PETROLOGY OF THE ARROYO PENASCO (MISSISSIPPIAN)

TAOS COUNTY, NEW MEXICO

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PETROLOGY OF THE LOWER ARROYO PENASCO (MISSISSIPPIAN)

TAOS COUNTY, NEW MEXICO

by

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THESIS

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The Department of Geological Sciences and the Foundation receive my thanks for the various awards. Also, I appreciate Dr. Robert Louck's patience with my bizarre work schedule.

Of course, there are many others who had a hand in this undertaking, but the catalog would read like the listing of warriors in an epic poem. For these people, simply, thank you.

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ABSTRACT

The Lower Arroyo Penasco, which is probably of Mississippian age, is a relatively thin clastic unit composed of medium- and coarse-grained sand and gravel. It rests on a topographically irregular Precambrian crystalline basement or its regolith and grades conformably upward into a complex carbonate sequence.

Nowhere in the studied field area does the lower part of the formation exceed fifteen meters in thickness. The dominant mineral is quartz which comprises over 95% of the framework material, thus making the sandstone categorically a quartzarenite.

The unit was deposited within 10° or 15° of the Mississippian equator in a marginal system of high-energy braided streams, beaches, and tidal flats. This system alternately underwent periods of monsoonal flooding and aridity.

An authigenic suite of minerals began forming soon after deposition and an episode or episodes of grain embaying and solution fracturing. Large amounts of quartz first precipitated as overgrowths. A complex assemblage

of minerals including illite, chlorite, calcite, dolomite chert, chalcedony, pyrite, and apatite then followed, not necessarily in the preceding order. Microcline, which in some areas may have comprised 5% of the sandstone was replaced by illite, chlorite, or calcite; some may have been weathered and leached out of the system. There is practically no porosity.

This sandstone with very few fossils grades into a calcitic, dolomitic, and dedolomitic carbonate unit, the Upper Arroyo Penasco.

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INTRODUCTION

Statement of Problem

This thesis involves an examination of the lower clastic portion of the Arroyo Penasco Formation, the oldest sedimentary unit in Taos County, New Mexico. The assigned ages range from Devonian through Mississippian. The purpose of investigating the sandstone member of the Arroyo Penasco Formation is to describe its features and from these interpret the conditions and processes related to the source and governing its deposition and subsequent alteration.

In Taos County, the Arroyo Penasco Sandstone rests upon either Precambrian crystalline rock or its overlying regolith and grades upward into a complex carbonate-evaporite sequence. Both the Precambrian rock and carbonate strata are closely related to the complex history of the thin sandstone unit.

The outcrops of the Arroyo Penasco Formation considered in the study are located in the Picuris Mountains and Tres Ritos Hills of the Sangre de Cristo Range which is part of the Southern Rocky Mountains. Several researchers have examined the formation in this area, but most of their work concerns the complex nature of the carbonates, the fauna contained therein, and attempts to date the formation;

age relations are still unresolved. Little detailed petrographic study has been done on the clastic section that consists predominantly of quartz grains and pebbles. No identifiable fossils have been found in the unit. Original depositional terrain, climate, and tectonic activity, as well as burial, have imparted a complex character or aspect to this relatively thin stratigraphic section.

The body of this thesis, then, revolves around an array of established tools, procedures, and concepts that when combined yield an accurate description and viable interpretation of early Arroyo Penasco history.

SETTING

Location and Accessibility

Taos County is in northernmost central New Mexico (Fig. 1); the county covers 2256 square miles (Schilling, 1960). The area of specific concern in this thesis is located in the southern half of the county, the best Arroyo Penasco outcrops beginning about five miles south of Taos just outside Talpa (Fig. 2) in the eastern Picuris Range. The outcrops at this location are the northernmost exposures of the formation in the state. All the outcrops studied are within a mile of paved roads, although access to most involves fording streams and climbing steep and narrow valleys upon leaving the highway. All the land belongs to and is in the care of the National Forest Service which has cut many service roads into heavily forested areas. In other counties these roads provide the only access to Arroyo Penasco rocks. However, in Taos County, the best outcrops are along State Highway 3 between Ranchos de Taos and Tres Ritos.

Most of the locations are between 2100 meters (7000 feet) and 2400 meters (8000 feet) above sea level, usually between 60 and 100 meters higher than the Indian towns in the valleys. State Highway 3 follows the Rio Grande de Rancho (sp. variable) south from Talpa for about 16 kilom-

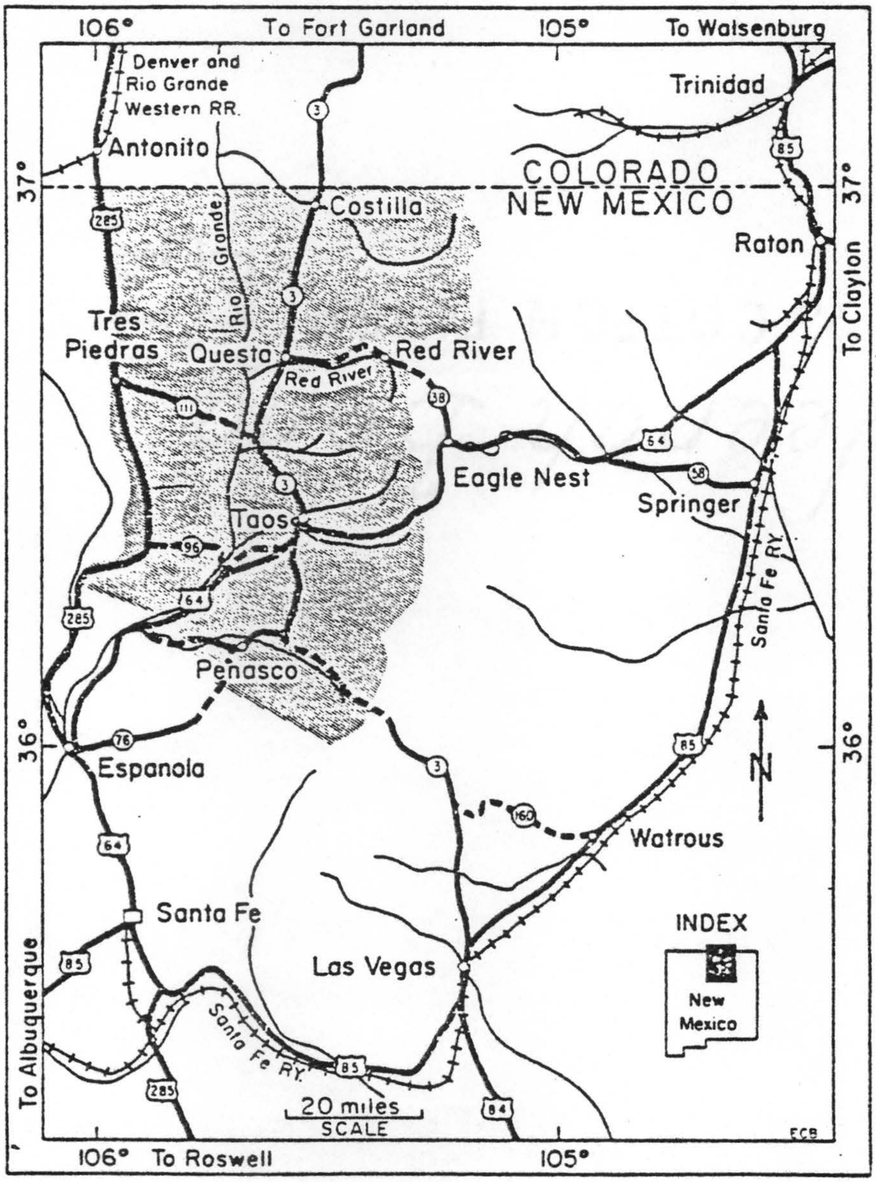


Figure 1. Location map of Taos County. From Schilling (1960).

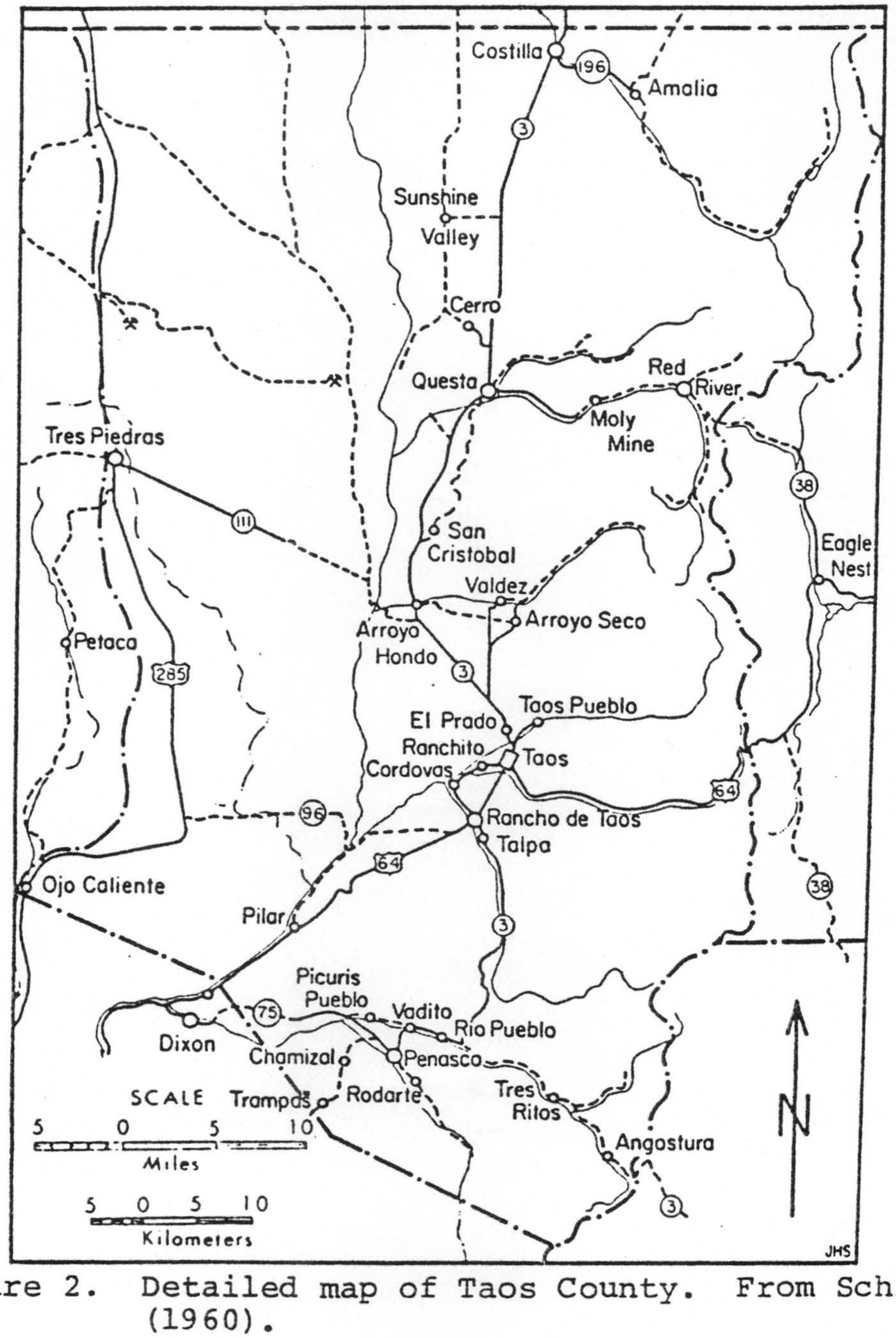


Figure 2. Detailed map of Taos County. From Schilling (1960).

eters then follows the Rio Pueblo into Tres Ritos. These rivers must be crossed to reach the outcrops. The exposures between the villages of Rio Pueblo and Tres Ritos mark the southern limit of this study.

Physical Features

Taos County exhibits a variety of physiographic features (Fig. 3) that are the result of a continuous and varied geologic history. Simply, two large divisions are readily apparent: the Rio Grande Depression in the western half and the north-trending Sangre de Cristo Mountains in the southern and eastern part of the county.

The Rio Grande Depression has two distinct regions. The Taos Plateau or Taos Plain (Fig. 4) is a southwestern extension of the San Luis Valley or Basin of Colorado. Although most of the plateau is level, hills ranging from 2100 meters (6900 feet) to 2450 meters (8100 feet) are scattered over its extent. Most of these hills are dead or dormant volcanoes. The plateau appears smooth from a distance but its unconsolidated sediment is cut by many stream channels as it gently slopes up to the foothills of the Sangre de Cristo. Taos (Fig. 5) rests at the juncture between the depression and the mountains at an elevation of about 2100 meters (7000 feet).

The Rio Grande Gorge (Fig. 6) is the second dis-

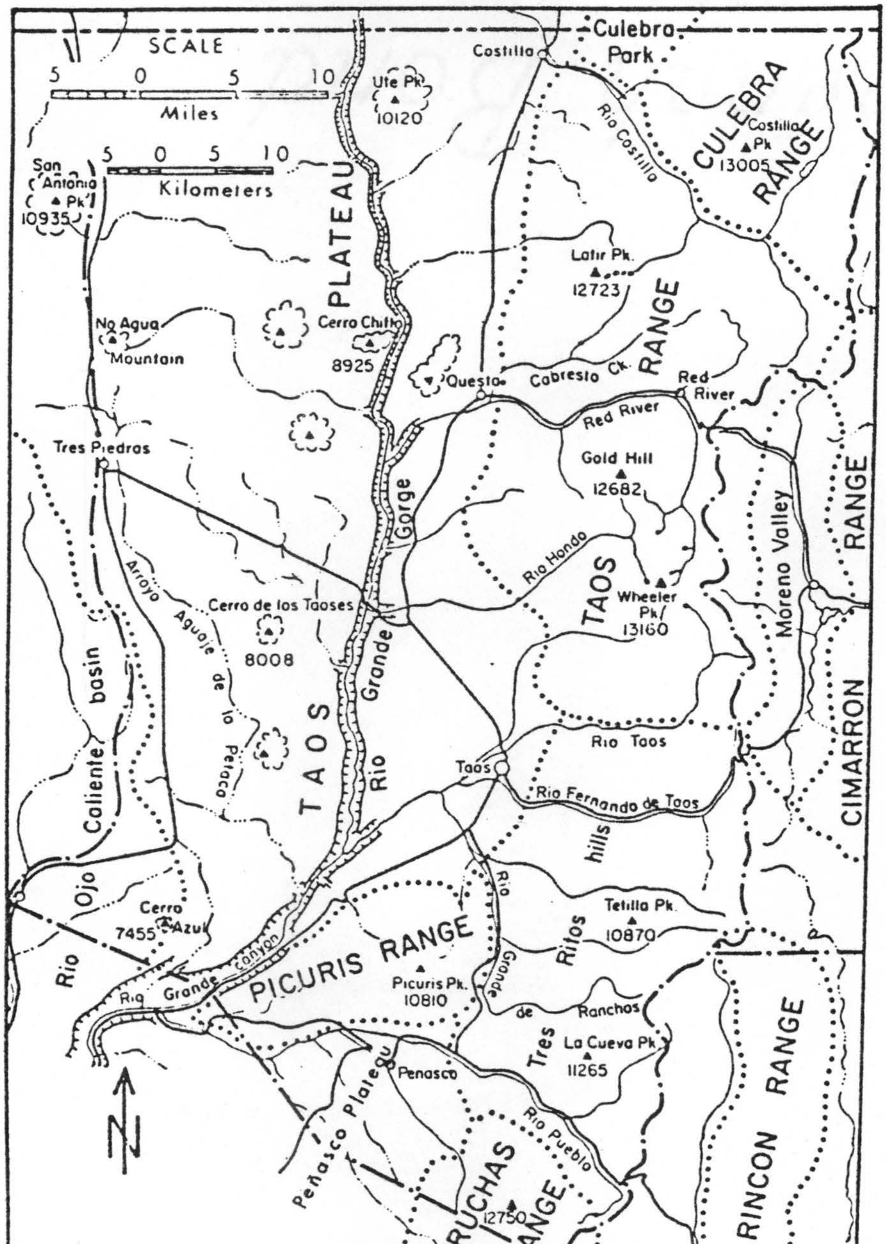


Figure 3. Physiographic map of Taos County. From Schilling (1960).

Figure 4. Taos Plateau viewed from the D.H. Lawrence Ranch above Arroyo Hondo looking south.

Figure 5. Taos and Taos Range viewed from above Talpa looking north.

Figure 6. Rio Grande Gorge with Picuris Mountains in background; viewed from Highway 64 bridge looking south.

tinct feature of the depression and cuts southward across the Taos Plateau through unconsolidated sediments and volcanic flows. The volcanics provide the resistant material that forms the gorge's vertical cliffs that range from 90 meters at the Colorado Border to over 300 meters at Pilar; westward from the mountains, streams flow through narrow valleys, and shallow arroyos cut across the plain to the gorge (Schilling, 1960). No flowing streams exist on the west side of the gorge; the trend of arroyos is southeastward.

Culebra Park in the north and Penasco Plateau in the south comprise minor features of the Rio Grande Depression.

The Sangre de Cristo Mountains are the other large physiographic division in Taos County with five ranges contributing to the southern extension of the Rockies. The Culebra Range in the northeast, with Costilla Peak attaining a height of 3940 meters (13,005 feet), forms only a minor portion of the Taos County ranges.

The major range in the county is the Taos Range (Fig. 7) which contains Wheeler Peak with an elevation of 3985 meters (13,150 feet), the highest in New Mexico. The western front of this range rises very sharply from the Taos Plateau into many massifs that reach above the timberline at 3580 meters (11,800 feet). Ninety percent of the

Figure 7. Rio Grande de Rancho Valley with Taos Range in background; viewed from Beaver Ridge looking north.

Figure 8. Picuris Mountains with Taos rooftops in foreground; viewed from Taos looking south.

streams flow perennially through deep valleys toward the Rio Grande (Schilling, 1960).

The Picuris Range (Fig. 8) lies about eight kilometers (five miles) southwest of Taos and is an isolated spur of the north-trending Sangre de Cristos. Its eastward boundary is marked by the perennial Rio Grande de Rancho above which to the west are secondary ridges formed by the Arroyo Penasco, the primary ridges being the more resistant Precambrian rocks. The highest point is Picuris Peak at 3275 meters (10,810 feet). Intermittent streams have cut deep valleys into crystalline rock and, depending upon which slope they drain, empty either into the Rio Grande or Rio Pueblo.

East of the Picuris Range, on the other side of the Rio Grande de Rancho, are the Tres Ritos Hills. The topography here is not as rugged because most of the crystalline rocks are overlain by a thick section of relatively unresistant sedimentary strata. The Rio Pueblo runs through the southern portion of the hills, and it is here that many good exposures of Arroyo Penasco rocks are found.

The last range is the Truchas which forms the extremely rugged Pecos Wilderness Area. This southern portion of the Sangre de Cristo Mountains offers the highest and most spectacular peaks in the area, many being over 3600 meters (12,000 feet) and exhibiting many glacial features. Most of the Truchas Range is resistant crystalline rock, and the Pecos River cuts a gorge through it that is more than 300 meters deep in places (Sutherland, in Miller, et al., 1963).

Climate and Vegetation

Taos County has a semi-arid climate on the plateau and in the lower reaches of the mountains. At its elevation of 2100 meters (7000 feet), Taos receives about 33 centimeters (13 inches) of moisture annually and has average temperatures of 26.3° Fahrenheit in January and 68.5° Fahrenheit in July; the ranges receive at least 25 centimeters (10 inches) more precipitation and become wetter and colder the higher one goes (Schilling, 1960). The rainy season occurs in July and August with thunderstorms in the afternoons. Deep snow covers the higher elevations through the winter and is on the peaks usually through summer; the plain remains free of major accumulations even in the winter.

Sagebrush and some grasses cover the Taos Plateau. In the Picuris Range, pinon, juniper, scrub oak, and mountain mahogany cover much of the slopes; high areas and canyons are wooded with Ponderosa pine (Schilling, 1960). Most of the field area is covered with this vegetation, making mapping and tracing of outcrops difficult. No detailed maps of the area exist. At the higher elevations fir and aspen displace the pines; only Alpine grasses and schrubs grow above the timberline. Along the rivers and springs are cottonwoods and willows.

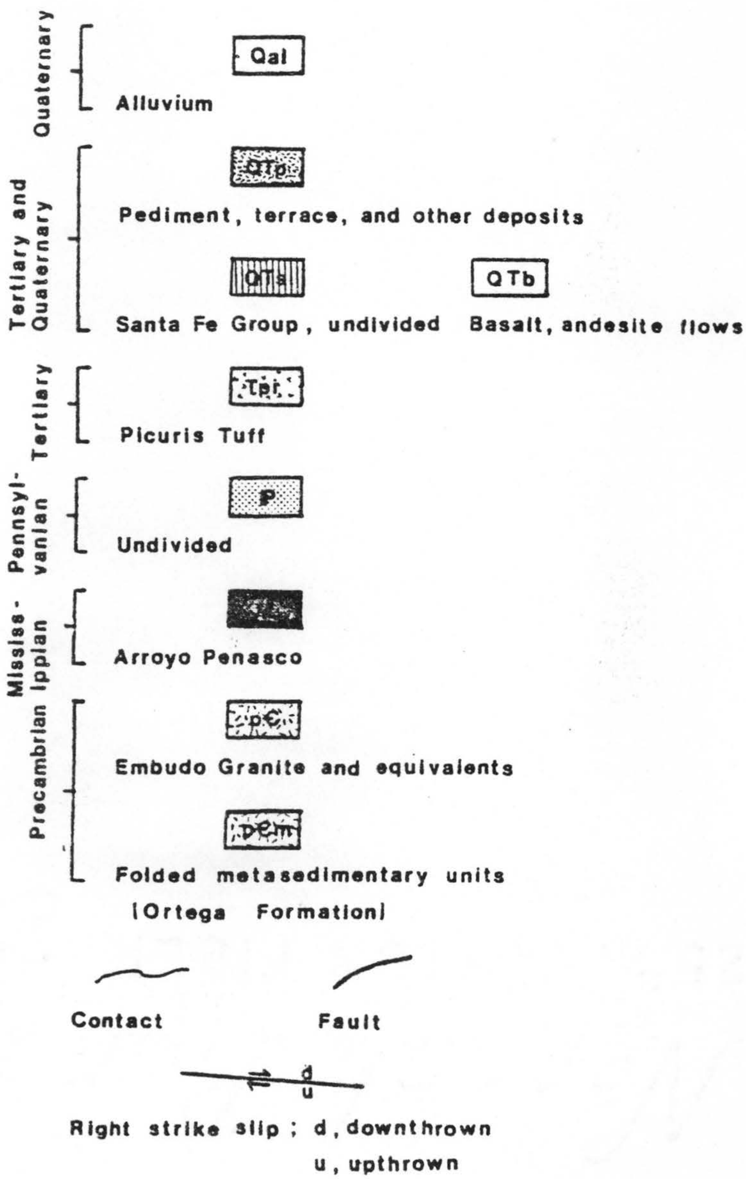
Hazards also abound in the area. Of course, the rugged topography and talus-covered slopes pose conditions that, when combined with certain climatological events, become real threats to hikers and campers. Certain flora and fauna are also harmful.

GEOLOGIC HISTORY

Miller, Montgomery, and Sutherland (1963) describe the observable structural patterns (Fig. 9) in the area as extremely complicated, these being the result of four major periods of deformation. Briefly, Montgomery relates the major episodes.

1) Precambrian, which entails the following events:
   a) Folding along east-west axes of metasedimentary rocks that are exposed in the Tres Ritos Hills, the Picuris Range, and the Truchas Range. Along with the folded Precambrian metasediments, are young metaigneous and igneous intrusions. Metaquartzites, schists and phyllites comprise the various layers of the folded metasediments (middle-high metamorphism). Kyanite, sillimanite, staurolite, muscovite, biotite, and quartz are the major minerals associated with these rocks. The granites in the field area are mainly alkali-feldspar granites, and some also show evidence of metamorphism. Associated with the intrusions are pegmatites that, along with the granites, contain tourmaline, rutile, and zircon that appear in the Arroyo Penasco sedimentary rocks.
   b) Thirty-eight kilometers of right strike separation

Explanation



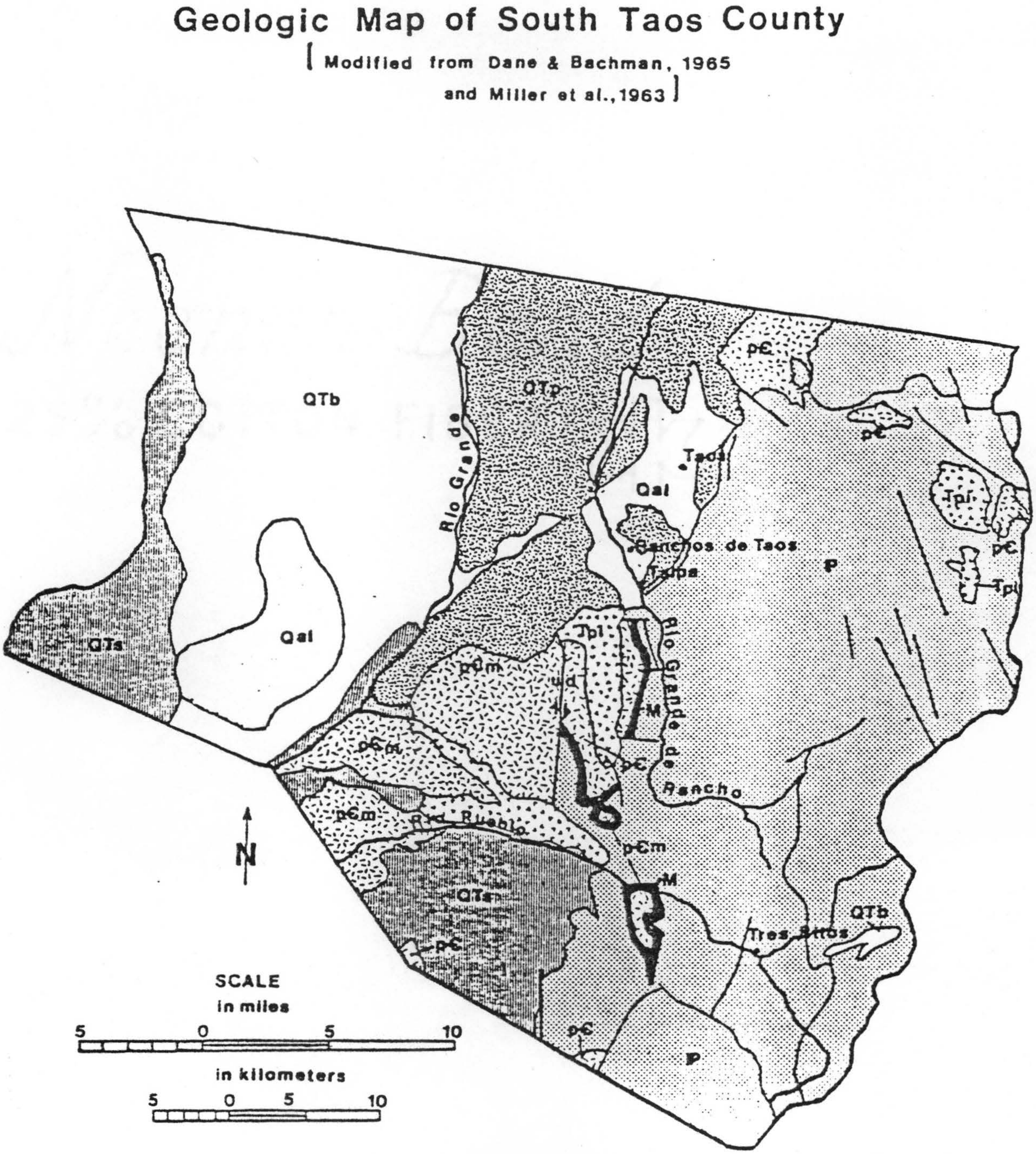


Figure 9. Geologic map of south Taos County. Modified from Dane and Bachman (1965b) and Miller et al., (1963).

on the north-trending Picuris-Pecos Fault. This fault passes through the Picuris Range about 7 kilometers west of the Rio Grande de Rancho. Montgomery (1963) states that most stike-slip movement occurred in Precambrian time. The Precambrian rock was then eroded until the Devonian or the Mississippian when the Arroyo Penasco was deposited.

2) Pennsylvanian uplift on the west side of the Picuris-Pecos fault, which, according to Sutherland (1963), involved two episodes of deposition east of the fault. During the active faulting in the Pennsylvanian, coarse sediment was deposited as deltas prograded into the basin or Taos Trough. During periods of quiescence fluvial and high-constructive deltaic systems fluctuated with carbonate shelf sediments. Sutherland states that the clastics were shed from the Uncompahgre Highlands west of the fault.

3) Mesozoic-early Cenozoic deformation that is marked primarily by vertical uplift on the west side of the Picuris-Pecos Fault.

4) Middle and late Cenozoic deformation that resulted in the uplift of the mountains. Miller (1963) divides post-Laramide time into three divisions:

a) Widespread volcanic activity in middle Tertiary time.

b) Formation of the Rio Grande Depression in Miocene time by normal faulting along the west boundary of the Sangre de Cristo Mountains. Widespread volcanic activity ceased in late Tertiary time, but large amounts of sediments were shed from the mountains into the down-faulted portions to the west. More movement might have occurred along the Picuris-Pecos Fault during this time.

3) Further faulting, erosion, sporadic vulcanism, and glaciation occurred in the Pleistocene.

The above sequence outlines the more active tectonic periods of geologic history. The most realistic ages assigned the Arroyo Penasco are either Devonian (Baltz and Read, 1960), or Mississippian (Armstrong, 1967). Whatever the case, this formation apparently was deposited during an interval of relative quiescence.

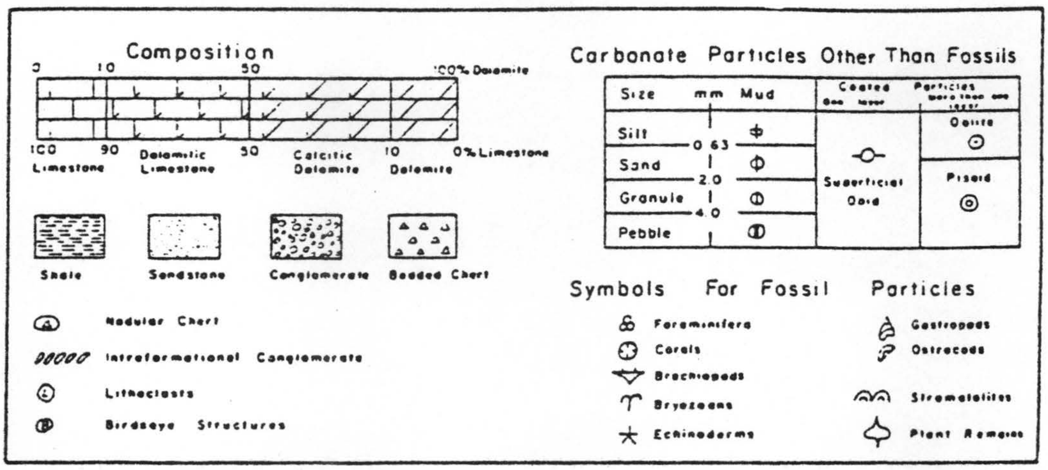
PREVIOUS WORK

Since 1904 when Read et al. mapped the entire clastic-carbonate unit of this study as the lowest member of the Sandia Formation, Magdalena Group, Pennsylvanian age, stratigraphic nomenclature and chronology have fluctuated, depending on the researcher. The major publications pertinent to the "debate" include Baltz and Read (1960), Baltz (1965), Sutherland (in Miller, et al., 1963), and Armstrong (1955, 1967).

The name Arroyo Penasco was given to the rocks overlying the Precambrian in northern New Mexico by Armstrong in 1955. Based on endothyrid fauna in the limestones, he assigned a Mississippian age to the entire section of rock between the Precambrian and Pennsylvanian (Fig. 10).

Baltz and Read (1960) discarded the name Arroyo Penasco and introduced a system that divided the strata into a complex sequence with various dates and names. Their basis for rejecting Armstrong's stratigraphy was the similarity of these rocks with Devonian ones in Colorado and their mistrust of the then untested efficacy of dating with Endothyra. They proposed the name "Espiritu Santo" for the lowest clastic-carbonate unit and assigned to it an Upper Devonian date.

EXPLANATION



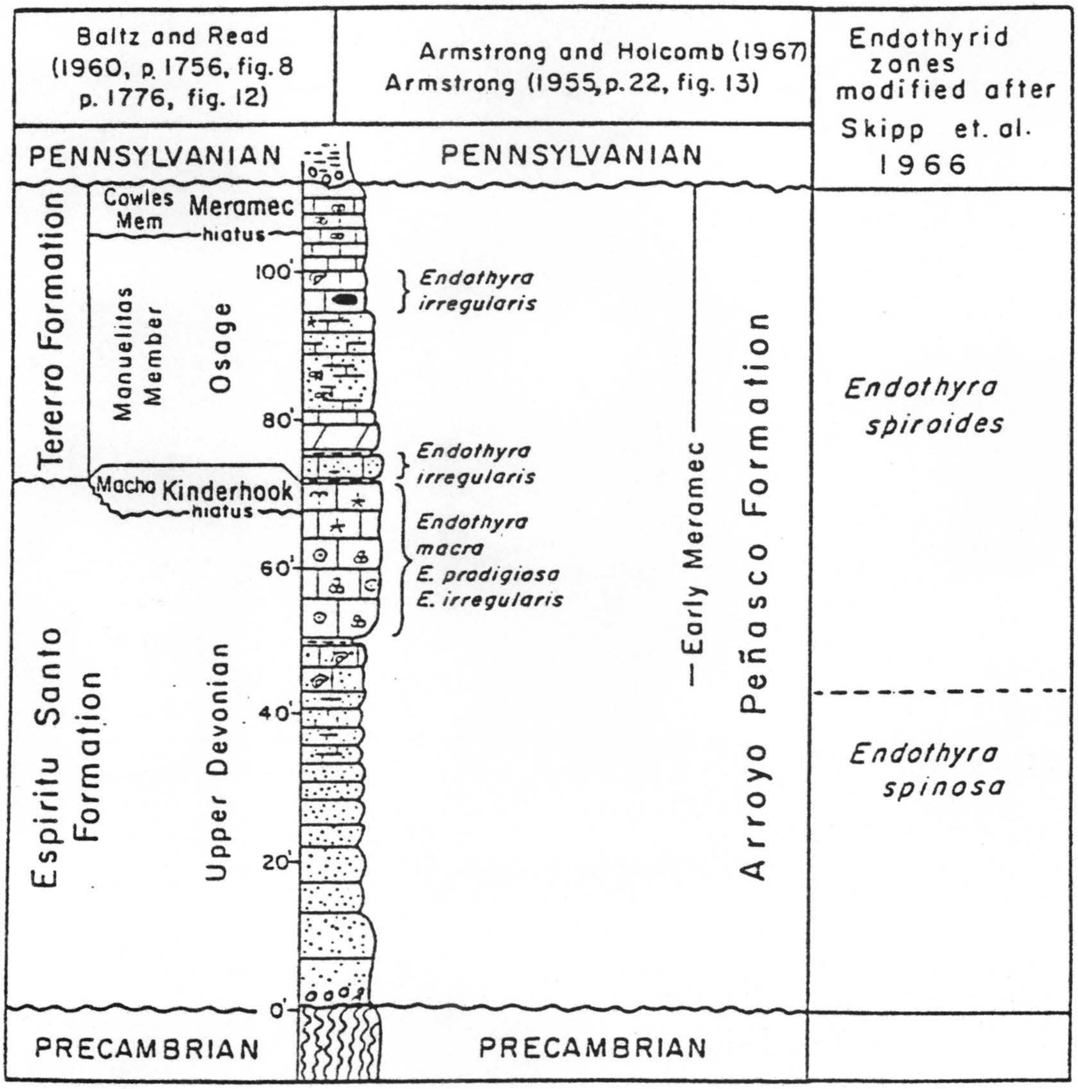


Figure 10. Stratigraphic columns with various divisions and ages. From Armstrong (1967).

In 1963, Sutherland followed Baltz and Read's revision but removed the clastic unit from the Espiritu Santo Formation, named it the Del Padre Sandstone, and assigned any age from Late Precambrian to Early Mississippian.

In 1965 Baltz reaffirmed his original Devonian date and name for the unit. The 1:500,000 geologic map of New Mexico edited by Dane and Bachman (1965b) follow Baltz in his usage.

In an extensive study, Armstrong (1967) asked for a return to his 1955 terminology. This was based on his faunal work involving the unit and a wide areal analysis of the stratigrpahic and lithologic relationships within the unit. Armstrong assigns an Early Meramecian age to all the carbonate rocks and lists as probable that same age for the clastic section. He includes this basal unit as the initial phase of a cycle that was transgressive across a Precambrian peneplain.

This study follows Armstrong's terminology and dates. Stratigraphic relations observed in the field tend to support Armstrong's interpretation. Relevant observations will be presented in succeeding sections.

FIELD RELATIONS AND METHODS

Field work was accomplished during the summer of 1977, December of 1977, and March of 1978. Reconnaissance was facilitated by the use of the 1:63,360 map of Miller et al. (1963) that covers the extreme southern part of the county; the 1:500,000 map of New Mexico compiled by Dane and Bachman (1965b); the Ranchos de Taos and Tres Ritos Quadrangles (1964) of the USGS; and the works of Armstrong (1967), Sutherland (in Miller et al., 1963), and Baltz and Read (1960).

With the aid of these tools, a thorough search of south Taos County revealed that the most complete and best exposed outcrops are usually within view of New Mexico State Highway 3. In the Rio Grande de Rancho Valley, one must ford the river and travel up the narrow canyons that cut through the Picuris eastern slope. Usually the best outcrops appear in these canyons 150 meters above the road, elev., 2200 meters (7200 feet), or along a secondary ridge crest at about 2400 meters (7900 feet). The primary ridge at 2500 meters is held up by Embudo Granite.

The Arroyo Penasco beds in this area (Fig. 12) begin at Ponce de Leon Springs and extend south for about 4.2 kilometers (2.5 miles). Southward until Rio Pueblo Valley, the strata have been faulted farther from the road

Location Map of Arroyo Penasco Sections

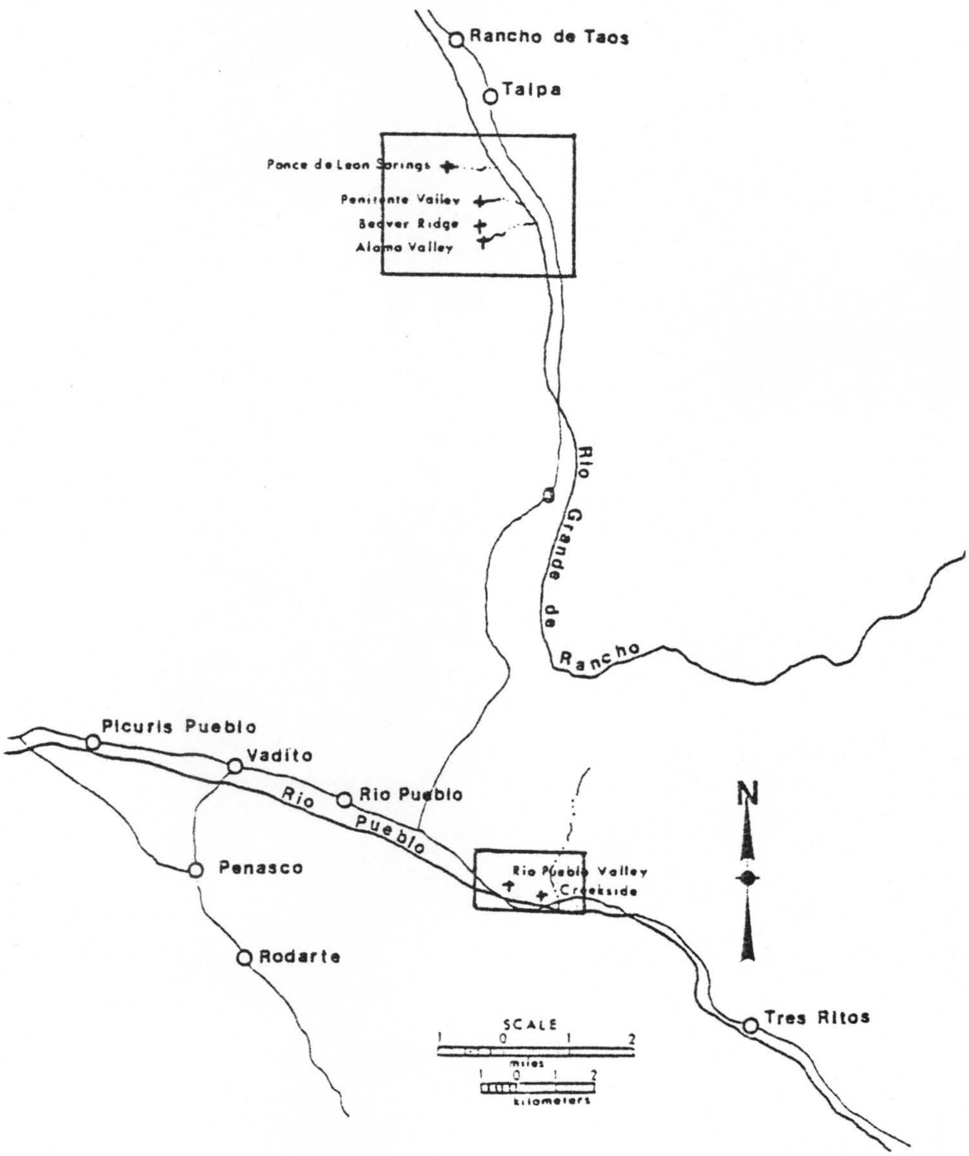


Figure 11. Location map of Arroyo Penasco sections.

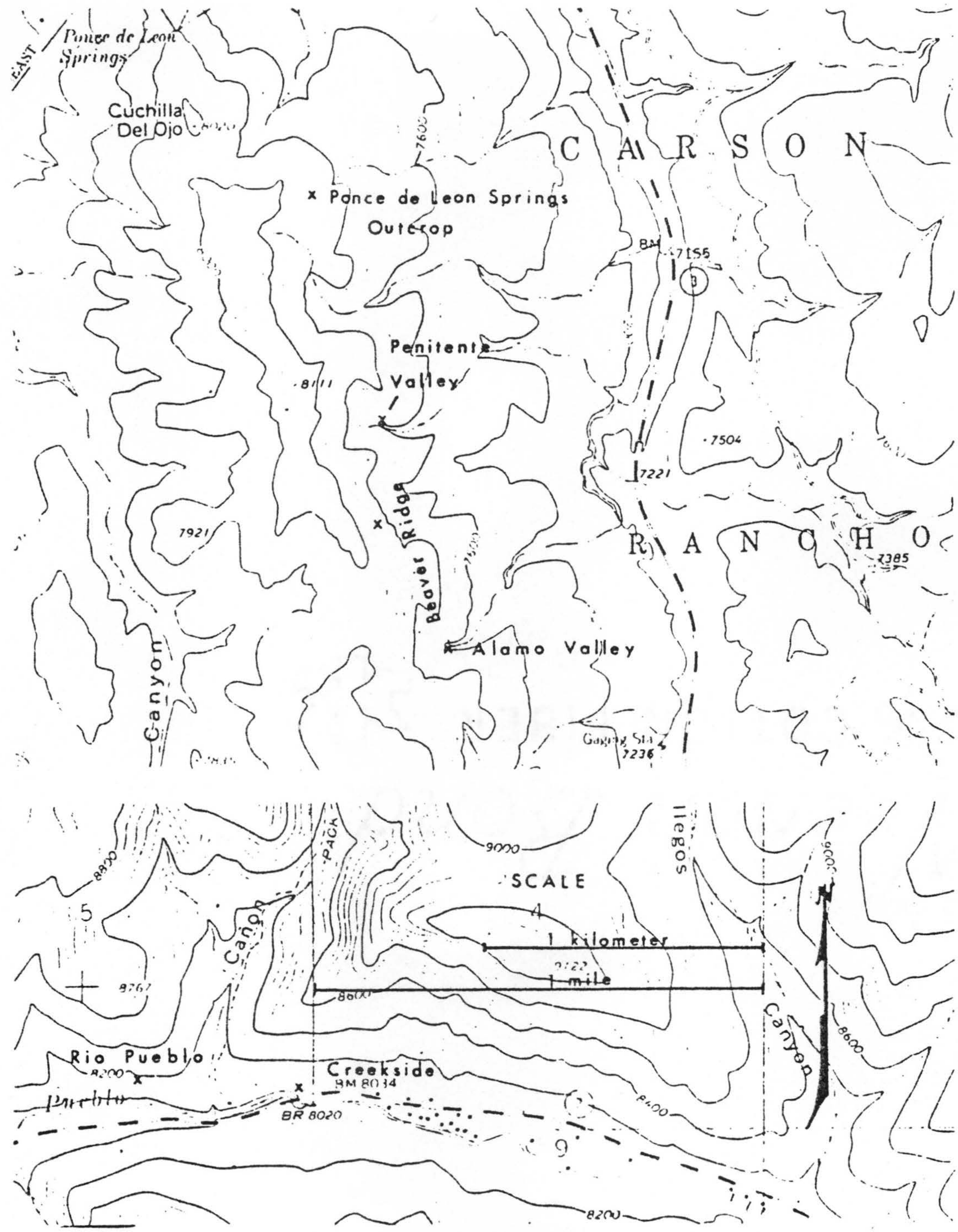


Figure 12. Detailed maps of outcrops. See Figure 12. From Ranchos de Taos and Tres Ritos Quadrangle sheets. U. S. Geol. Sur. (1964).

and in an orientation that has not permitted good exposure. The beds in this valley dip at angles between 70° and 80° NE and strike between N25°W and N40°W.

In Rio Pueblo Valley, a small, well-exposed section appears 5 kilometers (3.0 miles) east of the junction of State Highways 75 and 3 on Highway 3 and extends only 1.5 kilometers (1 mile) eastward. Faulting has obscured any further exposures. The beds dip 25° NE and strike N50°W. The exposures here occur along the Rio Pueblo on the north side.

Measured sections were done in six areas (Figs. 11, 12) and over 200 samples were taken over the entire area. Beginning in the Precambiran and measuring to the Mississippian-Pennsylvanian contact, hand specimens were taken every several feet. Even the carbonate portion of the Arroyo Penasco was extensively sampled to determine a stratigraphic boundary between it and the lower clastic section.

STRATIGRAPHY

Precambrian and Upper Arroyo Penasco

The Arroyo Penasco rests either on the Embudo Granite, the Ortega Metasedimentary unit, or their intensely weathered surfaces. The granite is usually gray and coarsely crystalline with the dominant microcline crystals sometimes several centimeters in diameter. The rock is an alkali-feldspar granite with 0-5% plagioclase and 20-60% quartz. This Precambrian intrusive or its regolith underlies all the examined outcrops in Rio Grande de Rancho Valley. Baltz and Read (1960) report the Precambrian in the area of Ponce de Leon Springs as being a quartzite, but it is actually a granite.

In Rio Pueblo Valley the Arroyo Penasco was deposited on the Ortega Metaquartzite. This unit is composed of quartz crystals that are obviously the products of earlier sedimentary episodes. But the dominant mineral is microcline, probably the metamorphic product of an argillaceous matrix or an arkose. The foliation is delineated by biotite or muscovite. In other areas the Ortega is almost entirely quartz.

The clastic Arroyo Penasco conformably grades into or interfingers with the carbonate section at all areas.

No evidence of an unformity was found. Rather the clastic unit usually changes within two meters from a sandstone with clay cement, to a sandstone with a clay and calcite spar cement, then to a sandy sparite, and finally to a sandy micrite. The boundary between the two sections is arbitrarily that point where the unit changes from a sandy sparite to a micrite with less than 50% terrigenous material.

Outcrop Features and Structures

Outcrop Thicknesses and Bedding Characteristics

The outcrops in southern Taos County range from about six meters to 15 meters in thickness. The thicknesses of the outcrops vary over the field area as much as 10 meters (Fig. 13), indicating a very irregular Precambrian peneplain. Sutherland (in Miller et al., 1963) offers a regional map of the Arroyo Penasco with thicknesses over a much larger region (Fig. 14). The recorded 700 foot thickness is probably not an Arroyo Penasco outcrop; it is bounded by faults and is of a later tectonic-depositional episode (Armstrong, 1967).

The bedding is very similar at all outcrops with beds as thin as a centimeter (Fig. 15) and others as thick as two meters. The more massive beds appear in the middle and upper parts of the clastics where silica cement is more

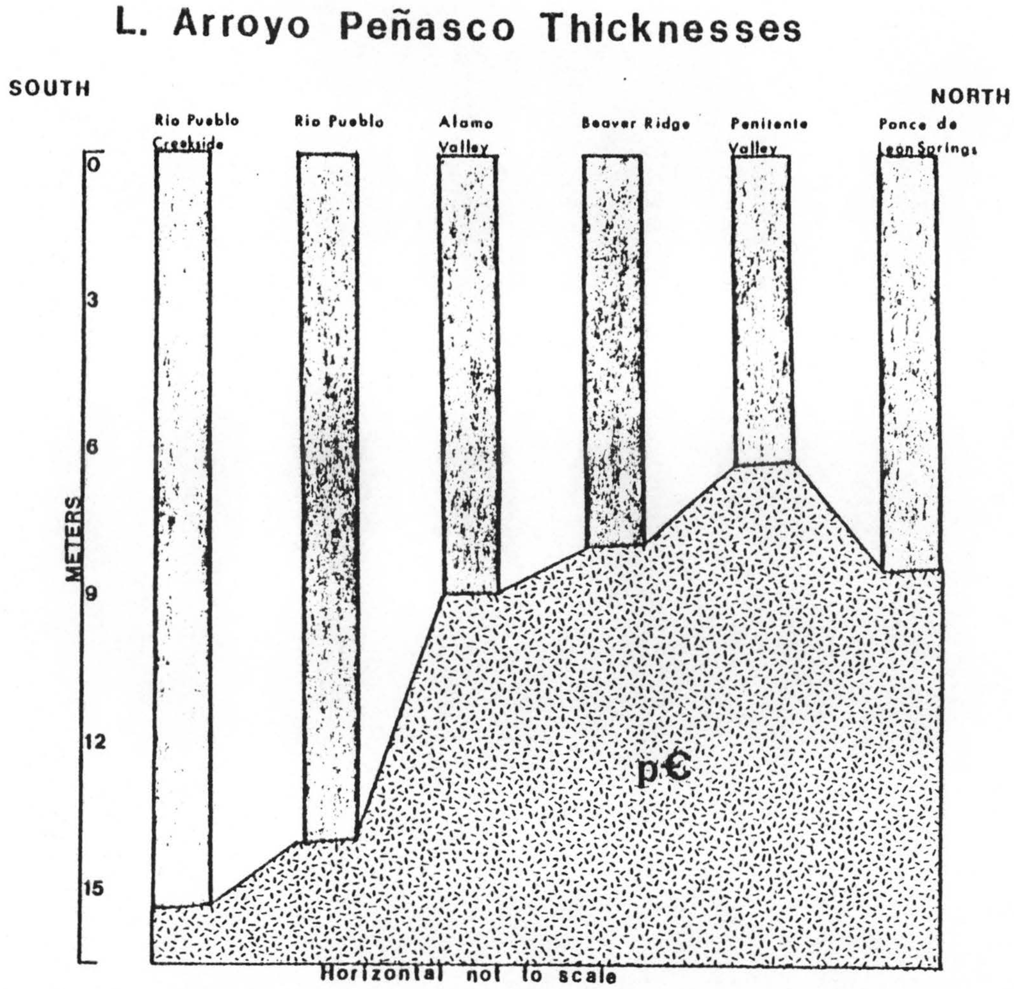


Figure 13. Lower Arroyo Penasco thicknesses in Taos County.

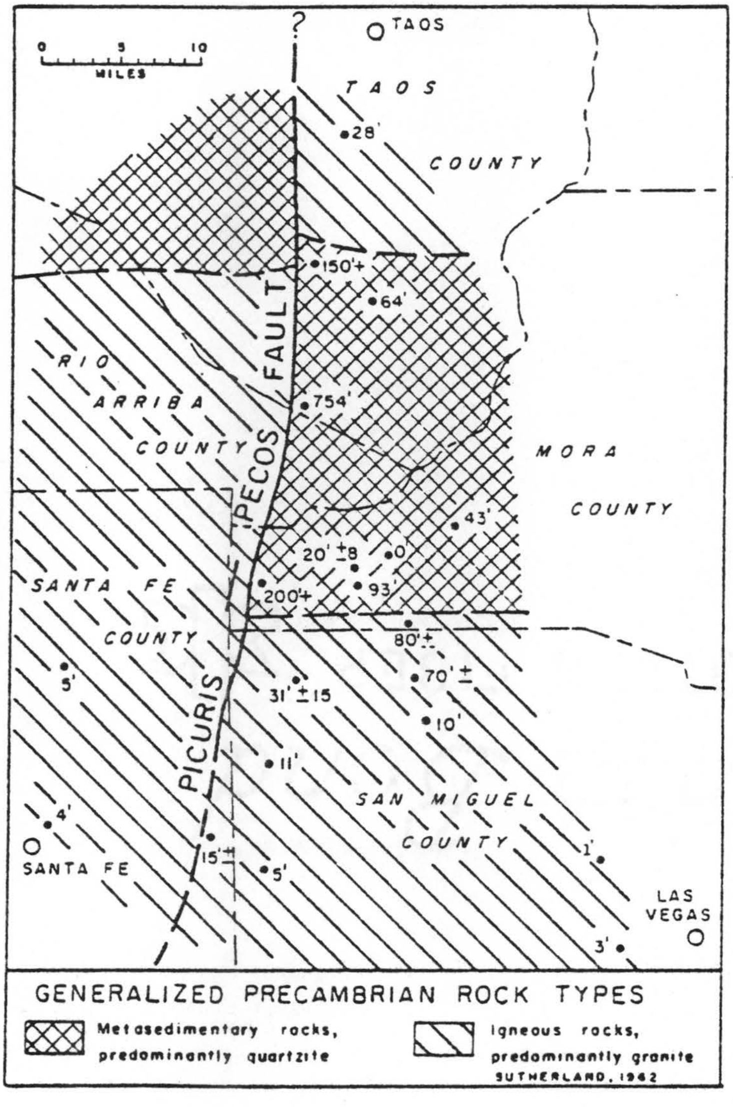


Figure 14. Thicknesses of lower Arroyo Penasco in northern New Mexico. From Sutherland in Miller et al., (1960).

Figure 15. Arroyo Penasco outcrop composed of thin beds. Penitente Valley 3 meters above section base.

abundant; the less resistant beds have a larger portion of clay cement and are less well-differentiated (Fig. 16).

There are two dominant bedding types: lenticular beds and coextensive tabular beds. The lenticular beds are at the most one meter thick and about five meters wide, pinching out to a feather edge at both sides (Fig. 17). The tabular beds maintain a constant thickness as long as the outcrop is visible (Fig. 17); these are probably sheetlike in three dimensions. An intermediate type exists, that being a lenticular bed of wide extent (15 m) that pinches out on both sides. The tops of many beds are scoured by later overriding units.

At the transition zone of clastic to carbonate, the beds usually become less resistant and less defined. This zone grades upward into a massive section of gray, extremely resistant lime mudstone.

Sedimentary Structures and Related Characteristics

Planar (Fig. 18), medium trough (Fig. 19), and low angle tabular (Fig. 20) cross-stratification types are present throughout the beds in the formation. Planar stratification occurs predominantly in the tabular beds or at the top of lenses. Low angle tabular cross-stratification also occurs with the planar. The medium scale troughs are associated with the bottom of lenses or some-

Figure 16. Lower Arroyo Peñasco outcrop in Rio Pueblo Valley. The lower units are less well-defined than the higher ones; the lower beds have more clay and less quartz cement.

Figure 17. Rio Pueblo Valley outcrop. Notice small lenticular paleochannel (c) at bottom of unit. Tabular beds at top.

Figure 18. Planar bedding delineated by hematite. Beaver Ridge 2 meters above section base.

Figure 19. Medium-scale trough cross-bedding. Beaver Ridge 1.5 meters above section base.

Figure 20. Medium-scale low-angle tabular cross-bedding. Rio Pueblo Creekside 15 meters above section base.

times beds of the intermediate type. Also a herringbone pattern (Fig. 21) is present: tabulars slanting alternately in opposite directions. These stratification types are delineated by iron stains in a white silica-cemented field (Fig. 19) or white streaks (silica) in a green chloritic, illitic field (Fig. 22).

Azimuths on the cross-stratification are very difficult to measure. On beds where readings were ascertained, there appeared to be no dominant transport direction; rather the currents flowed bi- or multi-directionally. There are exceptions that are associated with groups of lenses where transport was east to west.

Considering grain size trends, the typical fining upward sequence is present in most beds. An angular gravel and cobble lag is frequently at the bottom of beds but also is present in the center of beds where it forms a very sharply delineated band (Fig. 23). The features to note here are the extreme angularity of the pebbles as well as the extreme break in grain size. From the previous observations it follows that these pebbles were not transported very far and were introduced quickly and sporadically into the system.

Other sedimentary structures include mudcracks, crystal casts, and burrows. The mudcracks (Figs. 24, 25) indicate two things: the subaerial exposure of the sedi-

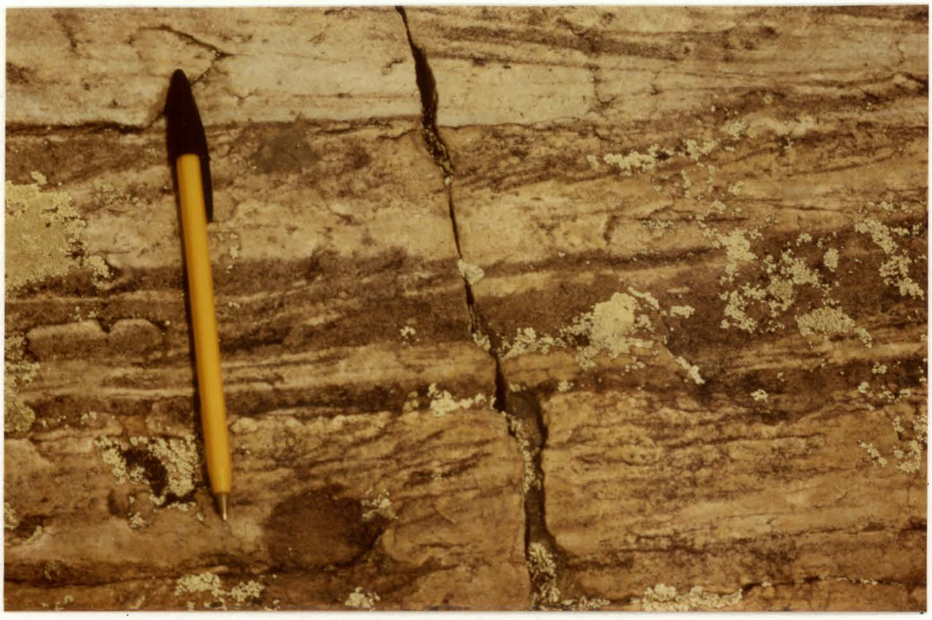


Figure 21. Herringbone cross-bedding indicating bidirectional currents. Rio Pueblo Creekside 9 meters above section base.

Figure 22. Maculose texture. The white blebs are primary quartz cement; the green matrix is chlorite and illite. Rio Pueblo Creekside 6 meters above section base.

Figure 23. Angular pebbles of quartz in middle of bed.
Beaver Ridge 1.0 meter above section base.

Figure 24. Mudcrack impressions in coarse-grained unit.
Beaver Ridge 1.0 meter above section base.

Figure 25. Mudcrack impressions. Beaver Ridge 1.5 meters above section base.

Figure 26. Crystal casts and mudcrack impressions indicating subaerial exposure and presence of evaporites. Penitente Valley 1.5 meters above section base.

ment and the presence, albeit minor, of mud in the system at one time. The cubic-shaped crystal casts (Fig. 26) are evidence that the sediment at one time contained evaporites that were also subaerially exposed. And the burrows (Fig. 27) are the trace fossils of an animal whose organic remains were not preserved.

At one location there is a linear zone of gray blebs (Fig. 28) that is more resistant than the surrounding sandstone. These are actually regions of chert-cemented sand, and probably represent paleosilcretes to be discussed later. Also there are beds that exhibit a maculose appearance (Fig. 22). This is due to patchy quartz cementation prior to chlorite and illite precipitation. Finally, instead of six detailed descriptions of outcrops (that do appear in verbal form in Appendix I), a composite outcrop description is presented in Figure 29.

Figure 27. Relic worm burrow. Penitente Valley 3 meters above section base.

Figure 28. The blue blebs are paleosilcrete (ps) concretions composed of chert-cemented sand. Beaver Ridge 2 meters above section base.

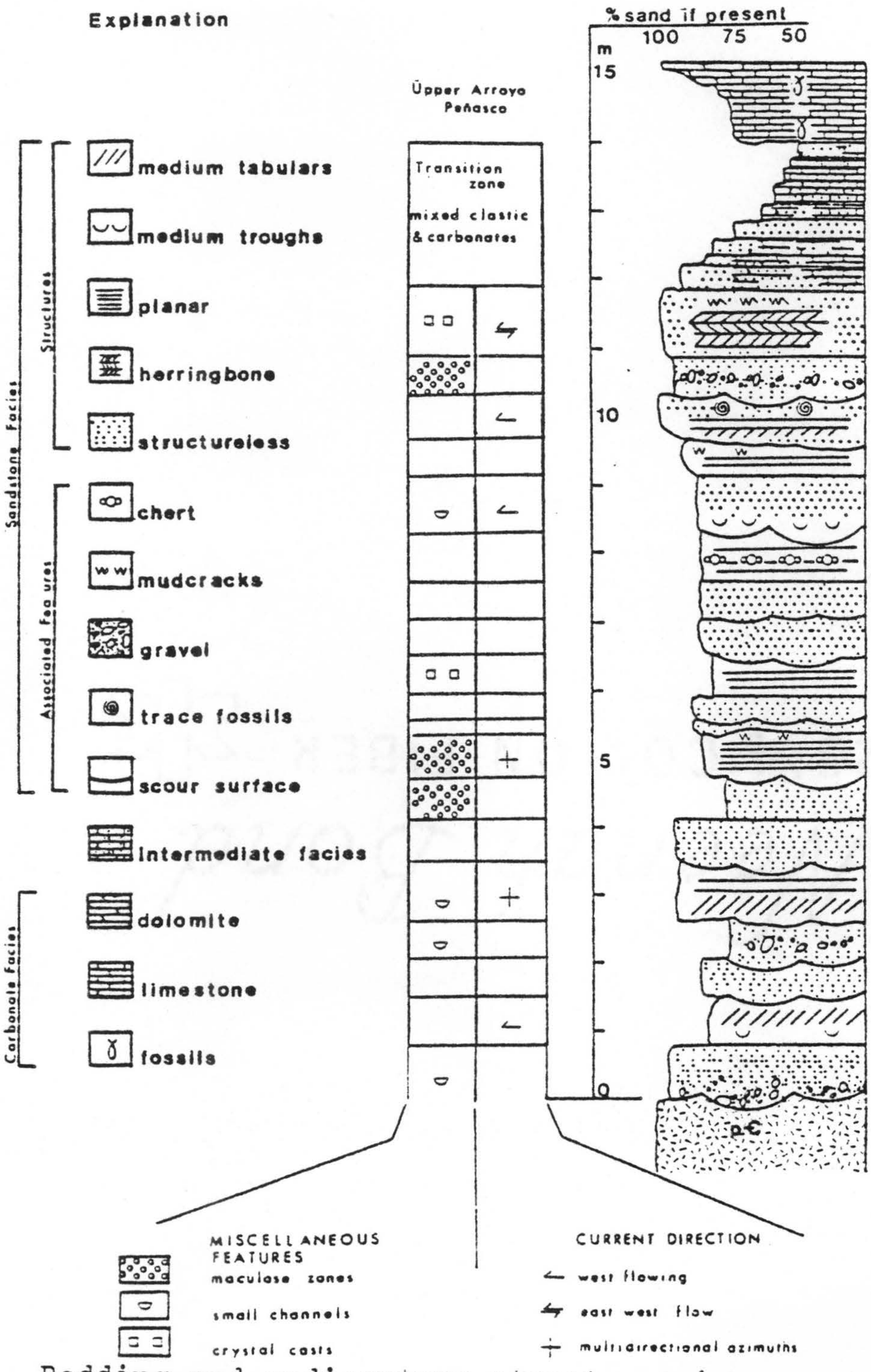


Figure 29. Bedding and sedimentary structures in Lower Arroyo Penasco. A composite almost real section for any given locality of the six that were studied.

PETROGRAPHY AND LABORATORY ANALYSIS

Previous Work

Armstrong (1967), Sutherland (in Miller et al., 1963), and Baltz and Read (1960) have done limited thin section analysis of the Arroyo Penasco. In his studies, Armstrong concentrated more on the examination of the carbonates and their diagenesis. Sutherland used Folk's classification (1974) but only to the extent of giving the five-fold name. He did not go into detail on grain types, clay morphology, or diagenesis. Baltz and Read's analyses primarily discussed textural relations and grain identification.

Methods

For petrographic analysis, several types of microscopes were used: a Zeiss binocular petrographic microscope with a maximum magnification of 3000X; a Leitz binocular microscope (500X); an Olympus OM-1 35 mm camera adaptable to both microscopes; and accessory tools for both scopes. The departmental scanning electron microscope served to better delineate clay types and relationships. Magnification with acceptable resolution seldom exceeded 2000X. For complete clay and carbonate identification x-ray diffraction was employed. Staining (Lindolm and Finkelman, 1972) and etching techniques enabled identification of the several carbonate minerals.

Over 200 thin sections were examined and point-counted. For most sections a count of 100 grains sufficed, but for superdetails 200 to 400 grains were counted. Folk's classification (1974) is used throughout in both clastic and carbonate descriptions. The appendix sample number is appended to each thin section micrograph.

TERRIGNEOUS COMPONENTS

Quartz

Because quartz comprises greater than 95% of the framework grains in most thin sections, the entire Arroyo Penasco falls categorically in the quartzarenite clan (Fig. 30). As an aside, the observation should be mentioned that in many samples, especially those rich in clays and carbonates, there appears to have been replacement of grains that were originally framework. These grains were probably feldspar, and in some cases these fragments would have comprised a framework fraction greater than 5%. The rock would then fall into the subarkose clan. Such alteration, however, incorporates the grains into what is now recognized as part of the matrix or cement.

Texture

Because quartz forms such a large fraction of the clastic material, its textural characteristics can be ascribed to the sediment as a whole. The degree of sorting varies inter- and intrastratally according to the flow regime of the current and grain sizes available at the time of deposition. Within the Arroyo Penasco sorting values run the gamut from very poorly sorted (Phi standard deviation = 2.00) to very well sorted (Ø S.D. = .35).

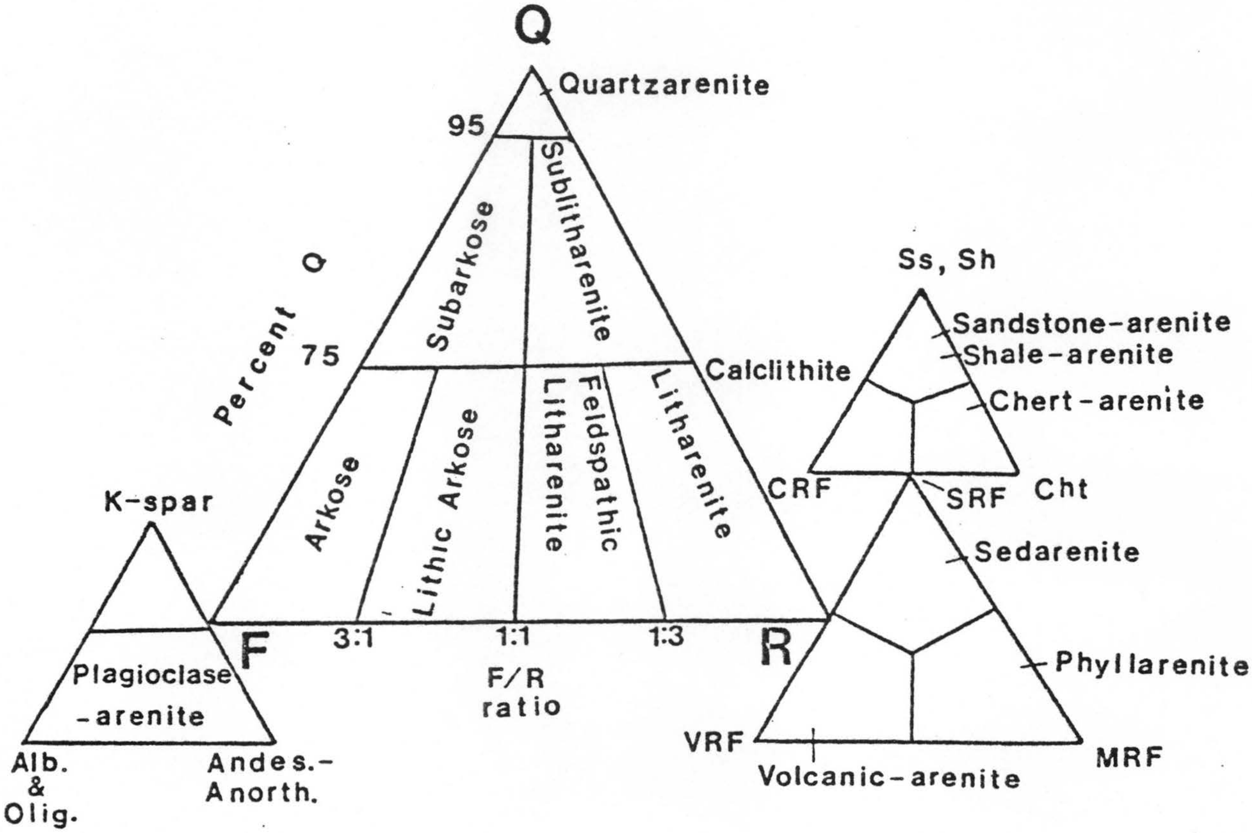
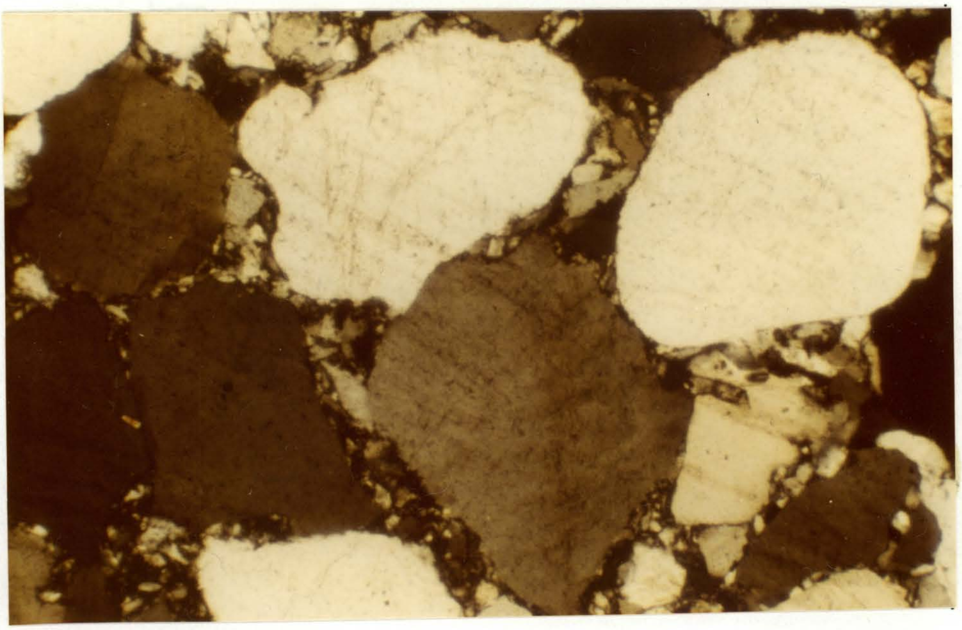


Figure 30. Sandstone classification. From Folk (1974).

This measure is simply a numerical correlative of the disparity in grain sizes found in one particular specimen.

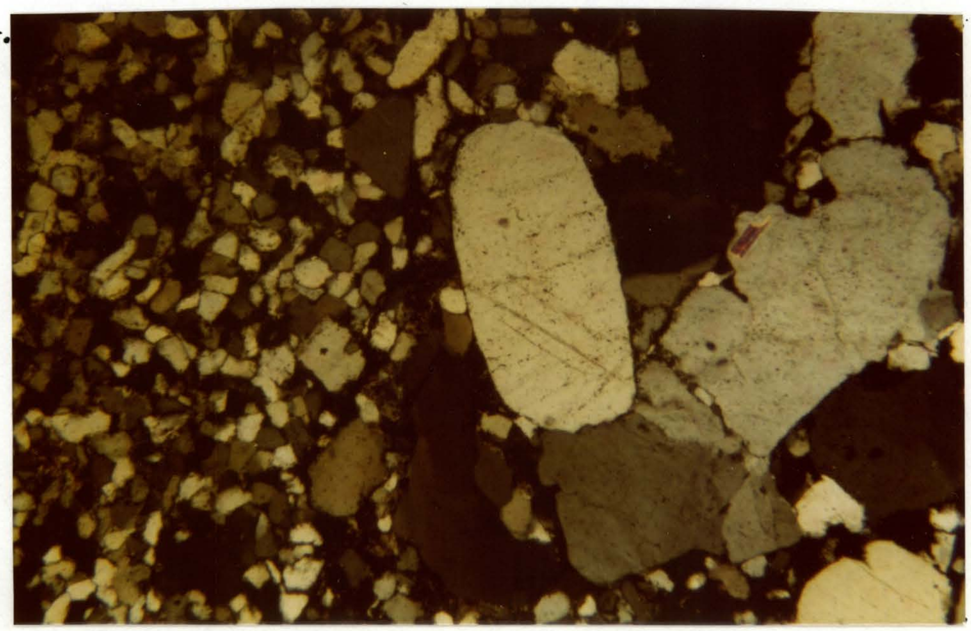
In this formation, the quartz sizes range from silt (.004 mm, 8ϕ) through small cobbles (64 mm, -6ϕ). Likewise, roundness values run the complete spectrum. In this formation individual grain roundness is determined either by the number of sedimentary cycles experienced or the current duration and intensity in the last depositional environment. In some samples, many grains are very round (5-6 ρ) (Folk, 1955), others angular (1-2 ρ), all being the same size. Obviously, transport to this depositional site did not completely determine the roundness; the round grains inherited their values from a previous cycle. On the other hand, some sections display high sorting and roundness values; considered with the bedding and stratification types, this sand roundness is probably a product of its depositional environment.

In some cases the sediment is bimodal. In thin section this bimodality is expressed either homogeneously where the two grain sizes are mixed throughout (Fig. 31) or segregated into distinct regions (Fig. 32). In the first case, the sediment sorting seems to be a result of aeolian deflation and mixing of sizes by weak currents; the second case indicates a process, probably a pulsing current, where the two size populations are each well sorted and isolated



1.0mm

Figure 31. Homogeneous bimodality. Perhaps a product of aeolian deflation. Crossed nicols. Sample # 89.



.5mm

Figure 32. Zoned bimodality. Probably the result of variable currents. Crossed nicols. # 14X.

from each other. Grain size and sorting also determine cements as in Figure 33 where well sorted, fine grains are silica-cemented and poorly sorted, coarse grains are cemented by calcite as well as primary silica.

A diagenetic phenomenon occurs in the Arroyo Penasco, often subsequent to deposition, that alters the shape and roundness of the grains. Solutions dissolve silica, and as a result grains display embayments, solution-enlarged fractures (grikes), and abnormal roundness values (Figs. 34, 35, 36, 37). This solution eliminates original grain features, especially where both incipient overgrowths and mother grains were dissolved. Some of these embayed and fractured grains are inherited. But they could not have been transported far or vigorously and remained intact because of the fragile shape effected by dissolution. At certain locations all grains both fine and coarse are dissolved, bespeaking total in situ alteration. In addition, polycrystalline grains are noticeably absent in regions of high dissolution.

Poorly sorted sands with less than 5% original terrigenous clay are considered submature; well sorted sands with roundness values greater than (3 ρ) and less than 5% original terrigenous clay are considered supermature. These end members of the maturity scale and the intervening types are all encountered in the Arroyo Penas-

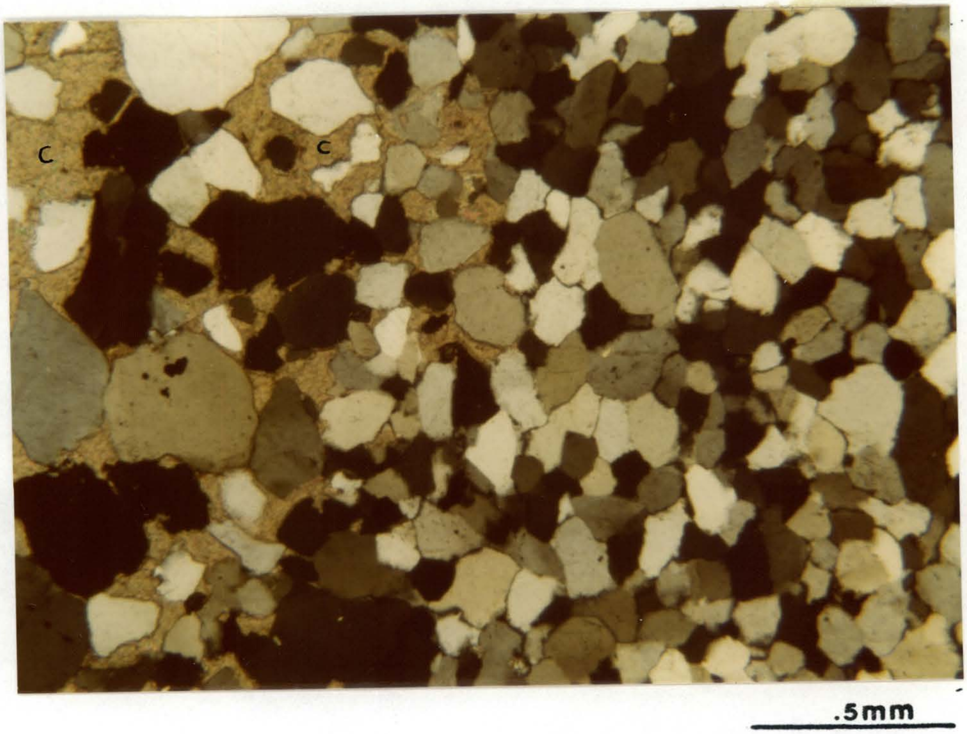
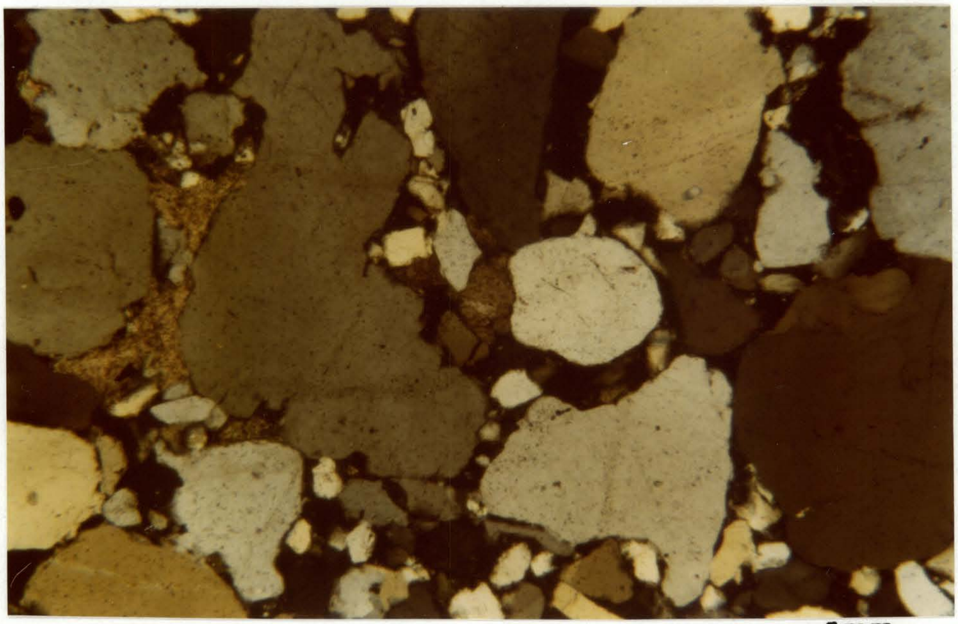


Figure 33. Grain-size-determined cement zones. The fine-grained zone is completely cemented by quartz. The coarse-grained zone had enough space for both quartz and poikilotopic calcite (c). Crossed nicols. # 23X.

.2mm

Figure 34. Embayed quartz grains in clay matrix. Plane light. # 6.



.5mm

Figure 35. Embayed quartz grains exhibiting a bimodality. This bimodality could be a result of deposition or in situ solution fracturing. Crossed nicols. # 17X.

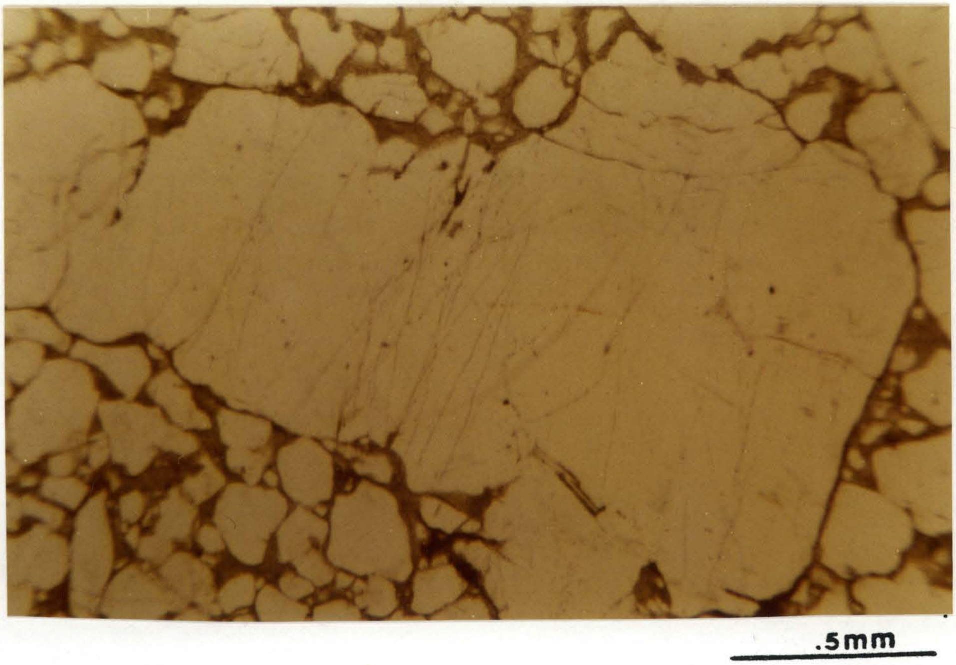


Figure 36. Solution fractures or grikes following strain trails in quartz grain. Plane light. # 123.

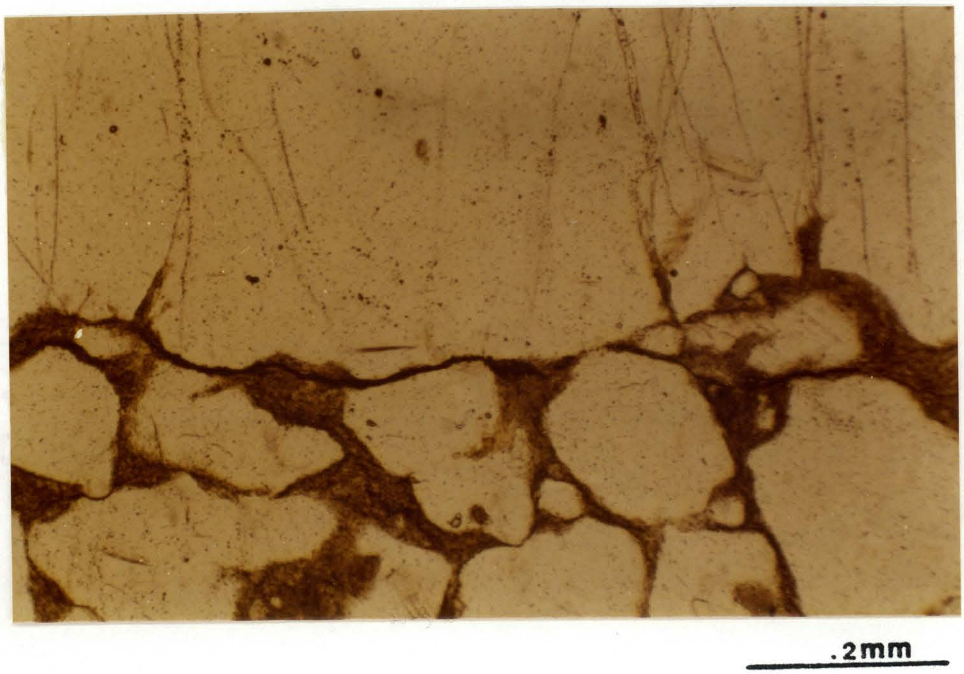


Figure 37. A more detailed micrograph of solution fractures. Plane light. # 123.

co. Admittedly, there is some detrital clay, but it is usually less than 2 or 3%. There is the possibility that some of the clays are recrystallized detrital residue and now appear authigenic. The section on authigenic minerals addresses this problem. In addition, there is also the phenomenon of clay infiltration subsequent to deposition. This also gives erroneous maturity values and will also be examined later.

The silt fraction comprises a very small percentage of clastic material. It could be infiltered from later depositional events or be an aeolian deflation product (Fig. 31). The clastic portion of the Arroyo Penasco, then, is a relatively coarse-grained unit that was deposited by currents in the upper flow regime. For complete textural information see Appendix I.

Fabric and Packing

The descriptions used in this section are from the classification system modified by Adams (1964) (Fig. 38). In none of the samples is there a high degree of pressure solution (Type I). Most of the rock has no porosity, and there is always at least one type of cement and in many places as many as six types. The highest amount of porosity found, about 10%, appears to be the result of leaching of feldspar grains replaced by calcite or clay (Fig. 39).

Fabric Class

I. High degree of pressure solution, flattened grains, no porosity, no cement, sutured contacts

Fabric Class

II. Moderate degree of pressure solution, approximately equidimensional grains, little or no porosity, little or no cement, primarily concave--convex contacts with some flat, sutured contacts
   A. Cemented by
      1. Quartz overgrowths
      2. Quartz overgrowths with minor amounts of calcite
      3. Quartz overgrowths with some clay

Fabric Class

III. Minor degree of pressure solution, mostly original grain outlines, often some porosity, long or tangential contacts
   A. Poorly cemented (but normally tightly packed)
      1. Quartz overgrowths
      2. Calcite
      3. Dolomite
      4. Clay
   B. Well Cemented
      1. Quartz overgrowths
      2. Calcite
      3. Dolomite
      4. Clay

Fabric Class

IV. No pressure solution, original grain outlines, good porosity and (or) cementation w/no porosity, tangential contacts and floating grains
   A. Cemented but porous
      1. Calcite
      2. Dolomite
      3. Clay
   B. Cemented, no porosity
      1. Calcite
      2. Dolomite
      3. Clay

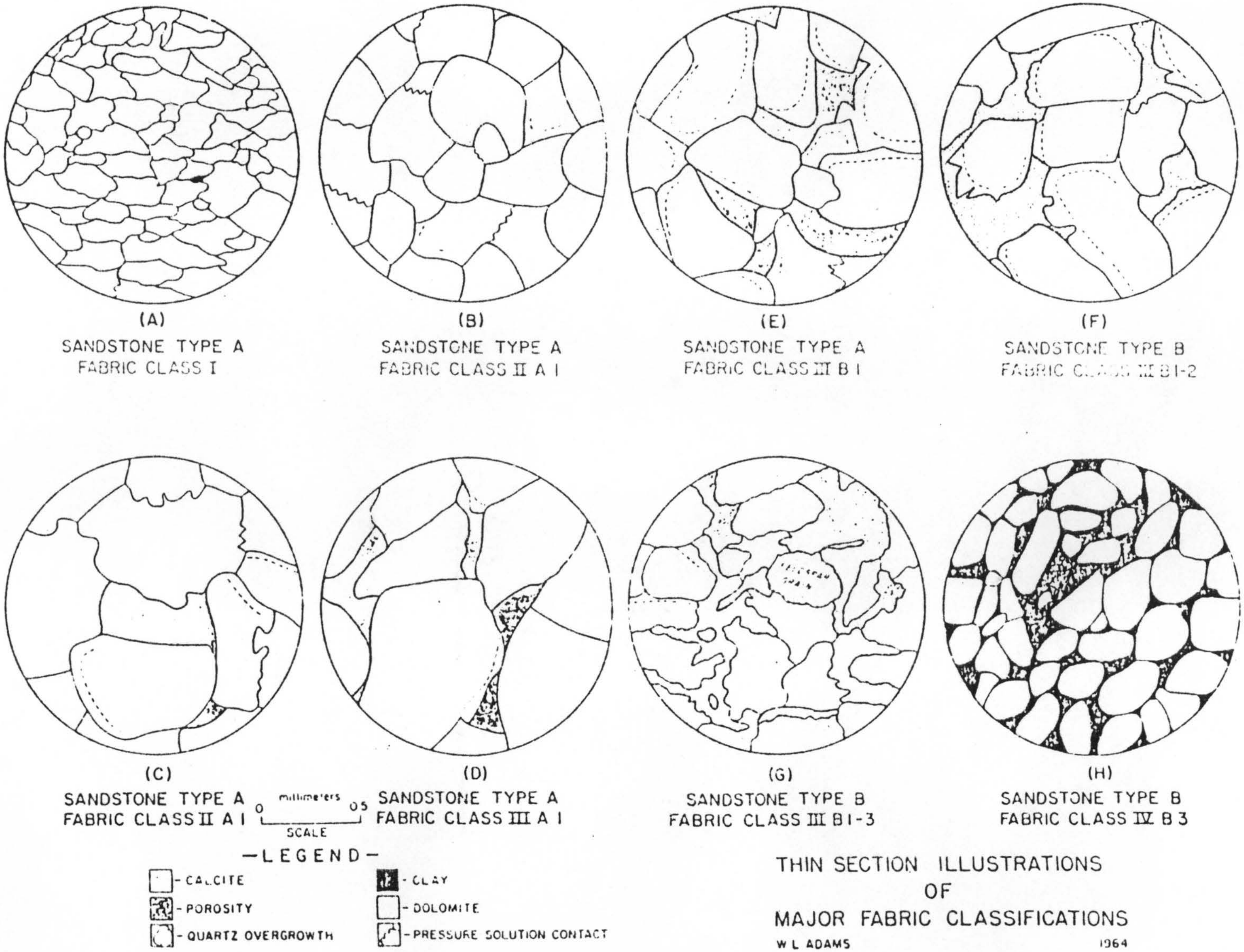


Figure 38. Fabric classification. From Adams (1964).

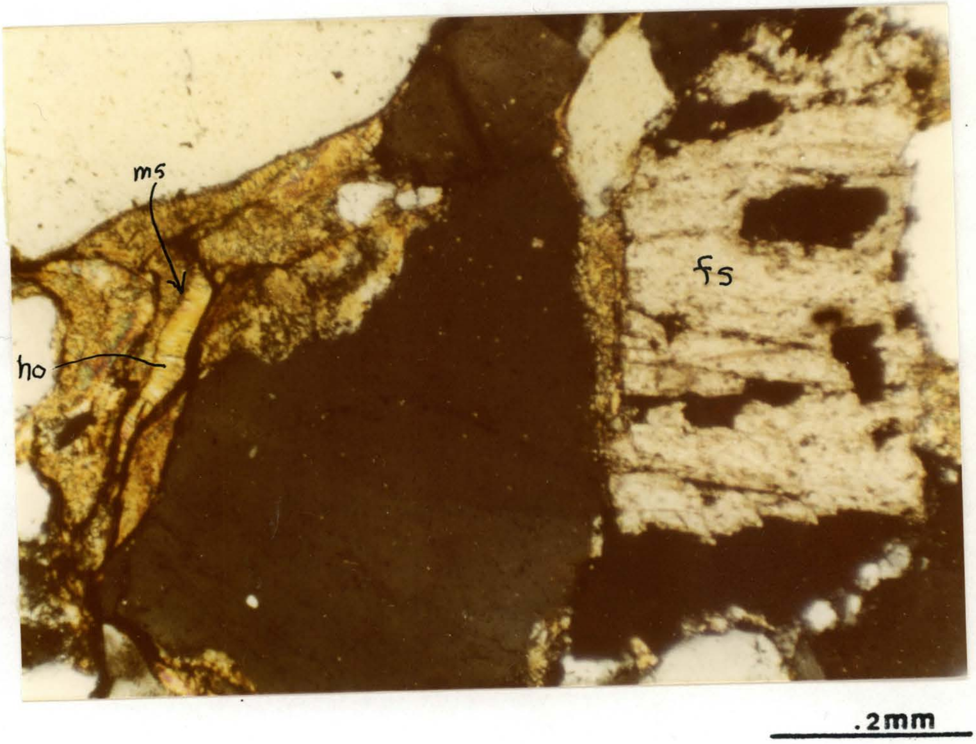


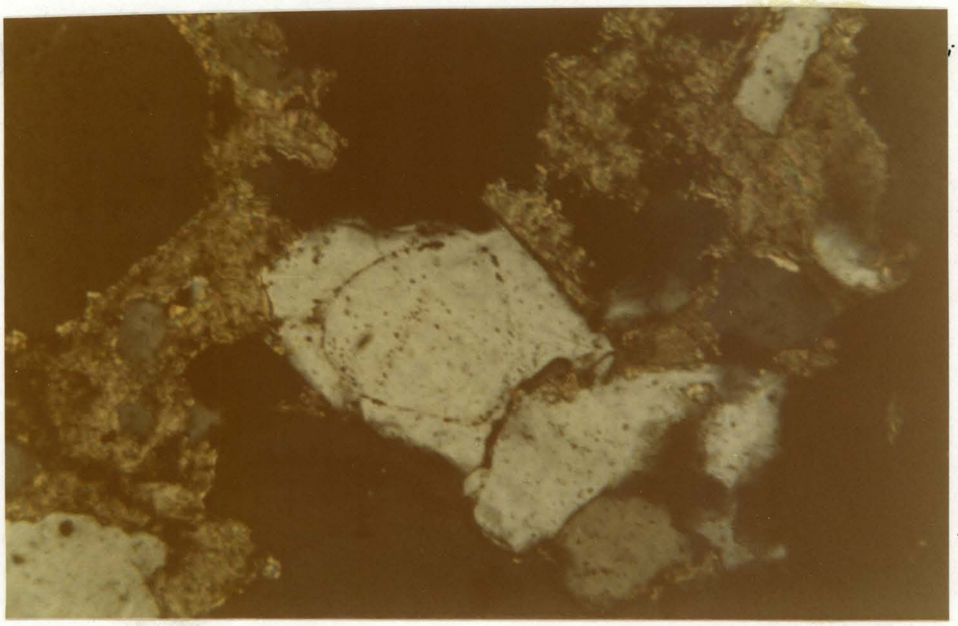
Figure 39. Leached replaced feldspar (fs) and illite with medial sutures (ms) and horrent orientation (ho). Crossed nicols. # 22X.

In some of the formation a moderate degree of pressure solution has occurred; such rocks are cemented with quartz, clay, and calcite and combinations of the three (IIA-1, IIA-2, IIA-3, IIA-2,3). 75% of the specimens are III B types with combinations of cements. IV B types are also present but many have undergone an early silica cementation stage. Such a diversity of fabric types indicates different diagenetic episodes and variable cementation rates. Those sandstones that experienced early silica cementation followed relatively quickly by clay or calcite cementation show a 'normally' packed fabric (type III). Those sandstones that exhibit only a slight amount of early silica precipitation and no other early cements are the most densely packed. The fabric, therefore, appears controlled by the type of intrastratal fluids flowing during a time previous to emplacement at a depth great enough for extensive pressure solution. That is, early cementation "freezes" the rock and preserves the "loose" fabric; grains in rocks that are of type II are not locked in place and, hence, free to move and merge into one another.

Quartz Types

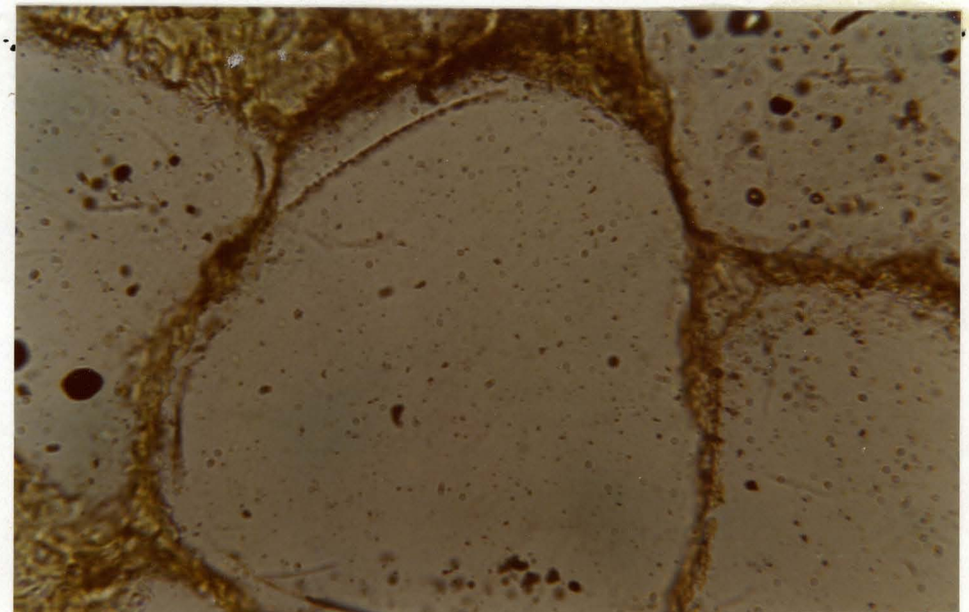
All empirical and genetic quartz types are present in the Arroyo Penasco: non-undulose-slightly undulose, common plutonic quartz; undulose, metamorphic, plutonic quartz; semicomposite, vein quartz (bubbly); composite undulose and non-undulose, metamorphic quartz.

The most numerous quartz types comprise a continuum from straight extinction through undulose extinction. The grains that fall in this typological niche are usually in the fine to medium grained categories. As a criterion for provenance determination these grains are useless (Blatt, 1963), most exhibiting high roundness values under overgrowths. In most cases, they are the product of many cycles that have altered original depositional imprimaturs (Figs. 40, 41). Of more use for provenance analysis are the polycrystalline grains, these occurring in the grain sizes coarser than 0.5 mm (medium-grained). Folk (1974), Blatt and Christie (1963), Blatt (1967), Basu et al. (1975), and Young (1976) all agree that certain types of polycrystallinity indicate grades of metamorphic sources and aid in distinguishing igneous from metamorphic provinces. The various touchstones for such determinations are crystal number within one grain size, crystal shape, and boundary relations. In all studies, it has been found that lower grade grains contain more crystal units (Fig. 42). Gneisses and granites usually show fewer units, and these are distinctly polygonized (Young, 1976) (Fig. 43). Grains from lower grades in addition to high polycrystallinity indices with many crystals are elongated with sutured



.4mm

Figure 40. Extremely well-rounded quartz grain with overgrowth. Probably a recycled grain and reworked (?) overgrowth. Crossed nicols. # 169.



.06mm

Figure 41. Well-rounded recycled quartz nucleus. Overgrowth is probably an in situ product. Plane light. # 130.

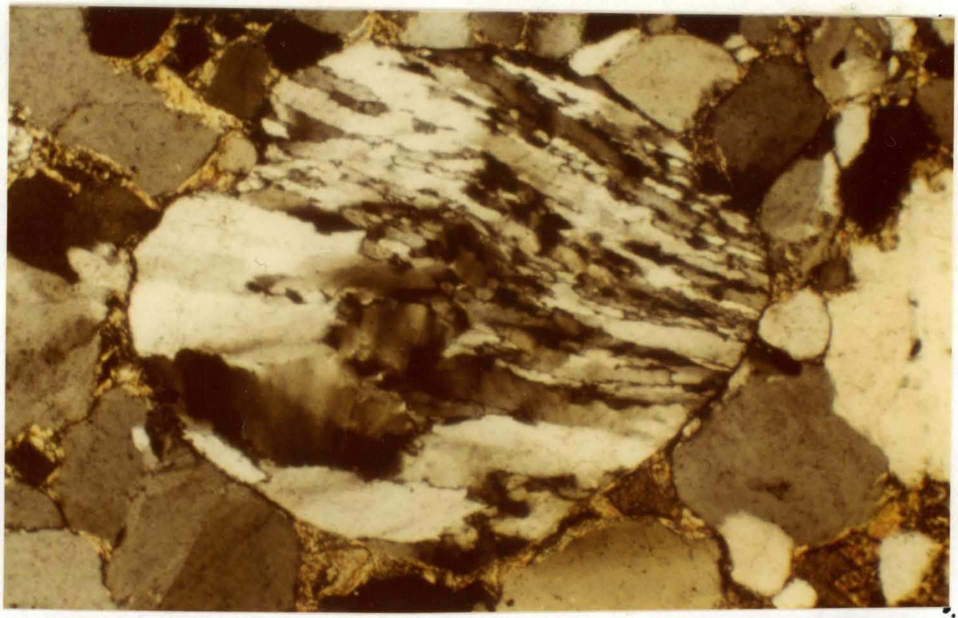


Figure 42. Well-rounded grain of stretched metaquartzite with many crystal units. Crossed nicols. # 156.

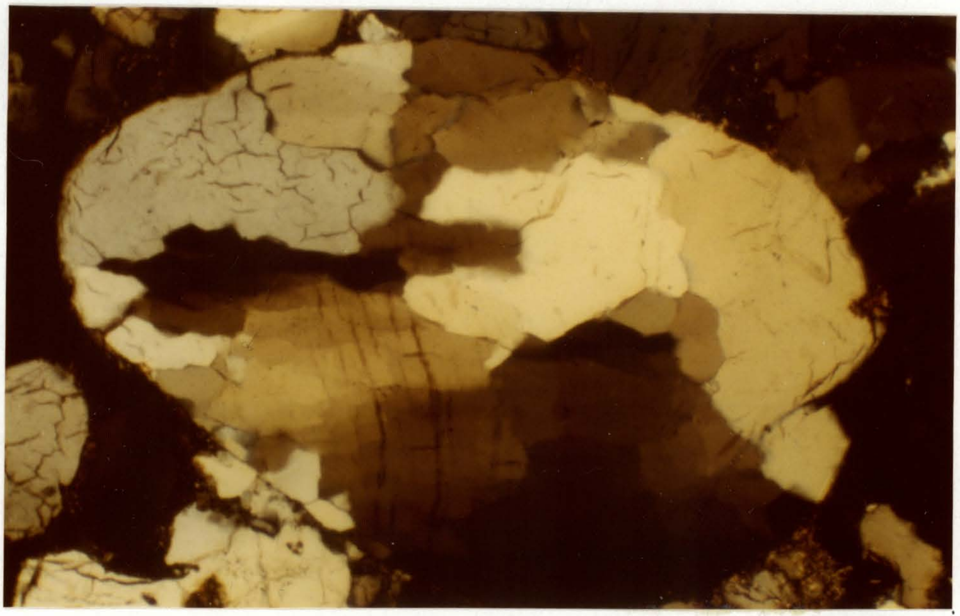


Figure 43. Polyganized quartz grain with relatively few crystal units. Crossed nicols. # 84.

grain boundaries (Fig. 42).

The polycrystalline grains in the Arroyo Penasco are seemingly of these lower grades with many crystal units that are frequently stretched and sutured. This again indicates low-medium rank metamorphism with shearing or tectonic deformation. There are only a few examples of well polygonized units in the collected samples.

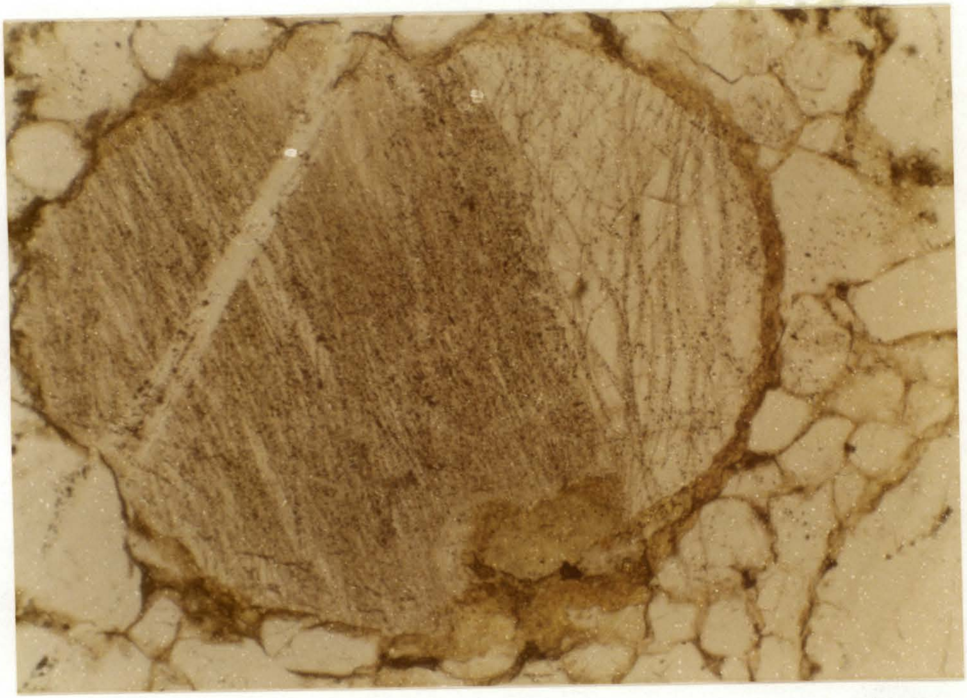
Harrell and Blatt (1978) have determined a sequence of mechanical durabilities for the quartz types: micropolycrystalline quartz > finely crystalline quartz > coarsely polycrystalline quartz > monocrystalline quartz. This sequence and the Griffith 'Fracture Theory' may explain the paucity of coarsely polycrystalline units. The theory simply states that microfractures cause grain disaggregation more readily in corasely crystalline units because the stress can be applied over greater areas. In finely polycrystalline rocks the fractures must cross many crystals and crystal boundaries (Harrell and Blatt, 1978). In short, the ratio of finely polycrystalline aggregates to coarsely crystalline aggregates in the Arroyo Penasco may not yield accurate provenance contributions simply because of preferential chemical and mechanical elimination of high-grade metamorphic and igneous rocks. Harrell and Blatt (1978) state that monocrystalline quartz is ubiquitous, not because it is more mechanically durable, but because its chemical stability is much higher than that of any polycrystalline quartz.

In addition to the quartz types already mentioned, there is semicomposite quartz that is very bubbly (Fig. 44). This is indicative of a hydrothermal provenance (veins or pegmatites). Also it has been noted that at certain stratigraphic horizons very angular pebbles of vein and metamorphic quartz exist (Fig. 23). This is simply an indication of local origin because pebble-sized material is usually well rounded after only several miles of transport. However, most of the material in the coarser sand sizes is highly rounded (5-6 e). There is no grain size trend in the formation except in individual beds. And even in this case, the fining upward trend may be interrupted by an interval of pebbles.

So it is the coarse grained polycrystalline fraction that yields a provenance determination, this being low to high grade metamorphic and igneous, the finer sizes indicating probable recycled sedimentary origins. Throughout the following description of the terrigenous grains more complete information will be added regarding sediment sources.

Inclusions in Quartz Grains

The vast majority of the quartz grains have some sort of inclusion, either vacuole, microlite, or both.



.4mm

Figure 44. Vein quartz with clay coat. Note myriad bubbles indicative of hydrothermal origin. Plane light. # 15.

The usual three kinds of vacuoles are present: gas, liquid, and two-phase. A uniformity in size prevails among the types, none being noticeably large. Most of the vacuoles are entrained across grains but not transecting the associated quartz overgrowths (Fig. 44). Notwithstanding, some sections show trails traversing across many grains (Fig. 45). The first case indicates stress before silica precipitation; the second case indicates stress after cementation. Typically, vein quartz has a much larger number of vacuoles than the other quartz types. Microlites also appear in the quartz grains in several mineral forms: ilmenite, muscovite, zircon, tourmaline, rutile needles, and microcline. In some cases, one or several of these minerals form strain trails across grains.

Rock Fragments

Sedimentary and metamorphic rock fragments occur in minor amounts throughout the formation. Metamorphic rock fragments manifest schistose and gneissic attributes: the fragments are either finely or coarsely polycrystalline, but, unlike the aforementioned types in the quartz section, these grains are riddled with aligned muscovite crystals (Fig. 46). They are granular particles (2-4 mm). This type of granule bears great similarity to the Ortega Metaquartzite that underlies the Arroyo Penasco in Rio

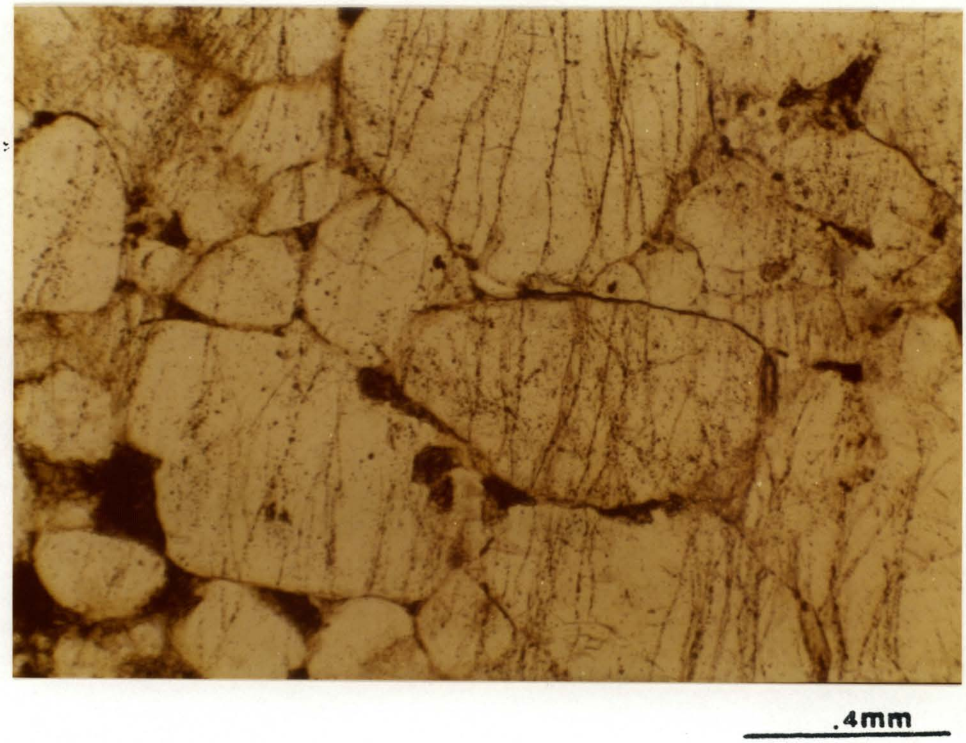


Figure 45. Strain trails traversing many grains. Plain light. #141.

Pueblo Canyon. These types of fragments probably do not persist in a depositional environment for the same reasons that apply to regular polycrystalline quartz. They can then be considered as first cycle material and directly attributable to nearby metamorphic provinces.

In addition to the remnants of crystalline basement, there are also several types of sedimentary rock fragments. The most abundant is chert comprised of microcrystalline quartz crystals (Folk and Weaver, 1952). These detrital remnants (Fig. 47) occur most frequently in the upper part of the formation where the unit is changing from clastic to carbonate. They are granules, larger by many diameters than the accompanying quartz grains and are subangular-angular. Various carbonates are often included in the chert. Also coarse, well rounded grains of length-fast chalcedony occur (Fig. 48). Coarse, subangular sandstone fragments, clay and mud clasts are strewn throughout. The sandstone is comprised of well sorted, -rounded, and -cemented fine quartz grains (Fig. 49) and represent the destruction and distribution of lower or lateral units of the Arroyo Penasco. Likewise, the clay and mud clasts of chlorite and chlorite-quartz silt are debris from other parts of the formation. The chert, carbonate, and chalcedony are, similarly, products of older limestone deposits.

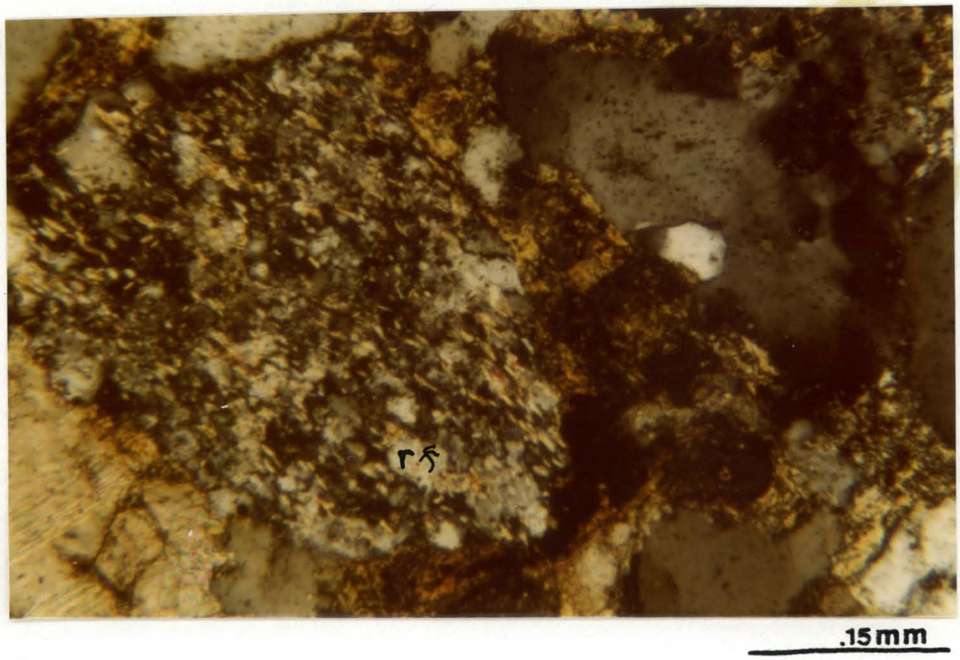


Figure 46. Metamorphic rock fragment (rf) with aligned muscovite flakes. Crossed nicols.# 19X.

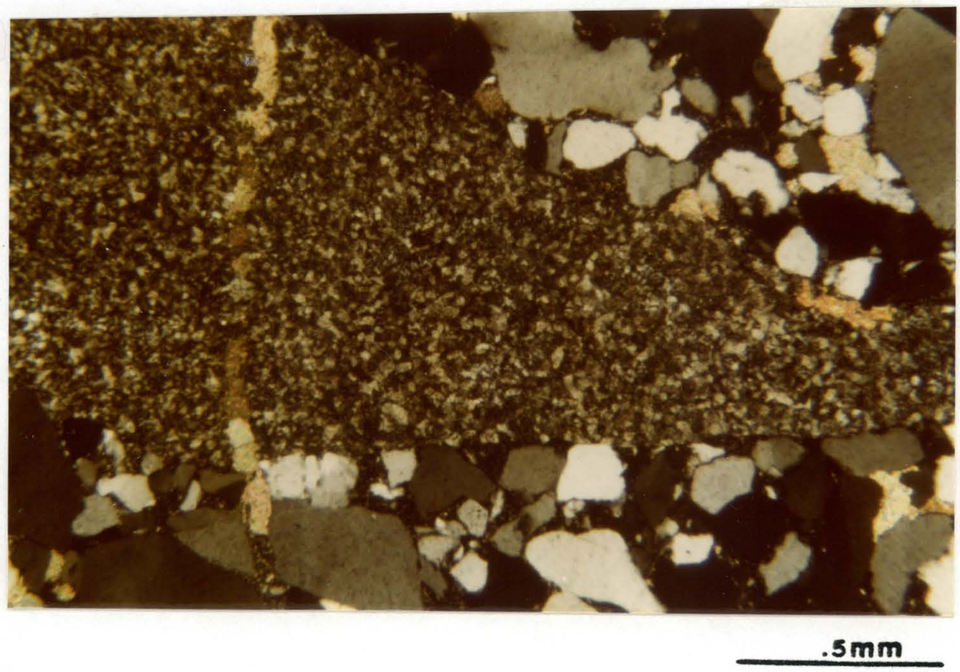


Figure 47. Detrital chert with carbonate vein. Crossed nicols.# 17X.

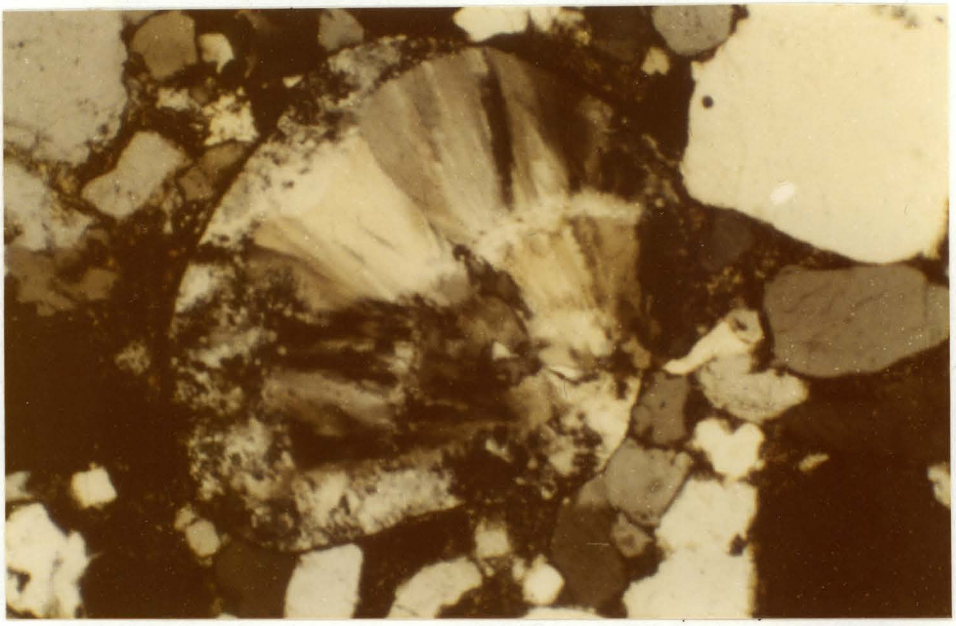


Figure 48. Granule of length-fast chalcedony. Crossed nicols. # 15.

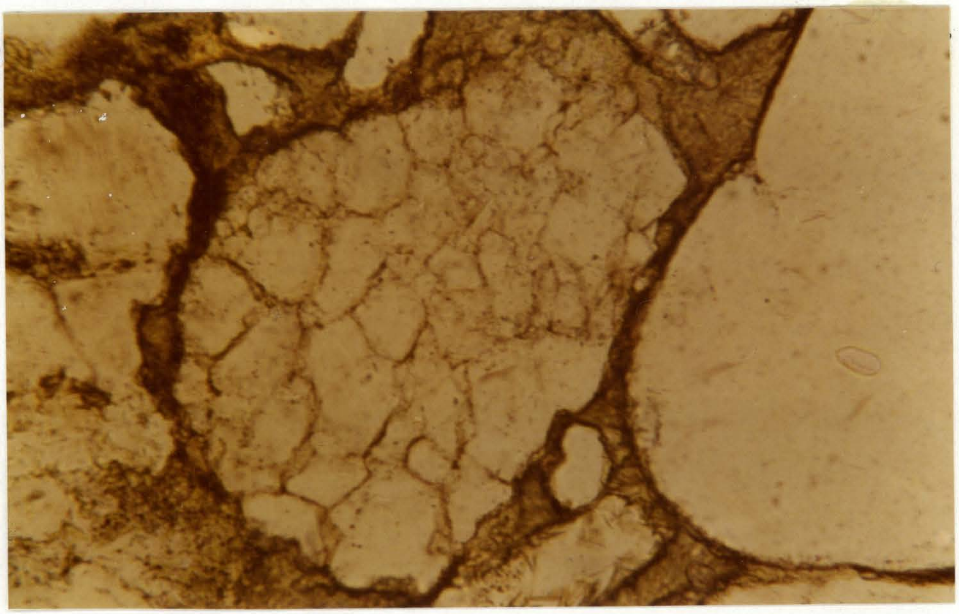
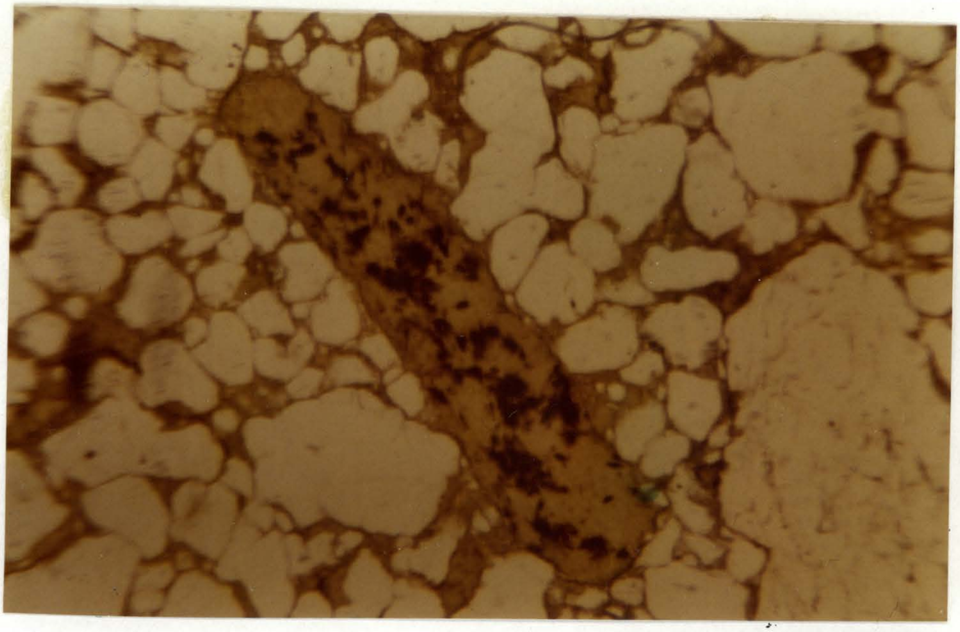


Figure 49. Fragment of reworked sandstone with clay coat. Plane light. # 140.

Feldspar

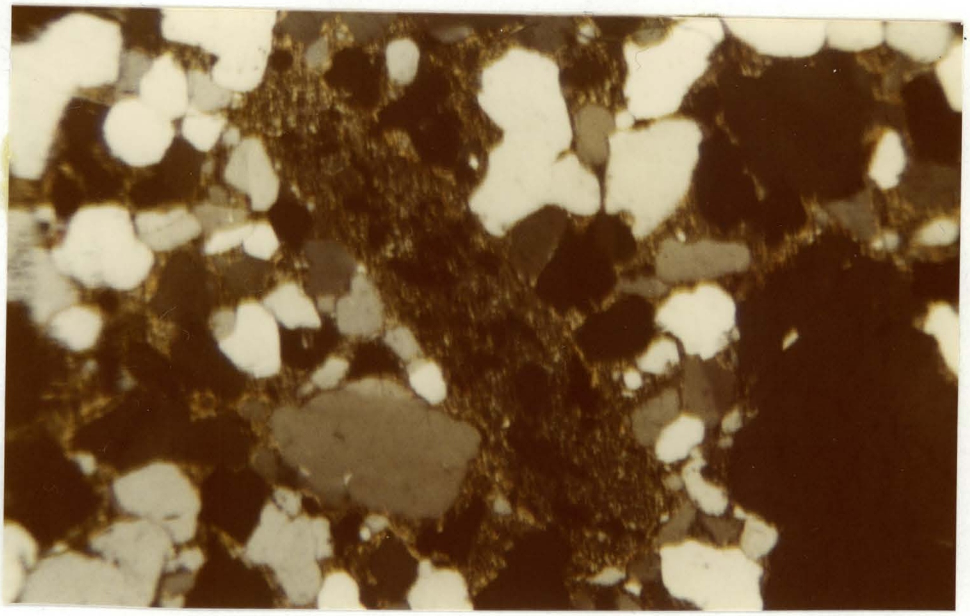
Because of the composition of the basement rocks underlying the Arroyo Penasco, which are largely feldspathic, one might assume that when weathered these would yield a sandstone of arkosic or subarkosic composition. Such is not the case. Not more than 3% feldspar is present in any section, and this fraction is undergoing alteration. As mentioned previously, there are many areas that appear to have once been framework material but are now an authigenic part of the rock; it is probable that these grains were originally feldspars, and if so, would have given the sandstone its expected feldspathic character (Figs. 50, 51). The absence of feldspars is, in part, a result of recycling of much of the sand in conjunction with the weathering and leaching regimes. However, the absence of the alkali feldspars could explain the presence of illite, a topic that will be discussed in the sections in clays and diagenesis.

The existing feldspars do reflect the composition of the Precambrian granites and metasediments, microcline being the most dominant type of potassium feldspar (Figs. 52, 53). Some grains that have undergone extensive replacement by carbonates and chlorite have a small unaltered core that has the gross optical characteristics of either quartz or orthoclase. But there is so little left to



.6mm

Figure 50. Originally a framework grain (feldspar?) altered now to chlorite. Plane light. # 123.



.6mm

Figure 51. Crossed nicols view of chloritized grain in illite matrix. # 123.

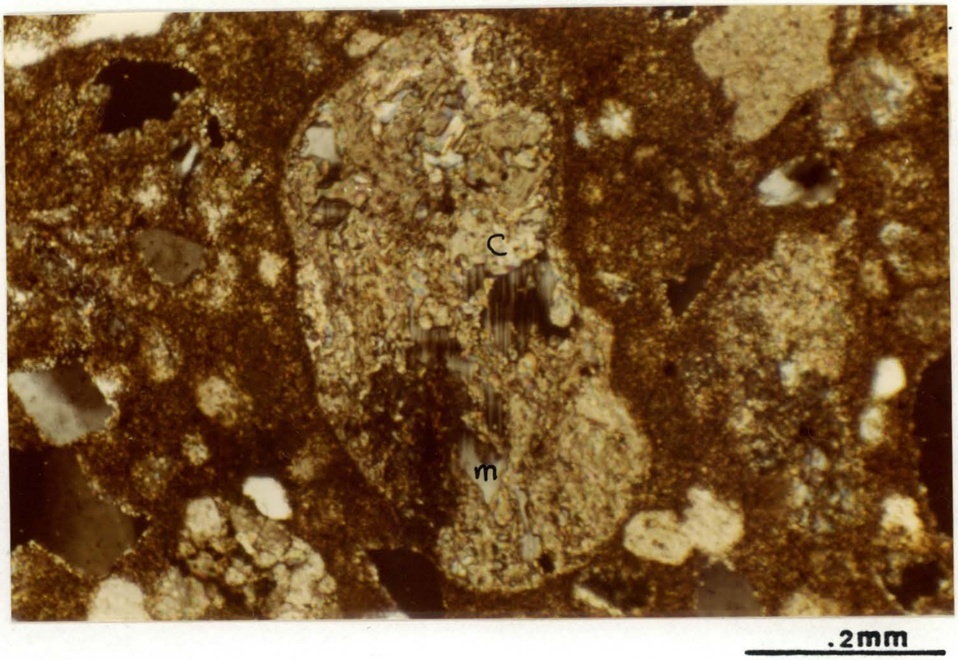


Figure 52. Microcline (m) being replaced by calcite (c); in a micritic cement. Crossed nicols. # 97.

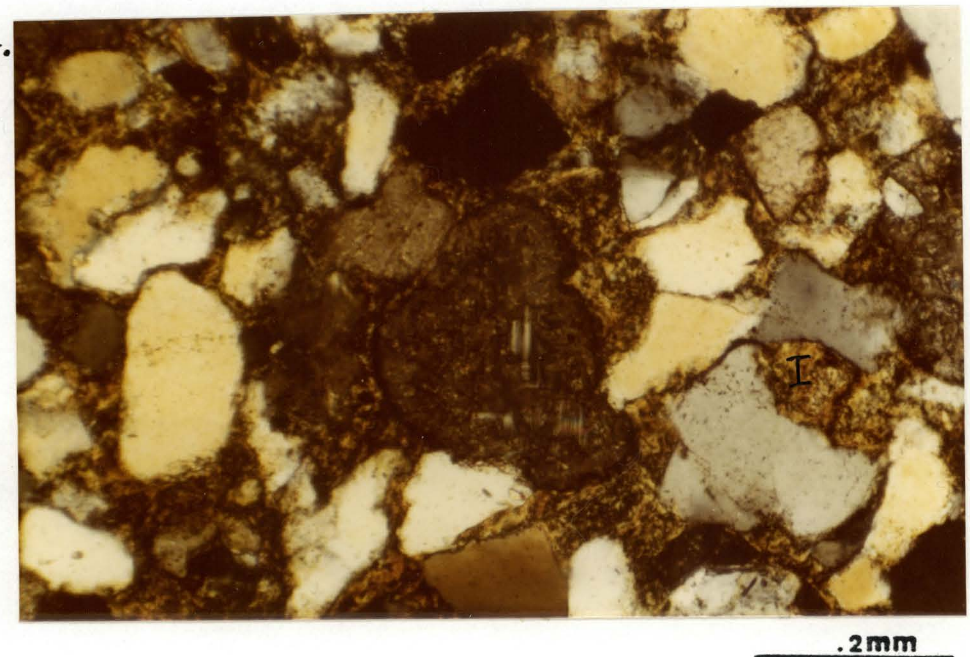


Figure 53. Microcline being replaced by calcite; in an illitic (I) matrix. Crossed nicols. # 84.

analyze that positive identification is difficult (Fig. 54). Probably the grains are K-spars. None of the microcline is fresh or unaltered, carbonate replacement being the only definite type of alteration. No sericitization is evident, and the grains replaced by clays offer few clues to their former identity. Great diversity exists in microcline size and roundness: the range in size being from .1 mm to .75 mm, and the roundness values from angular to well rounded.

Mica

Although biotite is present in underlying Precambrian rocks, none was observed in thin section. Muscovite is the dominant phyllosilicate. It is identifiable as detrital in the coarser sizes by its crystal clarity, brilliant colors under crossed-nicols, crystal shape, and cleavage. The muscovite that is larger than silt is usually frayed at crystal ends and contorted and crumpled by pressure of quartz grains (Fig. 55). In no section did coarse muscovite constitute more than 1% of the rock. It is obviously derived from the basement rocks.

When muscovite approaches clay size, it is commonly referred to as illite. Illite partakes of three basic structures or polymorphs: 1M illite, 1Md illite, and 2M illite (Carroll, 1970). The first two are prod-

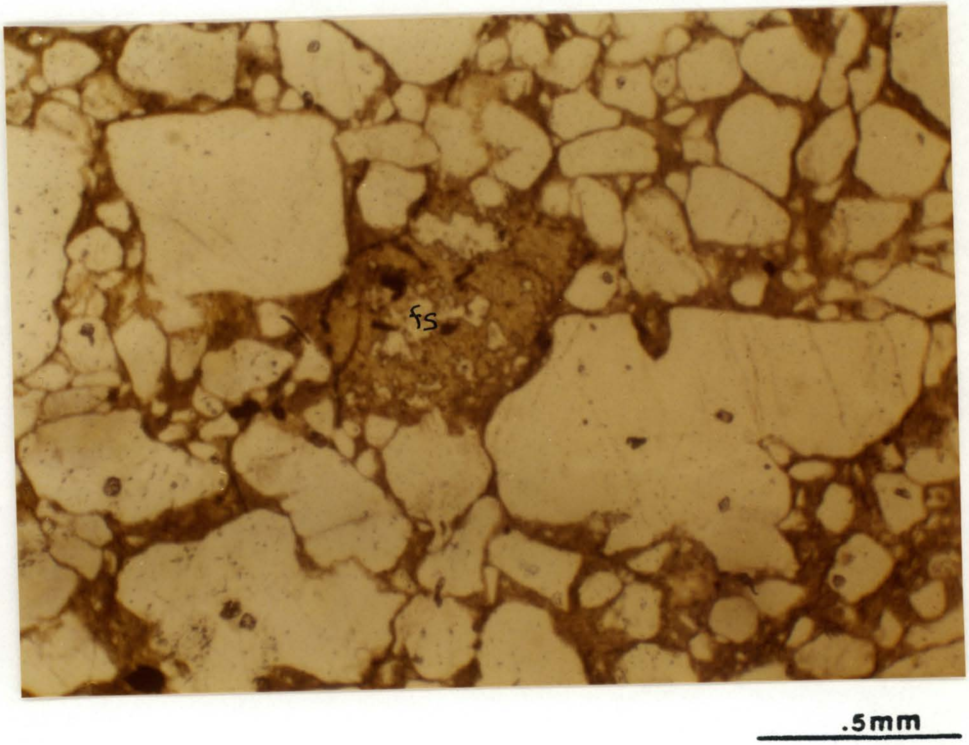


Figure 54. Feldspar (fs) being replaced by chlorite. Plane light. # 8.

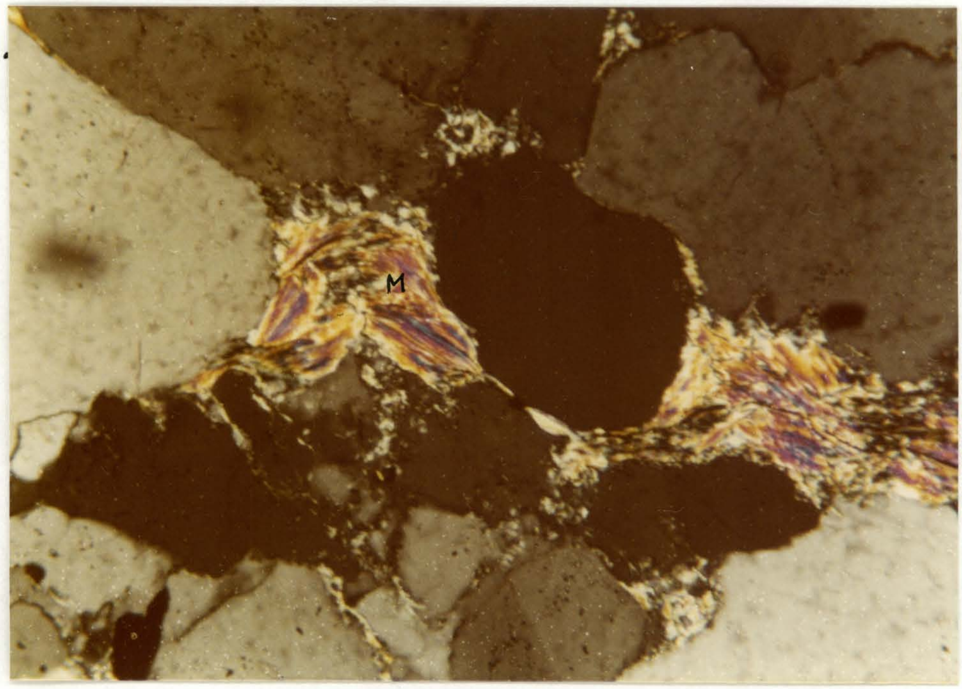


Figure 55. Deformed 2M muscovite (M). Crossed nicols. # 17.

ucts of low temperature ($<250^{o}C$) diagenetic processes. 2M illite is a product of low grade metamorphism or extremely deep burial. When it occurs in a sediment, it is almost always the detrital residue of rocks subjected to metamorphic conditions (Carroll, 1970). Extremely powerful magnification, x-ray diffraction, and electron microscopy is needed to distinguish it from the lower order polymorphs. Only a small fraction of the clays was recognized as the 2M polymorph; its presence will be discussed in clay and diagenesis sections.

Ultrastable Minerals

The heavy or ultrastable mineral suite is composed of zircon, rutile, and tourmaline, none individually or in combination forming greater than 1% of the sediment.

These minerals occur either alone in a random manner throughout most of the sections or in concentrated, well delineated placers in the more mature sandstones. These placers also contain organic debris and a variety of opaque minerals (pyrite and ilmenite) that have been crushed and mixed. Often stylolitization occurs or is highlighted along these placers.

All the minerals have a similar grain size median of 0.075 mm (fine sand) with an occasional individual reaching a diameter of 0.2 mm. Very angular grains often accompany very well rounded grains, again an indication that several injections of new material were introduced during the deposition of the sands comprising the unit.

Zircon is the most abundant, exhibits high relief, high birefringence, no pleochroism, and no idiomorphism. Rutile is red-brown in plane light, occasionally exhibits cleavage, and also has high relief. Tourmaline is almost always well rounded, green in plane light, and has a high birefringence. Neither rutile nor tourmaline are idiomorphic, and all grains of the ultrastable suites indent quartz upon compaction. No peculiar or noticeable trends were observed in relation to their occurrences.

Detrital Clays and Iron Oxides

Except at the base of one outcrop, most of the clay in this formation is considered of authigenic origin. The only clays recognized as detrital are mixed or "dirty" clays, usually occurring with various iron oxides (Figs. 56, 57). These clays are the result of either a primary depositional event or later episodes of infiltration. They assume the habit of thin coats that are either circumgranular or geopetal covering only the top of the grain. In a few cases, these coats are rather thick and may represent relic soil cutans (Figs. 44, 49). The clays in Figure 58 may be infiltered or original detrital residue;

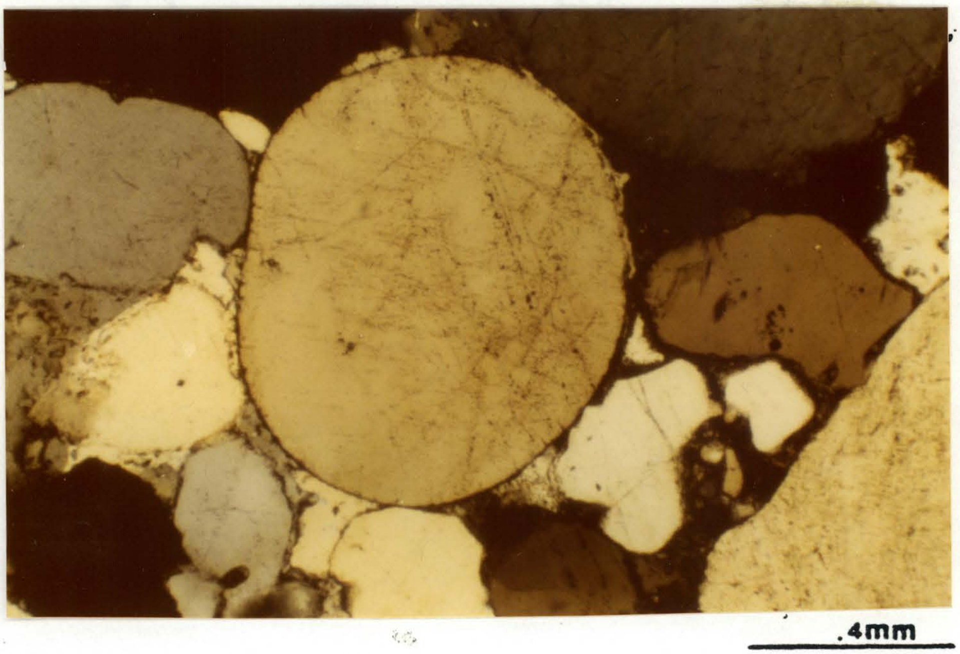


Figure 56. Well-rounded quartz grain with coat of iron oxide. The cement is quartz. Crossed nicols. # 140.

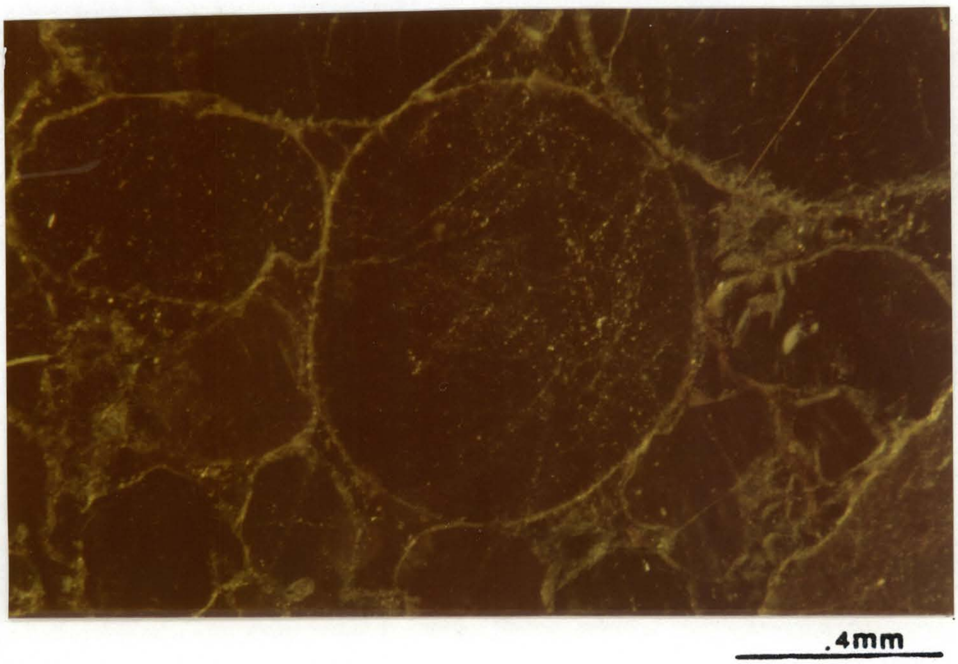


Figure 57. Well-rounded quartz grain in reflected light. The metallic yellow border on grains is limonite-stained clay. # 140.

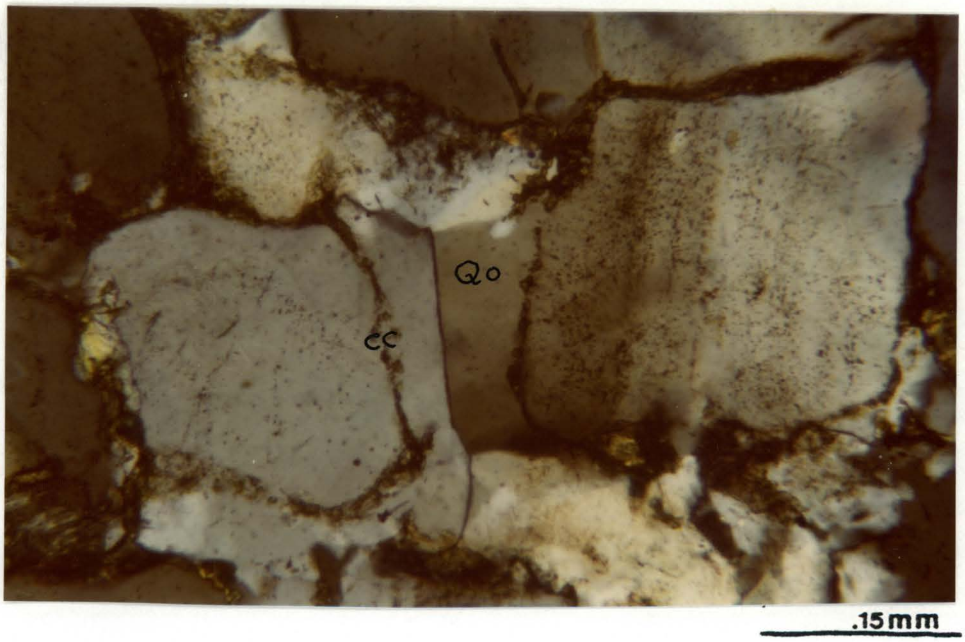


Figure 58. Infiltered clay coat (cc) between grain and quartz overgrowth (Qo). Crossed nicols. # 133.

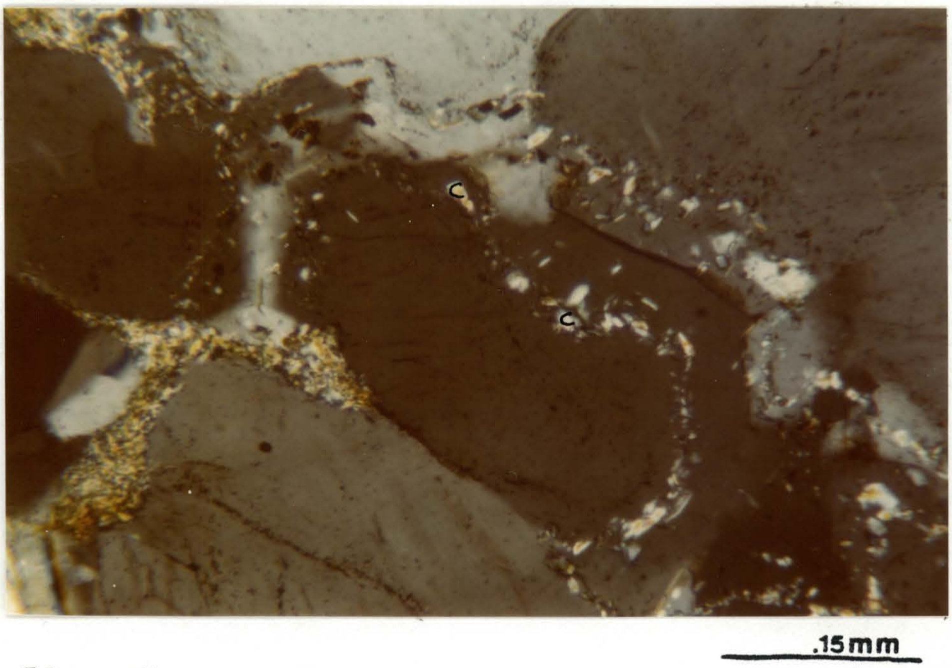


Figure 59. Clay particles (c) (?) delineating grain. These could be infiltered products or precipitates. Crossed nicols. # 136.

whereas, the clay in Figure 59 may be infiltered, detrital residue, a coprecipitate with quartz, or is being replaced.

Some of the coats are definitely an infiltered residue, the evidence being an early silica meniscus cementation (McBride _in_ Jonas and McBride, 1977) stage after which is deposited a clay coat (Fig. 60). These coats are a heterogeneous mixture of illite, chlorite, unidentified clays, and either limonite or hematite. Such coats do not inhibit silica precipitation as authigenic rim chlorite does. Far less than 1% of the rocks are composed of these coats.

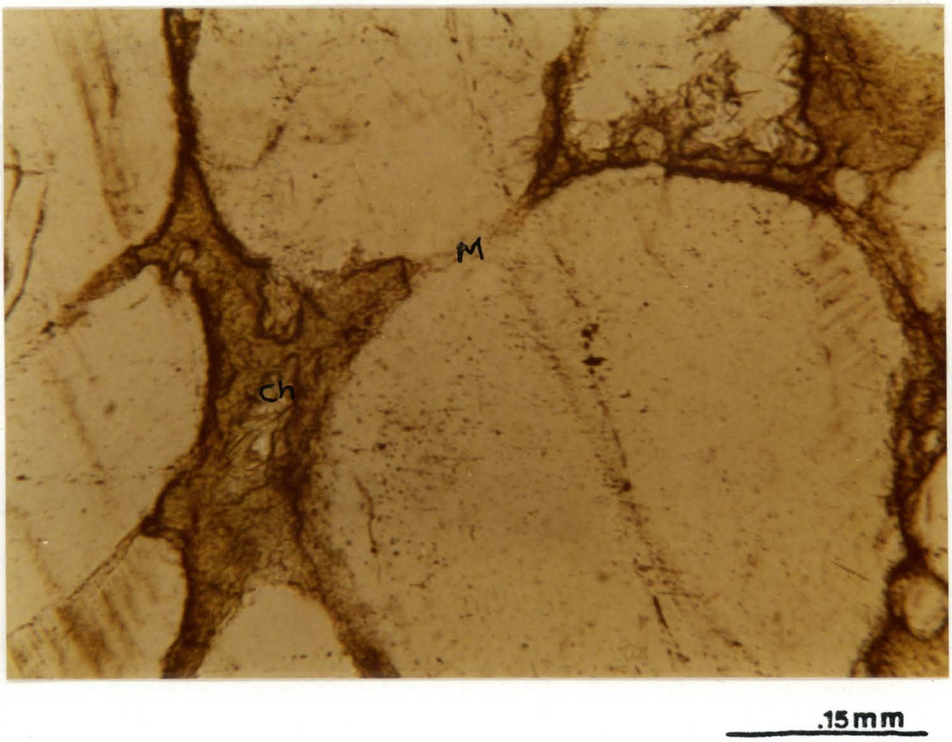


Figure 60. Meniscus (M) quartz cement with authigenic chlorite (ch). Plane light. # 140.

DIAGENETIC MINERALS

This section lists and describes the various orthochemical minerals; their formation is dealt with in the section entitled Diagenesis.

Quartz

Quartz constitutes the largest fraction of the minerals formed during the lower Arroyo Penasco's complex diagenetic history. Five basic types are present: overgrowths (including meniscus cement), idiomorphic crystals, fracture and pore fillings, chert, and chalcedony.

The most common of these types is the overgrowth. Most are readily visible under the microscope, the boundary between original grain and authigenic silica being dust, vacuoles, clay, or iron oxide coats (Figs. 40, 41). Only when the surrounding diagenetic material is predominantly clay or calcite does delineation of the overgrowths become difficult or impossible. This is because of two factors either alone or in combination (Jonas and McBride, 1977). The first is an occultation, simply a physical phenomenon in which the clay or carbonate overlaps or is smeared over part of the grain and conceals the overgrowth. The second factor actually concerns the dissolution of the overgrowth during the precipitation of the later cements. Seemingly, the first case is the most common in these sections.

The overgrowths exhibit both euhedral and irregular terminations. The formation of euhedral faces (Figs. 61, 62) indicates growth in open pores and is an important criterion in judging the detrital or authigenic origins of clays. There are euhedral terminations against both clay and calcite. Frequently, overgrowths have not grown evenly around the grains, and, rarely, a meniscus cement is encountered.

More than one overgrowth stage is exhibited in some sections (Fig. 63), and both euhedral and irregular overgrowths assume these multiple growth stages. The most numerous examples of these multi-precipitation events occur in an unusual chert-cemented zone (Fig. 63). These are strange overgrowths in that they grow evenly and concentrically around the grain, perfectly maintaining the curving shape of the detrital nucleus. This kind of concentric evolution apparently ceases after a time as illustrated in Figure 63. Only in the chert zone does this phenomenon occur. All overgrowth occurrence is not noticeably affected by clay coats either thick or thin. Finally, some overgrowths contain inclusions of anhydrite and celestite(?).

Idiomorphic quartz crystals have grown in the carbonates in the transition zone between the lower and upper Arroyo Penasco. Most of these crystals are about 0.2 mm in diameter, exhibit progressive zoning, and have carbonate

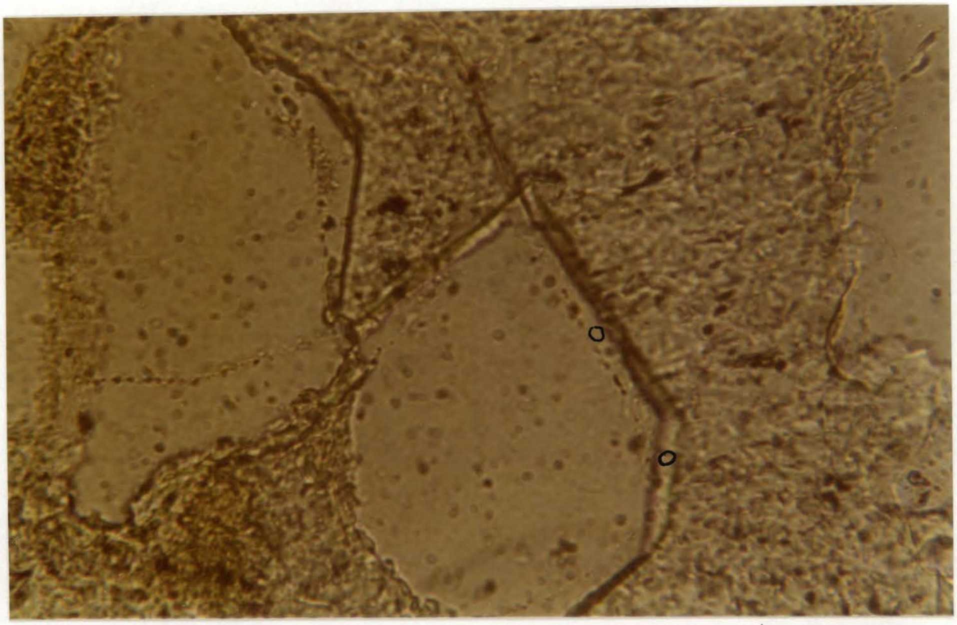


Figure 61. Multiple euhedral quartz overgrowths (o) in clay cement. Plane light. # 17X.

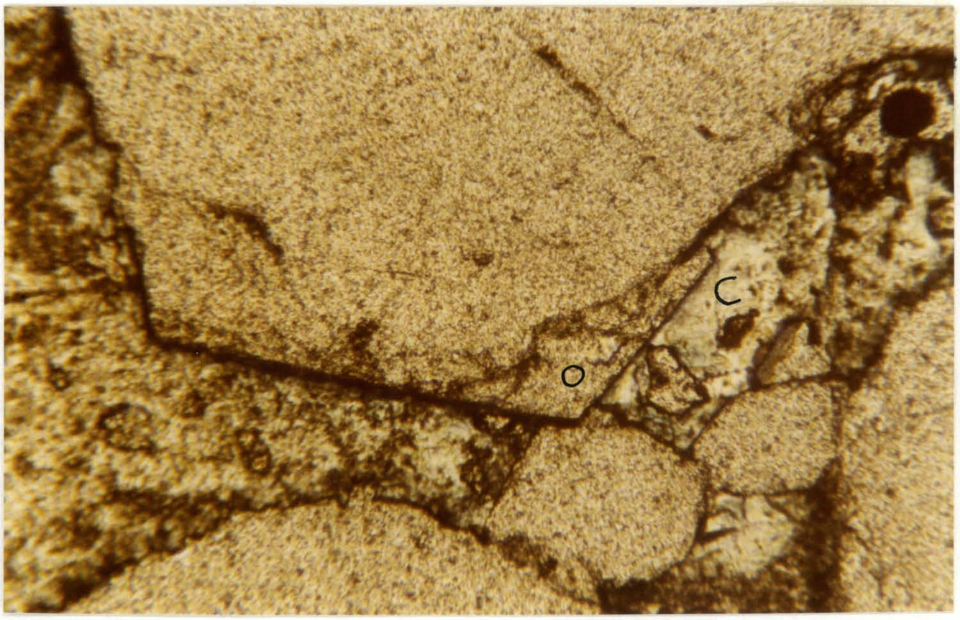
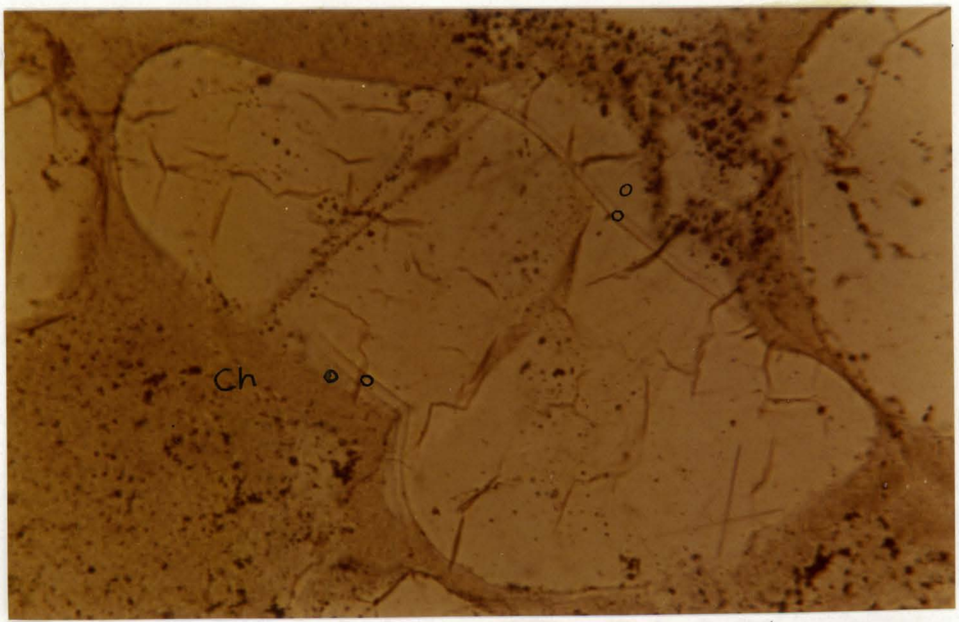
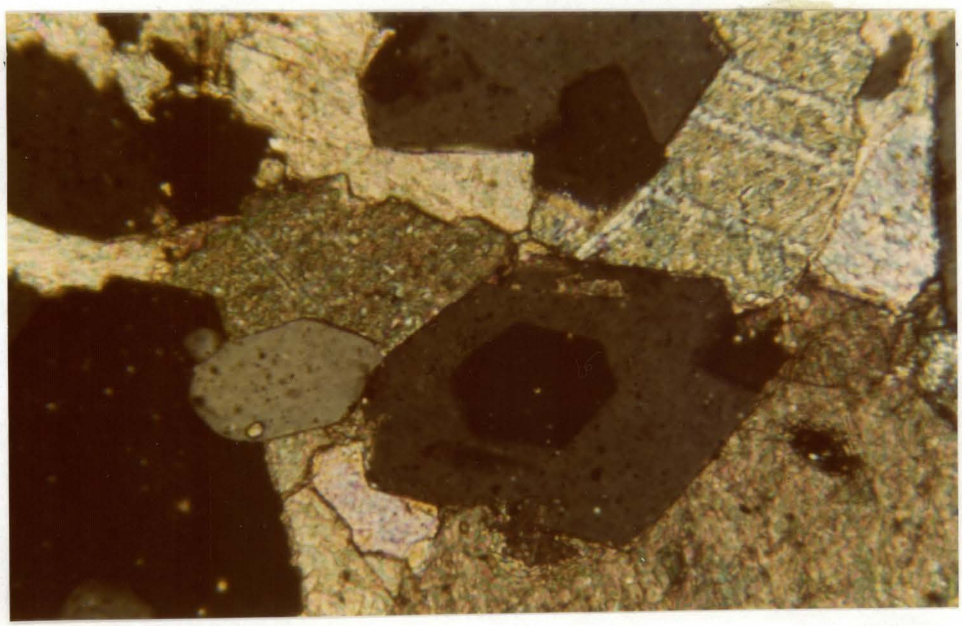


Figure 62. Euhedral quartz overgrowth (o) in calcite (c). Plane light. # 169.



.2mm

Figure 63. Multiple concentric quartz overgrowths (o) in chert (ch). Plane light. # 159.



.15mm

Figure 64. Authigenic zoned quartz. Note different extinction angles for crystal. Formed in calcite. Crossed nicols. # 98.

inclusions. The zoning is best exemplified in Figure 64 where the extinction orientation of the two zones is obviously but inexplicably different. Some grains exhibit many phantom crystal faces but their extinction orientations are the same.

Occasionally, these authigenic crystals are surrounded, or partially so, by a zone of chalcedony (Fig. 65). Usually, however, the chalcedony occurs embedded in calcite in the habit of rosettes (0.15 mm) without the central quartz nuclei (Fig. 66). The chalcedony is length-slow quartzine. Length-fast chalcedony occurs also, normally as an amorphous mass of fibers in calcite.

Chert occurs under two guises: as a replacement of carbonate cement and as a primary cement. The latter appearance, as mentioned previously, occurs at one outcrop in one stratigraphic horizon intercalated between a hematite-clay cemented sandstone (Figs. 28, 67). This chert is nearly isotropic (Fig. 68), so small are its crystals (1 micron); whereas the crystals in the replacement chert range up to 20 microns (Fig. 69).

The last types of authigenic quartz fill pores or fractures (Fig. 70). When touching a quartz grain, the fracture fill assumes the orientation of the grain. These fractures seldom exceed .1 mm in width but at times cut across an entire thin section. Chlorite replaces these

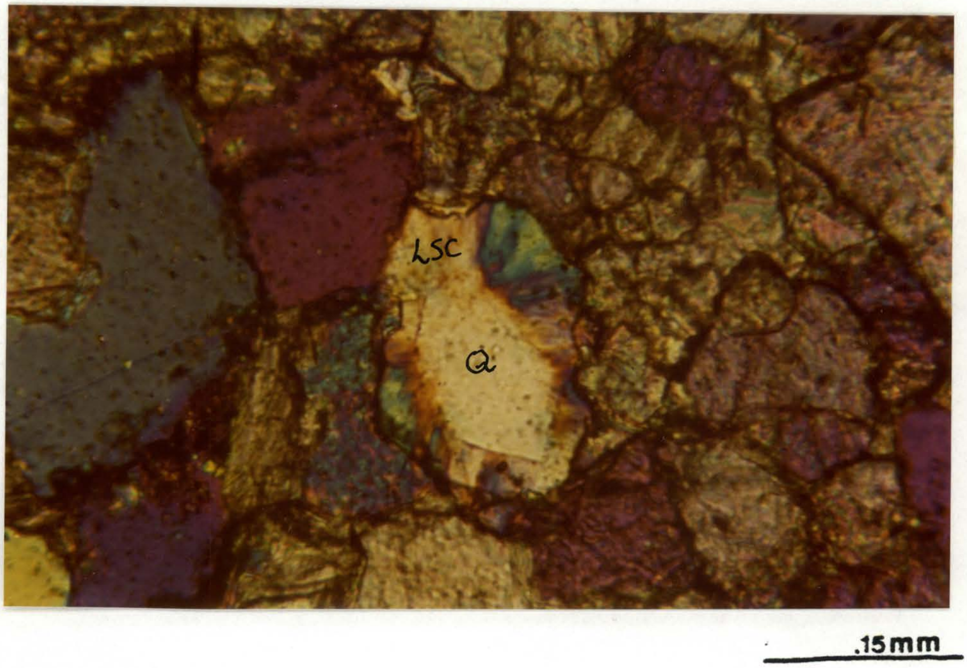


Figure 65. Length-slow chalcedony (LSC) on authigenic quartz (Q). Crossed nicols with gypsum plate. # 97.

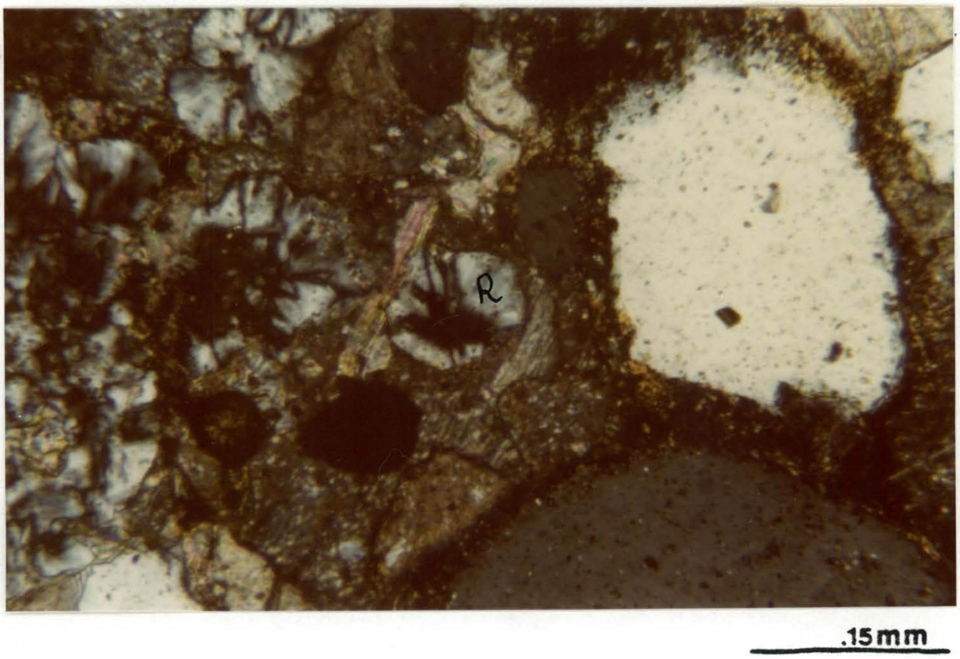
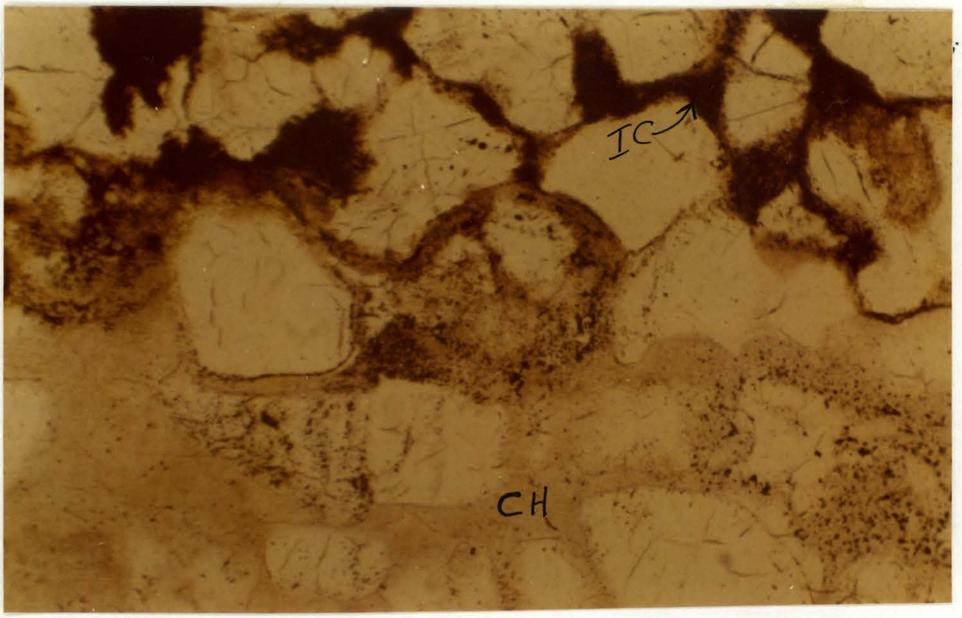
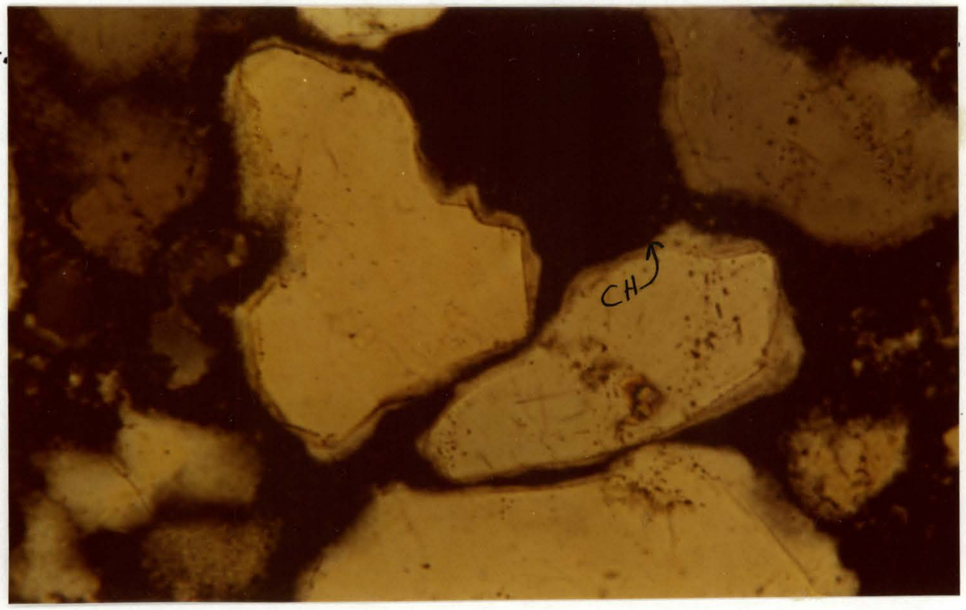


Figure 66. Rosettes of length-slow chalcedony (R), probably replacements of evaporites. Crossed nicols. # 98.



.5mm

Figure 67. Zones of chert (CH) and iron-clay (IC). Portion of a paleosilcrete. Plane light. # 159.



.2mm

Figure 68. Multiple quartz overgrowths in chert zone. Note embayed grains. The chert (ch) is nearly isotropic under crossed nicols. # 159.

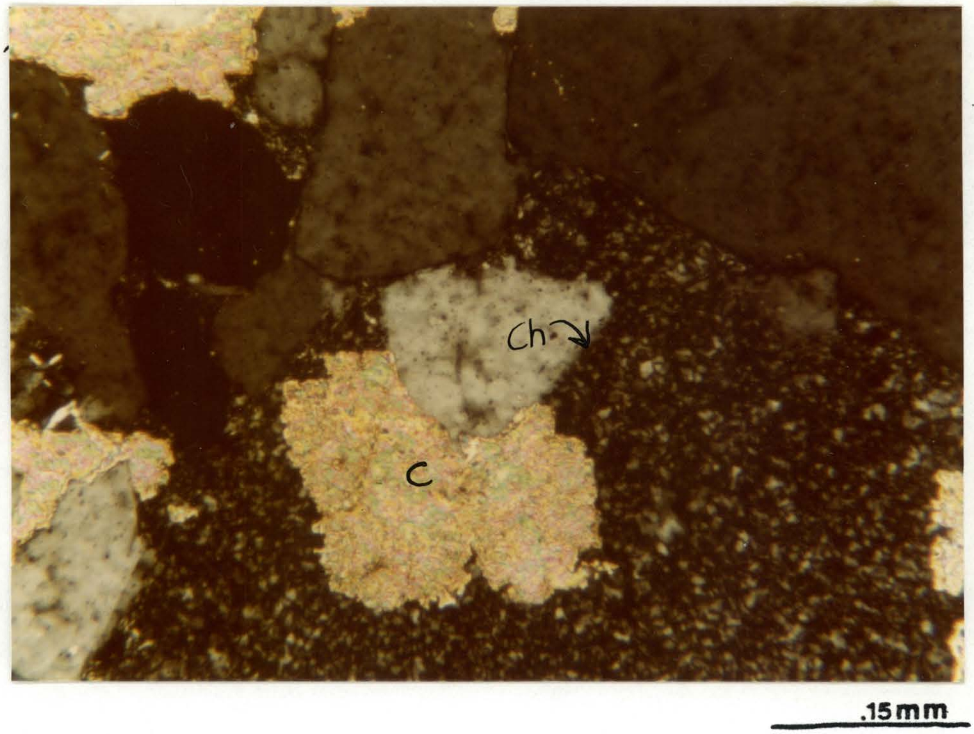


Figure 69. Chert (ch) replacing calcite (c). Crossed nicols. # 17X.

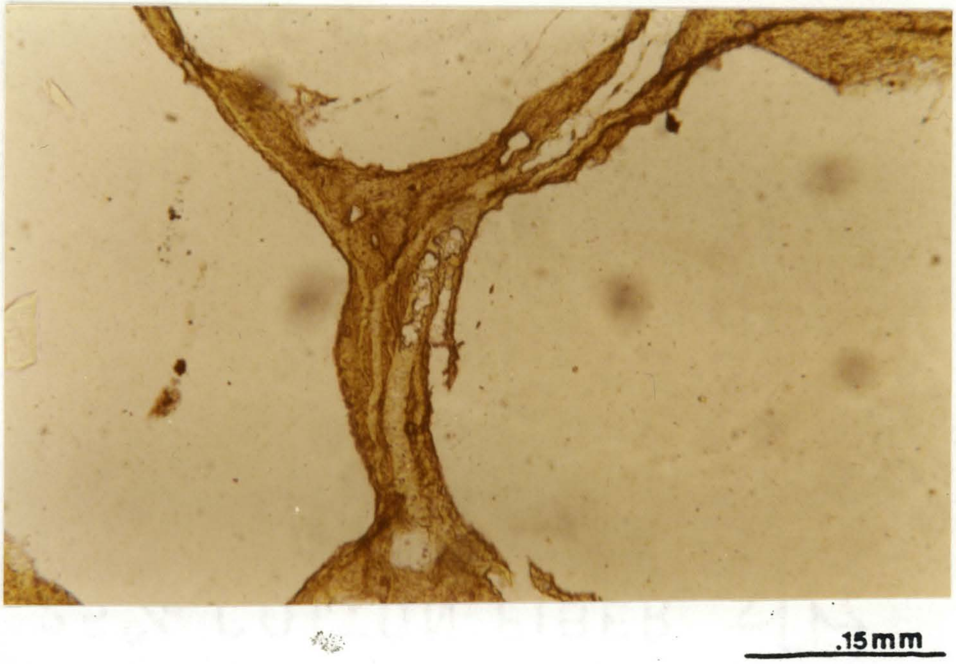


Figure 70. Fractures filled with quartz being replaced by chlorite. Plane light. # 123.

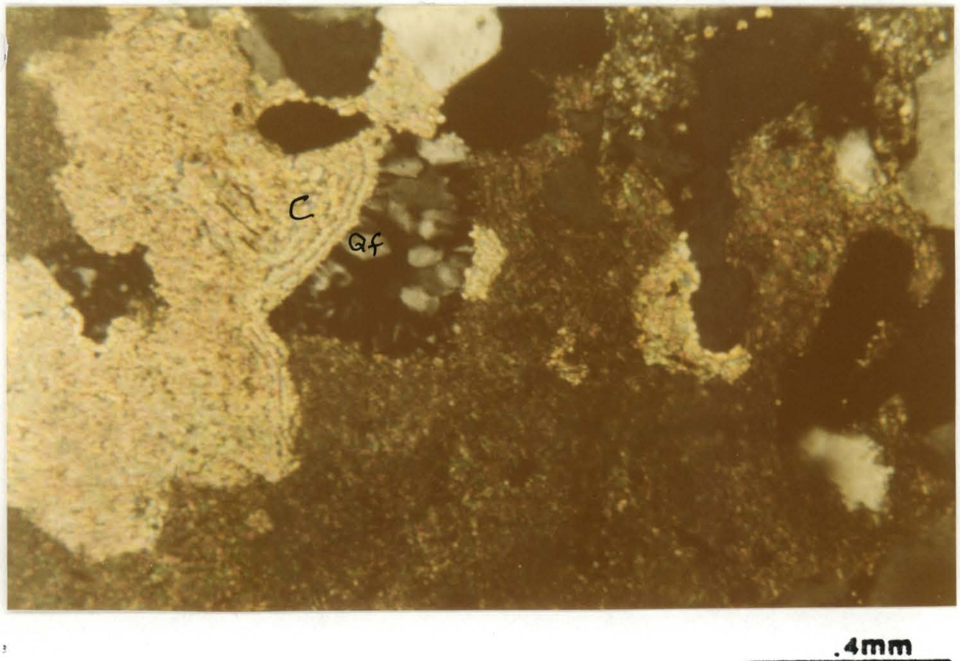


Figure 71. Zoned ferroan calcite (c) and pore quartz fill (Qf). Crossed nicols. # 17X.

grains in places. The pore fill (Fig. 71) is a rare phenomenon seen only in those sections where carbonates did not completely fill the pore or where the section is composed of granules and pebbles and pores were very large.

Illite

Authigenic illite assumes several forms and in some places constitutes up to 20% of the rock. In the majority of instances, it occurs as a mass of fuzzy fibrous sheaths that are arranged tangentially around grains or pore boundaries, and, when distinguishable, are about 10-15 microns long. It appears to have precipitated after the initial silica and carbonate cementation stages and fills the entire pore. Medial illite cement sutures (Fig. 39) are located in various parts of the pore, usually the central, and like medial boundaries in quartz cementation, indicate growth from the pore margin outward (Figs. 72, 73, 74, 75). Important authigenic indicators are the concentrically banded color zones (Fig. 73) seen under crossed nicols, the complete absence of silt, the structure of individual flakes when viewed with the SEM (Fig. 76), and the purity but poor crystallinity of the clay. Sometimes, especially in later pore precipitation episodes, the illite developed in a fashion horrent to the earlier illite cement (Fig. 39). Also illite appears filling in pores as small book-

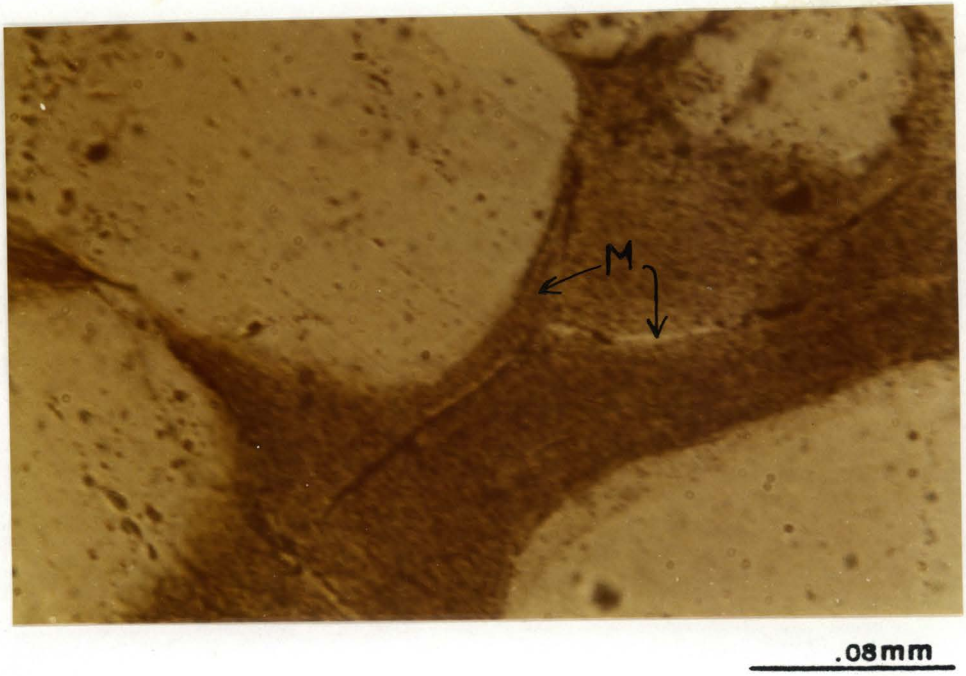


Figure 72. Medial sutures (MS) in illite. Plane light. # 134.

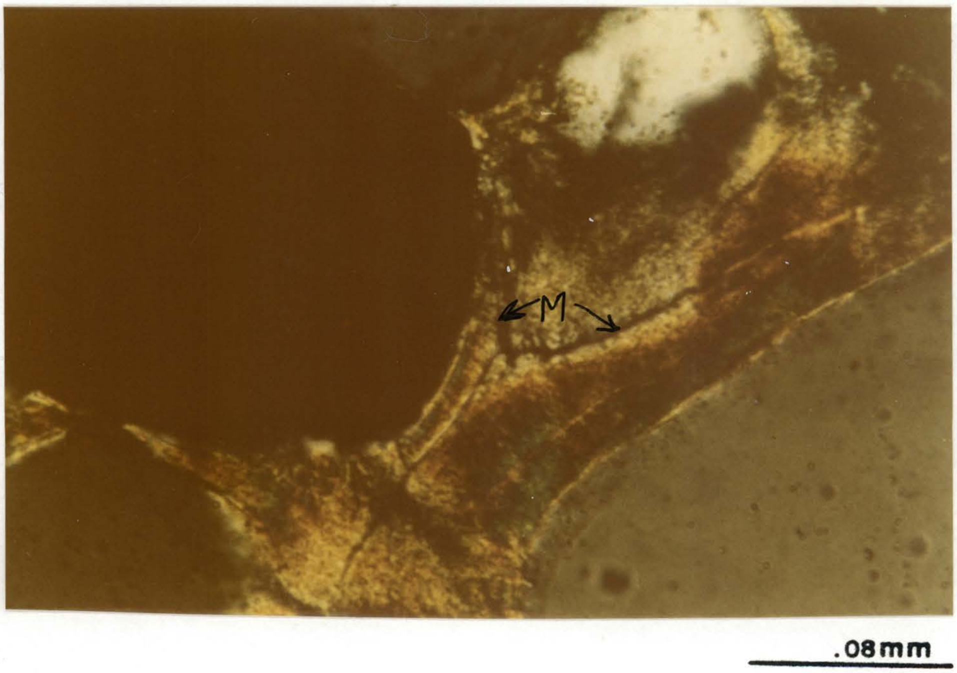


Figure 73. Medial sutures (MS) and concentric color banding indicating illite authigenesis. Crossed nicols. # 134.

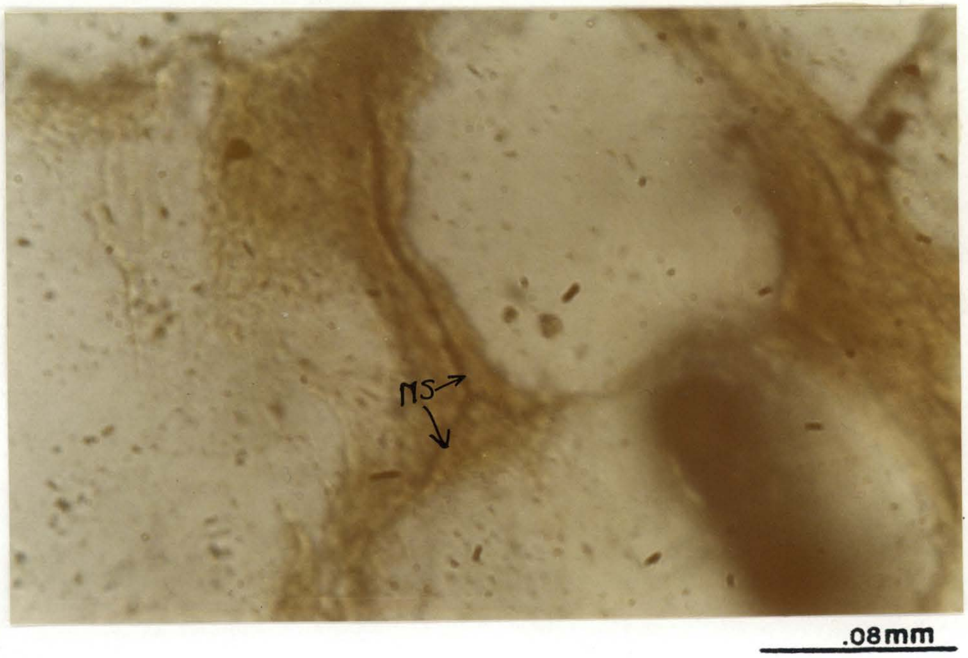


Figure 74. Medial sutures (MS) forming a triple junction. Plane light. # 162.

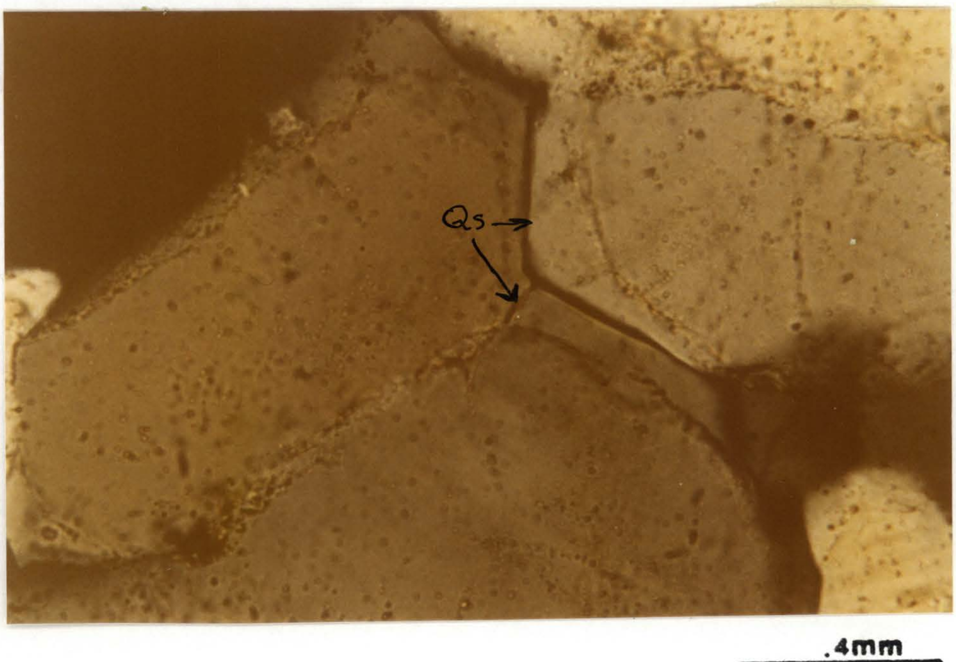
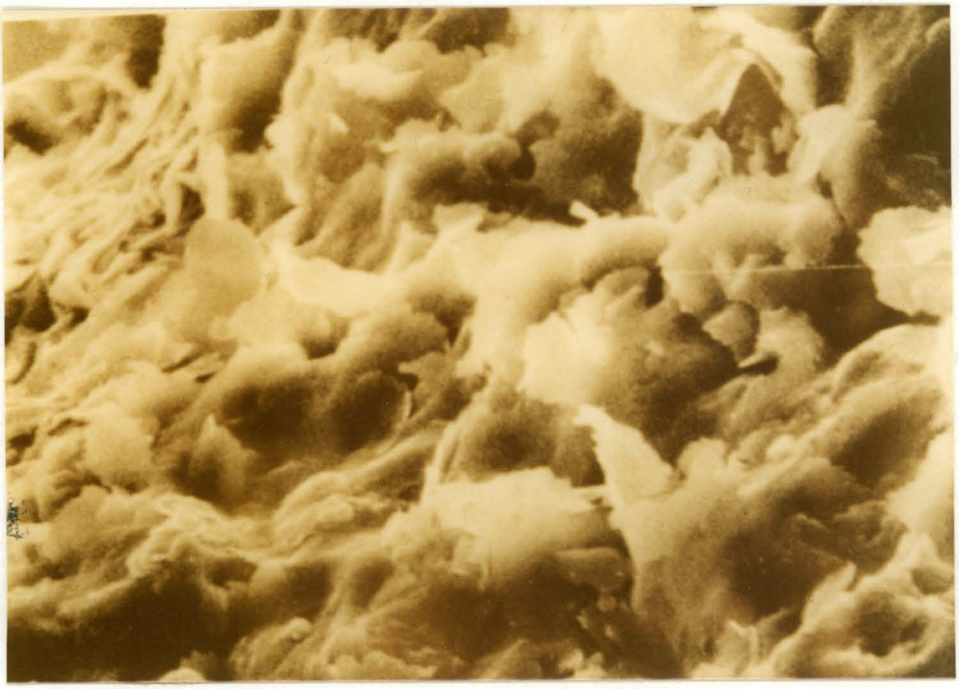


Figure 75. Medial quartz overgrowth sutures (Qs) forming triple junction. Crossed nicols. # 133.



25μm

Figure 76. Scanning electron micrograph of authigenic illite flakes. # 5.

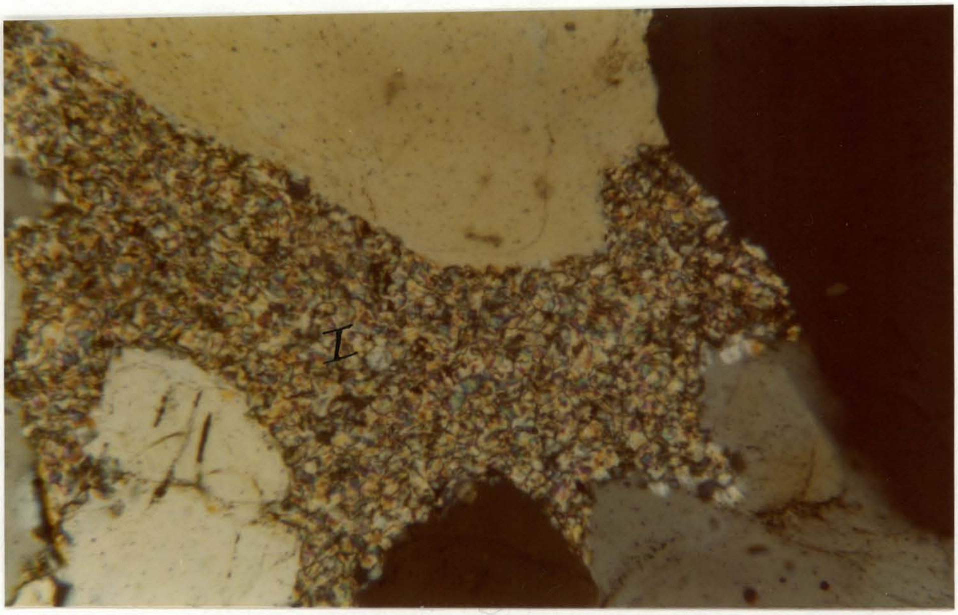
lets of flakes (Figs. 77, 78) or plates (40 microns long, 20 microns wide). In plane light, the illite is clear to pale green; under crossed nicols it attains a first order blue interference color.

In other cases, the illite occurs as discrete crystals in quartz and quartz overgrowths, this occurrence usually in conjunction with chlorite (Figs. 79, 80). SEM photogrpahs show illite and chlorite flakes are apparently dissolving the quartz.

Chlorite

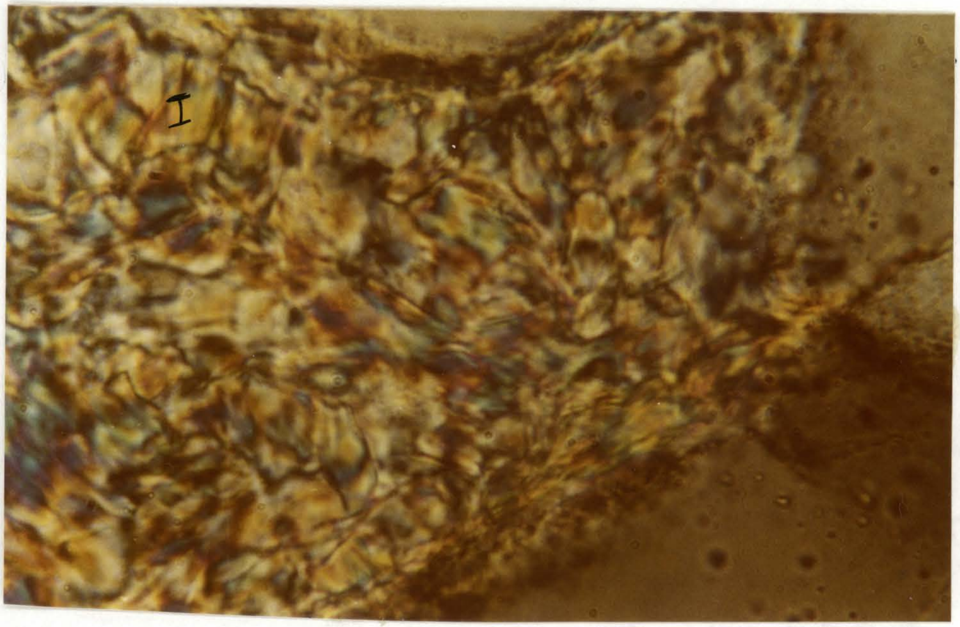
Like illite, chlorite assumes several structures, and also comprises up to 15% of certain rocks by volume. It manifests three distinct forms: vermicular groups of flakes (Fig. 80), individual shards or laths, and flakes scattered throughout illite or quartz (Figs. 81, 82).

The vermicular chlorite is a homogeneous congregation of worm-like, intertwining growths. The length of each "worm", ranges from 20 to 100 microns, and the width is about 20 microns. Flakes 1 micron thick comprise these units. This form of chlorite forms isolated patches (usually in an illite matrix) that exhibit sharp boundaries, suggesting that this is a replacement mineral, probably of feldspar. This chlorite has the typical gray to light yellow birefringence and is pea-green in plane light.



.15mm

Figure 77. Illite (I) and quartz overgrowths (Qo). Crossed nicols. # 14.



.04mm

Figure 78. Booklets of authigenic illite (I). Crossed nicols. # 14.

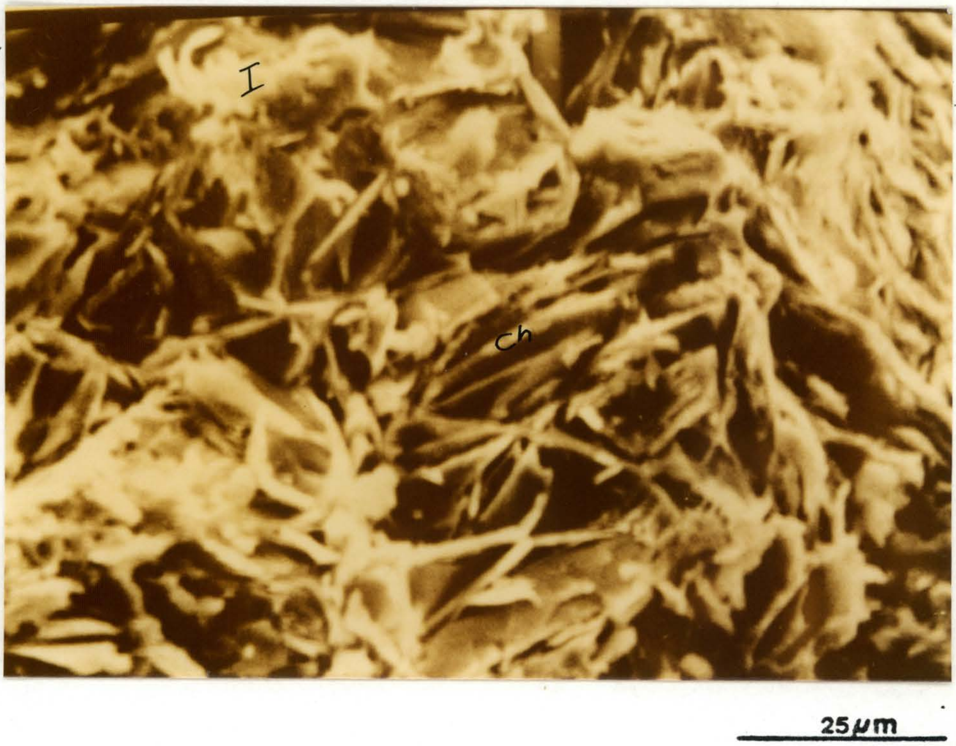


Figure 79. Scanning electron micrograph of chlorite (ch) and illite (I) flakes. # 5.

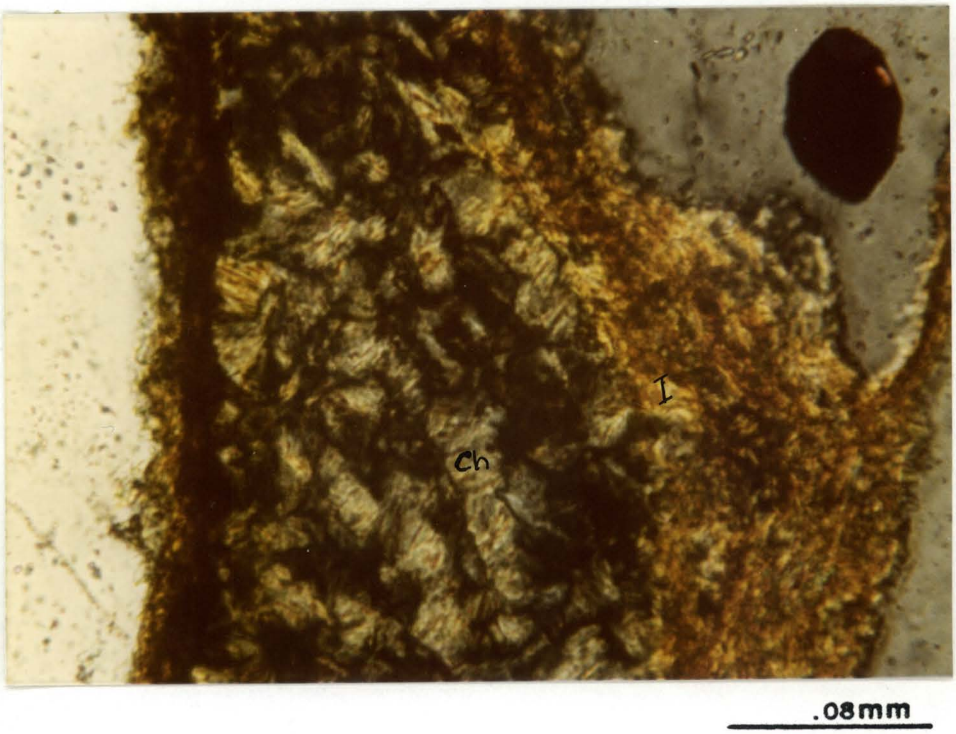


Figure 80. Nest of vermicular chlorite (ch). High birefringent matrix is illite (I). The chlorite is probably a feldspar replacement. Crossed nicols. # 123.

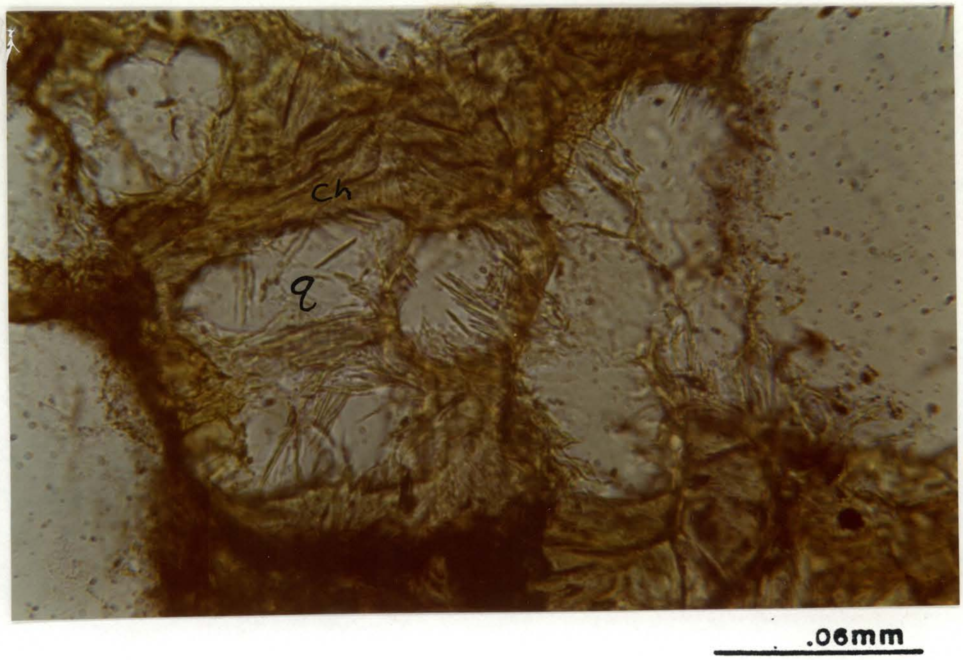


Figure 81. Chlorite (ch) replacing quartz (q). Plane light. # 128.

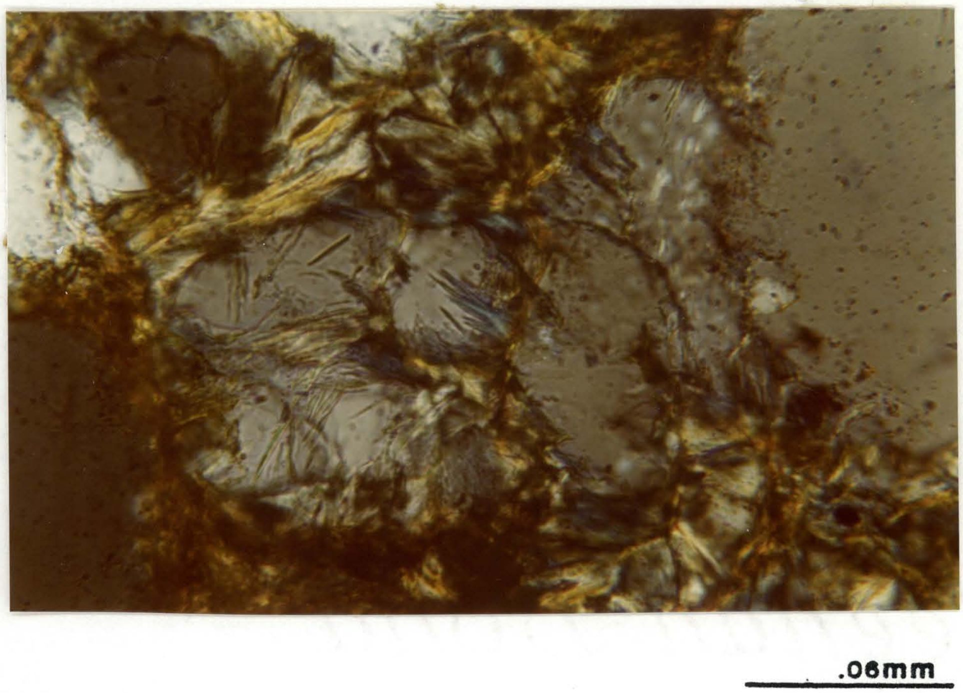


Figure 82. Characteristic Prussian blue extinction colors of chlorite; replacing quartz. Crossed nicols. # 128.

The second type similarly occurs in homogeneous masses but also and more noticeably as laths 20 microns long and 1-2 microns wide in quartz and quartz overgrowths. Apparently, it is replacing the quartz. This type exhibits a Prussian blue extinction color along with its low gray and straw-yellow birefringence; the shards are pale green in plane light.

Finally, chlorite occurs as distinct flakes scattered throughout illite cement or quartz overgrowths. They are about 10 microns in diameter and 1 micron thick. They exhibit a birefringence similar to the other forms.

Calcite

Various types of calcite have formed throughout the Arroyo Penasco, but most is in the top at the transition between clastic and carbonate units. Eight types are present: poikilotopic cement, finely to coarsely crystalline spar cement (.02 mm to 1.0 mm), slightly ferroan spar cement, slightly ferroan replacement calcite, replacement calcite, micrite (about 2 microns), microspar, and a fracture-fill cement.

Poikilotopic regions of calcite (Fig. 83) are the most widespread. This type forms in a patchwork fashion, each distinct sector surrounding many quartz grains. The calcite that is replacing feldspars and quartz either does or does not assume the poikilotopic crystal orientation.

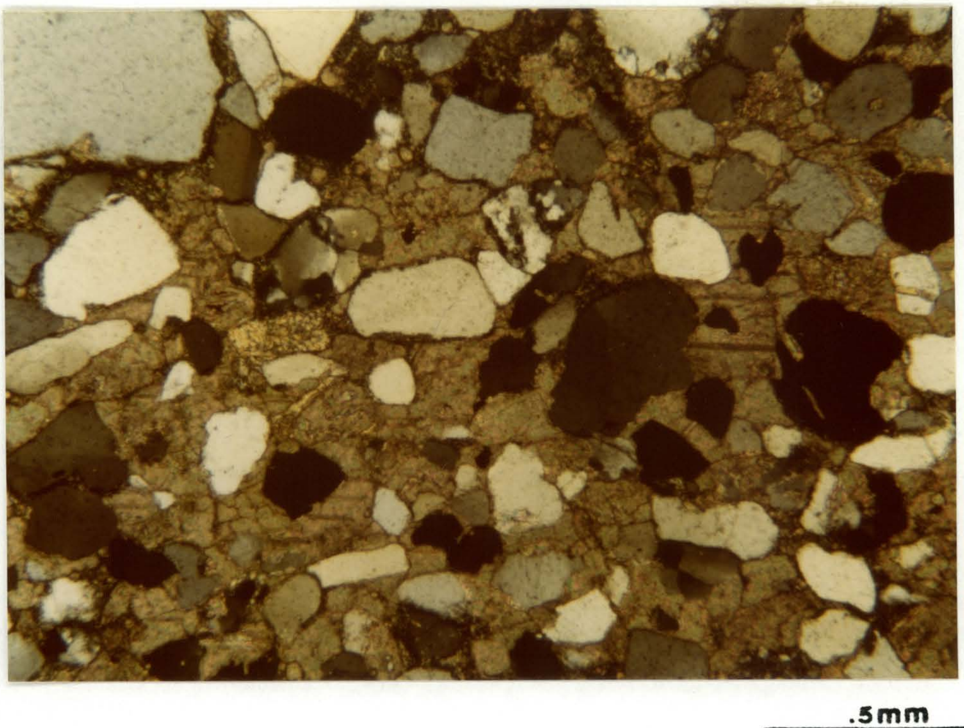


Figure 83. Loosely packed quartz grains in poikilotopic calcite cement. Crossed nicols. # 34.

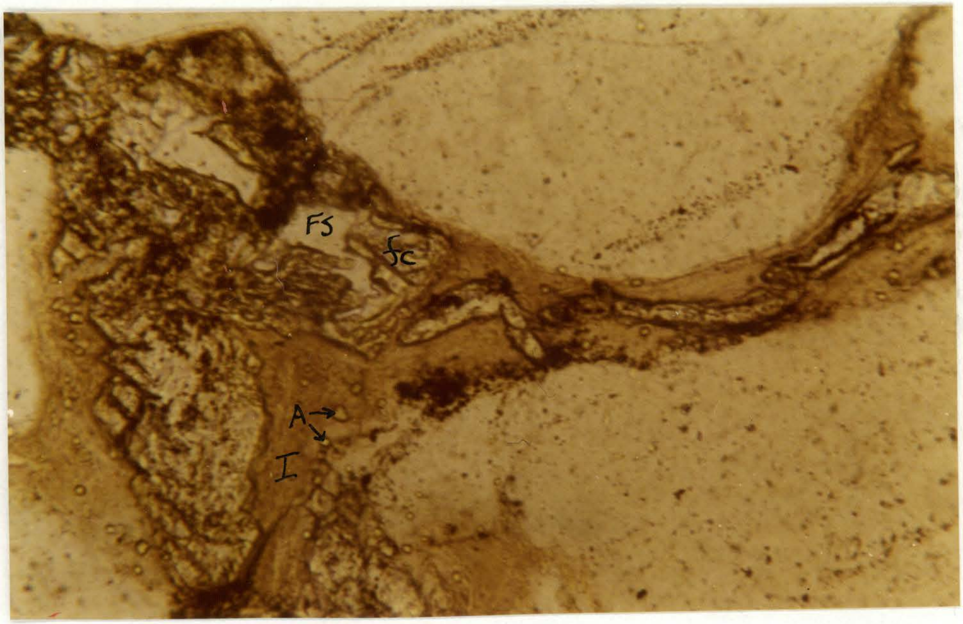
Slightly ferroan calcite replaces feldspars; and often, even though separated by an illite cement, under crossed nicols, the replacement crystals in large sectors extinguish at the same orientation (Figs. 84, 85). The distinction between true spar cement, either ferroan or plain, and the replacement cements is sometimes difficult. The ferroan calcite can be identified by compositional zoning (Fig. 71), accompanying aggregates of framboidal pyrite which form both in pores and on replacement crystals, and staining techniques (Fig. 86). Some of the replacement calcite is being leached (Fig. 39).

Sparry calcite, both plain and ferroan, occurs in the transition zone where authigenic quartz, chalcedony, and dolomite have formed. These types gradually merge into a dense, predominantly micritic lime-dolostone free of clastics; this is the true upper Arroyo Penasco. At lower intervals intermixed with the spar, calcitic micrite and microspar surround loosely packed clastic grains. Delineation of replacement grains is much clearer here than in sparry regions (Fig. 52).

Much later in the history of the formation, after episodic faulting, a poikilotopic calcite filled fractures and faults (Fig. 87).

Dolomite

Dolomite-dedolomite rhombs (Fig. 88), are scattered



.2mm

Figure 84. Feldspar (FS) being replaced by ferroan calcite (fc). Note apatite crystals (A) in illite (I). Plane light. # 84.

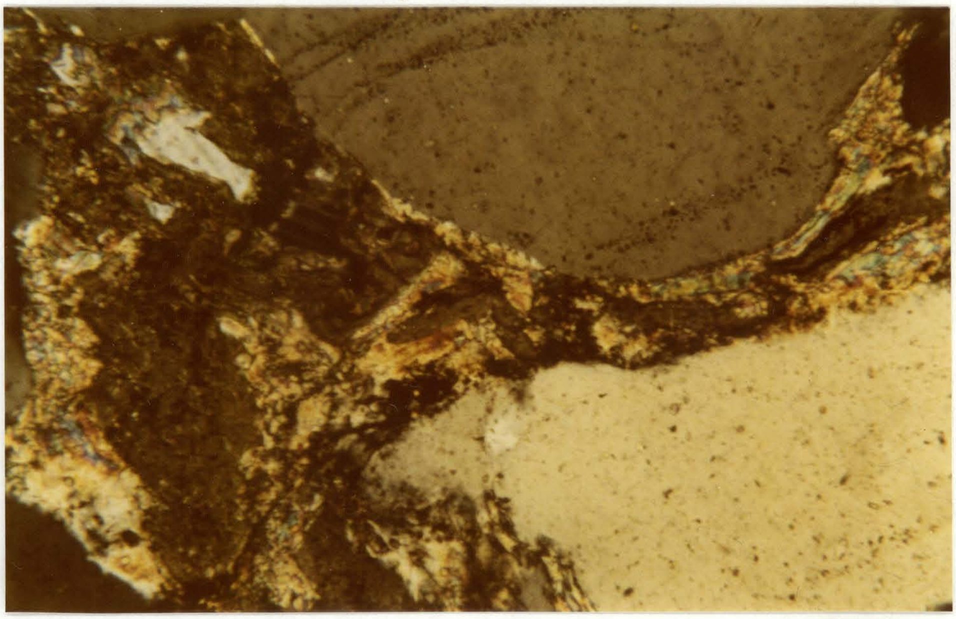


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Figure 85. Unitary extinction of replacement calcite under crossed nicols. # 84.

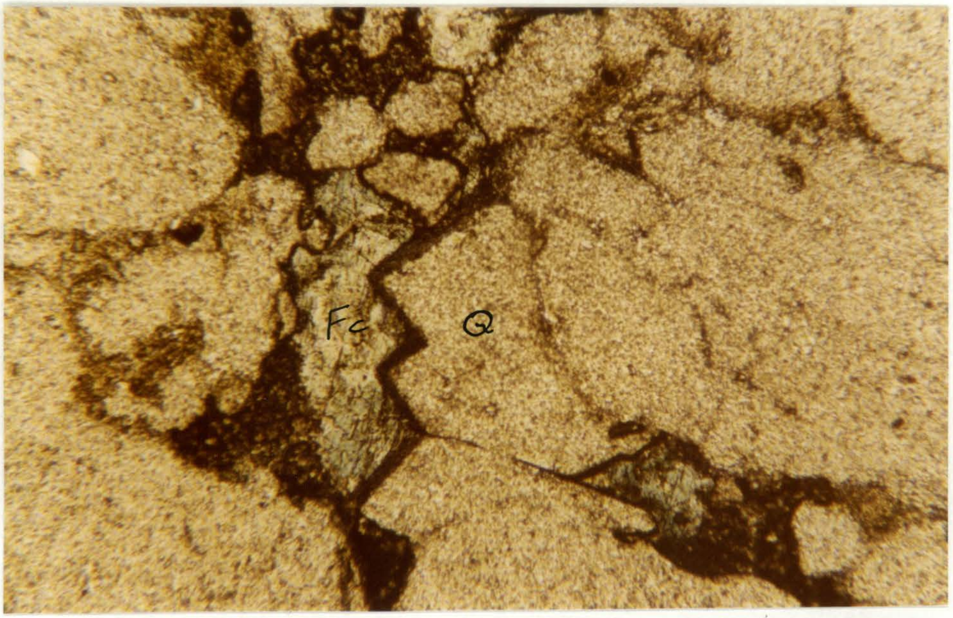

Figure 86. Ferroan calcite (Fc) in plane light stained blue. Note euhedral quartz overgrowths (Q). # 169.

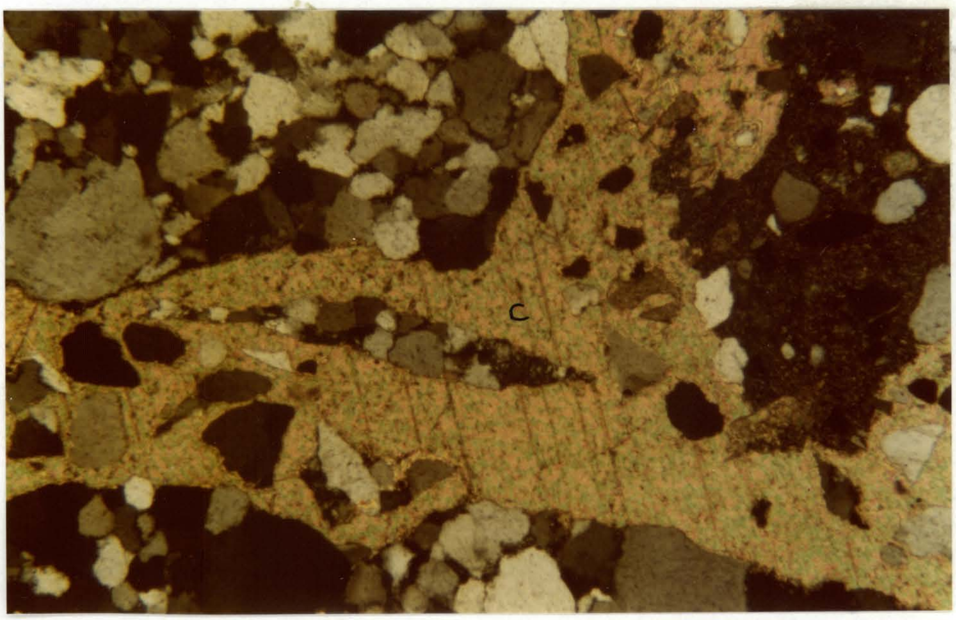

Figure 87. Poikilotopic calcite fracture fill (c). Crossed nicols. # 24X.

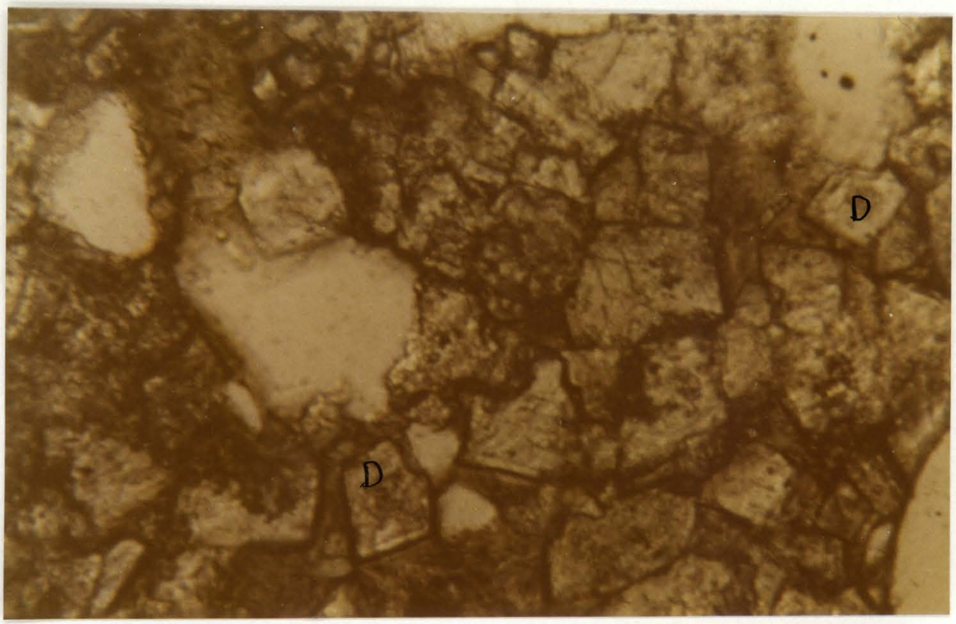

Figure 88. Dolomite and dedolomite rhombs (D). Plane light. # 171.

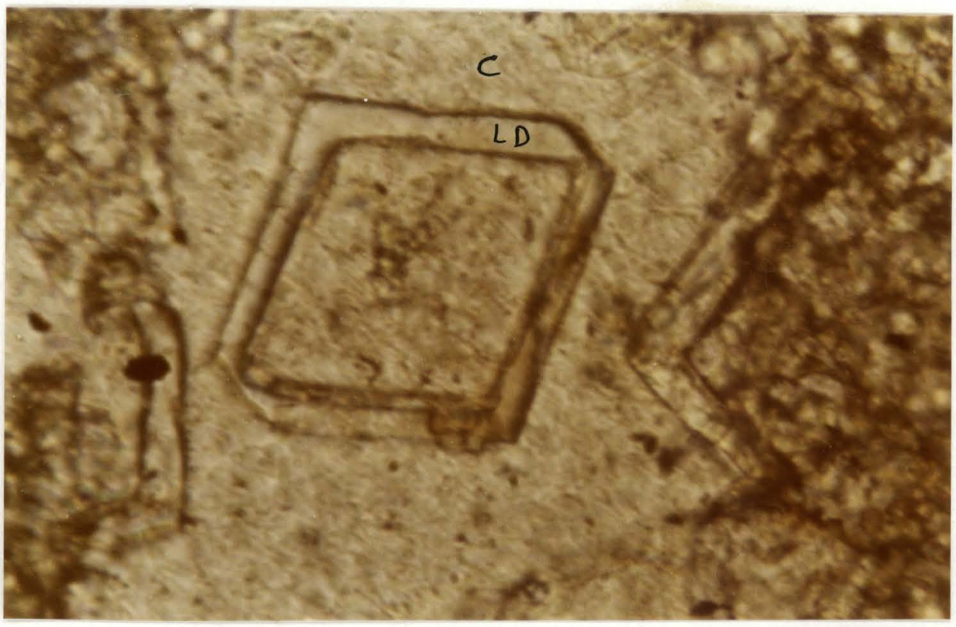

Figure 89. Dolomite with limpid perimeter (LD) in calcite (c). Plane light. # 171.

throughout the calcite, especially in the upper part of the clastic section. Some of the rhombs consist of a limpid rind of dolomite and dirty calcite core (Fig. 89). In places these rhombs are surrounded by poikilotopic calcite which extinguishes in the same orientation as the calcite inside the rhomb. Other rhombs are entirely dedolomitized. These rhombs range in size from 50 microns to 150 microns.

Limpid dolomite (Fig. 90) also occurs in illite along with apatite and framboidal pyrite. Here dedolomitization has not taken place. These crystals are slightly smaller than those embedded in calcite.

Pyrite

Pyrite developed as framboids 10 microns in diameter; most of this pyrite has altered to hematite; these are associated with carbonates and clays (Fig. 90). Also, amorphous microconcretions of pyrite (Fig. 91) cementing quartz grains are present. Again pyrite is altering to hematite or limonite.

Iron Oxides

Hematite and limonite are ubiquitous, occurring as stains due to surficial weathering processes, as a replacement of pyrite, as coatings on sand grains, and as a minor

Figure 90. Limpid dolomite (LD), framboidal pyrite (py) now hematite, in illite (I). Plane light. # 19X.

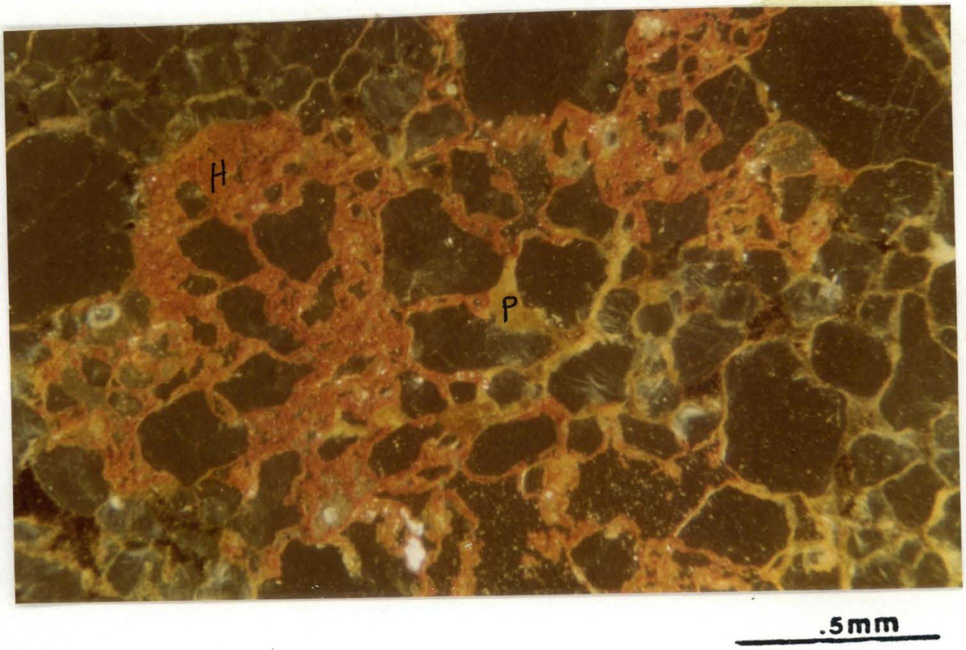

Figure 91. Massive hematite (H) after pyrite (p). Reflected light. # 129.

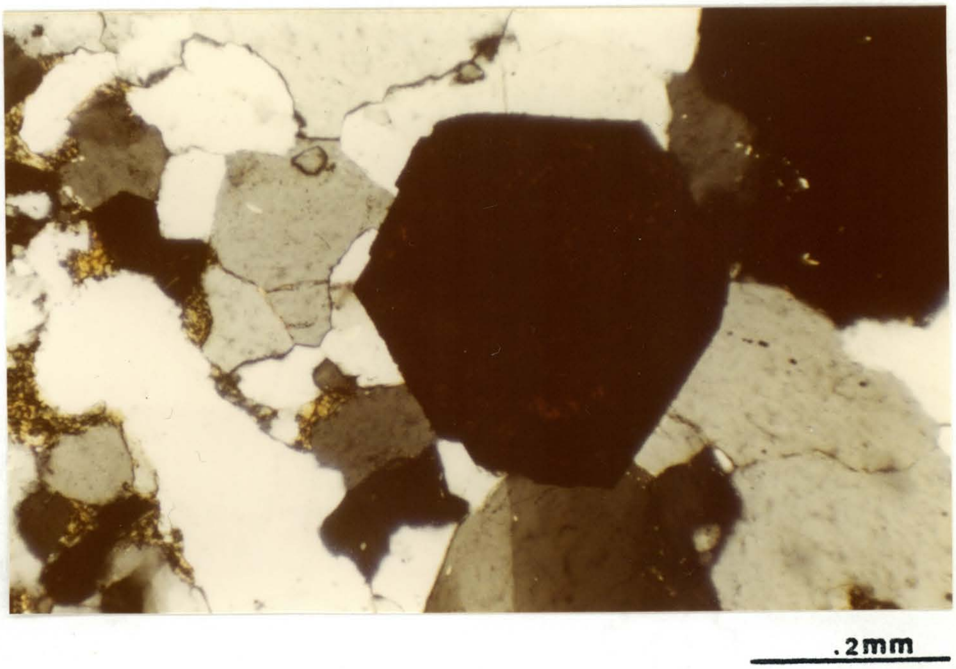

Figure 92. Hexagonal crystal of hematite. Crossed nicols. # 20.

cement. Goethite appears in minute quantities as a translucent yellow film on quartz grains and in clay regions. Hexagons .2 mm to .4 mm in diameter (Fig. 92) are also present, but they have all been altered to hematite or were hematite originally. If altered, they could have been pyrite.

Apatite

Perhaps the most unusual diagenetic mineral occurs as euhedral apatite crystals. These are equidimensional hexagonal barrels (Fig. 93) whose dimensions range from 5 microns to 30 microns, most being in the 10 micron category. They appear in the rocks around Ponce de Leon Springs near the Precambrian-Mississippian contact. They cluster most densely in the illite zones, but some appear to be included in quartz overgrowths (Fig. 94). Because of their small size and scarcity, identification was a vexation, but they are characterized by high relief, indices of refraction (ϵ, ω ; 1.63), pale green color, first order gray interference colors, and crystal habit. Documentation of such an occurrence has not been found in the literature.

Other Minerals

A mineral that cements quartz grains and is included in overgrowths has tentatively been identified as

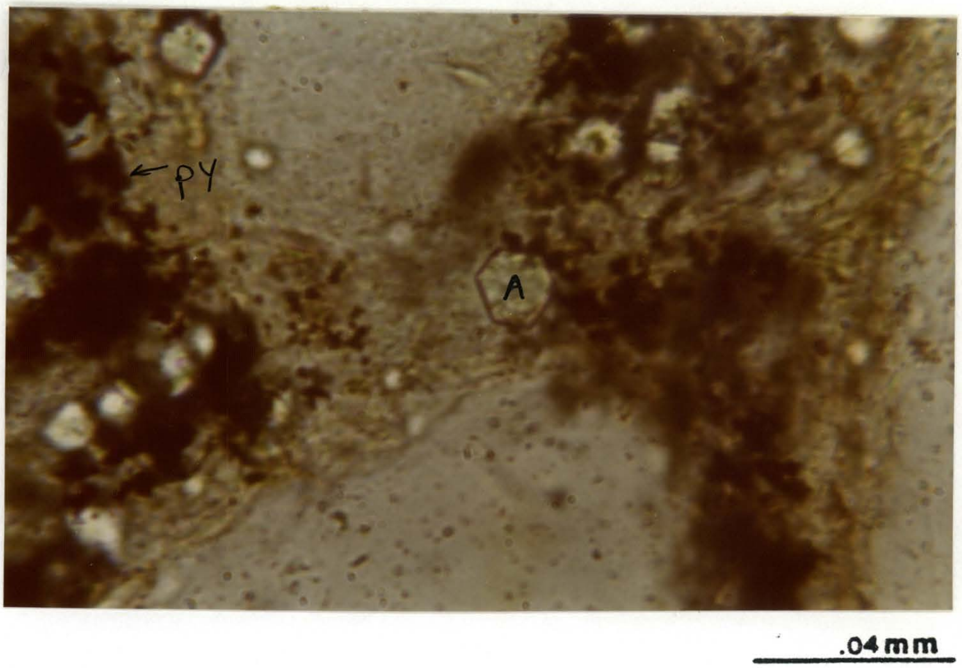

Figure 93. Apatite (A) and framboidal pyrite (py). Crossed nicols. # 84.

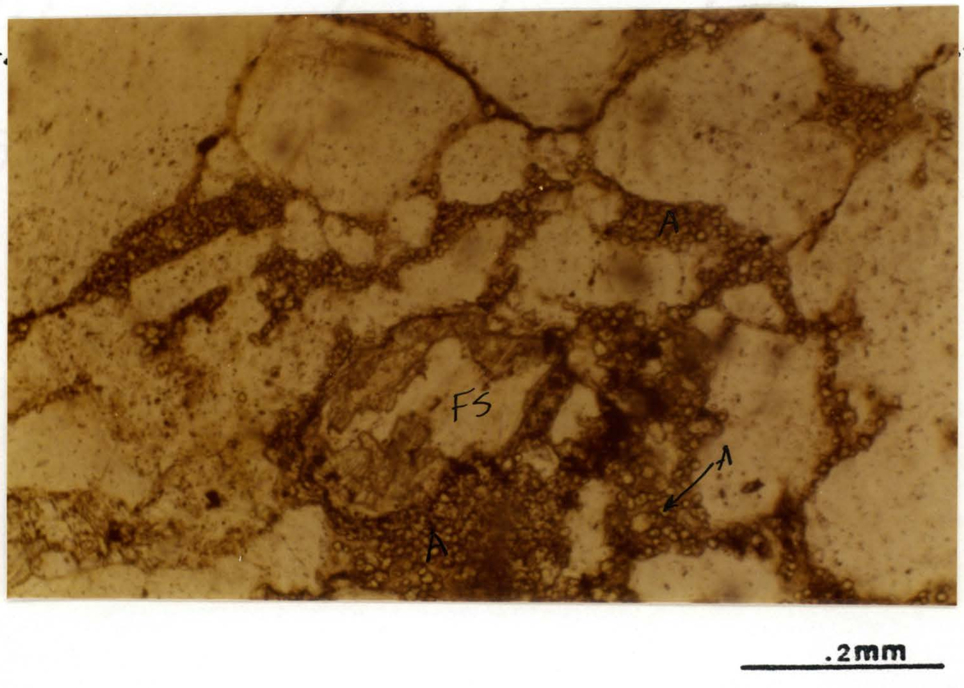

Figure 94. Nest of apatite crystals (A) and a feldspar grain (FS) being replaced by calcite. Plane light. # 84.

celestite (Fig. 95); (orthogonal cleavages, (+), orthorhombic, low birefringence). Armstrong (1967) reports minor amounts in higher portions of the Arroyo Penasco. This mineral could also be barite. The length-slow chalcedony could signify the original presence of gypsum or anhydrite (Folk and Pittman, 1971).

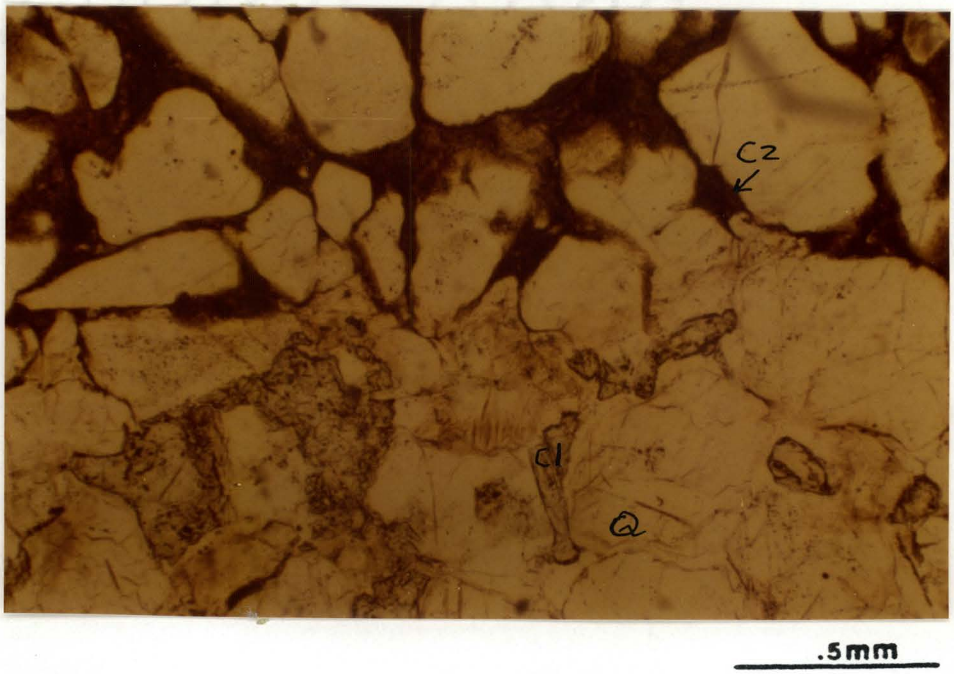

Figure 95. Quartz-cemented zone (Q) with celestite (Cl) and clay zone (cz). A portion of the maculose fabric. Plane light. # 4.

ALLOCHEMS

Allochems are present in the forms of unidentified fossil fragments. These are variously crinoid columnals, pelecypod hash, and broken foraminifers (Fig. 96). They are most prevalent in the transition zone. Only infrequently do fossils appear in the clastic section. Entire ostracods are present in places in the upper section where carbonates begin to dominate (Fig. 97).

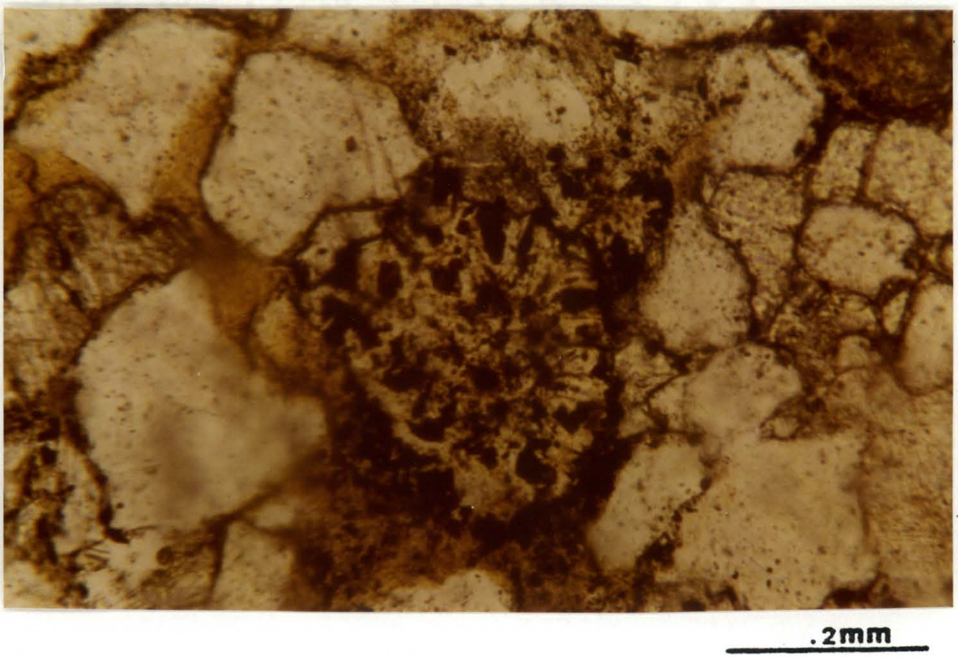

Figure 96. Unidentified fossil with pyrite in chambers. Plane light. # 98.

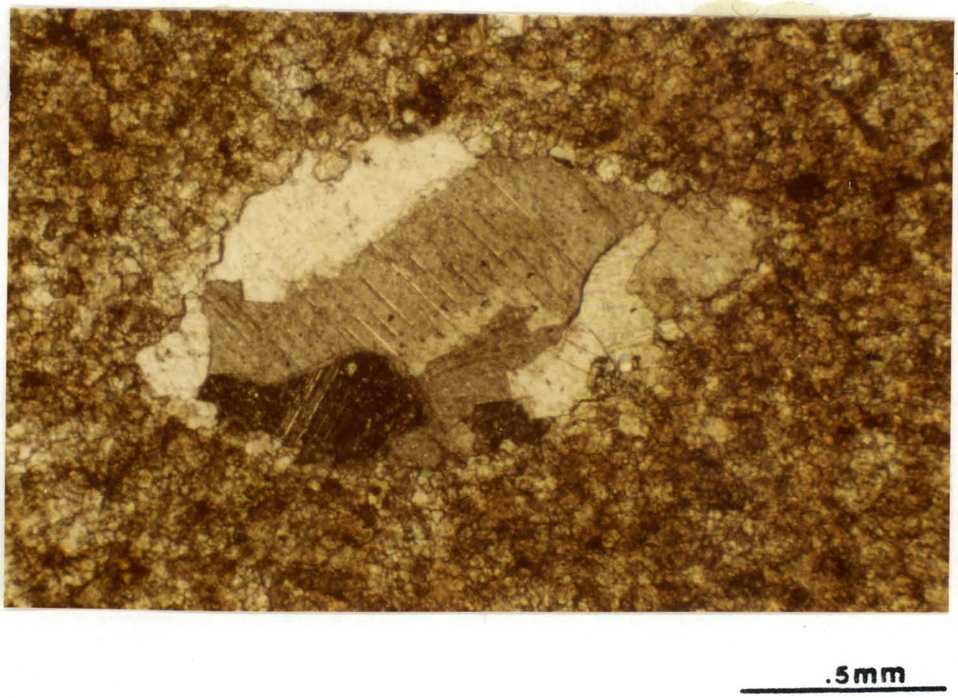

Figure 97. Ostracod in lower-upper Arroyo Penasco. Crossed nicols. # 40.

DEPOSITIONAL SYSTEMS AND ENVIRONMENT

The Arroyo Penasco is characterized by a number of features that indicate a system of high but fluctuating currents. Such regimes are common on Precambrian peneplains.

McKee (1962) reports that the stratification types of the Nubian Sandstone in Africa conform to those found in a fluvial environment, these being, for the most part, medium tabular cross-stratification types with foreset azimuths restricted to one direction. Many other features common to fluvial systems are present in the Nubian but the ubiquity (99%) of this cross-stratification type is diagnostic.

Harms (1978) gives several other characteristics of the Nubian Sandstone: it rests on an arkosic Precambrian basement, but quartz comprises 100% of the sediment; rounded and angular grains are intermixed; a heavy mineral suite of tourmaline, zircon, and rutile with well rounded grains mixed with angular is present; coarse-grained sediments dominate; embayed grains are present; and infiltrated clays are the rule instead of codepositional clays.

Except for the bedding types, these features are all found in the Arroyo Penasco. The feldspars in the

Nubian probably were altered and removed from the system, the evidence for this being dissolution porosity. The shape and varying degrees of rounding of the quartz grains and heavy mineral suite indicates a multicycle sediment and local sources. According to Harms (personal communication, 1978), the embayed grains represent the effects of lateritic processes. As Walker et al. (1978) maintain, coarse sandy systems rarely contain clay that is anything but infiltered. This is especially true in arid environments. Such is the case for the Nubian and Arroyo Penasco, although both were ostensibly deposited in environments that were humid periodically, this being inferred by the associated laterite and silcrete.

Other types of environments that develop on Precambrian surfaces are tidal and marine environments as is the case of the upper Flathead of Wyoming (Bell, 1970) and environments intermediate between marine and fluvial such as the Tapeats Sandstone of Arizona (Hereford, 1977). Bell (1970) gives as evidence of tidal and beach deposited sediments in the Flathead the presence primarily of parallel-stratification interbedded with very thin shale units. This is typical of much of the Arroyo Penasco. Underlying these deposits, Bell has a channel system that was transgressed by the marine currents. As in the Arroyo Penasco, mudcracks in the Flathead are numerous and indicate subaerial exposure as well as thin beds of shale.

For deposition of the Tapeats system, Hereford (1978) believes that a marginal system of marine, tidal flat, beach, and braided streams was responsible. A wide dispersion of foreset azimuths is characteristic of tidal flats and offshore deposits; in contrast, scour-and-fill structures and low variation in azimuths are evidence of fluvial systems. In the Arroyo Penasco, these sedimentary structures and associated beds alternate, indicating a series of advances and retreats of the systems involved. For the Arroyo Penasco, then, a system similar to the Tapeats is envisioned as illustrated in Figure 98. A slight modification of Hereford's model is needed to encompass the occurrences of dolomite and the evidence of evaporites, the presence of which is inferred from crystal casts and small amounts of length-slow chalcedony (Folk and Pittman, 1971) and celestite seen in thin section. Various forms of dolomite, calcite, and authigenic silica are among the indications of a schizohaline environment, a condition wherein periods of high humidity and fresh and brackish waters alternate with aridity and hypersaline waters. A fluctuating water table of varying chemistry is associated with such an environment.

A composite progression of scenarios (Figs. 99, 100, 101) from Mack and Suttner (1977), Dott and Batten

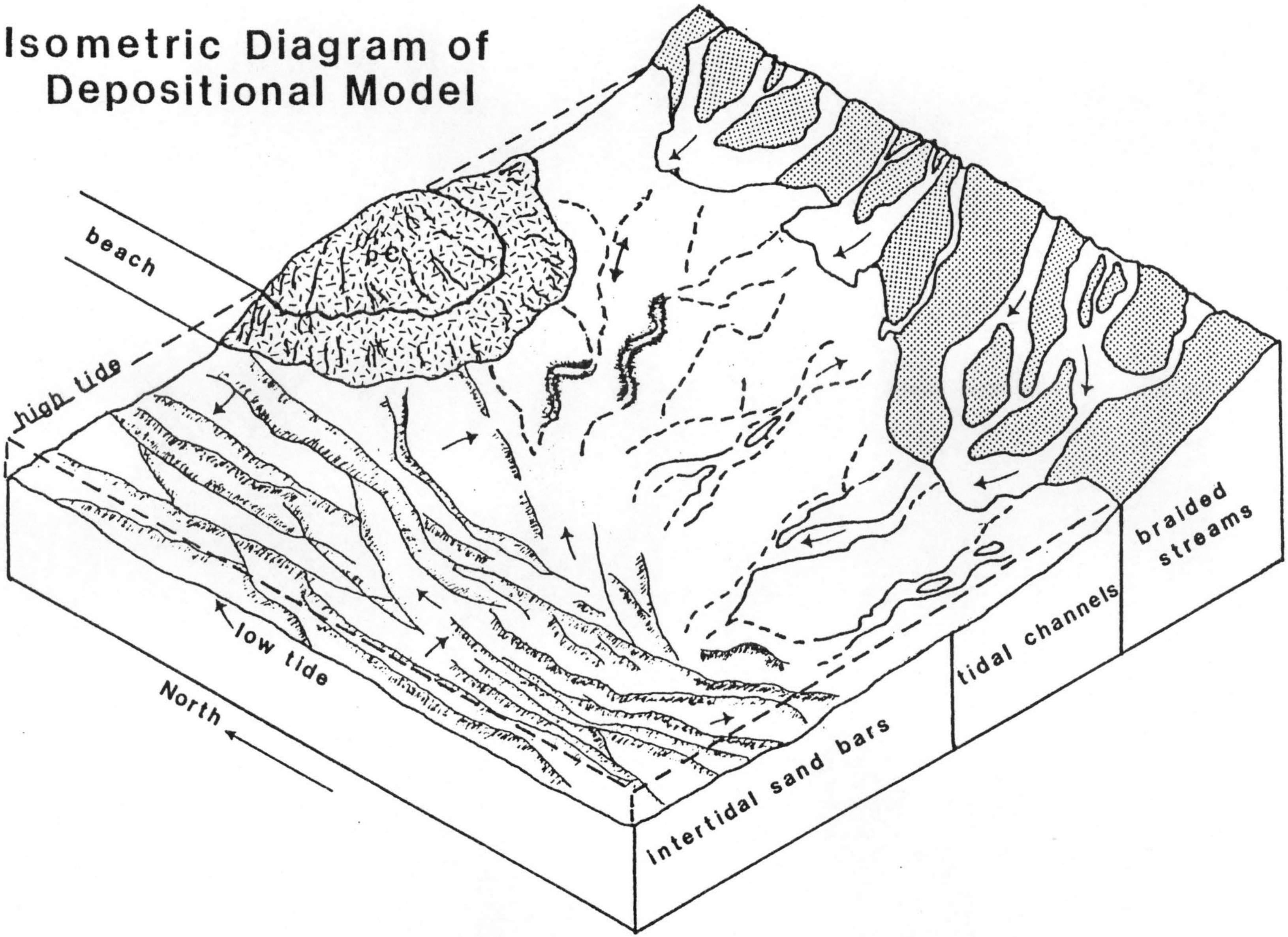

Figure 98. Depositional model. Modified from Hereford (1977).

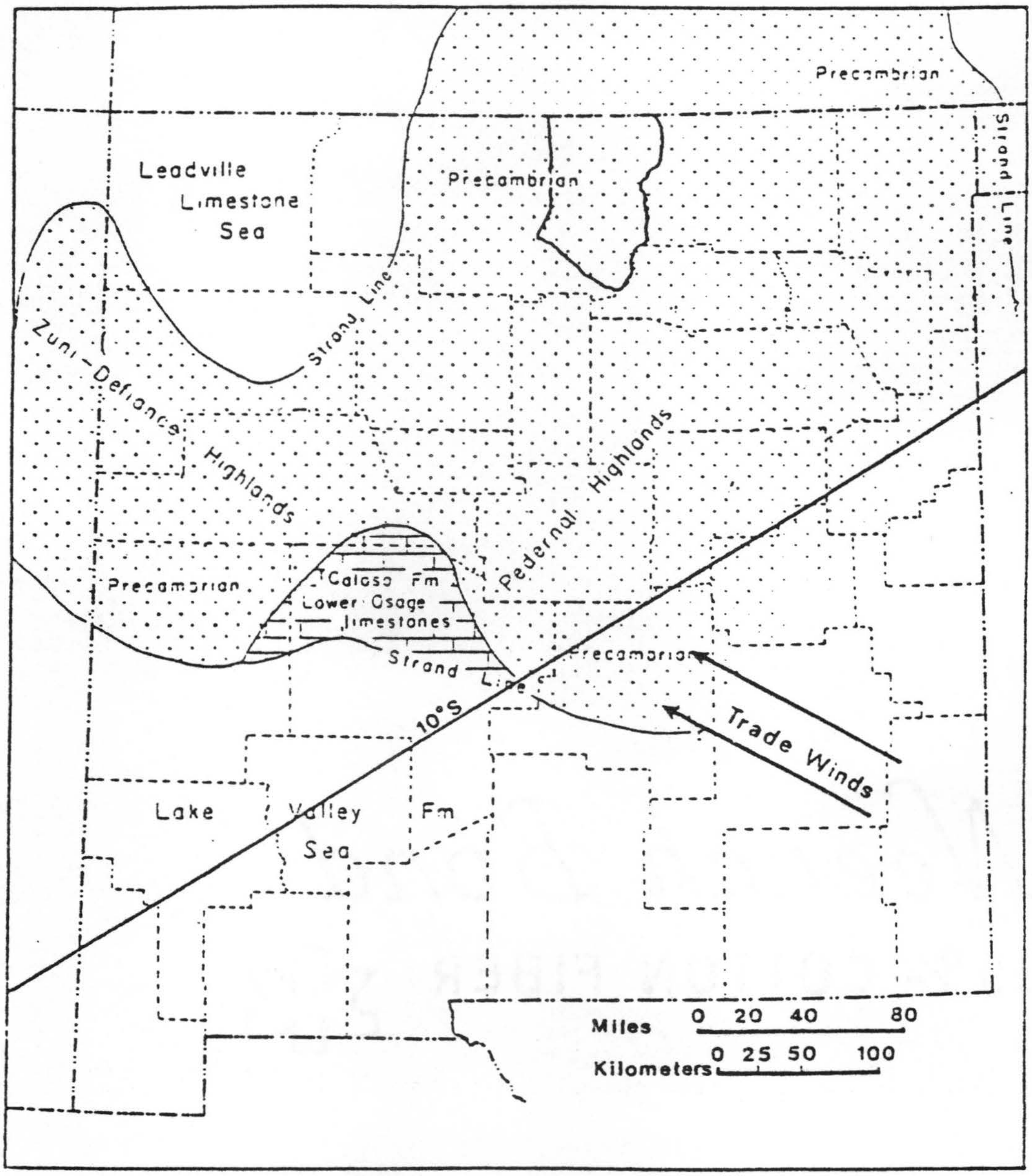

Figure 99. Paleogeography before the beginning of Upper Osage Time and Arroyo Penasco deposition. Compiled from Armstrong (1967), Dott and Batten (1971), and Mack and Suttner (1977).

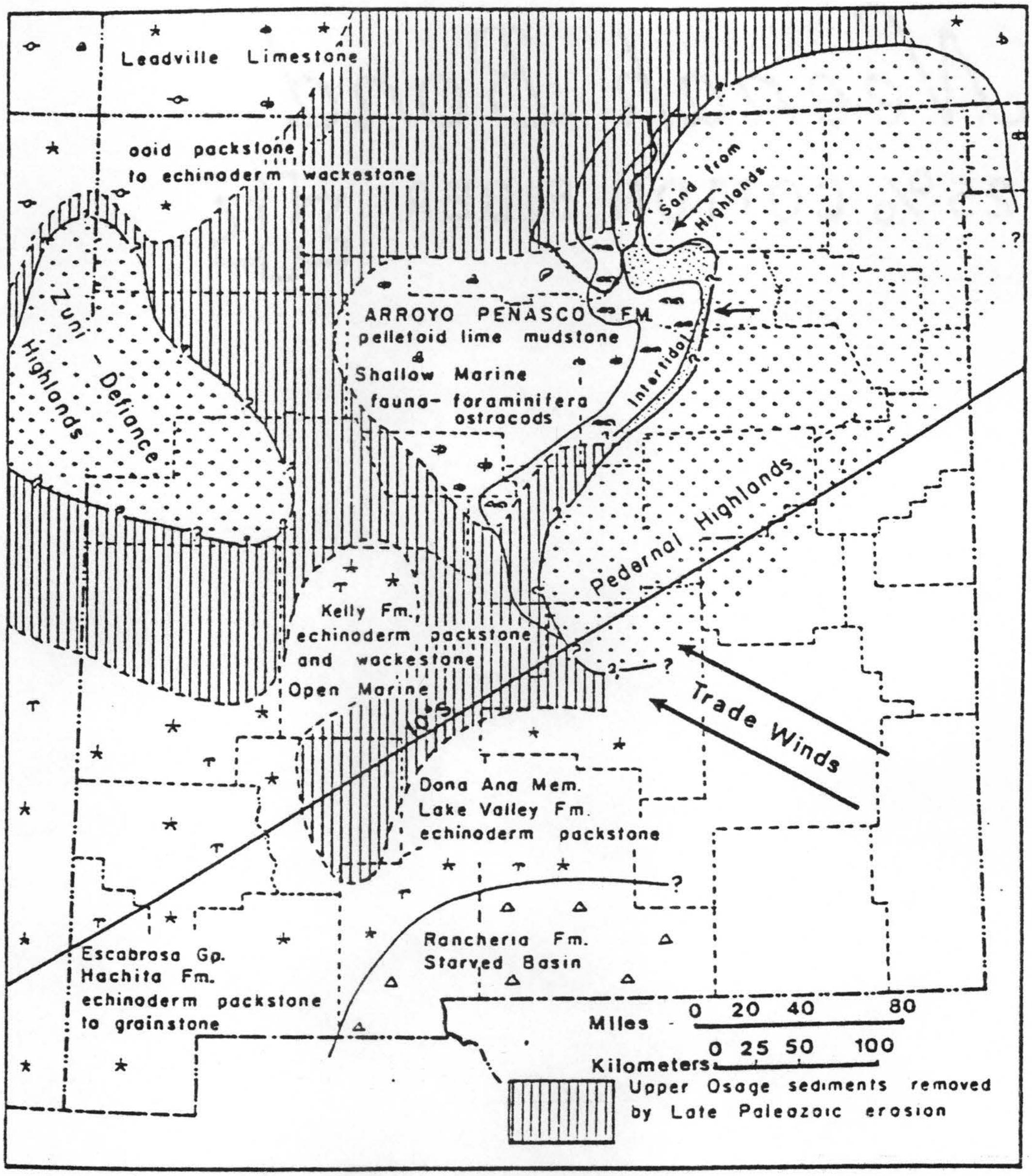

Figure 100. Diagrammatic representation of Arroyo Penasco depositional patterns during early to middle Mississippian Time. Compiled from Armstrong (1967), Dott and Batten (1971), and Mack and Suttner (1977).

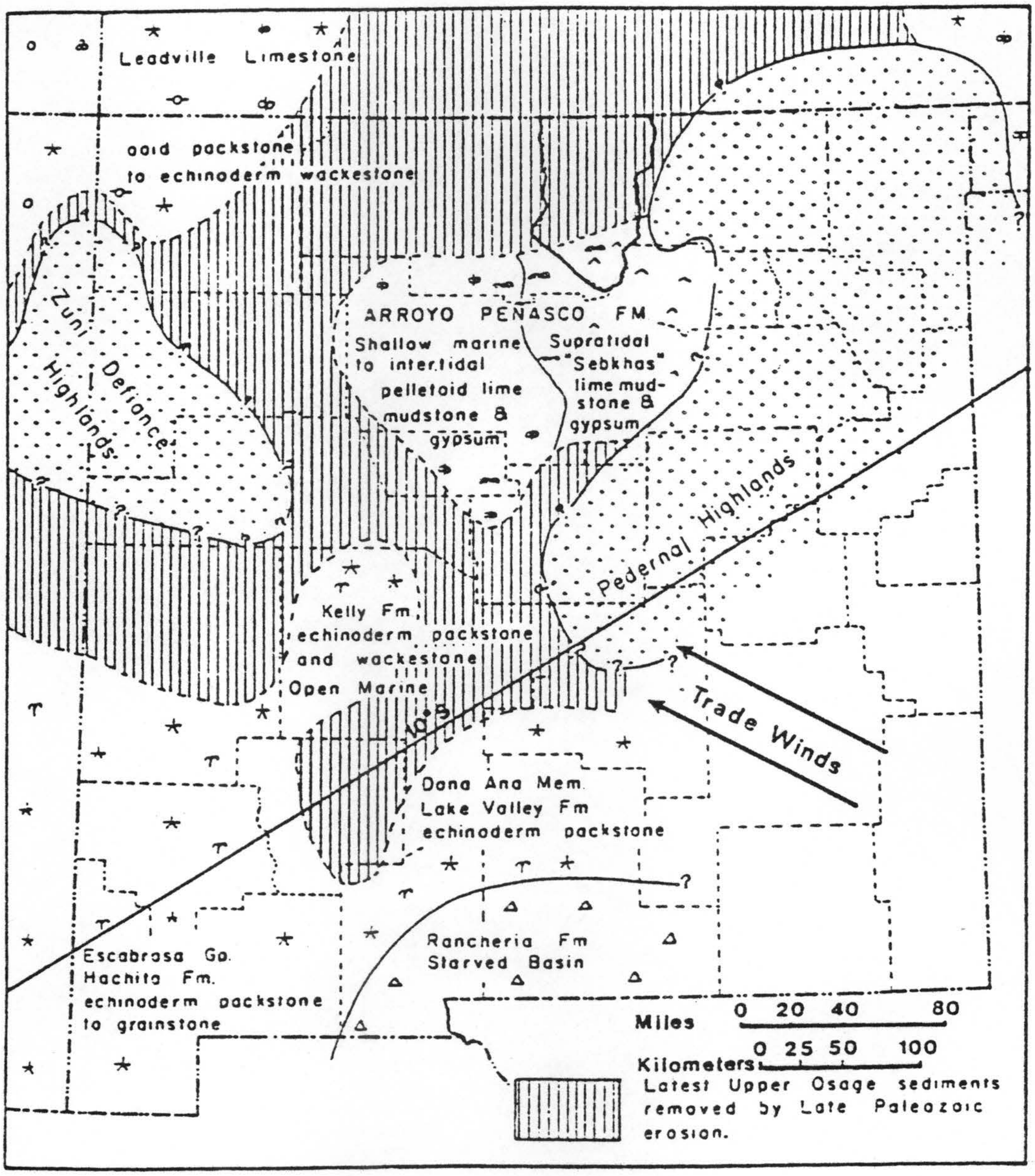

Figure 101. Diagrammatic representation of facies patterns at end of Lower Arroyo Penasco deposition. Compiled from Armstrong (1967), Dott and Batten (1971), and Mack and Suttner (1977).

(1971), and Armstrong (1967) show the probable evolution of the Arroyo Penasco. These indicate that the area was tropical within 10^{o} of the equator and subject to easterlies that at certain times brought in monsoonal rains and that at other times were dry. So periods of high evaporation (evaporite formation stage) alternated with times of high humidity (silcretes, laterites, limpid dolomite stage). These various diagenetic stages and more on their significance will be discussed in the next section.

Likewise, the angular pebbles, lack of clay, and sedimentary structures indicate a system that had high velocity alternating currents and locally high gradients. The depositional system, then, was marginal between marine and fluvial, consisting of Precambrian monadnocks poking through a terrain drained by braided streams with flashy discharges that fed beaches and tidal and sebkha-like flats (Fig. 102). Minor aeolian transport is also a probability. These systems spread a thin veneer of sand over a large area and were subject to an extremely variable climate with periods of high and low rainfall which produced a variety of sedimentary structures and was also partially responsible for the subsequent complex diagenesis.

Figure 102. Aerial photograph of braided streams and monadnocks in North Africa similar to a portion of Arroyo Penasco depositional facies. From Reineck and Singh (1975).

DIAGENESIS

Silica

Subsequent to deposition, dissolution of quartz grains began in the basal Arroyo Penasco beds. Evidence of silica solubility includes extensive grain embayment, the presence of solution fractures or micro-grikes, abnormal roundnesses for many of the quartz grain shapes, lack of polycrystalline grains, and a crude bimodality (Crook, 1968; Cleary and Connolly, 1972; Blatt, 1967; Raeside, 1959).

Experimental studies (Siever, 1972; Morey, 1962) show that quartz is slightly soluble in waters where pH values hover around 9.0 (Fig. 103) and solubility increases with rising pH and temperatures. Most meteoric water ranges from pH values of 7 to 9 (Fairbridge, 1967); Pettijohn et al. (1973) and Crook (1968) state that most soils and weathering profiles do not exceed a pH value of 9, and most modern soils are acidic (Crook, 1968). Notwithstanding, Crook (1968), Cleary and Connolly (1972), Blatt (1967), and Davis (1974), suggest that soils or weathering profiles provide an unstable environment for quartz, the reason being the presence of organic compounds that mobilize silica from the quartz grain. In modern soils the root

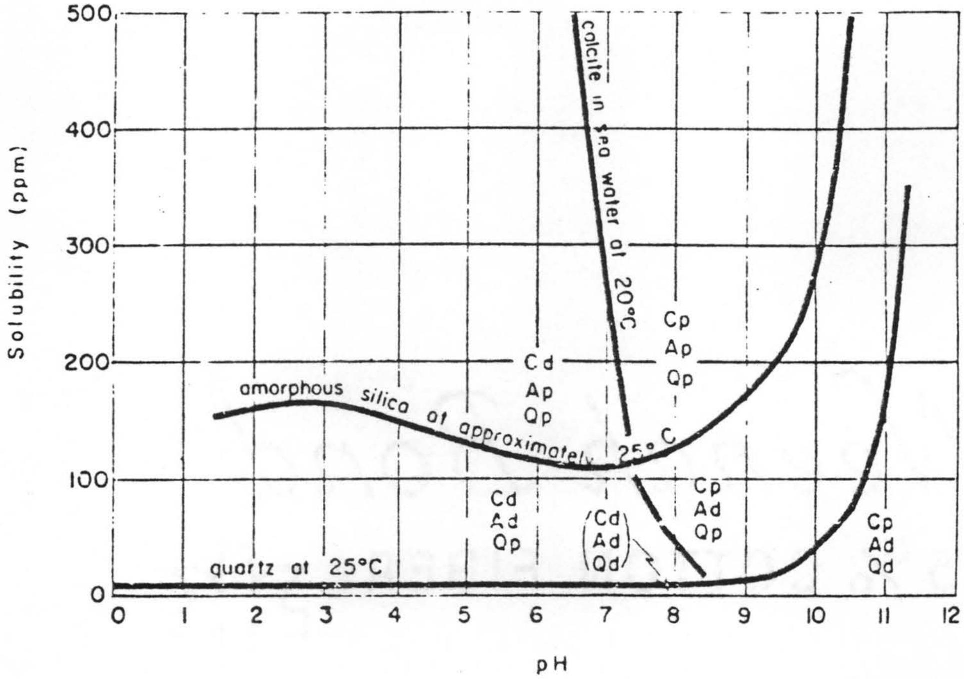

Figure 103. Silica and calcite solubilities. From Blatt (1966).

zone is the locus of greatest solution of quartz (Cleary and Connolly, 1968), and it is in this zone where mineralogical maturity is reached.

Another environment where quartz dissolution occurs is in Magadi-type lakes or playas, as described by Surdam et al. (1972) and Rooney et al. (1969). These environments are characterized by high salinities and pH values approaching 12, indicating that the waters are extremely alkaline; moreover, groundwater moving through these areas assumes a high alkalinity that is carried over some distance Rooney et al. (1969). The dominant cation in these areas is sodium that usually combines with the carbonate radical. Conceivably, potassium along with sodium could be a by-product of the weathering of exposed granite basements, thus raising the alkalinity and pH into a range that allows silica dissolution.

The causes for precipitation in these environments are not certain, but some investigators (Surdam et al., 1972; Rooney, et al. 1969) believe that flushing with normal fresh water would increase the acidity and generate precipitation. Magadi cherts are the typical product in these environments, but other forms of silica might come out of solution under different mineralogical or environmental circumstances.

As far as dissolution is concerned, it seems, then, that either high alkalinities and pH values or organic activity engenders the conditions necessary. In the Arroyo Penasco, there is no evidence of roots or plant fragments, although pyrite could be an indirect indication of their presence. The more feasible picture is one that includes a creation of high alkalinities in the groundwater. The occurrence of carbonates, anhydrite, and celestite, in certain intervals of the formation indicates that such might have been the case.

The silica dissolution process, whether by organic or physical chemistry, dictates an evolution of sorts in the sediment. Cleary and Connally (1972) report that as solution continues on granites and gneisses, it is possible to produce a profile consisting mostly of monocrystalline quartz, the polycrystalline quartz being far more chemically unstable (Blatt, 1967; Harrell and Blatt, 1978). The quartz in the heavily embayed zones of the Arroyo Penasco does not have polycrystalline quartz, although the source area is metamorphic and igneous. Thus, much of the polycrystalline quartz could be breaking down in situ due to chemical activity. Higher in the section embaying ceases and polycrystalline quartz markedly increases.

Also of note is the fact that dissolution in the form of microgrikes or reentrants is taking place in the monocrystalline quartz (Figs. 104, 105). Commonly, this solution follows old fractures lines deeply into the

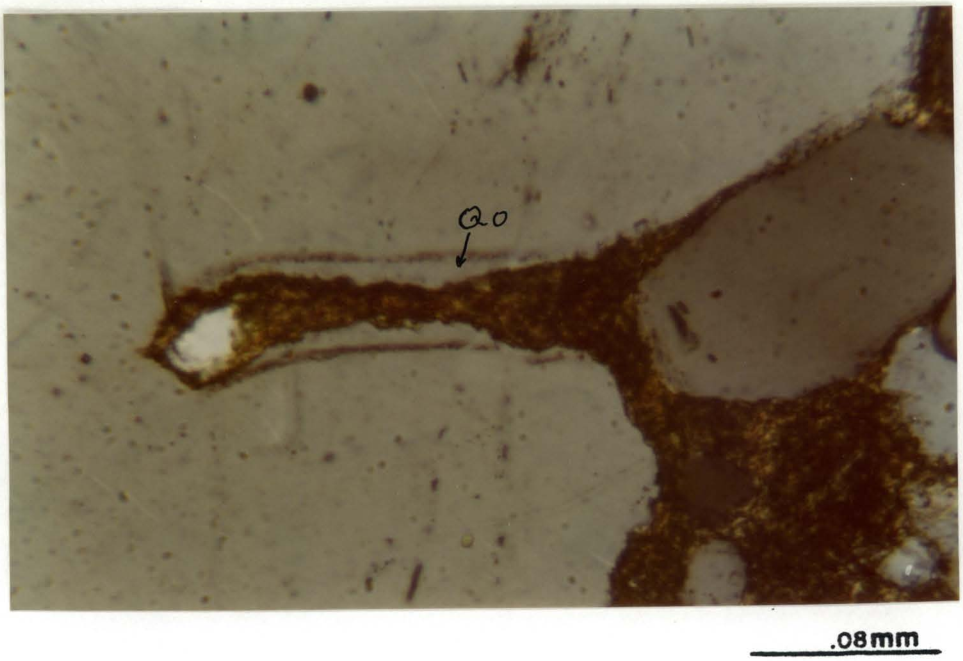

Figure 104. Reentrant or grike with quartz overgrowth (Qo). Crossed nicols. # 130.

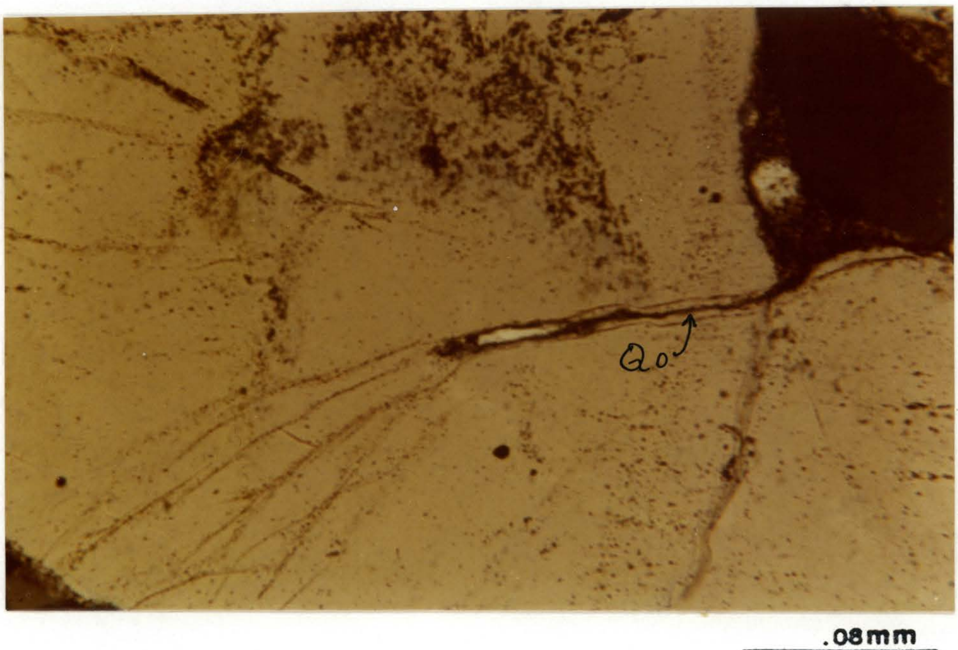

Figure 105. Reentrant following strain trails with quartz overgrowth (Qo). Plane light. # 130.

grain (Figs. 36, 37). So it would appear that not only polycrystalline quartz breaks down but also the "stable" monocrystalline quartz. Crook (1968) maintains that such activity increases the maturity of the sediment and alters Folk's textural maturity scheme, not only by breaking down the quartz into grains of a more similar size but also by rounding. The grains in the Arroyo Penasco do seem to be unusually round for their odd shapes, but textural maturity has not been increased, rather a silt fraction or fine sand fraction has been created that makes the sediment less mature (Fig. 35). It seems that the large monocrystalline grains can be broken down only so far and the maturation or "immaturation" process comes to a halt; this might depend on the amount of strained grains in the sediment. But there is no doubt that this solution introduces problems in determining environment by grain size. Many of the intervals of embayed grains appear bimodal; whether this is actually a depositional or in situ chemical phenomenon cannot be truly ascertained (Fig. 35).

Whether the quartz grains were dissolved or not, most of them formed nuclei for early quartz overgrowths. These overgrowths were precipitated prior to most of the carbonate and clay cementation. Euhedral overgrowths that formed against illite and calcite (Figs. 61, 62), "clean" borders between mother grain and overgrowth (Fig. 63), clean grain-grain contacts (Fig. 50), silica-meniscus cement (Figs. 60, 106), and multiple overgrowths indicate precipitation at an early time, probably in an environment of fluctuating waters, perhaps near the boundary of vadose and phreatic zones. This is inferred because some grains have an even, circumgranular overgrowth, and others have multiple overgrowths, indicating variations in water table depth or chemical composition of the water. Also, the embayed grains exhibit thick silica overgrowths after solution and embaying (Fig. 107), but, again, before the clay.

Sources of silica as summarized by McBride (in Jonas and McBride, 1977) include the following:

1) Pressure solution
2) Clay mineral alterations during burial
3) Replacement of quartz and silicate grains by carbonate
4) Dissolution of opaline skeletal grains
5) Koalinization of feldspar
6) Dissolution of quartz silt grains in shale
7) Groundwater
8) Sea water
9) Dissolution of quartz grains in sandstone
10) 2 micron to 50 micron chips of quartz produced by abrasion.

Sources 2, 4, 6, and 10 seem unlikely or difficult

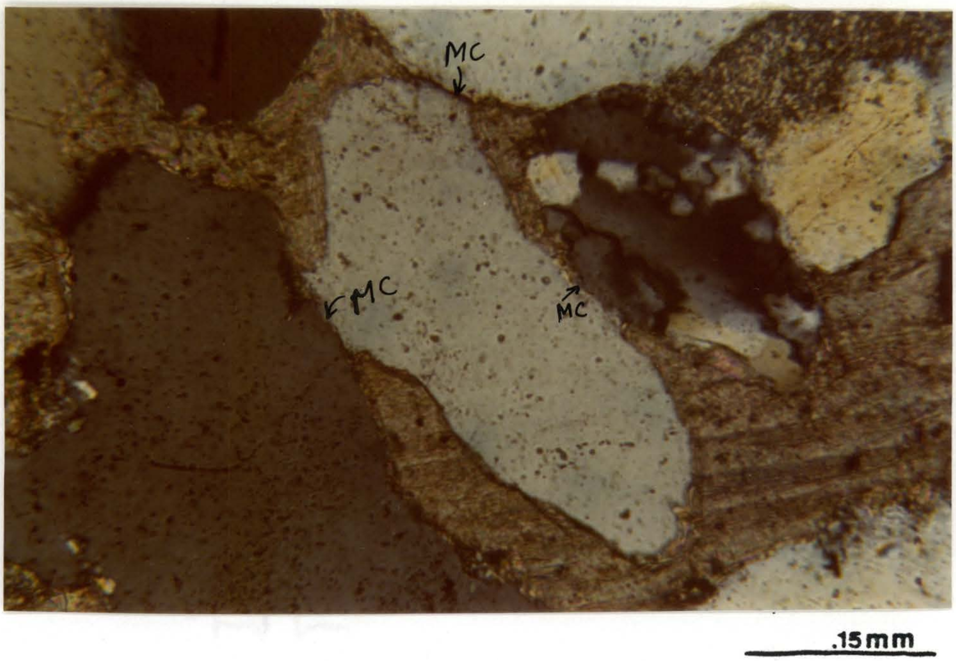

Figure 106. Quartz meniscus cement (MC) in calcite. Crossed nicols. # 97.

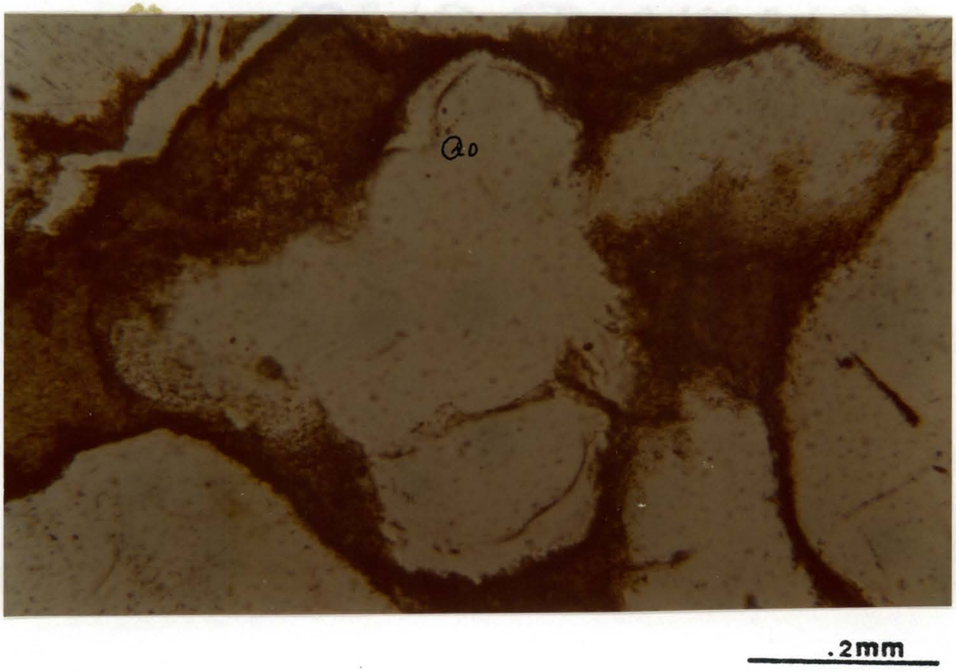

Figure 107. Embayed quartz grain (Qo) with thick overgrowth in clay. Plane light. # 123.

to evaluate. So pressure solution, replacement, kaolinization, groundwater, perhaps sea water, and dissolution should be considered.

Pressure solution is evident in some sections but cannot volumetrically account for the overgrowths present. Calcite is replacing quartz and more noticeably, feldspars in some areas; kaolinite, likewise, could have replaced feldspars, thus releasing silica, although through time the kaolinite was altered to chlorite or illite. These, then, are probable sources. But a more accessible mechansim would be the silica dissolved in the prior embaying and fracturing episodes. This in conjunction with groundwater movement seems to better explain quartz precipitation.

The groundwater either lowered the pH, causing silica to precipitate or reintroduced it into the system when the environment was more acidic.

A monsoonal regime is envisaged that would periodically yield a large enough volume of meteoric water to effect such an end. Great amounts are needed to precipitate quartz in shallow zones (Jonas and McBride, 1977), and seasonal storms along with tides could conceivably move enough water through the system to account for overgrowths and also cyclic episodes of growth or solution.

The various types of microcrystalline quartz as defined by Folk and Weaver (1953) are also present in the formation. These include chert comprised of equidimensional crystals about 1-20 microns in diameter and chalcedonic quartz, a fibrous variety that can attain lengths of up to 200 microns.

The microcrystalline chert occurs as replacement of carbonates, as a precipitate associated with carbonates, and more singularly as a paleosilcrete along certain levels in the formation.

This silcrete is very similar to that described by Stephens (1971) and Smale (1973). It occurs in the Arroyo Penasco either as blebs or streaks that are continuous laterally. It is gray (pale brown in thin section) and more resistant than the surrounding sandstone. The matrix or cement is an almost isotropic chert that cements well rounded quartz grains many of which are embayed (Fig. 108) and have double overgrowths (Fig. 63). The silcrete is intercalated between a hematitic clayey sandstone (Fig. 67). The pairing of the chertiferous silcrete with iron oxides is common as evidenced by its occurrence with laterite in Australia and Africa (Stephens, 1971) and Terrazzo type deposits also in Africa and Australia (Smale, 1973). Smale (1973) believes the major factors governing the silica deposition to be: (a) reduction in pH from greater than 9 to less than 9; (b) presence of Al_2O_3, Fe_2O_3, or MgO; (c) presence of NaCl or Na_2SO_4.

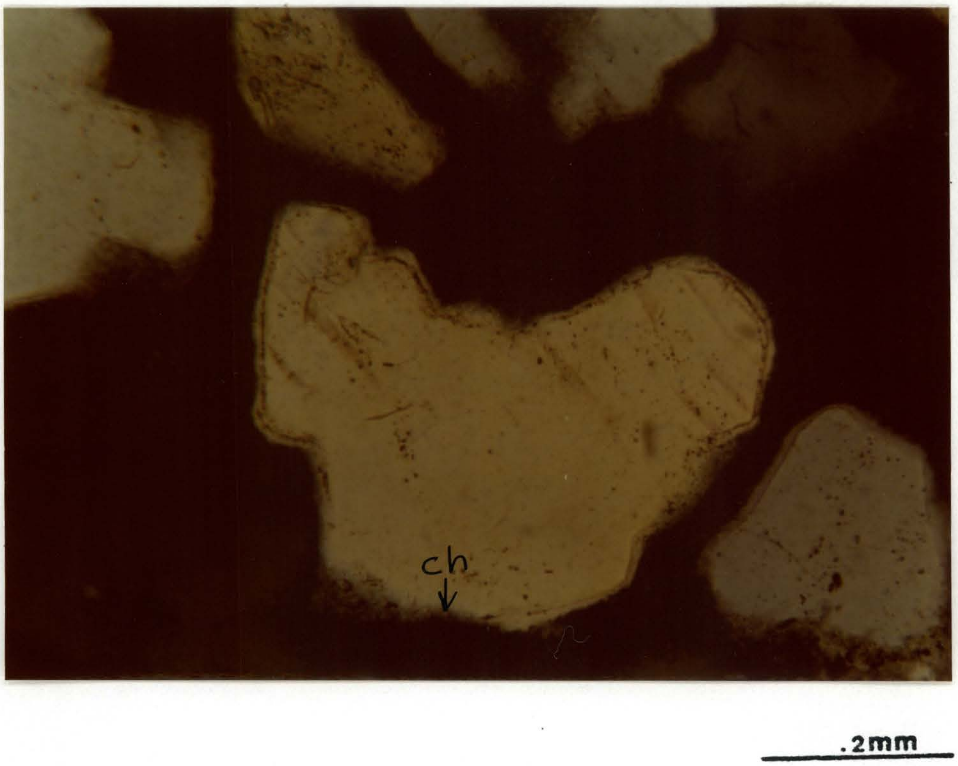

Figure 108. Embayed quartz in isotropic chert (ch) (paleosilcrete). Note well-delineated quartz overgrowth. Crossed nicols. # 159.

The presence of hematite in the surrounding sandstones certainly indicates the presence of iron. Since the unit was deposited in a coastal environment, the presence of salt cannot be construed as unusual. Evaporite crystal casts are present in the strata nearby. Smale (1973) also continues by saying that silcrete forms where drainage is poor, "and that a fluctuating water table such as might be caused by alternating periods of heavy and light rainfall, is likely to be important." The sources of silica might be weathering of potassium feldspar, laterite-forming type processes, and kaolinization.

The similarity of silcrete formation with that proposed for the megaquartz is not accidental. The causes and sources of the two types of silica are the same. The reason for the precipitation of chert instead of quartz is due to the disruption of orderly precipitation by the development of many nucleation sites (Jonas and McBride, 1977). High concentrations of Na and Mg ions as required by Smale (1973) probably produce the difference between quartz and chert precipitation, perhaps in the same manner that they retard crystal growth in calcite and aragonite (Jonas and McBride, 1977; Folk, 1974).

In addition to the aforementioned silcrete-associated chert, there is also a coarser chert (Fig. 75), length-fast chalcedony, and quartzine, a length-slow variety of chalcedony (Fig. 65). These are associated with carbonates, pyrite, hematite, and limonite and indi-date another mode of silica precipitation as defined by Siever (1962) and Namy (1974). Silica precipitation in this instance is triggered by the decay of organisms associated with the carbonate environment. Decaying matter lowers the pH to about 6.5 causing silica to precipitate and calcite to dissolve locally. The pyrite and iron oxides could be residue from organic decomposition.

According to Folk and Pittman (1971), length-slow chalcedony precipitates from solutions of high pH or high sulfate concentrations. The presence of quartzine rosettes (Fig. 66) is ostensibly an indication of sebkha-like conditions. However, its close association with regular chert and legnth-fast quartzine, in addition to euhedral crystals of megaquartz, is seemingly paradoxical. But such associations actually fit a schizohaline model quite well. With its phantom growth zones indicating multiple growth periods, the euhedral quartz, along with the length-fast chalcedony and regular chert represent relatively low pH values; length-slow chalcedony represents a more saline phase with higher pH values.

Silica precipitation probably continued irregularly throughout the rock's history, much of the silica derived from pressure solution. Certainly, after the rock was lithified and fracturing and faulting took place, silica was deposited in the voids.

Illite

The structure of illite is well covered in works by Millot (1970) and Grim (1953). However, it is necessary to state that illite is the term applied to clay minerals with a structure similar to muscovite, this being a 2:1 clay mineral structure with potassium making up the charge deficiency of the silica-aluminum layers (Fig. 109). Illite manifests three polytypes: 1Md, which is disordered and poorly crystallized; 1M, an intermediate form, better crystallized than 1Md; and 2M with a crystalline structure similar to true igneous or metamorphic mica, i.e., of high temperature origin.

In order to determine whether illite and chlorite are indeed authigenic minerals, it is helpful to know what polytype is present. This aids in determining whether the matrix is an actual phyllosilicate cement, a detrital protomatrix, or a pseudomatrix made of squashed rock fragments (Triplehorn, 1967; Dickinson, 1970).

Both Triplehorn (1967, 1970) and Dunoyer de Segonzac (1970) utilize x-ray diffraction to distinguish between the polytypes. Since the 2M polytype is the form appearing as the main component of detrital illite, identification of the other two would indicate neoformation, diagenesis, or partial recrystallization in the sediment. According to Dunoyer de Segonzac, the intensity ratio of

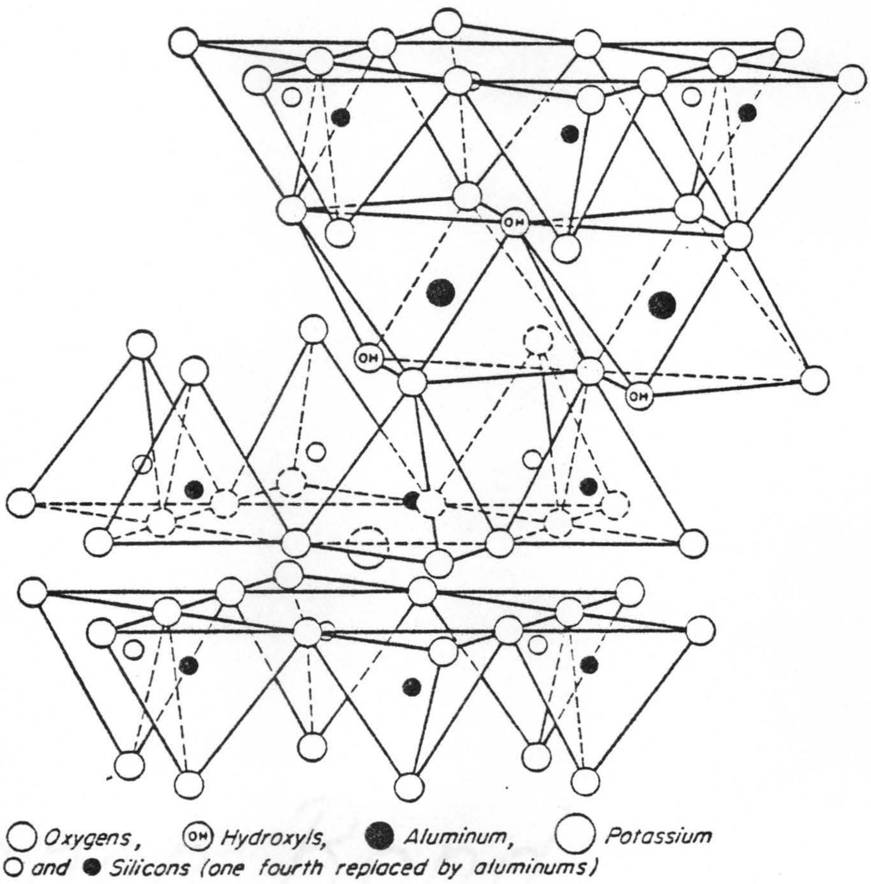

Figure 109. Structure of illite. From Grim (1953).

the 5-Å and 10-Å peaks and the width of 10Å peaks at half heights yield figures that place the clay in a certain diagenetic pigeonhole (Figs. 110, 111, 112). These diagrams depict the realms at which each type forms. The anchizone is transitional between relatively shallow diagenesis and the epizone where metamorphism begins. Triplehorn (1967, 1970) also utilizes peak characteristics as well as peak locations to classify the clay. Six x-ray patterns are presented (Fig. 113) along with an "ideal" 1M (low temperature) trace by Triplehorn (1967) and plotted on Dunoyer de Segonzac's diagenetic chart (Fig. 110). The results indicate that the pure 2M crystallinity has not been attained; rather 1M and 1Md clays of low temperature origin are present and are ostensibly not detrital (Triplehorn, 1967).

Other modes of distinguishing between detrital and authigenic illite require the use of the petrographic and electron microscopes.

Under the microscope, authigenic clays exhibit certain characteristics. Dickinson (1970) lists radial plates on grains, concentric color zonation, and medial sutures as evidence of authigenesis. Wilson and Pittman (1977) offer in a detailed list (Fig. 114) a number of features that are useful in such a determination. It should be noted that criterion number seven, that of clay

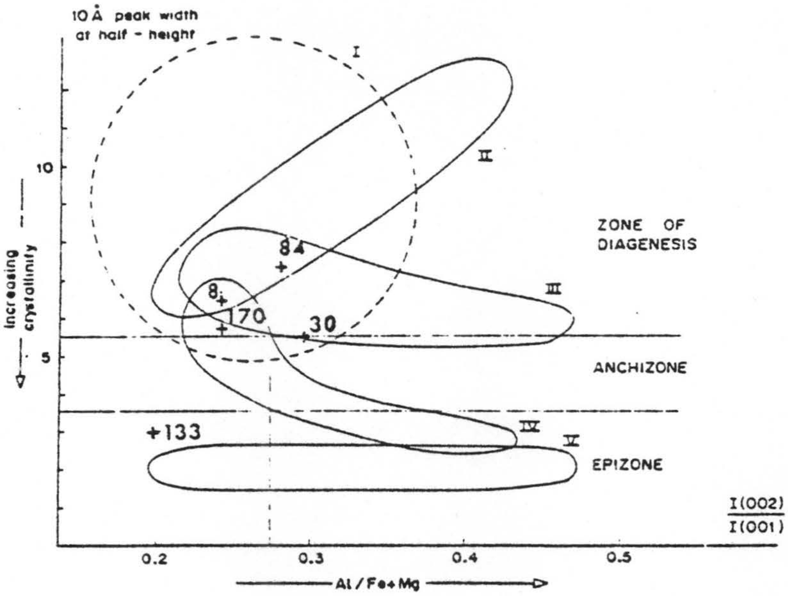

Figure 110. Zones of illite formation as determined from x-ray characteristics. Selected Arroyo Penasco samples are plotted. From Dunoyer De Segonzac (1970).

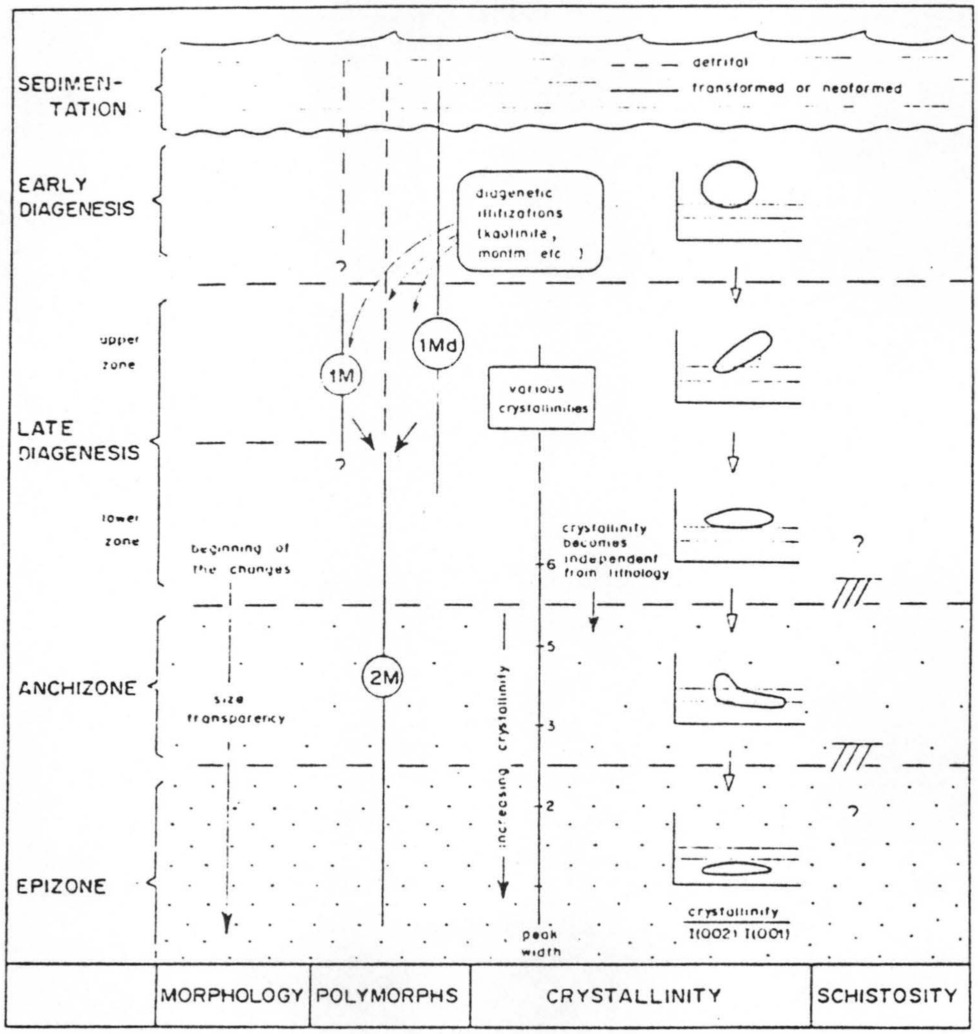

Figure 111. Relative depths of formation of illite types.
From Dunoyer De Segonzac (1970).

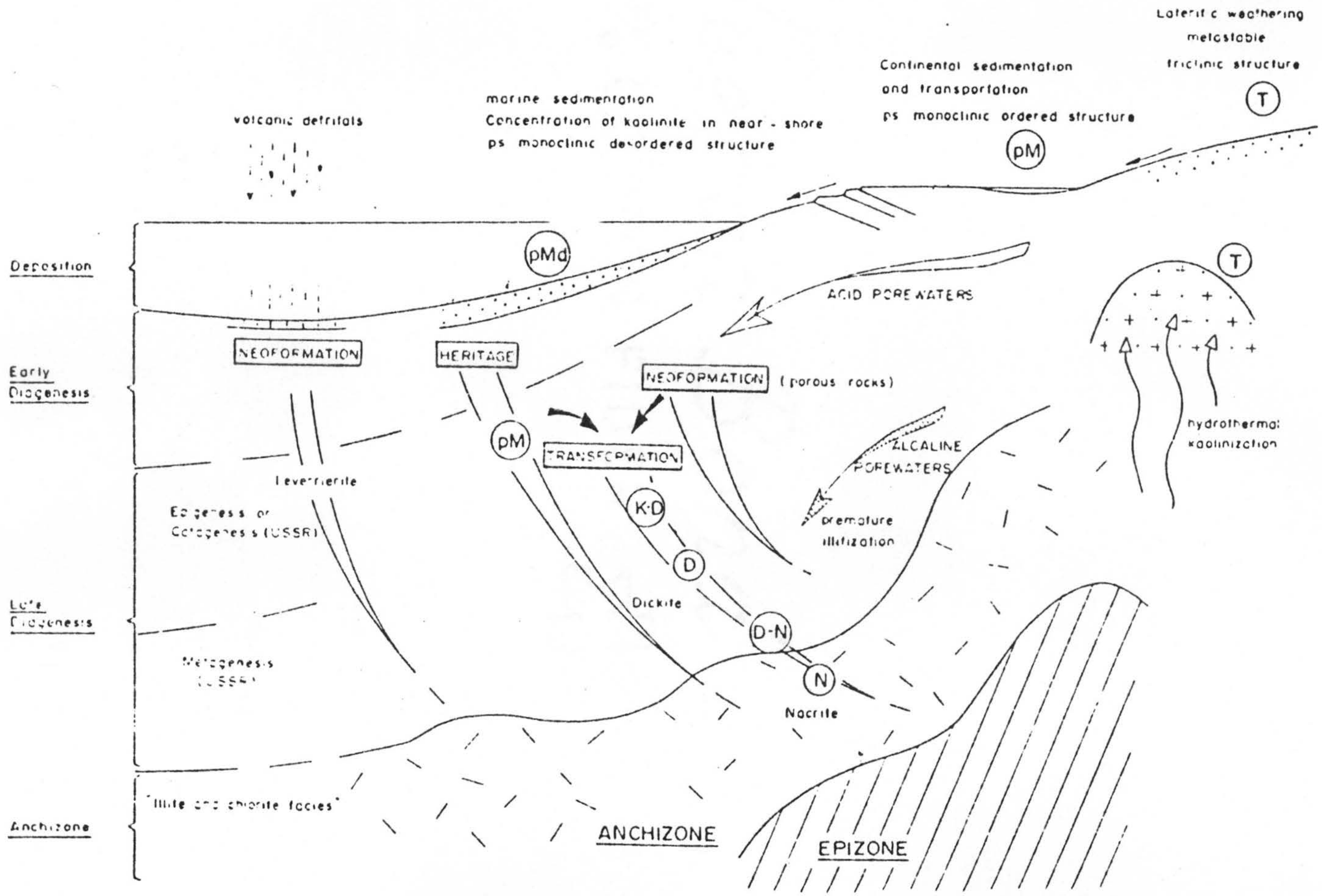

Figure 112. Environments of illite formation. From Dunoyer De Segonzac (1970).

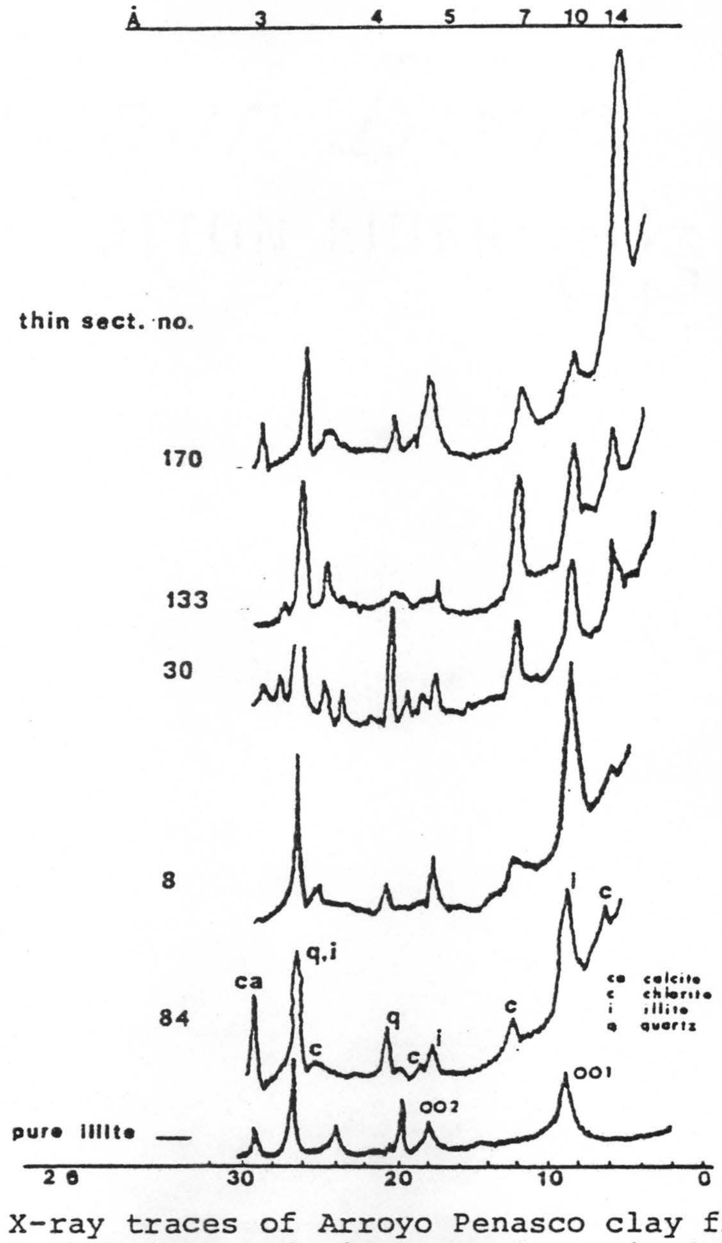

Figure 113. X-ray traces of Arroyo Penasco clay fractions. Peak height and width are determined by degree of crystallinity and, hence, illite type. Chlorite and illite are the dominant clays with the amounts, in relation to each other, varying from section to section. See Figures 110, 111, and 112.

Criteria	Reliability	Frequency of Occurrence	Frequency of Occurrence for Illite	Frequency of Occurrence for Chlorite
Composition				
1) Absence of impurities	O	C	C	U
2) Clay assemblage monomineralic	X	R	C	C
3) Significantly different from associated shales	+	U	?	?
4) Concentric color zoning	O	R	U	R
Morphology				
5) Crystal outlines	+	C	U	U
6) Delicate projections	+	C	C	R
7) Undeformed	O	C	C	C
8) Pseudomorphous replacement	+	R	C	U
Structure				
9) Low-temperature polytypes	+	?	C	C
10) High degree of crystallinity	O	U	C?	C?
Texture				
11) Gap in grain-size distribution (silt fraction lacking)	X	C	U	U
12) Large particle size	O	C	U	U
Distribution				
13) Pore linings missing at grain contacts	+	C	C	C

Criteria	Reliability	Frequency of Occurrence	Frequency of Occurrence for Illite	Frequency of Occurrence for Chlorite
14) Scattered pore fillings	X	C	C	C
15) Fracture fillings	+	R	C	C
16) Absent in early diagenetic concretions	+	C	?	?
17) Cover diagenetic components formed at earlier stage	+	C	C	C
18) Laminae with abrupt lateral terminations	+	R	-	-
19) Radial alignment of individual flakes	O	C	R	R
20) Medial sutures	O	R	U	R
21) Bridges between detrital grains near points of contact	+	C	R	R

X = unreliable

O = generally reliable

+ = very reliable

R = rare

C = common

U = ubiquitous

? = unknown

Figure 114. Reliability of criteria for authigenic origin of clay in sandstones and illite and chlorite in the Arroyo Penasco. Modified from Wilson and Pittman (1977).

deformation, is an almost worthless touchstone for authigenesis. Early diagenetic clays will, of course, undergo compaction and deformity just like detrital grains (Fig. 115). The illite in the Arroyo Penasco has many characteristics that are indicative of authigenic formation (Fig. 114). Especially of note are the medial sutures, concentric color zoning, radical break in grain size distribution, and large particle size. The illite that appears to be replacing quartz could be similar to Triplehorn's micas that are growing on or in the quartz grain (1967).

Illite is formed where the waters have a high K^+/H^+ ratio; K^+/Na^+, K^+/Mg^+ ratios also affect its formation, lower ratios producing montmorillonite and chlorite respectively (Weaver and Pollard, 1973). In this case, illite is probably the result of the alteration in saline water of the feldspars contributed by the thinly-veneered basement (Triplehorn, 1967). The illite appears to have come after the quartz overgrowths and, if calcite is present, usually after or along with its precipitation. In replacing the feldspars, calcite can release potassium which then allows illite to form, thus explaining the occurrence of the two together.

So illite formed relatively early in the environment. Burial to a maximum depth of 3300 meters (Sutherland, <u>in</u> Miller et al., 1963) no doubt effected some reordering in the structure (1Md → 1M) but not enough to form

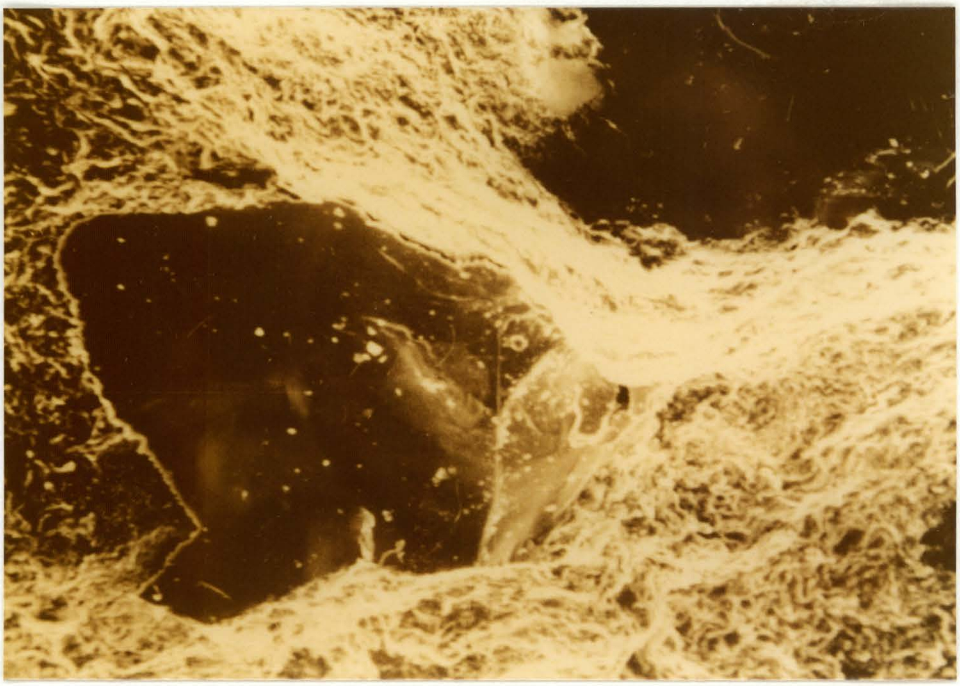

Figure 115. Scanning electron micrograph of authigenic illite now deformed because of compaction. Note embayed quartz grains. #5.

the 2M polytype. It is also conceivable that illite could have replaced or is a pseudomorph after kaolinite (Weaver and Pollard, 1973). This might be the explanation for the booklets of illite in places.

Triplehorn (1967) summarizes the findings of Kulbicki and Millot (1963) in which they describe a 'fan and accordion' facies in sandstones, referring to the appearance of the illite (Fig. 78). This is a result of two diagenetic changes in a sediment with feldspars, mica, and illite. Early postdepositional changes caused these minerals to form kaolinite of the 'fan and accordion' facies. These are preserved if oil saturates a formation. If not, kaolinite having the 'fan and accordion' characteristics is changed to illite. So, the illite in the formation could have formed step-wise or directly; whatever the case, it is definitely authigenic.

Chlorite

Chlorite comprises as much as 15% of the phyllosilicate cement in some sections. It is classified as a 2:1:1 mineral (Fig. 116). According to Jonas and McBride (1977) it is identical with other 2:1 minerals except that it contains an octahedral layer of magnesium hydroxide occupying interlayer positions usually occupied by cations, with iron sometimes substituting for magnesium. The basal

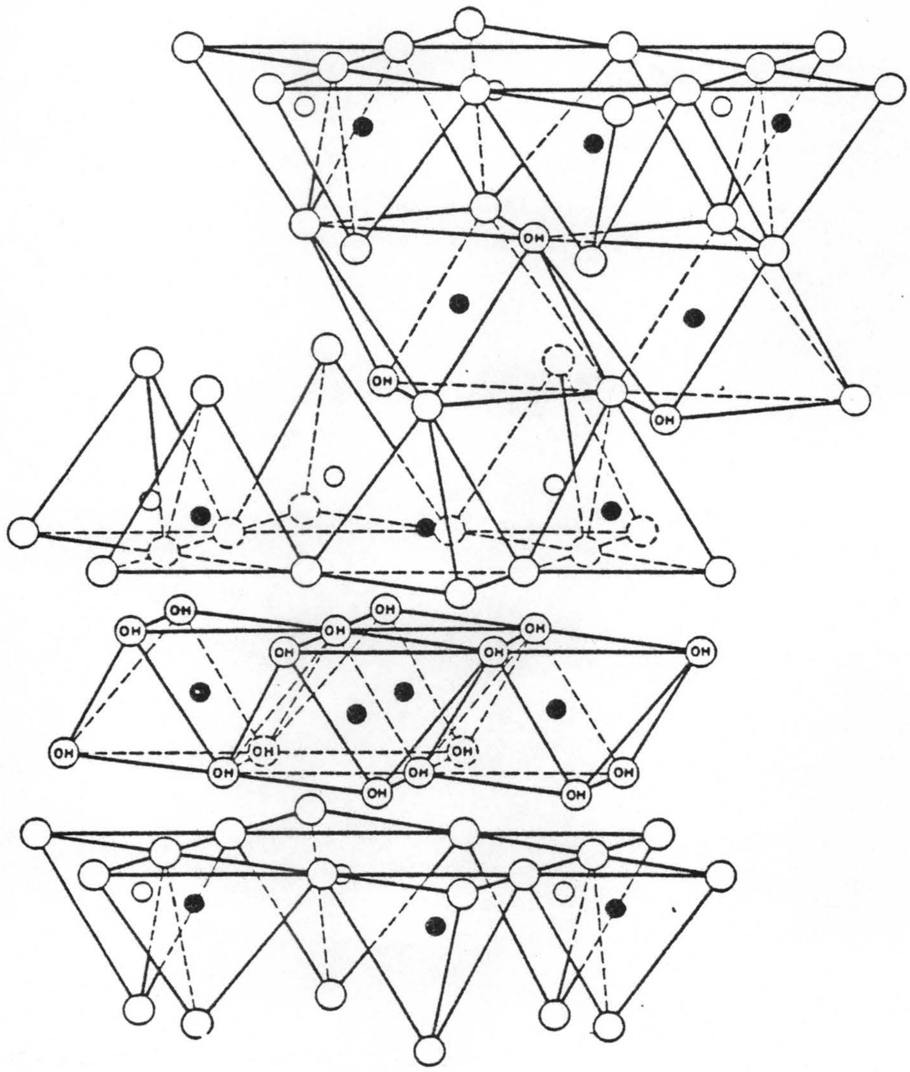

Figure 116. Structure of chlorite. From Grim (1953).

spacing is 14Å as opposed to 10Å for illite.

The definitive work on chlorite polytypes is by Hayes (1970). Four forms are described: Ia, two Ib types, and a IIb, the differences being in the bonding of the sheets. Like illite, certain polytypes are characteristic of authigenic formation.

In chlorites, the three type I's are indicative of authigenesis, but Hayes (1970) states that the occurrence of IIb is problematical. However, it is likely that it is a detrital remnant like 2M illite. There is a difficulty in determining whether chlorite was originally type I or II, this being the occasional transformation of both types to a mixed vermiculite-chlorite or vermiculite structure. Type I weathers much more easily than type II, so through time type I chlorite is probably the form that alters to the vermicular structure.

Since vermiculite and chlorite both have 14Å basal partings, it is necessary to glycolate or heat samples to identify the minerals. Such a procedure was carried out on several samples (Fig. 117).

The two treatments either partially collapsed, shifted, or expanded the peaks in some of the samples, indicating that chlorite has undergone some transformation to a mixed vermiculite-chlorite or vermiculite structure. Another good possibility is that the form is that of a swelling chlorite with a structure that collapses with heat

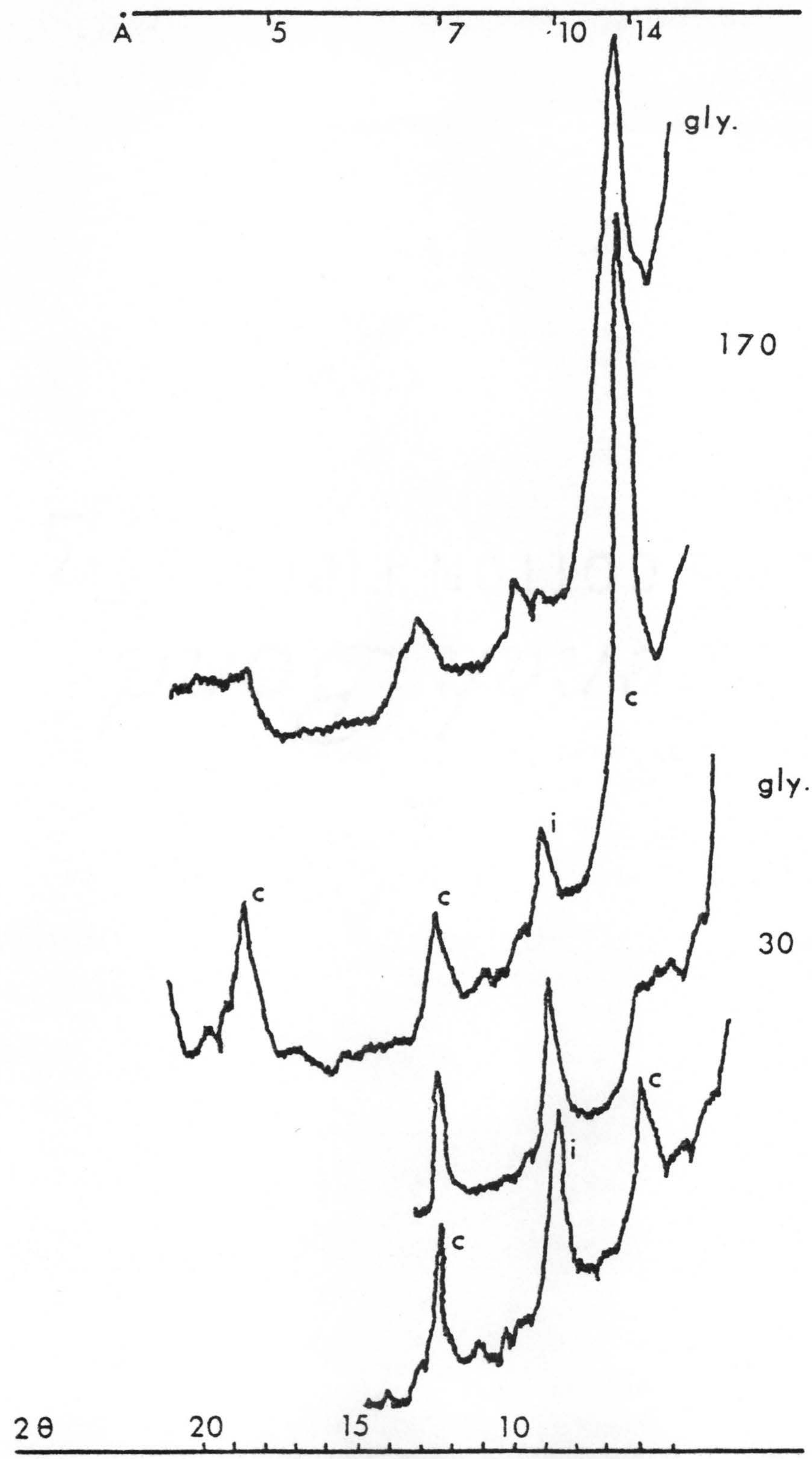

Figure 117. Comparison of x-ray traces of chlorite samples before and after glycolating (gly). The collapse of 30 indicates that the chlorite is not pure; 170 changed very little.

or expands when glycolated (Carroll, 1970). Whatever the case, these treatments suggest that the chlorite was the more unstable I polytype, and therefore, of diagenetic origin.

Like illite, chlorite has microscopic criteria that can be applied to verify authigenic origin (Fig. 114). Some of the more important diagenetic features are: pseudomorphous replacement both of quartz but predominantly of feldspar, crystal outlines (Figs. 81, 82), and large particle size (Figs. 81, 82).

Chlorite's vermicular form (Fig. 80) can be explained in two ways: either it is pseudomorphous after kaolinite booklets (Triplehorn, 1970), or it is a mixed layer chlorite-vermiculite and either heating or weathering has impressed or created the vermicular form. Neither process can be discounted.

Both iron-rich and magnesium-rich varieties of chlorite are present. Solutions with these cations and of reducing nature and alkaline pH values must have been present for chlorite to form. Probably, chlorite started precipitating with the carbonates and has been forming, replacing, or recrystallizing through time (Fig. 127).

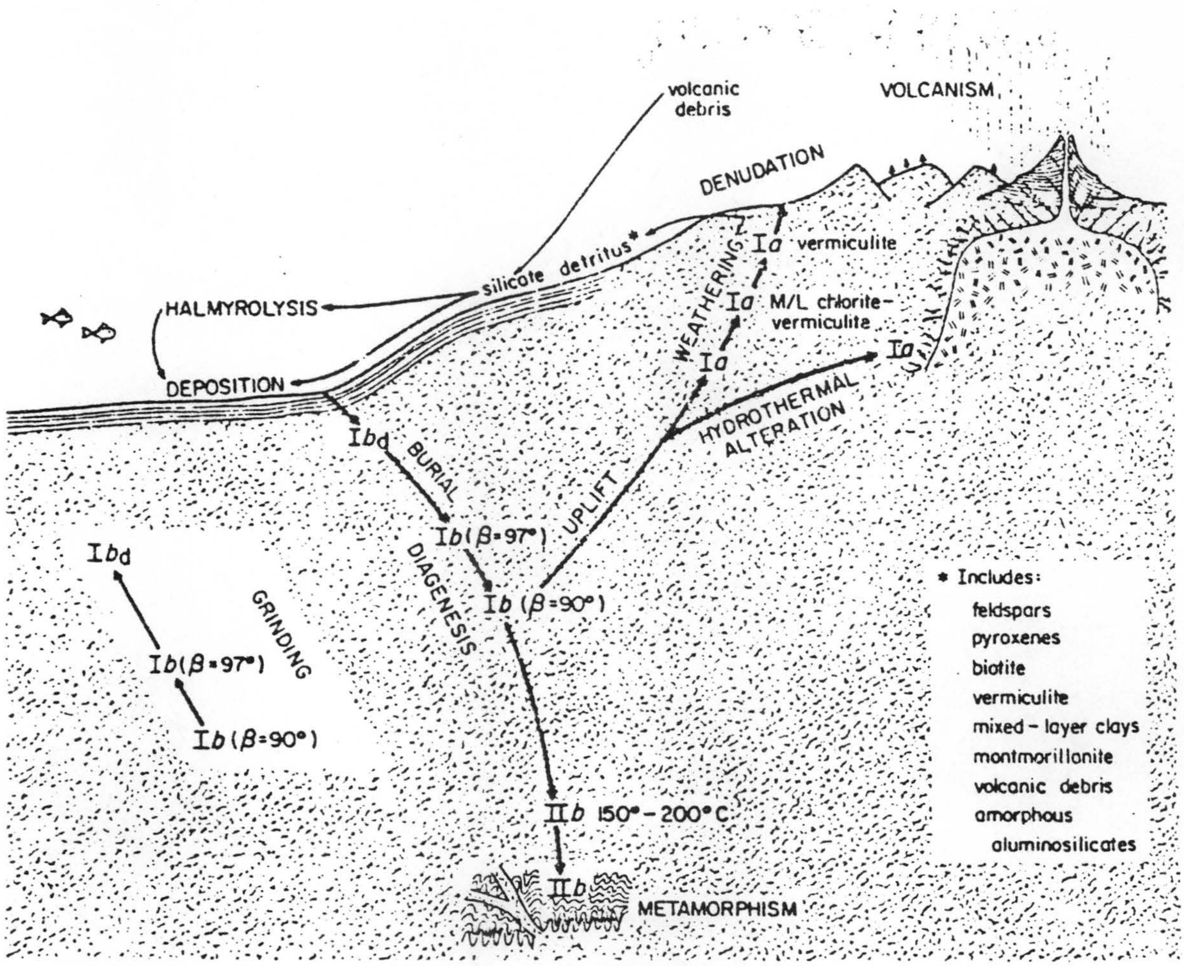

Figure 118. Zones of authigenic chlorite formation. From Hayes (1970).

Carbonates and Evaporites

The topic of carbonate diagenesis is so complex that only an abbreviated discussion will be presented. In his 1966 paper on sandstone diagenesis, Blatt gives an excellent summary of the conditions needed to precipitate calcite. Simply a pH greater than about seven (Fig. 103), a source of calcium, and the carbonate radical are required. McBride (in Jonas and McBride, 1977) lists several sources, those pertinnet to this paper being sea water, dilution or mixing of brines, and redox reactions involving organic matter. All of these at some time were probably important in the relatively early precipitation of the carbonates in the Arroyo Penasco.

In some sections quartz precipitation preceded the carbonates; elsewhere, the carbonates appear to be the first cement. Poikilotopic calcite, coarse sparry calcite, ferroan calcite (zoned), replacement ferroan and normal calcite are all common. Along with these are dolomite rhombs with limpid perimeters and "dirty" calcite interiors (dedolomites) and some micrite and microspar. Their physical description has already been given.

The occurrence of all these together suggests an environment that underwent great fluctuations in water chemistry (Fig. 119). Poikilotopic and coarse spar require a low magnesium to calcium ratio for crystals to

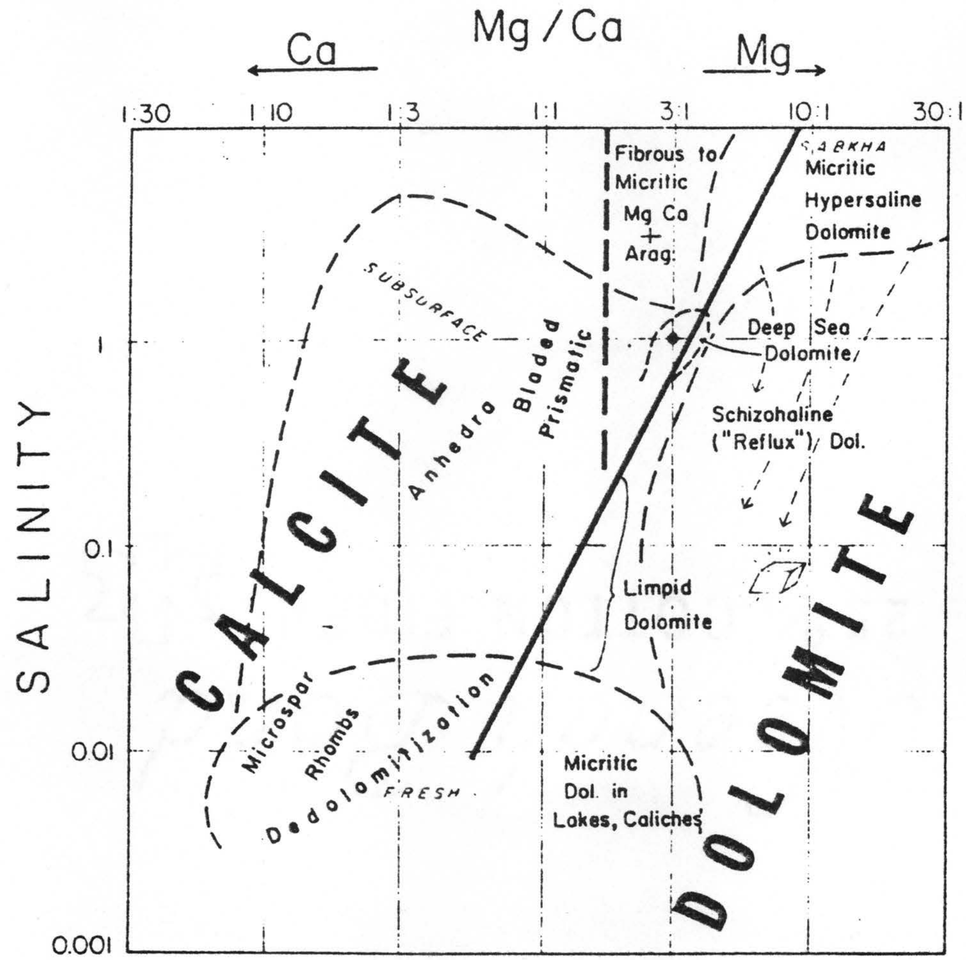

Figure 119. Environments of calcite and dolomite formation. From Folk and Land (1975).

attain such a large size (Folk and Land, 1975). So either the water was relatively fresh or the magnesium was "snatched" by dolomite or chlorite (Folk, 1973). In this case, a combination of the two is feasible with calcite precipitating from diluted solutions and dolomite incorporating the magnesium, thus allowing large calcite and dolomite crystals to form. The fact that the dolomite is limpid indicates that a refluxion mechanism might have been operating in a system similar to a sebkha being flushed with fresh water (Folk and Land, 1975). The hypersaline environment provides the magnesium, but the fresh or brackish water allows a situation for unconfined crystal growth.

The presence of a slightly ferroan calcite also indicates that the environment was one that periodically changed. The iron content in calcite along with framboidal pyrite are characteristic of reducing conditions. The fact that the ferroan calcite is zoned means that waters were alternately oxidizing and reducing, each zone representing an iron-free or iron-rich cycle. The combination of coarse quartz grains and micrite cement is partial evidence that at times calcite crystal growth was restricted either by cationic or sulfate poisoning. Microspar is also present, indicating flushing of cations to allow crystal growth of micrite to a larger size (2 microns

10 microns) (Longman, 1977).

Anhydrite, celestite, and possibly barite have formed in the carbonates, another indication that at some period the environment was hypersaline. And, again, the length-slow chalcedony rosettes are interpreted to be replacement of evaporites (Folk and Pittman, 1971). Likewise, the replacement of chert and some quartz grains (Fig. 120) by carbonates and vice versa testifies to the fluctuating chemistry of the solutions.

It is apparent that dolomite has calcite cores (Figs. 88. 89), but that this is evidence of dedolomitization, as Armstrong (1967) suggests, may not be correct in every instance. Instead, dolomitization may be the process at work. Evidence for this is the unitary extinction of the core and external poikilotopic calcite. It is difficult to see how a core of calcite could have acquired the same crystallographic orientation through the dolomite perimeter unless the perimeters were fractured. These dolomite rhombs are similar to those formed in schizohaline environments as discussed by Folk and Siedlecka (1974).

There are also tiny limpid rhombs preserved in clay cement. The cores have not been affected, this possibly due to clay sealing. The rhombs are so small and infrequent that positive identification is difficult; they could be siderite.

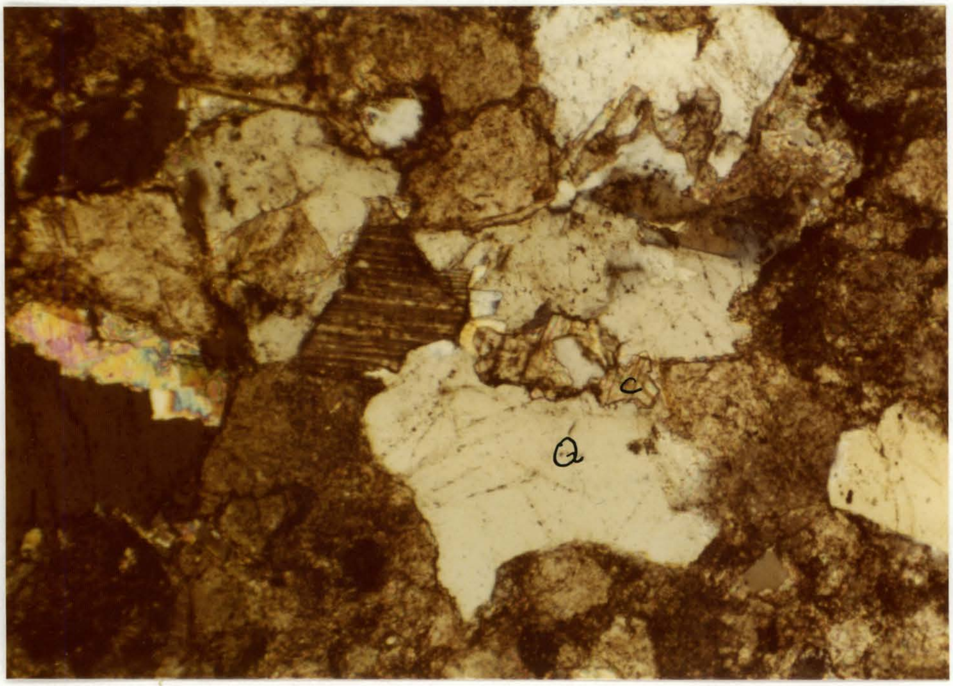

Figure 120. Quartz (Q) being replaced by calcite (c). Crossed nicols. # 21.

In conjunction with the above minerals, celestite ($SrSO_4$) and barite ($BaSO_4$) are found as patchy cements or inclusions in silica cemented regions. The silica is apparently replacing these sulfates which are products of hypersaline, high pH waters. In nearby units the length-slow chalcedony is present, probably as the anhydrite replacement. So again, the various habits of the carbonates, silica minerals, and sulfates, indicate an environment that is not a stable one.

Pyrite and Iron Oxides

As illustrated in Figure 121, pyrite or iron sulfide can form either under acid or alkaline conditions but only in a reducing environment. Most investigators associate organic decay and bacterial activity with pyrite formation, particularly the framboidal variety, the framboids deriving their form from the infilling of organic globules (Richard, 1970). Other workers (Sweeney and Kaplan, 1973; Elverhoi, 1977) maintain that these framboids are the result of inorganic processes. Some of the few fossils in the Arroyo Penasco have their spherical chambers filled with pyrite, partially confirming the organics-pyrite association (Fig. 96). These framboids exhibit a size uniformity. Whatever the case, the presence of the mineral indicates a reducing environment, a con-

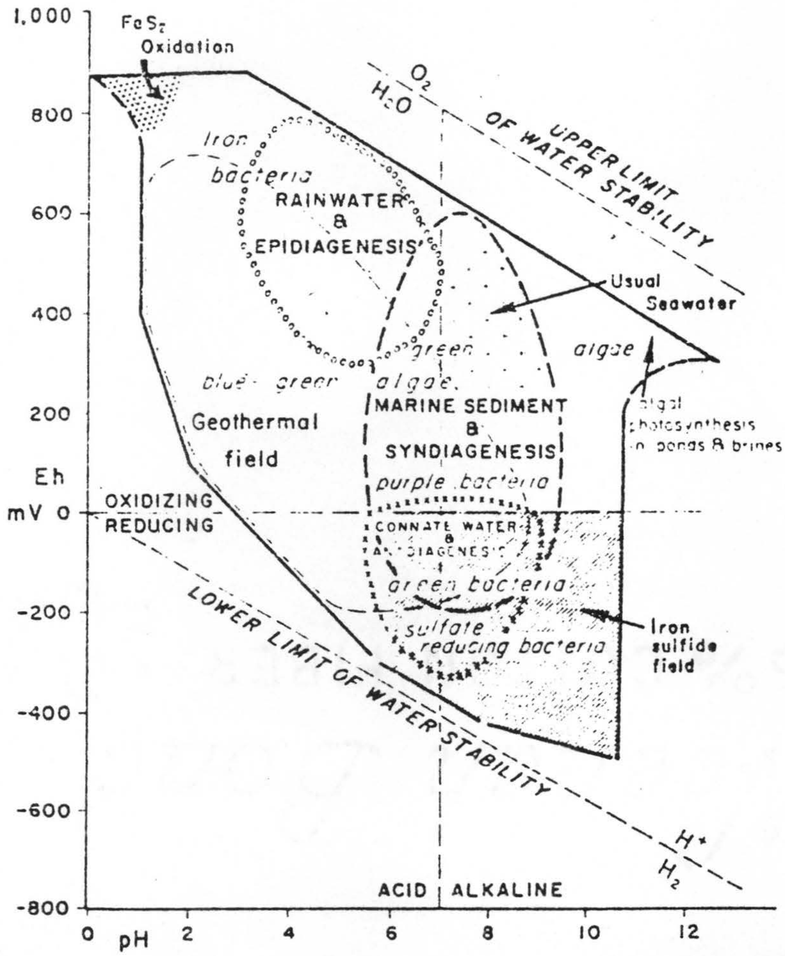

Figure 121. Chemical environment for pyrite formation. From Fairbridge (1967).

dition verified by the ferroan calcite in which it is often embedded.

Czynscinski and others (1978) have documented the occurrence of authigenic pyrite in tidal flats and beaches associated with sulfate production. They also have developed a model of pyrite oxidation to iron oxides and hydroxides (Fig. 122). This takes place in two phases: the oxidation of pyrite to ferrous iron and the oxidation of ferrous iron to ferric iron. According to Czynscinski et al. (1978) Folk and Siedlecka's (1974) "schizohaline environments provide examples of situations in which less saline, oxygenated waters may replace original connate waters, and permit sulfide oxidation to take place." The weathering of pyrite ultimately leads to red bed development. But this development is of no paleoclimatic significance and has no source implications because of complete *in situ* formation (Czynscinski, 1978). The proposed oxidizing mediums are meteoric groundwaters rich in oxygen possibly introduced after a drop in sea level or during monsoonal flooding. The idea is then offered that the hematite and limonite that is disseminated throughout the Arroyo Penasco is from the weathering of pyrite.

Feldspar

Although Dapples (1967) maintains that phyllomorph-

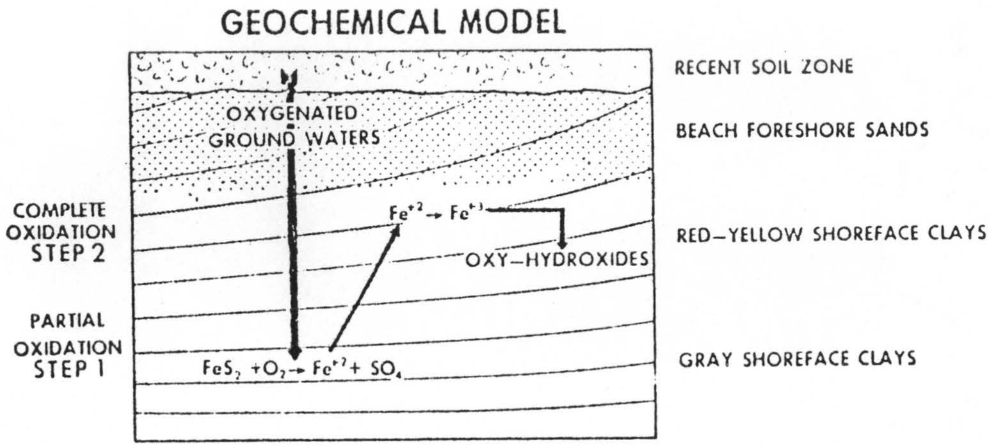

Figure 122. Geochemical model of pyrite formation and transformation. From Czynscinscki et al. (1978).

ic changes (feldspar alteration) in the calcite-feldspar system are effected by late burial, such may not be the case in the Arroyo Penasco. Blanche and Whitaker (1978) have documented feldspar alteration in early poikilotopic calcite, a similar situation to that observed in this formation. Conditions that would account for such an occurrence would be an absence of sodium, potassium, and silica in solution and a neutral to acid environment (Nagtegaal, 1978). Calcite can precipitate in neutral waters if calcium and carbonate concentrations are high enough. This might take place when a formation was flushed with fresh or brackish waters that temporarily leaches potassium and silica and introduces CO_2. If refluxion brought the flushed potassium and silica back into this system of hypersaline, evaporitic conditions, illite and chlorite might then precipitate.

Another sequence of events is envisaged for the chlorite-rich sands. There are many areas in this sandstone that appear to be replacement. These replacement grains are comprised of nests of the aforementioned vermicular chlorite growths. This chlorite may be pseudomorphous after early kaolinite replacement of feldspars. Todd (1968) states that weathering of K-spar in the soil zone will yield either K-mica or kaolinite, depending on the weathering and leaching rates. High weathering plus high leaching means rapid loss of K^+ and kaolinite formation. Slow leaching of K^+ would yield K-mica. K-mica could then be transformed to kaolinite through time and kaolinite to chlorite. Or, chlorite could have replaced the microcline directly and eventually assumed the vermicular structure.

The feldspars at Ponce de Leon Springs are associated with replacement by slightly ferroan calcite. This calcite replaces feldspar in an unusual fashion: all the replacement carbonate in a large region has the same extinction angle (Figs. 92, 93). Ostensibly, this is evidence of replacement before the clay cement. Transmission of the crystallographic orientation would not be possible otherwise. The ferroan calcite, feldspar, and pyrite occur together. The formation of this association is moot. Why did ferroan calcite replace the feldspar and not precipitate into pores? The environment must have been right for iron and carbonate nucleation on the feldspar but not in the pore. But, again, the feldspar mineralogical and morphological associations are signs of a variable environment. The leaching of the carbonates that replaced feldspars could have occurred at almost anytime.

The amount of clay in the Arroyo Penasco probably does not account for all the original feldspar. Similarly, there is no shale that could have been a "reservoir" for feldspar constituents. Much of the feldspar detritus, then, had to be leached out of the system.

Apatite

The presence and significance of macrocrystalline apatite is difficult to explain and assess. There is no mention in the literature of euhedral apatite crystals forming in sediments, especially sandstones. Most sedimentary apatite occurrences are in phosphorites that are associated with limestones and organic phosphates. This apatite is microcrystalline.

The idiomorphic apatite in the Arroyo Penasco is probably fluorapatite ($Ca_{10}(PO_4)_6F_2$) or monetite ($CaHPO_4$). Of all the varieties, these minerals possess the right optical properties (McConnell, 1973). According to Krauskopf (1967), even the formation of phosphorites is poorly understood. Most investigators agree that phosphorites form where phosphates are being brought up from oceanic depths by upwelling currents. This cannot be the case for the apatite of the Arroyo Penasco.

After closely studying its relation to the other cements, it appears that it is not the primary cement as first thought; its pairing with quartz would be antipathetic. It seems more likely to be associated with illite occurrence. The pH range needed to precipitate apatite is slightly lower than calcium carbonate, about that of illite, and the apatite crystals are packed densely in some illite zones. Moore and Zouestiagh (1974) report that consolidating, illitic sediments are frequently conduits for phosphate ions. Perhaps, the illite during early consolidation loading of the Arroyo Penasco was transporting phosphate ions. If calcium, hydrogen, and fluorine contents were high enough, then apatite formation is likely given illite pH values.

A possible source for these phosphates is the groundwater that flows through rocks cut by pegmatites. These igneous rocks could be the source. Apatite does not belie its Greek-derived name - "I deceive".

A List of Diagenetic Features and Their Significance

I. Silica

a. Dissolution: embaying and griking - very early diagenetic feature - pH greater than 9.

b. euhedral overgrowths: early formation in open pores - pH less than 9.

c. zoned and multiple overgrowths: early formation in fluctuating water levels or silica content.

d. chert: after multiple overgrowths, zoning - associated with laterite formation - alternating periods of high acidity and alkalinity.

e. authigenic zoned quartz: replacement of carbonates - fluctuating waters.

f. carbonate replacement of quartz grains: high alkalinity.

g. length-slow chalcedony: replacement of evaporites - schizohaline environment.

h. chert and length-fast chalcedony: cationic poisoning prevents megaquartz - also replaces carbonates.

II. Carbonates

a. poikilotopic calcite: shallow marine or upper phreatic - low Mg^{++}/Ca^{++} ratio.

b. coarse spar: low Mg^{++}/Ca^{++} ratio - replacement of feldspar, high alkalinity.

c. ferroan calcite: Fe^{++} present, reducing waters.

d. limpid dolomite-dedolomite: refluxion of hypo- and hypersaline waters.

e. micrite: high Mg^{++}/Ca^{++} ratio.

f. microspar: uncaged micrite; lowering of high Mg^{++}/Ca^{++} ratio; fresher water.

g. silica replacement and vice versa: fluctuating water chemistry.

h. feldspar replacement: sector extinction common; early diagenesis, before illite; feldspars are nucleating centers; both plain and ferroan.

III. Illite

a. 1Md and 1M: early diagenesis - 7-9 pH values - high K^+ density.

b. 1Md → 1M: progressive crystallization - burial to at least 3300 meters.

c. calcite/illite relation: illite precipitated after.

d. chlorite/illite: coprecipitates in places.

e. pseudomorphous after kaolinite(?): change from acid to basic pore waters.

IV. Chlorite

a. formation of I and Ib polytypes: early diagenesis proceeding through time - Mg^{++} and Fe^{++} present.

b. large crystal size: progressive crystallization as with illite.

c. progressive replacement of quartz and feldspar: change to basic waters.

d. transformation to vermiculite structures: burial and subsequent weathering.

e. possible replacement of kaolinite: waters changing from acidic to basic.

V. Pyrite

a. two types: framboidal - amorphous.

b. framboidal: organic(?) - oxidizing to hematite.

c. amorphous: inorganic/organic(?) - oxidizing to hematite and limonite.

d. both types: form in reducing waters.

VI. Apatite

a. euhedral: authigenic formation.

b. occurrence: associated with illite; pH 7-9.

c. formation: early - upon consolidation.

Figure 123 illustrates the diagenetic sequences and products.

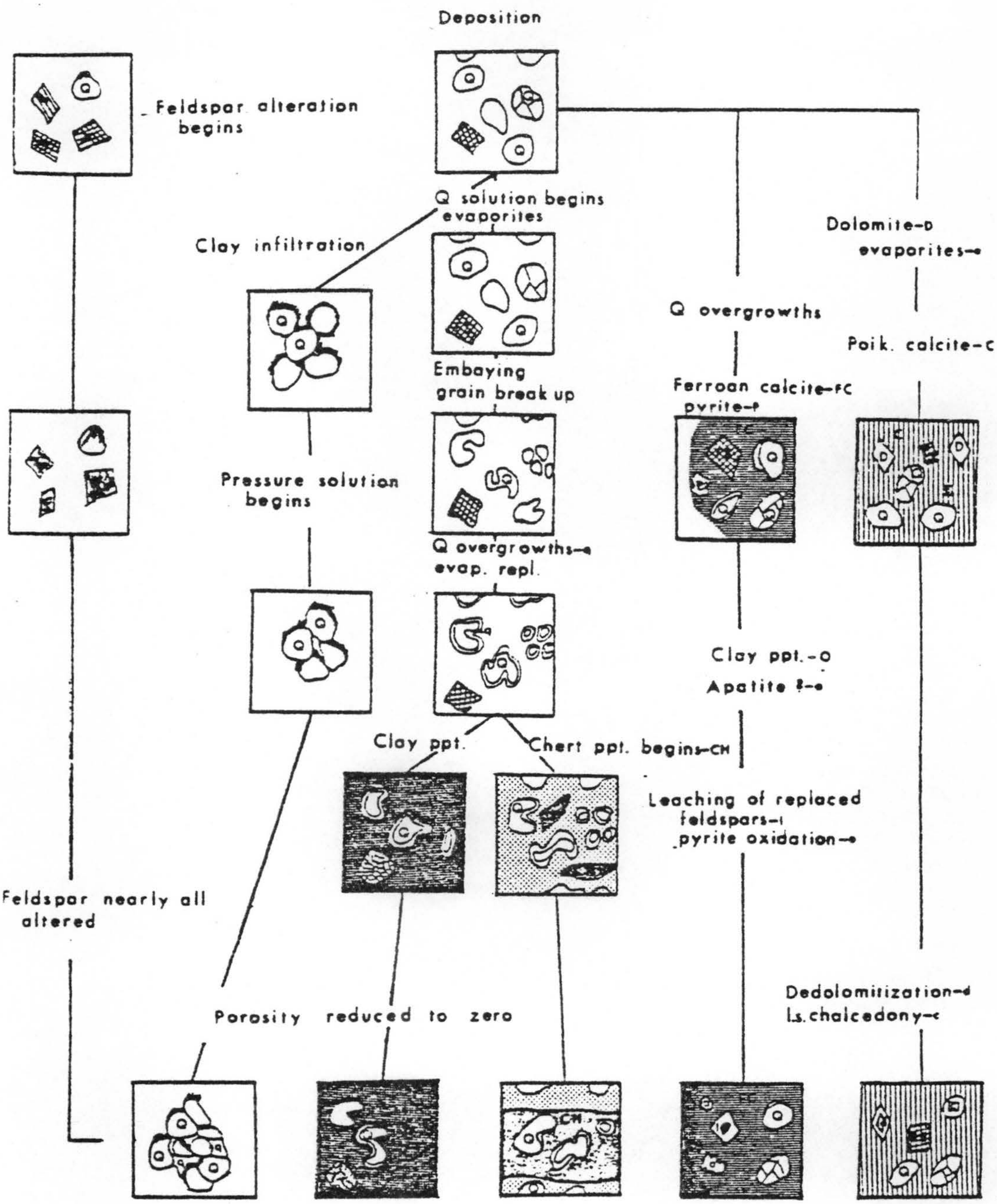

Figure 123. Diagenetic pathways in the Lower Arroyo Penasco.

CONCLUSION

The basal portion of the Arroyo Penasco Formation was deposited in a system of braided streams, beaches, tidal and sebkha flats during a quiescent tectonic period. These quartzose sediments varied greatly in size; there was little detrital clay, that present being infiltered. Aeolian deflation accounts for some grain bimodalities. These depositional regimes were located within 10° or 15° of the equator with prevailing easterly winds that were probably monsoonal during parts of the year. In other seasons, evaporation rates were high engendering elevated salinities in the pore waters. The result of this fresh and saline periodicity was a fluid chemistry that effected the development of many sympathetic and antipathetic mineral assemblages. The relative coarseness of the sediment allowed large pore spaces in which diagenetic cements could start precipitating early. Because water chemistry fluctuated so much, these cements formed, recrystallized, or underwent replacement at a relatively shallow depth. Not in spite of, but because the unit was so thin did this complex diagenesis occur. Intercalated between a Precambrian crystalline complex and a multi-mineralic carbonate sequence, this unit became a sieve for cations and anions, the result being a rock with mineral assemblages that often defy complete interpretation.

APPENDIX

Descriptions, both detailed and superdetailed follow Folk's 1974 scheme (p. 151-156). Rock colors are informal, and stratigraphic locations are given in feet instead of meters for better correlation with previous works.

I. 1, Precambrian, Ortega metasedimentary unit, Taos County, New Mexico, heavily faulted area in Rio Pueblo Valley, underlying Arroyo Penasco.

II. Quartz,potassium feldspar, biotite, muscovite schistose gneiss.

III. Well-indurated: green, noticeably foliated.

IV. Predominantly quartz and feldspar with biotite defining the foliation. Quartz crystals (grains) range from .063 mm to 1.0 mm with the mean being .25 mm. At one time, a poorly sorted sandstone. The feldspars are sericitized and chloritized.

I. 2, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, heavily faulted Rio Pueblo Valley; first appearances of Arroyo Penasco; 10 ft. of cover between Precambrian and Arroyo Penasco

II. Clayey, pebbly medium sandstone: illitic immature (?) micaceous quartzarenite.

III. Well -indurated; yellow-brown, somewhat weathered; very poorly sorted pebbly sandstone; taken from what appears to be a paleochannel.

IV. A. 72% quartz, all of which is undulose or semicomposite of metamorphic origin; 4% altered feldspars; 23% illite, which is probably a mixture of authigenic and infiltered fractions; 1% muscovite; 1% limonite. Many grains exhibit embaying and griking.

B. Rock is about 80% terrigenous, depending on amount of clay that is actually detrital, infiltered residue. 20% appears to be of authigenic origin. Homogeneous, loose packing, no porosity, unoriented. Mean size of framework grains .5 mm; range .06 mm to 4.0 mm; poorly sorted, clayey, pebbly sandstone; immature-submature.

C. Mineral Composition.

1. Terrigenous: quartz 72% (undulose, angular, 72%; vein, angular, 28%); altered feldspar (?), 4% (now illite); muscovite, 1%; tourmaline, tr.; zircon, tr.; rutile, tr.; probably some illite.

2. Orthochemical: illite, 23% (?); limonite, 1%; hematite after "massive" crystalline pyrite, tr.; goethite, tr.; chlorite, tr.

I. 3, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, seven feet above first appearance.

II. Granular medium sandstone: illitic chlorite siliceous submature quartzarenite.

III. Green with white circular areas; at base of channel.

IV. A. 72% quartz most of which is semicomposite; 5% quartz cement; 9% chlorite, most of which appears to be replacement (feldspar); clay, mostly illite; some limonite. Solution has accounted for rounded grains, embaying, and griking.

B. Rock is about 75% terrigenous, the rest being the various cements. There are clay-free zones with only quartz cement; loose packing, no porosity, unoriented. Mean size is .75 mm; range, .125 mm to 1.5 mm; moderately sorted granular medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 72% (undulose 36%; vein, 56%; composite, 2%; composite, stretched, 2% subround).

2. Orthochemical: illite, 13%; chlorite, 9% (largely replacement); quartz, 5%, as overgrowths and fracture fill; limonite, 1%.

I. 4, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 9ft. above base of outcrop.

II. Medium-coarse sandstone; illitic chloritic siliceous submature quartzarenite.

III. Mottled in light and dark green; quartz fracture fill; bottom of channel.

IV. A. 72% is framework quartz; 15% illite, some of which may be detrital; 6% chlorite, much being replacement; 3% unidentified material, probably quartz silt. Grains are embayed and griked.

B. Rock is about 75% terrigenous. Some clay may be infiltered residue. Illite, quartz, and chlorite are authigenic; also goethite and celestite. Some areas are clay free, quartz being the cement; loose packing, no porosity, unoriented. Mean grain size is about .75 mm; range, .125mm to 1.5 mm. Moderately sorted medium-coarse sandstone; submature.

C. Mineral Composition

1. Terrigenous: quartz 72% (undulose, 74%; semi-composite, 26%; subround); some infiltered clay; tourmaline, tr.

2. Orthochemical: illite, 15%; chlorite 6%, much of which has probably replaced feldspars; quartz, 4%, as overgrowths; celestite, trace; goethite, tr.

I. 5, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 12 ft. above base of exposure.

II. Pebbly, granular medium-coarse sandstone: illitic chloritic siliceous submature quartzarenite.

III. Green; resistant; no structures.

IV. A. 83% quartz framework; illite, about 11%, some of which may be infiltered; chlorite, 2%, appearing to be a coprecipitate with quartz. Embaying and griking are present in many grains.

B. Rock is about 85% terrigenous. Illite, chlorite, limonite, quartz overgrowths, anhydrite (?), and hematite are all orthochemical. Homogeneous, moderate packing, no porosity, unoriented. Mean grain size is .75 mm; range is from .06 mm to 5.0 mm; poorly sorted pebbly granular medium to coarse sandstone; submature.

C. Mineral Composition

1. Terrigenous: quartz, 83% (74% undulose; semi-composite vein, 24%; composite, 1%, subround); some illite may be infiltered.

2. Orthochemical: illite, about 11%; chlorite, 2%; quartz, 3%; anhydrite, tr., (being replaced by quartz); hematite after "massive" crystalline pyrite; limonite, 1%.

I. 6, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 14 ft. above base of unit.

II. Granular coarse sandstone: siliceous illitic, chloritic submature quartzarenite.

III. Mottled in white and green.

IV. A. 86% quartz, most of which is metamorphic in origin; detrital material, 1% (iron-stained clay). The orthochemical constituents are: quartz overgrowths, 6%; illite, 5%; chlorite, 2%; celestite, tr.; anhydrite, tr. The rock has a mottled appearance because of clay-free, quartz zones inside regions of clay/quartz cemented zones. The grains are embayed and griked.

B. The rock is composed of 86% quartz framework and about 1% detrital, iron-rich clay. The orthochemical constituents include: quartz, 6%; illite, 5%; chlorite, 2%; celestite, tr.; anhydrite, tr. Mottled because of differential cementation; moderate packing, no porosity, unoriented. Mean grain size is 1.0 mm; range from .13 mm to 3.0 mm; poorly sorted granular corase-very coarse sandstone; submature.

C. Mineral Composition

1. Terrigenous: quartz, 86% (undulose, 62%; semicomposite vein, 28%; composite, 10% subround, subangular); detrital clay, iron-stained, 1%; illite (?).

2. Orthochemical: quartz overgrowths, 6%, most in clay-free zones; illite, 5%; chlorite, 2%; celestite and anhydrite as inclusions in quartz overgrowths.

I. 7, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 17ft. above base.

II. Medium sandstone: illitic hematitic siliceous quartzarenite.

III. White sandstone; hematite and limonite splotches.

IV. A. 84% framework quartz. Splotches of hematite cement certain sections; illite and some quartz cement most of the rock. The grains are embayed and griked. Bubble trails in quartz cut across grain boundaries.

B. About 90% of rock is terrigenous. The remainder is composed of authigenic illite as pore cement and replacement (2%), hematite, and some quartz and chlorite. Homogeneous; moderate packing, no porosity, unoriented. Mean grain size is .4 mm; range is .13 to 3.0 mm. Poorly sorted medium sandstone; submature.

C. Mineral Composition

1. Terrigenous: quartz, 84% (undulose, 80%; semicomposite vein, 20% subround); detrital clay, 1 %; ultra stables, 1%; zircon; rutile; tourmaline.

2. Orthochemical: illite, 9%, as pore fill and replacement of feldspar; hematite after pyrite, 2%; quartz, 1%.

I. 8, Mississippian (?), Arroyo Penasco, 21 feet above first appearance of ss (31 ft above PE outcrop), Taos County, New Mexico, faulting prevalent.

II. Pebbly granular medium sandstone. Chloritic submature (?) quartzarenite.

III. Megascopic Properties: Well-indurated, green-brown mottled; outcrop sample, so subject to weathering; structureless; pebbly sandstone - appears polymodal.

IV. Microscopic Description

A. As stated above the rock is a pebbly, granular sandstone with a chlorite matrix or cement. Although it is a quartzarenite, the grains themselves present problems in that embaying and dissolution processes have occurred along with apparent clay infiltration or precipitation and diagenetic episodes. Parts of the rock contain irregular "dirty" patches of clay and silt and other areas are relatively clean, viz., they are composed of large embayed quartz grains "floating" in authigenic chlorite. This then leads one to believe that certain areas have undergone more "extensive" or different diagenesis than others.

B. Texture (this is inexact because of possible multiple infiltration episodes):

1. Fundamental end-members

a. Percent terrigenous materials: 86.5% ± 2.7%
b. Percent allochemical:
c. Orthochemical: 13.5 ± 2.7%

quartz ovg. .5%
illite 1.5%
chlorite 11.5%

d. Main rock group: terrigenous

2. Fabric

a. General homogeneity: clay and silt appear in patches, i.e., there is an irregular, mottled appearance; also, regions are almost all authigenic chlorite. The appearance leads to the belief that an original very coarse fraction was deposited. Later episodes washed in clay and silt, which came to rest not as a homogeneous, regular matrix but as one that is differentially distributed throughout the rock.

b. Packing: the packing is normal; quartz grains show no evidence of pressure solution. Relatively few quartz grains show grain/grain contacts. The fact that good (clean) grain/grain contacts, albeit few, are present indicates that the coarse grains were deposited before clay infiltration. The quartz grains, coarse fraction mainly, are embayed. The embaying occurred after deposition and before quartz overgrowths. Also clay replacement and growth obfuscates packing in some sections. In addition, quartz grains appear to be "eaten" by chlorite-ragged rims.

c. Porosity before cementation: porosity probably changed periodically, not primarily from cementation, but from infiltration (although diagenesis later probably alters infiltered material). Any quantification for stage porosity would be very inexact.

d. No orientation of any grains.

3.*Grain Size Entire Sediment:

a. Median: 1.4 ϕ or .38 mm
Extreme Range: .016 mm to 2.8 mm
6 ϕ to -1.5 ϕ

16-84% .18 mm to 1.2 mm
2.4 ϕ to -.25 ϕ

(A bimodality would manifest itself in the form of detrital vs. infiltrated fraction).

b. Gravel fraction: 4.5% (all grains between -1 ϕ to -2 ϕ).

c. Sand fraction: 92%

d. Mud fraction: this determination is problematical. Consideration of all grains coarser than fine silt yields a 3.5% fraction.

(If the "infiltered" sediment is, instead, detrital, then many inferences concerning the rock change.

For instance, the "infiltered fraction" comprises about 9% of the rock. This, of course, would place the rock in the texturally immature category).

e. Slightly granular medium sandstone: chloritic illitic siliceous submature quartzarenite.

4. Grain Shape:

a. Idiomorphism: none of the grains, including the ultrastables, exhibits any idiomorphism.

b. Sphericity: sphericity values in this specimen cover a wide range: .25 to 1.0. The grain size and specific values exhibit no special relationship.

*Detrital count (as opposed to infiltrated or authigenic fraction).

c. Roundness: Original quartz grain roundness has been obliterated by solution. Where overgrowths are visible, roundness values appear high. There are very angular grains, but again, most of the grains exhibit high roundness values.

5. Textural Maturity: After much closer examination, most quartz grains do appear to have overgrowths, although they are very small and many have been dissolved. Together with grain/grain contacts, these overgrowths are a positive proof that the clay fraction in here is probably not detrital, but either an infiltration product or the result of precipitation and diagenetic processes. These features indicate that the rock is submature.

b. Bonding agents: Chlorite is the primary or principal bonding agent. In the rock now, quartz plays a secondary bonding role with iron oxides playing a very minor part. Illite occurs as a minor element.

C. Mineral Composition

1. Terrigenous minerals:

a. Quartz

1. Quartz
2. Identified by optical properties and associated aspects.
3. % present in section: 86% ± 2.7%.
4. Occurrence: generally uniform distribution.
5. No physical orientation of peculiar nature.
6. Grain size: see description for entire sediment.
7. No idiomorphism.
8. Average sphericity: .75.
9. Roundness: between 4-5 (Folk, 1974).
10. The grains have undergone a process that is dissovling the quartz. As a result the grains are embayed and have etched or "ragged" perimeters. At this stage, the rock appears very loosely packed with no indentation of grains by one another. The grains have grikes.
11. Overgrowths are present on many grains. On those grains that lack overgrowths, dia-

genetic processes may have removed the overgrowths, as well as part of the mother grain. The overgrowths are delineated by surface, residual water, dust, or a very small amount of detrital clay. The remnant overgrowths comprise a very small fraction of the volume.

12.-19.

20. Inclusions:

   a. Bubbles (usually in trains) are the dominant inclusions. Most grains have a few; however, no grain is noticeably riddled with bubbles. Most grains are relatively clear of inclusions.
   b. Dust - occurs in trains as above.
   c. Ilmenite - as hexagonal x's.
   d. Idiomorphic - zircons: rare.
   e. Tourmaline - very small idiom x's; rare.
   f. Muscovite - rare.
   g. Rutile needles.

   Bubble trains cut across grains, indicating stress after deposition and cementation.

21. Alteration: Throughout the slide, the quartz grains are embayed and the perimeters frayed or ragged as if dissolution were taking place. Thus, the more I look at this slide, the more I suspect that many of the embayments are not relicts but are products of <u>in situ</u> alteration. It appears that after deposition and a very <u>minor</u> amount of infiltration (enough to coat slightly some grains so as to delineate overgrowths), a period of quartz precipitation occurred. Of course, more than one episode might have happened punctuated by interludes of infiltration. But at some point, quartz began dissolving and presumably a major infiltration or precipitation episode occurred. More discussion on this later.

22. Varieties of Quartz: Common quartz is constituent quartz grain. Inclusions are rare, and any bubble trains or dust trails traverse neighboring grains in instances.

So it appears that some of the stress reflected in the grains is due to in situ deformation rather than deformation at the source. In areas of advanced chloritization (areas where chlorite is seemingly the only clay) the large quartz grains appear more embayed, the grains farther apart (far fewer grain/grain contacts), and fewer smaller grains.

23. Antipathies and Affinities: The matrix that appears "dirtier" has far more silt sized grains than the green matrix.

24. The steps of alteration in this rock are complex: It appears that upon deposition grains that may or may not have been embayed (or only partially so) were deposited. Dust, clay, and some water droplets were deposited and delineate later overgrowths. Infiltration rims may have been deposited on grains at some stage. Several episodes of quartz overgrowth and infiltration or precipitation might have occurred. Some quartz grains have overgrowths that completely surround the grain while others appear to have meniscus bridges, indicating a complex water table activity. At some point a large amount of material was infiltered or precipitated. Most of this was chlorite. Initially, then, basic waters and perhaps Fe- and Mg-rich solutions dissolved and griked quartz. In some reregions authigenic and replacement chlorite filled porous zones and incorporated the original matrix. Later history included fracturing of the rock; filling of fractures with silica and subsequent replacement of fracture fill with chlorite.

25. Since the quartz is common and slightly undulose, it obviously had to have been derived from intrusive rocks. Many of the grains are round, yet an angular population is present. The embaying and dissolution processes have obfuscated many characteristics. The provenance will be discussed in the conclusion.

b. Other terrigenous materials

1. Rutile-trace; dark brown; angular to round; average size .05 mm.

2. Zircon-trace; angular to round; average size .08 mm.

3. Trace of tourmaline.

4. Infiltered or precipitated clays and oxides:

a. Infiltered or precipitated rims - iron oxides and clays that form layers on grains or are distributed randomly as broken pieces throughout matrix. Deposited after deposition because in places grains "penetrate" layer to touch one another. Composition of these "layers" is probably a combination of illite, chlorite, hematite, limonite, and quartz dust.

b. Chlorite: much of what is presumably infiltered chlorite is composed of irregular shaped clay-sized particles. Some are flayed platelets, others are spheres, and some are ragged sheaths. These are all stained with iron oxides, and some illite and clay-sized quartz particles appear intermingled. Bits of iron oxide also appear. In some areas this matrix appears to be forming a network of flowing fibers, all chlorite, with no other clays or particles appearing. These areas merge into the homogeneous clean matrix. This could be a stage of new or different crystal formation.

2. Allochemical grains

3. Orthochemical minerals

a. Quartz occurs in two modes - as an overgrowth and fracture fill.

i. Overgrowth - after embaying and griking; most quartz before clay infiltration or deposition. In place, there are relatively thick clay coats separating an overgrowth from its mother. So there may have been more than one episode of silica precipitation. Further evidence to support this and complicate matters is the presence of what appears to be menislus cement. This indicates a fluctuation of the water table.

ii. As a fracture fill: after consolidation of the rock, fracturing took place. Through these fractures, silica-rich solutions precipitated quartz. So throughout the rock, small quartz veinlets appear, and, when in contact with a quartz grain, possess its optical orientation. These veinlets are in turn being replaced by chlorite. Some have been replaced entirely by chlorite. So there is a network of quartz, quartz/chlorite, and chlorite veinlets.

b. Chlorite.

Chlorite appears in two modes: as an authigenic matrix and replacement of feldspar grains and quartz fractures.

i. Authigenic Matrix/Replacement - The authigenic matrix appears as a "nest" of swirling chlorite fibers, in which quartz grains are embedded as raisins in a pudding. The entire mass is slightly stained by limonite, but there are no other impurities; illite, silt, and other clays are absent. Some of the quartz grains have dark oxidized rims, probably a remnant of early infiltration.

ii. Replacement: In areas where chlorite is replacing feldspar grains, or fracture-fill, or precipitating with silica, the mineral is a is a clear, unstained green. It initially takes the form of single flakes, but as chloritization proceeds books and then masses of platelets form. This chlorite is, then, the product of a later stage of diagenesis or of several later episodes.

c. Iron oxides.

Limonite and hematite comprise only a very minor portion of this rock, usually appearing as a stain or very small detrital or infiltered particles that were an early part of the rock's history.

d. Illite.

Illite occurs in very minor amounts as a clear high, birefringent fibrous crystal. Possibly it is simply very tiny detrital muscovite.

e. Pyrite.

Small amounts of pyrite are present usually in association with the formation of the clear chlorite.

D. 1. Structures: This specimen was taken from a bed where no primary sedimentary structures were evident. Perhaps, the succeeding diagenetic episodes have obfuscated any original apparent bedding features. The entire (3 ft) bed (probably a wide channel) had no grain size trends, either vertically or horizontally. Throughout, it appeared to be a poorly sorted pebbly, granular sandstone.

2. Joints and fractures are numerous and faulting during various times moved the rock both vertically and horizontally (see history). These features, of course, played their part in diagenesis of the rock.

3. Weathering and alteration: Naturally iron oxides appear on the exposed outcrops, but the framework grains have been unaltered; and the matrix appears to have survived relatively fresh.

E. Interpretation and Paragenesis

1. Source Area:

a. Geology: As mentioned before, the rock contains common and undulose quartz. So the source area must have been of an intrusive nature (or reworked sediments-not much evidence for this).

b. Relief is rather difficult to infer considering other specimens from the area. But from this sample alone, one would assume that the poor sorting and large grain size indicates an area of high relief. Yet many of the grains are very well rounded. The resolution is supplied, if one envisions an area of rather low relief with locally higher areas of crystalline rock that periodically shed coarse debris (Monadnocks).

c. Climate: The absence of feldspars suggests two things: (1) there were none to begin with or (2) a humid climate and low relief area eliminated them. There are very few detrital micas present.

d. The size of the grains indicates that transport was not far. The shape also supports this. But again quartz dissolution hides some of the mechanical aspects.

2. Depositional Area

a. The poor sorting, geometry of bedding, and grain size indicate that this rock was originally part of a shallow channel system. In conjunction with other samples this could be a braided tributary entering a shallow shelf basin or even a tidal channel. Subaerial exposure for periods is probable considering the apparent complex diagenetic history. It appears then that this area could have been a broad plain with Monadnocks that periodically or seasonally saw monsoon-like storms that swept volumes of water in broad channels. If subaerially exposed long enough a simple rocky soil might have evolved.

b. The depth of water, then, was shallow; currents rather strong; salinity probably very variable from hypo to hypersaline; and burial rates rapid.

F. Economic Importance

1. With no porosity or valuable minerals, no one would be interested in this unit.

2. However, the complex nature of deposition, solution, infiltration, and diagenesis could furnish

one some academic interest.

I. 9, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, from 21 ft. above base of outcrop.

II. Fine-medium sandstone: illite, chlorite submature quartzarenite.

III. Resistant olive sandstone.

IV. A. 79% quartz framework; illite and chlorite both as cement and replacement; also areas of hematite and chert cement. Slightly bimodal. Some grains are embayed and griked.

B. About 80% terrigenous with quartz (79%) and detrital clay rims on some grains (2%). Illite and chlorite are the cements and replace some grains. Grossly segregated into fine and coarse grained layers. A slight bimodality exists (.13 mm and .7 mm fractions). Moderate packing, no porosity, unoriented. Moderately sorted fine-medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 79% (undulose, 80%; semicomposite vein, 20%; subangular, subround); detrital, iron-stained clay rims, 2%).

2. Orthochemical: illite 12%; chlorite 6%; hematite in isolated splotches; chert cement in large isolated areas (5 mm x 5 mm).

I. 10, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 23 ft. above base of unit.

II. Granular medium-coarse sandstone: siliceous, chloritic submature quartzarenite.

III. Mottled in white and green; white areas round or linear following planar stratification; quartz filled fractures.

IV. A. About 82% quartz framework. 10% quartz overgrowths; 5% chlorite cement and replacement. Some grains embayed and griked. Slightly bimodal as in 9. Some clay-free, all-quartz zones.

B. About 85% terrigenous with quartz the only framework grain except for 1% zircon. Quartz overgrowths comprise 10%; chlorite, 10%; illite, 2%. Bimodality in the same as in 9. Mottled.

C. Mineral Composition.

1. Terrigenous: quartz, 82% (undulose, 86%; vein, 7% subangular); tr. of muscovite; zircon, 1%).

2. Orthochemical: quartz overgrowth, 10%; illite, 2%; chlorite, 5%. Moderate packing, no porosity, unoriented. Mean grain size is .5 mm. Range is .13 mm to 2 mm. Poorly sorted granular medium-coarse sandstone; submature.

I. 11, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, fualted Rio Pueblo Valley, 25 ft. above base of unit.

II. Medium sandstone: siliceous submature quartzarenite.

III. Gray-white; planar stratification.

IV. A. Quartz framework, 74%; quartz overgrowth, 25%. Many grains round under overgrowths, some embayed.

B. 74% terrigenous: Overgrowths (25%) give appearance of much pressure solution. Homogeneous, loose packing, no porosity, unoriented. Median grain size is .35 mm; range is .25 mm to .75 mm. Moderately sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous quartz, 74% (undulose, 76%); vein, 10%; composite, 2%; subround-round; tourmaline, zircon, muscovite, tr.

2. Orthochemical: quartz overgrowths, 25%.

I. 12, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 27 ft. above base of contact.

II. Medium sandstone: siliceous submature quartzarenite.

III. Gray-white; planar stratification.

IV. A. 72% quartz framework; 27% quartz overgrowths. Some embayments.

B. 72% terrigenous; 28% authigenic (27% quartz, 1% illite). Homogeneous, loose packing, no porosity, unoriented. Median grain size is .4 mm; range is .25 mm to .75 mm. Moderately sorted medium sandstone. Moderately sorted.

C. Mineral Composition.

1. Terrigenous: quartz, 72% (undulose, 80%; vein, 18%; composite, 2%; round).

2. Orthochemical: quartz overgrowths, 27%; illite, 1%.

I. 13, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 31 ft. above base of unit.

II. Medium sandstone: illitic siliceous (chloritic, hematitic) quartzarenite.

III. Mottled in white and green; channel sandstone; low angle trough cross-stratification.

IV. A. 80% quartz; 14% illite, 3% chlorite, 3% quartz with minor amounts of hematite. Some overgrowths have celestite inclusions. Clay is limonite-stained.

B. 80% terrigenous; 20% clay and quartz overgrowths. Homogeneous, moderate packing, no porosity, unoriented. Mean grain size is .25 mm; range is .13 mm to .60 mm. Well sorted fine-medium sandstone; mature.

C. Mineral Composition.

1. Terrigenous: quartz, 80% (undulose, 70%; vein,

20%; composite, 10%; subround); zircon, tr.

2. Orthochemical: illite, 14%; chlorite, 3%; hematite after pyrite, tr.; celestite, tr.; goethite, tr.; limonite, tr.

I. 14, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 33 ft. above base of unit.

II. Fine-medium sandstone: siliceous illitic submature-mature quartzarenite.

III. Light green sandstone; unresistant; limonite stained.

IV. A. 80% quartz; 14% quartz and 6% illite. Quartz overgrowths delineated by clay.

B. 80% terrigenous; 20% authigenic. Homogeneous, loose-moderate packing, no porosity, unoriented. Mean grain size is .25 mm; range is .25 mm to .75 mm. Well sorted fine-medium sandstone; mature.

C. Mineral Composition.

1. Terrigenous: quartz, 80% (undulose, 70%; semi-composite vein, 20%; composite 10%; subround-round); zircon, tr.

2. Orthochemical: quartz, 14%; illite, 6%; hematite, tr.

I. 15, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 38 ft. above base of unit.

II. Granular fine, coarse sandstone: siliceous chloritic illitic bimodal submature quartzarenite.

III. Mottled in white and dark green; resistant.

IV. A. 73% quartz framework; 13% quartz overgrowths; 8% chlorite; illite 6%. Bimodal. Clay-free quartz zones; chert splotches (or large sedimentary rock fragments); splotches of hematite.

B. 75% terrigenous; 25% authigenic. Bimodal (modes:

.15 mm and .6 mm). Some grains extremely round in coarse mode. Clay-free quartz zones. Coarse-fine zones. Moderate packing, no porosity, unoriented. Mean grain size is - fine mode .15 mm, coarse mode .6 mm; range .13 to 1.0 mm. Modes are poorly to moderately sorted.

C. Mineral Composition.

1. Terrigenous: quartz, 73% (undulose, 76%; vein, 20%; sedimentary rock fragments, 1%; composite (stretched), 2%; subangular-round; zircon, tr.

2. Orthochemical: quartz overgrowths, 14%, chlorite cement and replacement, 8%; illite, 2%; goethite, tr.; limonite, tr.; hematite.

I. 16, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 39 ft. above base.

II. Fine, coarse sandstone: illite siliceous bimodal mature quartzarenite.

III. Green sandstone; structureless.

IV. A. 84% framework quartz; at the most, 16% authigenic. Bimodal.

B. 84-90% terrigenous; 10-16% orthochemical, depending on clay fraction that is actually authigenic. Bimodal (.15 mm fine mode and .75 mm coarse mode median). Homogeneous, moderate packing, no porosity, unoriented. Mean grain size of fine mode is .15 mm moderate- well sorted and rounded; coarse mode is .75 mm and well sorted and rounded. The two modes are mature.

C. Mineral Composition.

1. Terrigenous quartz, 84% (undulose, 64%; semicomposite vein, 24%; composite 2%; stretched metamorphic, 10%); zircon, tr.; tourmaline, tr.; iron-stained clay, 3%.

2. Orthochemical: quartz, 3%; illite, 6%; chlorite, 4%; hematite after pyrite, tr.

I. 17, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 42 ft. above base of unit.

II. Coarse sandstone: siliceous illitic submature quartzarenite.

III. White sandstone; hematite, limonite-stained; structureless.

IV. A. 85% framework quartz; 11% quartz overgrowth; 4% illite. Some grains embayed and griked.

B. 85% terrigenous; 15% authigenic. Homogeneous, moderate packing, no porosity, unoriented. Mean grain size is .55 mm; range from .13 mm to 2 mm. Poorly sorted coarse sandstone.

C. Mineral Composition.

1. Terrigenous: quartz, 85% (undulose, angular, 58%; vein, 26%; composite, 16%; round); muscovite, tr.; zircon, tr.; rutile, tr.

2. Orthochemical: quartz, 11%; illite, 5%; pyrite, tr.

I. 18, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 44 ft. above base.

II. Granular medium-coarse sandstone: siliceous submature quartzarenite.

III. Gray-green laminated.

IV. A. 85% framework quartz; 12% quartz overgrowths, 3% clay.

B. 85% terrigenous; 15% orthochemical. Homogeneous, moderate packing, no porosity, unoriented. Mean grain size is .5 mm; range is .13 mm to 4 mm. Poorly sorted granular medium-coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 85% (undulose, angular,

70%; semicomposite vein, 26%; composite, 4%; round); zircon, tr.

2. Orthochemical: quartz overgrowth, 12%; illite, 2%; chlorite 1%.

I. 19, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 45 ft. above base of unit.

II. Medium sandstone: siliceous submature quartzarenite.

III. Light gray-green sandstone; quartz fracture fill. Planar and low-angle cross stratification.

IV. A. 81% framework quartz, 19% authigenic material. Some embayed and griked grains.

B. 81% terrigenous; 19% orthochemical. Homogeneous, moderately packed, no porosity, unoriented. Medium grain size .5 mm; range, .13 mm to 2.0 mm. Poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 81% (undulose, 38%; semicomposite vein, 32%; composite 10%; angular-round); muscovite, tr.; zircon, tourmaline, rutile, tr.

2. Orthochemical:quartz, 16%; chlorite, 2%; celestite (?), 1%.

I. 20, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 47 ft. above base of unit.

II. Fine, coarse sandstone siliceous bimodal submature quartzarenite.

III. Green iron oxide stain; hematite; laminated.

IV. A. Framework quartz 80%; 20% authigenic constituents. Zoned: pyrite altering to hematite zone; clay-free zone; "dirty" zone. Bimodal. Embaying.

B. 80% terrigenous; 20% orthochemical. Bimodal in fine (mean, .15 mm) and coarse (mean, .75 mm); both moderately sorted. Zoned into a hematite after pyrite zone, clay-free zone, "dirty" zone. Moderately packed, no porosity, unoriented. Bimodal moderately sorted sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 80% (undulose, 56%; semi-composite vein, 24%, composite 10%; angular-round); iron-stained clay, 2%; zircon, tr.

2. Orthochemical: quartz, 15%; illite, 1%; hematite, 1%; chlorite 1%.

I. 21, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 48 ft. above base.

II. Sandy sparite or medium sandstone: calcitic dolomitic submature quartzarenite (clastic grains comprise 50% of rock).

III. Gray clastic limestone; fractured; iron-stained.

IV. A. A sandy dedolomitic limestone (sandy calcarenite). Coarse sand grains are embayed and griked.

B. Quartz grains comprise 40-50% of rock; carbonates comprise 50-60%. Homogeneous, loosely packed, no porosity, no orientation. Median grain size is .5 mm, range is .06 mm to 3 mm. Poorly sorted.

C. Mineral Composition.

1. Terrigenous: quartz, 45% (runs the gamut of quartz types and roundness values).

2. Orthochemical: calcite, fine-medium crystalline spar; dedolomite rhombs (perimeter is limpid dolomite), .125 mm; "massive" pyrite, up to .5 mm crystals, 1%, celestite, tr.

I. 1X, Precambrian, Embudo Granite, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, underlying Arroyo Penasco (in Penitente Valley).

II. Alkali feldspar granite.

III. Light pink intrusive with green areas.

IV. An intrusive rock containing microcline, quartz, muscovite, zircon, garnet, rutile and various opaques. Microcline crystals are being sericitized and reach 3 mm size. Quartz crystals range from .06 mm to 1.0 mm.

I. 2X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 2 ft. above base of unit (in Penitente Valley).

II. Fine sandstone: siliceous submature quartzarenite.

III. Green sandstone; laminated.

IV. A. Laminated (delineated by grain size) sandstone with 90% framework quartz. Heavy and stable mineral placers present. Porosity in coarser grained areas.

B. 90% terrigenous; 10% quartz orthochemical cement with some illite. Laminated, pressure solution, 5% porosity, unoriented. Mean size is .2 mm; ranges from .06 mm to 3 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 90% (a complete range of quartz types, round to angular); zircon, tourmaline, and rutile in placers about .06 mm, round and angular.

2. Orthochemical: quartz overgrowths 10%; illite, tr.

I. 3X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 5 ft. above base of unit (Penitente Valley).

II. Fine-medium sandstone: siliceous illitic submature quartzarenite.

III. Dark green sandstone; crystal casts or mudcrack impressions.

IV. A. 80% quartz framework with quartz, illite and hematite cement. Taken from unit with mud cracks and crystal casts (?). Some embaying.

B. 80% terrigenous: 10% quartz cement, 5% illite, tr. of hematite. Homogeneous, 5% porosity, pressure solution, unoriented. Mean grain size is .25 mm; range from .06 mm to .75 mm; moderately sorted fine-medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz 80% (undulose and semi-composite, angular through round); muscovite, tr.; microcline, tr.

2. Orthochemical: quartz, 10%; illite 5%; hematite after pyrite, tr.

I. 4X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 6 ft. above base (in Penitente Valley).

II. Fine sandstone: siliceous mature quartzarenite.

III. Gray-green sandstone; fractured; limonite-stained.

IV. A. A mature sandstone with 83% framework quartz. Grains round under overgrowths.

B. 83% terrigenous; 15% quartz overgrowths, some illite. Homogeneous, some pressure solution (moderately packed), no porosity, unoriented. Mean grain size is .7 mm; range, .06 mm to .75 mm. Well sorted fine sandstone; mature.

C. Mineral Composition.

1. Terrigenous: quartz, 83% (undulose, some angular, many round); tourmaline.

2. Orthochemical: quartz, 15%; illite, 2%; hematite, tr.

I. 5X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 10 ft. above base (Penitente Valley).

II. Medium sandstone: siliceous, illitic submature quartzarenite.

III. Light green and brown; mottled; green areas, fine grained-brown areas, coarse grained.

IV. A. A laminated sandstone with 85% framework grains. Porosity may be because of plucking.

B. 85% terrigenous; 4% quartz cement and 4% illite cement. Laminated (silty, fine-, medium-grained layers), moderately packed, 7% porosity, unoriented. Mean grain size is .4 mm; range, .03 mm to 1.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 85% (undulose and semi-composite, subangular); zircon.

2. Orthochemical: quartz, 4%; illite, 4%; hematite, tr.; chlorite, tr.

I. 6X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 15 ft. above base (Penitente Valley).

II. Medium sandstone: illitic submature quartzarenite.

III. Green-brown sandstone; planar and trough cross-stratification.

IV. A. Quartz, 86% framework; illite, 12% orthochemical. Slight embaying of quartz grains.

B. 86% terrigenous; illite and quartz cement. Homogeneous, loosely packed, 2% porosity, unoriented. Mean grain size is .5 mm; range, .13 mm to 1.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 86% (undulose and semi-composite, subangular); tourmaline, tr.; rutile, tr.

2. Orthochemical: illite 12%; quartz, tr.

I. 7X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 17 ft. above base (Penitente Valley).

II. Fine sandstone: illitic siliceous submature quartzarenite.

III. Laminated in green (fine) and brown (coarse) zones; limonite stain.

IV. A. Laminated sandstone, 79% quartz framework. 10% porosity.

B. 79% terrigenous; illite and quartz cement; laminated, by grain size, loose to moderate packing, 10% porosity, unoriented. Mean grain size is .25 mm; range is from .06 mm to .75 mm; poorly sorted fine sandstone; submature.

I. 13X, Precambrian, Embudo Granite, Taos County, New Mexico, faulted Rio Grande de Rancho, underlying Espiritu Santo (Alamo Valley).

II. Alkali feldspar granite.

III. Pink crystals; dark green crystals.

IV. An intrusive rock containing microcline, quartz, biotite, and opaques. Microcline crystals exceed 10 mm size. Quartz range, .06 mm to 1.0 mm.

I. 14X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, at base of exposure (Alamo Valley).

II. Granular very fine, coarse-very coarse sandstone: siliceous bimodal submature quartzarenite.

III. Chartreuse sandstone; pebbly; hematite; fractured.

IV. A. A bimodal sandstone. The quartz framework comprises about 90% of the rock. Vein and stretched metamorphic quartz are conspicuous.

B. 90% terrigenous; 7% hematitic clay and 3% quartz comprise the orthochemical fraction. A homogeneous bimodality, well-packed (pressure solution), no porosity, unoriented. Mean grain size is 1.0 mm; range, .03 mm to 4 mm; modes are poorly to moderately sorted (mean sizes: .08 mm and 1.0 mm), a coarse-very coarse sandstone; submature in both modes.

C. Mineral Composition.

1. Terrigenous: quartz 90% (undulose, semicomposite, composite (undulose and stretched); coarse mode subround, fine mode subangular).

2. Orthochemical: quartz 3% (probably an under estimate); hematitic illite (?), 7%.

I. 15X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 10 ft. above base (Alamo Valley).

II. Coarse sandstone: siliceous illitic submature quartz-arenite.

III. Green, resistant sandstone.

IV. A. A coarse sandstone with some embaying on larger grains.

B. 85% terrigenous; 6% quartz cement and 4% authigenic illite. Homogeneous, moderately to well packed, 5% porosity, unoriented. Mean grain size, .75 mm range, .13 mm to 3.0 mm. Poorly sorted coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 85% (undulose, angular through round).

2 Orthochemical: quartz, 6%; illite, 4%.

I. 16X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 16 ft. above base (Alamo Valley).

II. Fine-medium sandstone: siliceous submature quartzarenite.

III. Gray-green sandstone.

IV. A. Framework 90% of rock. Quartz overgrwoths may be underestimated; they obfuscate pressure solution determination and roundness of original grains.

B. 90% terrigenous; 9% quartz cement. Homogeneous, moderately-well packed, no porosity, unoriented.

Median grain size, .25 mm; range, .06 mm to 2.0 mm; poorly sorted fine-medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz 90% (undulose, subround); zircon, tr.; tourmaline, tr.

2. Orthochemical: quartz 9%; illite, 1%; chlorite, tr.

I. 17X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 28 ft. above base (Alamo Valley).

II. Granular v. fine, coarse sandstone: calcitic bimodal submature quartzarenite.

III. Gray sandy limestone.

IV. A. A calcitic sandstone with detrital and authigenic (?) chert. Bimodal. Grains embayed and griked.

B. 81% terrigenous; authigenic calcite (poikilotopic) and clay. Homogeneous bimodality, some pressure solution, no porosity, no orientation. Mean grain size: bimodal in .08 mm (mean) and 1.0 mm (mean) modes; range from .06 to 4 mm; moderately sorted in modes, granular coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 81% (undulose, composite, semicomposite, embayed); chert, tr.; chalcedony (length-slow), tr.; muscovite, tr.

2. Orthochemical: calcite, 14% (poikilotopic); illite and chlorite, mixed, 5%; chert, tr.; ankerite, tr.

I. 18X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 30 ft. above base (Alamo Valley).

II. Sandy fossiliferous micrite (terrigenous fraction is poorly sorted with grains from .03 mm to 1.0 mm; the fossils are fragments but appear to be from pelecypods, gastropods, and crinoids).

III. Dark gray; fractured.

I. 19X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico faulted Rio Grande de Rancho Valley, 33 ft. above base (Alamo Valley).

II. Medium sandstone: calcitic submature quartzarenite.

III. Brown laminated sandstone.

IV. A. Calcareous sandstone with dolomite in clay fraction; the framework comprises 69% of rock. The unit is laminated; intercalated with micrites.

B. 69% terrigenous (this is low because some calcite has replaced grains, probably feldspar); 26% calcite, both replacement and orthochemical (poikilotopic). Laminated, loose packing, no porosity, unoriented. Mean grain size .4 mm; range from .06 mm to 1.0 mm; poortly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 69% (undulose, semicomposite; subround); CO_3 replaced grains, feldspar (?) up to 5%.

2. Orthochemical: calcite, 26%, partially poikilotopic, crystal size .5 mm; also replacement; illite 4%; hematite after framboidal pyrite, tr.; dolomite, tr.

I. 21X, Precambiran, Embudo Granite, Taos County, New Mexico, faulted Ponce de Leon Springs, underlying Arroyo Penasco.

II. Alkali feldspar granite.

III. Gray-green coarsely crystalline.

IV. Microcline (10 mm), quartz (1 mm), biotite, muscovite.

I. 22X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, at base of unit (Penitente Valley).

II. Medium-coarse sandstone: calcitic, illite submature quartzarenite.

III. Green sandstone; unresistant.

IV. A. 84% framework quartz, calcitic and illitic; partial calcite replacement, remnants of replaced grains leached out (feldspar).

B. 84-89% terrigenous; illite 5%, replacement calcite 5%; Homogeneous, moderately packed, 2% porosity, unoriented. Mean grain size .5 mm; range, .13 mm to 1.0 mm; poorly sorted medium-coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz 84% (undulose, semicomposite; angular and round); feldspar, perhaps, at one time leached and replaced by calcite.

2. Orthochemical: illite, 5%; replacement calcite, 5%; quartz, 2%.

I. 23X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, at base lateral to 22X (Penitente Valley).

II. Medium sandstone: siliceous submature quartzarenite

III. Olive sandstone; fractured.

IV. A. A laminated sandstone with calcite in coarse grained laminations. Calcite is poikilotopic. Quartz is initial cement. Ultra stable heavy mineral placers.

B. 76% terrigenous; 21% quartz cement, 3% calcite. Laminated, some pressure solution, no porosity, unoriented. Mean grain size, .4 mm; range, .06 mm to 2.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 76% (undulose, semicomposite; subround, subangular); zircon, tr.

2. Orthochemical: quartz, 21%, obfuscates original grain shape; poikilotopic calcite, 3%; illite clay, tr.; hematite, tr.

I. 24X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, fault breccia (Penitente Valley).

II. Medium sandstone: siliceous submature quartzarenite.

III. Green brecciated sandstone.

IV. A brecciated sandstone with coarse spar filling the fractures.

I. 25X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 4 ft. above base (Penitente Valley).

II. Fine-medium sandstone: siliceous submature-mature quartzarenite.

III. Light gray; fractured.

IV. A. A mature sandstone with quartz overgrowths obfuscating original shape and pressure solution amount.

B. 72% terrigenous; 27% quartz overgrowths. Homogeneous, no porosity, unoriented. Mean grain size is .25 mm; range, .06 mm to 1.0 mm.

C. Mineral Composition.

1. Terrigenous: quartz, 72% (undulose); zircon, tr.

2. Orthochemical: quartz 27%; illite, 1%; hematite, tr.

I. 26X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 5 ft. above base (Penitente Valley).

II. Medium sandstone: siliceous submature quartzarenite.

III. Light gray; fractured.

IV. A. Medium sandstone with authigenic apatite.

B. 74% terrigenous; 24% quartz cement. Homogeneous, no porosity, unoriented. Mean grain size is .4 mm; range, .06 mm to 3.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 74% (undulose; subround).

2. Orthochemical: quartz, 24%, that obfuscates grain shape; apatite, tr.; illite, 2%; hematite after framboidal pyrite; calcite, tr.

I. 27X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, Rio Grande de Rancho Valley, 7 ft. above base (Penitente Valley).

II. Fine sandstone: siliceous submature sandstone.

III. Light gray; limonite-hematite stain.

IV. A. Sandstone with stable mineral placers.

B. 77% terrigenous; 19% quartz cement. Homogeneous, packing loose (?), no porosity, unoriented. Mean grain size is .25 mm; range, .03 mm to 2.0 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 77% (undulose, semicomposite; round (?)); rutile, tr.; zircon, tr.; tourmaline, tr.

2. Orthochemical: quartz, 19%; illite, 3%; calcite, 1%.

I. 28X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 10 ft. above base (Penitente Valley).

II. Medium sandstone: calcitic, siliceous submature quartzarenite.

III. Gray sandstone; laminated.

IV. A. Calcite-cemented sandstone; poikilotopic calcite; slight grain embaying.

B. 75% terrigenous; calcite, 19%; quartz cement 6%. Homogeneous, some pressure solution, no porosity, unoriented. Mean grain size is .4 mm; range from .06 mm to 1.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 75% (undulose, semicomposite; subangular).

2. Orthochemical: calcite, poikilotopic, 19%; quartz, 6%.

I. 29X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, lateral to 28X (Penitente Valley).

II. Fine sandstone: siliceous, illite submature quartzarenite.

III. Olive sandstone; mud cracks (?).

IV. A. A fine sandstone with dessication cracks. Authigenic apatite present.

B. 74% terrigenous; quartz cement, 18%; illite cement, 6%. Homogeneous, some pressure solution, no porosity, unoriented. Mean grain size is .25 mm; range, .03 mm to 1.0 mm; poorly sorted fine sandstone, submature.

C. Mineral Composition.

1. Terrigenous: quartz, 74% (undulose, slightly undulose; angular to round); zircon, tr.; muscovite, tr.

2. Orthochemical: quartz, 18%; illite, 6%; chlorite, 2%; apatite, tr.

I. 30X, Mississippian age, Arroyo Penasco (Armstrong), 12 ft. above P∈ regolith, Taos County, New Mexico; faulting is common in the area.

II. Very fine-fine sandstone: siliceous illitic chloritic mature quartzarenite.

III. Megascopic description: The rock is a well-indurated, light gray sandstone, slightly mottled and laminated. Megascopically, quartz appears to be the major cement and grain. There are no fossils. Sorting looks good.

IV. Microscopic description: This specimen was taken from a bed that appeared sheetlike rather than lenticular. The unit is laminated with occasional fractures and is near a unit below that exhibits mud crack impressions. Zircon, toumaline, and rutile grains appear in placers, the grains ranging from angular to round. The quartz grains are predominantly very fine to fine with occasional medium and coarse grains. There is a break in population size, viz., a slight bimodality is present. The sandstone is mature. Cements include quartz, illite, and chlorite-quartz composing the largest fraction of orthochemical substances. Slight amounts of pyrite and limonite/hematite are also present.

B. Texture

1. Fundamental end memebers

a. Terrigenous materials:

Quartz

	% of Rock	% of grains	w/noticeable traces of
vf	27 ± 3.1	36 ± 3.2	zircon, rutile and
f	43.5±3.4	56 ∓ 3.4	tourmaline
med	7.5±1.6	7 ± 1.6	
cse	1	1	

b. Allochems:

Pyrite? limonite/hematite

c. Orthochemical constituents:

Quartz	16% ± 2.4
Illite	5% ± 1.6
Chlorite	1%

Trace of pyrite, limonite, hematite.

d. Main rock classification: Terrigenous rock.

2. Fabric

a. The rock is homogeneous except for placers of heavy minerals and some regions where quartz is the only orthochemical substance; slight fining upward trend.

b. The rock shows pressure solution between some quartz grains. Heavy minerals indent or penetrate quartz grains.

c. Porosity before cement by quartz and clays
21%.
Porosity after quartz cement
5-6%
Porosity, present
0%

d. No orientation except for illite around grain.

3. Grain size

a. Entire sediment

Median: 2.85 ϕ - .14 mm
Range: 0 -4 ϕ - . 5 mm to .0625
16%-84%: 2.3ϕ - 3.3 .2mm - .1 mm
A slight bimodality with 7-8% in the .25 mm-.75 mm range and 92-93% about .1 mm.

b. No gravel fraction.
c. Sand fraction (as above).
d. Mud fraction (no detrital mud).
e. Very fine - fine sandstone.

4. Grain shape

a. Idiomorphism - no idiomorphic grains (not even in heavy, ultrastable grains).

b. Sphericity - there exists a wide range in sphericity values from .25-1.0, but the majority exhibit a high (.75) sphericity.

c. Rounding - overgrowths and pressure solution obfuscate much of the rounding; nevertheless, many grains have high roundness values (as high as 6ρ). The entire fine fraction could be very round, but, again grain boundaries are difficult to discern. The heavy minerals exhibit a wide range in roundness values.

5. Textural maturity

The rock, excluding the medium and coarse fraction, is mature to supermature. The coarse fraction (deduced from other thin sections) could be a secondary or later population from rivers or weathering of "high" relief areas.

6. Bonding agents

a. quartz

b. illite
c. chlorite
d. limonite hematite

C. Mineral Composition.

1. Terrigenous minerals

a. Quartz

1. quartz
2. identification-optics + environmental association
3. 78% $\pm$ 2.9% of rock is detrial quartz
4. ubiquitous in this specimen.
5. no discernible orientation
6. for grain size analysis see analyses for entire sediment
7. no idiomorphism
8. sphericity
   range .25-1.0
   average .67-.80
9. Roundness ranges from 2-5 e ; but this is apparent because, again, overgrowths not well delineated on many grains. Most grains appear to be 4 e .
10. Pressure solution; some Q grains identical others; ultrastable heavy minerals indent quartz.
11. Overgrowths are present on most grains but, again, not delineated well on many.

12-19.

20. Inclusions

a. rutile needles in some grains
b. tourmaline (clear to pale green, elliptical-hexagonal, some doubly terminated)
c. bubbles (some grains have so many, they look like Swiss cheese); bubble trains; dancing bubbles; boehme lamellae
d. zircon (idiomorphic, doubly terminated)
e. apatite
f. small, blue rutile-like needles
g. muscovite
h. rutile (sanguine prisms)
i. ilmenite

21. Quartz is quite stable.

22. Quartz species

- straight (common)

- semicomposite
- quartz w/boheme lamellae
- undulose
- slightly undulose

23. Antipathies/affinities - quartz overgrowths better delineated in zones exclusively quartz cemented.

24.

25. Derivation

Metamorphic (semicomposite vein quartz); only a trace.
Plutonic (common quartz).
Reworked sediments (indirect evidence by maturity); only a trace.

b. Muscovite/illite (see orthochemical description)

1. Muscovite/illite

The micas in this thin section could be detrital or the result of infiltration, but there are several things that contradict this:

1. flakes are fresh - not frayed
2. clean and homogeneous
3. post quartz overgrowth phase (overgrowths would inhibit infiltration - Hayes)
4. authigenic concentric color banding
5. flakes not crushed between grains
6. flakes coat pores and not grains.

c. Zircon

1. zircon
2. optical property identification and association with other grains
3. occurrence: less than 1% by estimation
4. most grains concentrated in placers along with other heavy minerals
5. no physical orientation present
6. average size .07 mm
7. most grains are rounded - no idiomorphism
8. sphericity .8 for average; the sphericity values fall in a very narrow range

9. The smaller zircons tend to be the most angular (1-2ρ), and some larger grains have roundness values between 2-5ρ. So there is a large range in grain roundness, the average being 3ρ with a continuous gradation existing between the extremes.

10. The zircons look pitted but no indent quartz grains.

11. Some grains have what appear to be overgrowths. These overgrowths may re relict.

12-19.

20. No inclusions
21. No alteration
22. Grains are one of a kind.
23. Occurs in placers with tourmaline and rutile.
24.
25. Several origins are possible:
    a. recycled sediment
    b. a product of intrusive igneous or metamorphic rocks.

d. Tourmaline

1. tourmaline
2. identification by optics and association with other heavy minerals
3. composes less than 1% of rock, this by estimation
4. most grains occur in placers, although there are several that appear randomly throughout the slide
5. no physical orientation
6. .07 mm on average, most cluster in this range
7. no idiomorphism
8. sphericity .8, although an occasional individual may be around .3 (w/).
9. roundness varies between 2-5ρ with a continuous gradation between the extremes - there appears to be a disarticulation in some of the grains
10. tourmaline indent quartz grains
11. no apparent overgrowths

12.-19.

20. no inclusions
21. again some grains appear to be breaking up

22. varieties - by color, which is, perhaps due only to grain orientation
    a. light green-dark green pleochroism
    b. chartreuse - slight pleochroism
    c. light blue green - dark blue green
23. grains again occur in placers with other heavy stable minerals
24.
25. derived from sources similar to those of zircon

e. Rutile

1. rutile
2. identified by optical properties and mineral association
3. less than 1% in section, this by estimation
4. as the zircon and tourmaline occur in placers
5. no physical orientation
6. .075 mm in diameter; very uniform
7. no idiomorphism
8. sphericity average .75-.8, this in a narrow range
9. the grains vary in angularity or roundness from 2e to 5e
10. some grains have a "spongy" surficial appearance and are on the verge of breaking up. Other grains are fresh. Rutile indents quartz.
11. no overgrowths

12.19.

20. no inclusions
21. some oxidation appears, as well as mechanical alteration
22. The variety appears to be one, but with many varying stages of roundness and alteration.
23. again occurs in placers with other stable, heavy minerals
24. The alteration is difficult to identify, if alteration it is.
25. see tourmaline, zircon for origins.

f. There are patches that appear to be the altered remnants of clastic grains. Limonite, hematite, and pyrite have replaced the original. There is no habit left for accurate determination of original grain, although they (patches) are concentrated in the placers.

2. Allochemical grains

   a. Framboidal hematite after pyrite which could have replaced organic residue. There is also amorphous pyrite that has not been altered. The pyrite, though, may be orthochemical.

3. Orthochemical minerals

   a. Quartz

      1. quartz
      2. identified by optical properties
      3. composes 16% ± 2.4% of the rock
      4. The quartz overgrowths are uniformly distributed throughout the specimen but are difficult to see in many cases. There are portions of the slide where there is no clay and here quartz overgrowths are quite well-delineated. Perhaps, these regions were sites of more rapid silica precipitation and quartz overgrowths grew larger and occupied pore space before clay precipitation, which cut off or restricted further quartz growth. These overgrowths give the rock an appearance of immaturity, which is false, <u>viz</u>., the overgrowths obfuscate the roundness and sphericity. The overgrowths are delineated by dust trains or minute bubbles.
      5. The overgrowths are syntaxial.
      6. grain size -
      7. Occasional forms euhedral crystal faces where growth was relatively uninhibited.
      8. Sp. -
      9. roundness -
      10.-19.
      20. Authigenic chlorite occurs in random crystals in some overgrowths. Possibly a second phase of quartz cementation occurred after illite, as some illite rests between quartz cements.
      21. Quartz cement is fresh (in situ) but some grains may have carried reworked overgrowths.
      22.
      23. antipathies and affinities - "maculose" (clay free) zones
      24. Quartz was precipitated before illite and chlorite. This fact is indicated by grain contacts between quartz (clean contacts). The illite overlies the quartz overgrowths

tangentially. Chlorite crystals are present in random orientation and are included in the illite and quartz overgrowths and occasionally penetrate the perimeter of the clastic grain. Chlorite could be either replacing quartz and illite or filling microfractures and pore space, perhaps both. Or a co-precipitate with quartz.

25.

b. Illite

1. illite
2. identified by optical properties and x-ray diffraction
3. 5% $\pm$ 1.6% illite in entire rock
4. Illite occurs in most of specimen (except in maculose zones) as a pore lining with crystals tangential to quartz overgrowths and also occurs as a pore filling.
5. Illite occurs as sheaths forming tangentially to quartz; in the pore, it grows as random xls or in concentrically colored bands.
6. Illite crystal outlines, if authigenic, are almost impossible to see, and here this is also the case. But some illite "sheaths" are between 50-100 microns.
7. idiomorphic outlines in authigenic illite difficult to distinguish.
8.
9.
10. The illite is not bent or indented by the quartz. Chlorite needles seem to interpenetrate the illite in some areas.

11.-19.

20. Inclusions

    a. chlorite appears as flakes in illite
    b. flakes (see chlorite)
    c. average 10-15 m
    d. random orientation
    e. composes 1-2% of rock

21. The illite is fresh, clean authigenic illite.
22. This clay is probably 1M (or 1Md) illite.
23. The illite does not occur in "maculose" zones.
24. The illite forms after an initial quartz overgrowth stage and probably before or perhaps with the chlorite.
25.

c. Chlorite

1. chlorite
2. identified by x-ray diffraction and optics (light green flakes)
3. composes 1-2% of rock
4. occurs throughout rock except as illite in the maculose zone
5. The flakes or needles are randomly oriented, occurring in the illite cement and penetraing Q overgrowths and grain perimeters. Occasionally, the flakes parallel the illite or Q grain surface.
6. The needles are almost all in the 10-15 microns range with some individual crystals reaching 25 microns.
7. The chlorite occurs as idiomorphic flakes or needles; the outlines of each crystal are very clear.
8.
9.
10. The chlorite appears to penetrate quartz and illite, either as replacement or cavity fill. If the crystals are not in a crosscutting relationship, they appear to be parallelling the illite structure as pore fill. Could have precipitated with quartz.

11.-20.

21. Chlorite is the most unaffected of the orthochemical constituents. It looks very fresh and "clean".
22. The chlorite is of one species.
23. Affinities and antipatheis: does not occur in maculose zones; does not "penetrate" ultrastables.
24. Again the chlorite is euhedral and in places appears to be included in quartz overgrowths and quartz grain itself.
25.

d. Hematite/limonite (tr.)

Hematite appears in parts of the slide in veinlets that parallel the placers and laminations. Apparently it is pseudomorphous after framboidal pyrite; hematite and limonite also appear in an irregular fashion in places where alteration of heavy minerals has occurred. These orthochemical constituents form only a trace in the rocks and are probably due to outcrop weathering.

e. Pyrite - occurs in irregular splotches; perhaps as a result alteration of organics or hydrothermal activity.

D. Structures, etc.

1. Sedimentary structures

a. planar cross-stratification
b. heavy mineral placers
c. in close proximity are crystal casts, mud crack impressions, and worm tubes(?).

2. Tectonic

a. fractures
b. faulting

E. Interpretation and Paragenesis

1. Source area

a. Geology - The sediment described herein was derived from either a very complex source area or from a multiple source. There are several types of quartz which indicate multifarious sources:

1. Quartz with Boëhme lamellae, great undulosities, semicomposite aspect - metamorhpic.
2. Very well rounded quartz grains - recycled sediments lack of feldspars.
3. Non-undulose quartz - intrusive, igneous.

The possibility exists that some of this quartz was derived from the basin itself, viz., the weathering of monadnocks almost entirely composed of quartz rocks that were very small grained. The fact that some quartz and ultrastable grains are angular suggests that the sand is not entirely recycled, but rather, was fed either by tectonic "squirts" or local erosion of crystalline rock protruding through the regolith.

b. Relief - Mineralogy, grain size, maturity all indicate an area of general low relief and rather low tectonism. However, an area of high energy reworking of sands can exist and produce fine grained, mature sandstones and be located in an area of high tectonism and relief. More specimens need to be examined to form a better idea of actual conditions.

c. The lack of feldspars might indicate an area of humid and hot conditions (or simply an area with no feldspars, i.e., metaquartzite would be no indicator at all).

d. Length of transport: the small grain size and roundness might indicate lengthy transport or simply constant reworking in a high energy site of deposition.

The upshot of all this being that more needs to be done in the way of analysis on the source area. Paleoreconstruction reveals that this area was located $\pm$ 10 of the equator; that it is the initial formation of a basin; that the winds were from the southeast, that highlands which would create an orographic effect probably existed all around the incipient basin. All these conditions plus a complex mineralogy make source reconstruction difficult.

2. Depositional Area

a. Horizontal laminations, heavy mineral placers, textural maturity, environmental associations indicate a beach or shallow shelf margin.

b. The water was shallow with moderate to high currents, wave activity, and hypersaline (difficult on this); but a newly forming restricted basin might be reflective of these conditions. Organisms have very little effect on the sediments.

3. Diagenetic and Post-diagenetic Changes

a. Age relations: Q ppt, illite, chlorite(?), outcrop weathering organic pyrite weathering.

b. Intrastratal fluids that were silica-rich probably responsible for first quartz cement stage, then K-rich waters precipitated illite, iron and magnesium-rich waters precipitated chlorite and perhaps some iron opaques.

c. Post-emergent weathering oxidation of pyrites and opaques.

F. Economic Importance

1. none
2. valuable for analysis of authigenic or orthochemical constituents.

I. 31X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 14 ft. above base (Penitente Valley).

II. Fine sandstone: calcitic siliceous submature quartzarenite.

III. White limey sandstone; unresistant.

IV. A. A fine calcitic sandstone, the calcite being poikilotopic and some perhaps replacement.

B. 75% terrigenous; calcite, quartz, illite, and hematite are authigenic products. Homogeneous, slight pressure solution, no porosity, unoriented. Mean grain size is .2 mm; range, .06 mm to 1.0 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 75% (straight, undulose semicomposite, subangular); rutile, tr.

2. Orthochemical: calcite, 14%; quartz, 6%; illite, 3%; hematite after pyrite, 2%. Illite precalcite phase(?).

I. 32X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 16 ft. above base (Penitente Valley).

II. Fine sandstone: calcitic submature quartzarenite.

III. White limey sandstone; friable.

IV. A. A sandstone with poikilotopic calcite cement.

B. 69% terrigenous; calcite, 27%, as slight replacement and much spar precipitate; the remainder being authigenic chlorite, illite and quartz. Homogeneous, loosely to moderately packed, no porosity, unoriented. Mean grain size is .2 mm; range, .06 mm to .75 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 69% (straight, undulose, semicomposite; subangular).

2. Orthochemical: calcite, 27%; chlorite and illite, 3% (post-calcite); quartz, 1%; hematite, tr.

I. 33X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 17 ft. into section (Penitente Valley).

II. Fine sandstone: calcitic submature quartzarenite.

III. White limey sandstone; friable.

IV. A. A fine sandstone with poikilotopic calcite cement.

B. 75% terrigenous; 22% calcite cement. Homogeneous, moderate packing, no porosity, unoriented. Mean grain size is .25 mm; range, .06 mm to .75 mm; moderately sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz 75% (straight, undulose, semicomposite; subangular).

2. Orthochemical: calcite 22%; quartz, 1%; illite, chlorite, 2%.

I. 34X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 19 ft. into section (Penitente Valley).

II. Medium sandstone: calcitic very slightly bimodal submature quartzarentie.

III. Tan sandstone; unresistant.

IV. A. A slightly bimodal sandstone with replacement and poikilotopic calcite. Feldspar replaced by chlorite then calcite.

B. 75% terrigenous; 22% calcite. Homogeneous, loose packing, no porosity, unoriented; bimodal, the mean of the modes being .1 mm and .75 mm and poorly sorted; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 75% (quartz exhibits all types; the coarse mode is round, and the fine is subround); chert, 2%. Subarkosic if feldspars were preserved.

2. Orthochemical: calcite, 22%; chlorite, 2%; hematite after pyrite.

I. 35X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 20 ft. into section (Penitente Valley).

II. Fine sandstone: calcitic illitic submature quartzarenite.

III. Brown sandstone; slightly mottled.

IV. A. A sandstone with microcline being replaced by calcite. Could be subarkosic if feldspar preserved. Carbonate replacement then clay formation.

B. 68% terrigenous; 23% calcite, 9% chlorite (may be feldspar replacement also). Homogeneous, moderate packing, no porosity, unoriented. Mean grain size is .25 mm; range, .06 mm to 1.0 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 68% (undulose; subangular); feldspars.

2. Orthochemical: replacement calcite, 23%; 9% chlorite; hematite after framboidal pyrite, tr.

I. 36X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 21 ft. into section (Penitente Valley).

II. Medium-coarse sandstone: calcitic bimodal submature quartzarenite.

III. Light brown sandstone; unresistant.

IV. A. A bimodal sandstone with calcite as cement and feldspar replacement.

B. 58% terrigenous; 34$ calcite. Homogeneous, loosely packed, 3% porosity, unoriented. Bimodal means are .15 mm and .75 mm, both moderately sorted. Submature.

C. Mineral Composition.

1. Terrigenous: quartz 58% (all quartz types present; coarse mode, round; fine mode, angular).

2. Orthochemical: calcite, 34%; hematite after "massive" and framboidal pyrite, 4%; chlorite, 1%.

I. 37X, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 21 ft. (Penitente Valley).

II. Medium sandstone (fine, coarse): calcitic bimodal quartzarenite.

III. Brown sandstone.

IV. Actually calcite forms 60% of rock, but 14% is replacement of framework feldspar(?). The calcite matrix is micritic. The lower formation-upper formation boundary. Very good coarse, fine bimodality.

I. 38X, Mississippian, upper Arroyo Penasco, Taos County, New Mexico, Rio Grande de Rancho Valley, 22 ft. into section (Penitente Valley).

II. Sandy micrite; sand is very fine, perhaps a deflation product; grades into pelecypod biomicrite (40X).

III. Dark gray limestone; sandy.

I. 82, Precambrian, Embudo Granite, Taos County, New Mexico, faulted Ponce de Leon Springs, underlying Arroyo Penasco.

II. Alkali feldspar granite.

III. Pink, coarsely crystalline.

IV. Microcline (sericitized), 10.0 mm crystals; quartz, 3.0 mm; muscovite; biotite.

I. 84, Mississippian, Arroyo Penasco, base of unit 6 ft. above PE contact, Ponce de Leon Springs, Taos County, New Mexico; from a region that is heavily faulted.

II. Granular medium-coarse sandstone: siliceous calcitic illitic submature quartzarenite.

III. Megascopic Properties: well-indurated; a limonite-stained, gray-green-brown mottled sandstone: laminated-zones of medium-coarse, poorly sorted regions separated by linear zones of coarse, poorly sorted regions; quartz grains are obviously major framework grain; matrix difficult to determine megascopically.

IV. Microscopic Descriptions

A. Brief summary: This rock is a pebbly, granular medium-coarse sandstone with the grains separated into two types of crude bands, one of medium size and the other of coarse size. It is a quartz-arenite with several % feldspar and a few grains of ultrastable minerals. The specimen contains quartz cement, an illite/chlorite authigenic matrix (pore fill), slightly ferroan calcite replacing the feld-spar and filling the remainder of space not filled by clay, quartz, and hematite after framboidal pyrite. The most unusual feature is the occurrence of silt-sized apatite crystals that are ubiquitous in the clay matrix throughout the slide. Most sedimentary apatite is usually cryptocrystalline and associated with bones and teeth.

B. Texture

1. Fundamental end-members

a. % terrigenous - 78-79% ± 2.8%
b. % allochemical -
c. % orthochemical - 21-22% ± 2.8%
d. main rock group: terrigenous rock.

2. Fabric

a. General homogeneity: poorly segregated into bands of coarse-medium grains.

b. Packing: many of the quartz grains "touch" vis a vis overgrowths but there is a noticeable degree of pressure solution and grain indentation. The apatite grains float in the matrix; so, if they are original detrital constituents then orthochemical development has displaced them, <u>but they are authigenic</u>.

c. Porosity before and after cementation:

before - 22%
after - 0%-1%

d. no orientation observed

3. Grain Size

a. Entire sediment: median .6 mm or .75 ϕ
range .125 mm-5mm or 3mm- (-2.3 ϕ)
16-84% range .3 mm - 1.3 mm
1.75 ϕ - (-.35ϕ)

sorting $\frac{1.75\phi - (-.35\phi)}{2} = 1$

poorly sorted

Sediment is polymodal.

b. Gravel fraction: comprises 5% of framework grains, most of which are in the -1.0 ϕ to -2 ϕ range (the largest particle in thin section being 5.0 mm).

c. Sand fraction: comprises 95% of framework grains, ranging from 3ϕ to -1 ϕ
median .85 ϕ
sorting .95 = poorly

d. Mud:

e. Textural name: pebbly, granular coarse sandstone.

4. Grain shape

a. Idiomorphism: no idiomorphism in clastic grains.

b. Sphericity: range .25-1
average .7

c. Roundness: ranged from 3-6 ϱ with average about 4 ϱ. As with sphericity, roundness values of a specific value seem to have little relation to grain size.

5. Textural Maturity: The rock is submature with the clay present being either infiltered or authigenic. The apatite in the .01-.025 mm range is authigenic.

6. The original quartz overgrowth bond is the most pronounced and probably the most effective of the cements. Authigenic chlorite and illite along with calcite are secondary cements; and much of the calcite is replacement. There are patches of hematite which also serve as bonds, albeit minor.

C. Mineral Composition.

1. Terrigenous Minerals

a. Quartz

1. quartz
2. identification obvious
3. percentage present: 98-99% ± 1.2% of framework by point count
4. occurrence: evenly distributed throughout slide
5. no physical orientation
6. grain size of mineral: practically that of sediment etc.
7. idiomorphism: as above
8. average sphericity: as above
9. average roundness: as above
10. etching, etc: Some quartz grains indent others; there is some pressure solution and contact by overgrwoths. Etching is not apparent.
11. Overgrowths are visible on most grains.
12.19.
20. Inclusions
    a. bubbles - number varies greatly from grain to grain; some vein quartz possess many bubbles mostly in trains or tracks; some possess or contain very few, but all contain some. These bubbles are the most abundant inclusion.
    b. dust - as with bubbles, occurs randomly in grain or in trails. The number, again varies from grain to grain.
    c. tourmaline - rare
    d. ilmenite - rare
    e. zircon - rare
    f. muscovite - rare
    g. rutile - as needles in some grains

21. alteration not noticeable
22. Definition or varietites within the species (stretched quartzite in Rf category):
    - Most of the quartz has semicomposite or very undulose* extinction and is rather bubbly indicating that it is probably vein quartz; metamorphic origin is then implied (bolstered by extreme undulosities).
    - A small percentage has low undulosity and fewer bubbles indicating common quartz.
    - I'm including stretched metaquartzite here since it comprises a small %: there is one grain in the middle of slide, round, 1.5 mm - a beautiful specimen.
    - Much is composite.
23. Antipathies
24. The quartz is undergoing pressure solution.
25. The straight extinction, semicomposite nature undulosities, and the presence of stretched metaquartzites indicate a mixed plutonic-metamorphic source. The size of some of the stretched metaquartzite indicates that source area and site of deposition were rather close (Blatt) probably within 10 or so miles. Common quartz indicates probable intrusive sources in the area. So the source was multiple - predominantly metamorphic with some intrusions. (Since granite underlies the sediment, close proximity of intrusives not even moot).

b. RF - metaquartzite placed in quartz (there may be enough present to justify calling it a "lithic" quartzarenite).

c. none

d. Feldspar

1. microcline or potassium feldspar (orthoclase) (in minor amounts)
2. optical ("tartan" pattern)
3. percentage present in section: 1-2% ± by point count (The original amount was probably higher, but calcite has, in some cases, replaced the feldspar entirely). The grains range from about .25 mm (2ø) to 1.5 mm (-.6ø) with the average being .77 mm (2.5ø).
4. Feldspar grains tend to group in coarser grained regions, in this case more in the

*Boëhme lamellae present

middle of this section where the two bands of coarse grained particles are. This probably occurs from sorting.

5. No physical orientation.
6. See 3. The amount is so small that statistical analysis is almost impractical. If the calcite were mostly replacement, and the calcite patches that appear to be originally feldspar grains are counted as such, then the rock would be a subarkose rather than a quartzarenite.
7. No idiomorphism.
8. Alteration too advanced to estimate sphericity.
9. Alteration too advanced to estimate roundness.
10. No overgrowths apparent.

11.-19.

20. Inclusions: calcite replacement obfuscates any good view on inclusions.
21. None of the feldspars are fresh. All are being or have been replaced by calcite. The larger grains probably more resistant or still extant because of their size. The alteration is obviously epigenetic (feldspars transformed to calcites probably would not be transported as such). However, in the granite beneath, some of the feldspars are undergoing carbonate replacement, but this is probably part of the same process that is producing the alteration in their clastic counterparts.
22. The feldspars are all alkali. Most are microcline, but some could be orthoclase, although orientation may give this latter appearance.
23. Again, the feldspars tend to congregate sic with their coarse brothers, that is, there has been a sorting that has now produced not only regions with grains of different size but regions of different composition - the finer-grained regions being mainly quartz with apatite laden authigenic clay and coarser-grained regions that are quartz-feldspar-calcite-rich.
24. Again the feldspars are being assaulted by calcite. I believe most of the calcite to be replacement.
25. The feldspar is coarse grained and similar in composition to the underlying granite. Before calcite replacement there appears

to have been no alteration. So the feldspars probably were derived locally. Begging the question,* the region based on paleogeography was within 10°-20° of the equator. The area then probably was humid at times and feldspars could not have survived distant transport unaltered.

e. mica-trace observed (1M muscovite)

f. rock fragments-stretched metaquartzite, laced under quartz

g. zircon - angular to well rounded; .08 mm; only a scant trace

h. rutile - round; .08 mm; scant trace

i. tourmaline - round; .2 mm; green

2. Allochemical Grains

3. Orthochemical Minerals

a. Quartz

1. quartz
2. optical identification
3. 6% ± 1.3% by point count
4. Most grains possess quartz overgrowths. Of course, some overgrowths are more pronounced on some grains than others.
5. syntaxial to mother grain
6.
7. no euhedral crystal terminations
8. sphericity
9. roundness
10. The overgrowths are present on most grains except at points of original grain contact. Growth was eventually stopped and clay and calcite filled remaining pore space. Overgrowths do not appear to be etched. In some cases the overgrowths merge.
11. Quartz grains are nucei.

12.-19.

20. Inclusions

a. identity

1. bubbles - most bubble trains don't pass through org. Strain primarily predepositional.

*of grain condition to yield provenance conditions

2. dust - tr.
3. apatite (see later description)
4. clay - tr.

21. no discernible alteration
22. variation within species: none
23. affinities and antipathies: none observed
24. chemical age relations: Apatite appears to be included in some overgrowths; so possibly apatite before quartz before illite and chlorite before calcite and pyrite.
25. derivation: Silica-rich stratal solutions (pegmatites, hydrothermal activity in area).

b. Apatite

1. apatite
2. identified by optical methods and a hurried x-ray diffraction analysis:

   the crystals are hexagonal (euhedral)
   low birefringence
   w index of refraction -1.63
   uniaxial (-)
   clear-light green, slightly pleochroic
3. percentage:

   1% by point count
4. Occurrence in slide: appears most of the time in the clay-filled pores throughout entire slide. Some pores contain many crystals and other pores only one or two. Appears included in some quartz overgrowths and calcite cement. In the slide, it is so ubiquitous that it may have precipitated early in the diagenetic history when pore space was at a maximum. (Also inclusions in overgrowths support this). More on this later.
5. no physical orientation
6. grain size:

   range: .0075-.025 mm (5Ø to 7Ø or v.f. to med (7Ø) - (5.3Ø) silt range)

   The small size naturally makes optical identification and other analyses very difficult.

7. idiomorphism: The crystals are examples of "ideal" idiomorphism, that is, they are euhedral, indicating that there were no obstacles blocking crystal growth. The

crystals are almost equidimensional: the length of the crystals is about that of the hexagonal (w) cross-section.

8. sphericity
9. roundness
10. The crystals are not etched; the crystal outlines are very strongly delineated showing no signs of dissolution. The crystals are so small that growth of other diagenetic materials either enclosed them or pushed them aside.
11. no nuclei

12.-19.

20. inclusions: none
21. The apatite appears extremely stable; there is no evidence of alteration.
22. only one variety: the only distinction being size
23. There do not appear to be any affinities or antipathies.
24. Chemical and age relations with other minerals: Here we get to the nut of the problem. One gets the impression from several features that apatite was the first authigenic product: its euhedral nature; its apparent inclusion in quartz overgrowths; its appearance in all the pores throughout the slide, as if the fluid from which the apatites precipitated flowed through pores that were free of any other material. It is possible these observations and conclusions are erroneous. More research is needed to ascertain the precipitation conditions necessary. Now it appears that solutions rich in calcium and phosphorous flowed along the PE-sedimentary igneous contact and into the formation. Whether the fluid was hot, the Eh and Ph conditions, and again the actual sequence of diagenetic events will be researched more exhaustively. But up till now, the mode of occurrence at this locality is unique, with the apatite not belying its Greek derivation - "I deceive".
25. source of detrital material

c. Illite

1. illite - a clear to light greenish brown lineated mass in plane light; birefringence that of muscovite with lower birefringent

patches, which are probably chlorite.

2. identified by x-ray diffraction and optical properties
3. amount in present: 5% ± 1.5% by point count (difficult to ascertain because some appears mixed with chlorite).
4. Distributed throughout the slide rather uniformly as a pore lining and fill.
5. Physical orientation: no apparent orientation.

6. Grain size: zones of concentrically colored clay, forming "sheaths" of authigenic clay fibers which are probably composed of probably even smaller particles beyond the resolution of 500X. The fibers or sheaths reach up to .125 mm in length.
7. poor idiomorphic development
8. not relevant
9. not relevant
10. Etching is difficult to ascertain. The illite's relation to apatite is the most important feature. Observation indicates that clay growth displaced or "carried" apatites into the various pore areas. The apatites are embedded in the clay, not appearing to have grown "in situ". Such an occurrence might be indicated by apatite crystals disrupting fibers. But again the size of both constituents obstructs accurate interpretation. SEM scans should solve some of these problems.
11. no nuclei for illite

12.-19. not applicable

20. Inclusions: apatite crystals as above.
21. Illite is undergoing no alteration. The illite is a post-depositional product.
22. The illite is probably a mixture of 1M and 1Md illite, that is, it is a variety of authigenic illite and more disorganized in illite (more on this in later discussions of clay types). There is some 2M illite but this is probably detrital. Much of this from x-ray. Also, the illite appears mixed with chlorite, and mixed-layer illite-chlorite is a possibility.
23. The illite occurs as pore lining and filling throughout the slide. No apparent antipathies or affinities.
24. Age relations:

1. apatite?
2. quartz
3. illite-chlorite
4. calcite and hematite (pyrite)

25. Source:

d. Calcite (slightly ferroan)

1. ferroan calcite
2. identified optically, by staining and x-ray
3. % in slide 5.5 ± 1.6% by point count.
4. Occurs more in areas where feldspar occurs, viz., it is replacing or has replaced feldspar, although it is also a pore fill. This means, since the slide is segregated into medium-coarse zones and the feldspar is coarse, that the calcite occurs more in certain linear zones where there is feldspar to be replaced or has been replaced.
5. The orientation of calcite varies from area to area, but each distinct area has same orientation (coarse spar areas).
6. Grain size: varies according to feldspar grain size or pore size to be filled.
7. No idiomorphism apparent: shape controlled by replacement feldspar grain or cavity (pore).
8.
9.
10. Again, appears to conform to feldspar shape or pore shape. If a pore fill, its relation to apatite is similar to illite's. That is, the apatite appears as inclusions in cavity filling being "carried" or displaced by calcite growth.
11. Feldspar are nuclei for calcite replacement.

12.-19. not essential

20. Inclusions: generally, if replacement, no inclusions are present, but if a pore fill, pyrite hematite and apatite are present. The pyrite was framboidal. Most is now all hematite. This pyrite was probably a co-precipitation product with the calcite. Later discussion on pyrite.
21. The calcite, which is slightly ferroan, is post-depositional. Evidence, being its spatial relation to illite and quartz and stages of feldspar replacement.
22. The calcite falls into two categories:
    a. replacement: relatively free of pyrite; large areas of spar that do have relict

feldspar grain shape; also no apatite inclusions; almost non-ferroan.

b. pore fill: more ferroan; pyrite hematite; "smaller"; apatite inclusions.

23. Antipathies and affinities: as observed in 22.
24. Age relations:
    1. apatite
    2. quartz
    3. clay
    4 calcite and pyrite
25. detrital

e. Chlorite

1. chlorite
2. identified by optical properties and x-ray.
3. Exact amount difficult to estimate, but this amount is very small compared to illite, probably about 1%.
4. Occurs usually with illite or as rare isolated groups of flakes-throughout slide.
5. random orientation
6. Some flakes have crustalized up to about .025-.030 mm (replacement chlorite).
7. Identifiable flakes are idiomorphic.
8. Sphericity
9. Roundness
10. Etching
11.
12.-19.
20. Inclusions
21. Chlorite is epigenetic.
22. Two types:

    a. One occurs as clay, that is, as a pore fill with illite. This chlorite is often difficult to see in the petrographic microscope (1) because of inability to separate from illite and (2) the small amount present. Possibly there exists a transition mixed layer illite-chlorite. This occurrence is very likely though very difficult to document even with x-ray and SEM.
    b. The second type appears to be the product of chloritization of feldspar(?) or quartz(?) in some areas. Its occurrence is minor, but best documents the presence of chlorite in the rock. It is out of the clay matrix and "embedded" in quartz

overgrowths and forms the measurable needles or flakes. Coprecipitate with quartz?

23. Affinities and antipathies: the chlorite (both types) probably formed after quartz cementation but before calcite and pyrite, although minor chloritization could have occurred almost anytime.

24.-25.

f. Iron oxides - hematite after framboidal pyrite, massive hematite after pyrite, pervasive limonite stain, etc.

1. hematite
2. identified by optical properties
3. % present 2 ± .9% with hematite after framboidal pyrite comprising the largest fraction.
4. Occurs relatively evenly throughout slide with occasional concentrations or pockets of hematite afp's (after framboidal pyrites).
5. no common physical orientation
6. average hematite aft .01 mm with average of less than .002 mm to about .025 mm.
7. idiomorphism
8. sphericity
9. roundness
10. No apparent etching: the framboids appear as raisins in a pudding with calcite as the major medium (they do appear in clay matrix in very small amounts).
11.

12.-19.

20. inclusions
21. All the hematite is epigenetic, most being an alteration of pyrite framboids.
22. Varieties:
    1. hematite after pyrite framboids
    2. massive hematite after pyrite
    3. hematite/limonite stain (outcrop weathering)
    4. hematite "infiltration: rim on some grains and in matrix (apparently after quartz overgrowths but before clay) - probably iron-stained clay.
23. Affinities and antipathies: framboids concentrated in and around calcite.
24. Age relations:
    1. apatite
    2. quartz

3. a clay-rich hematite rim
4. clay
5. calcite and pyrite (hematite) with minor chloritization after or with quartz sometimes.

The calcite (weakly ferroan) and pyrite (organic matter)probably both precipitated out of basic, reducing waters rich in organic material and $CaCO_3$ organic matter pyrite hematite.

25.

g. tr. of unaltered organic material ("allochem")

D. Structures, etc.

1. The basal unit is crudely segregated into bands from 1 to 2 cm of about the same grain size: coarse, medium coarse.

2. Minor jointing.

3. Limonite stain due to outcrop weathering; some calcite dissolved from pores.

E. Interpretation and Paragenesis

1. Source area

a. Geology - some quartz is very undulose, semi-composite, composite, and stretched metamorphic, thus indicating a metamorphic source. A large amount of common quartz is present, as well as feldspar. The feldspar is microcline and if the altered patches of calcite represent original feldspar, the rock would be on the border of quartzarenite/subarkose. The feldspar is very similar to the underlying PE basement. So the geology included metamorphic rocks with metamorphic quartz types and vein quartz. Common quartz and feldspar indicate igneous intrusives, and the various heavy minerals and apatite indicate pegmatites.

b. Relief - most of the quartz grains are: round but angular ones present; coarse; and the feldspar grains probably fresh upon burial. This indicates several, seemingly poosing views to me. The fact that the quartz is stretched, undulose and composite yet unbroken indicates short transport distance. The feldspars were deposited fresh, or rather not extremely weathered upon erosion. This again indicates short transport distance. The feldspar type speaks for a local source; the upshot is that if locally derived, extreme relief is not required to explain coarseness and feldspar freshness. Probably a monadnock-type terrain existed, the crystalline "knobs" sticking out above a Precambrian crystalline peneplained regolith. A shallow sea could then inundate the plain at times yet portions of crustal line islands would be subaerially exposed.

c. The feldspar, if only deposited after short transport, yield little information on climate. Even in a humid environment rapid weathering and burial yield fresh feldspars. At the time of erosion and deposition (early Mississippian) the area was located within about 10^{o} of the equator. Such an area, then, probably experienced monsoonal type climates with rapid fluctuations in fluidity, temperature, and tides (if basin edge). The rock, because of apparent local origin, would yield no weathering indicators except that no mafics associated with metamorphic or rocks are left. Some of the hematite could be the weathering residium of mafics.

d. local transport

2. Depositional area

a. part of beach-braided stream area
b. The water was probably shallow being of storm, tidal, and "fluvial" "character". The currents varied in strength, but strong currents were the rule with a schizohaline environment (due to seasonal fluctuations) and rapid burial. This place was probably not a good place to live.

3. Diagenetic and Post-diagenetic changes

a. Age relations and mode of origin of authigenic constituents: this has been discussed previously but in summary a tentative list:

1. apatite - no trace from outcrop within 1/2 mile; probably due to local chemistry of

waters at contact or pegmatite.
2. quartz - acid, "cool" water
3. iron-rich clay solutions rich in K^+, Silica, Fe^{++}; Mg^{++}
4. clays
5. calcite and pyrite (organic matter) reducing and basic H_2O
6. outcrop weathering of hematite.

F. Economic importance

1. no mineral economic importance
2. apatite occurrence very unusual

I. 85, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 3 ft. into section.

II. Fine sandstone: siliceous submature quartzarenite.

III. Red-green sandstone; mud cracks.

IV. A. Slightly porous siliceous sandstone; porosity due to leached feldspars?

B. 83% terrigenous; 13% quartz cement; slightly laminated; quartz obscures packing and grain shape, 3% porosity, unoriented. Mean grain size is .25 mm; range, .06 mm to 1.0 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 83% (straight, undulose; semicomposite).

2. Orthochemical: quartz 13%; hematite after framboidal pyrite, tr.

I. 86, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 4 ft. into section.

II. Medium sandstone: illitic, siliceous slightly bimodal submature quartzarenite.

III. Light green sandstone; laminated; hematite stain.

IV. A. A slightly bimodal sandstone with authigenic apatite.

Some embaying.

B. 91% terrigenous; 4% illite, 2% quartz cement. Laminated, moderate packing, no porosity, -noriented. Mean mode sizes, .1 mm and .5 mm; coarse mode poorly sorted, fine mode moderately sorted; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 91% (undulose; subangular); zircon, tr.; tourmaline, tr.; rutile, tr.

2. Orthochemical: illite 4%; quartz 2%; hematite after framboidal pyrite, 3%; apatite, tr.

I. 87, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 6 ft. into section.

II. Fine sandstone: siliceous slightly bimodal submature quartzarenite.

III. Dark green sandstone with pale streaks.

IV. A. Slightly bimodal siliceous sandstone.

B. 88% terrigenous; 8% quartz cement. Homogeneous, moderately packed, 3% porosity, unoriented. Bimodal means, .1 mm and .4 mm, modes being moderately sorted; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 88% (undulose mostly, some composite, semicomposite, and straight; subangular); zircon, tr.

2. Orthochemical: quartz, 8%; hematite after pyrite, 1%; tr. of illite.

I. 88, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 8 ft. into section.

II. Fine-medium sandstone: siliceous, calcitic submature quartzarenite.

III. Light green sandstone with pale streaks.

IV. A. A slightly laminated siliceous calcitic sandstone; calcite is poikilotopic.

B. 80% terrigenous; 20% authigenic. Laminated, moderate packing, no porosity, unoriented. Mean grain size is .25 mm; range is .06 to 1.0 mm; poorly sorted fine-medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 80% (all quartz types, most undulose; subangular); zircon and tourmaline, tr.

2. Orthochemical: quartz cement, 11%; illite, 3%; calcite, 5%, poikilotopic; hematite after framboidal pyrite, 1%.

I. 89, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 10 ft. into section.

II. Very fine-coarse: siliceous bimodal submature-mature quartzarenite.

III. Green sandstone with pale streaks.

IV. A. A bimodal laminated quartzarenite.

B. 91% terrigenous; 9% authigenic. Laminated, by grain size, moderate packing, no porosity, unoriented. Mean of modes, .1 mm and .6 mm; both modes well sorted; submature to mature.

C. Mineral Composition.

1. Terrigenous: quartz, 91% (straight, undulose, and semicomposite; subangular).

2. Orthochemical: quartz, 7%; poikilotopic calcite, 1%; hematite after framboidal pyrite, 1%.

I. 90, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 11 ft. into section.

II. Very fine, coarse sandstone: illitic bimodal submature-mature quartzarenite.

III. Unresistant sandstone; hematite stain.

IV. A. A bimodal sandstone. Coarse grains embayed.

B. 78% terrigenous; 14% illite cement. Homogeneous bimodality, moderate packing, no porosity, unoriented. Bimodal means, .1 mm and .5 mm, both moderate-well sorted; submature-mature.

C. Mineral Composition.

1. Terrigenous: quartz, 78% (undulose mainly; coarse mode embayed and rounded; fine mode, subangular, subround), zircon, tourmaline, tr.

2. Orthochemical: illite, 14%; quartz, 3%; hematite after framboidal pyrite; poikilotopic calcite, 2%.

I. 91, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 17 ft. into section.

II. Fine sandstone: siliceous, illitic, calcitic submature quartzarenite.

III. Green sandstone; laminated.

IV. A. Laminated, placered multi-cemented sandstone.

B. 78% terrigenous; 22% authigenic products. Laminated by grain size (.5 mm, .15 mm); moderate packing, 1% porosity, unoriented. Coarse laminae, poorly sorted; fine laminae, well sorted; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 78% (undulose; subangular); zircon, tourmaline in placers, 1%.

2. Orthochemical: quartz, 7%; illite, 7%; poikilotopic calcite, 4%; hematite, 3%.

I. 92, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 13 ft. into section.

II. Fine sandstone: calcitic siliceous slightly bimodal submature quartzarenite.

III. Gray-green sandstone.

IV. A. A slightly bimodal sandstone with poikilotopic calcite cement; embayed coarse grains.

B. 79% terrigenous; 10% calcite. Homogeneous, loose to moderate packing, no porosity, unoriented. Grain size mean, .25 mm; range, .06 mm to 1.0 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous; quartz, 79% (straight, undulose, semicomposite; subangular); tourmaline, zircon, tr.

2. Orthochemical: poikilotopic calcite, 10%; quartz, 6%; illite clay, 3%; hematite after pyrite, 2%.

I. 93, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 15 ft. into section.

II. Fine sandstone: siliceous illitic hematitic submature quartzarenite.

III. Green sandstone with pink streaks.

IV. A. Fine sandstone; mud cracks.

B. 86% terrigenous; 14% authigenic. Slightly laminated, by grain size; moderate packing, no porosity, unoriented. Mean grain size is .2 mm; range, .06 mm to 1.0 mm; poorly sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 86% (undulose; subangular); zircon, tr.

2. Orthochemical: quartz, 5%; illite, 5%; hematite, 4%.

I. 94, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 16 ft. into section.

II. Fine, coarse sandstone: siliceous bimodal submature-mature quartzarenite.

III. Light maroon; limonite stain.

IV. A. A siliceous laminated bimodal sandstone. Fine, fine-coarse segregation. Rounded under overgrowths.

B. 82% terrigenous; 13% quartz cement. Laminated, packing obscured; no porosity, unoriented. Mean of modes, .125 mm and .5 mm; moderate sorting in modes; submature in the modes.

C. Mineral Composition.

1. Terrigenous: quartz, 82% (undulose, round); zircon, tr.

2. Orthochemical: quartz cement 13%; illite, 4%; hematite after framboidal pyrite.

I. 95, Mississippian, upper Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, at boundary beginning upper portion, 20 ft. into section.

II. Sandy micrite.

III. Dark gray sandy limestone.

I. 96, Mississippian, upper Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 24 ft. into section.

II. Sandy micrite.

III. Dark gray limestone.

I. 97, Mississippian, Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 27 ft. into section.

II. Medium sandstone; calcitic siliceous submature quartzarenite.

III. White sandstone.

IV. A. Interfinger of lower formation; sandstone with poikilotopic and replacement calcite.

B. 65% terrigenous; 25% calcite, 5% quartz, 5% illite and chlorite. Homogeneous, loose packing, no porosity, unoriented. Mean grain size is .5 mm; range, .06 to 1.5 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 65% (straight, undulose, semicomposite; subangular through round); chert, tr.; feldspar, replaced.

2. Orthochemical: calcite, 25%; quartz, 5%; illite, 5%; chlorite, tr.; hematite.

I. 98, Mississippian, Arroyo Penasco, Taos County, New Mexico, faulted Ponce de Leon Springs, 31 ft. into section.

II. Sandy sparite or fine sandstone; calcitic submature quartzarenite; 50% terrigenous - 50% authigenic.

III. White-gray mottled sandstone; unresistant.

IV. An interfinger of lower portion; medium crystalline calcite cement and replacement calcite; authigenic euhedral quartz with euhedral internal shadows; length-slow chalcedony rosettes; massive hematite after pyrite.

I. FS2, Precambrian, Ortega Metasedimentary unit, Taos County, New Mexico, faulted Rio Pueblo Valley, underlying Arroyo Penasco (creekside).

II. Microcline, quartz, muscovite; microcline sericitized; quartz, .1 mm to 2 mm; foliation defined by muscovite; some biotite. Mean quartz size .1 mm.

III. Green, foliated, very resistant basement.

I. 123, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, base of section (creekside).

II. Pebbly granular, medium sandstone: illitic chloritic bimodal submature quartzarenite.

III. Maculose sandstone with green matrix and white blebs.

IV. A. A slightly bimodal sandstone, with grains rounded, embayed, and griked by solution. Both modes embayed. Some hematitic clay coats.

B. 84% terrigenous; 9% illite, 5% chlorite, 2% quartz. Uniformly bimodal, loose packing, no porosity, unoriented. Bimodal means, 1.5 mm and .4 mm; submature in both modes.

C. Mineral Composition.

1. Terrigenous: quartz, 84% (undulose, straight, semicomposite; subround); zircon, tr.; rutile, tr.; tourmaline, tr.; hematitic clay coat, tr.

2. Orthochemical: illite, 9% (some could be infiltered); chlorite, 5%, most replacement; quartz overgrowth and fracture fill, 2%; hematite, tr.

I. 124, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 3 ft. into section (creekside).

II. Granular fine, coarse sandstone: illitic chloritic bimodal submature quartzarenite.

III. Mottled sandstone in light and dark green.

IV. A. A slightly bimodal sandstone similar to 123. Embayed and griked.

B. 74% terrigenous; 22%, mostly authigenic clays. Homogeneous bimodality, loose packing, no porosity, unoriented. Bimodal means, .25 mm and 1.5 mm; moderate to poorly sorted; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 74% (undulose; straight, semicomposite; subround to round by solution); zircon, tr.; some clay(?) - detrital rims(?).

2. Orthochemical: illite, 11%; chlorite, 11%; quartz, 3%; limonite, 1%.

I. 125, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 6 ft. into section (creekside).

II. Very fine-coarse sandstone: illitic chloritic submature quartzarenite.

III. Mottled sandstone in light and dark green.

IV. Very similar to 124; embayed and griked. Bimodality, .1 mm and .75-1.0 mm; 75% framework quartz; 15% illite; 6% chlorite, clays probably mostly authigenic.

I. 126, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 7 ft. into section (creekside).

II. Pebbly granular medium sandstone: chloritic illitic siliceous slightly bimodal submature quartzarenite.

III. Mottled sandstone in light and dark green.

IV. Very similar to 125; 78% framework quartz; 11% chlorite; 5% illite; 6% quartz. Slightly bimodal. Embayed and griked. Iron oxides. Quartz range, .1 mm to 5.0 mm. Modes as above, the smaller grains possibly derived from underlying Ortega metasedimentary unit. Much chlorite is replacement.

I. 127, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 9 ft. into section (creekside).

II. Medium sandstone: chloritic illitic siliceous submature quartzarenite.

III. Gray sandstone with slickensides.

IV. Bimodality not apparent as in above. Very similar in other aspects; 80% quartz framework; 7% authigenic illite; 9% chlorite; 4% quartz cement. Poorly sorted. Mean, .4 mm; range, .06 mm to 3.0 mm; embayed and griked; zircons rounded.

I. 128, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo, 11 ft. into section (creekside).

II. Medium sandstone: chloritic illitic submature quartz-arenite.

III. Mottled sandstone in light and dark green.

IV. A. Slightly embayed quartz; bimodality nonexistent.

B. 87% terrigenous; 13% authigenic. Homogeneous, some pressure solution, no porosity, unoriented. Mean grain size is .5 mm; range, .13 mm to 2.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 87% (straight, undulose, semicomposite; subround, griking not pronounced).

2. Orthochemical: chlorite, 5%, replacing feldspars (?); illite, 5%; quartz, 3%; limonite and hematite intermixed with clay.

I. 129, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 13 ft. into section (creekside).

II. Medium sandstone: illitic hematitic submature quartz-arenite.

III. Mottled sandstone in maroon and green.

IV. A. Sandstone embayed and griked and heavily stained and cemented with hematite. Clays identity is somewhat obscured by hematite; some hematite forms rims around grains.

B. 76% terrigenous; 24% orthochemical - illite, chlorite, hematite. Homogeneous, some pressure solution, no porosity, unoriented. Mean grain size is .4 mm; range, .06 mm to 2.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigneous: quartz, 76% (undulose, semicomposite; subround); hematite and some clay(?).

2. Orthochemical: illite, 12% (?); chlorite, 4%; quartz, 4%; hematite, 4%, some being framboidal after pyrite; celestite (?) replaced by quartz.

I. 130, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 15 ft. into section (creekside).

II. Medium-very coarse sandstone: illitic siliceous bimodal submature quartzarenite.

III. Mottled sandstone is light and dark green.

IV. A. A bimodal sandstone, embayed and griked.

B. 87% terrigenous; 13% authigenic. Homogeneous bimodality, moderately packed, no porosity, unoriented. Mean of modes, .3 mm and 1.0 mm; moderately sorted in modes; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 87% (undulose, semicomposite; subround; zircon, tr.

2. Orthochemical: illite, 6%; quartz overgrowth and fracture fill, 4%; hematite, 1%.

I. 131, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley.

II. Fine, corase sandstone: illitic siliceous bimodal submature quartzarenite.

III. Light green; limonite stain.

IV. Similar to 130; laminated; 80% quart framework; 2% mixed chlorite and illite; 2% hematite; mean of modes .125 mm and 1.0 mm; submature in modes. Quartz fracture fill and overgrowths celestite replaced by quartz.

I. 132, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 19 ft. into section.

II. Fine, coarse sandstone: illitic bimodal submature quartzarenite.

III. Mottled sandstone in maroon and green; unresistant; fractured.

IV. Similar to 131; 81% quartz framework; 13% illite, some of which is grain replacement; 4% quartz; 3% limonite and hematite, some in iron-clay rims; mean of modes .125 mm and .75 mm; submature.

I. 133, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 21 ft, into section (creekside).

II. Granular very coarse sandstone: siliceous chloritic submature quartzarenite.

III. Dark green sandstone.

IV. A. Very coarse sandstone with much composite and semicomposite quartz.

B. 86% terrigenous; 14% authigenic. Homogeneous, pressure solution, no porosity, unoriented. Mean grain size 1.0 mm; range, .1 mm to 4.0 mm; poorly sorted very coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz 86% (semicomposite, composite; subround to round).

2. Orthochemical: quartz, 9%; chlorite, 5%; hematite, tr.

I. 134, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 25 ft. into section (creekside).

II. Fine sandstone; siliceous mature-supermature quartzarenite.

III. Maculose sandstone; green matrix, white blebs.

IV. A. A siliceous mature quartzarenite; overgrowths hide some roundness values and pressure solution.

B. 88% terrigenous; 12% orthochemical. Homogeneous, no porosity, unoriented. Mean grain size .2 mm; range, .125 mm to .5 mm. Well sorted fine sandstone; mature-supermature.

C. Mineral Composition.

1. Terrigenous: quartz, 88% (undulose; round); muscovite, tr.; tourmaline, tr.; rutile, tr.

2. Orthochemical: quartz, 78%; chlorite, 3%; illite, 1%.

I. 135, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 27 ft. into section (creekside).

II. Medium sandstone: siliceous submature quartzarenite.

III. Green resistant sandstone.

IV. A. Laminated, mottled sandstone. Some embaying.

B. 90% terrigenous; 10% orthochemical; clay-free siliceous zones, some pressure solution, no porosity, unoriented. Mean grain size is .4 mm; range, .06 mm to 1.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 90% (undulose, semicomposite; subround(?).

2. Orthochemical: quartz, 6%; illite, 2%; chlorite, 2%.

I. 136, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 28 ft. into section (creekside).

II. Medium sandstone: siliceous submature quartzarenite.

III. Mottled light green and white.

IV. A. Mottled due to clay-free siliceous zones throughout clay-siliceous zones; celestite and anhydrite inclusions(?); inclusions mark some original grain boundaries.

B. 86% terrigenous; 10% quartz cement. Laminated and mottled, packing appears loose, no porosity, unoriented. Mean grain size, .4 mm; range is .06 mm to 2 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 86% (undulose, semicomposite, stretched composite; round(?)).

2. Orthochemical: quartz, 10%; illite, 4%; hematite, tr., chlorite, tr., some grain solution (embaying).

I. 137, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 31 ft. into section (creekside).

II. Medium sandstone: siliceous submature quartzarenite.

III. Light gray; laminated; limonite stain.

IV. A. Very similar to 136; 86% quartz framework; 11% quartz cement; 2% illite cement; limonite; hematite; zircon, rutile, tourmaline; some embaying.

I. 138, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Peublo Valley, 33 ft. into section (creekside).

II. Medium sandstone: illitic siliceous submature quartzarenite.

III. White sandstone.

IV. A. Laminated illitic sandstone; some embaying and griking.

B. 81% terrigenous; 11% illite, 8% quartz. Laminated, some pressure solution, no porosity, unoriented. Mean grain size is .4 mm; range, .06 mm to 1.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 81% (undulose, stretched composite, semicomposite; subangular); some iron-stained clay rims; muscovite, tr.

2. Orthochemical: illite, 11%; quartz, 8%.

I. 139, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 36 ft. into section (creekside).

II. Fine, coarse sandstone: illitic bimodal submature-mature quartzarenite.

III. Olive sandstone.

IV. A. Bimodal illitic quartzarenite; grains delineated by light iron-clay rims (after deposition).

B. 85% terrigenous; 13% illitic cement. Laminated bimodality-coarse-fine-coarse; some pressure solution (very slight), no porosity, unoriented. Mean of modes, .13 mm and .7 mm; fine mode well sorted, mature; coarse mode, moderately sorted, submature.

C. Mineral Composition.

1. Terrigenous: quartz, 85% (undulose; fine, subround; coarse, well rounded); some early hematitic clay; muscovite, tr.

2. Orthochemical: illite, 13%; quartz, 1%; chlorite, 1%; hematite and limonite.

I. 140, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 39 ft. into section (creekside).

II. Fine, coarse sandstone; chloritic siliceous bimodal submature-supermature quartzarenite.

III. Dark green sandstone.

IV. A. Beautiful bimodality. Circumgranular chlorite-limonite rims then pore quartz cement, illite, and chlorite. Rims after deposition.

B. 87% terrigenous; 13% orthochemical. Bimodal, very little pressure solution, no porosity, unoriented. Mean of modes, .15 mm and 1.0 mm; fine mode, moderately sorted, coarse mode, well sorted; submature, supermature.

C. Mineral Composition.

1. Terrigenous: quartz, 87% (undulose, semicomposite, composite; fine mode, subround; coarse

mode, well rounded).

2. Orthochemical: chlorite, 6%; quartz, 2%; limonite-stained throughout; illite, tr.

I. 141, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 44 ft. into section (creekside).

II. Medium sandstone: hematitic-chloritic siliceous mature-supermature quartzarenite.

III. Maculose sandstone: green and white.

IV. A. Mature-supermature iron-clay, quartz cemented sandstone.

B. 86% terrigenous; 14% orthochemical. Mottling due to clay-free siliceous zones, moderate packing, no porosity, unoriented. Mean grain size is .35 mm, range, .13 mm to .5 mm; well sorted medium sandstone; mature-supermature.

C. Mineral Composition.

1. Terrigenous: quartz, 86% (undulose, semicomposite, composite; subround-well rounded); rutile; tourmaline.

2. Orthochemical: hematitic chlorite, 9%; quartz, 5%.

I. 142, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 46 ft. into section (creekside).

II. Medium sandstone: siliceous submature quartzarenite.

III. Maculose sandstone; white and green.

IV. A. Mottled sandstone.

B. 86% terrigenous; 13% quartz overgrowths. Slightly laminated and mottled, packing obscured; no porosity, unoriented. Mean grain size is .35 mm; range from .13 mm to 2.0 mm; poorly sorted medium sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 86% (undulose; subround(?)); zircon, rutile.

2. Orthochemical: quartz, 13%; illite, 1%; hematite, 1%.

I. 143, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 48 ft. into section (creekside).

II. Granular coarse sandstone: siliceous submature quartzarenite.

III. Light green sandstone.

IV. A. Sandstone with schistose metamorphic rock fragments.

B. 86% terrigenous; 14% siliceous. Homogeneous; moderate pressure solution, no porosity, unoriented. Mean grain size, 1.0 mm; range, .13 mm to 3.0 mm; poorly sorted coarse grained sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 86% (semicomposite, stretched composite, composite; subround-round), muscovite.

2. Orthochemical: quartz, 14%; trace of hematite.

I. 144, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Pueblo Valley, 51 ft. and last of section (creekside).

II. Pebbly granular coarse sandstone; siliceous chloritic hematitic quartzarenite.

III. Green sandstone with white pebbles.

IV. A. Pebbly sandstone.

B. 83% terrigenous; 14% orthochemical. Clay-free zones, moderate packing, 3% porosity, unoriented. Mean grain size is 1.0 mm; range, .13 mm to 5 mm; poorly sorted pebbly coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 83% (as in 143).

2. Orthochemical: quartz, 5%; chlorite, 5%; hematite, 4%.

I. 153, Precambrian, Embudo Granite, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, underlying Arroyo Penasco (Beaver Ridge).

II. Alkali feldspar granite.

III. Pink, coarse crystals in dark green "matrix".

IV. Microcline, sericitized, 10.0 mm crystals; quartz, 2.0 mm crystal; biotite.

I. 154, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, at base (Beaver Ridge).

II. Medium sandstone: siliceous submature-mature quartzarenite.

III. Green sandstone with pale streaks.

IV. A. Siliceous sandstone; some grains delineated by thin clay layer under overgrowths.

B. 74% terrigenous; 23% orthochemical. Homogeneous, pressure solution, 3% porosity, unoriented. Mean grain size, .4 mm,; rnage, .13 mm to 2 mm; moderately sorted medium sandstone; submature-mature.

C. Mineral Composition.

1. Terrigenous: 74%, quartz (straight, undulose, semicomposite; round(?); tourmaline.

2. Orthochemical: quartz, 19%; hematitic chlorite 4%.

I. 155, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 1 ft. above base (Beaver Ridge).

II. Medium sandstone: siliceous mature-supermature quartz-arenite.

III. Light green sandstone.

IV. A. Better sorted than 154; overgrowths obscure roundness; porous; carbonate grains.

B. 72% terrigenous; 22% orthochemical. Homogeneous, 6% porosity, unoriented. Mean grain size, .35 mm; range, .13 mm to 1.0 mm; well sorted medium sandstone; mature-supermature.

C. Mineral Composition.

1. Terrigenous: quartz, 72% (undulose, semicomposite, straight, stretched composite; round(?)); muscovite.

2. Orthochemical: quartz, 16%; chlorite, 2%; hematitic clay, 3%; illite, 1%.

I. 156, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 3 ft. into section (Beaver Ridge).

II. Granular coarse sandstone: siliceous hematitic-chloritic(?) submature quartzarenite.

III. Green sandstone with white pebbles.

IV. A. Porous hematite siliceous sandstone; porosity due to grain leaching(?); chert.

B. 77% terrigenous; 16% authigenic(?). Mottled, some pressure solution, 8% porosity, unoriented. Mean grain size is .75 mm; range, .13 mm to 4 mm; poorly sorted granular coarse sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 77% (undulose, semicomposite, stretched composite, straight; subround): muscovite.

2. Orthochemical: quartz, 8%; hematitic-chlorite (?), 8%.

I. 157, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 4 ft. into section (Beaver Ridge).

II. Fine sandstone: hematitic-chloritic(?) siliceous mature-supermature quartzarenite.

III. Light green sandstone; unresistant; fractured.

IV. A. Mature sandstone near mud cracks.

B. 82% terrigenous; about 18% orthochemical. Homogeneous, some grain interpenetration, no porosity, unoriented. Mean grain size, .15 mm; range, .06 mm to 5 mm; moderate-well sorted fine sandstone; mature-supermature.

C. Mineral Composition.

1. Terrigenous: quartz, 87% (undulose, straight, semicomposite; round(?)); tourmaline; rutile; zircon.

2. Orthochemical: hematitic chlorite, 8%; chlorite, 8%; hematite, 3%.

I. 158, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 5 ft. into section (Beaver Ridge).

II. Fine-medium sandstone: siliceous hematitic-argillaceous submature quartzarenite.

III. Light green sandstone, unresistant.

IV. Except for poorer sorting, identical to 157. Mud cracks.

I. 159, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 6 ft. into section (Beaver Ridge).

II. Medium sandstone: chert-cemented, siliceous, hematitic submature quartzarenite.

III. Resistant dark gray chert region in brown sandstone.

IV. A. Chert-cemented zone intercalated between siliceous, hematite zone, which is in turn between siliceous zone. Packing much looser in chert zone (very little grain contact). Some grain interpenetration in other zones. Overgrowths in all zones. Embayed grains.

B. 70% terrigenous; 22% chert. Linear zones as above; packing as above; no porosity, unoriented. Mean grain size is .35 mm; range, .06 mm to 1.0 mm; poorly to moderately sorted; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 70% (undulose, straight, semicomposite; round); .35 mm tourmaline, round.

2. Orthochemical: chert, 22%; quartz, 6%; hematitic clay, 2%.

I. 160, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, lateral to 159 (Beaver Ridge).

II. Fine sandstone: siliceous, chert-cemented supermature quartzarenite.

III. Dark gray chert cemented region in grown sandstone.

IV. A. Supermature sandstone with chert, siliceous zone and siliceous hematite zone. 13% chert, 9% quartz in one zone, 19% quartz, 3% hematitic clay in other. Not much grain interpenetration.

B. 78% terrigenous; 22% orthochemical; segregated as above; packing as above; no porosity, unoriented. Mean grain size .2 mm; range, .06 mm to .5 mm; well sorted fine sandstone; supermature.

C. Mineral Composition.

1. Terrigenous: 78% quartz (straight, undulose; well-rounded); rutile.

2. Orthochemical: as above.

I. 161, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, lateral to 160 (Beaver Ridge).

II. Fine sandstone: chert-cemented, siliceous hematitic-clay cemented supermature sandstone.

III. As in 160.

IV. Identical to 160 except a lamina with silt, fine bimodality. Some grains clay replaced and leached (feldspar).

I. 162, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 9 ft. into section (Beaver Ridge).

II. Fine sandstone: siliceous illitic submature quartzarenite.

III. Light green sandstone; unresistant.

IV. A. Placered sandstone (zircon, rutile, tourmaline).

B. 74% terrigenous; 26% orthochemical. Homogeneous, some interpenetration, no porosity, unoriented. Mean grain size .25 mm; range, .06 mm to 1 mm; moderately sorted fine sandstone; submature.

C. Mineral Composition.

1. Terrigenous: quartz, 74% (undulose, straight, semicomposite; subround(?).

2. Orthochemical: quartz, illite, 9%.

I. 163, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, lateral to 162 (Beaver Ridge).

II. Identical to 162.

I. 164, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 10 ft. into section (Beaver Ridge).

II. Fine-medium sandstone: siliceous illitic submature quartzarenite.

III. Green sandstone.

IV. Similar to 163 but coarser and poorly sorted; 2% porosity.

I. 165, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 12 ft. into section (Beaver Ridge).

II. Fine-medium sandstone; siliceous illite submature quartzarenite.

III. Light green sandstone; unresistant.

IV. Similar to 163; placered with tourmalines; 2 % porosity.

I. 166, Missisippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 13 ft. into section (Beaver Ridge).

II. Fine sandstone: siliceous submature quartzarenite.

III. Brown sandstone with green streaks.

IV. Less clay than above units, an iron-stained clay - 2%. Quartz cement 15%; tourmaline and zircon.

I. 167, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 14 ft. into section (Beaver Ridge).

II. Identical to 166 but no hematite; clay is illite.

III. Dark green sandstone.

I. 168, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 16 ft. into section (Beaver Ridge).

II. Fine sandstone: siliceous illitic submature quartzarenite.

III. Light gray sandstone.

IV. Similar to above units; 86% framework; 12% quartz cement; 2% illite.

I. 169, Mississippian, lower Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho, 17 ft. into section (Beaver Ridge).

II. Granular fine, very coarse sandstone: calcitic chloritic bimodal chert-bearing mature quartzarenite.

III. Light gray sandstone; unresistant.

IV. A. Chert, chalcedony replacing poikilotopic calcite, cement in a bimodal fine, very coarse sandstone. Coarse grains round, embayed and griked.

B. 88% terrigenous; 12% orthochemical. Homogeneous, little interpenetration of grains, no porosity, unoriented. Bimodal mean grain sizes are .15 mm and 1.5 mm; coarse mode well sorted; fine mode, moderately sorted; mature.

C. Mineral Composition.

1. Terrigenous: 85% quartz (undulose, straight, semicomposite, composite; round, subround); chert, 3%; reworked calcite (?).

2. Orthochemical: calcite, 6%; chlorite, 6%; length slow chalcedony, tr.; chert, tr. Euhedral quartz overgrowths also present.

I. 170, Geologic Age - Mississippian; from Arroyo Penasco formation, Taos County, 2 miles south of Talpa; much faulting.

II. Granular coarse sandstone: calcitic submature quartzarenite.

II. Megascopic Properties: well-indurated, but relative to underlying sandstone, unresistant; gray-grown; iron oxides probably weather to give brown color; unfossiliferous; sorting appears moderate to poor; coarse grained; quartz is the main constitutent and CO_3 material probably accounts for its relative softness.

IV. Microscopic Description.

A. Summary: a quartzarenite with 30% CO_3, most of which appears to be a replacement product of several mineral types. The rock has a host of accessory clastic minerals (stables, ultrastables, etc.). Framboidal and massive hematite are present as oxidized remnants of pyrite. The clays appear to be authigenic, but minor infiltration is a possibility. The median grain size is . 55 (1Ø) with poor sorting (1).

B. Texture

1. Fundamental end-members

   a. terrigenous materials: 66.5 $\pm$ 3.4%
   b. allochemical materials: 0%
   c. orthochemical: 33.5 $\pm$ 3.4%
   d. main rock group terrigenous

2. Fabric

   a. general homogeneity: homogeneous
   b. packing: Pressure solution is present, i.e., quartz grains interpenetrate occasionally; CO_3 replaced grains usually indented by quartz grains.
   c. porosity before cementation: if CO_3 is not replacement, the Ø would be 33.5%; if instead, the CO_3 is replacement, as much of it seems to be, the original porosity would vary from a minimum of 5% to about 30% depending on the relative amounts of authigenic vs. replacement CO_3. After complete cementation, the Ø is 0.
   d. orientation: none noted

3. Grain size

   a. entire sediment
      median: .5 mm or 1Ø units
      extreme range: .125 mm to 2 mm
      4Ø to -1 Ø units
      16-84% range: .23 mm to 1.04 mm
      2.1 Ø to .05 Ø
      sorting: 1 poor

      The CO_3 replaced grains are smaller than the quartz grains. The CO_3 replacement grains average about .25 mm, the quartz grains about .5 mm.
   b. gravel:
   c. sand: entire sediment
   d. mud:
   e. complete textural name: medium-coarse sandstone

4. Grain shape

   a. The authigenic clay may exhibit idiomorphism - will need for this.
   b. sphericity .5
      range .2 - 1.0
      This property and variation with composition - not noted.
   c. Roundness runs the gamut; a lot of well rounded small grains.

5. Textural maturity: submature.

6. Bonding agents:

   1. calcite
   2. chlorite
   3. quartz
   4. illite
   5. hematite

   effectiveness of bonding from incr. to decr.

C. Mineral Composition.

a. Quartz

   1. quartz
   2. optical and associative identification
   3. 66% $\pm$ 3.4% of rock by point count
   4. uniformly distributed
   5. physical orientation
   6. grain size: see entire sediment
   7. no idiomorphism
   8. sphericity: see B4
   9. roundness: see B4
   10. etching: minor
   11. Overgrowths are present. Probably some overgrowths have been dissolved away. Also the overlap of calcite on the quartz grain hides some overgrowths.

12.-19.

   20. Inclusions

      a. muscovite
      b. bubbles: much in trains
      c. dust
      d. ilmenite
      e. rutile-needles
      f. zircon-idiomorphic
      g. tourmaline
      h. hematite

21. Post-depositional etching of quartz by calcite
22. Varieties
    1. common quartz - very small amount: 4%
    2. undulose: 36%
    3. semicomposite: 40%
    4. composite (much w/musc. incl): 18%
    5. stretched metaquartzite: 2%
23. Affinities and antipathies: composite quartz and semicomposite quartz in lesser amounts seem to be undergoing minor etching and replacement by CO_3. Possibly some of grains that area completely replaced were stretched metaquartzite, but more like feldspars.
24. Quartz - minor post-depositional etching by calcite; also minor replacement by calcite.
25. Derivation: Vein quartz from metamorphic rocks (semicomposite). Composite quartz has much (relative) muscovite; probably from schistose quartzite; metaquartzite from metamorphic region. Much of the undulose quartz is probably metamorphic. Only a minor amount of plutonic. Strain trains do not transgress grain boundaries, so much of stress is predepositional.

b. RFS - see quartz

c. Chert - Only a few grains, some of which are undergoing dissolution and replacement by CO_3 or vice versa. Perhaps, some or many of the CO_3 replacement grains were originally chert. Both overlying and underlying units contain chert. The clastic sediments below contain both authigenic and detrital chert and some of the dolomites and limestones above contain authigenic chert. Chert ranges in size from .25 mm to .5 mm. In any case, chert is reworked.

d. F.S. - a possibility that some CO_3 replacement grains could have been F.S.

e. Mica - again, only a trace, but it (muscovite) occurs throughout the slide, much probably coming from breakdown of composite quartz in which it was originally included. It is problematical, the occurrence of mica in the chlorite matrix. Some is no doubt detrital, but some is probably authigenic.

f. Rfs (rock fragments) - see quartz.

g. Zircon - tr. - angular to subround; .06 mm
h. Tourmaline - green; angular-subround; .07 mm - .28 mm
i. Rutile - trace
j. Clay: There is the possibility of chlorite and illite being detrital infiltration. However, the clays were introduced after quartz overgrowths and after calcite, and, if infiltrated have undergone recrustallization.
k. Iron oxides and iron stained clay: again these products could be detrital, but the framboidal form of the hematite belies this interpretation.
1. Type of rock - quartzarenite

2. Allochemical grains

3. Orthochemical minerals

a. Calcite

1. calcite
2. identified optically and by x-ray and etching
3. 29 $\pm$ 3.1% by point count in rock
4. occurs uniformly through slide
5. no important note on physical orientation
6. grain size of apparent CO_3 replacement grains varies greatly but generally much smaller than median for quartz.
7. Very little, if any, idiomorphism.
8. Roundness and sphericity are reflection os
9. original grain shapes; roundness usually quite high.
10. Etching: slight
11. Most of CO_3 probably replacement

12.-19.

20. Inclusions - some framboidal hematite and dolomite XIs (trace) and minerals it is consuming.
21. The calcite is the "predator" mineral in all cases and is probably all epigenetic.
22. Varieties of calcite
    1. replacement: the dominant type*
    2. pore filler: very little pore space to occupy probably.

    *The replaced minerals can only be guessed: probably some types of quartz, some chert, probably feldspars.
23. Affinities and antipathies: the replacing calcite seemingly favors relatively small grains.

24. The calcite is one of the last, if not last, of the authigenic constituents. The calcite and pyrite probably came in after the initial quartz overgrowths, the clays coming in afterward.
25. The calcite could have come from dissolution of overlying CO_3 strata and its flow through strata, along contacts, and through faults. It is probably not a product precipitated with the clastic grains.

b. Hematite

1. hematite, limonite
2. identified optically
3. 2.5 $\pm$ .9% in slide by point count
4. occurs in patches throughout slide
5. no orientation of note
6. - framboids in clay to very fine silt size range.
   - massive patches of hematite up to .25 mm (some of these patches are still composed of pyrite).

7.-20.

21. Pyrite probably altering to hematite (and to pyrite, perhaps a product of organic reduction).
22. Two types
    - massive (either partially hematite or some pyrite still remaining);
    - framboids - all hematite.
23. Antipathies and affinities: most appear in clay matrix and very little in calcite. This could be evidence for replacement calcite instead of pore fill.
24. Hematite replacing pyrite which may be product of organic reduction or reduction of iron minerals w/SO_4 reduction ($CaSO_4$ in above strata).
25. Derivation as above.

c. Pyrite - see above discussion.

d. Chlorite

1. chlorite
2. ID by optical and x-ray
3. 2$\pm$ .9% by point count
4. uniformly distributed
5. physical orientation of no paramount note
6. grain size: clay size - authigenic
7. if authigenic idiomorphic: SEM shall resolve

8.
9.
10. In places looks as if it may have replaced something.
11.-20.
21. Freshness, etc: came after quartz overgrowths and calcite either as infiltration or more probably precipitation. If a result of infiltration, then pores filled very uniformly and clay is rather "clean", i.e., uniform in size and composition.
22. Varieties: some clay areas seem to have undergone more extensive or complex crystallization, and there exists as an admixture of chlorite and illite.
23.
24. Emplaced after quartz and calcite; its relation with hematite is difficult to determine.
25. The chlorite could be a precipitate of waters rich in Mg^{++} and Fe^{++}, K, Al, and SiO_2 or an infiltration product that underwent some degree of recrystallization. I prefer it as direct precipitate due to flow of stratal fluids. There are enough minerals in the area to produce the right water chemistry.

e. Quartz overgrowths

1. quartz
2. optical identification
3. less than 1%
4. Occurs on many quartz grains when not visible; may be because it has no "dust" to delineate it, or calcite has eaten it, or transgressed its optical boundaries.
5. syntaxial orientation
6.-9.
10. etched by calcite
11. of course, has clastic nuclei
12.-19
20. inclusions: few
21. first authigenic product, now being eaten by calcite
22.
23.
24. as above
25. product of silica-rich acidic waters

f. illite - trace

g. dolomite - trace: dolomite rhombs .01-.02 mm, very few

D. Structures

1. sedimentary structures - non-existent
2. some fractures and joints
3. probably oxidation of iron minerals - product of weathering.

E. Interpretation and Paragenesis

1. Source area: metamorphic: at least 75%, probably 90%
   a. geology: plutonic: 5%-10%
      reworked: 5%-10%

   b. relief: most of clastics locally derived - locally high relief (monadnocks) relative to peneplaned regolith.

   c. climate: grain material gives no clue. If clays were infiltration then temperate and rather dry. But if precipitates of sediments leached above then humid and tropical (if clays precipitated soon after clastic deposition).

   d. length of transport: derived locally: coarse grain size and nature of grains.

2. Depositional area

   a. environment of deposition - with the dearth of sedimentary structures at this stratigraphic level, interpretation is based on grain size, sorting, and associated facies. The section came from a bed that, if a channel, was an extremely wide one. Since associated facies suggest shallow shelf, beach, and wadi type environments, this particular interval probably represents a channel, rather wide, but whether fluvial or tidal, is difficult to say.

   b. The water was shallow with strong ephemeral flows or tides that rapidly buried the sediment, thus preventing reworking and sorting.

3. Diagenetic and post-diagenetic changes

   a. age relations

1. quartz
2. calcite
3. clays

b. effect of intrastratal fluids - probably responsible for all of above

c. effects of post-emergent weathering oxidation of pyrite hematite

F. Economic importance

1. porosity - 0
2. rock offers diagenetic sequence puzzles.

I. 171, Mississippian, Arroyo Penasco, Taos County, New Mexico, faulted Rio Grande de Rancho Valley, 24 ft. (Beaver Ridge).

II. Sandy dedolomitic spar.

III. Dark gray limestone.

IV. Limpid dedolomite (rims limpid). .125 mm; spar is medium crystalline; sand is poorly sorted, medium grained; rounded.

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