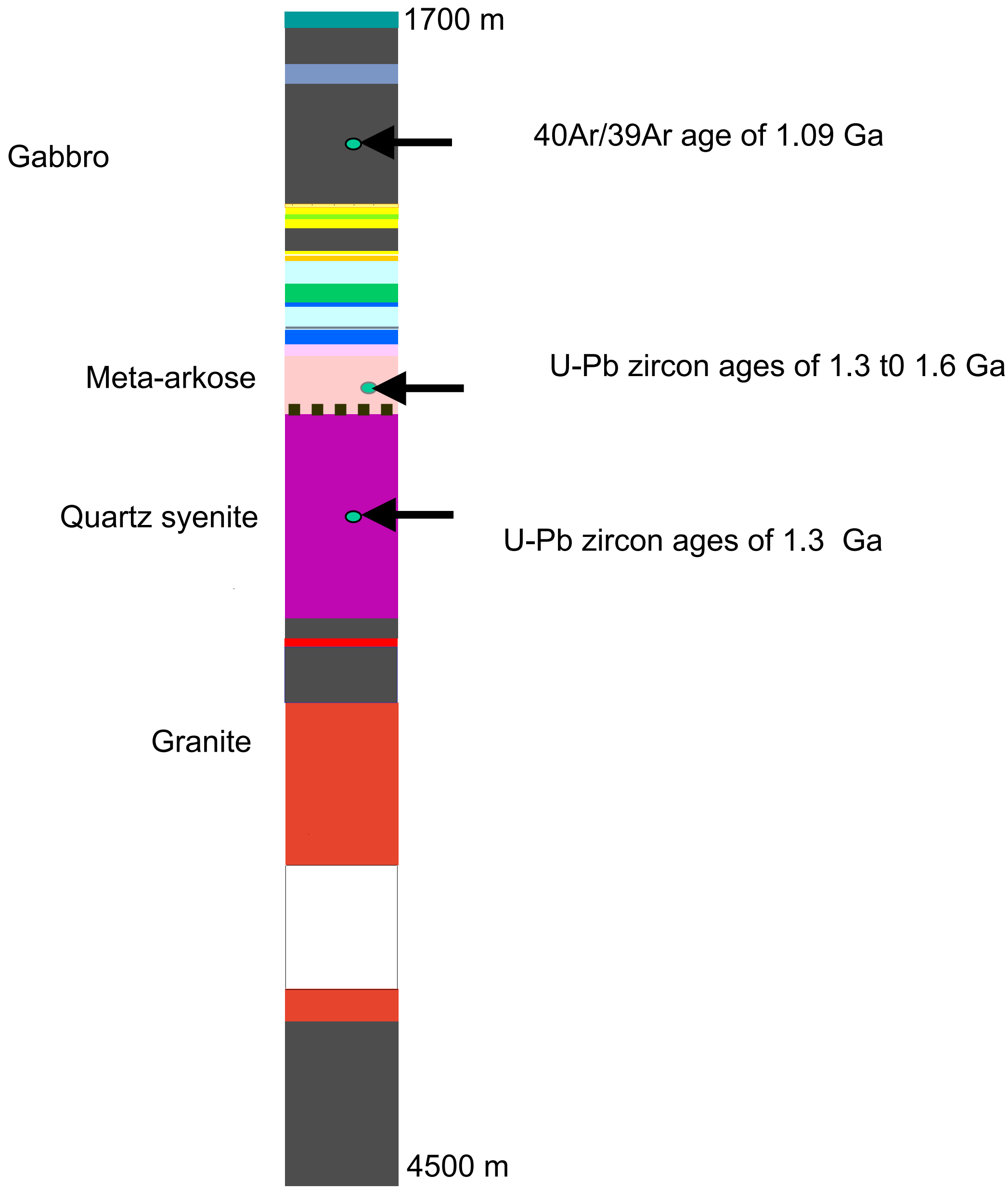


Figure 19. Preliminary results of geochronologic analysis based on $^{40}Ar/^{39}Ar$ and SHRIMP U-Pb zircon methods.

which the Grenville Orogeny occurred (Mosher, 1998). Preliminary geochronologic analysis of 8 detrital grains of zircon indicate that the meta-arkose, the basal unit of the Debaca sequence, yields SHRIMP U-Pb zircon ages ranging from 1308 ± 52 to 1708 ± 14 Ma. These data indicate that the sediment was both locally (from the underlying 1.33 Ga quartz syenite) and distally derived (from older basement exposures).

Seismic analysis

Three strong reflectors were recognized in a regional seismic reflection line across the Tucumcari Basin, near the Mescalero 1 (Figure 20). These reflectors have been designated in this study as A, B, and C. A is a strong, laterally discontinuous reflector that has been interpreted as the base of the Debaca sequence. It appears to pinch out to the north (right hand side of the Figure 20). B is a strong reflector that occurs obliquely at a depth of ~ 5 km. It has been interpreted as an intrusion of gabbro. This interpretation is supported by the results of petrographic analysis of cuttings of the well Mescalero 1. C is a strong lateral reflector that represents the top of the Proterozoic basement.

A significant Phanerozoic fault cuts across the line in the vicinity of the reflector A. The northern edge of the basin appears to be truncated by a high angle fault just off the edge of the available line, suggesting that the Debaca sequence was accumulated in a structural basin developed by extensional tectonism.

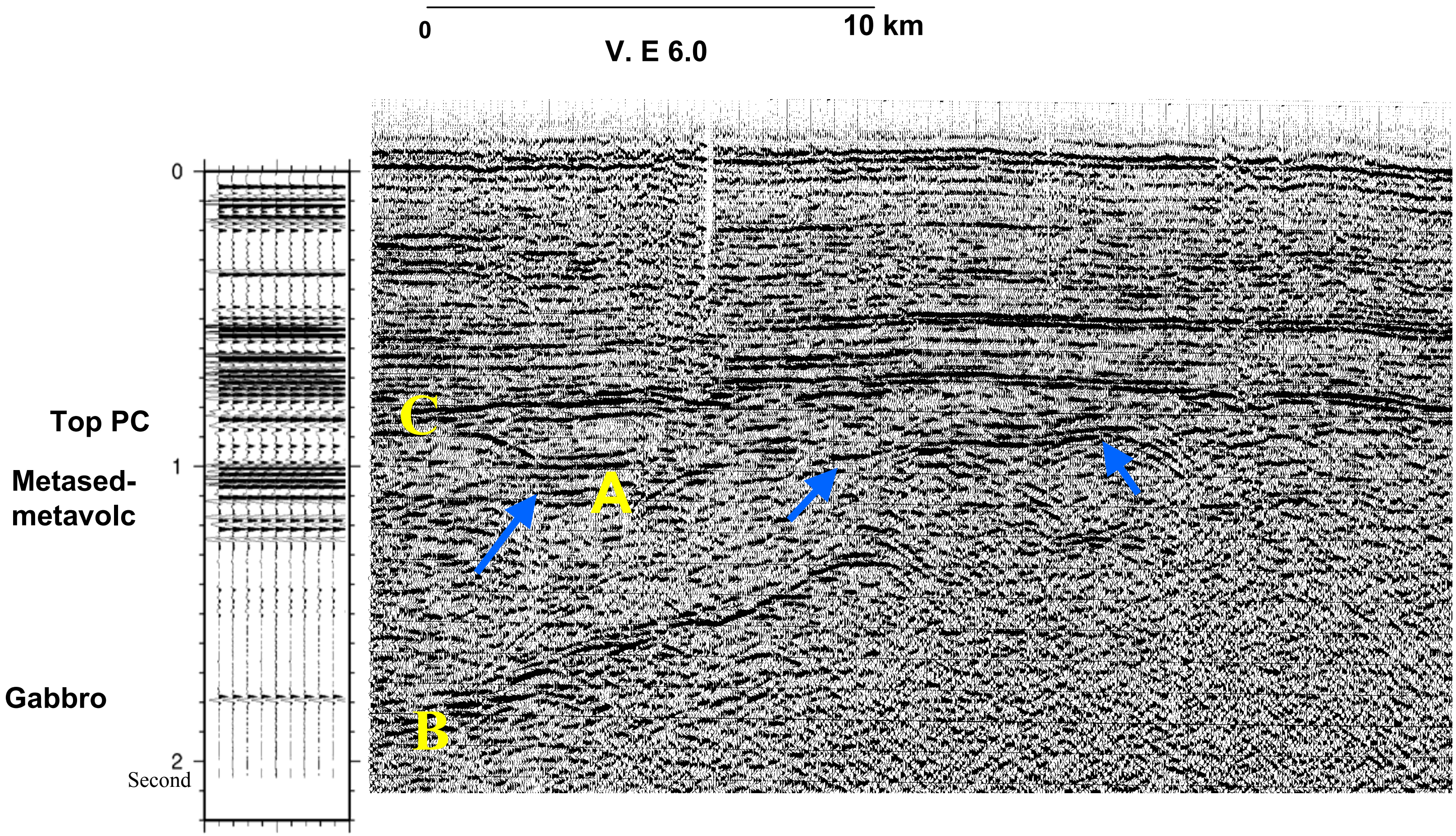


Figure 20. Seismic reflection lines across the Tucumcari Basin, showing strong basement reflectors. The vertical column, on the left of the diagram, is a synthetic derived from the sonic log from a nearby well. Keys: The letter A and highlighted with arrows show base of the Debaca sequence. C represents the top of the Proterozoic basement, and B represents an intrusion of gabbro.

In general, there is a good agreement between the results of the seismic line and the results of the petrographic analysis of cuttings in the Mescalero 1 well. For example, the intrusive body of gabbro in the lower left corner of the seismic line was identified at the bottom of Mescalero 1 by petrographic analysis of cuttings (at depth of 4100 - 4500 m) as shown (Figure 3). Similarly, the reflector on the seismic line interpreted as the Debaca sequence is equivalent to the erosional contact between the Debaca sequence and the underlying quartz syenite (at depth of 2540 m in Figure 3) that was also identified by petrographic analysis.

DISCUSSION

Summary of lithology, age, and basal relationships

Detailed petrologic and geochronological studies of basement rocks penetrated by the well Mescalero 1, indicate that the metasedimentary and metavolcanic rocks in this drillhole fit the composition of the Debaca Terrane that occurs primarily in the subsurface of west Texas and southeast New Mexico. The Debaca sequence in this well consists, from bottom to top, of meta-arkose, arkosic metasediment, dolomitic quartzite, quartzose dolomite, volcaniclastic metasediment, meta-rhyolite, tuffaceous metasediment, dolomitic marble, and hornfels. The Debaca sequence was intruded by several bodies of gabbro. As a result of the intrusion of gabbro some of the carbonate rich rocks were converted to marble and parts of the sediments were converted to hornfels. The association of immature volcaniclastic rocks, rhyolitic and mafic volcanism, and carbonates in the Debaca sequence suggest deposition in a shallow-water, extensional active continental rift, as was postulated by Mosher (1998) for a similar assemblage in west Texas near Van Horn. The significant difference in U-Pb SHRIMP ages determined for eight detrital grains of zircon (from1308 ± 52 to 1708 ± 14 Ma) from the meta-arkose indicates that the Debaca Terrane was accumulated during a period in which regional erosion prevailed, resulting in deposition of zircons from source rocks of different ages. The U-Pb zircon age determined for the quartz syenite (1334 ± 52 Ma), which underlies the Debaca sequence, is coincident with the youngest age determined for detrital grains of zircon from the meta-arkose, suggesting that the quartz syenite is one of the sources for the meta-arkose. This interpretation is supported by petrographic analysis that identified a weathering profile in the contact between the meta-arkose and the quartz syenite, which in turn indicates an erosional contact between these two units. This interpretation is also supported by the presence of abundant fragments of syenite in the meta-arkose, especially in the lower portion of this unit near the contact with quartz syenite. This erosional contact shows up clearly on seismic reflection lines across the Tucumcari Basin. The Debaca sequence is pinching out to the north, and is truncated by a high angle fault, suggesting that the Debaca sequence was deposited in a structural basin, possibly developed by extensional tectonism. As mentioned before, the age of the Debaca Terrane can be reasonably constrained between 1.1 and 1.334 Ga.

Correlation with other Mesoproterozoic rocks in west Texas and New Mexico.

The rocks of the Debaca sequence in Mescalero 1 have lithologic and age affinities with surface exposures in the Franklin Mountains and the Van Horn area of west Texas, as well as small outcrops in the Sacramento Mountains in south-central New Mexico. The ages of Thunderbird Rhyolite, Mundy Breccia, and Castner Marble in the Franklin Mountains overlap with the period of deposition of the Debaca sequence (1.1-1.3 Ga, this study). An U-Pb zircon age for a bed of volcanic ash within the Castner Marble yielded an age of 1260 ±20 Ma (Pittenger et al. (1994). Similarly, rhyolite from the upper part of Thunderbird Group yields an U-Pb zircon age of 1111 ±20 Ma. These ages are comparable to the age bracket for the rocks in Mescalero 1. Rocks of the Debaca in Mescalero 1 may correlate with Allamore and Tumbledown Formations in the Van Horn, Texas area (Bickford et al., 2000). The Allamore Formation is dominated by carbonates with interbedded basalt and felsic tuff, while the Tumbledown Formation is made up of basalt flows with volcanic sandstone and felsic tuffs. U-Pb ages of rhyolites, tuffs, and ashes in the Allamore and Tumbledown formations are 1243 to 1256 Ma (Bickford et al., 2000). A small outcrop of basement rocks including quartzite, siltstone, and shale cut by diabase dikes at the western base of the Sacramento Mountains is assumed to be Debaca Terrane (Denison and Herrington, 1969), however, this assumption needs to be proved by geochronological study. Denison and Hetherington (1969) noted that north of an E-W line through the center of Otero County, New Mexico, carbonates in the Debaca sequence are rare and the section becomes more argillacous and arkosic; however, our results suggest that this generalization is not true. The sediments are not as strongly metamorphosed north of this line (Denison and Herrington, 1969).

Correlations with other Mesoproterozoic rocks in the southwest U.S.

The age of the Debaca Sequence in Mescalero 1 overlaps with the ages of other Mesoproterozoic rocks elsewhere in the southwest U.S. For example the Pecos Mafic Igneous Complex (PMIC), Texas has an U-Pb zircon age of 1163 ±4 Ma, as reported by Keller et al. (1989). PMIC magmatism was approximately coeval with granitic, syenitic, and rhyolitic magmatism in the Franklin Mountain of west Texas and the Sacramento Mountains of New Mexico (Kargi and Barnes (1995). Ages in these areas are comparable to the age bracket for the rocks of Debaca in Mescalero 1.

Similarly, the Apache Group in Arizona has U-Pb zircon, K-Ar and Rb-Sr isochron ages that are similar to those in Mescalero 1. Wrucke (1989) published an U-Pb zircon age of 1150 ±30 Ma for the diabase, and an U-Pb zircon age of 1100 ±15 Ma for a sill of diabase in the little Dragon Mountain, southern Arizona. A K-Ar method on biotite for the Sierra Ancha sill indicates an age of 1140 ±40 Ma. The Rb-Sr isochron dating was applied for a diabase sill in central Grand Canyon, giving a result of 1070 ±30 Ma (Wrucke, 1989). A recent geochronologic study performed by George Gehrels (2000, Personal comm.) on an ash bed within the Apache Group, has contributed significantly with the better understanding of the possible depositional age of at least part of the Apache Group. U-Pb zircon ages indicate that this ash bed was deposited between 1300 and 1250 Ma ± 10 Ma. This depositional age is correlative with the possible age of deposition of the Allamoore Formation and Debaca Terrane west of Texas and east of New Mexico, respectively.

The ages of the Cardenas basalt and basaltic sills that overlay and intrude the basal portion of Unkar Group are also Mesoproterozoic. Elston and McKee (1982), proposed a Rb-Sr age of 1,070 ±30 Ma for a sill of basalt that intrudes the lower part of Unkar Group. Larson et al. (1994) obtained a Rb-Sr isochromn from the Cardenas Basalt of 1103 ± 66 Ma , and Timmons et al. (2001) reported a Rb-Sr age of 1070 ± 70 Ma for the Cardenas Basalt. These geochronologic information together with the field evidence reported by Timmons et al. (2001), indicate that the Unkar Group was deposited in a basin created by a NW structural system related to the 1.3 to 1.1 collision.

Well log analysis

The relatively high uranium values determined by natural gamma-ray spectral log analysis for the volcaniclastic metasediment and some of the dolomitic units suggest that these rock units had higher permeability than others units, creating a migration pathway for fluids (Kowalski and Asekun, 1979). The appearance of smoky quartz, which acquires its color due to radiation damage, in the dolomitic intervals is consistent with the high uranium contents of these beds. The presence of pyrite in these units is an indication of reducing conditions conducive to concentration of uranium from the migrating fluids.

CONCLUSIONS

- Mineralogical and geochemical associations of the basement rocks penetrated by Mescalero 1 identified three major intrusive rock types (gabbro, quartz syenite, granite) and a metasedimentary-metavolcanic sequence in this Proterozoic section. The metasedimentary-metavolcanic sequence fits the descriptions of the Debaca and underlying Panhandle Terranes discussed by previous workers in eastern New Mexico.

- One sample of biotite from gabbro in the upper part of the section yielded an $^{40}Ar/^{39}Ar$ age of 1090 ±4 Ma. Because gabbro intrudes the other Proterozoic rock units it appears to be the youngest unit within the basement; therefore, the entire sequence of basement rock types cut by Mescalero 1 may be older than 1.09 Ga. The quartz syenite, which underlies the Debaca sequence, yields a SHRIMP U-Pb zircon age of 1334 ±52 Ma. On the basis of the ages of gabbro and quartz syenite, the age of the Debaca Terrane can be reasonably constrained to be between 1.1 and 1.334 Ga. These ages are similar to those found for rocks equivalent to the Debaca sequence in the Franklin Mountains and the Van Horn area.

- The metasedimentary-metavolcanic sequence rests on weathered quartz syenite of the underlying granite-rhyolite (Panhandle Terrane) in this well. This erosional contact shows up clearly on seismic reflection lines across the Tucumcari Basin.

- On the basis of natural gamma-ray spectral log analysis, most of the horizons of volcaniclastic metasediment exhibit high uranium values, suggesting that these rock units had higher permeability than the rest of the units, creating a migration pathway for fluids.

- Each of the major rock units has a characteristic signature on the geophysical logs. For example, gabbro has a density of ~3.0 gm/cm^3 and low total gamma activity. In contrast, the quartz syenite has a density of ~ 2.70 gm/cm^3 and a total gamma ray of ~ 115 GAPI. This type of analysis is useful for correlating with other wells in which cuttings or logs are not available.

- This study indicates that application of careful calibration of petrophysical interpretations with cuttings petrology results in a better understanding of the Proterozoic basement rocks in east-central New Mexico.

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APPENDIX

Table 1. Binocular scope observation of cuttings

5700-5750- metasediment- Fine-grained and light to dark gray. Cuttings generally are flat and sometime elongated. The rock is easily crushed with knife, and effervesces vigorously with cold dilute hydrochloric acid.

5750-5770 Metasediment- Fine-grained, pale green, and siliceous. At microscopic scale this rock shows a spotted texture.

5770-5780-Metasediment- Fine -grained, pale green, and very soft. It effervesces strongly with cold dilute hydrochloric acid.

5780-5790 -Metasediment- Very fine-grained, light green, and soft. It effervesces with cold dilute hydrochloric acid.

5800-5810- Metasediment- fine-grained dark gray to black. Cuttings commonly are flat, and occasionally elongated. Two types of chips are distinguished in this interval; one type which is reddish in color and effervesces strongly with cold hydrochloric acid and another type is pale green, and does not effervesces with hydrochloric acid.

5820-6100- Gabbro - medium- to coarse- crystalline , dark green and phaneritic in texture. The rock is mostly composed of plagioclase, pyroxene, olivine and lesser amounts of biotite, and chlorite. In general, plagioclase is tabular and may display a sub-parallel. Could be cumulate, too.

6110-6250- Hornfels- Fine-grained, dark gray when dry and creamy when wet. It shows a spotted texture.

6250-7080- Gabbro- medium to coarse crystalline, dark green, dominated by plagioclase, pyroxene, and olivine. Magnetite, biotite and lesser amounts of hornblende are present in this rock.

7080-7110- Dolomitic Marble - Fine-grained, light green to white in color. A sugary texture is observed only at high magnification. Cuttings generally effervesce with cold dilute hydrochloric acid. Dissemination of a black mineral is observed, which gives a spotted texture to the rock.

7110-7210 – Volcaniclastic metasediment - Fine-grained, light green, carbonate-cemented, and commonly reactive with cold dilute hydrochloric acid. Fine-grained, white cuttings may also occur, which generally do not effervesce with cold dilute hydrochloric acid.

7210-7260- Volcaniclastic metasediment- Very fine-grained, green when dry and pale green when wet, with relicts of altered feldspar. This rock is as hard as quartz and does not effervesce with hydrochloric acid.

7260-7350 - Tuffaceous metasediment- Fine-grained, light green to white carbonate coated, with visible quartz and pyrite.

7350-7510- Gabbro, medium-crystalline, dark green, dominated by plagioclase, biotite, magnetite, olivine, and pyroxene. Sericite occurs as alteration of plagioclase and chlorite replaces almost totally the mafic minerals.

7510-7530- Tuffaceous metasediment- Two types of chips are distinguished in this interval: 1) milky white, fine-grained with very low hardness, which is not reactive with hydrochloric acid, and 2) greenish to yellowish, low hardness and not reactive with acid.

7530-7550- Argillaceous metasediment- Fine-grained, black in color, and sometime finely foliated. This rock is very soft and does not effervesce with hydrochloric acid.

7550-7620-Meta-rhyolite- very fine-crystalline to cryptocrystalline, and locally porphyritic. The rock is dark brown to chocolate in color and may exhibit a conchoidal fracturing. Pyrite, magnetite, and micro-veinlets of quartz, potassium feldspar, and biotite are observed.

7620-7660 –Dolomitic quartzite - Fine-grained, light gray to white, moderately to strongly reactive with cold, dilute hydrochloric acid. Generally, this rock exhibits a lower hardness than quartz.

7660-7750- Dolomitic quartzite- fine to medium-grained, salt and pepper appearance. It is very friable when scratched with a knife. The rock effervesces weakly to moderately with cold, diluted hydrochloric acid. Incipient bands of dark gray quartz intercalated with carbonate are observed.

7750-7820- Dolomitic quartzite- fine to medium-grained, sugary texture, with incipient bands of vitreous and locally smoky quartz intercalated with bands of light gray minerals (calcite and dolomite). Well-developed cubic crystals of pyrite may be observed.

7820-7880- Volcaniclastic metasediment- Fine-grained, light green with fragments of volcanic rock with vitreous quartz eyes.

7880-7940- Volcaniclastic metasediment- Fine-grained, dark green to gray, dominated by small euhedral crystals of amphibole and sporadic books of biotite in a very fine groundmass. Flow structure is observed in some fragments.

7940-7990- Volcaniclastic metasediment- Fine-grained, light green, with sporadic crystals of amphibole in a fine-grained groundmass. The rock is easily scratched with a knife and some chips may react with hydrochloric acid.

7990-8020- Quartzose dolomite- Fine to medium-grained, light gray, sugary texture, dominated by dolomite, calcite, and quartz.

8020-8060- Dolomitic Quartzite- Fine to medium-grained, black sugary texture, characterized for incipient bands of dark to smoky quartz grains intercalated with bands light colored minerals including dolomite and calcite.

8060-8110- Dolomitic quartzite- Fine -grained, clastic texture, white to creamy in color, dominated by rounded to sub-rounded quartz grains cemented by carbonate.

8110-8150 – Carbonate-coated metasediment-Fine to medium-grained, light gray, clastic texture dominated by rounded to sub-rounded quartz grains coated by carbonate.

8150-8170- Quartzose dolomite- Fine to medium-grained, light gray, dominated by angular fragments of sedimentary-clastic rocks which comprise rounded to sub-rounded quartz grains and carbonate.

8170-8200- Quartzose dolomite -Fine to medium-grained, Dark gray to black, sugary texture, and brecciated. The rock contains vitreous and smoky quartz and dolomite and calcite.

8200-8240- Quartzose dolomite-Fine to medium-grained, light gray, salt and pepper appearance, and sugary texture. Quartz, dolomite and calcite dominate the rock. Quartz may occur as vitreous and/or smoky rounded to sub-rounded grains. The rock is fragile when scratched with a knife, and the hardness may vary from low, in the area where dolomite and calcite dominate, to high in those places where the dominant mineral phase is quartz.

8240-8300- A**rkosic metasediment**-Fine to medium-grained, pink, tan, to creamy in color, fragmentary texture, dominated by fragment of volcanic rocks which in turn comprise quartz and feldspar.

8300-8740 Meta-arkose- Medium-grained to coarse-grained, pink to reddish colored, and clastic texture with visible rounded fragments of feldspar and vitreous and smoky quartz. Fragments are cemented by carbonate. The rock is strongly reactive with hydrochloric acid. In its basal portion the unit contains fragments of syenite. Such fragments contain feldspar, white phyllosilicate, chlorite, and hematite.

8740-9620 –Quartz Syenite- Medium to coarse-crystalline, and pink to reddish in color. Cloudy potassium feldspar, and lesser amount of plagioclase, amphibole, chlorite, magnetite and quartz dominate the rock. Plagioclase is almost totally replaced by white phyllosilicate. Chlorite and hematite may occur as replacement of amphibole and magnetite respectively. In the upper portion of this interval, quartz syenite exhibits a secondary deep red coloration due to the oxidation of iron minerals such as pyrite and magnetite. This suggests an erosional unconformity between the quartz syenite and the overlying meta-arkose.

9620-10390- Quartz syenite- at this interval quartz syenite is fresher and exhibits a light green to pale pink color. The rock contains the same mineral species that are present in the upper segment of syenite.

10390-10550- Gabbro- Medium-crystalline, light green dominated by plagioclase feldspar, pyroxene, and olivine.

10550-10670- Gap (no sample)

10670-10700 - Quartz diorite- Medium to coarse-crystalline, brownish gray when dry, pale gray when wet. The rock is dominated by plagioclase, potassium feldspar, mafic minerals including hornblende, biotite and magnetite, and lesser amount of quartz (about 10%).

10700- 11050- Granite- Pulverized probably due to drilling problem, dark brown in color when dry. When washed the rock shows a pink to brownish and exhibits a granitic texture with visible euhedral to subhedral crystals of feldspar, quartz, and altered mafic minerals. Locally this unit shows a red stain, which is an artificial color attributable to drilling fluids

11050 – 11090 – Granite- Coarse-crystalline, dark brown when dry, pink to pale reddish when wet, and granitic texture with visible quartz, feldspar and lesser amounts of mafic minerals.

11090-11150- Granite- Pulverized probably due to drilling problem, dark brown in color when dry, and pink to brownish when washed. The rock shows a phaneritic to porphyritic texture with visible euhedral to subhedral crystals of feldspar, quartz, and altered mafic minerals.

11150-11260 Granite-Coarse-crystalline, red in color when dry and brownish when wet.

11260-11400- Granite- chips are pulverized, creamy to brownish when dry, and pink when washed. The brownish color is due to drilling fluids.

11400-11410- Granite- Coarse-crystalline, gray to brownish when dry, the color may be pink if the sample is washed. The rock is composed of potassium feldspar, quartz, plagioclase and mafic minerals. Chlorite and sericite occur as a product of alteration**.**

11410-11470- Granite, pulverized, gray in color when dry and pink when washed.

11470-11530- Granite- Coarse-crystalline, pale pink in color when wet.

11530-11600- Pulverized granite**.**

11600- 11900- Granite-Coarse-crystalline, light gray to brownish when dry and pink when washed. Feldspar, vitreous quartz, and mafic minerals dominate the rock. The mafic minerals commonly are replaced by chlorite.

11900-13300 –Gap

13300-13600 Granite- Coarse-crystalline, pink in color, dominated by potassium feldspar, quartz and mafic minerals.

13600-14,500- Gabbro- Coarse-crystalline, brownish when dry and light green when wet. Plagioclase, pyroxene, olivine, and lesser amounts of biotite dominate the rock.

Table 2. Microscopic Description

6080-90 Gabbro-Medium to coarse crystalline, with a cumulate to sub-ophitic texture developed by the occurrence of subhedral crystal of olivine embedded within large crystals of pyroxene and interlocked between plagioclase crystals. Plagioclase feldspar is the dominant mineral species, followed by pyroxene, olivine and lesser amount of amphibole. In general, plagioclase feldspars are tabular and may display a sub-parallel orientation suggesting flow structure. Biotite and magnetite are very important accessories mineral in this rock. Books of biotite showing cores of magnetite are commonly observed. Other accessories minerals present are apatite, rutile and titanite. Chlorite, hematite, epidote and carbonate are observed as a product of alteration of former minerals. Chlorite, the most important alteration mineral, occurs as a result of replacement of mafic minerals (hornblende and biotite). Hematite of supergene origin is a result of replacement of magnetite. Epidote and carbonate may replace plagioclase.

6140-50 Hornfels-Fine-grained with spotted texture developed by fine, light brown biotite suggesting contact metamorphism. Relics of plagioclase and quartz phenocrysts are observed within a gray (with polarized light), very fine-grained, and recrystallized groundmass. Groundmass is cryptocrystalline and dominated almost entirely by very fine-grained microlites of quartz. Accessory minerals are pyrite and rutile. Pyrite occurs as dissemination of small cubic crystals. Rutile, dark brown with cross-nicols, commonly occurs as aggregate of small and rounded grains. Laths of randomly oriented muscovite and flaky sericite occur in plagioclase phenocryst places. Ghosts of quartz phenocrysts, commonly recrystallized, are present. Late micro-veinlets of microcrystalline quartz are observed. The rock has been strongly altered and the dominant alteration minerals include white phylosillicate (muscovite and sericite), carbonate, and lesser amount of chlorite. The presence of spotted texture, banding, and recrystallization in this rock may be evidence of thermal or contact metamorphism.

6400-10 Gabbro - medium to coarse-crystalline, granular, dominated mainly by plagioclase feldspar, pyroxene, olivine and lesser amount of amphibole. This rock has a cumulate to subophitic texture developed by subhedral crystals of olivine embedded within largest crystal of pyroxene. Plagioclase crystals are prismatic and may be partially replaced by sericite. Hornblende occurs as prismatic crystals, commonly replaced by chlorite. Magnetite and biotite are important accessory minerals. Biotite, which commonly occurs as interstitial, is flaky, deep red, and sometime sub-rounded. It commonly is altered to chlorite. Generally, biotite shows rims of chlorite, and also may form halos surrounding magnetite crystals. Magnetite generally occurs as euhedral crystals and commonly in spatial relationship with mafic minerals (biotite and hornblende). Apatite, rutile and titanite may be also present as accessory minerals.

6730 Gabbro- The rock is coarsely crystalline comprised of plagioclase as the dominant mineral phase. Plagioclase commonly is euhedral and may show Carlsbad-albite twins. Olivine, pyroxene and hornblende constitute important mineral species in this rock. Biotite and magnetite are the most important accessory minerals. Magnetite commonly forms core of biotite plates. Biotite may occur as interstitial and may be partially replaced by chlorite.

7075-60- Gabbro- Coarsely crystalline and composed of plagioclase as the dominant mineral phase, followed by olivine, pyroxene and hornblende. The rock exhibits an ophitic to sub-ophitic texture developed by aggregate of small crystal of olivine embedded within large crystals of pyroxene. Biotite and magnetite are present as the main accessory minerals. Biotite commonly occurs as books exhibiting cores of magnetite, and sometime it can show rings of chlorite.

7100-20 Dolomitic Marble **-**Fine-grained, composed fundamentally by recrystallized carbonate (calcite and dolomite) and quartz. Trace of deformed plates of Phlogopite is present. The rock exhibits an incipient spotty texture developed by a dark to black mineral? with undulatory extinction whose size varies from 63 to 200 microns. Euhedral crystals of pyrite are common in this unit.

7160-**70** V**olcaniclastic metasediment**- Fine-grained, brecciated, dominantly made up of fragments of at least three different sources: igneous intrusive rocks, volcanic rocks, and sedimentary rocks. Fragments of igneous intrusive rocks comprise, mostly, potassium feldspar, plagioclase and quartz. Fragments of volcanic rocks, which generally are strongly altered, comprise white phyllosilicates, kaolinite, and carbonate. Some fragments of volcanic rocks exhibit a devitrified appearance. Fragments of sedimentary rocks are dominated by rounded to sub-rounded quartz grains, cemented by carbonate. Some plagioclase grains preserve Carlsbad twins, and microcline crystals develop tartan twinning. Calcite replacing feldspar is observed. Calcite also occurs as stringers cutting the entire mineralogy of the rock, which suggests a late event.

7240-50- volcaniclastic metasediment. Made up of angular fragments of quartz, feldspar (microcline) and chert. The presence of microcline stable suggests an immature character for this rock. The angularity of the fragments in this rock may indicate that this unit was formed relatively close to the source of the fragments. However, sub-angular fragments of quartz exhibiting a half part rounded and a second half angular are common. Some of these fragments show evidence of chemical attack at the boundary of the angular portion, suggesting that the angularity of these fragments may be due to corrosion during chemical weathering. Trace amounts of apatite (15-30 microns) are observed.

7510-20: **Tuffaceous metasediment** composed mainly by flaky and randomly oriented phyllosilicate (muscovite), quartz and carbonate which commonly occur as anhedral grains coating white phyllosilicate an quartz.

7560-70 Metarhyolite- very fine grained to cryptocrystalline, well-developed flow structures, and sporadic relicts of former minerals. Such former minerals are interpreted to be biotite, hornblende, titanite, and feldspar on the basis of their shapes and alteration products. Ghosts of biotite (up to 300 microns) showing cores pyrite and surrounded by incomplete rings of chlorite are observed. Tabular relicts of amphibole are completely replaced by fine chlorite and carbonate. White phyllosilicates and carbonate replace relicts of feldspar. Skeletons of titanite, preserving the well-distinctive twinning, are pseudomorphed by carbonate. Pyrite and locally magnetite are observed. Pyrite occurs as dissemination on the groundmass and filling microfractures. Magnetite occurs as sporadic, small crystals disseminated in the groundmass.

7580-90B- Metarhyolite- Very fine crystalline to crystopcrystalline with well-developed flow structures. This rock locally shows remnants of rock-forming minerals which appear to be biotite, hornblende, and feldspar, which in turn may be replaced by one or two of the following minerals: chlorite, carbonate, and white phyllosilicates. Late veinlets of plagioclase of hydrothermal origin are observed. Rutile, occurring as small crystals and subhedral crystals disseminated in the groundmass. Rutile is also interpreted of hydrothermal origin.

7590-7600 Metarhyolite showing banding flows and relicts of quartz, feldspar and mafic minerals, which are totally replaced by chlorite and carbonate. Microveinlets of carbonate cross-cutting the groundmass are observed.

7620. Metarhyolite- Aphanitic to cryptocrystalline with incipient spotted texture only appreciated at high magnification. Ghosts of quartz and feldspar phenocrysts are present, suggesting a rhyolite protolith. In places, some quartz phenocrysts are recrystallized. This rock, locally, exhibits a banding or flow structure. White phyllosilicates occur in feldspar sites suggesting a selective character. Patches of carbonate in feldspar sites are present. Euhedral crystals of pyrite are observed. In places pyrite is oxidized.

7740- Dolomitic Quartzite The rock shows well developed bands of coarse-grained quartz intercalated with bands of dolomite, calcite and lesser amount of deformed muscovite, which commonly occurs in spatial relation with micro-shear zones.

7830-Volcaniclastic metasediment -Microscopically the rock shows fragmental texture, comprising fragments of quartz, feldspar and hornblende, and chert within a fine-grained groundmass which includes microlit of feldspar, quartz and, mafic minerals. Groundmass may be partially replaced by carbonate, iron oxide and chlorite. Quartz commonly occurs as fragments (angular and sub-rounded with up to 300 microns) and also as euhedral crystals ranging between 20 and 150 microns. Generally, quartz exhibits numerous fluid inclusions. Most of the quartz fragments exhibit a concentric fracture pattern. In cases, some of the fragments have been dismembered into several smaller fragments which in turns have been sub-rounded what suggests that this rocks has been re-worked. Fragments of plagioclase, on another hand, shows Tartan twinning be partially replaced by sericite. Patches of coarse-grained carbonate occurs as interstitial to quartz and feldspar fragments**.** Rutile occurs as small (10 micron) rounded grains commonly forming aggregate within the groundmass.

8000- Dolomitic quartzite- Bands of coarse-grained minerals including dolomite and calcite, intercalated with bands of fine, anhedral quartz, which in turn is characterized by showing suture contact and undulatory extinction.

8250- Arkosic metasediment- Microscopically the rock exhibits a clastic-fragmentary texture, including fragments of quartz, feldspar, and chert within a fine-grained groundmass. Fragments of igneous rocks showing a graphic texture similar to those reported by syenite. The grondmass is comprised of very fine-grained quartz, carbonate, and iron oxide. Quartz fragments commonly are angular to sub-rounded, and may contain fluid inclusions. Some fragments of quartz are transparent and show an angular to sub-rounded shape. In places these quartz fragments displays a preferential orientation. Feldspar occurs as euhedral crystals and also as fragments. This mineral species is dominated by plagioclase; however, K-feldspar is also present. Most of the feldspar may be replace by calcite, which occurs as well, developed crystals. Accessories minerals comprise zircon, rutile and a high relief fine-grained mineral, which occurs interlocked in the groundmass.

8690- Arkose. Fine to medium-grained, comprised of fragments of igneous rock (syenite), quartz and potassium and plagioclase feldspar within a fined-grained groundmass, which is dominated by very fine-grained quartz grains and carbonate. Quartz fragments commonly show concentric fracturing, and may contain fluid inclusions. Carbonate, characterized by a high relief and strong birefringence, commonly occurs as interstitial to quartz and feldspar grains, and locally, occurs as a selective replacement of plagioclase feldspar. Plagioclase feldspar is also replaced by white phyllosilicates.

8840-50- Quartz Syenite-The rock is coarse-crystalline, granular texture with myrmekitic intergrowths of potassium feldspar and quartz, in which one mineral forms wormy texture within the other. The development of a myrmekite texture in syenite evidenced by K-feldspar intergrowth with quartz with sinuous contact at the boundaries, may suggest a very low metamorphism where mineral grow in rocks that are already solid and compete for space with other minerals. In general, the rock is composed of K-feldspar, plagioclase and lesser amount of quartz. Potassium feldspar commonly is euhedral to sub-hedral, equant, and 1 to 2 mm in size. Plagioclase, when no altered, occurs as laths with size varying between 0.5 to 1.5 mm. Quartz occurs as minute, anhedral crystals, generally as inclusion or intergrowth or interstitial to feldspar. Accessories minerals are magnetite, amphibole, biotite, ilmenite, tourmaline, zircon and rutile. The uppermost part of this unit in the well has been partially oxidized, consequently, hematite occurs as a replacement of former magnetite. Alteration minerals are sericite and well-developed crystals of muscovite as an alteration product of feldspar. Chlorite commonly replaces amphibole and magnetite. This rock shows a remarkable increment in quartz content at depth passing transitionally from syenite to quartz syenite.

9830-40 Quartz Syenite- Coarsely crystalline, hypidiomorphic granular texture, with locally granophyric or myrmekitic texture characterized by intergrowths of potassium feldspar and quart. Quartz commonly forms wormy or cuneiform blebs within potassium feldspar. Potassium feldspar, plagioclase and quartz in decreasing order dominate the rock. K-spar occurs commonly as large, light gray megacryst embedding darkest, generally euhedral crystal of quartz. Accessory minerals are hornblende, biotite, magnetite, epidote, apatite, zircon and garnet. Alteration minerals include chlorite, white phyllosilicates, and epidote. Chlorite commonly replaces mafic minerals. White phyllosilicates and epidote may feldspar.

11210-20 Granite porphyry- Texturally this rock is porphyritic and exhibits large phenocrysts of plagioclase (1.2-2.0 mm), K-feldspar, and quartz, supported by a matrix of the same composition (quartz (0.01-0.1mm), feldspar and mafic mineral in decreasing order). Accessories minerals are magnetite, tourmaline, apatite, zircon, and ilmenite. Feldspar phenocrysts generally are altered to white phyllosilicate

13600-10 Gabbro- Coarsely crystalline, equigranular composed dominantly of plagioclase, pyroxene, and olivine. Other minerals are biotite, hornblende, epidote, and magnetite. Bio
tite and hornblende generally exhibit a cuneiform habit.