THE STRUCTURE AND PETROLOGY OF THE JOHNNY LYON HILLS AREA
COCHISE COUNTY, ARIZONA

Thesis by

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ABSTRACT

The Johnny Lyon Hills area is located in Cochise County in southeastern Arizona. The rocks of the area include a central core of Lower pre-Cambrian igneous and metamorphic rocks surrounded by a complexly faulted and tilted section of Upper pre-Cambrian and Paleozoic strata. Limited exposures of Mesozoic and Tertiary sedimentary and volcanic rocks are present at the north end of the map area. Late Tertiary and Quaternary alluvium almost completely surrounds and overlaps upon the older rocks.

The older pre-Cambrian rocks include a section of more than 9000 feet of generally moderately metamorphosed graywackes, slates and conglomerates of the Pinal schist injected in zones by somewhat younger rhyolite sheets. The original sediments were deposited in a geosyncline whose extent probably included large parts of Arizona, New Mexico and west Texas. During the Mazatzal Revolution the Pinal schist was deformed into northeast-trending, steeply dipping and plunging structures and the entire local section was overturned steeply toward the northwest. The pre-Cambrian Johnny Lyon granodiorite was emplaced as a large epi-tectonic pluton which modified the metamorphic character of part of the Pinal schist. Larsen method determinations indicate an age of about 715 million years for this rock, which is about the minimum age compatible with the geologic relations.

The Laramide orogeny produced numerous major thrust faults in the area involving all rocks older than and including the Lower Cretaceous Bisbee group. Major compression from the southwest and subsequent superimposed thrusting from the southeast and east are indicated. Minimum thrust displacements of more than a mile are clear and the probable displacements are of much greater magnitude. The crystalline core behaved as a single structural unit and probably caused important local divergences from the regional pattern of northeast-trending compressive forces. The massif was rotated as a unit 40 degrees or more about a northwest-trending axis overturning the pre-Cambrian fold axes in the Pinal schist.

Swarms of Late Cretaceous(?) or Early Tertiary(?) lamprophyric dikes cross the Laramide structures and are probably related to the large Texas Canyon stock several miles southeast of the map area. Intermittent high angle faulting, both older and younger than the dikes, has continued since the Laramide orogeny and has been superimposed on the older structures. This steep faulting combined with the fundamental northwesterly Laramide structural grain to produce the northwesterly trends characteristic of the mountain ridges and valleys of the area.

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INTRODUCTION

Purpose and Scope of the Study

Southeastern Arizona has been one of the major sources of copper and other base metals for this country's growth. The Dragoon quadrangle, in which the Johnny Lyon Hills are located, contains a small but active mining district in the Johnson Camp area. Because of the presence of this district, and because of a general policy of increasing the fund of geological knowledge on this important region, the Mineral Deposits Branch of the U. S. Geological Survey created a Little Dragoons project in 1944, under John R. Cooper, to study the areal and economic geology of the quadrangle. Responsibility for completing the study of the Johnny Lyon Hills was given to the writer by Cooper in 1950. The approach to the work has been made by detailed field mapping supplemented by petrographic studies in the laboratory.

The area of pre-alluvial bedrock exposed in the Johnny Lyon Hills is one of the largest in the quadrangle and displays some significant geologic relationships and formations not found elsewhere in the quadrangle or in other parts of southeastern Arizona. Particular attention has been given to the lithology, structure, origin and age of the older pre-Cambrian crystalline rocks, and to the general structure and stratigraphy of the younger pre-Cambrian, Paleozoic, Mesozoic and Cenozoic formations found in the area.

Previous Work

No detailed investigations of this area had been made prior to this study. N. H. Darton (1924, 1933, map sheet 21), made a reconnaissance examination of the area and recognized the presence of Apache group and Paleozoic formations resting upon the older schist. Bryan et al (1934) examined the margin of the area in connection with a study of the ground water resources of the San Pedro River Valley. L. A. Heindl (1952) briefly visited the area during this study and examined the map compilations. The structural interpretations he has published, however, are in part his own.

Field Work

In the summer of 1949, the writer joined the Little Dragoon project to assist in the mapping of the Johnny Lyon Hills area. In 1950, the writer was placed in charge of the field party on the project in the absence of J. R. Cooper, and the mapping of the area was completed during summer field seasons in 1950, 1951 and part of 1952. A total of eleven months was spent in the field.

In addition to the work of the author, contributions to the field mapping were made by Cooper during the summer of 1949, by A. E. Disbrow in 1949 and 1950, by J. MacKallor in 1951, and, briefly, by C. T. Wrucke in 1952. All mapping, except for limited reconnaissance work, was done by plane table and alidade, after the establishment of a triangulation system based upon the control points established for the U. S. Geological Survey topographic map of the Dragoon quadrangle, edition of 1943. Aerial photographs were used in reconnaissance.

GEOGRAPHY

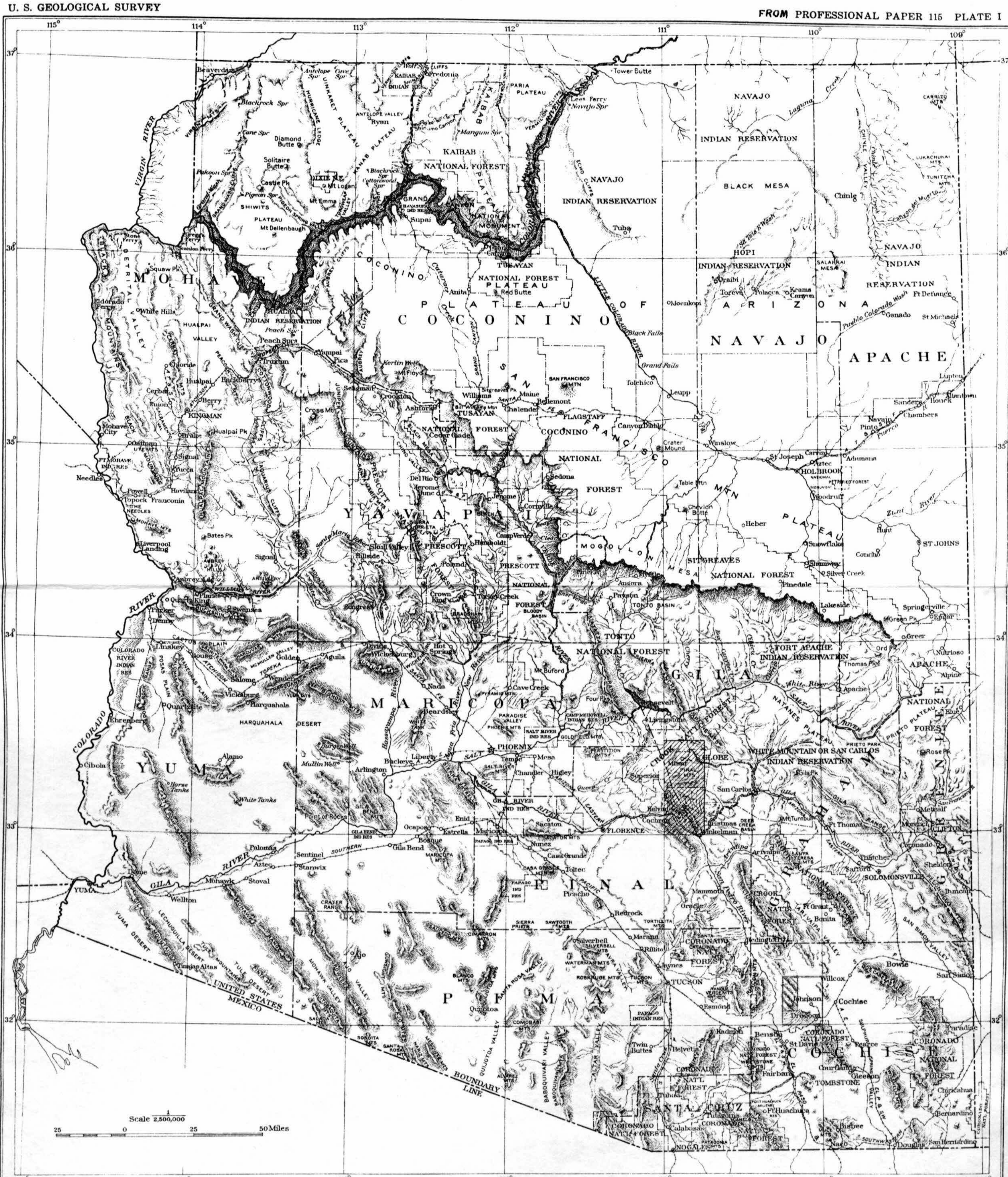
Location of the Map Area

The Johnny Lyon Hills are situated on the western edge of the Dragoon quadrangle in northwestern Cochise County, Arizona (pl. III, IV). They are a group of hills with moderate relief rising on the east side of the north-northwest trending San Pedro River Valley. (See also plate V, a topographic map of the Happy Valley quadrangle, adjacent to the Dragoon quadrangle on the west.) The map area is accessible by graded road from three directions. It may be approached from Tucson to the west via Tanque Verde, Redington and Cascabel, a distance of fifty miles to the edge of the map area on the Willcox road. It may be reached from Benson, on the San Pedro River to the southwest, via Pomerene, a distance of fifteen miles to the Keith Ranch road, or of twenty-two miles to the Willcox-Cascabel road. The third direction of entry is from Willcox, about twenty-two miles to the east. The roads are generally accessible most of the year to ordinary vehicular traffic, and are maintained periodically. However, during the summer rainy season, all of the access roads are usually temporarily closed at least once by the activity of cloud bursts. The Willcox-Cascabel road which crosses the map area, east-west, is the only fairly reliable road in the area.

Most of the other roads are merely access trails developed by local ranchers which take advantage of passable washes or ridges as the weather conditions permit. The only ranch house in the area is that of Mr. M. M. Keith who often has been kind enough to assist the author in traversing the very steep grades of the road to his home.

U. S. GEOLOGICAL SURVEY

FROM PROFESSIONAL PAPER 115 PLATE I



Drawn from General Land Office and U. S. Post Office maps
National forests from latest proclamations (January, 1919)

GENERAL MAP OF ARIZONA

DRAGOON QUADRANGLE showing the Johnny Lyon Hills area

The San Pedro River, whose course is subparallel to and several miles west of the map area, is a major drainage feature of southeastern Arizona, originating in Mexico to the south and trending north-northwest to a junction with the Gila River. The hills trend northwest to the foothills of the Galiuro Mountains. They are separated by a broad high alluviated valley, Allen's Flat (fig. 1), from the Winchester Mountains to the northeast. A major tributary of the San Pedro River, Tres Alamos Wash, separates the Johnny Lyon Hills from the Little Dragoon and Dragoon Mountains to the southeast. Southwest across the San Pedro River Valley and beyond Benson lie the Whetstone Mountains. West, across the river, rise the massive ridges of the Rincon Mountains which shut Tucson from view. Northward the Rincons extend into the even loftier Santa Catalina Mountains whose Mount Lemmon, with an elevation of 9,185 feet, is one of the highest peaks in southern Arizona.

Climate

The climate of the map area is remarkably pleasant and invigorating considering the low latitudes in which it is found. Almost the entire area is above 4,000 feet elevation, and the altitude and summer rains tend to moderate the desert summer high temperatures. The mean annual temperature at Willcox, elevation 4,167 feet, is about 59°F., while at Benson in the bottom of the San Pedro River valley at an elevation of 3,585 feet, the mean annual temperature is about 63°F. At Willcox the extreme maximum temperature over a period of fifteen years was 110°F., but the mean temperature for July is about 80°F. with a daily range of about 30°, assuring cool, restful nights. Southeastern Arizona enjoys 80 to 85 percent of the possible hours of sun-

Figure 1. The southern Johnny Lyon Hills viewed from the Willcox-Cascabel road in Allen's Flat at a distance of eight miles northeast from the hills.

Figure 2. Vertical bluff in consolidated alluvium on the east side of Tres Alamos Wash (foreground). The floor of the wash at this point (SW $\frac{1}{4}$, sec. 33, T. 15 S., R. 21 E.) is interpreted as related to the Aravaipa terrace in the San Pedro River valley.

Figure 1

Figure 2

shine, more than almost any other part of the country. This, plus the low humidity, is in part responsible for an annual evaporation loss of about 80 inches per year.

The annual precipitation in the vicinity of the Johnny Lyon Hills is in the range of 10 to 13 inches, with more than one-third falling in the months of July and August. These summer rains are generally violent downpours, short in duration, in contrast to the longer and more gentle rains of the winter rainy season.

Vegetation

The Johnny Lyon Hills are in a transition zone between the lower Arizona Succulent Desert and the higher Grasslands floral environments. The former environment is best represented on the marginal alluvial aprons around the hills at elevations of 4,000 to 4,500 feet. The succulents include many species of the cacti genera: barrel cactus (*Ferocactus*); hedgehog or strawberry cactus (*Echinocereus*); fishhook or pincushion cactus (*Mammillaria*), prickly pear and cholla cacti (*Opuntia*); less commonly the saguaro cactus (*Carnegiea*); and rarely the reina-de-la-noche, or night-blooming cereus (*Peniocereus*). Other succulents include *Yucca*, sotol (*Dasylirion*) and the century plant and lechugilla (*Agave*). Creosote-bush (*Larrea*), catclaw (*Acacia*), ocotillo (*Fouquieria*), salt bush (*Atriplex*) and palo verde (*Cercidium*) are the more common shrubs. Along the washes mesquite (*Prosopis*), cottonwood, (*Populus*), willow (*Salix*), Arizona walnut (*Juglans*), ironwood (*Olneya*) and sacaton (*Sporobolus*) are common. Many grasses and flowering annual species are also present in the Desert zone.

At higher elevations, above 4,500 feet, grasslands flora is much more common. On The Mesa, for example, several species of grama (Boutelous), muhly (Muhlenbergia), fescue (Festuca) and bear grass (Nolina) spring up rapidly and thickly after the summer rains begin. At these elevations, too, live-oak, manzanita and juniper make rather common appearances while pinyon pine is rarely seen in the area. These are the most productive areas for forage for the cattle that roam the area.

No one who has worked in desert regions such as the Johnny Lyon Hills can fail to be impressed by the wonderful demonstrations of floral vitality and regeneration when the annual rains supply a little moisture. But even in the driest of seasons, the water-storing and phreatophytic characteristics of many of the plants permit them to stay green and to soften what would otherwise be a rather stark landscape.

(For more detailed discussions of the climate and vegetation see, for example, Smith (1930) and Kearney and Peebles (1951).)

PHYSIOGRAPHY

When Ransome (1903, pp. 14-16) first outlined the physiography of Arizona, he cited three major subdivisions: (1) the Colorado Plateau region, in the northern part of the s tate; (2) the Mountain region in a broad northwest-trending belt through the center of the state; and (3) the generally lower Desert region of wide basins and low mountain ranges in the southwestern part of the state.

The Johnny Lyon Hills fall within the Mountain region defined by Ransome, which has also been called the Mexican Highland of the Basin and Range province by Fenneman (1931). They are typical of the mountains of the region in that they are northwest-trending short ridges separated from other similar ranges by high valleys deeply filled with fluviatile and lacustrine conglomerates.

While topographically not as impressive as many of the surrounding mountains, rugged hills in the southern part of the area have a maximum relief of 1,850 feet. The highest elevation is on Sheep Camp Ridge, 5,730 feet, some 2,400 feet above the bed of the San Pedro River in the center of the valley to the west. Both Sheep Camp Ridge and the adjacent Keith Peak, elevation 5,633 feet, have many slopes on which talus has accumulated at an angle of repose greater than 30°. Other prominent elevations in the southern part of the area are Gold Mine Ridge, west of Sheep Camp Ridge, and the Catclaw Hills, southwest of Keith Peak. Javelina Hill and Lechugilla Hill are conspicuous in the southeastern part of the map area. A series of low, dissected hogback ridges trend north-northwest from Lechugilla Hill, and gradually rise in elevation to a culmination in

Rattlesnake Ridge, north of the Willcox-Cascabel road. At the north end of Rattlesnake Ridge, slightly offset, is Kelsey Peak, the highest point north of the road. A series of irregular ridges trends northwest from Kelsey Peak, out of the area.

The entire map area lies within the drainage basin of the San Pedro River. However, two large tributaries of the San Pedro are competing with each other, and with the direct drainage to the river for the area's runoff. On the east side of the Johnny Lyon Hills, Tres Alamos Wash is partly incised (fig. 2) in a rather broad and dissected valley. This wash drains most of the eastern and southern parts of the area. It also gathers runoff from large areas of Allen's Flat and more than half the Little Dragoon Mountain in a drainage basin of almost 150 square miles. In contrast to most of the tributaries of the San Pedro River, Tres Alamos Wash flows in a south-southwest direction between the Johnny Lyon Hills and the Little Dragoon Mountains before swinging west to its junction with the north-flowing San Pedro River.

On the north edge of the map area, the youthful valley of Kelsey Canyon is deeply incised between the Paleozoic ridges to the south and the steep-faced benches of the Galiuro volcanics to the north. The canyon trends west to the San Pedro River, and although it is somewhat circuitious, it nevertheless has a rather steep gradient. The shortest distance from its divide with the Tres Alamos Wash drainage in Allen's Flat, to its junction with the San Pedro River, is about ten miles. Water falling on the Tres Alamos side of the divide must flow more than 35 miles to a junction with the outflow of Kelsey Canyon. As a result the Kelsey Canyon drainage has pirated and will continue to pirate the drainage from Rattlesnake Ridge and Allen's

Flat once tributary to Tres Alamos Wash.

Direct flow to the San Pedro River by smaller washes is also encroaching on the Tres Alamos drainage. Good examples of this can be seen on the west side of Rattlesnake Ridge, north of the Willcox-Cascabel road. Farther south, similar competitions are also taking place in the Catclaw Hills. At one point in the upper part of Dry Tank Wash which flows into Tres Alamos Wash, a vigorously eroding, west-flowing ravine has only twenty-five feet of elevation and 1,000 feet horizontal distance as an obstacle to its capture of the upper square mile of Dry Tank drainage.

Kirk Bryan (1926) has pointed out that in the Quaternary history of the San Pedro Valley there have been several renewed incisions of the river which rather abruptly lowered the base level for its tributaries. The last two of these incisions have not yet been communicated to the upper part of Tres Alamos Wash which therefore is handicapped in the competition for runoff.

Among the most striking physiographic features in the Johnny Lyon Hills are several widespread erosion surfaces of low relief. In the direct drainage to the San Pedro River, a surface locally called The River Slope (figs. 3,4) extends from Rattlesnake Ridge west to the top of dissected bluffs above the river, and from a short distance north of the Cascabel road south to the foot of Sheep Camp Ridge. Within the map area the surface truncates the pre-Cambrian Johnny Lyon granodiorite but it is also continuous westward for two miles or more on Tertiary and Quaternary valley fill. It has an average gradient to the west of about 300 feet per mile on both granitic rock and alluvium. The eastern limit of the surface is an irregular scarp about 150 feet

Figure 3. The upper part of The River Slope seen from the north flank of Sheep Camp Ridge. Most of the visible surface is developed on exposed granodiorite. Kelsey Peak is on the skyline in the center background.

Figure 4. The River Slope and the north end of Sheep Camp Ridge, looking south-southeast from the vicinity of the American mine.

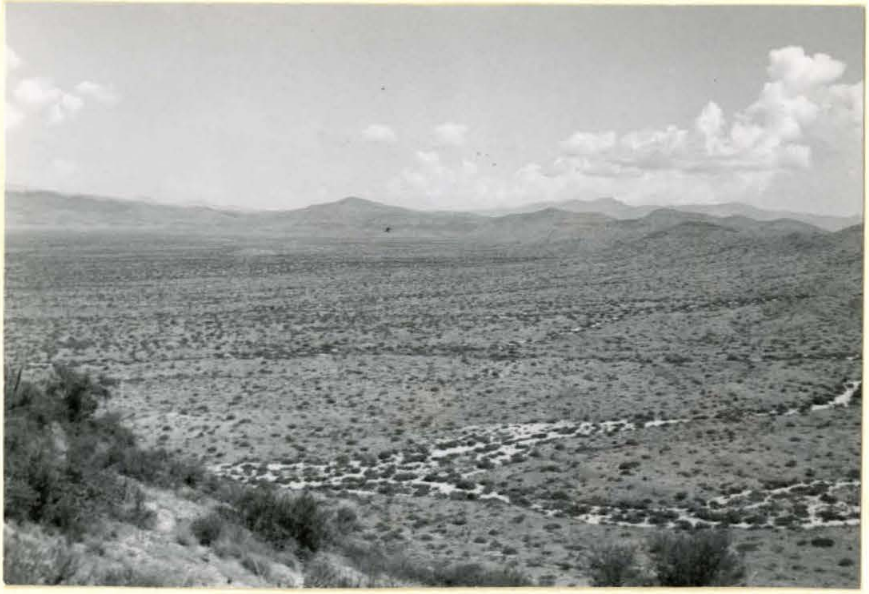


Figure 3

Figure 4

high which is localized along much of its length by a major north trending shear zone in the granodiorite.

Dissection on most of this surface is currently active. Most of the gullies have gentle banks and are rarely more than 5 to 10 feet deep. At the western edge of the surface, repeated incision of the San Pedro river has lowered the base level and has initiated more pronounced dissection. Where the surface is developed on the granodiorite, the igneous rock is deeply weathered to a coarse gruss. Exposures of the bed rock are sufficiently common to permit the mapping of the alluvium contact shown in plate I, within a distance of about 100 feet. Much of the overlying alluvium is an arkosic aggregate derived from the granodiorite and the contact is inconspicuous and difficult to distinguish in some places.

Another prominent surface, called The Mesa, lies in the Tres Alamos Wash drainage east of The River Slope, and truncates the Johnny Lyon granodiorite and Pinal schist. It extends from the Willcox-Cascabel road south to the latitude of Javelina Hill and Sheep Camp Ridge. From the top of the scarp on the west it extends one to two miles eastward before marked dissection starts to break up its continuity. It has an average gradient of about 200 feet per mile to the east.

The relief of this surface is somewhat greater than that of the river slope. A number of resistant formations tend to stand up in low residual ridges as much as 25 feet above the surface. These include silicified lenses in major shear zones in the granodiorite, the contact metamorphic hornfels zone in the Pinal schist, and on the frayed eastern edge, the resistant tilted beds of Pioneer shale and

Bolsa quartzite. Dissection is also more advanced over a greater part of The Mesa than on The River Slope.

The scarp between The River Slope and The Mesa reflects the different local base levels from which the surfaces of erosion were generated. Capture of The Mesa drainage by the more direct drainage of The River Slope is taking place south of the Willcox-Cascabel road.

Another erosion surface truncates the Tertiary and Quaternary alluvium east of Rattlesnake Ridge, on the west side of the Tres Alamos drainage. It has an average gradient of about 150 feet per mile to the east and is moderately dissected over much of its extent.

Remnants of other erosion surfaces can be seen on the dissected alluvial benches on both sides of Tres Alamos Wash in the southeastern part of the map area.

The origin of the various erosion surfaces will not be explored in much detail. Lawson (1915), Bryan (1923, 1925, 1926), Johnson (1932a, b), Davis (1938), Howard (1942) and many others have considered the origin of such uniform surfaces of erosion and transportation at the base of desert mountain ranges. Bryan (1925a, p. 93) has given the name mountain pediment to these surfaces. Lateral planation by streams issuing from the mountains; sheet floods; backwearing of the mountain slopes at constant angles determined by boulder size, nature of rock disintegration and rillwash; base level control of constant, rising or declining alluvial edges; and many other factors have been proposed and considered by students of desert geomorphology.

In the Johnny Lyon Hills, there is local evidence of lateral planation on the surfaces, but the deep weathering, and rill wash observed during rainstorms appear to be more important in the erosion at the base of the steep slopes, in the granodiorite. Further there is a general tendency for the steep slopes above The River Slope surface to maintain a uniform angle of 25°-30°, where outside structural factors do not intervene. The transition from erosion surface to mountain slope is not particularly abrupt but does take place within 100 feet in most places. There is every indication that the erosion surface on The River Slope is continuing to grow headward at the present time. It is concluded that the granitic pediments are forming by backwearing of the mountain slope under the combined influence of boulder control, granular disintegration and rill wash. Lateral planation appears to be more important in the regrading of the erosion surface out from the base of the mountains.

Regrading and stripping are characteristic of all the erosion surfaces in the Johnny Lyon Hills. Isolated residuals of older alluvium capping low interfluvial areas can be found on all of the surfaces. The position of the edge of the alluvial apron on the granitic surfaces is clearly determined by erosion in most places. The surfaces on which the alluvium rests appear to be as regular as the present subaerial surfaces. In some cases, such as at the north end of The River Slope, renewed dissection appears to be responsible for the stripping. Elsewhere on The River Slope, dissection is so slight that the stripping appears to be more of a lateral shaving rather than a down cutting action. Whether such regrading is a normal late stage "policing" action of erosion on a pediment, or whether it implies that the present surface is for the most part a stripped suballuvial bench of an earlier geomorphic cycle has not been determined.

Bryan (1926, 1934) has recognized two principal levels of pediments in the San Pedro Valley. The older and higher surface has been called the Tombstone pediment surface and is best developed at the base of the Dragoon Mountains, north of Tombstone. After a rejuvenation of the San Pedro River, a new, lower surface of erosion was developed. This surface is called the Whetstone pediment for its prominence along the northeast face of that range. The geomorphic cycle was once again interrupted and the river cut a new terrace of limited lateral extent to which Bryan gave the name Arivaipa terrace. According to Bryan (1925b, p. 342) a new period of downcutting commenced at the mouth of the river in 1883, and by 1892 a trench had been cut 125 miles upstream. At present this trench is 10 to 25 feet deep along most of the river.

The pediments cannot be followed continuously from the type localities, but by reference to the Arivaipa terrace, The River Slope pediment of the Johnny Lyon Hills is correlated with the Whetstone pediment. The downcutting which preceded the development of the Arivaipa terrace appears to have been developed in Tres Alamos Wash (fig. 2) as far north as the junction with Thompson Wash. Beyond that point there is no basis for correlation with the San Pedro drainage (fig. 5). This makes it difficult to place The Mesa surface, or the surfaces to the north in Allen's Flat, in Bryan's classification because base level of upper Tres Alamos Wash has not been affected by the more recent fluctuations in the San Pedro Valley.

Figure 5. Tres Alamos Wash and the southeastern side of Javelina Hill, viewed from the northeast. The down cutting which preceded the development of the Aravaipa terrace on the San Pedro River is not recorded in Tres Alamos Wash at this place.

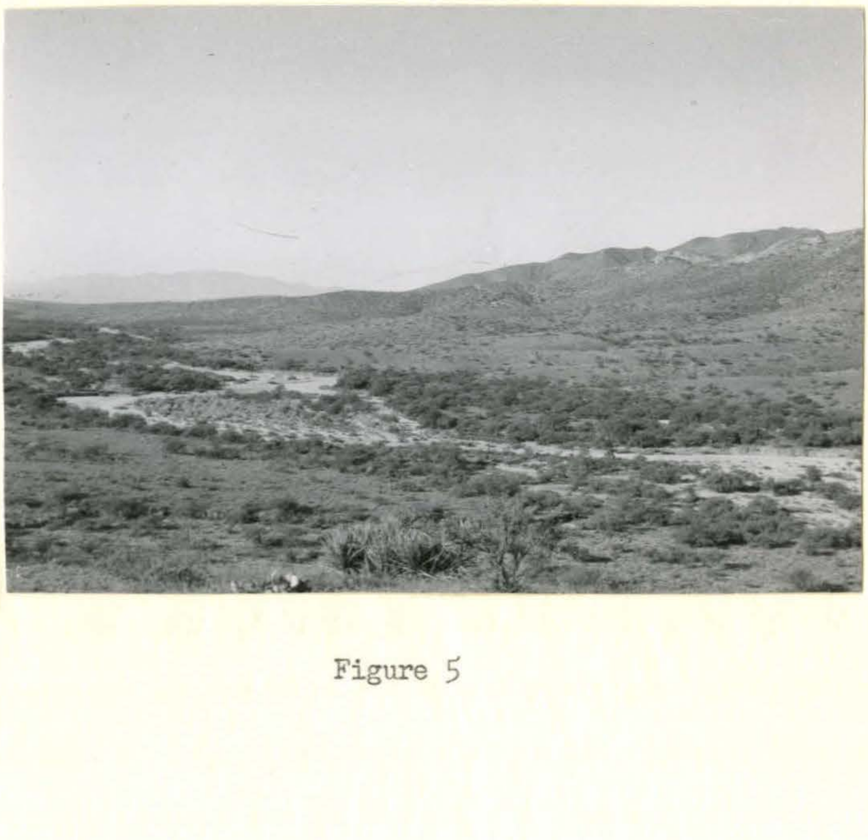


Figure 5

GEOLOGIC FORMATIONS

Introduction

The rocks of the Johnny Lyon Hills area resemble the geologic formations in many of the mountain ranges of southeastern Arizona in their diversity of lithology, age and origin. They include:

(1) A thick lower pre-Cambrian complex of deformed metasedimentary and metavolcanic rocks intruded by a large granodiorite pluton, and with numerous minor injections of rhyolite sheets and dikes. The complex is truncated by a very regular erosion surface probably equivalent to the Ep-Archean unconformity of the Grand Canyon.

(2) Erosional remnants of two lower formations of the upper pre-Cambrian Apache group and an associated diabase sheet resting in angular unconformity on the older complex. The maximum thickness is about six hundred feet with an overall relief of one or two hundred feet on the upper erosion surface.

(3) A thick section of Paleozoic sedimentary rocks in which the Ordovician and Silurian are the only systems unrepresented. Although no recognized Permian rocks are exposed, they are very probably present but concealed by Quaternary alluvium. The formations are nearly parallel to the underlying Apache group.

(4) Triassic(?) or Jurassic(?) volcanic breccias, tuffs, and conglomerates and Cretaceous sedimentary rocks whose total thicknesses are obscured by faulting and alluvium.

(5) Swarms of lamprophyre dikes and sills probably of late Cretaceous or early Tertiary age. The dikes crosscut Laramide thrust faults

involving most of the older rock formations.

(6) Lower(?) or middle (?) Tertiary conglomerates and volcanics (with associated dikes) representing the edge of a great volcanic pile found in the Galiuro and Winchester Mountains to the north and northeast of the map area.

(7) Upper Tertiary and Quaternary fanglomerates, alluvial sands and fine-grained lacustrine beds which blanket the valleys and lap up on the hills.

A composite, generalized section of the rocks of the area is given in table 1.

Pioneering contributions to the stratigraphy of southeastern Arizona were made by Dumble (1902), Ransome (1903, 1904, 1915, 1916, 1919), Lindgren (1905) and Darton (1925). Their efforts defined the framework of formations upon which subsequent geologic mapping has been based. Important contributions which have clarified or added details to the regional stratigraphy, have been made by Stoyanow (1936, 1943, 1949), McKee (1951), and many others.

The stratigraphic column in the Johnny Lyon Hills was reconstructed from the local geologic relations and from regional stratigraphic correlations. Much comprehensive work on the stratigraphy of the Dragoon quadrangle (in which the map area lies) has been done by John R. Cooper (1950a, b), in the course of his study of the Little Dragoon Mountains and the Johnson Camp mining district. Detailed descriptions of Cooper's work on the upper Paleozoic rocks in collaboration with James Gilluly and J. S. Williams of the U. S. Geological Survey appear in a recent professional paper (Gilluly, et al, 1954) of that organization. The stratigraphic descriptions and discussions

Table 1

Summary Section of Rocks Exposed in the Johnny Lyon Hills Area

Age		Formation	Lithology and Remarks	Thickness (feet)
Quaternary and Tertiary (Pliocene)		Alluvium	Unconsolidated, or only partly consolidated conglomerates, sands and fine-grained lake deposits.	0-600 +
		Unconformity		
Tertiary		Galiuro volcanics	Interbedded pyroclastics, conglomerates, and flows of basalt, andesite, latite and rhyolite. Some rhyolite dikes.	1000 +
Tertiary		Three Links conglomerate	Partly consolidated coarse conglomerates and sands derived from both sedimentary and volcanic rocks.	500-700
		Unconformity		
Late Cretaceous or Early (?) Tertiary		Lamprophyre dikes and sills	Thin tabular bodies up to 3 miles in lateral extent which cut across the Laramide structural features.	
		Unconformity		
Lower Cretaceous	Bisbee group	Morita-Cintura formations, undifferentiated	Interbedded sandstones and shales.	200 +
Lower Cretaceous	Bisbee group	Glance conglomerate	Coarse limestone conglomerate, tightly cemented.	200-400 +
		Unconformity		

Table 1 (Con't)

Age		Formation	Lithology and Remarks	Thickness (feet)
Jurassic or Triassic		Walnut Gap volcanics	Andesitic and dacitic pyroclastic breccias, tuffs and conglomerates.	500-1000
		Unconformity		
Pennsylvanian (Probably including concealed Permian strata)	Naco group	Earp formation, lower member	Interbedded slates, siltstones and thin limestones.	300 +
	Naco group	Horquilla formation	Thin- to thick-bedded gray fossiliferous limestones with numerous thin shale interbeds and occasional tan dolomites.	1300 +
		Disconformity		
Lower Pennsylvanian or Upper Mississippian		Black Prince formation	Thin- to thick-bedded pink-gray limestones with a 10 to 30 foot basal purple shale member.	170
		Disconformity		
Lower Mississippian		Escabrosa limestone	Interbedded gray limestones and dolomites, massive, crinoidal, cherty.	600-700
		Disconformity		
Upper Devonian		Martin formation	Thick-bedded tan and gray dolomites with reddish shale and sandstone units in middle and in upper 30 feet.	205-240
		Disconformity		

Table 1 (Con't)

Age	Formation	Lithology and Remarks	Thickness (feet)
Middle and Upper Cambrian	Abrigo formation	Lower member, olive shales with minor limestones and sandstones, 390-475 feet, capped by quartzite 1-45 feet; middle member, sandy thin-bedded, nodular limestones, 260 feet; upper member, sandy dolomites, limestones and sandstones, 150 feet.	740-800
Middle Cambrian	Bolsa quartzite	Thick-bedded red brown to tan and white quartzites, generally with conglomerate at the base.	400-480
	Unconformity		
Upper Pre-Cambrian	Diabase sill	Altered gray-green diabase sill, weathering red-brown. Thickness varies as result of overlying erosional unconformity.	0-250 +
Apache group	Pioneer shale	Purple and brown thin-bedded argillites with basal gray quartzites.	280-300
Apache group	Scanlan conglomerate	Interbeds of angular pebble conglomerates in a gray feldspathic quartzite matrix.	0-25
	Unconformity		
Lower Pre-Cambrian	Johnny Lyon granodiorite	Coarse-grained, pink weathering granodiorite pluton which intrudes the Pinal schist.	
	Pinal schist	Great thickness of metamorphosed and folded graywackes, subgraywackes, slates and conglomerates, intruded by two generations of rhyolite sheets and sills.	9000 +

which follow are extensions of the Little Dragoon Mountains stratigraphy, particularly with reference to the Paleozoic and Mesozoic rocks.

Some of the formations are present within the map area only in fault blocks, and are obscured by the Tertiary and Quaternary alluvium. Complete sections of these formations are not available, but summary descriptions are given.

Lower Pre-Cambrian System

Pinal schist and associated rhyolite sheets

Introduction

Ransome (1903, p. 23) gave the name Pinal schis<u>ts</u> to the crystalline schists abundantly present in the Pinal Mountains. These rocks previously had been called "Arizonian slates" by Blake (1883, p. 238-239), but Ransome's usage had been accepted generally and Pinal schis<u>t</u> has been applied subsequently to the pre-Cambrian schist of southeastern Arizona. In the type locality, the formation was described as laminated gray sericitic schists with interbedded quartzose grits of sedimentary origin and occasional amphibolite-schist representing basic eruptive rocks. They are strongly foliated approximately parallel to the bedding, nearly vertical in dip, and intricately intruded by many granitic bodies. The younger Apache group is separated from them by a profound unconformity.

In the Johnny Lyon Hills area, almost all of the exposures of pre-Cambrian schists are found south of the Willcox-Cascabel road in an irregular arcuate belt between the Johnny Lyon granodiorite which intrudes it, and the younger rocks which either overlap it in sedimentary unconformity or have been thrust upon it. The belt is south to southwesterly in trend, about nine miles long, and almost two miles in maximum width. At its northern end, the belt is a narrow wedge with its apex about a quarter of a mile south of the Willcox-Cascabel road. Four and a half miles to the south, at Javelina Hill, it is more than a mile and a half wide. It then passes southwest under Keith Peak to the edge of the map area, with a number of structural offsets. In the marginal parts of the adjacent Johnny Lyon granodiorite pluton, inclusions of schist up to 1,500 feet long and 500 feet wide are found. South of Keith Peak, recent dissection of the Tertiary and Quaternary alluvial deposits has opened isolated windows through which are seen additional outcrops of Pinal schist, as well as younger formations.

In addition to the principal belt, a small block of Pinal schist is enclosed in the thrust plates in the vicinity of the American mine, in the northwest corner of the area.

Northeast of Keith Peak, the Mesa erosion surface extends across the schists to the base of Javelina Hill, and to the low ridges of Pioneer shale and Bolsa quartzite. Dissection has developed local relief up to 50 feet along the main tributaries to Tres Alamos Wash. On the flanks of Javelina Hill a relief of several hundred feet has been developed. The nearly vertical, relatively uncrumpled beds of metasediments (fig. 6) crop out in excellent exposures almost everywhere.

Southwest of Keith Peak, the Pinal schist is exposed in a series of low, but rugged hills with relief of 500 to 600 feet. Exposures are equally good in this area, except where the overlapping alluvium

Figure 6. Typical interbedded slates and graywackes of the Pinal schist exposed in a shallow ravine north of Javelina Hill. Note the joint surfaces nearly normal to the bedding.

Figure 7. Alternating slates and graywacke beds in the Pinal schist in a scoured gulley bottom west of the Catclaw Hills. The knife blade points to the top of the beds as indicated by graded bedding in each graywacke-slate pair. Note the divergent bedding and cleavage.

Figure 6

Figure 7

has not yet been stripped during the current episode of dissection.

Lithology of the Pinal schist

General

The Pinal schist in the Johnny Lyon Hills area consists of a great thickness of metasedimentary rocks into which younger rhyolite sheets have been intruded. In addition, amphibolite inclusions in the Johnny Lyon granodiorite apparently represent relics of former basaltic flows once contained in a part of the Pinal schist section now removed from observation by magmatic engulfment, erosion or sedimentary overlap. During a major pre-Cambrian deformation, the section of rocks was steeply tilted, and was subjected to a generally low-rank intensity of dynamothermal metamorphism. The subsequent intrusion of a pre-Cambrian granodiorite pluton transformed numerous inclusions and the adjacent margins of the schist into contact hornfels rocks. Late Mesozoic or early Tertiary orogeny has modified the pre-Cambrian structural relations to some degree, and has locally sheared the Pinal into cataclastic phases.

Despite the several metamorphic stages in its history, the Pinal schist in the Johnny Lyon Hills commonly has much of its original lithologic character well-preserved. Information on the original lithologic composition, structures and textures can be obtained with considerable success, permitting description of the rocks in terms of their original character and providing data not available in most other exposures of the Pinal schist in southern Arizona.

Most of the Pinal schist represents clastic sedimentary rocks derived from terranes rich in volcanic rocks but containing also quartzites, slates, and granitic rocks. Impure flaggy sandstones of graywacke type were graded vertically to, or interbedded with, siltstones and shales in monotonous cyclic repetition. (See figure 7.) They were uniformly well bedded with individual beds ranging from less than one inch to three or four feet in thickness. Locally, massive thick-bedded sandstones without shale interbeds, or equivalent units of sandstone-free shales accumulated to thicknesses of 10 to 100 feet and these units were laterally gradational into the mixed lithologies. Rather uncommonly, conglomerates of small pebbles and granules accumulated in thicknesses up to 50 or 75 feet. They were largely devoid of bedding and were lenticular in form. Seldom did they extend more than a few hundred feet laterally without decreasing in grain size and grading into sandstone.

The cyclical nature of the vertical variations in lithology produced a great uniformity in the composite section. There were no distinctive individual lithologic units representing widespread changes in sedimentation conditions. The accumulation of sediments followed a simple pattern consistent over much time and space, which is still well-preserved and is revealed now by the induration and tilting which deformation has produced.

Metamorphosed conglomerates

Coarse clastic rocks are uncommon in the metasedimentary sequence of the Pinal schist. They are restricted to lenses of fine-pebble and granule conglomerate which grade laterally into finer sediments within relatively short distances. Bedding is poorly developed and the foliation is expressed moderately, weakly or not at all.

The conglomerates are gray to dark gray with coarse grains comprising up to 75 percent by volume of the rock in a poorly sorted finer-grained matrix. The coarse grains range from 2 to 15 mm in major diameter. Their shapes are of two types: (1) slightly flattened, ellipsoidal, subrounded to well-rounded grains, commonly quartz, quartzite, chert, or feldspar; and (2) strongly flattened and somewhat stretched lens-like grains (fig. 8a, b) commonly quartzites, volcanic rocks, or slates. Much of the flattening is clearly due to shearing effects during metamorphism, but some represents the original clastic form. The relative proportions of the two types of grains vary greatly in short distances within a single conglomerate. The grain-rounding in most cases is clearly abrasive, but some grains of quartz appear to be volcanic phenocrysts rounded by resorption.

The composition of the pebbles is diverse. Volcanics, quartzites, and slates or phyllites are the most abundant rock types represented. Rounded and individual grains of quartz, chert and feldspar up to 7 or 8 mm are often present. Grains with well-developed micrographic intergrowths of quartz and potash feldspar are uncommon but recurrent in thin section. A few grains show coarse quartz and plagioclase feldspar intergrowths strongly resembling granitic texture. Unfortunately none of these grains are large enough to be interpreted unequivocally.

The quartzite fragments vary from monomineralic rocks to sericitic quartzites, and fragments transitional to quartz-sericite schist are present. Slates, phyllites and mica schists appear in the same specimens.

The volcanics are almost entirely acid rock fragments in which

Figure 8a. Photomicrograph. Sheared fragments of quartzite, volcanic rocks and quartz in a conglomerate in the Pinal schist. Note the shear surfaces in the quartzite fragment in the upper left, which sever an opaque grain and offset quartz grain boundaries. Plain polarized light. Mag. x 26 diameters. Spec. L-124b.

Figure 8b. Same field, crossed nicols.

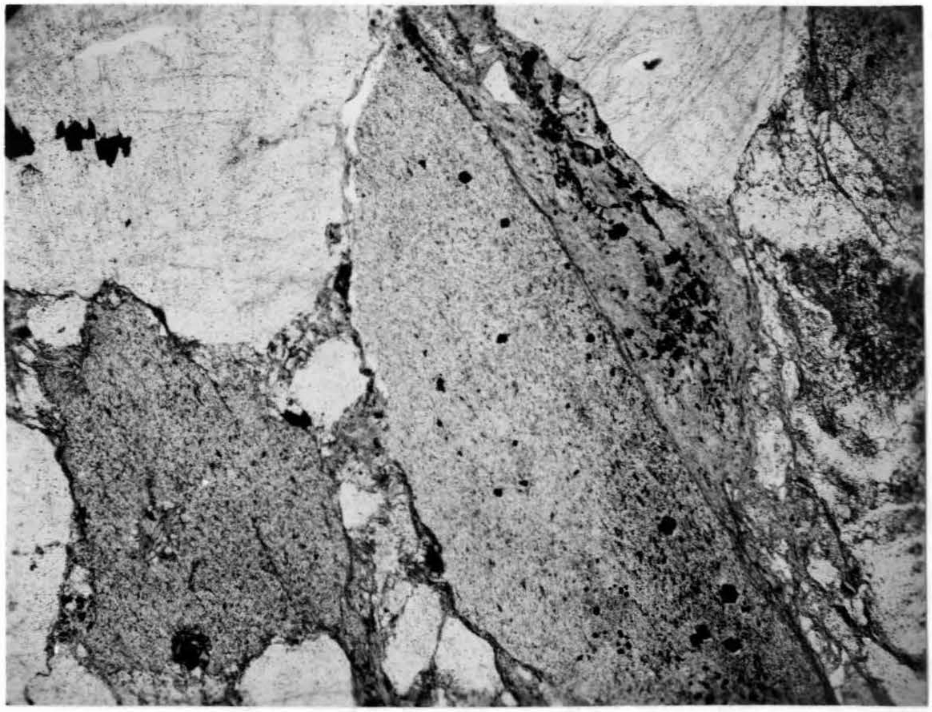


Figure 8a

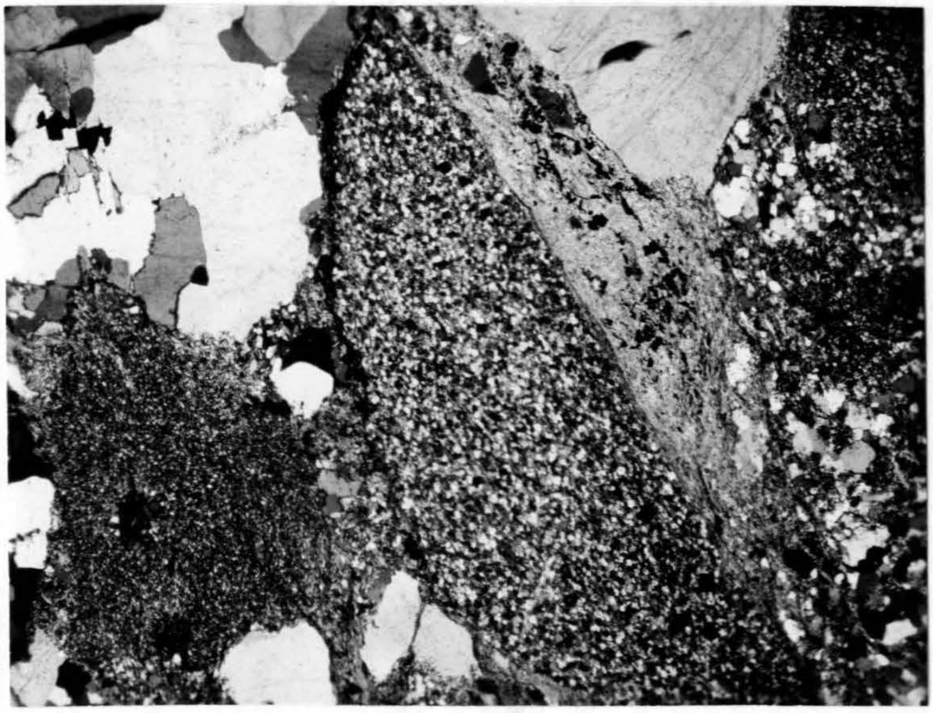


Figure 8b

quartz and sodic plagioclase are common phenocrysts. The groundmass materials have been recrystallized into fine-grained quartz-albite-sericite mixtures. Basic volcanic fragments are quite rare with less than a dozen noted in the thin sections examined. They are largely altered to chlorite-biotite-quartz-albite assemblages.

The matrix of the conglomerates is an intergrowth of quartz, feldspar, sericite, chlorite, biotite, epidote and opacites, analagous in general composition to the sandstone and siltstone phases of the Pinal schist.

Metamorphism has produced flattening and stretching in fragments of the more amenable rock types and some development of granulated tails on the quartz and quartzite fragments. Reconstitution has not been intense except in some of the fine-grained volcanics. The matrix has recrystallized with consequent orientation of the micaceous minerals and growth of albite. Minor shear surfaces marked by concentrations of sericite, chlorite, and opaque grains, parallel the foliation, but rarely cut rock fragments.

Metamorphosed sandstones

The impure sandstones are now light-gray to dark greenish-gray, compact and tough rocks in which sand grains of quartz, feldspar, and various types of rocks are megascopically visible in a finer-grained matrix. They commonly weather light to dark brown. In hand specimen the outstanding physical characteristics are strong induration, poor sorting, common graded bedding, veneers of slate or phyllite from the adjacent beds, and sparse internal foliation.

Microscopic examination reveals that among the sand grains, quartz is generally the most abundant mineral, followed by albite and sodic oligoclase, rock fragments, microcline, perthite, and opaque minerals. The lithic fragments represent the same rock types found in the conglomerates. The grains are usually angular to subrounded but well-rounded grains are not uncommon (fig. 9a, b). The grain size may range from 1/16 to 4 mm and generally extends over all or a large part of this range in a single bed. Vertical gradation in the size and abundance of the coarser grains within many individual beds constitute excellent graded bedding (see Shrock, 1948, p. 78, et seq.). In the better preserved rocks, the present grain size and shape appear to be essentially original, with only a slight attack by recrystallization or replacement on the edges. Some undulatary extinction developed during the regional deformation. The fragments have a slight tendency to have their larger dimensional axes oriented parallel to the bedding but to a degree probably compatible with sedimentational orientation.

The matrix material is completely gradational in size with the coarser grains and may be so abundant as to isolate the individual sand grains (figs. 10, 11). Measurements of the volume percentages of material finer than 0.05 mm on two typical rocks where the particle size graded continuously up to sand grains of 1 and 2 mm, gave 65 percent and 55 percent, respectively.

The matrix composition includes all the minerals found in the coarser grains plus sericite, chlorite and/or biotite, epidote group minerals, calcite, leucoxene, and limonite, as well as sparse amounts of such accessory minerals as apatite, zircon, tourmaline and rutile. The presence of some fine-grained stilpnomelane in some rocks is

Figure 9a. Photomicrograph. Graywacke in the Pinal schist, containing subangular to rounded clastic grains up to granule in size. Plain polarized light. Mag. x 26 diameters. Spec. L-122.

Figure 9b. Same field, crossed nicols.

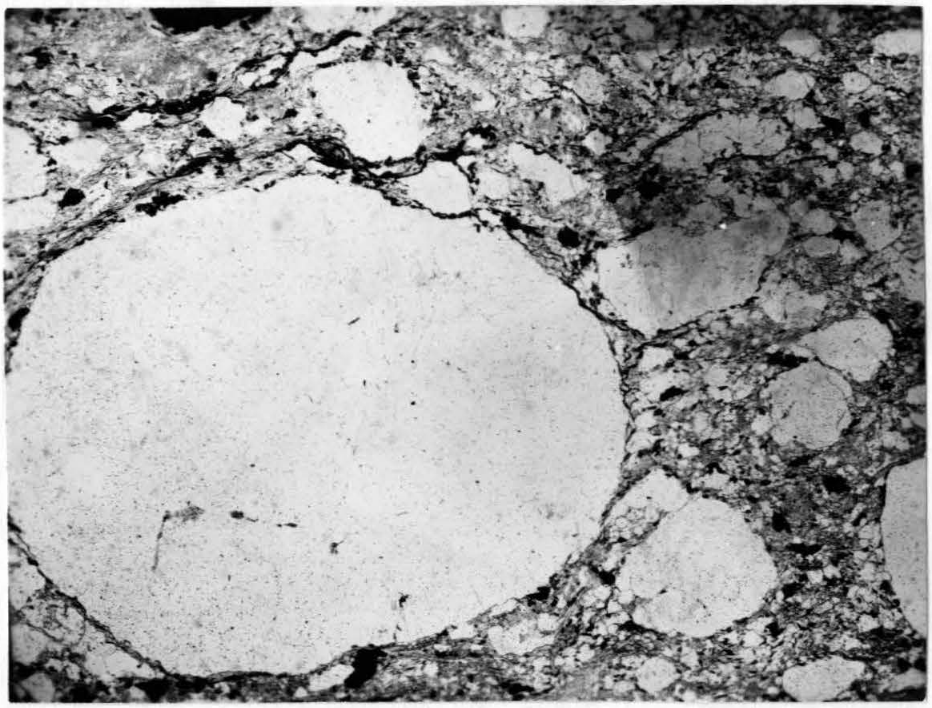


Figure 9a

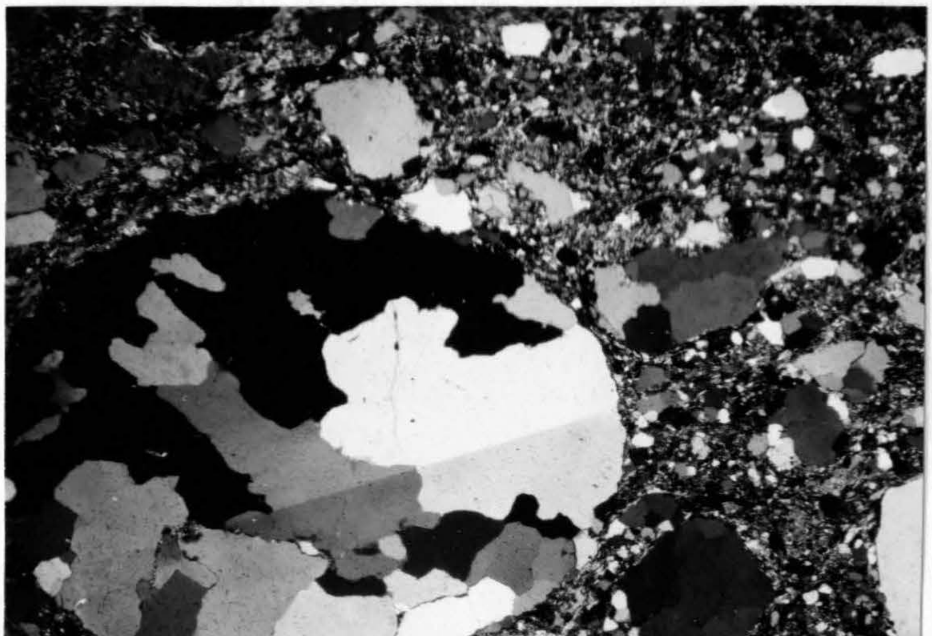


Figure 9b

Figure 10a. Photomicrograph. Graywacke in the upper part of the Pinal schist section showing the characteristic sedimentary textures, despite evidence of some shearing. Plain polarized light. Mag. x 26 diameters.

Figure 10 b. Same field, crossed nicols.

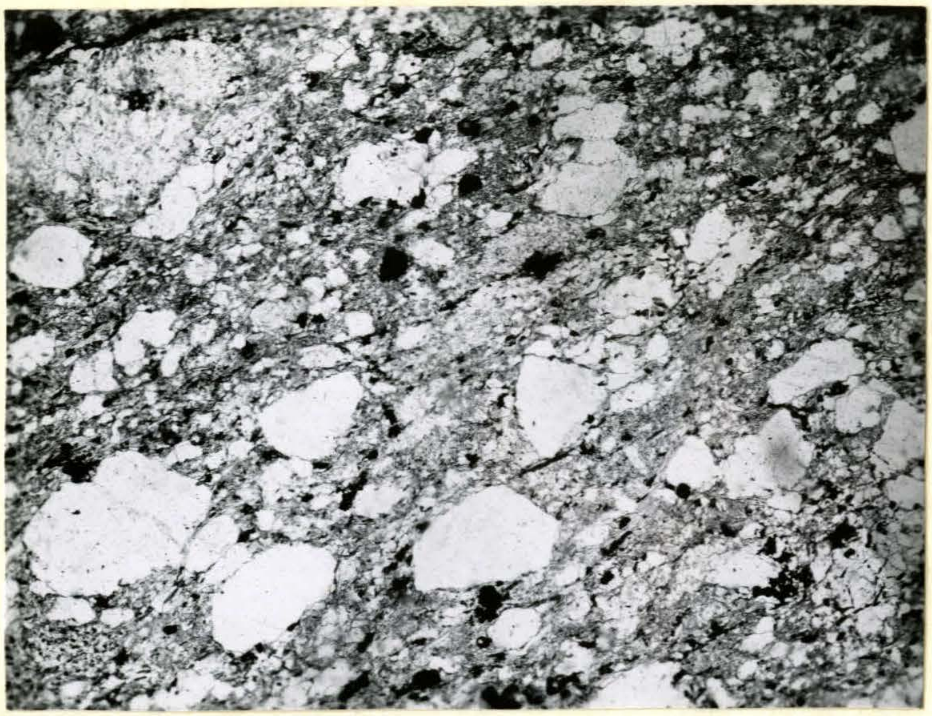


Figure 10a

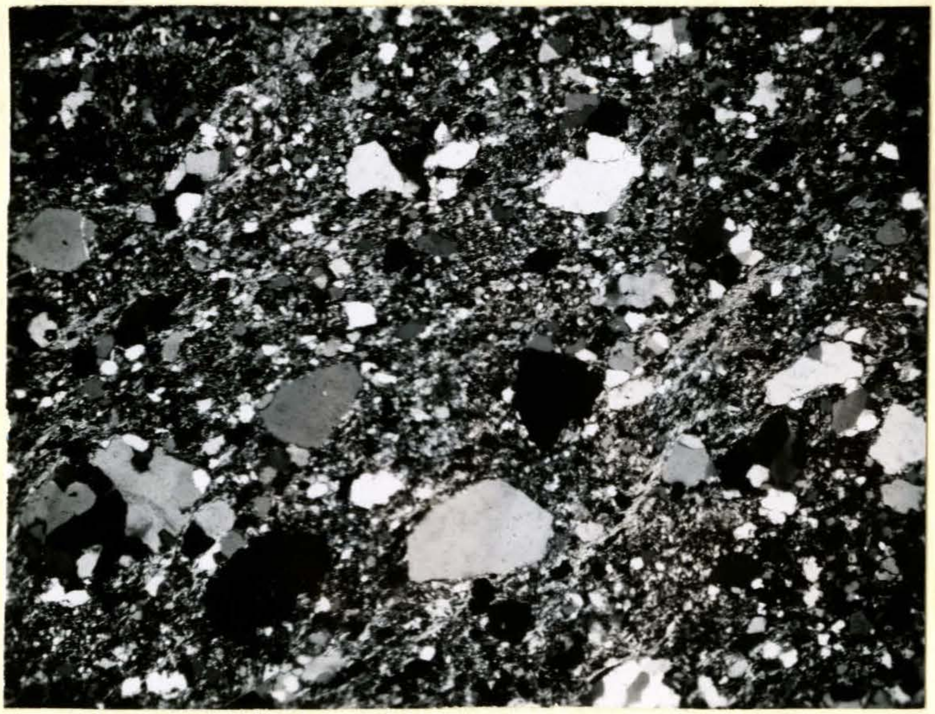


Figure 10b

Figure 11. Photomicrograph. Typical graywacke in the lower part of the Pinal schist section, showing essentially original sedimentary texture. Crossed nicols. Mag. x 26 diameters. Spec. L-307b.

Figure 12. Photomicrograph. Feldspar-rich graywacke in the lower part of the Pinal schist section. Crossed nicols. Mag. x 26 diameters. Spec. L-204c.

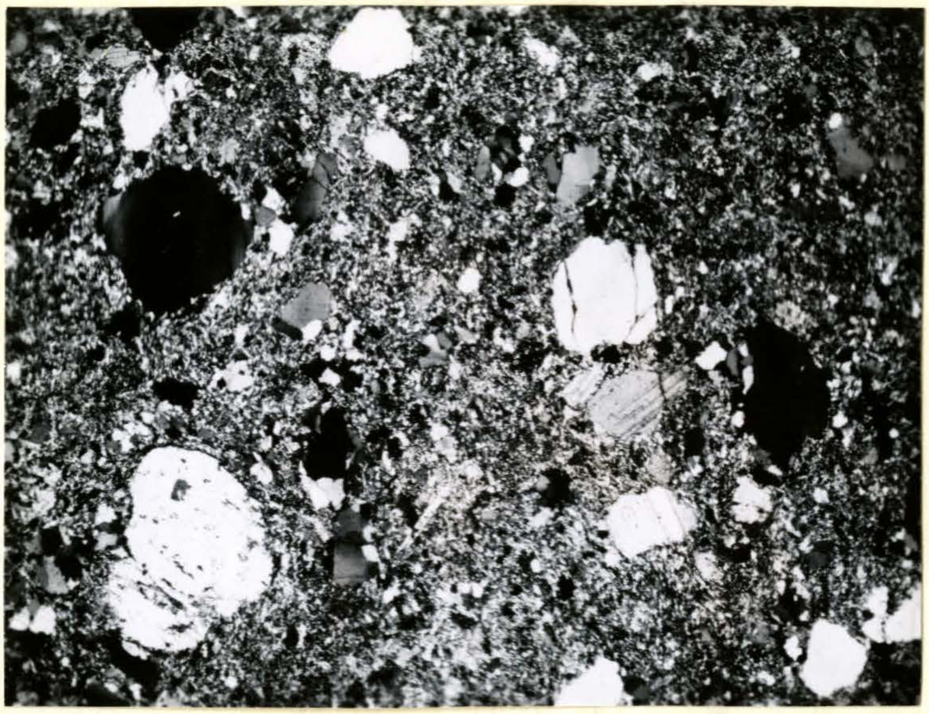


Figure 11

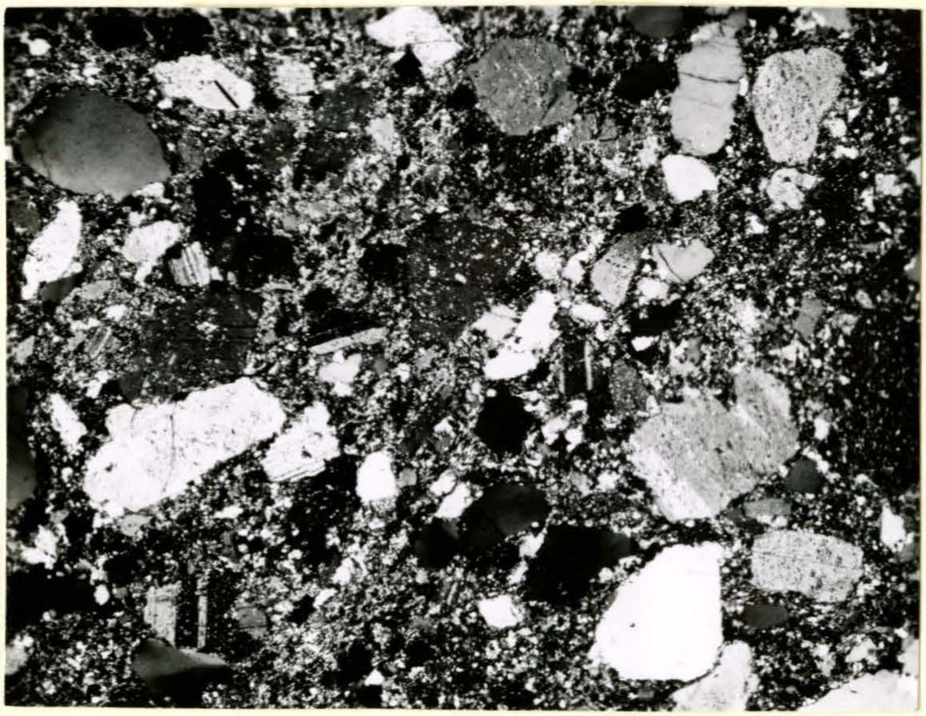


Figure 12

suspected from petrographic examination, but cannot be confirmed by X-ray methods because of the difficulties in preparing suitable concentrates. Because of its original argillic composition, the matrix has been more sensitive to metamorphism than the coarser grains. Recrystallization and reconstitution have produced a dense interlocking texture. Some of the finer sericite has somewhat lower indices and birefringence than 'normal' muscovite and appears to be illitic in character. The sericite, chlorite, and biotite are in flakes weakly to strongly oriented parallel to the schistosity and are associated with granoblastic quartz and feldspar. Magnetite is localized in the vicinity of aggregates of biotite and chlorite and develops idioblastic outlines.

The composition of most of the sandstones is in general restricted to the following ranges, from estimates based on 16 beds examined petrographically:

Quartz	40 - 50 percent
Albite & sodic oligoclase	5 - 20 percent
Potash feldspar	0 - 5 percent
Sericite	20 - 40 percent
Chlorite and/or biotite	6 - 12 percent
Opaque minerals	3 - 5 percent
Other minerals	1 - 2 percent
Rock fragments	0 - 25 percent

Precise determinations of mineral composition are limited by the difficulty of analyzing the abundant and fine-grained matrix material.

On a textural basis, using 0.05 mm as the arbitrary upper grain size limit, the matrix varies from 35 percent to 75 percent of the total rock. In general the higher the ratio of sand grains to matrix, the higher are the ratios of quartz to feldspar, quartz to sericite, and rounded and subrounded sand grains to subangular and angular grains.

A few extreme variations in composition have been observed. Two beds of limited extent were found to have compositions more closely approaching that of high silica quartzites. Their estimated compositions are:

	L-103	L-217a
Quartz	85 percent	90 percent
Feldspar	tr	—
Sericite	5-7	5-7
Chlorite and biotite	5	1
Opaque minerals	3-5	1
Others	tr	tr
Max. grain size	0.5 mm	4 mm

The estimated average matrix material (finer than 0.05 mm) of these beds is 20 percent by volume in which quartz is a major constituent. In outcrop pattern the beds resemble local reworked deposits in current channels. They contain some of the rare cross-bedding found in the Pinal schist.

Another type of sandstone limited in exposures to the southern part of the area consists of thick beds which appear to be more tuffaceous in composition. The average estimated composition of two beds is:

	L-204a	L-204c
Quartz	25 percent	35 percent
Feldspar (albite & sodic oligoclase)	55*	45
Sericite	5-10**	8-10
Chlorite	3-5	3-5
Opaque minerals	3	1
Other minerals	1	3-4
Rock fragments	5	1
Maximum grain size	2 mm	2 mm
Percent matrix (0.05 mm)	10 percent	30 percent

* Sericitized

** In matrix

These rocks contain less fine-grained matrix than the average sandstones and have a higher feldspar content (fig. 12). The grains are angular to subangular and show little evidence of sorting. The resemblance to crystal tuffs is marked. They are intruded by a thick sheet of rhyolite porphyry which is probably not much different in composition (see table 4). Unfortunately the limited outcrop of these beds prevented their use as stratigraphic markers.

With increasing intensity of metamorphism the sandstones are more visibly affected by dynamic than by thermal effects. The large sand grains are elongated parallel to the foliation and display mortared rims and tails, as well as internal granulation. The feldspars are dislocated and an irregular perthitic texture is developed in some of the microclines. These effects tend to increase the apparent proportion of matrix for the growth by recrystallization of the fines does not compensate for the concurrent mechanical reduction of the coarse grains. The resulting rocks are so-called semi-schists (Turner in W. T. and G., 1953, pp. 205, 216). Extreme granulation and recrystallization occurs in those grit beds interbedded with argillaceous material which are subjected to such intense folding as to separate into boudins.

Within the matrix, the effects of increasing regional metamorphism principally involve recrystallization of the quartz and growth of sericite, chlorite, biotite and albite. The chlorite appears both as a precursor and as a retrogressive successor of the biotite. The last is fine-grained in ragged flakes up to 0.2 - 0.4 mm. It is pleochroic in pale yellow (X) to golden olive-brown (Y, Z). It commonly appears to have nucleated around magnetite grains. All of the micaceous minerals assume a strong orientation in the more deformed rocks. The metamorphic albite is generally fine-grained, but may be as coarse as 1-2 mm. It is full of inclusions of sericite and quartz.

In summarizing the lithologic characteristics of the better preserved sandstones in the Pinal schist it may be said that typically they are gray, well-indurated medium and fine-grained clastic rocks with an argillaceous matrix, poorly sorted in grain size and mineralogy and commonly vertically graded in texture. The general term, graywacke, is applied to these rocks solely on the basis of these physical characteristics.

According to Lyell (1837, p. 451), the term, graywacke, was applied to the so-called Transition series of the Harz Mountains in Germany by the Wernerian school of geology, at the beginning of the

19th century. At that time these rocks (mid-Paleozoic) were the lowest rocks in the recognized geologic column to contain fossils. They were interpreted as transitional in character between the Primary rocks (or crystallines) and the Secondary series (or unaltered sediments). Lyell stated, "The characteristic group called 'Grauwacke', an old miner's term, is an aggregate of small fragments of quartz, flinty slate (or Lydian stone) and argillaceous schist cemented together by argillaceous matter." Lyell disagreed with Wernerian attempts to attach a peculiar time significance to this lithology, and called it "an accidental variety of argillaceous sandstone, probably in some case altered by heat."

This original sense of an impure sandstone, containing rock fragments as well as individual mineral grains, characterized by argillaceous matrix, and indurated, perhaps, "by heat" is the historical precedent for the application of the name graywacke made in this paper.

In surveying the literature, the usages of graywacke by various workers (e.g. Bailey, 1930, 1936; Grout, 1932, pp. 275, 308; Tyrrell, 1933; Rept. Comm. Sed., 1935-36; Twenhofel, 1939, pp. 289, 290; Krynine, 1940, 1943; Pettijohn, 1943, 1949, pp. 243-257, 1954; Dapples et al, 1953; Gilbert, in Williams, et al, 1954; Folk, 1954, and many others) are so diverse as to appear to recommend abolition of the term. Pettijohn (1949) gave an excellent review of the literature on the problems up to that date.

More important than the semantic dispute regarding the term graywacke is the significance of this lithology, regardless of label, as a part of the characteristic suite of rock types which has been proposed on modern principles of sedimentation and tectonics as the geosynclinal facies. Inasmuch as the original graywacke locality is cited as a prime example of this facies, it is believed that continued used of the name in its original sense is wiser than its abandonment. It might be pointed out here for students of the more refined classifications that the usage of graywacke practiced here corresponds generally to the combined high and low rank graywackes of Krynine (1948), the graywackes and subgraywackes of Pettijohn (1949) and Krumbein and Sloss (1951) and the feldspathic and subfeldspathic, lithic graywackes of Gilbert (Williams et al, 1954). Because of the variability in the feldspar content of the sandstones of the Pinal schist no further subdivision has been employed.

Among the sandstones examined petrographically, a generalization can be made that the samples with more abundant quartz, less feldspar and less matrix, are more common in the upper part of the Pinal schist section. Two beds of this type both displaying excellent graded bedding, have been sampled and analyzed chemically, and the analyses, together with mineralogical and textural data, are given below, together with average graywacke and subgraywacke analyses from Tyrrell (1933) and Pettijohn (1949).

Table 2

	Collected in $SW\frac{1}{4}$, sec. 10 T. 15 S., R. 21 E. W. Blake, analyst, 1953 L-24a	L-123b	Average of 30 graywackes Tyrrell, G.W., 1933, p. 26	Average of 3 subgraywackes Pettijohn, F.J. (1949, p. 256, t. 66, col. d.)
SiO_2	75.09 percent	79.53 percent	68.1 percent	77.8 percent
TiO_2	0.58	0.57	0.7	0.6
Al_2O_3	11.36	9.91	15.4	9.5
Fe_2O_3	3.11	3.26	0.3(?)	0.9
FeO	0.94	0.71	3.4	2.6
MgO	1.03	0.69	1.8	1.6
CaO	1.26	0.38	2.3	1.2
Na_2O	2.64	1.52	2.6	2.0
K_2O	1.86	2.25	2.2	1.5
H_2O+	1.46	1.16	2.1	1.6
H_2O-	0.26	0.13		0.1
P_2O_5	0.08	0.08	0.2	-
MnO	0.09	0.06	0.2	0.2
	99.76 percent	100.25 percent	99.3(?) percent	99.60 percent

Modal Analyses	L-24a	L-123b
Quartz	43 percent	46 percent
Albite and sodic oligoclase	5	6
Potash feldspar	-	1
Sericite	38	34
Chlorite and biotite	8	9
Epidote	-	1
Ore minerals	5	4
Others	0.3	0.1
	99.3 percent	101.1 percent
Max. grain size	$\frac{1}{2}$ mm	4 mm
Percent matrix (finer than 0.05 mm)	50 percent	40 percent

The modal analyses were made by point counter technique (Chayes, 1949). The limitations placed on any quantitative petrographic technique by samples with an abundance of fine-grained material less than 50 microns in diameter are in effect here. It is considered that these modes are biased so as to emphasize the colored and more birefringent micaceous minerals over the less prominent quartz and feldspar. Some indication of this is obtained by recalculating the Na_2O content of sample L-24a to equivalent albite. The 2.64 percent of soda is equivalent to more than 22 percent albite molecule, but only 5 percent feldspar is recognized in the modal analysis. A paragonitic sericite may be responsible for part or all of this discrepancy, but it is probable that some albite in the matrix has not been recognized because of its fine-grained obscurity.

The chemical analyses of the two Pinal schist specimens are more similar to those published for subgraywackes by Pettijohn than for typical graywackes (Tyrrell, 1933). Unfortunately, no comparison of even approximate modal analyses can be made. The technical difficulties of measuring modes has undoubtedly repressed the published appearance of reliable pairs of chemical and mineral analyses with accompanying textural data. Until such information can be obtained, the complete significance of chemical analyses for materials classified according to texture or mineralogy is not clear. For example, it is readily calculated that many sandstones which would mineralogically and texturally qualify as Krynine's high rank graywacke or Pettijohn's graywacke (i.e. containing more than 10 percent feldspar) yield chemical analyses similar to the average "subgraywacke" in table 2. In table 3 are listed the mode and a reasonable chemical equivalent for a purely hypothetical rock to illustrate this point.

Table 3

Hypothetical Mode		Hypothetical Chemical Analysis	
Quartz	60 percent	SiO_2	78.9 percent
Plagioclase (An_{87})	15 percent	TiO_2	1.0
Muscovite	15 percent	Al_2O_3	10.2
Chlorite	5 percent	Fe_2O_3	0.7
Magnetite	2 percent	FeO	2.6
Ilmenite	2 percent	MgO	0.9
Calcite	1 percent	CaO	1.2
	100 percent	Na_2O	1.6
		K_2O	1.8
Matrix finer than 0.05 mm = 40 percent		H_2O comb.	1.3
Max. grain size = 2.0 mm		CO_2	0.4

One must conclude that the chemical analyses of the graywackes and subgraywackes as listed by Pettijohn and others are not fully representative of the range of material which they consider to fall into the assigned compartments of their classifications. And one wonders whether this gap reflects a natural scarcity of transitional rock types or rather a lack of sufficient published chemical and accurate mineralogical data to permit a valid generalization on the average chemical composition of their principal types.

Metamorphosed siltstones and shales

The finer-grained metasedimentary rocks (grain size predominantly less than 0.05 mm) of the Pinal schist include thin, dense, unfoliated siltstones, slates with excellent cleavage, phyllites which are commonly knotted, and fine-grained mica schists.

The siltstones are typically dark gray and are much closer to the sandstones in textural character than to the very fine-grained slates. Graded bedding is not uncommon within them, particularly if a few sand grains are present. Compositionally they are essentially identical with the matrix material of the coarser beds. They occur both as individual beds usually less than three inches thick and as intermediate phases of beds that grade vertically from sandstone to slates.

The slates and phyllites also occur in two sedimentary habits: (1) as an interval ranging from a fraction of an inch to a few feet in thickness between coarser beds into one of which it may grade texturally; and (2) as thicker intervals up to 75 or 100 feet with sandstone interbeds rare or absent. In both types of occurrence they are typically gray to dark blue-gray and may show laminar banding with lighter gray or gray-green beds. Original sedimentary channelled surfaces are not uncommon. This channelling is indented into the top of slate beds on a scale of fractions of inches and is usually marked by a local concentration of coarse grains in the overlying grit bed. Use of this phenomenon has occasionally supplemented graded bedding in determining tops of beds. Very uncommonly, the banded slates in a given interval display highly contorted beds whose unsystematic folds and breaks appear to be the result of some type of original sedimentary slumping. This phenomenon is confined entirely to a single interval and is not shared by the adjacent sandstone units.

Compositionally, the slates and phyllites are more sericitic than chloritic. An estimated average mineral composition for a representative slate or phyllite is:

Sericite	45 percent
Chlorite	15
Quartz	35
Feldspar	2-3
Magnetite and Ilmenite	2-3
Epidote	Trace
Tourmaline	Trace
Zircon	Trace
Apatite	Trace

These rocks possess well developed flow cleavage and may also display one or more prominent lineations in the form of sets of persistent fine wrinkles. Faint to lustrous sheens appear on the cleavage as the phyllitization of the rocks increases. The microscopic texture is lepidoblastic with the fine-grained quartz largely obscured by the 'fluidal' micas. The wrinkles common in hand specimen are reflected microscopically by folding and false cleavages intersecting the schistosity.

Many of the phyllites and fine-grained mica schists are spotted or 'knotted' by numerous dark green porphyroblasts, one-half to four mm in diameter. These 'knots' are elongated parallel to the local fold axes in some outcrops but commonly they show a more or less random orientation. The knots are surrounded by a phyllitic to schistose matrix, coarser in texture but similar in composition to the less recrystallized slates and phyllites.

Two types of knots are visible microscopically, usually in the same specimens. One type consists of plates of chlorite, probably clinochlore, up to 1 mm which are ragged, poikiloblastic and which have grown athwart the foliation. Rarely, these plates have traces of biotite apparently as relics and the chlorite is therefore considered pseudomorphous. The second type of knot is usually an aggregate rich in chlorite by comparison with the surrounding material, but containing also much undigested sericite, quartz and opacites. The aggregate generally is lens-like in form, up to 4 mm long, and oriented in the plane of the principal foliation. The texture of the inclusions suggests that these knots originated as incipient developments of ferromagnesian minerals which have subsequently been replaced by fine-grained chlorite (pinite ?). In a few of the specimens examined a skeletal mineral of low positive relief and low 1st order birefringence is preserved, probably cordierite (?), but the porphyroblasts are too crowded with inclusions to permit positive identification.

The larger knots of the second type may have their inclusions arranged so as to preserve some of the original details of bedding planes. In some rocks, these planes have been rotated commonly to an angle of 40^{o}-70^{o} with the rest of the bedding features in the rock. (See fig. 13). These lenses display pressure shadows of sericite-free quartz in various stages of development at their corners. The sericite and chlorite surrounding the aggregates are strongly oriented but diverge in their orientation to 'flow' around the knot.

Figure 13. Photomicrograph. Porphyroblastic phyllite in the Pinal schist. The inclusions in the chloritic knots are oriented in planes reflecting original bedding. These planes have been rotated into various orientations oblique to larger bedding features that are parallel to the principal foliation visible in the photograph. Plain polarized light. Mag. x 26 diameters. Spec. L-1.

Figure 13

Amphibolites

In a limited area north of Sheep Camp Ridge, numerous amphibolite inclusions are found in a hybrid phase of the Johnny Lyon granodiorite. A detailed discussion of their lithology and occurrence is found on pp. 163-178. Although they are often considerably modified by reaction with the granodiorite, remnants of a strong pre-intrusion foliation and abundant hornblende-rimmed quartz grains which strikingly resemble relict amygdules suggest that these inclusions were sheared basic metavolcanics in the Pinal schist. Although no other amphibolites have been found in the Johnny Lyon Hills section, the Pinal schist of the Little Dragoon Mountains has numerous bodies of greenstone, some of considerable extent and some showing evidence of an original basaltic flow character.

Although the foliations of some of the inclusions are approximately parallel to the foliation in the main body of schist, such foliations are not common enough to confirm the existence of a roof pendant. The scattered and unoriented nature of many of the blocks reveals them clearly as dislocated xenoliths. They have been preserved by their engulfment from a part of the Pinal schist section no longer visible in the Johnny Lyon Hills.

Total thickness of the Pinal schist

Limited by erosional, intrusive, and tectonic contacts, the exposures of the Pinal schist in the Johnny Lyon Hills are such that only a minimum value for the thickness of the formation can be estimated there. The estimation is based upon conclusions from numerous graded bedding determinations. Along a general line measured from the intrusive contact with the Johnny Lyon granodiorite near the SE corner of sec. 4, T. 15 S., R. 21 E., and trending southeast to the unconformable Pioneer shale, scores of nearly vertical graded graywacke beds consistently indicate the same direction of the top of the section, i.e., to the northwest. For a horizontal distance of more than a mile and a half, only one clear reversal of the top direction is indicated and that can be limited to a thickness of less than 200 feet of beds. This reversal is quite close to the rhyolite porphyry sheet zone yet does not duplicate that unit and is therefore believed to be the result of subordinate isoclinal folding. At the southeastern end of this section a number of closely spaced reversals of graded bedding indicate tight isoclinal folding is present and must be avoided in estimation of thickness. Eliminating the latter portion of the section and with due allowance for the other reversal, some 9,000 feet of beds are interpreted as forming a continuous overturned section with the top to the northwest. Much of the rest of the Pinal schist in the map area appears to be a southwestward projection of this section and the many graded beds also indicate tops to the northwest. This will be discussed further in the section on the structure of the Pinal schist.

To the 9,000 feet of probably unduplicated sedimentary beds, must be added unknown additional thicknesses of basic volcanic flows and sedimentary rocks. In the nearby Little Dragoon Mountains, a number of additional metasedimentary and volcanic units are recognized which suggest a total thickness for the Pinal schist in the combined areas of perhaps 20,000 feet or more.

Intrusive rhyolite porphyry sheets

Distribution and lithology

The rhyolite porphyry bodies, with one important exception, crop out in a zone generally 800 to 1,000 feet wide which is essentially conformable with the bedding in the Pinal schist. The zone is present in the schist for nearly six miles from the pre-Apache group unconformity one-half mile west of Lechugilla Hill, to the edge of the map area, southwest of Keith Peak. Over this distance it is overlapped for about one mile by the Paleozoic sediments forming Keith Peak, and is offset by several major thrust faults but it appears persistently until it is finally concealed by alluvium about a quarter of a mile west of the map area.

In detail the porphyry bodies within the zone are unresistant lenses and sheets up to 75 feet thick and continuous for distances up to 2,000 feet or more. The average size is probably 20 to 30 feet thick and one or two hundred feet long. The porphyry bodies occur repeatedly along two or three distinct horizons within the zone, for distances of a mile or more, but just as commonly they are found randomly distributed in the zone, or arranged in an en echelon pattern.

A simple sheet or lens-like form grossly conformable with the adjacent bedding is most common. In general the sheets are very steeply dipping and the outcrop pattern is essentially a cross-section normal to the sheet or lens. The ends of the bodies (the margins of the sheets) generally taper gradually and disappear. They may persist, however, with thicknesses less than one foot, for several hundred feet before disappearing or swelling into another body twenty or thirty feet thick. A single sheet may part and envelop a thin septum of metasedimentary rocks. One side of the parted body may wedge out while the other may part again. A single lens may terminate by sending several thin apophyses into the adjacent beds. In detail almost all of the porphyry bodies truncate the bedding somewhere along their contacts, but particularly at the ends. These are clearly intrusive contacts, for it is not uncommon to see thin apophyses of porphyry project concordantly into the bedding from a generally discordant contact.

A weak but consistently recognizable halo a few feet thick is induced in the adjacent rocks on all sides, particularly the slates and phyllites. In outcrop, this is manifested only by a purple or lavender cast developed in the fine-grained rocks. In thin sections, the contact slates and phyllites differ from similar rocks elsewhere in containing 1 to 40 percent finely divided hematite, 1 to 3 percent epidote, an unusual abundance (up to 40 percent) of nearly colorless chlorite, and abundant minute ptygmatic quartz veinlets. The finely divided hematite is apparently the cause of the coloration of the zone.

A mile south of the principal zone of rhyolite porphyry injections, a large body of rhyolite, with a number of thin satellite sheets is partly exposed in a wash in the SE$\frac{1}{4}$ sec. 32, R. 21 E., T. 15 S. Sharp incision of the wash through overlying alluvium has revealed a thickness of about 600 feet for this body and the exposed northeast end of the body sends dozens of thin sheets, a few inches to feet thick, into the adjacent metagraywackes. These thin sheets are generally concordant with the bedding, but many instances of cross-cutting injections are visible.

The typical, relatively unaltered rhyolite is a dark brown porphyritic-aphanitic rock, weathering red-brown to yellow-brown, with abundant large milky-white quartz 'eye' phenocrysts, more numerous but less conspicuous light-brown feldspar phenocrysts, and a few dark aggregates set in a dense, massive brown groundmass.

No perceptible chill zone or consistent textural variations between the center and margins of the rhyolite bodies has been observed, where the original margins are well preserved.

The quartz phenocrysts average 3 to 5 mm, but commonly attain 8 to 10 mm in diameter. They are resorption-rounded and show all stages of corrosion and embayment by the groundmass material (fig. 14). The feldspar phenocrysts are invariably sericitized and are sodic plagioclase in the range Ab_{90-85}. The feldspar is subhedral to euhedral, although sometimes broken, and ranges from $\frac{1}{2}$ to 2 mm in diameter. The dark aggregates are usually elongated intergrowths of magnetite, ilmenite and some incipient biotite apparently pseudomorphic after an original mafic mineral. The texture suggests that most of this alteration was an igneous rather than metamorphic effect. The elongation of the dark aggregates and a weak orientation of the quartz eyes suggest a slight original flow structure. Zircon and apatite are recognizable accessory minerals, usually associated with the dark minerals.

The groundmass is a very fine-grained intergrowth of quartz, albite and probably potash feldspar. It contains 15 to 20 percent strongly oriented sericite in all specimens examined. Scattered opacites in the groundmass commonly have minute grains of biotite associated with them.

An estimated average mineral composition is:

Figure 14. Photomicrograph. Rhyolite porphyry with typical phenocrysts of resorbed quartz and altered sodic plagioclase in a fine-grained sericitic groundmass Collected from the center of a large intrusive sheet. Crossed nicols. Mag. x 26 diameters. Spec. L-3.

Figure 15. Photomicrograph. Sheared rhyolite porphyry with granulated phenocrysts and schistose groundmass. Collected from the margin of an intrusive sheet. Crossed nicols. Mag. x 26 diameters. Spec. L-5.

Figure 14

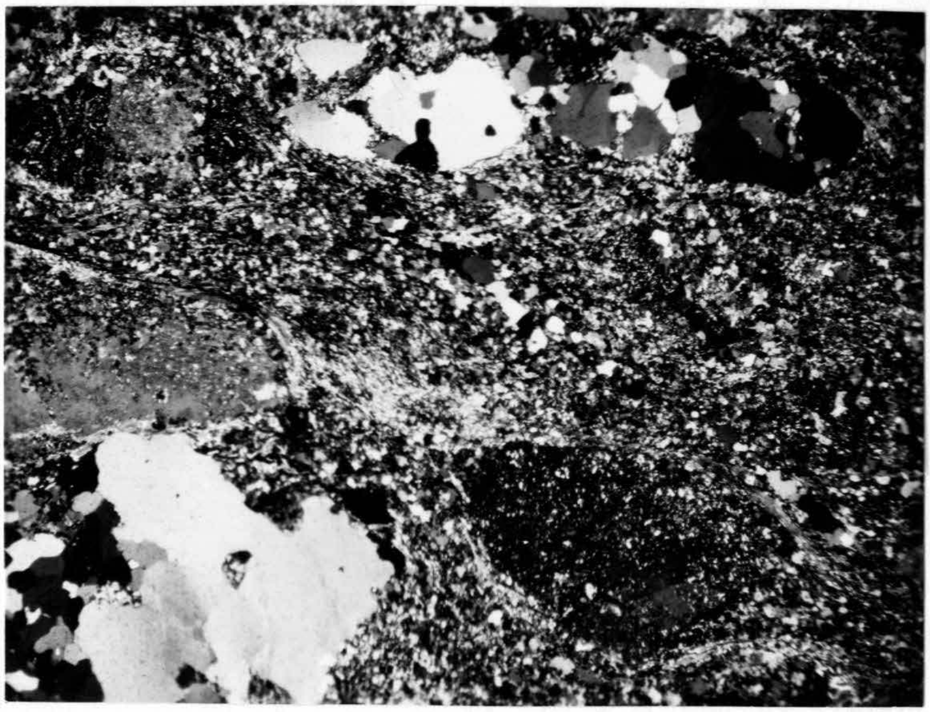


Figure 15

Phenocrysts	
Quartz	10 percent
Plagioclase	10-20
Opacite-biotite pseudomorphs	5
Groundmass	65-70

Analysis of one of the least altered specimens gave the following chemical and normative compositions (table 4). For comparison, the only other published value of an analysis of a 'rhyolite' in the Pinal schist is given. This sample was collected by Ransome (1919, pp.33, 34, 36, 37) from Granite Mountain west of Ray, Arizona. An average of 3 rhyodacites from Johannsen (1932, vol. II, p. 358, table 179, no. 305) is also given.

Table 4

	L-314b, West side of Javenlina Hill, $SE\frac{1}{4}$ sec. 16 T. 15 S., R. 21 E., Johnny Lyon Hills (W. Blake, analyst)	Rhyolite schist, Granite Mountain, Ray district (G. Steiger, analyst)	Average of 3 rhyodacites (227E) from Johannsen
SiO_2	70.45 percent	72.87 percent	69.33 percent
TiO_2	0.59	0.66	0.29
Al_2O_3	14.08	12.89	14.23
Fe_2O_3	2.09	2.40	2.00
FeO	1.62	1.76	1.90
MnO	0.07	0.07	0.13
MgO	1.00	0.82	1.00
CaO	2.06	1.90	3.31
Na_2O	3.54	3.01	3.72
K_2O	3.35	3.03	3.15
H_2O^-	0.07	0.26	(0.94
H_2O^+	1.05	0.64	
P_2O_5	0.17	0.13	0.10
	100.14 percent	100.44 percent	100.10 percent

Table 4 (cont'd.)

Normative Compositions

		L-314b	Ray Rhyolite
Salic:			
	Quartz	30.48 percent	38.76 percent
	Orthoclase	20.02	17.79
	Albite	29.87	25.15
	Anorthite	10.29	9.45
	Corundum	0.82	1.22
		91.48 percent	92.37 percent
Femic:			
	Hypersthene	2.90	2.00
	Ilmenite	1.06	1.22
	Magnetite	3.02	3.48
		6.98 percent	6.70 percent
	C. I. P. W. class.	I, 4, 2, 3	I, 3, 2, 3

The chemical analysis supports the petrographic evidence that the porphyry is actually a rhyodacite, or quartz latite. The field term, rhyolite porphyry, has been preserved as a general name, because as yet, the many pre-Cambrian rhyolites (so-called) known in southern and central Arizona have had insufficient analytical study to justify petrographic subdivision. However, the chemical analyses of the Ray 'rhyolite' schist (Ransome, op. cit.) and of the Johnny Lyon Hills sample, indicate a need for either subdivision or reclassification as a group.

None of the rhyolites examined is completely free of the effects of dynamic metamorphism. Sericitization of the groundmass is always present and the mica is invariably strongly oriented. Recrystallization of the groundmass has resulted in poorly defined oriented overgrowths on the quartz and feldspar phenocrysts. The feldspars all show some alteration to sericite and chlorite replaces some of the biotite. The best preserved specimens are found in the centers of the larger bodies. On the margins and on the ends, particularly of the smaller bodies, the dense brown groundmass may be converted to pale yellow or gray mica schist in which the feldspar phenocrysts have nearly disappeared because of granulation and sericitization, and the quartz 'eyes' have been sheared almost beyond recognition (fig. 15). Quartz veinlets and larger masses develop along the ends of the bodies apparently as segregations during the reconstitution of the rock. The end product of the dynamic effects is a schistose rock, which is impossible to distinguish in hand specimen from some of the gritty quartz-sericite schists of sedimentary parentage. Such intense effects are common, but are not the rule and in general the porphyry has survived the regional metamorphism without losing its igneous identity.

Origin and age

The rhyolite porphyry bodies are the oldest intrusive igneous rocks exposed in the Johnny Lyon Hills area. Their intrusive nature is revealed by numerous cross-cutting contacts and apophyses, by weak contact metamorphic haloes, by the shapes of the bodies, and by their locally random distribution within the principal zone.

Inasmuch as extrusive rhyolites are known in the Little Dragoon Mountains (Cooper, 1950) and elsewhere in the pre-Cambrian section in Arizona (Wilson, 1939, p. 1121; Anderson, 1951, p. 1341 et. seq.), careful examinations were made in the field for any critical evidence of a possible extrusive flow origin for this porphyry. Positive identification of the rhyolite porphyry as extrusive would carry important stratigraphic significance in the local Pinal schist section. None was found and, in view of the generally excellent preservation of the rhyolite and the associated graywackes and slates, it cannot be assumed that such evidence (e.g. flow brecciation, spherulites, flow banding, etc.) has been destroyed by metamorphism. The rhyolite porphyry must be accepted as a hypabyssal intrusive type which was injected in a remarkably persistent zone, but was not restricted to that zone. The porphyry zone appears to be within a uniform stratigraphic horizon from its trend and attitude, but outside stratigraphic control to confirm this is lacking. Nevertheless, the zone provides a mapping unit of importance in interpreting the structure.

The age of the rhyolite porphyry intrusives is best understood in their relation to the Pinal schist. The porphyry bodies are intrusive into the Pinal metasedimentary rocks and are therefore younger. They were emplaced before the completion of the regional deformation of the Pinal schist and the intrusion of the Johnny Lyon granodiorite. They are, therefore, as old as, or older than the major pre-Cambrian orogeny involving the Pinal schist. This age relation is similar to that of the much larger body of intrusive rhyolite porphyry exposed in the Little Dragoon Mountains (Cooper, 1950; in Anderson, 1951, pp. 1334-1335). It is quite possible that the rhyolite porphyry bodies were injected into the Pinal schist shortly after its deposition.

A similar rhyolite porphyry (see analyses, p. 65) in the Pinal schist from Ray, Arizona was described by Ransome who believed the rock to have been of probable flow origin because field relations indicated it "was once a fairly regular layer in those sediments and not an irregular intrusion." Intrusive sheets similar to those in the Johnny Lyon Hills would also form a fairly regular layer. Intrusive rhyolite masses are reported included in the Red Rock rhyolite of the Yavapai schist in the Mazatzal Mountains (Wilson, 1939, p. 1120); intruded into the Yavapai schist of the Bagdad, Arizona area (Anderson, 1951, pp. 1336-1338); and intruded into the Colcord group of the Diamond Butte Quadrangle (Gastil, 1953).

Mica rhyolite sheets

Distribution and lithology

In the Pinal schist west and southwest of Keith Peak, a series of generally concordant, thin white mica rhyolite sheets, forms a definite zone over two miles long. This zone parallels the brown rhyolite porphyry zone, lies about 500 feet south of the latter (or stratigraphically below in the inverted section) and shows similar offsets by thrust faults. Unlike the porphyry zone, the mica rhyolite zone consists of a single line of slightly en echelon sheets over half its length while for the rest of its length it is a double line of sheets.

The sheets of mica rhyolite range from one to fifty feet in thickness and from 50 feet to almost half a mile in length. An individual sheet tends to maintain a constant thickness over most of its length and does not display the lens-like form of some of the rhyolite porphyry bodies.

The mica rhyolite is a white rock slightly more resistant than the adjacent schists, and weathering creamy white or tan. It has a uniform porphyritic aphanitic texture except for a one or two inch chill zone where phenocrysts are not so abundant.

The phenocrysts are small, averaging 1/2 to 2 mm, and not very prominent, although they represent about 25 percent of the rock. They include quartz, sodic plagioclase, and muscovite with a few rare grains of garnet. The quartz is subhedral to euhedral with dipyramidal β-quartz forms, and shows only slight resorption effects. The feldspar is also subhedral to euhedral and is apparently plagioclase, Ab_{85-95}, extensively sericitized. The muscovite forms well developed plates which distinguish this rhyolite. Garnet, rounded to irregular, slightly pinkish in thin-sections is present in some specimens.

The groundmass is a very fine-grained (less than 0.05 mm) intergrowth of quartz, albite, potash feldspar, and oriented sericite. An estimated average mineral composition for the rock is:

Phenocrysts		
	Quartz	10 percent
	Plagioclase	12-15
	Muscovite	2-3
	Garnet	trace
Groundmass		75

No chemical analysis is available for this rock.

In contrast to the rhyolite porphyry in the nearby zone, the

Figure 16. Photomicrograph. Mica rhyolite with typical euhedral quartz, plates of muscovite, and sericitized oligoclase in a very fine-grained groundmass. Crossed nicols. Mag. x 26 diameters. Spec. L-109.

Figure 16

mica rhyolites generally show no metamorphic modification either on the margins or the ends of the sheets. Sericitization is the only alteration visible, and although the sericite is distinctly oriented in the groundmass this is not to the same degree found in the nearby porphyry. There are, however, a few small thin sheets of a schistose muscovite rhyolite found in the schist adjacent to the Johnny Lyon granodiorite. This rock, compositionally identical with the non-foliate mica rhyolite, has its foliation parallel to the schistosity of the surrounding metasediments.

Origin and age

The intrusive igneous origin of this rock is readily apparent in the texture, composition and field relations. The age of the intrusion is not so clear-cut. The mica rhyolite is quite probably pre-Cambrian because a small body of it appears to be truncated by the pre-Apache group unconformity on the southwest side of Keith Peak. Its general lack of metamorphic textures places it as younger than the metamorphism of the Pinal schist and the associated rhyolite porphyry. It is possible that it is older than the Johnny Lyon granodiorite and that it assumed a schistose character from local mechanical adjustments when it happened to be in the vicinity of the intruded granodiorite pluton.

Metamorphism of the Pinal schist

General

Various parts of the Pinal schist have been subjected to as many as five or more episodes of metamorphism or hydrothermal alteration.

Two of these episodes produced effects of major importance: (1) the regional metamorphism accompanying the pre-Cambrian deformation of the Pinal schist and (2) the post-deformational contact metamorphism associated with the intrusion of the Johnny Lyon granodiorite. Localized, faint haloes of alterations around the rhyolite porphyry sheets (p. 63) formed prior to or during the regional metamorphism. Another widespread phenomenon is the retrogressive metamorphism which probably represents a considerably younger episode than either (1) or (2). Cataclastic metamorphism locally erased all earlier effects when Laramide thrusting transected the Pinal schist. A number of lesser vein and shear features have not been successfully related to any of the aforementioned effects and may possibly represent still other episodes during which the earlier character of the Pinal schist was modified.

Regional metamorphism

Except where clearly younger metamorphic stages have modified or masked it, the mark of a major regional deformation is expressed to some degree on all of the Pinal schist and associated rhyolite porphyry bodies. A well developed cleavage or schistosity is present in all of the fine-grained and in many of the coarser-grained metasedimentary rocks. Over a considerable area, repeated tight isoclinal folds and persistent asymmetrical drag folds to which the schistosity is the axial plane, attest to the intensity of deformation. Transverse shear surfaces which obliquely truncate beds and then turn into the plane of the bedding are common. Locally, the folded and sheared beds have been deformed into the conspicuous, rod-like tectonic feature called boudinage.

The structural evidence for the mechanical deformation of the Pinal schist is accompanied by a generally less conspicuous change in the texture and mineralogy of the rocks of the formation. The excellent preservation of much of the original sedimentary textures has already been discussed. In many of the beds, for example, the metamorphic recrystallization and reconstitution has been moderate and confined to the fine-grained argillic matrix. Without exception however, there is always some evidence, inevitably including micro-schistosity, which brands these rocks as metamorphic. The mineral assemblage (quartz-albite-muscovite-chlorite-epidote) is typical of their low metamorphic rank and the rocks are texturally proper slates and graywackes. Many of these rocks apparently have never risen above the muscovite-chlorite subfacies of the greenschists facies as classified by Turner (1948, pp. 96-97). If the biotite-chlorite facies was once attained, retrogression has erased all evidence by which it is recognized elsewhere in the section.

With evidence of more intense local folding and shearing such as appears in the southeast side of the Pinal schist belt from Keith Peak to the western edge of the map area, the graywackes are converted to micaceous quartzo-feldspathic semi-schists and the slates to porphyro-blastic phyllites and mica schists. The mineral assemblages include chlorite-(or biotite-chlorite-) muscovite-quartz-albite-epidote. The biotite is commonly fine-grained and associated with the muscovite and chlorite. In some of the porphyroblastic phyllites biotite once formed tabular porphyroblasts which were largely replaced by chlorite, in a retrogressive episode. Locally there is some suggestion of cordierite(?). In general, even where the dynamic effects have been most pronounced, the maximum rank of regional metamorphism attained was apparently the biotite-chlorite subfacies of the greenschist facies (Turner, 1948, pp. 94-95).

Because of the fine-grained and inconspicuous nature of both the biotite and chlorite in almost all of the rocks, and because retrogression of biotite to chlorite apparently has been common, no boundary between the muscovite chlorite and biotite-chlorite subfacies has been mapped. Except for the previous generalization that biotite appeared more frequently in samples collected along the southeastern margin of the belt, the pattern of the distribution of biotite vs. chlorite at the present time does not have any recognizable regularity.

The origin of the regional metamorphism is clearly causally related to the regional deformation. The low rank of the metamorphism indicated that the temperatures never exceeded those probably in the normal geothermal gradient of a deeply buried sedimentary section (i.e. 250-300 degrees C.). But burial to these depths has never been demonstrated to be sufficient for the advent of metamorphism. The prominent role of deformation as a necessary factor in the metamorphism of the Pinal schist is impressive. It was responsible not only for the large structures, (see the section on structure of the Pinal schist, pp.91-126) but was also active in the intimate microscale of thin-sections where cataclastic degradation often competed with growth by recrystallization. It cannot be considered to have been merely a catalyst (Turner, 1948, p. 294) for the chemical reactions of recrystallization, but also a direct factor in the formation of the new metamorphic textures.

Although there are no direct indications of other important factors, possibilities do exist which because of the general lack of knowledge of the pre-Cambrian history in other nearby areas in this region cannot be evaluated. West of the map area, in the Rincon Mountains on the opposite side of the San Pedro River valley, lies an impressive complex of schists, gneisses and granites, unknown in detail. These conceivably could contain synkinematic intrusive masses related to the orogeny which deformed the Pinal schist and which could represent a contributing source of heat for the regional metamorphism. With the present status of knowledge on the pre-Cambrian of southeastern Arizona, such speculation cannot be tested and must be deferred until more work is done.

Contact metamorphism

Inasmuch as the entire exposed belt of Pinal schist is marginal to the Johnny Lyon granodiorite pluton, it is not surprising that contact metamorphism has left important effects on the schist. The intrusive contact is exposed for about nine miles and dips southeast between the schist at angles ranging from 80° to 45° or less. Fragments of granodiorite were observed as inclusions in a Tertiary lamprophyre dike intruded into the schist nearly a mile from the present contact. This suggests, of course, that the intrusive underlies the Pinal schist for a considerable distance.

A band of Pinal schist varying from 300 to 800 or 1,000 feet in width immediately adjacent to the pluton, is perceptibly modified in the present surface exposures. A widespread and conspicuous effect is a marked iron oxidation coloration which has given the normally gray schist a brownish hue. This is a surficial phenomenon apparently related to a recent weathering of certain contact metamorphic minerals.

Samples have been collected and studied from this contact zone and from nearby schist inclusions in the granodiorite, and, although no systematic mapping of the zone has been attempted, some observations on its distribution and intensity can be made.

The most pronounced recrystallization and reconstitution has taken place in the schist inclusions within the pluton and in a band, 25 to 200 feet in outcrop width, immediately adjacent to the intrusive. The schistosity has been erased and the prominent structure is a compositional and textural banding that reflects the original alternation of graywackes and slates (fig. 17). The older sedimentary and metamorphic textures have been either modified (fig. 18) or destroyed.

The former graywackes have been converted to granoblastic quartz-muscovite-biotite-plagioclase-microcline hornfels. The biotite is generally considerably or completely chloritized and fine-grained sericite has developed in the feldspar. While the texture is only slightly coarsened, if any, the mica and feldspar are completely recrystallized and only the quartz shows remnants of its originally clastic texture.

The former slates and phyllites have been completely transformed into coarse-grained porphyroblastic hornfels with mica plates up to 1 cm in diameter, and andalusite prisms up to 2 or 3 cm long and 1 cm in diameter. Simple mineralogical assemblages are rare and replacement textures are common. A single compositional band may contain quartz, microcline, twinned oligoclase and untwinned

Figure 17. Laminated hornfels in the Pinal schist, thirty feet from the intrusive contact of the Johnny Lyon granodiorite. The schistosity has been erased and the only planar structure is the compositional banding reflecting original bedding compositions.

Figure 18. Pseudo-graded bedding in the contact metamorphic hornfels of the Pinal schist. Originally fine-grained argillaceous beds (slates) have recrystallized to a coarser texture than the graywacke interbeds.

Figure 17

Figure 18

albite, muscovite in coarse plates and as fine-grained sericite shreds, andalusite, biotite partly chloritized, chlorite pseudomorphs after some more nearly equant Mg, Fe-rich mineral, (cordierite(?) or almandite(?)), and a complement of minor accessory minerals. Textural relations and some of the beds with simplest mineralogic compositions suggest an early high temperature equilibrium assemblage of quartz-andalusite-cordierite-muscovite-oligoclase reflecting potash-deficient rock in the amphibolite facies. But invariably the early andalusite is partly replaced by white mica (fig. 19) and microcline appears, suggesting potassium metasomatism probably from the granodiorite. Cordierite, as such, has never been found, but common chloritic pseudomorphs after an earlier equant mineral suggest the possibility of its former presence. No garnet has been recognized in this or any other part of the contact metamorphic zone, although some chlorite aggregates may represent pseudomorphs. Alteration of high rank minerals downward is present in all the specimens examined.

Between the innermost zone and the rest of the schist is a broader band, up to 700 or 800 feet wide, where reconstitution is not as marked as recrystallization. This band grades laterally into the andalusite-bearing band and it differs from the latter in that it has albite to the exclusion of oligoclase, considerable epidote and no potash feldspar. Quartz is recrystallized and the muscovite and biotite are quite coarse.

Texturally, almost no megascopic changes developed in the coarser metasedimentary rocks of this band, although the microschistosity is in part erased and recrystallization has developed a partial mosaic texture. In the originally fine-grained rocks, the

Figure 19a. Photomicrograph. Muscovite (m) replacing andalusite (a) in a hornfels of the contact metamorphic aureole developed in the Pinal schist by the Johnny Lyon granodiorite. The replacement is both peripheral and internal. Plain polarized light. Mag. x 65 diameters. Spec. L-401.

Figure 19b. Same field, crossed nicols.

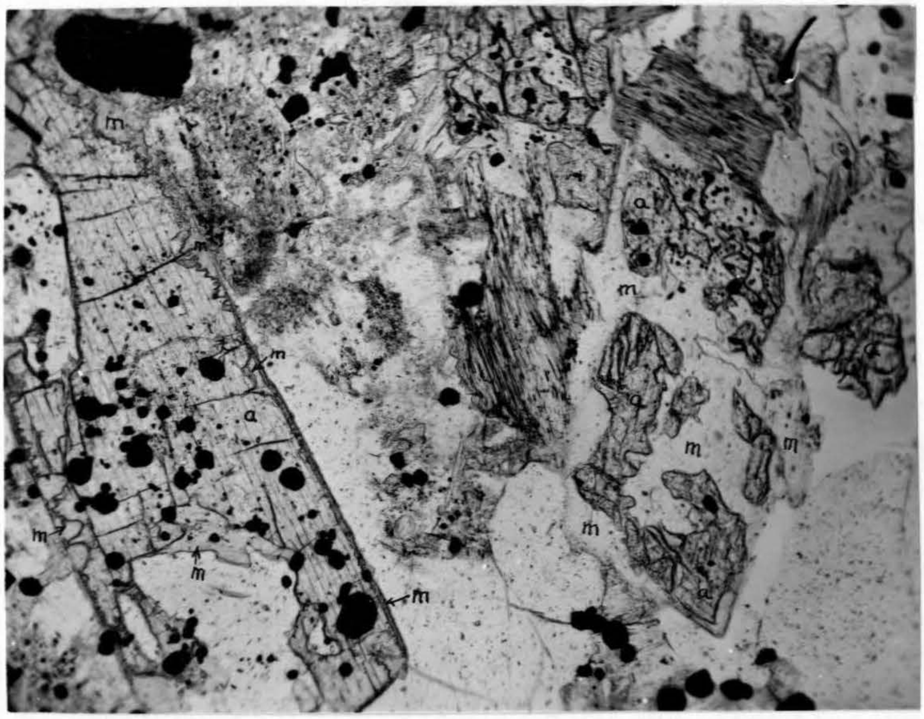


Figure 19a

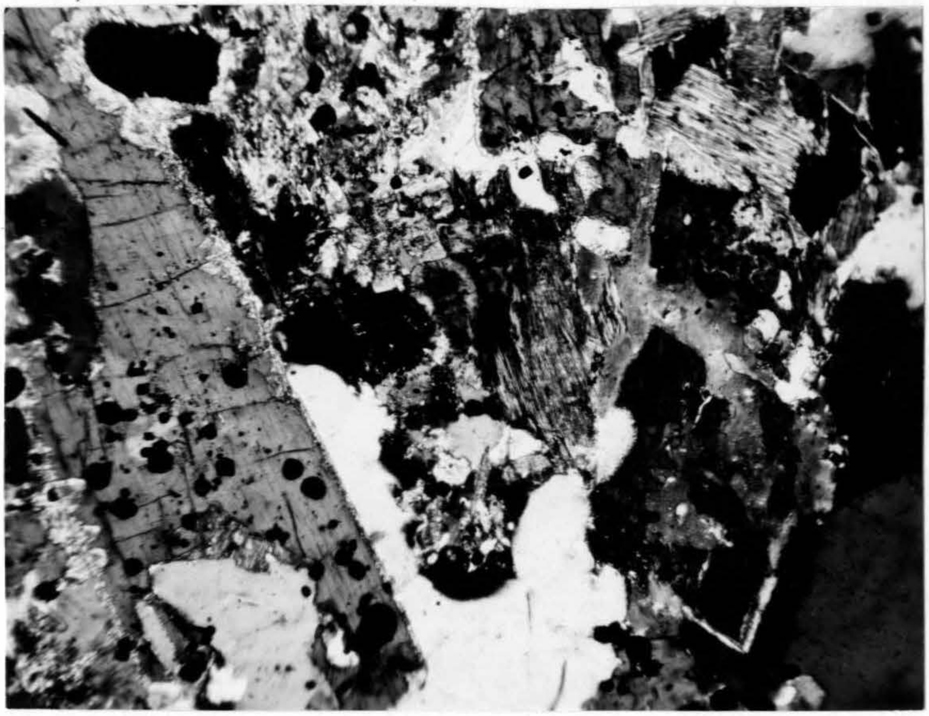


Figure 19b

growth of biotite and muscovite produced plates several millimeters in diameter and gave the rocks a pronounced porphyroblastic texture. On the outer edge of the contact zone the transition to the unmodified schists is gradual with the older dynamic metamorphic textures becoming increasingly prominent. Mineralogically, there is no significant difference between the outer contact metamorphic halo and the rest of the Pinal schist.

In summary, the contact metamorphism reached its maximum intensity in the amphibolite facies and within a relatively short distance was limited in intensity to the greenschist facies.

The maximum intensity observed in these argillaceous sediments is in agreement with the mineral assemblages recognized in amphibolitic inclusions in a hybrid phase of the granodiorite and which are discussed with the latter in a later section.

For a pluton of this composition the intensity of metamorphism is compatible with many studies of similar systems. It is somewhat surprising, however, that a pluton of at least twenty square miles, and probably much larger, should have such a limited zone of effects. Possibly, some of the porphyroblastic slates and phyllites much farther from the contact have been developed in response to the thermal contribution of the intruded body. Some of these porphyroblasts appear to grow across the schistosity (see p. 54) and are therefore very late in the regional metamorphism or followed it.

Even less conspicuous than the size of the metamorphic halo, are evidences of fluid emanations from the granodiorite. Except for apparent introduction of potash (to form later microcline and sericitize andalusite) in the innermost part of the zone, and for occasional tourmaline-rich areas in the schist there is little in the schist that can be considered as an addition from the magma. Only if an appreciable fraction of the retrogressive history of the schist (and the alteration of the granodiorite itself) resulted from hydrothermal solutions originating in the magma could the latter be said to have a regional rather than a local influence on the lithology of the Pinal schist.

The tourmalinization effects are sufficiently unusual to merit some elaboration. Three principal localities have been noted where black tourmaline has been conspicuously concentrated in the Pinal schist. At the north end of the belt, for a distance of about one mile, the schist near the intrusive contains scattered short thin quartz veins in which radiating bursts and numerous randomly oriented crystals of coarse schorl up to 2 inches long are common. Differing from this occurrence are two black tourmaline-rich veins which occur in the schist further south. One of the veins is found on the east side of the saddle between the klippe and the main thrust plate on Javelina Hill in the NE$\frac{1}{4}$,sec. 15. The other vein is exposed in the schist near the intrusive contact about a mile west of Keith Peak, in the SE$\frac{1}{4}$ sec. 19.

The black tourmaline-rich veins are actually breccia zones that average 3 to 6 inches wide, in which angular platy fragments of schist, up to one inch in diameter are imbedded in a dense black matrix (fig. 20). This matrix, which comprises 40-60 percent of the zone, is predominantly black tourmaline. Innumerable stubby prisms, averaging 0.1-0.2 mm long, form a felty intergrowth with associated finegrained quartz, iron oxides and sericite. The veins are parallel to

Figure 20a. Handspecimen of a breccia of angular fragments of Pinal schist in a dense matrix of fine-grained black tourmaline with minor quartz, sericite and iron oxides. Spec. L-201. Natural size.

Figure 20b. Photomicrograph. Thin section from above specimen in plain polarized light. Mag. x 26 diameters. Spec. L-201.

Figure 20a

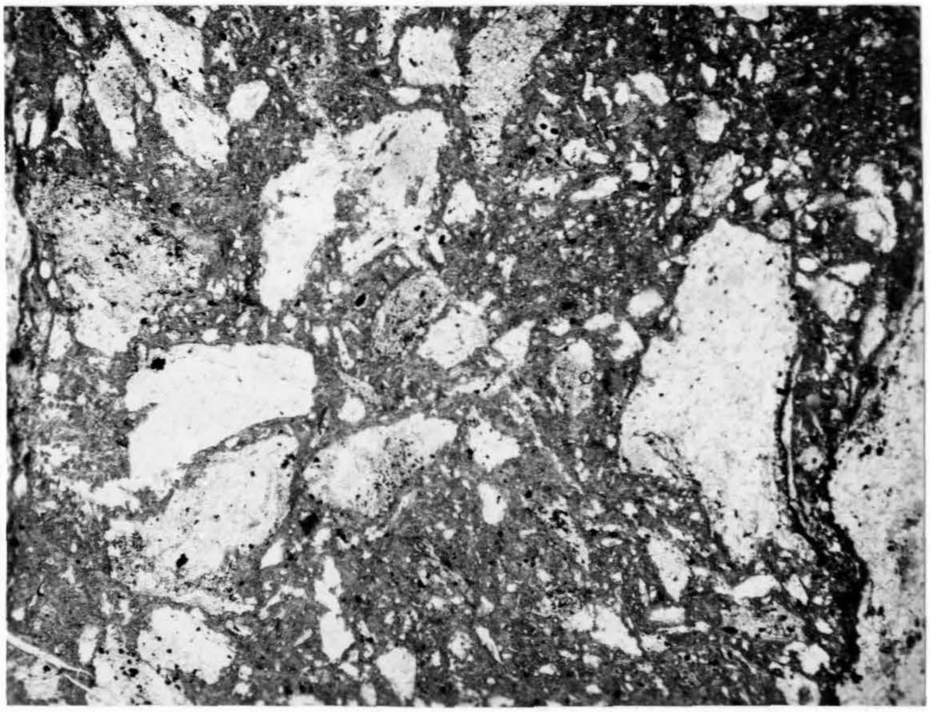


Figure 20b

the bedding in the schist and can be followed along a single horizon in each case for a distance of about 250 feet before disappearing. The brecciation does not extend beyond the tourmaline occurrence, and it is interpreted as having formed as a direct result of pneumatolytic or hydrothermal fluid surges along the channelways.

The spatial relations between two of the three black tourmaline occurrences and the intrusive contact suggest that this boron activity was associated with the plutonic emplacement. It is worth noting, however, that tourmaline has not been observed as an accessory mineral in the granodiorite although it is present in some of the associated pegmatites. The presence of a similar tourmaline as minute scattered irregular grains in many of the specimens of the schist examined may be a related phenomenon but it is not in such abundance as to preclude an original sedimentary origin for these dispersed grains.

Cataclasites of Laramide age in the Pinal schist

The important Laramide thrust faults which intersect the Pinal schist modify the structural trends within the schists for distances of several hundred feet from their traces. The earlier schistosity and bedding may be mechanically rotated, new cleavages developed and new small folds thrown into the section. Important changes in the texture and mineralogy of the schist form only in a restricted zone usually only 2 to 20 feet thick at the sole of a thrust. Within this zone, a cataclastic texture develops which makes distinction between the metasedimentary rocks of the schist and the enclosed pre-Cambrian rhyolites, very difficult.

In the steep-walled ravine between Sheep Camp Ridge and Keith Peak ($SE\frac{1}{4}$ sec. 17, T. 15 S., R. 21 E.) the thickest of these cataclasite zones is exposed. The zone is confined largely to the schist just above the sole of the great plate which constitutes most of the adjacent ridges and appears to be about 50 feet thick. It includes remnants of former mica rhyolite as well as graywackes. All visible evidence of original bedding and schistosity is destroyed. The mottled blue-gray and brown rocks are now very fine-grained, and are structureless except where they are cut by some irregularly spaced shears and joints.

In thin-section, this material is a heterogeneous mixture of highly sheared and granulated quartz grains, very fine-grained sheared sericite aggregates; coarser oriented sericite shreds and rotated fragments of slate and graywackes. Recrystallization is slight or absent at some points and prominent elsewhere. It takes the form or porphyroblastic white mica, full of inclusions, and of somewhat granoblastic quartz, twinned albite, and platy muscovite in a now highly foliated groundmass.

Even near this, the most intense zone of cataclasis observed in the Pinal schist, the formation assumes essentially its normal lithologic character within 50 feet of the sole of the thrust. It must be concluded that the influence of the Laramide thrusting on the metamorphism of the Pinal schist is predominantly a local one.

Retrogressive metamorphism

It is a conspicuous characteristic of the Pinal schist that textures frequently suggest the presence of former porphyroblastic minerals such as cordierite or possibly almandine, but the present mineral is invariably chlorite in fine-grained aggregates. Biotite is rather common but chloritized biotite is very abundant. Andalusite always displays partial sericitization and oligoclase frequently is sericitic. Such effects are more pronounced in the contact metamorphic zone, because of the higher initial rank of metamorphism, than in the rest of the schist.

In most cases, this retrograde mineral alteration does not seem to be related to a deformational episode. The single exception is found in the Laramide cataclastic zones where sericitization of feldspar and chloritization of biotite related to shearing is sometimes prominent. In general, the alterations are pseudomorphous with excellent preservation of original form.

The causes and timing of the widespread metamorphic readjustment to the lowest rank greenschist facies are probably multiple. Chemical readjustments to such low temperature equilibrium assemblages probably require some special mechanism to speed up the reactions. Since deformation cannot be called upon, probably aqueous pore solutions related to hydrothermal activity are the most reasonable conditions to invoke. Inasmuch as all phases of schist are downgraded, including the border zone next to the granodiorite, this effect is as young as or younger than that body. The granodiorite, itself, has a pervasive hydrothermal alteration (see pp.159-161) which is probably related in its origin to the retrogression in the schist. Certainly, late-stage deuteric or hydrothermal solutions derived from the granodiorite or its source could have contributed. Major shear zones on The Mesa (see page 181 and plate I) of post-Johnny Lyon granodiorite and pre-Apache group-age cross the intrusive contact from the pluton into the schist and show extensive hydrothermal mineralization, much of which is pre-Cambrian, but some of which may be as young as Tertiary. These could have been the channel ways for circulating hydrothermal solutions.

Some effects younger than the Laramide thrusting are clear. The development of coarse, undeformed, poikiloblastic muscovite crystals in otherwise comminuted cataclasites, both in the schist and granodiorite, argues for special conditions conducive to reconstitution. Silica-carbonate-pyrite mineralization in many of the Laramide fault zones confirms a late Cretaceous or Tertiary hydrothermal activity.

The presence of abundant Tertiary lamprophyre dikes, miles in length and up to 100 feet in width is also noteworthy. These ubiquitous rocks invariably show the pervasive alteration which is characteristic of their breed. These effects are much more intense than the alterations in the adjacent schist and it is possible that the lamprophyres sharedwith the surrounding schist some of the high water and carbon dioxide concentrations which they reflect.

Structure of the Pinal schist

General

The Pinal schist exposures in the Johnny Lyon Hills have already been described as an arcuate belt about nine miles long and south to southwesterly in trend. The width of this belt averages about three-fourths of a mile but attains a maximum of almost two miles. The belt curves around the intrusive Johnny Lyon granodiorite which lies to the northwest. On the east and southeast it is bounded by overlapping younger sedimentary rocks, late pre-Cambrian to Quaternary in age.

The structural elements within the belt are generally uniform in trend. The most marked deviations are found in the vicinity of the major Laramide thrust faults which transect the belt. These deviations are limited in area, and in general the older structures within the fault blocks are intact without much additional complication. The principal structural elements include sedimentary, metamorphic and igneous features as well as purely tectonic features.

Original sedimentary structures

Well preserved bedding may be recognized throughout most of the section. The prevailing strike is northeasterly, varying from due north at the north end of the belt to N. 60°-75° E. at the southwest end. The beds generally dip to the southeast but are commonly nearly vertical. Only in the areas of strong boudinage development has all evidence of bedding been removed. Widespread occurrences of graded bedding provide a useful criterion for top and bottom determinations. Dry stream beds where intermittent scouring has prevented an accumulation of the iron and manganese oxide stains found on most outcrops, and where abrasion has perhaps tended to etch out the matrix around the coarser grains thus emphasizing them, are particularly good sites for recognition of graded bedding. Rarely, small-scale, local cross-bedding and current channelling may also be found and used in the same way.

The profound angular unconformity between the older pre-Cambrian Pinal schist and Johnny Lyon granodiorite, and the younger pre-Cambrian

Apache group while not a sedimentary structure within the schist must influence any consideration of the older structures. It serves as a datum which must be restored to the horizontal before any reconstruction of structure within the schist is complete. Its remarkably regular erosion surface (see p. 196) permits its use as a structural reference plane with a minimum of complications.

Structures related to regional metamorphism

The metamorphic structures include both planar and linear elements. The most prominent planar feature is a steeply-dipping schistosity which is essentially parallel to the bedding in most exposures of schist. The schistosity strikes due north at the northernmost end of the belt, but gradually swings into a northeasterly trend until a strike of about N. 60° E. prevails where the belt intersects the western border of the map area. As is the case with the bedding, the dips are generally steep to the southeast ranging from 65 degrees to vertical.

Southwest of Keith Peak, a systematic divergence between the bedding and the schistosity is developed. This divergence appears only on the southeast side of the Pinal schist belt in the area. The rocks on the northwest side of the belt (i.e. closer to the margin of the granodiorite intrusive) have essentially parallel bedding and schistosity. The divergence is primarily one of strike, with the bedding striking more easterly (N. 55° E. to N. 80° E.) than the associated schistosity (N. 35° E. to N. 60° E.). The angle of divergence appears to increase gradually to the southeast along any line normal to the strike and reaches a maximum of 25 to 30 degrees. Both schistosity and bedding generally dip 70 to 90 degrees to the southeast but locally pass through the vertical to dips of 80 degrees to the northwest. These dips are usually within 5 degrees of each other and no consistent directional relation between the two dips could be recognized.

The schistosity takes the form of a pervasive cleavage in the slates and phyllites but is generally only weakly expressed in the metagraywackes. It is an axial-plane shear cleavage in relation to minor folds in the section (fig. 21). Recrystallization has contributed to the foliation where metamorphism was more intense than in the slates. Where dynamic effects have produced boudinage the major and intermediate dimensions of the boudins lie in the plane of the schistosity. Flattened pebbles and elongate porphyroblasts also lie in this plane.

A second planar structure is developed intermittently in the schist at numerous localities in the southwestern two-thirds of the Pinal belt. It is a sub-horizontal fracture cleavage, generally dipping to the west, northwest, or north and is nearly normal to the bedding and schistosity. It is locally very pervasive, particularly in the vicinity of the Laramide thrust faults, but in most outcrops it is irregularly spaced and is in part only incipient. This cleavage appears to be distinctly younger than the schistosity and microscopically has the aspect of a false cleavage. It may actually displace the schistosity and bedding one to several millimeters and then pass laterally into an undisplaced wrinkle in the schistosity. This produces striking linear elements visible in reflection from the wrinkled schistosity in strong sunlight (fig. 22). Best expressed

Figure 21. Small fold in interbedded slate-graywacke beds in the Pinal schist showing the axial plane cleavage.

Figure 22. Phyllite outcrop in the Pinal schist showing a steeply plunging older lineation (wrinkling) in the schistosity transected by a younger, sub-horizontal cleavage and wrinkling. The latter wrinkling is reflecting the light in the lower part of the photograph.

Figure 21

Figure 22

in outcrop as a linear intersection with the schistosity, the feature has been so mapped. From the orientation and frequency of distribution, this cleavage is interpreted as Laramide in age.

Numerous joints constitute still another type of planar structure commonly found in the Pinal schist. These have not been mapped but a conspicuous set (fig. 6) is nearly normal to the schistosity. It forms nearly equiangular rhombs on the intersected bedding and schistosity planes with one diagonal nearly vertical and the other nearly horizontal. These rhombs are responsible for the 'sharks-fin' type of outcrop usually seen in the schist areas. Other joint sets are present but are less persistent in distribution.

In addition to the Laramide(?) lineation, there are numerous other types of linear elements in the Pinal schist that generally have a common orientation. In approximate order of decreasing abundance, minor fold axes, intersections of bedding and schistosity, wrinkling in the schistosity, pencil structure in slates, boudinage structures, elongate porphyroblasts, and stretched pebbles provide the bases for lineation measurements. Generally, two or more of these elements occur together and are parallel. They may all be classified as b- lineations after the reference axes of Sander (as quoted in Knopf and Ingerson, 1938, p. 45; and Fairbairn, 1949, pp. 4-6).

The minor folds on which the attitudes of the axes were determined, range in amplitude from tens or hundreds of feet down to a fraction of an inch. Some of these involve dozens of beds in which numerous minute drag folds can also be observed in the interbedded slates (fig. 21). The larger folds closely approach isoclinal form, but many smaller folds, particularly those less than 10 feet in amplitude, are more open and display the asymmetrical form of drag folds. The axial-plane nature of the schistosity is well displayed in both types of folds.

Within a few hundred feet of the Laramide thrust faults, a few younger small folds have been developed whose relative age can be recognized by the fact that the schistosity as well as the bedding has been deformed. Although a new fracture cleavage may also be developed at these points, it is not axial plane and is readily distinguished from the older schistosity. These younger fold axes are not numerous enough to justify mapping them. It is worth noting that they plunge S. 30°-50° W. @ 0°-30° and appear to be parallel to the direction of movement of the thrust plates.

Where the bedding and schistosity are not parallel, the intersections of these S-planes constitute a consistent linear orientation. This is true whether the divergence is local as in the crest of a small fold, or persistent over a mile of outcrop. This feature is best developed in some of the color-banded slates, and in the interbedded slates and siltstones.

Wrinkling on the schistosity is very common. In addition to the wrinkling associated with the younger (Laramide?) transverse sub-horizontal cleavage, there is an older and finer-textured crenulation in many of the slates and phyllites (see figs. 22, 23). The amplitude and wavelength of the wrinkling are commonly only a millimeter, or less, but the pervasive, strongly oriented pattern usually permits easy measurements of the lineation. When found associated with small folds (fig. 23) or with boudins, it has a similar orientation.

Figure 23. Phyllite outcrop in the Pinal schist showing the parallelism between small fold axes and fine wrinkles in the schistosity.

Figure 24. Steeply plunging metagraywacke boudins in the Pinal schist give the appearance of a "pseudo-conglomerate". The projecting boudins and the pencil in the upper right corner indicate the direction of plunge.

Figure 23

Figure 24

Figure 25. Boudinage structure in the Pinal schist. The quartzite blades derived from former sandstone beds plunge steeply in the mica schist as indicated by the pencil at the top of the photograph.

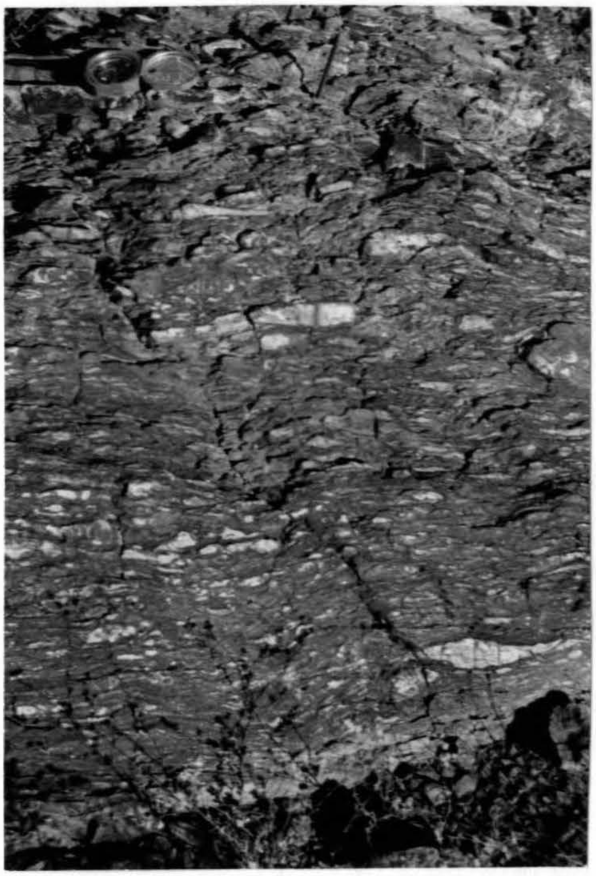


Figure 25

The origin of this wrinkling is not clear. It can be related to bedding-schistosity intersections in some places, but elsewhere it appears where these planes are parallel. It is possible that these crenulations are minute drag folds, but they are usually too small to establish clearly whether systematic asymmetry exists.

Pencil structures in the slates can be observed in slate beds in some of the cores of tight folds. They are formed by the intersection of bedding and the axial plane cleavage.

Boudinage structures are found principally in the southern exposures of the Pinal schist. The structure consists of isolated rods or blades of recrystallized muscovite-quartzite in a matrix of muscovite-chlorite schist. The rods are elongated in a common direction and have flattened elliptical cross sections whose longer axis is parallel to the schistosity (figs. 24, 25). These bodies of quartzite were formerly thin interbeds of graywacke in a slaty section of the Pinal schist. In response to deforming stresses, the section was tightly folded and the coarse-grained beds, lacking the capacity to flow as readily as the associated slates and phyllites, failed in extension and separated along lines parallel to the fold axes. Various arrested states, from the incipient local thinning ("necking down") of the graywacke beds to the actual parting into separated laths or rods, are visible in the area south and southwest of Keith Peak. In a small window through the alluvium in sec. 33, T. 15 S., R. 21 E., near Tres Alamos Wash, a most striking example of this "pseudo-conglomerate" is exposed. Only occasional relic crescentic cross-sections among the rods suggest originally folded beds in this outcrop.

The porphyroblasts of phyllites and schists have not been good sources of lineation data. The porphyroblasts are not very large or elongate in habit, and although preferred orientation is suggested locally, it cannot always be measured precisely. Where the best developed orientations are displayed, petrographic examination indicates a rotation of the porphyroblasts after growth. Only a half dozen acceptable measurements could be made and these are in agreement with adjacent wrinkles or fold axes.

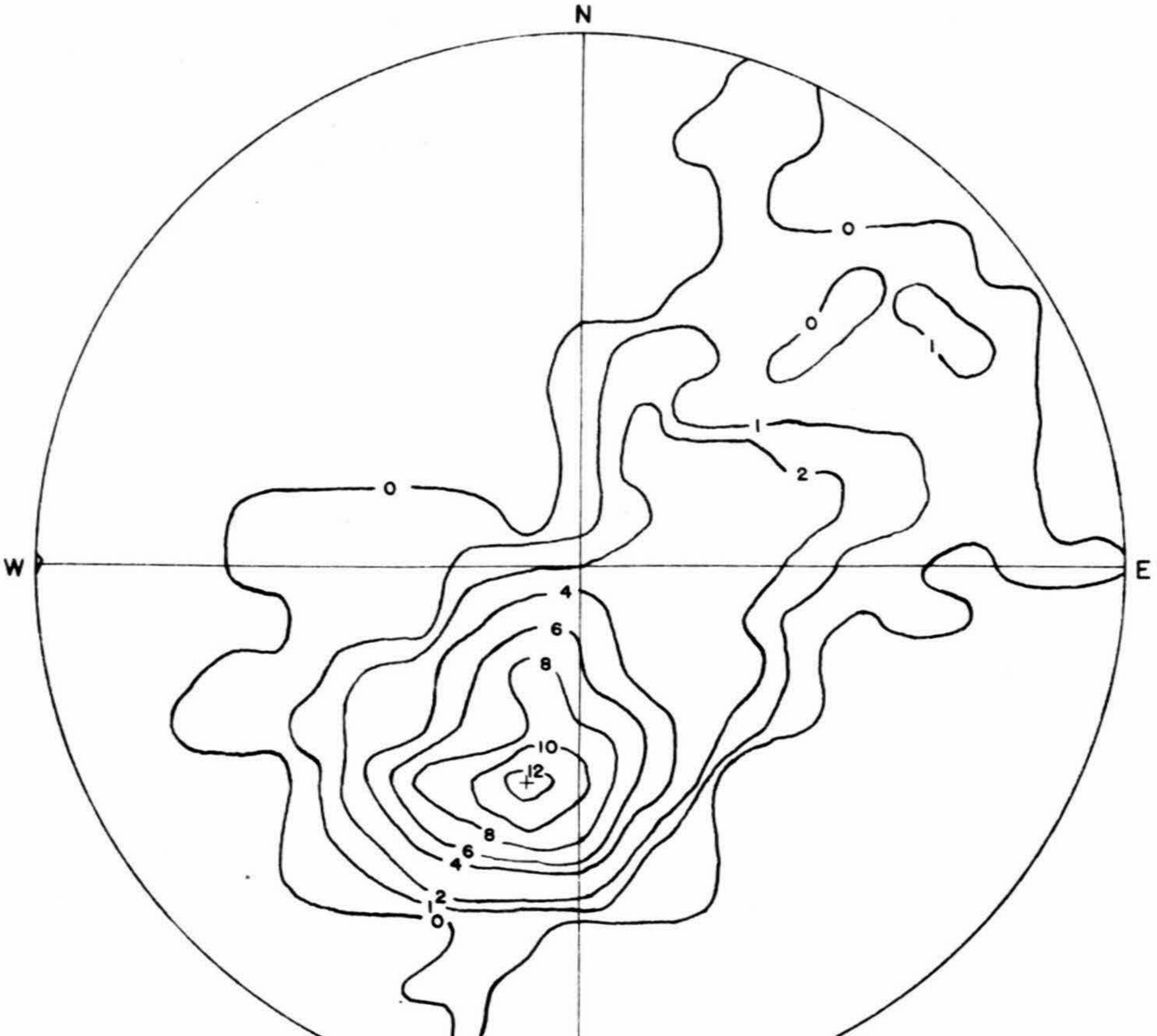
Remarks on the flattened pebbles of the infrequent conglomerates of the Pinal schist have already been made (p. 35). Some stretching in a preferred direction can be observed and this direction coincides approximately with other local lineation orientation. Unfortunately the stretching has not been so pronounced as to provide precise data.

The lineation data obtained from throughout the nine-mile belt show a considerable degree of consistency, whether plotted for individual localities, for the entire belt, or by the type of lineation feature. A plot of average values at 230 localities (fig. 26) obtained from most of the lineation types described and compiled from throughout the belt has been made on a Schmidt equal-area stereographic net. The maximum concentration of the linear elements is at a pole plunging S. 12 W. at 56 degrees. A circle with one percent of the total plot area, centered at this point contains 14 percent of the measured values. There is, in addition to this maximum, a less well-defined girdle of values lying on a plane of approximate orientation, N. 45 E. @ 70-75° SE. This plane corresponds to about the average attitude of the schistosity throughout the belt.

This plot includes all of the types of lineation mapped except-

Figure 26. Equal-area net plot of the average lineation attitudes at 230 localities in the Pinal schist throughout the Johnny Lyon Hills. Contoured at 0, 1, 2, 4, 6, 8, 10, 12%. Maximum concentration at pole plunging S12°W at 56°.

LINEATIONS AT 230 LOCATIONS IN PINAL SCHIST, JOHNNY LYON HILLS



CONTOURED AT
>0-1-2-4-6-8-10-12 %
MAXIMUM (+) AT POLE
PLUNGING 56° S12°W

Figure 26

ing the wrinkling formed by the younger, nearly horizontal transverse cleavage. Some of these lineations may have been subjected to some local post-Cambrian rotations, particularly in the vicinity of the Laramide thrust faults. However, no attempt has been made to eliminate suspicious observations from this compilation, and such younger influences may be considered to have contributed some dispersion to the original degree of preferred orientation.

In a few localities southwest of Keith Peak, there coexist two steep lineations, not in agreement and independent of the transverse cleavage. One of these is generally a bedding-schistosity intersection, and the other is wrinkling or small scale drag folding. The deviation between them may be as much as 30 or 40 degrees. Whether these are merely statistical variations from the general pattern of agreement of these features due to local conditions, or whether they represent two different episodes of deformation is not understood. They are an uncommon phenomenon.

Structural features related to igneous phenomena

The structural pattern of the Pinal schist is partly defined by such associated features of igneous origin as (1) the persistent zone of intrusive rhyolite porphyry sheets; (2) the mica rhyolite intrusive sheet zone; (3) the intrusive contact of the Johnny Lyon granodiorite. Although all of these features are younger than the Pinal schist, they formed at different times and give some information on the nature of subsequent structural modifications in the older rocks.

The zone of rhyolite porphyry sheets has already been described, but it is desirable to review its age and structural relations. The porphyry was intruded into the Pinal schist preceding or during the major deformation and metamorphism of the host formation. It shared fully in the metamorphism but there is no evidence of duplication of the zone by folding or faulting. The zone maintains a thickness of 800-1,000 feet in its exposures as it passes through the belt of schist for a distance of six miles. It appears to be parallel to the bedding and schistosity throughout its length. The only other rhyolite porphyry outcrops are in limited exposures on the southeast side of the Pinal belt, two miles south of Keith Peak.

The exposures of the mica rhyolite intrusive sheet zone are confined to the Pinal schist southwest of Keith Peak. The sheets are essentially parallel to the bedding and the schistosity, and are also parallel to the rhyolite porphyry at a distance of about 500 feet southeast of the latter. They are definitely younger than the metamorphism of the Pinal schist and are interpreted tentatively as older than the Johnny Lyon granodiorite.

The emplacement of the large pluton of the Johnny Lyon granodiorite produced the intrusive contact which extends along the entire northwestern side of the belt. This contact is crescentic in trace and is obliquely discordant to the general bedding and schistosity in the Pinal schist. It is important in the interpretation of the later structural history of the Pinal schist, as a major element which has a more gentle southeastward dip than the older structures of the schist.

Pre-Cambrian fault structures

No major faults have been recognized that can be attributed to the regional deformation of the Pinal schist prior to the intrusion of the Johnny Lyon granodiorite. A number of planes of shearing can be seen to break the crests of some of the isoclinal folds but these surfaces represent limited displacements. It is possible that major faults with strikes paralleling the foliation and bedding of the schist are present, for such faults are to be expected in deformed zones of the type found here. Unfortunately, detailed stratigraphic markers by which such faults might be recognized are lacking in the schist. The continuity of the rhyolite porphyry sheet zone throughout all of the schist exposures does argue strongly against any important transverse displacements of the same age.

Subsequent to the intrusion of the Johnny Lyon granodiorite persistent, steep, north-south shear zones which were loci of later alteration developed in the intrusive. The easternmost of these shear zones offsets the Pinal schist-granodiorite contact in the NE$\frac{1}{4}$, sec. 9, T. 15 S., R. 21 E. The fault movement is difficult to analyze because of the irregularity of the contact, but a reverse displacement of the order of hundreds of feet is suggested. This is the only significant pre-Cambrian fault known to involve the Pinal schist.

Overall structure of the schist

The overall structure of the Pinal schist was formed during three major episodes in its history; (1) the pre-Cambrian regional deformation and metamorphism, (2) the pre-Cambrian post-orogenic plutonic intrusion, and (3) the late Cretaceous or early Tertiary regional deformation. To understand the older structures, the complicating effects of the younger structures must be taken into account. A brief preliminary account of the later effects is introduced here.

The emplacement of the Johnny Lyon pluton into the Pinal schist appears to have influenced the structural orientation of the schist at the northern end of the belt. Here the foliation trend swings from about N. 45° E. at Javelina Hill to the north-south trend at the pinch-out south of the Willcox-Cascabel road. This forty-five degree change is accompanied by a twenty or twenty-five degree swing in the same direction of the overlying unconformable strata. Therefore only twenty or twenty-five degree disturbance (the difference between the two changes of bearing) can be attributed, perhaps, to the pre-Cambrian emplacement of the pluton. Only a slight steepening of the dip of the foliation accompanies the distinct change in strike.

There is no evidence available from which to determine whether the intrusion of the pluton was responsible for an overall change of orientation of the schist belt. This requires a reliable reference structure of known pre-intrusive orientation, and none has been recognized.

As has already been noted, Laramide thrust faults transect the Pinal schist belt as well as younger strata. The stratigraphic and structural evidence indicate minimum displacements on these faults of one-half mile to more than a mile, and probably displacements that are considerably greater. For the faults directly involving the schist and granodiorite evidence indicates that the plates were thrust from the southwest along an approximate line bearing N. 30°-40° E. The present traces of these faults trend northwest and southeast with considerable irregularity.

One large normal fault, trending approximately N. 30° W., is younger than the thrusting. It appears on the west flank of Sheep Camp Ridge, and crosses the western brow of Keith Peak. This fault dips 50 to 60 degrees to the northeast and the northeastern block has been dropped 400 to 500 feet along the dip slip component. The displacement applies to the Pinal schist and granodiorite, both above and below the visible thrust faults, and must be considered as an important contribution to the left lateral offset of the intrusive contact northwest of Keith Peak.

As a result of the transverse faulting, the belt of Pinal schist has been divided into five major blocks (see fig. 27 and plate I). The northeastern block (I) extends from the thrust fault on the northeast side of Keith Peak to the erosional unconformity at the base of the Apache group. Keith Peak and Sheep Camp ridge constitute the next block (II) to the southwest, bounded by the thrust fault on the northeast and the large normal fault on the southwest. This block is still covered with younger rocks, except in the steep-walled gap between the two heights. The next block (III) lies between the normal fault on the northeast and an east-dipping major thrust fault. A small block (IV) lies between this thrust and a west-dipping thrust on the southwest side. The last block (V) extends from the multiple traces of this last fault, southwestward out of the map area.

Blocks II and III are offset segments of the same thrust plate,

Figure 27. Generalized geologic map of the Johnny Lyon Hills, showing the various blocks into which Laramide (?) faulting has separated the belt of Pinal schist.

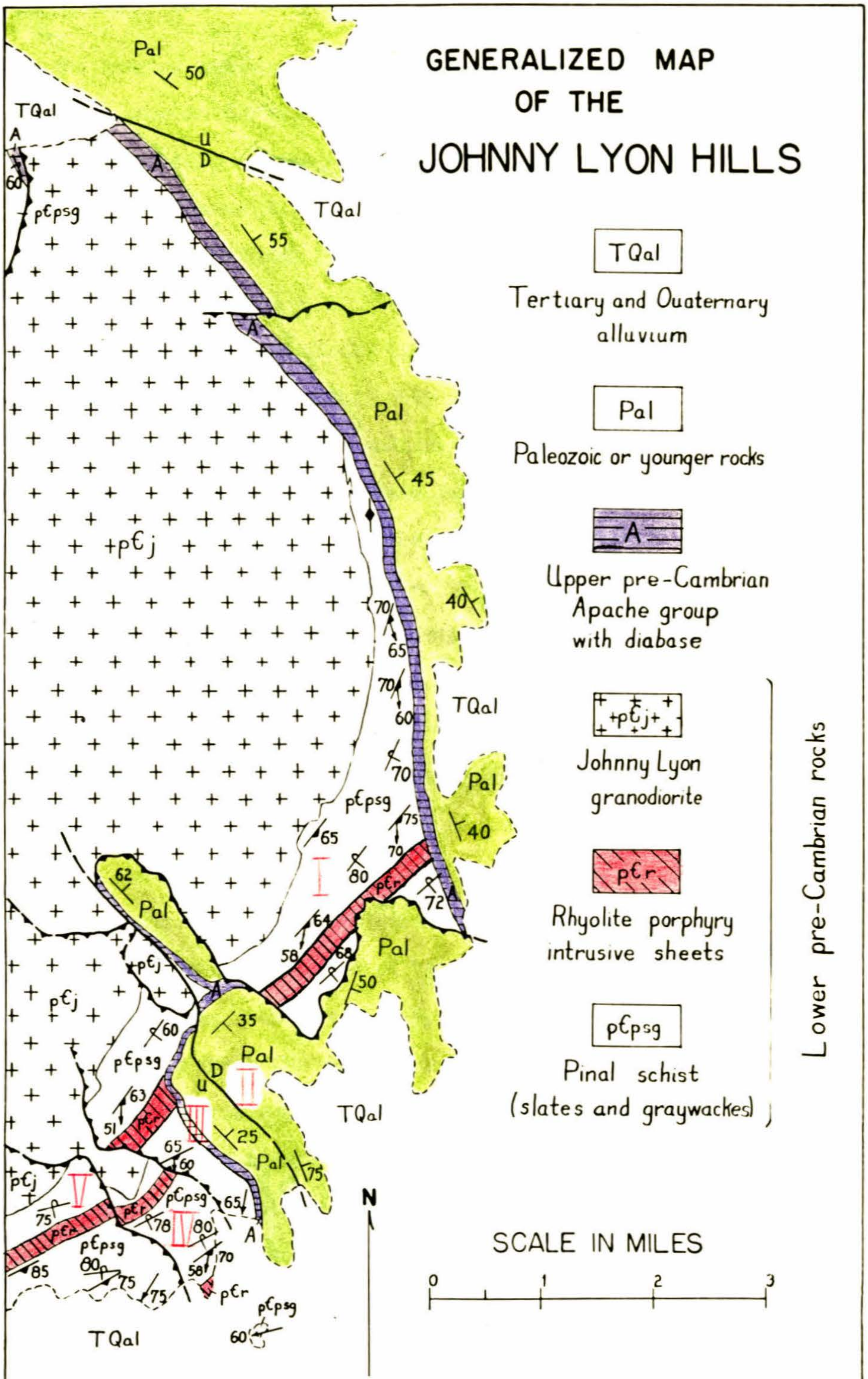

GENERALIZED MAP
OF THE
JOHNNY LYON HILLS
TQal
Tertiary and Quaternary alluvium
Pal
Paleozoic or younger rocks
A
Upper pre-Cambrian Apache group with diabase
+pЄj+
Johnny Lyon granodiorite
pЄr
Rhyolite porphyry intrusive sheets
pЄpsg
Pinal schist (slates and graywackes)
Lower pre-Cambrian rocks
N
SCALE IN MILES
0
1
2
3

Figure 27

and the limited exposures of schist in block II indicate it has the same character as the schist in block III. Blocks I and IV underlie blocks II and III, but are separated, of course, by the large normal fault on Keith Peak. Block V is also part of a thrust plate, which at present overlies block IV, and once may have overridden part of block III also.

All of the stripped blocks (I, III, IV, V) of the Pinal schist share many features in common. They are all bounded on the northwest by the intrusive contact and are bounded on the southeast by the alluvium. The zone of rhyolite porphyry sheets parallels the schistosity and bedding through the central interior of each block and maintains its fairly constant width. In all of the blocks except block I, mica rhyolite sheets constitute a lesser but still prominent zone, also paralleling the major planar structures, at a nearly constant distance from the rhyolite porphyry sheets. A limited number of thin (2 to 5 ft. thick) short sheets of sheared mica rhyolite are found scattered in the schist, close to the intrusive contact in blocks II, III, and V.

The sections of Pinal schist within the various blocks are similar. Each has a thick section of beds on the northwestern side of the block, ranging from more than 9,000 feet in block I to 2,500 feet in block IV, in which the sedimentary structures and textures are well preserved. Numerous graded bedding measurements indicate the tops of the beds are almost invariably to the northwest. These sections are therefore overturned since they dip to the southeast. There are a few reversals to the general relation, but in blocks I and III, it can be argued that these are not significant. In these blocks the principal reversals occur in a narrow belt about 200 feet wide immediately north of the rhyolite porphyry zone. Inasmuch as this intrusive zone, which appears to be older than the deformation, is not duplicated by this reversal, the dip reversal is interpreted as a minor isoclinal fold in the section. This argument cannot be applied at some of the other points of reversal, but nevertheless the predominant condition of overturned beds with tops to the northwest is clear.

The general parallelism of the schistosity and bedding which is characteristic of most of the schist, makes a gradual transition to a systematic divergence as any one of the blocks is traversed in a southeasterly direction. In the limited exposures on the east side of Javelina Hill, the schistosity appears to be a few degrees more northerly than the bedding. The divergence does not become impressive until a point 1,000 to 1,500 feet southeast of the edge of the rhyolite porphyry sheet zone is reached, in most of the schist exposures southwest of Keith Peak. At this position the schistosity is 10 to 15 degrees more northerly than the bedding, but with a similar dip. Farther southeast, bedding attitudes of N. 70°-80° E. at 70°-90° E. are intersected by schistosity attitudes of N. 40°-50° E. at about the same dip angles.

At approximately the same position in the section where the bedding plane-schistosity divergence becomes clear, series of asymmetrical folds commonly appear. These folds have axial planes parallel to the schistosity and axes of consistent orientation, plunging very steeply to south or southwest. Their amplitudes are measured in feet or tens of feet and a series of folds may sometimes be followed obliquely across the schistosity for distances up to several hundred feet. The asymmetry of the folds in the series is such as to suggest drag folds formed by a clockwise couple in which a force on the southeast side of the series moved southwest relative to an opposite force on the northwest side of the series. Figure 28 is a simplified diagram taken from field sketches and photographs, showing the typical orientation of folds in one of these series and the relation of the graded bedding in the folds. Note that the axes of the folds are overturned.

To the southeast of the series of asymmetrical folds, folding becomes more prominent. Most of the folds are tighter and more nearly isoclinal. Since even this section has graded beds with tops to the northwest prevailing, the reversals in graded bedding are often the first field indication of the folding. In some cases, the reversed beds can be walked continuously into each other, but commonly the fold limbs are separated by axial plane shear surfaces. Considerable sequences of alternating graded graywacke and phyllite can be recognized in mirror image relation to an axial plane. These folds range from a few feet to hundreds of feet between adjacent axial planes, and have amplitudes up to many hundreds of feet.

The axial planes of these folds are parallel to the schistosity, in general, and dip steeply to the southeast. The graded bedding corroborates that the northwest limbs of folds opening to the southwest are overturned. The graded bedding also indicates that the beds in the cores of these same folds are older than those in the limbs. As in the more asymmetrical folds, these tight folds plunge steeply, usually 50 to 80 degrees to the south or southwest. A few folds plunge vertically and very uncommonly a steep southeast plunging fold is observed. But again the conclusion is unmistakable that most of these

Figure 28. Sketch of asymmetrical folds in graded beds of Pinal schist southwest of Keith Peak. The cleavage is generally axial plane but commonly shows a slight radiating pattern in the crests of the folds.

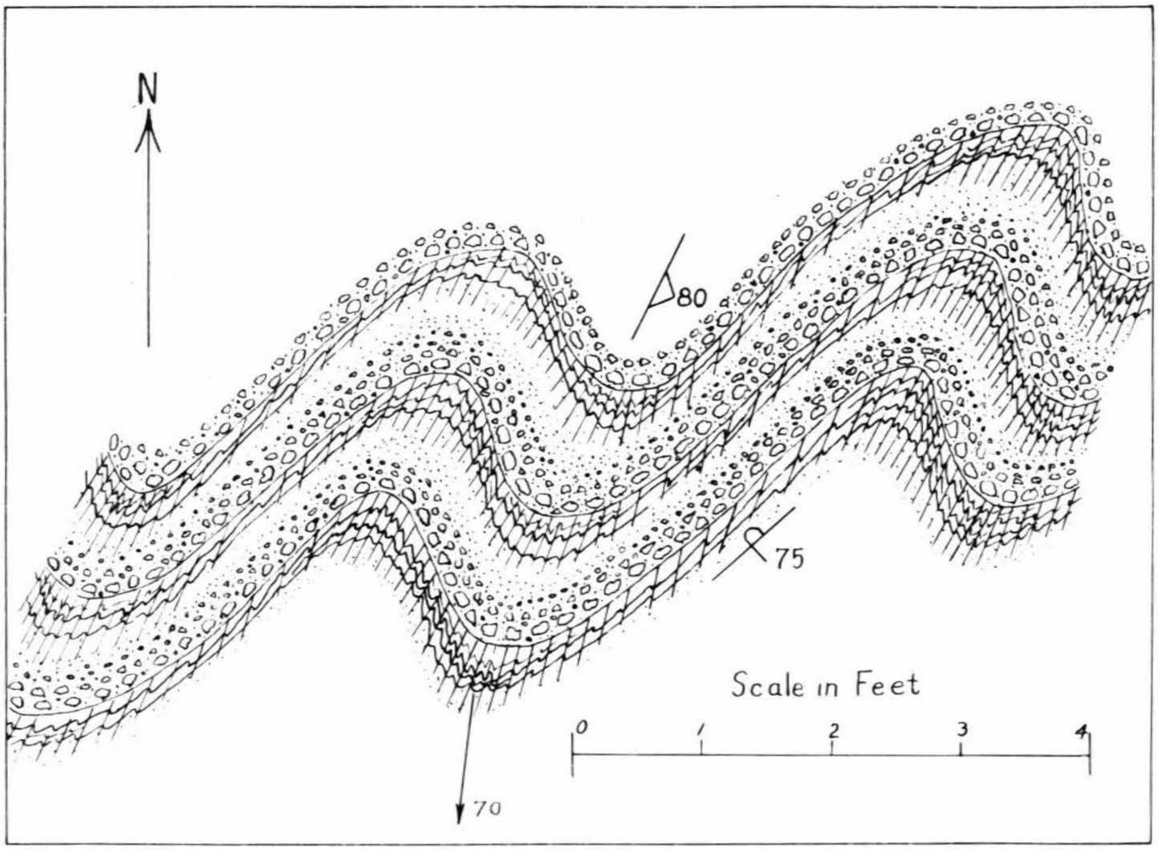


Figure 28

folds have axes which are overturned.

Dynamic metamorphism is much more important here, of course, than elsewhere in the blocks of schist. Lineation features are prominent and in general are parallel with the fold axes. The lineations include many types but most striking are the boudinage structures which may be seen in various stages of development. Their relation to the flowage associated with isoclinal folding of the beds of alternating and contrasting competency is clear.

Any attempt to integrate the various blocks into pre-Laramide structural pattern is limited by the fact that most of the intervening faults are thrusts of considerable displacement. The general directions of the thrusting and some idea of minimum displacements can be deduced from several lines of evidence, but this is insufficient for accurate reconstruction. The Laramide effects have contributed an apparent lateral shortening of the pre-Cambrian section in the direction of the pre-Cambrian structural trend. Some indication of the deviations from parallelism to this direction can be obtained from the apparent offset of such features as the intrusive contact, and the rhyolite porphyry and mica rhyolite zones. Of course, no corrections for vertical components of displacements on the thrust faults are feasible from the available data.

The general similarities of lithology, structure and metamorphism shared among the various blocks of Pinal schist indicate that they are segments of a formerly continuous structural unit. This northeast-southwest trending unit from which the present belt was developed, contained a steeply overturned but continuous section with parallel bedding and foliation. This section grades southeastward into a similar lithologic zone of systematically divergent bedding and schistosity where folding and dynamic metamorphic effects are increasingly prominent. The linear structures throughout the entire unit are consistently nearly parallel and are clearly b-lineations with respect to all magnitudes of folding observed in the field.

One possible interpretation of the Pinal structure (involving considerable extrapolation) places it within one limb and part of the core of a large anticlinal fold. This fold would have an amplitude on the order of ten miles and involve ten thousand feet or more of section. As sketched schematically in figure 29, the fold would be nearly isoclinal and trending northeast-southwest. Its northwest limb (the Johnny Lyon Hills section) is overturned and its axial plane inclined at a steep angle to the southeast. The axis of the large fold is assumed to be compatible with that of its subordinate folds and therefore plunges steeply to the southwest.

As this interpretation requires the fold axis to be overturned, there is a natural hesitation in accepting it. However, at this point one must consider the post-Cambrian structural influences which might have contributed to major overturning of older fold axes.

The northeastern end of the Pinal schist belt in the Johnny Lyon Hills is truncated by the pre-Cambrian unconformity at the base of the Apache group. The contact between the schist and the Pioneer shale crops out almost continuously from the Willcox-Cascabel road south to Tres Alamos Wash. It dips northeast at an average angle of about 42 degrees and trends N. 10° W. The present trend has been determined in part by numerous, small transverse right-lateral normal faults between which the beds strike about N. 30° W. To place the

Figure 29. Schematic diagram of a hypothetical major pre-Cambrian fold in the Pinal schist, parts of which may be exposed in the Johnny Lyon Hills.

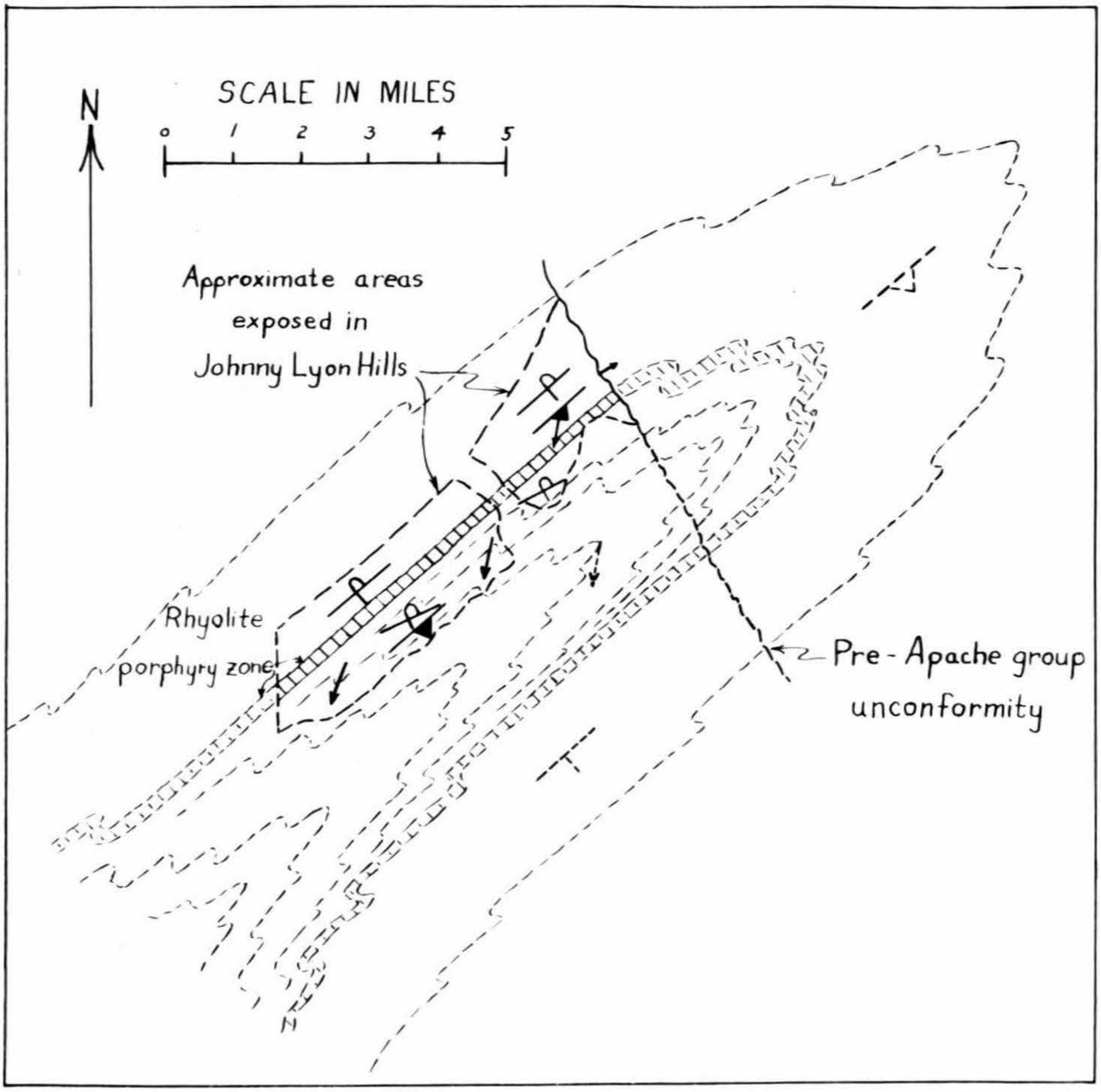

N
SCALE IN MILES
0
1
2
3
4
5
Approximate areas
exposed in
Johnny Lyon Hills
Rhyolite
porphyry zone
Pre-Apache group
unconformity

Figure 29

Pinal schist structural trends in their true pre-Cambrian orientation, it is necessary to perform a reconstruction which eliminates the faults and rotates the unconformity into a horizontal plane.

A stereographic solution for this reconstruction (see fig. 30) rotates the older structures 42 degrees about an axis striking N. 30° W. The regional foliation is transformed from N. 45° E. at 70° SE. to N. 63° E. @ 65° SE. The regional lineation is transformed from a plunge of S. 12° W. at 56° to S. 63° E. at 60°. By this restoration, the observed smaller folds and the speculative large fold are attributed with originally steeply plunging but normal axes. Their axial planes are still inclined to the southeast and each fold has an overturned limb.

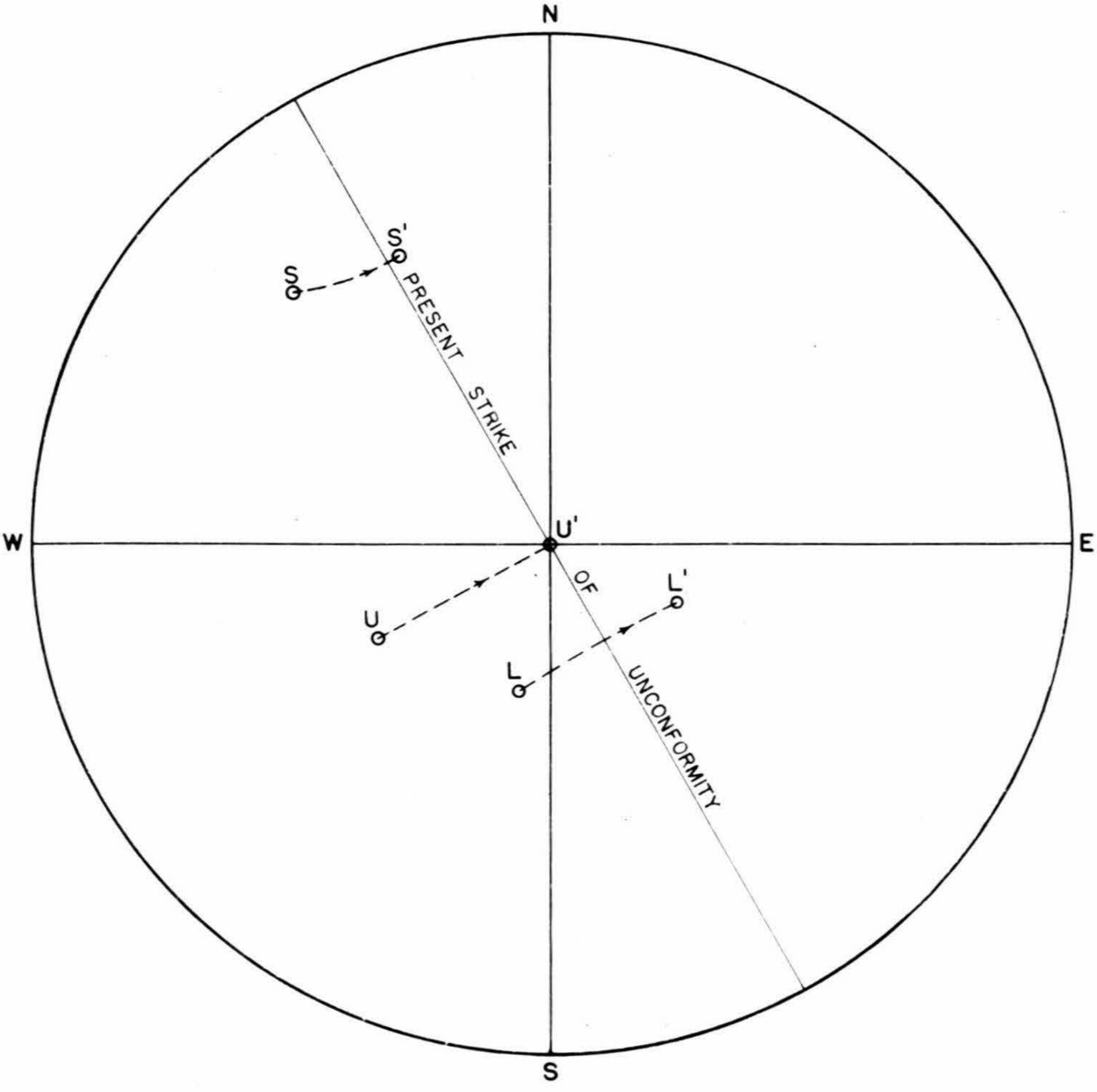
The size of the block which must be rotated to include all of the schist is greater than 6 miles in a northeast-southwest direction. The uniformity of structural attitudes, particularly the lineations throughout the schist, argues against any lesser size. A more than forty-degree rotation of such magnitude demands much from geological credibility. It should be pointed out however that the required NE-SW dimension of the rotated block is of no greater magnitude than that demonstrable in a horizontal direction. The present exposed trace of the pre-Apache unconformity in the Johnny Lyon Hills is more than 10 miles long and is rotated on the average of fifty degrees throughout its length.

If such a large block was rotated the implication exists that the southwestern end of the belt was once buried miles deeper than the northeastern end. Such a condition at the time of regional metamorphism might be expected perhaps to have produced a higher rank in

Figure 30. Stereographic solution for the restoration of the general foliation and lineation in the Pinal schist to its pre-Apache group orientation.

Present attitude of the Apache group = N30°W dipping 42°NE.
Present foliation = N45°E dipping 70°SE.
Restored foliation = N63°E dipping 65°SE.
Present lineation plunge = S12°W at 56°.
Restored lineation plunge = S63°E at 60°.

STEREOGRAPHIC SOLUTION FOR THE RESTORATION OF PRE-APACHE GROUP STRUCTURAL ATTITUDES IN THE PINAL SCHIST



	PRESENT	RESTORED
SCHISTOSITY POLE	S	S'
LINEATION	L	L'
UNCONFORMITY POLE	U	U'

Figure 30

nether extremity. The general uniformity of the rank of metamorphism throughout the belt does not confirm this.

The prevailing schistosity and bedding of the Pinal schist in Johnny Lyon Hills is in agreement with that of the Little Dragoon Mountains, and with the attitudes in the schist throughout southeastern Arizona. The tight folding requires strong compressive forces of northwest and southeast orientation. Such forces left their imprint almost everywhere the Mazatzal revolution is recorded throughout Arizona.

Origin of the Pinal schist

Field studies of the Pinal schist in the Johnny Lyon Hills and the extensive work in the nearby Little Dragoon Mountains by John R. Cooper and others, represent the first detailed investigations of the older pre-Cambrian schists in southeastern Arizona. The widespread exposures of older pre-Cambrian rocks in the two areas (figs. 27, 31, 32) and the relatively low rank of metamorphism in large parts of these areas, permitted some progress to be made in understanding the origin and complexities of the formation.

The late F. L. Ransome's early conclusions on the sedimentary origin (1903, p. 27; 1904, p. 26) of the schists and quartzites which underlay the great Ep-Archean erosion surface in southern Arizona, have been confirmed. His speculations on the basic extrusive origin of some of the associated amphibolite schists also have been confirmed. (The general soundness of Ransome's field observations makes some of his concise comments the best available source of information on much of the pre-Cambrian rocks of the region).

Figure 31. Map showing the distribution of older pre-Cambrian rock in the Dragoon quadrangle.

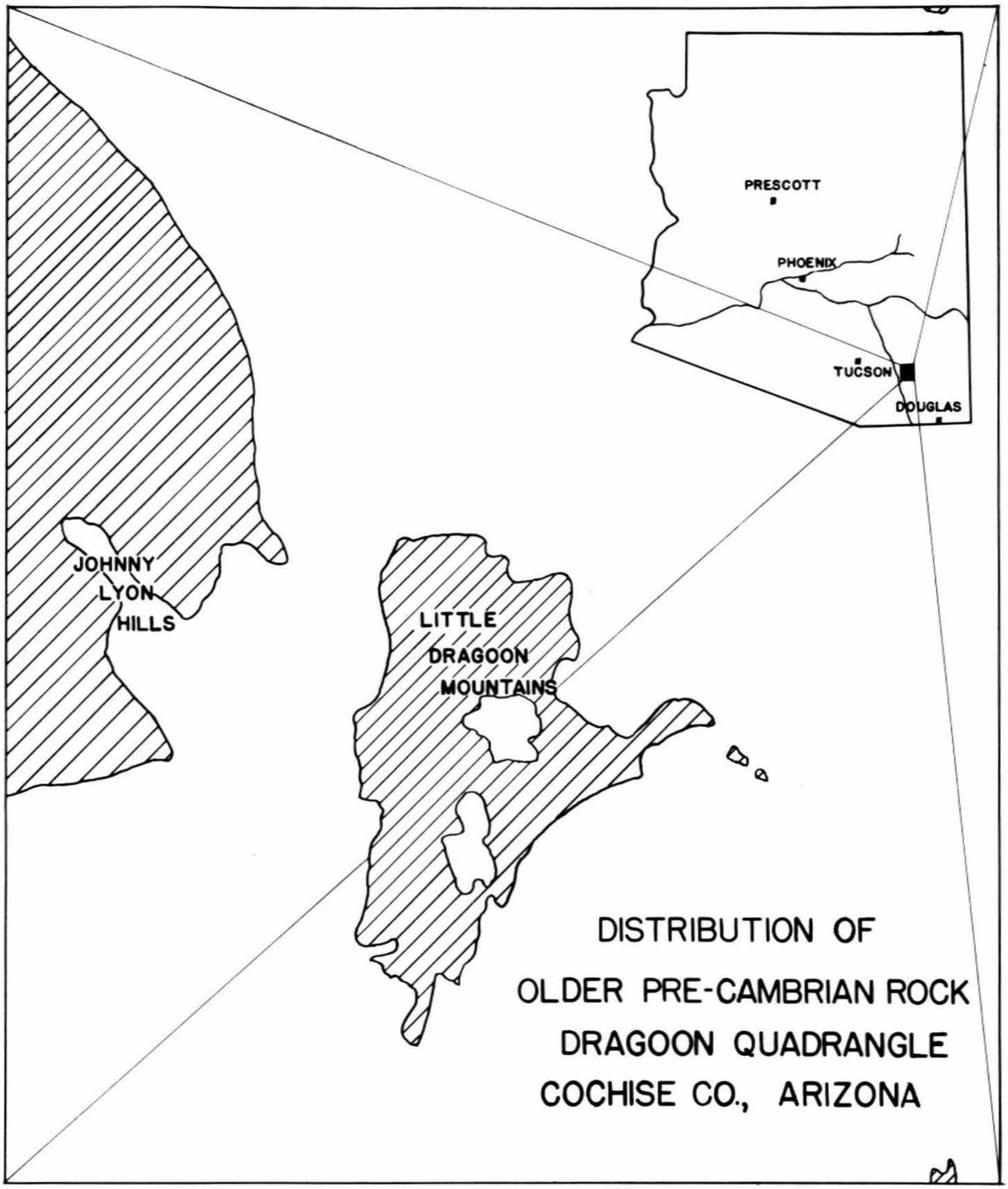
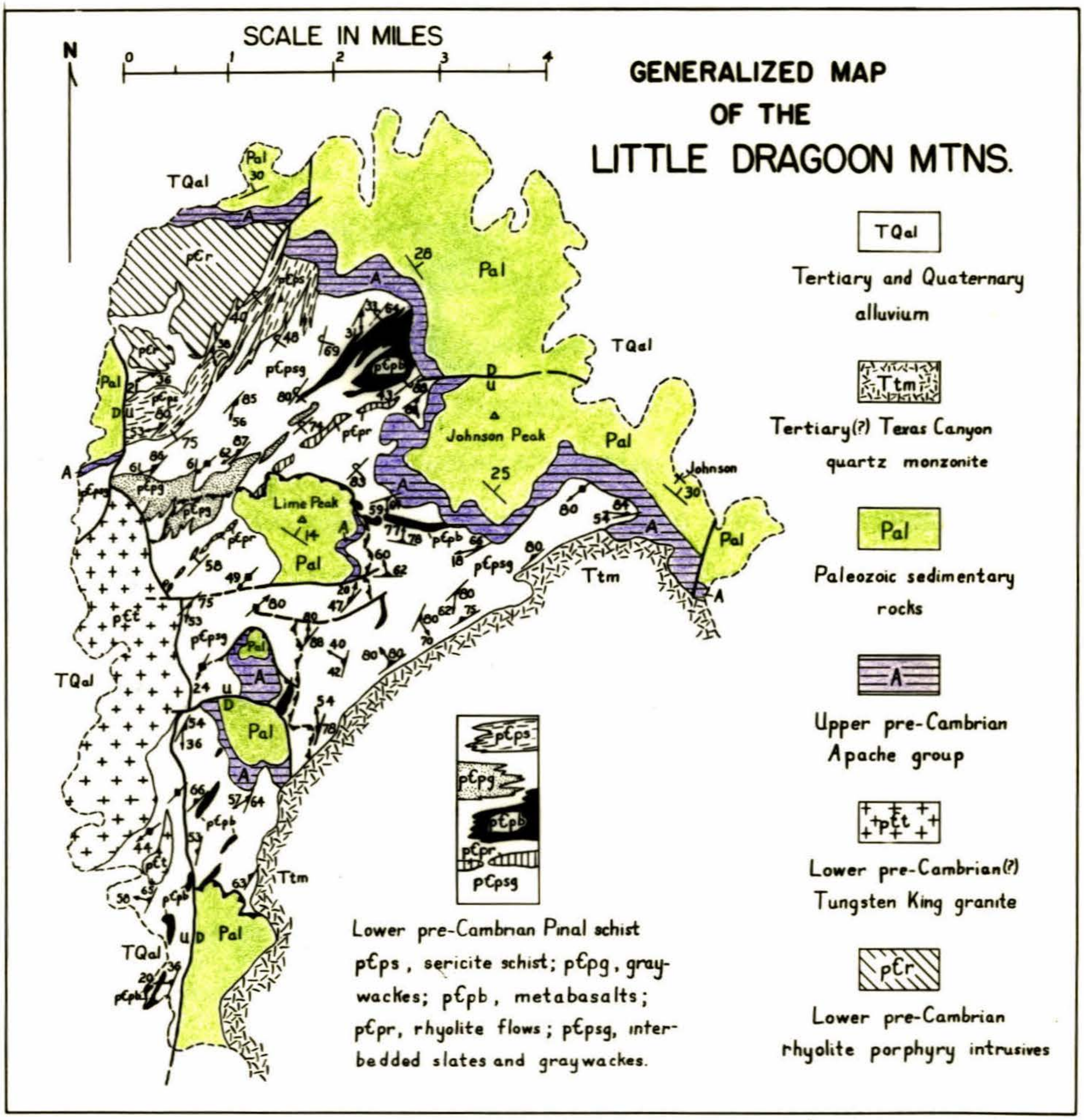

PRESCOTT
PHOENIX
TUCSON
DOUGLAS
JOHNNY LYON HILLS
LITTLE DRAGOON MOUNTAINS
DISTRIBUTION OF
OLDER PRE-CAMBRIAN ROCK
DRAGOON QUADRANGLE
COCHISE CO., ARIZONA

Figure 31

Figure 32. Generalized geologic map of the Little Dragoon Mountains.



Geology by J.R. Cooper
and others, U.S.G.S.

Figure 32

In the Johnny Lyon Hills, the sedimentary rock aspects of the formation are sufficiently well preserved to suggest the environment of accumulation. The major aspects of the formation, including the great thickness, the monotonous graywacke slate lithology, the volcanic clastic content, the graded bedding, and the associated amphibolites suggest deposition in a major geosyncline. That these phenomena are representative of the geosynclinal facies has become increasingly recognized in the recent progress of stratigraphy and sedimentation. Bailey (1930, 1936) demonstrated the existence of such characteristics in many geosynclinal prisms of diverse ages. Jones (1938) elaborated on this theme in discussion of geosynclines of Great Britain. The increased recognition of the primary relation between sedimentary facies and tectonism has resulted in widespread testing and application of these ideas.

In the Little Dragoon Mountains a similar sedimentary lithology is accompanied by extrusive igneous rocks, both basic and acidic. Cooper (1950a, p. 31; C. A. Anderson, 1951, pp. 1334-1335) has used the field term arkose for the arenaceous beds because of the conspicuous feldspar content visible in some hand specimens. Petrographic examination has established their similarity in composition and texture, with the graywackes of the Johnny Lyon Hills. The basic metavolcanics are associated with large masses of purple hematitic quartzite. In the greenstones which are texturally best preserved, the quartzite is only a slightly coarsened jaspery chert which pervades the fringes of the basic rocks. In Walnut Canyon (SW$\frac{1}{4}$, sec. 28, T. 15 S., R. 22 E.) one of the best examples of greenstones and chert displaying both quartz-calcite-chlorite amygdules (fig. 33) and suggestions of pillow structure,

Figure 33. Photomicrograph. Amygdule in a greenstone body in the Pinal schist in the Little Dragoon Mountains. The original cavity was lined first with chlorite (chl) and epidote (e) and then filled with quartz (q) and calcite (cal.). Plain polarized light. Mag. x 26 diameters. Spec. LD-1a.

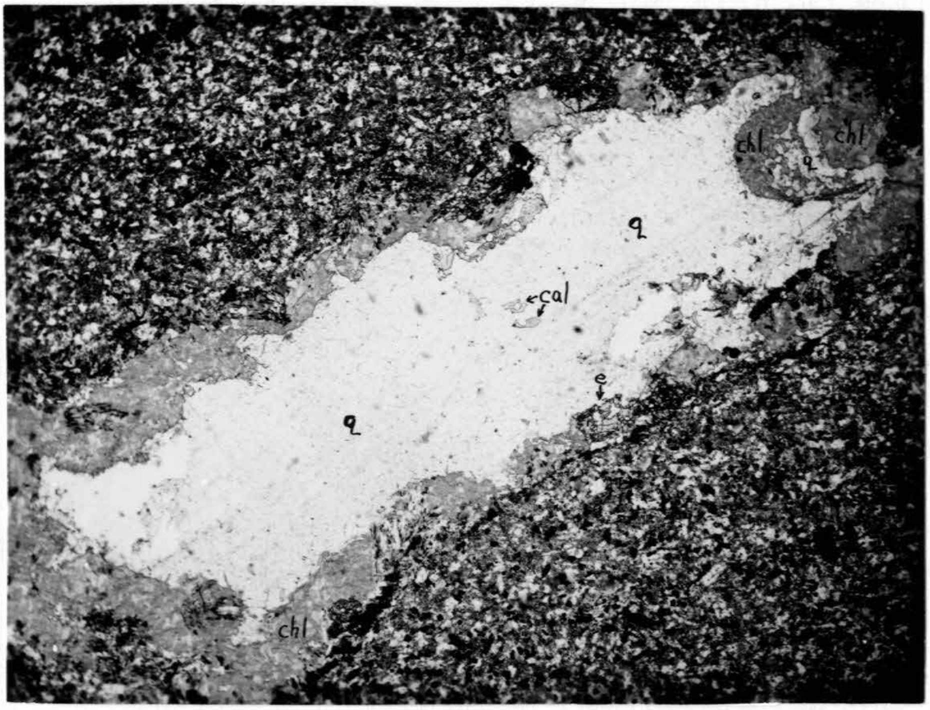


Figure 33

shows some evidence of soda metasomatism in the greenstone. Rapid* chemical analyses (table 5) of samples from the fine-grained (chilled?) margin (LD-1) and the interior (LD-2) of the body indicate a high soda/lime ratio and confirm extensive silification.

Table 5

Rapid* Analyses of Greenstones in the Pinal Schist,
Walnut Canyon, Little Dragoon Mountains.
(W. Blake, analyst).

	LD-1	LD-2
SiO_2	56.5 percent	65.5 percent
TiO_2	2.57	2.49
Al_2O_3	12.78	13.67
Fe_2O_3	9.70	3.09
FeO	8.91	2.12
MgO	4.94	4.78
CaO	0.43	0.43
Na_2O	1.60	2.82
K_2O	1.39	1.28
Total H_2O	3.56	2.45
P_2O_5	0.30	0.27
MnO	0.15	0.09
Total iron as Fe_2O_3	19.6	5.45
Total	102.83	98.99

*Less accurate than conventional method. See U.S.G.S. Circ. 165, 1952.

The dense marginal greenstone sample (LD-1), is presumably closer to the original volcanic composition than is the coarser grained sample

(LD-2). The former suggests an original basalt to which SiO_2 and H_2O had been added and almost all CaO was removed. It might have been a mafic andesite although the low alkali values do not support this. The sample from the interior of the greenstone body with clear-cut evidence of silicification shows a 75 percent increase in the Na_2O content. This soda can be related petrographically to albitization of the plagioclase, and suggests possible original spilitization. The obvious loss of CaO is to a degree not associated with most spilitization, and may reflect the influence of a later metamorphic or hydrothermal episode in this greenstone's history. If the albitization and silicification were syngenetic, then they constitute an association here that is common in many geosynclines.

The acid volcanics of the Little Dragoon Mountains are dense quartz-albite porphyries intercalated in the Pinal schist. Cooper (1950b) has demonstrated the extrusive nature of these bodies. They are similar in composition to most of the volcanic fragments found in the coarser graywackes and graywacke conglomerates and probably have a common source. No chemical analyses are available to determine whether they are keratophyric, but the petrography admits the possibility. Although the spilite-keratophyre suite is common in many geosynclines (Turner and Verhoogen, 1951, pp. 201-212), it is not always found. The clear evidence of considerable volcanic activity concurrent with sedimentation is in itself a major argument in favor of geosynclinal facies.

One may also introduce as negative evidence, the absence of such features as clean quartzites, or carbonate rocks, cross-bedding, evidences of wave disturbance of bedding, littoral deposits or other features of stable shelf, shallow marine environments. The general inference of the field observer is that the Pinal schist is a deep water accumulation, nourished perhaps by turbidity currents. Kuenen (1949, pp. 238-240, and many articles in the literature) ascribes graded bedding, and many coarse clastic abyssal deposits to this transportation mechanism.

The sources which contributed clastic material to the geosyncline are not exposed within the Dragoon quadrangle. No rocks older than the Pinal schist have been recognized anywhere in southern Arizona although such rocks may crop out in the Pinaleno and Rincon Mountains. Although volcanic terranes were clearly an important source of debris, metamorphic rocks, particularly quartzites, slates, and phyllites were equally well represented. To a much lesser extent granitic and granophyric rock fragments are also present in the section. One indication of the diversity of origin, comes from a zircon assemblage separated from several graywacke beds for purposes of age determination. These zircons display a wide variety of crystal habits, colors, and degrees of abrasion which emphasize the heterogeneous origin of the collection.

The thick section of the Pinal schist in the Dragoon quadrangle contains no recognizable important unconformities, and the entire sequence, without visible top or bottom, has an estimated thickness of 4 miles or more. The geographical magnitude of the basin, partly exposed in this area, must by implication have been large. Attempts to determine the complete extent of such a pre-Cambrian basin, will be limited of course by the scattered window-peering opportunities the more recent geological history permits.

The Pinal schist has been recognized as a formation in southern

Arizona from the Mexican border to north of the Globe-Miami area, and from the Dos Cabezas Mountains to the Tucson Mountains. Ransome, during the course of his studies in the region, was always impressed by the lithologic uniformity of the metamorphic rocks which were truncated by the Ep-Archean unconformity. He repeatedly referred to the light to dark gray mica schists and quartzites, and the occasional darker amphibolitic schist bands.

Lindgren (1905, p. 56) did not hesitate to correlate the old schists of the Morenci area with the rocks described by Ransome.

C. P. Ross (1925, p. 13) after his work on the schist in the Arivaipa and Stanley districts, stated, "The resemblance in stratigraphic relations, metamorphism and most of the petrologic characters is so striking as to leave no doubt of the correlation with the Pinal schist of Ransome." The overall extent of the formation as now recognized is more than 15,000 square miles.

In Central Arizona, the older pre-Cambrian rocks bear a relation to the Ep-Archean surface similar to the Pinal schist. The early workers, Jaggar and Palache (1905), gave the name Yavapai schists to these rocks, for the county in which they are so well exposed. They recognized the formation as predominantly metasedimentary. Lindgren in his work on the ore deposits of the Jerome and Bradshaw Mountains quadrangles (1926) examined the same rocks and confirmed the metasedimentary origin of much of the Yavapai schist, but pointed out the abundance of metarhyolites, greenstones and igneous tuffs. He believed these rocks to be the equivalent of the Pinal schists. Recent work by C. A. Anderson, S. C. Creasey, M. Krieger and others of the U. S. Geological Survey has given the Yavapai schist a much more rigorous examination. The details of the work have not yet been made available, but Anderson (1951) has summarized some of the work in a discussion of the older pre-Cambrian rocks of Arizona. The Yavapai schist can be subdivided into two blocks separated by a major north-trending fault in the Jerome quadrangle. The eastern block is characterized by non-foliated andesitic to rhyolitic flows, breccias, tuffs, and associated tuffaceous sediments (6,000 feet thick) containing jaspery iron ore beds. The section is intruded by large masses of granodiorite and quartz diorite and lesser bodies of gabbro. The western block consists of folded, schistose purple slates, tuffs and conglomerates underlain by andesitic and rhyolitic flows and pyroclastics, and overlain by volcanic breccias. The age relation between the two blocks is unknown, but they are grouped together in the Yavapai formation because of their mutual character of mixed volcanic and sedimentary origin.

In 1939, E. D. Wilson reported on many years of examinations of the older pre-Cambrian rocks of the Mazatzal Mountains and other areas in central Arizona. In the Mazatzal range he separated the older pre-Cambrian rocks into two groups, the older Yavapai group and the younger quartzites and shales of the Deadman, Maverick and Mazatzal formations which are unconformable on the Yavapai group. The Yavapai group contains the Alder series, composed of shales, grits, quartzites and conglomerates. The grits, which compose one-third of the formation, were flaggy to thinly laminated argillaceous sandstones with angular grains of quartz and feldspar in a finer matrix. By the definition given earlier in this paper they may be called graywackes. In fault relation to the Alder Creek series, are the other two members of the group; the Yaeger greenstone and the Red Rock rhyolite. Wilson considered the Alder series equivalent to sedimentary sections of the Yavapai schist elsewhere.

R. G. Gastil (1953) working in the upper Tonto Creek area has studied in rewarding detail a northeast-trending section of older pre-Cambrian rocks. A thick sequence of andesitic-rhyolitic flows, breccias and tuffs with slates, graywackes and other metasedimentary rocks rest on the Mazatzal quartzite and representatives of Wilson's other formations from the Mazatzal Mountains. Gastil concluded that the area was part of a major geosynclinal trough (whose floor showed considerable oscillation). More or less continuous sedimentation, abetted by concurrent volcanism, produced the entire section of older pre-Cambrian rocks now visible.

In the Bagdad area, Anderson, Scholz and Strobell (C. A. Anderson, 1951) found a mixed section of andesitic flows, rhyolitic-andesitic tuffs and tuffaceous sediments. In the White Picacho district east of Wickenburg, Jahns (1952, pp. 11, 12, 14) briefly reports intensely folded metamorphic rocks of mixed sedimentary and volcanic parentage with structural trends northeast to east-southeast and dipping northward at moderate to steep angles.

In the Vishnu schist of the Grand Canyon (Noble and Hunter, 1917; Campbell and Maxson, 1933), major metasedimentary components have been recognized.

Throughout all of central and southeastern Arizona, then, a pattern of volcanism and associated sedimentation is recognizable. Anderson in his comprehensive review (1951, p. 1345) pointed out that the repetitious nature and lenticularity of the volcanic rocks, the lack of diagnostic stratigraphic horizons in the sedimentary rocks, and younger faulting would make regional correlation of specific units very difficult even if the exposures were continuous. However, when viewed as parts of a pattern of geosynclinal accumulation, an overall correlation of sections is suggested.

Among the many types of geosynclines reported or suspected by various students of sedimentation and tectonics, the so-called orthogeosyncline of Stille (Kay, 1951, p. 4) is best documented. Schuchert (1923, p. 165) called it a monogeosyncline. These major linear troughs are found on the margins of stable continental interior masses or cratons. Quite typically, they are separated into a miogeosyncline near the stable shield, which grades outward into a deeper eugeosyncline where volcanic piles form geanticlinal arcs. These arcs are major sources of debris and their volcanic clastics and flows are characteristic of the eugeosynclinal deposits. Volcanic material becomes subordinate to continental debris in the miogeosynclinal lithology.

The existence of a major pre-Cambrian geosynclinal trough in Arizona is clear. The much greater abundance of volcanics in the Yavapai schist suggests that it may be a eugeosynclinal facies whereas much of the Pinal schist may represent a transition toward a miogeosynclinal facies because of the greater proportion of nonvolcanic clastics. This would imply (1) that a major continental shield existed somewhere in northern Mexico, and (2) that the linear trough was elongate approximately east-west to northeast-southwest. Schuchert once proposed (1923) a late Proterozoic Columbia shield in this region, but no proposal for an older positive area has appeared.

There is no informational basis for evaluating the first inference except to note that most proponents of accreting continents, generally visualize the Canadian shield as the major North American center.

The second inference can be tested, it is hoped, by detailed studies of the pre-Cambrian of New Mexico and western Arizona. Unfortunately, exposures of pre-Cambrian rocks in western New Mexico are limited by the great Cenozoic volcanic activity of the region. A number of studies of the pre-Cambrian in central and northern New Mexico (Just, 1937; Jahns, 1946; Stark and Dapples, 1946; Reiche, 1949; Barker, 1954) have described very thick sections of metasedimentary and metavolcanic rocks, both basic and rhyolitic. Just, (1937, pp. 12-14) in the Petaca-Picuris region, recognized a single orogenic episode and gave the name Pueblo to the geosyncline and revolution. He speculated on a correlation with the Vishnu schist of the Grand Canyon and with pre-Cambrian rocks in southern Colorado. He noted, and the more recent workers have confirmed, the predominance of northeast-southwest structural trends and evidence for northwest-southeast compression. These trends are very conspicuous in the Manzanita and Manzano Mountains (Reiche, 1946) and in the Los Pinos Mountains (Stark and Dapples, 1946).

Farther south in the Caballos Mountains (Kelley and Silver, 1952, pp. 32-33), limited areas of east-west trending metamorphic rocks with steep dips are reported. These include mica-schists, greenstones, and gneisses.

Going even farther afield, King and Flawn (1953) studied the thick sections of pre-Cambrian rocks exposed in the Van Horn Mountains area of west Texas. They recognized an older Carrizo Mountains group (more than 19,000 feet thick) of "altered sedimentary rocks including meta-arkose, metaquartzite, schist, phyllite and (rare) limestone" intruded by rhyolite anddiorite masses, now metarhyolite and greenstone. The evidence suggests it is a single sedimentary series, and the workers suggested (1953, p. 131) a possible correlation with the older pre-Cambrian rocks in Arizona.

Lacking such studies in western Arizona at this time, we can turn to the tectonic evidence available.

Geosynclinal stratigraphy cannot be divorced from tectonics. From the birth of the geosynclinal concept in the minds of Hall and Dana, the inseparable relation between crustal movement and major depositional basins has grown to be more clear. Studies of ancient mountain chains and modern island arcs have confirmed this relation. (See discussions by Kuenen, 1950, pp. 175-209; Knopf, 1948; Griggs, 1933). In all of these studies the direction of major crustal compression has been recognized as normal to the direction of e-longation of the basin, imparting a structural grain approximately paralleling the linear direction.

From the analysis of the structure of the Johnny Lyon Hills, it is clear that strong northwest-southeast compressional force had produced northeast-southwest structures. This is also the major trend in the Little Dragoon Mountains. Ransome reports this northeast-southwest grain with steep dips in the Mule Mountains (1904, p. 25), in the Globe area (1903, p. 24) and in the Ray areas (1919, p. 34). Lindgren (1905, p. 56) reported an east-west trend with steep dip to the south at Morenci. A N. 40° E. trend dipping vertically or steeply south prevails in the Stanley and Aravaipa districts

(Ross, 1925, p. 40). Throughout central Arizona, Wilson (1939) recognized the prevailing northeasterly trend in folds, thrust faults and steep imbricate reverse faults. Impressed by the magnitude of the structural relations, he proposed the term Mazatzal Revolution. He believed (1939, p. 1161; 1949) that the major northwest-southeast compressional forces doubtless involved a region much larger than central Arizona.

Wilson's belief is justified, for earlier work showed the same trends in the metasedimentary rocks of the Vishnu schist in the Grand Canyon (Noble and Hunter, 1917). In the pre-Cambrian complex of the Cerbat Mountains of northwestern Arizona, Schrader (1909) and Thomas (1949) also show the same northeast trend. In the Bagdad area, Anderson et al (C. A. Anderson, 1951, pp. 1335-1339) report that the Yavapai schist is strongly folded on northeast-southwest axes. Unfortunately, so little is known of the western Arizona geology that little of value to our problem can be extracted from the meager literature. Bancroft (1911) in his discussion of the metamorphic complexes in the desert ranges of northern Yuma county wisely would not make a blanket correlation with the Yavapai schists. In the oldest series of metasedimentary schists, he reported a prevailing northeast strike. But there is, nevertheless, an impressive unity in the evidence of pre-Cambrian tectonic orientation throughout much of Arizona as Wilson pointed out.

Although fewer regional data are available, it is worth noting that fold axes are reported to be generally easterly in plunge in the Johnny Lyon Hills (after rotation), Mazatzal Mountains, Upper Tonto Creek, Bagdad, and the Cerbat Mountain areas.

C. A. Anderson (1951, p. 1345) emphasized that all detailed work indicated only one period of orogeny was recognizable. N. E. A. Hinds' (1936, p. 100) arguments for a pre-Mazatzal "Arizonian Revolution" have not been substantiated as yet. Anderson, influenced by relations in parts of the Jerome-Prescott area (C. A. Anderson, 1951, pp. 1341-1343), described the prevailing structural trends in Arizona as "northwest, north, or northeast, indicating general east-west compressive forces during the orogeny." But the predominance of northeast trends in the various reports in the literature would seem to bear out Wilson's earlier conclusion as to the directions of compression.

Minor igneous intrusion (particularly of rhyolite porphyries and basic rocks) accompanied the deformational episode in much of Arizona. At the close of the deformation, widespread emplacement of masses of epi-tectonic granodiorite, quartz diorite, and granite occurred. The available evidence would indicate these were also essentially a single episode. Hinds (1938, p. 448) cited granite and aplite pebbles in the basal conglomerate of the Mazatzal quartzite to prove older granites must have existed. But this is not sufficient to demonstrate that the visible granite bodies are of two different ages. These older terranes have not been identified.

Age of the Pinal schist

The relation to the younger beds indicates that the Pinal schist is clearly pre-Cambrian. A considerable geological history has been deduced in the interval between the deposition of the original sediments and the truncation by the Ep-Archean erosion surface. As Anderson has pointed out (1951, p. 1346) in the immense length of pre-Cambrian time, it is conceivable that multiple orogenies could have occurred in Arizona, but the simplest explanation calls for only one period. Radioactive dating methods are now being applied to a number of pre-Cambrian rocks in Arizona and it is from this work that absolute age information must come.

Johnny Lyon granodiorite

Name and general relationships

The name, Johnny Lyon granodiorite, is given to the large body of coarse-grained igneous rock exposed west and north of the Johnny Lyon Hills. The outcrop pattern on the map (see plate I) is crudely that of a segment of a circle. The western chord of the segment coincides approximately with the edge of the map and is defined by the edge of the alluvium in the San Pedro River valley. At the north end of this chord, major thrust faulting also helps limit the body. The circular arc which defines the other boundaries of the granodiorite includes the intrusive contact with Pinal schist on the southeast and east sides, and the erosional unconformity of pre-Apache group age west of Rattlesnake Ridge which marks the northeastern limits.. The entire arc is modified in detail by post-Paleozoic faulting.

The area of this segment is slightly more than 20 square miles, constituting the most widely exposed rock type in the area with the exception of the Tertiary and Quaternary alluvium. Limited exposures within the basin fill of the San Pedro River valley, particularly in the vicinity of The Narrows, indicate that the same rock type is present as much as several miles west of the map area. It is not possible therefore to make any complete statement on the overall size of the pluton from the exposures in the Johnny Lyon Hills.

Original intrusive contacts are visible for about seven miles along the southeastern margins of the body. The granodiorite there is obliquely discordant with the structure of the Pinal schist into which it is intruded. As the contact bears toward the north, it is consistently 15 to 30 degrees more northerly in trend than the foliation and bedding in the adjacent schist. It should be pointed out however that there are mutual changes in both of these trends which are related to the change in orientation of the unconformably overlying Apache group.

The general dip of the intrusive contact is to the southeast. The trace of the contact on the topography and its offset by faults indicate a considerably smaller dip (30°-50° SE) than is characteristic of the structure of the schist (65°-85° SE). Numerous schist inclusions in the marginal areas of the granodiorite commonly have their internal structure parallel to that of the wall rock. East of Sheep Camp Ridge the inclusions are located from a few feet to a quarter of a mile from the contact and appear to have been connected to the main body of schist at the time of intrusion. This further indicates that the general projection of the wall rock contact would not be a great distance above the present topographic surface.

In detail the contacts are sharp with no evidence of a chill zone. Coarse textured granodiorite is immediately adjacent to the contact hornfels phase of the Pinal schist. Numerous crosscutting relations are visible and locally the apophyses project as sill-like sheets into the schist. Intermittently, the contact is concordant with relict bedding in the contact zone of the schist for distances up to several hundred yards. But consistently, the contact cuts obliquely across the section if followed for any greater distances. The map pattern at the margin of the schist is complicated in addition by numerous small aplite and pegmatite dikes which have not been distinguished from the main phase of the granodiorite on the map.

Only a little additional information is available on other parts of the original intrusive contacts. West and southwest of Sheep Camp Ridge numerous trains of schist inclusions in the granodiorite are aligned parallel to the regional structure and suggest the proximity of the southwestern contact, perhaps now covered by alluvium. Granodiorite is exposed at least three miles to the west, however, and the abundant oriented inclusions may represent a local projection of the wall rock or roof rock. Use of discontinuous outcrop relations in the granodiorite must be made cautiously because of the known major thrust faults, which may be accompanied by equally important concealed faults. Major displacements of the contacts are visible in the thrusting around the Johnny Lyon Hills. Farther north, in the vicinity of the American Mine, thrust slices of large displacements include a block of schist intruded by the granodiorite. Approximately a half-mile of cross-cutting relations is visible, but the thrust relationships permit few conclusions as to the original position of this contact. The direction of thrusting is apparently from the east suggesting the contact originally lay in that direction.

In considering the original roof and walls of the pluton, one must bear in mind that the tilting of the entire pre-Apache erosion surface, from Kelsey Canyon to south of Lechugilla Hill, indicates modification of the original position of the roof and walls. Dips of 40 to 65 degrees east are common in the overlying Pioneer shale. If the pre-Cambrian erosion surface is rotated to a horizontal position about an axis parallel to the present strike of the unconformity then the northeastern end of the granodiorite-schist contact appears to be close to the original roof and apparently steepens in dip southward to become a wall of the pluton. For example, a contact striking due north and dipping 50 degrees east would be rotated to N. 55° E. dipping 23° SE., while a contact striking N. 45° E. and dipping 50° SE. would be transformed to N. 81° E. dipping 53° SE. Where the Pioneer shale rests directly upon the granodiorite (i.e. north of the Willcox-Cascabel road) the original roof was removed in pre-Cambrian time.

Topographic expression

Most of the Johnny Lyon granodiorite exposures are on two prominent bedrock surfaces, The River Slope on the west and The Mesa on the east. These surfaces are characterized by low relief except along the drainage divide where the step-like discordance between the higher Mesa and lower River Slope involves a difference of 150 to 250 feet in elevation. The location of this break is controlled in part by a major alteration zone with abundant resistant zones of silicification. The granodiorite on the erosion surfaces is deeply decomposed and blanketed by gruss, up to several feet thick. Boulders of disintegration are uncommon except along the 'step' where western drainage is deeply incising the margin of the eastward draining Mesa. Local irregularities in the surfaces are generally reflections of alteration of the granodiorite. Many of the larger silicification zones form the low ridges rising above the surrounding granodiorite (fig. 34).

The relative rarity of boulders of disintegration is certainly related to a general lack of coarse joint-bounded blocks such as might be expected if a rock of this type were to survive from its cooling period with no subsequent major structural complications. The Johnny Lyon granodiorite, however, has experienced widespread post-crystallization fracturing, shearing and alteration which have modified the original joint pattern, much reduced the joint-block size, and influenced its weathering characteristics over large areas. As a result it does not have the geomorphic expression of an idealized granitic rock type.

West of Sheep Camp Ridge there is a group of hills in the granodiorite with relief of over a thousand feet. These hills lie within structurally complicated areas and their weathering character also appears to have been modified. It is possible that until relatively recent times they were covered by a cap of resistant Paleozoic sedimentary rocks in thrust relation, similar to those of Sheep Camp Ridge. The San Pedro River drainage is now vigorously attacking these elevations.

Lithology

The lithologic character of the Johnny Lyon granodiorite is, in general, quite uniform. There are in addition to the principal type, however, several subsidiary phases including: (1) numerous inclusions, some of which have reacted to produce hybrid rocks, (2) pegmatites

Figure 34. Large masses of white quartz and silicified granodiorite (foreground and right middleground) sustain low ridges above the surface of The Mesa along the major alteration zones in the Johnny Lyon granodiorite. Photograph taken south of The Mesa Tank looking north with the northern Johnny Lyon Hills and the Winchester Mountains on the skyline.

Figure 35. Surface of a weathered boulder in the Johnny Lyon granodiorite showing the typical slightly porphyritic texture in which altered plagioclase crystals are the coarse white grains.

Figure 34

Figure 35

and aplites, (3) hydrothermal alteration zones, and (4) a wide variety of cataclastic modifications. These minor phases represent only two or three percent of the total area of exposed intrusive, and the otherwise homogeneous igneous rock appears to be part of a single pluton with only limited variations in composition and texture.

Main phase

The main phase of the Johnny Lyon pluton is typically a medium to coarse-grained, somewhat porphyritic, gray to gray-green hornblende-biotite granodiorite (fig. 35). In hand specimen, coarse white plagioclase, gray quartz, scattered pink potash feldspar, dark green platy biotite and greenish-black prismatic hornblende are the principal minerals seen. Brilliant brown euhedral sphene crystals 1/2 to 2 mm in diameter are commonly visible as a minor constituent.

Upon weathering the rock assumes a pink-brown cast against which yellowish-white to greenish-white altered plagioclase crystals stand out in contrast to the iron oxide stained quartz and chloritized biotite and hornblende. The rock disintegrates into granules a few to ten mm in diameter which compose the gruss blanket on the granodiorite erosion surface.

From thin sections (fig. 36), the fresh rock can be described as medium to coarse-grained, hypidiomorphic-granular, commonly with a slight seriate porphyritic texture. Plagioclase crystals, ranging up to 15 by 10 mm are subhedral to euhedral, tabular and zoned. They vary in composition from An_{32-35} at the cores to An_{20-22} at the rims. Oscillatory and reverse zoning are common but the rims are consistently

Figure 36a. Photomicrograph. Typical Johnny Lyon granodiorite with altered, subhedral plagioclase, clear quartz, biotite with some chlorite (cl) replacement microcline (m) and hornblende (hb) and a characteristic large sphene (s) crystal. Plain polarized light Mag. x 26 diameters. Spec. L-312b.

Figure 36b. Same field, crossed nicols.

Figure 36a

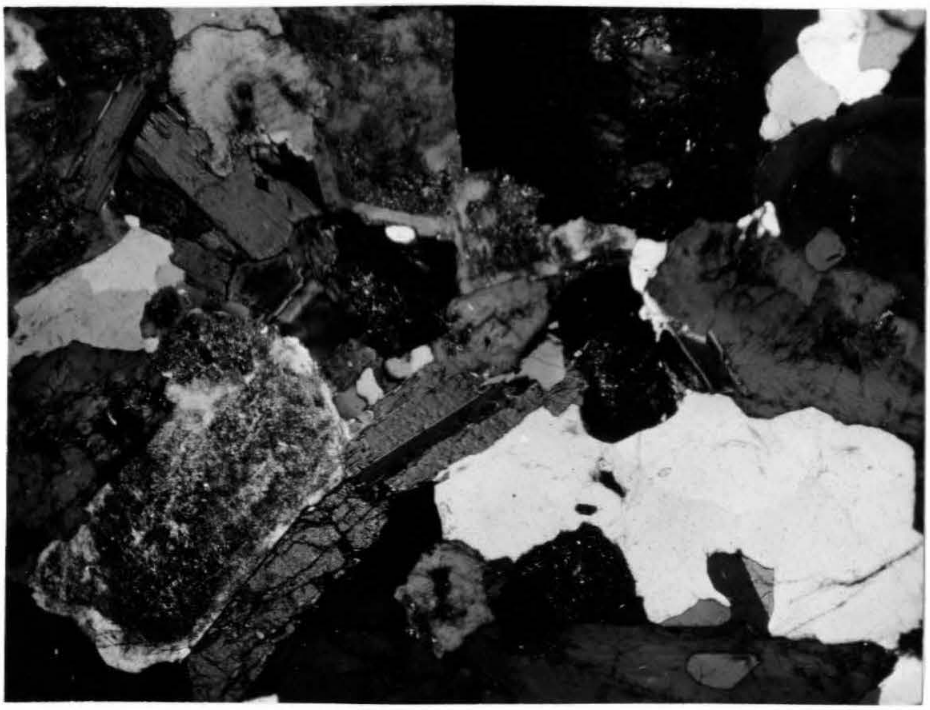


Figure 36b

more sodic than the cores. The usual alteration minerals in the plagioclase are almost completely absent from this sodic rim. Small irregular spots of more sodic oligoclase whose distribution is independent of the zoning are common within the grains. Myrmekite is common in small anhedral grains, 1/4 to 1 mm and in fringing overgrowths on tabular plagioclase crystals where microperthite is usually present as the adjacent mineral. More rarely the myrmekite appears to be a partial replacement of an earlier euhedral plagioclase.

Microcline and microcline-microperthite form inequant, anhedral grains, 1 to 5 mm in diameter. They appear to be localized on boundaries of other mineral grains and show replacement textures involving all the other major minerals, commonly including quartz. The myrmekite texture appears to be contemporaneous or younger since it is rarely found outside of the potash feldspar association. The microperthite generally consists of minute blebs or wispy films of albite more concentrated toward the centers of the grain. Somewhat coarser ragged patch perthite is also visible, however.

The quartz commonly forms aggregates of anhedral grains up to 15 mm in diameter with individuals up to 8 to 10 mm. Some of the aggregates present suggestions of spheroidal or nodular form, while others are in more interstitial positions to the other minerals. Moderate undulant extinction and scattered trains of minute liquid inclusions are usually present. Very minute rutile(?) needles are present as abundant inclusions.

Biotite forms ragged anhedral to platy subhedral grains up to 5 to 6 mm in diameter. It is pleochroic: pale straw-yellow (X), dark olive-brown (Y), dark olive-brown (Z). The β index is 1.639. 2V (-) is estimated at 3 degrees. The biotite usually contains numerous inclusions of the accessory minerals.

Hornblende crystals, up to 6 mm long, form subhedral to euhedral prisms. They are pleochroic: pale yellow (X), bottle-green (Y), blue-green (Z), with absorption formula, $X<Y<Z$. $\alpha = 1.646$, $\beta = 1.661$, $\gamma = 1.668$, 2V (measured) = $64°(-)$, $Z \wedge C = 19°$. Twins are common. The hornblende also contains numerous accessory minerals as inclusions and may show slight evidence of primary reaction to form biotite, and epidote or clinozoisite.

The accessory minerals include magnetite, apatite, sphene, zircon, allanite and thorite in order of decreasing abundance. The magnetite forms subhedral grains up to 0.3 to 0.4 mm and is probably titaniferous. Sphene occurs as striking, large subhedral to euhedral grains up to 2 mm long. Some smaller, ragged grains of sphene appear to be alteration products in biotite. Apatite and zircon are generally minute prismatic inclusions, 0.05 to 0.2 mm in length. The zircon is a zoned hyacinth variety, beautifully euhedral. The allanite is intimately related to scattered epidote grains and like most of the accessories is most abundant in association with the biotite and hornblende. A few large grains up to 0.8 mm have been observed as alterations on plagioclase. Thorite has not been identified in thin section but its presence has been recognized in heavy mineral separates. Table 6 contains chemical, normative and modal analyses of typical specimens of the granodiorite. For comparison, Johannsen's average of chemical analyses of 80 granodiorites (1932, vol. II, p. 344) is also given.

Table 6

Modal Analyses

Point Counter Method

Specimen No.	L-233	L-312
Location and distance from intrusive contact	SW$\frac{1}{4}$, sec. 33 T. 14 S., R. 21 E. 1$\frac{1}{2}$ miles	SW$\frac{1}{4}$, sec. 20 T. 14 S., R. 21 E. 2 miles
Quartz	23.5 percent	25.8 percent
Plagioclase	42.4	45.3
Myrmekite	0.8	2.0
Microcline-perthite	12.7	14.2
Biotite	12.9	6.4
Hornblende	5.6	4.0
Ore minerals	1.4	1.3
Sphene	0.5	0.6
Apatite	0.1	0.2
Zircon	0.2	0.1
Allanite	0.1	-
	100.2 percent	99.9 percent
	3865 points on 14 sq. cms.	3734 points on 13 sq. cms.

Table 6 (Con't)

Chemical Analyses

	L-233	L-312	Average of 80 granodiorites
SiO_2	66.24 percent	68.89 percent	66.13 percent
TiO_2	0.50	0.45	0.51
Al_2O_3	15.83	15.02	15.50
Fe_2O_3	1.58	1.40	1.62
FeO	2.00	1.89	2.70
MnO	0.08	0.08	0.07
MgO	1.75	1.43	1.73
CaO	3.89	3.44	3.70
Na_2O	3.89	3.84	3.55
K_2O	2.85	3.14	3.17
H_2O comb.	1.20	0.88	0.89
P_2O_5	0.19	0.17	0.17
others	N.D.*	N.D.*	0.07
	100.00 percent	100.68 percent	99.90 percent

*Not determined
W. J. Blake, analyst

Johannsen, 1932
Vol. II, p. 344

Normative Analyses

		L-233	L-312
Salic			
	Quartz	21.25 percent	25.02 percent
	Orthoclase	17.79	18.35
	Albite	32.91	32.49
	Anorthite	17.18	14.46
Femic			
	Diopside	1.19	2.22
	Hypersthene	5.07	3.99
	Magnetite	2.30	2.09
	Ilmenite	0.94	0.91
		98.63 percent	99.53 percent
C.I.P.W. Class.		I,4,3,4	I,4,3,4

No specimens of the granodiorite have been observed that are completely free of so-called alteration minerals. Minerals of the epidote group are very common. Zoisite and clinozoisite aggregates replace plagioclase; epidote is an alteration of plagioclase, hornblende and biotite; allanite is seen associated with the other members of the group. A late magmatic origin for most of these minerals seems probable. Where hydrothermal alteration has been most intense, and most recognizable, the epidote group is rare or absent.

Chlorite is the major alteration mineral of biotite and hornblende. It is a penninite-type and usually includes fine needles of leucoxene, epidote or clinozoisite, and iron oxides as co-products of decomposition. These are often in oriented arrangement revealing the pseudomorphous nature of the alteration.

An illitic sericite and finer grained clay minerals pervasively replace up to 50 percent of the plagioclase in many of the specimens examined. The sericite generally forms felty to oriented interlocking mats of very fine-grained shreds (less than 0.05 mm) which give the plagioclase a semi-opaque appearance. The fine-grained character and gradational optical characteristics make estimation of proportions difficult but sericite appears to be the most abundant of these minerals.

Finely divided clay(?) minerals also give a faint cloudy effect to the microperthite, but it is largely free from alteration.

Limonite is a weathering by-product which may be concentrated around magnetite and mafic minerals, or dispersed through the rock giving the rocks its characteristic weathering hue.

The main phase of the pluton is generally consistent in mineral composition over the area examined. Table 7 lists modal analyses of specimens collected from widely separated points. The average value may be classified according to Johannsen (1932, vol. II, p. 318 et. seq.) as a granodiorite, 227P.

One interesting variation in the composition is the lack of hornblende in the border 1/4 to 1/2 mile of pluton against the Pinal schist. In addition to specimens L-234 and L-221 listed in table 6, five other specimens collected in this zone along the contact, from the Willcox-Cascabel road to southwest of Keith Peak, contain only a trace or no amphibole at all. Although not completely lacking, sphene also shows an apparent decrease in the marginal zone. This compositional character appears to be transitional to the principal type, where it can be followed through nearly continuous field exposures.

The textural relations in the main phase of the granodiorite suggest a sequence of crystallization, based on euhedralism and replacment textures, as follows. Tabular plagioclase and prismatic hornblendes were the first crystals to form. Biotite succeeded the hornblende in the late stages of plagioclase formation. This, in turn, was followed by quartz crystallizing in aggregates. Microcline-perthite and myrmekite appear to be later than much and perhaps most of the quartz. The microcline-perthite habitually occupies positions interstitial to all other major minerals and it has replacement relations to all of these minerals including quartz. The general localization of myrmekite on the contact between plagioclase and potash feldspar suggests that it is either contemporaneous with or younger than the latter. Among the accessory minerals apatite,

Table 7

MODAL ANALYSES OF SAMPLES OF THE JOHNNY LYON GRANODIORITE

Analyses by the Point Counter Method

Specimen No.	L-208	L-224	L-226	L-234	L-221
Location and distance from present contact	SE$\frac{1}{4}$, sec. 20 T. 14 S., R. 21 E. 1$\frac{1}{4}$ miles	SE$\frac{1}{4}$, sec. 6 T. 15 S., R. 21 E. 2$\frac{1}{2}$ miles	NW$\frac{1}{4}$, sec. 8 T. 15 S., R. 21 E. 1$\frac{1}{2}$ miles	SE$\frac{1}{4}$, sec. 21 T. 14 S., R. 21 E. 200 yds.	SW$\frac{1}{4}$, sec. 34 T. 14 S., R. 21 E. 200 yds.
Quartz	30.4 percent	24.9 percent	21.3 percent	26.1 percent	22.5 percent
Plagioclase	43.7	53.9	55.0	49.2	49.0
Myrmekite	0.9	0.7	2.1	1.3	1.1
Microcline-perthite	7.1	7.3	8.1	10.1	14.5
Biotite	12.5	8.6	7.3	10.6	11.5
Hornblende	3.4	2.0	3.1	tr	-
Ore minerals	1.7	1.5	1.2	1.7	1.2
Sphene	0.2	0.6	1.4	0.5	-
Apatite	0.2	tr	0.1	0.5	0.1
Zircon	tr	0.3	0.1	tr	tr
Allanite	-	-	0.3	tr	-
Total	100.1 percent	99.8 percent	100.0 percent	100.0 percent	99.9 percent

zircon, and magnetite appear to have started crystallizing early in the sequence. Sphene crystallized both early and late. Epidote group minerals including allanite appear to have formed in late magmatic stages in part.

In addition to deuteric modification there has been widespread hydrothermal alteration in the pluton. It is very difficult to establish criteria for the distinction between deuteric and hydrothermal effects, particularly when weathering changes are superimposed. Grim (1952, pp. 316-330) has summarized the current status of knowledge on the formation of chlorite, sericite, and clay minerals. The epidote system is still imperfectly understood (see Ehlers, 1953, pp. 231-251). Convincing evidence on the wide stability ranges of many of these minerals from late magmatic to low temperature hydrothermal conditions has been obtained from both field and laboratory evidence.

In the Johnny Lyon pluton, the pervasive deuteric and/or hydrothermal alteration has modified from 2 percent to 40 percent of the original minerals in the various specimens examined. The magnitude of these effects, particularly to the west and southwest of Sheep Camp Ridge and Keith Peak suggests sweeping hydrothermal action. In many cases these effects appear to have been superimposed on, or to have developed concurrently with the mechanical degradation of the granodiorite in the various cataclastic phases originating during the Laramide deformation. However, there is also evidence for a pre-Cambrian episode of hydrothermal alteration in the three north-trending major zones on The Mesa or adjacent to it. These will be discussed in a later section.

Inclusions and hybrid granodiorite

Scattered throughout the granodiorite are inclusions of several lithologic types. Various phases of the Pinal schist are represented, generally in tabular blocks ranging from a few inches up to a thousand feet in major exposed diameter. Many of these inclusions, now isolated from the main body of schist, may be interpreted as roof pendants because of the consistent parallelism of their internal structures with the structure in the main body. Others have been definitely displaced and rotated from their original positions.

The inclusions whose derivation is assigned to the Pinal schist are: (1) Coarse-grained mica-rich hornfels apparently formed from the slates and graywackes; (2) amphibolite of basaltic origin; and (3) porphyritic rocks whose composition and texture suggest the rhyolite porphyry in the Pinal schist.

Metasedimentary inclusions

The mica-rich aluminous hornfelses are most abundant. They show no visible evidence of reaction with the granodiorite, and there are only rare suggestions of metasomatic influences during their recrystallization. The metamorphic character of these inclusions has already been discussed in the section on contact metamorphism of the Pinal schist.

Amphibolite inclusions and hybrid granodiorite

The amphibolite inclusions are found in various stages of modification in an irregular shaped body on steep slopes about a mile north of Sheep Camp Ridge, in S$\frac{1}{2}$, sec. 5, T. 15 S., R. 21 E. Varying in size from a few inches to tens of feet in diameter they are clotted together in a heterogeneous mixture despoiling the general uniformity of the granodiorite color and texture. They are associated with both contaminated and normal granodiorite, the latter forming crosscutting dikes (see figs. 37-39) and irregular injections into the other lithologic types. Scattered small fragments of modified amphibolite and hybrid granodiorite are common throughout a large area to the west and southwest of the main body.

The amphibolite, as seen in the least modified phase, is a dark gray-green foliated rock, weathering dark brown. It is fine-grained, with most crystals less than a millimeter in diameter. Numerous flattened lenses of fine-grained black hornblende aggregates up to 10 mm in diameter, are in strong parallel orientation in a fine-grained, gray-green matrix of feldspar and more hornblende. A few larger plagioclase crystals up to 3 to 5 mm in diameter are present. Distinctive grains of coarse quartz with dark rims of fine-grained hornblende are common. These quartz grains are irregularly ellipsoidal, up to 8 mm in major dimension and are aligned with the foliation.

Microscopic examination (figs. 40, 41) yielded an estimated mode as follows:

<u>L-230a</u>

Hornblende	55 percent
Calcic oligoclase	40
Chlorite	3-5
Epidote	1-2
Quartz	1-2
Sphene	$\frac{1}{2}$
Microline	Trace

Figure 37. A dikelet of normal granodiorite cutting a mafic hybrid phase produced by reaction of the granodiorite with numerous amphibolite inclusions.

Figure 38. An irregular dike of normal granodiorite cutting an aggregate of amphibolite inclusions in various stages of modification in a matrix of early crystallized or clotted hybrid granodiorite. Note the coarse white plagioclase crystals which grew in the inclusion above the tip of the knife blade, and see the enlargement in figure 39.

Figure 37

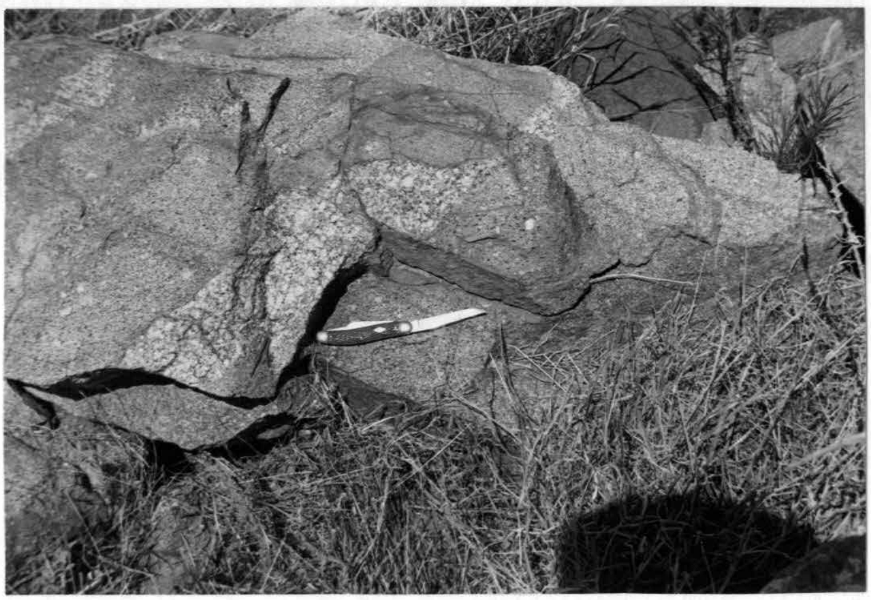


Figure 38

Figure 39. A specimen collected at the outcrop shown in figure 38, from a position above the knife blade. The inclusion on the right clearly displays original foliation in the orientation of the aggregates of dark hornblende. The large white plagioclase crystals have grown athwart the foliation and appear to be identical in composition and zoning with the coarse plagioclase in the cross-cutting granodiorite. A number of quartz grains (q) rimmed by hornblende are visible. Scale, 1:1.

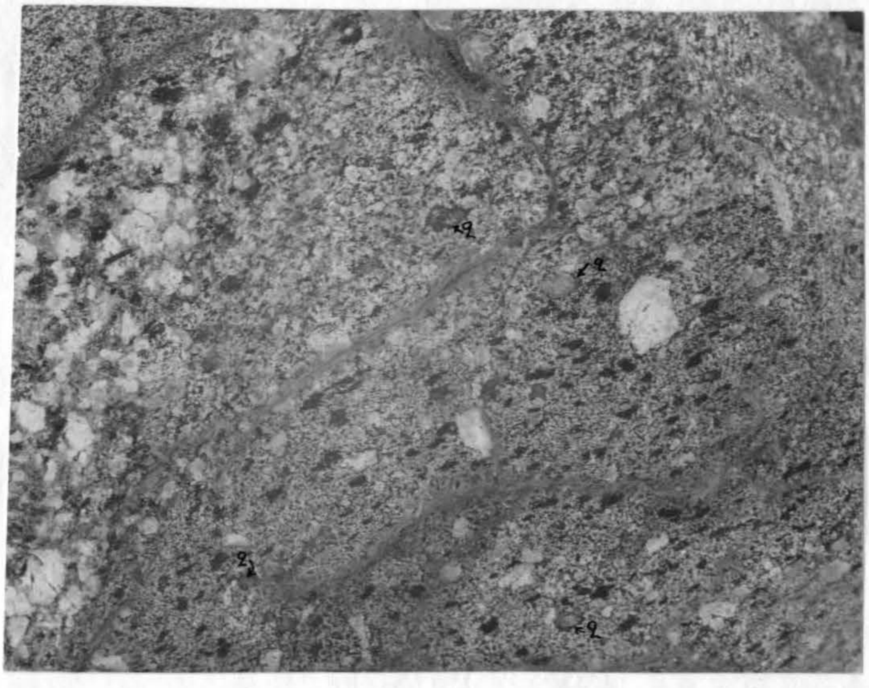


Figure 39

Figure 40. Photomicrograph. Elongate amphibole aggregates in a groundmass of plagioclase and hornblende in one of the least modified amphibolite inclusions observed in the hybrid phase of the Johnny Lyon granodiorite. Plain polarized light. Mag. x 26 diameters. Spec. L-230a.

Figure 41. Photomicrograph. Hornblende-rimmed quartz "eye" characteristic of all the amphibolite inclusions observed in the Johnny Lyon granodiorite. These features are interpreted as former amygdules. Plain polarized light. Mag. x 26 diameters. Spec. L-230a.

Figure 40

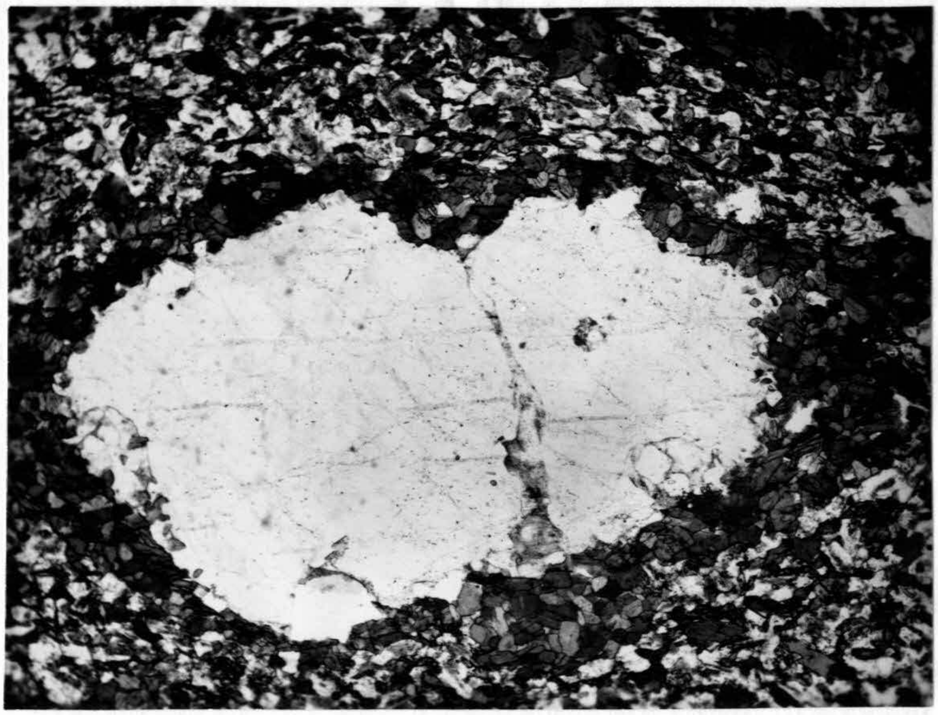


Figure 41

Trace quantities of apatite, magnetite, zircon, allanite are present.

The hornblende in the aggregates and in the groundmass is uniform except for rare actinolitic cores. The grains are anhedral to subhedral, ranging in size from less than 0.01 mm to 0.5 mm. Their optical characteristics are: pleochroic, pale yellow (X), bottle-green (Y), dark blue-green (Z), absorption $X<Y<Z$: indices $\alpha = 1.646$, $\beta = 1.661$, $\gamma = 1.669$; 2V (calculated) = $71^\circ(-)$, $Z\wedge C = 18\frac{1}{2}^\circ$. The essential identity of this hornblende with the hornblende of the typical granodiorite is clear. The actinolitic cores are pale blue-green and have smaller extinction angles ($Z\wedge C = 12^\circ$) and higher birefringence.

The plagioclase of the groundmass is anhedral to subhedral, subtabular, albite-twinned, and commonly slightly zoned. The grains average 0.1-0.3 mm in diameter. The average composition is about An_{25-28}. A single coarse euhedral crystal, about 3 mm in diameter, is about An_{35}. Almost all the plagioclase shows partial alteration of the cores to sericite and kaolinite.

The hornblende-rimmed quartz 'eyes' are conspicuous ovoids in thin section and appear to have been recrystallized to single grains. They contain inclusions of hornblende around the margins, and are surrounded by dense rims of fine-grained hornblende (fig. 41).

The chlorite is pseudomorphous after biotite and contains fine-grained leucoxene. Microcline occurs as rare small grains showing weak plaid twinning. Epidote is scattered in numerous skeletal crystals and aggregates of grains, up to 0.2 to 0.3 mm.

The foliation of the rock is expressed by subparallelism of the tabular plagioclase and elongate hornblende of the groundmass (fig. 39) in addition to the already mentioned oriented hornblende aggregates and quartz 'eyes'.

From its composition and texture, the amphibolite is believed to have been derived from a metabasalt similar to those found in the Pinal schist of Walnut Canyon in the nearby Little Dragoon Mountains. The quartz 'eyes' rimmed by hornblende are believed to represent former silica-chlorite amygdules (cf. figs. 33 and 41). The foliation reflects an earlier dynamic metamorphic episode in the rock's history. However, even in this least modified of inclusions, reconstitution at the level of the amphibolite facies plus some retrogressive metamorphism probably may be attributed to the influence of the intrusive. It has been observed that nowhere in the main body of the Pinal schist in the Johnny Lyon Hills area have conditions more intense than green schist facies been attained, except in the vicinity of the pluton. However, it is not possible to state unequivocally that these rocks achieved amphibolite rank solely as a result of the influence of the granodiorite. The rank of metamorphism of mafic rocks in the Pinal schist in the nearby Little Dragoon Mountains, changes drastically over short distances in some instances and reaches the amphibolite facies at some places.

Turner (1948, p. 76) has followed Eskola in defining the critical association of the amphibolite facies, in rocks of appropriate composition, as hornblende with anorthite-bearing plagioclase. In his staurolite-kyanite subfacies, Turner (1948, p. 84) recognized the following assemblage of minerals as one of those stable in the presence of excess potash, "(2) plagioclase-hornblende-biotite-epidote-microcline-quartz". Allowing for subsequent retrogression of the biotite to chlorite, this assemblage is essentially that of the least modified amphibolite in the intrusive. Sphene is the only common mineral present which is not listed by Turner, and this omission is consequent upon the simplifications Turner (and Eskola before him) followed in setting up the ACF diagrams for equilibrium mineral assemblages. Titanium is not considered as a component in their systems.

It is clear from earlier descriptions, that the main phase of the Johnny Lyon granodiorite (see tables 5, 6) has an igneous mineral assemblage equally correspondent to Turner's type assemblage for the amphibolite. It is not surprising, therefore, to find this particular amphibolite in approximate equilibrium with its host. The degree to which equilibration has been attained is indicated in several ways. The hornblende, and the biotite when still present, are optically nearly identical in the granodiorite and the amphibolite. The plagioclase of the two rocks has essentially the same composition. The original chloritic (?) linings of the quartz amygdules have been reconstituted to amphibole in equilibrium with the other phases.

Most of the inclusions of amphibolite have further modified toward the composition and texture of the granodiorite. Petrographic examination indicates that the modification involves recrystallization, reconstitution and metasomatism. Although individual inclusions may follow divergent paths and reach different stages, the general trend is toward a mafic, medium to coarse-grained somewhat igneous-appearing hybrid rock (fig. 42). An estimated mode of one of the most modified inclusions is given below:

Figure 42a. Photomicrograph. An amphibolite inclusion which has been strongly modified. This hybrid rock is somewhat igneous in appearance and has the composition of a mafic tonalite or granodiorite. The mineral species are identical with the minerals in the normal granodiorite and have suffered similar alteration effects. Plain polarized light. Mag. x 26 diameters. Spec. L-230d.

Figure 42b. Same field, crossed nicols.

Figure 42a

Figure 42b

L-230d	Wt. percent
Quartz	15
Plagioclase	40
Microcline	3-5
Myrmekite	tr
Hornblende	25
Biotite (and chlorite pseudomorphs after biotite)	12-15
Sphene	½
Ores	tr
Apatite	tr
Zircon	tr
Allanite	tr

A list of the more prominent variations in the transition follows:

(1) Grain size grows coarser, from 0.05 to 0.2 mm average size to 1 to 2 mm.

(2) The foliation is almost but not quite completely lost.

(3) The oriented aggregates of hornblende lose their prominence and tend to crystallize into larger and fewer crystals.

(4) A porphyroblastic texture develops initially but subsequently becomes inconspicuous because of the general coarsening of texture.

(5) Coarse, zoned plagioclase of calcic oligoclase composition, forms tabular porphyroblasts up to 8 mm in diameter which may make up to 10 to 15 percent of the rock.

(6) Quartz appears as a constituent of the groundmass in quantities up to 15 to 20 percent of the rock.

(7) Biotite becomes increasingly abundant while hornblende decreases somewhat.

(8) Microcline increases both as replacement grains in the groundmass and as cross-cutting veinlets. Myrmekite follows the microcline.

(9) Sphene develops from skeletal aggregates to well-formed crystals, but does not change appreciably in abundance.

(10) The accessory ore minerals appear to increase in abundance.

The hornblende-rimmed quartz amygdules, although recrystallized, remain prominent in all of these inclusions. All of the inclusions share in the presence of late-stage minerals including epidote, clinozoisite, allanite, chlorite, and sericite such as are found in the uncontaminated granodiorite.

The variations permit some conclusions to be drawn. The textural modifications were developed at the expense of the foliation but not so completely as to destroy it. Clearly, therefore, the inclusions never became particularly plastic or mobile. In addition to recrystallization of some of the plagioclase to coarse porphyroblasts, and of some of the fine-grained hornblende aggregates to large single grains, some reconstitution and metasomatism has occurred. Biotite grew at the expense of hornblende. Quartz and microcline replace all other major minerals. It is interesting to note that the chain of appearance of new minerals in the inclusions parallels the sequence of crystallization in the granodiorite; hornblende and plagioclase initially, followed by biotite, quartz and potash feldspar in that order. Microcline is clearly the latest major mineral as it occurs in numerous striking cross-cutting veinlets. The metasomatic activity, chiefly the addition of silica and potash, took place during the latter part of the crystallization history of the granodiorite, when the greatest discrepancy between the composition of the residual magma and the composition of the amphibolites existed. The tendency was to eliminate the concentration gradients. The changes in mineralogy reflected, only to a somewhat stronger degree, the shifting of the equilibria of the phases within the granodiorite itself. During the deuteric stages of crystallization in the latter, identical reactions and alterations took place in the inclusions and the host rock.

The hybrid granodiorite intimately surrounding the inclusions contains numerous ragged clots of fine-grained hornblende and plagioclase, and is quite variable in texture and composition. In addition to the clots of foreign origin, the abundance of coarse prismatic hornblende is locally increased, while the concentrations of potash feldspar and quartz decline. The contaminated granodiorite approaches the composition of the more modified inclusions. Only textural and structural criteria permit the separation of hybrid inclusions from hybrid magma and in many cases, they are insufficient and inconclusive.

Metarhyolite(?) inclusions

A common type of inclusion in the Johnny Lyon granodiorite is a gray porphyritic rock with a fine-grained groundmass surrounding grains of rounded quartz and altered tabular feldspar up to 12 mm in diameter. Found in randomly oriented blocks, a few inches up to two or four feet in average dimension, the inclusions show little or no reaction with the granodiorite. Petrographic examination reveals that the plagioclase is consistently altered to sericite, but is probably sodic oligoclase or albite. The texture of the quartz phenocrysts is suggestive of the resorption forms seen in the rhyolites in the Pinal schist. A number of coarse grains of chlorite with associated epidote and magnetite appear to be pseudomorphous after original biotite.

The groundmass consists of altered plagioclase intergrown with abundant quartz in an intricate, interlocking pattern, suggesting recrystallization from an originally fine-grained texture. Chlorite, epidote, magnetite and leucoxene are other minerals in the groundmass. Estimated original mineral percentages are quartz 40 to 45 percent, plagioclase 40 percent and biotite (now chlorite, magnetite, etc.) 10 to 15 percent. Traces of sphene, apatite and zircon are also present.

The composition of this type of inclusion is compatible with the available petrographic information for the rhyolites, and because of the textures, it is believed that they were derived from foundered blocks. Their relative abundance suggests that rhyolite bodies may have been common in parts of the schist no longer exposed.

Aplites and pegmatites

Numerous aplite and pegmatites are associated with the granodiorite, both in dikes cross-cutting the granodiorite and more abundantly as dikes and sheets conformable to the foliation and bedding in the adjacent schist. These bodies have not been distinguished from the granodiorite on the map because of their great number and generally small size. A few attain 600 to 800 feet in length and 40 to 50 feet maximum width. Some excellent examples are to be seen in the contact zone of the Pinal schist northwest of Javelina Hill.

Aplites and pegmatites may occupy separate positions or occur as apparent multiple injections into the same space. There is no apparent consistent sequence of intrusion and the contacts between aplite and pegmatite may be sharply defined, or gradational.

The pegmatites are generally simple in composition consisting of blocky pink perthite; white to light gray massive quartz; albite, commonly as the platy variety cleavelandite; and muscovite, the last sometimes in striking arborescent patterns intergrown with platy albite. Small crystals of black tourmaline and red garnet are uncommon accessory minerals. Zoning of the pegmatites is not conspicuous except for occasional quartz cores. Pegmatites within the Pinal schist are enriched in muscovite on their margins.

The aplites are of two types. A simple segregation type that forms small bodies within the granodiorite has a typical composition (estimated) of:

Quartz	35 percent
Oligoclase (Ab_{80-90})	40 percent
Microcline-microperthite	15 percent
Biotite (or chlorite-epidote pseudomorphs)	10 percent

This rock is fine-grained and sugary textured, except for occasional larger crystals of plagioclase similar to those in the granodiorite.

Larger aplites in well-defined dikes both in the intrusive and in the wall rock are also saccharoidal, medium-grained, and may have a typical composition of:

Quartz	35 percent
Oligoclase (Ab_{85-90}) (myrmekitic)	25
Microcline	30
Muscovite	5-10
Garnet	2-3

The former type of aplite is usually as deeply altered, and to the same minerals, as the granodiorite. The latter is distinctly less altered, probably in part because its minerals are less susceptible.

Altered phases

In addition to the general alteration imprints found throughout much of the granodiorite there are localized areas of more intense effects as in three nearly parallel bands trending due N. to N. 15° E. on The Mesa. These bands are 100 to 400 feet in width, 2½ to almost 5 miles in recognized length, and dip steeply to the west. The eastern band extends from at least a half mile north of Mesa Tank, southward to an intersection with the Pinal schist contact northwest of Javelina Hill. At this point it is accompanied by an offset of the contact of at least several hundred feet. The central band is 1/3 to 1/2 miles west of the first, and may be traced from about the same latitude on the north for approximately 3 miles southward. The western band can be followed almost continuously from near the base of the Scanlan conglomerate one mile north of the Willcox-Cascabel road, to the base of the northern end of Sheep Camp Ridge. This zone, over much of its length, is on or very close to the drainage divide between the Mesa and the River Slope and apparently has had considerable influence on the development of the local topography. There are suggestions of lesser zones among these three, but none has comparable dimensions or intensity of alteration.

The major elements of these alteration bands are (1) a central shear zone, (2) discontinuous lenses and sheets of intense silicification, and (3) an envelope of alteration which is usually gradational to normal granodiorite at the outer limits.

The shear zones are in part concealed by pervasive siliciification but the original granodiorite has been converted to cataclastic products ranging from massive-weathering, mylonitic augen gneiss to pulverulent breccia gouge. The gneissic textures are restricted in general to bands a few feet in width, whereas tabular bodies of gouge up to 100 feet wide are not uncommon. These cataclastic phases usually occupy a central position in the band but gouges are locally found with diverse attitudes in all parts of the band. The prevailing attitude of the gneissic foliation, gouge zones and silica bodies is 50 to 70 degrees to the west.

The silicification takes the form of pervasive replacement bodies in the brecciated granite, and of veins, from fractions of an inch to a few feet in width, commonly in anastomosing stockworks. The largest bodies ranging up to half a mile long and more than 100 feet wide are composites of both types. The silica is in the form of massive milky-white to gray quartz. It is commonly brecciated and recemented, and it contains inclusions of silicified granite and vugs lined with well developed crystals of milky quartz up to 1 inch in length. Most of the silicification is concentrated in the central shear zone, but a number of lenses occupy a slightly oblique orientation to the main trend of the band of alteration. These are more common in the central and eastern bands. "herever the silicification is predominant, it is reflected topographically in low ridges and knobs, etched out of the less resistant granodiorite by weathering and erosion (fig. 34).

The altered granodiorite that envelops the sheared and silicified zone varies considerably in its modifications, with the strongest effects generally developed near the center. On the margins, the granodiorite is limonite-stained, with chloritized mafic minerals and sericite-dulled feldspars. Toward the center, the plagioclase becomes increasingly albitic and darker in color. It may locally reach a composition of Ab_{95} with all of the original zoning erased and with abundant coarse sericite inclusions. The microcline-perthite develops a patchy perthitic texture and is stained by limonite. The biotite and hornblende are completely replaced by chlorite, calcite, limonite and leucoxene. Epidote becomes increasingly prominent toward the center in veinlets and masses of calcite, but where albitization is most extensive the epidote is uncommon or absent. Fine-grained clays are common in the gouge zones. Specular hematite and secondary copper minerals may be present, dispersed and in veinlets, in the more altered areas.

Some of the most intense hydrothermal effects can be observed in an elliptical area of alteration, half a mile northwest of Sheep

Camp Ridge and adjacent to the major western alteration band. This dark brown rock is exposed over an area a thousand feet long and 600 feet wide. The exposures suggest a pipe-like form, plunging steeply to the south-southwest.

The texture grossly resembles that of the granodiorite, but essentially all of the quartz has been removed, the feldspar is dark brown, yet has a fresh luster on cleavage surfaces. Numerous pockets with prominent yellow limonite are scattered throughout the rock. Under the microscope, the plagioclase is raggedly twinned and unzoned and has the optical character of Ab_{95-98}. It contains a fine limonite dust and minute crystals of kaolinite(?). Most of the grains are tabular, and 3 to 8 mm in diameter. The microcline forms a coarse patch perthite in large crystals. No myrmekite is present. Two types of chlorite are present: (1) a coarse-grained pleochroic green penninite(?) and (2) a non-pleochroic, very pale green prochlorite(?) in fine-grained colloform aggregates. The coarse chlorite is associated with leucoxene and limonite as pseudomorphs after the original mafic minerals. The fine-grained prochlorite(?) is intergrown with fine-grained albite, sericite, and limonite and has replaced an appreciable part of the rock. Only a trace of corroded quartz was observed. Sphene has been completely altered to leucoxene and the apatite crystals appear to be corroded. An estimated mode of the rock is as follows:

Albite	65 percent
Perthite	5
Chlorite	25
Limonite	2
Sericite	2
Leucoxene	1
Quartz	tr
Accessories	tr

The alteration bands appear to have originated in pre-Cambrian time. The western band can be traced northward to the great unconformity at the base of the Pioneer shale but no effects of it can be seen in the overlying Apache group. To the south this same band appears to pass under the thrust plate capping Sheep Camp Ridge without affecting it. Southwest of the ridge the band has not been recognized. Numerous lamprophyre dikes of Tertiary(?) age cut across all of the bands and show no displacement or increase in alteration. The possibility of recurrent passage of hydrothermal solutions through these zones must be considered, however. Localized in the vicinity of the western band are a number of cross-cutting veins of brown carbonate, quartz and limonite boxworks. They are similar in mineralogy to some of the phases within the altered zone, yet they appear to be younger than some of the small lamprophyres which they intersect. They are also identical in mineralogy with some of the mineralized rock in the post-Paleozoic fault zones. If these lamprophyres are Tertiary in age, a probability which cannot be conclusively checked in this area, then a second episode of hydrothermal activity is indicated.

Cataclastic phases

Deformation textures are fairly common throughout the granodiorite. Their presence in the major alteration bands has already been described. There also is a wide variety of mechanically degraded textures associated with the Laramide thrusting. Numerous localized shear and crush zones exist with as yet unrecognized relations to the major structures. These tectonic modifications range from impalpable loose gouge to dense, microcrystalline mylonites. The cataclasites may or may not be recrystallized, either as a result of metamorphism during deformation or from subsequent hydrothermal alterations.

The major thrust fault movements imposed megascopically visible effects of varied intensities. The granodiorite underlying the Sheep Camp Ridge is exposed at a number of points directly beneath the principal thrust on the north and northeast slopes. Pervasive intergranular shearing appears to be limited to a few inches or feet next to the fault and to the slices. The material at a greater distance below the sole has been fractured and somewhat broken but still retains its granitic texture. South and west of the Keith Ranch, the fault believed to be an offset continuation of the Sheep Camp Ridge fault has a more extensive zone of crushing. Visible shear effects extend 50 feet or more from the fault. A strong mineral grain shearing accompanied by a distinct fracture cleavage develops locally. Microscopic examination reveals that at least 60 percent of the rock has been reduced to a mortar of grains less than 0.5 mm in diameter surrounding coarser distorted quartz and plagioclase fragments. Fine-grained sericite seems to have developed after the deformation, for it shows little or no orientation and fills cross-cutting fractures.

One of the most extensive crush zones visibly related to the thrusting is exposed in the NW¼, sec. 30, T. 15 S., R. 21 E. and the NE¼, sec. 25, T. 15 S., R. 20 E. The northwestern extension of one of the Catclaw Hills thrust faults is located in a zone of massive cataclastic breccia 200 to 300 feet thick. The textures revealed microscopically have not been milled so fine as to be called mylonitic nor is there any visible foliation. A pervasive mechanical disintegration of the original granite minerals to smaller but still megascopic grains without recrystallization has occurred, followed by extensive alteration to sericite, chlorite, leucoxene, and limonite.

Numerous isolated areas and zones of deformed rock within the granodiorite cannot be related to specific deformational events in the geologic history of the pluton. Many of these occur to the west and southwest of Sheep Camp Ridge. In sec. 24, 25, T. 15 S., R. 20 E. there are at least two strong shear zones of N. 20°-30° E. trend and dipping steeply to the west. Along these zones, a strong foliation is locally developed and the granodiorite is converted to mylonitic augen gneiss (fig. 43). Flattened lenses of quartz and plagioclase are 'eyes' in a very fine-grained matrix representing 60 percent of the rock. The average grain size of the matrix is less than 0.05 mm while the porphyroclasts are up to several millimeters in dimension in the direction of flattening. Abundant sericite and chlorite in the matrix are strongly oriented parallel to the foliation. There is no other evidence of recrystallization.

Figure 43a. Photomicrograph. Augen gneiss developed in the Johnny Lyon granodiorite along a major shear zone of indeterminate age. None of the original igneous textures have been preserved and most of the original minerals have been converted to a fine-grained feldspar quartz-sericite-chlorite-iron oxide matrix surrounding the few coarse relict mineral fragments. Plain polarized light. Mag. x 26 diameters. Spec. L-211.

Figure 43b. Same field, crossed nicols.

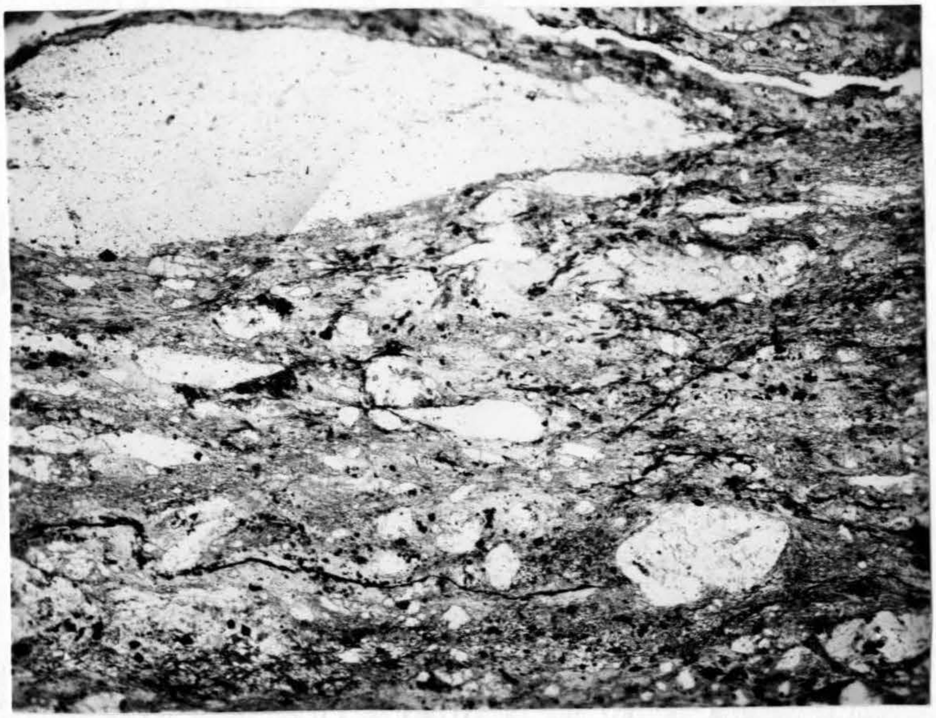


Figure 43a

Figure 43b

Uncommonly, mylonitization has proceeded so far as to leave almost no megascopic fragments. A slightly mineralized prospect pit in the NE$\frac{1}{4}$, sec. 13, T. 15 S., R. 20 E., reveals exposures of deformed granodiorite grading into a dense black aphanitic rock bounded by slickensided fracture surfaces with a waxy luster. Petrographic examination reveals that more than 75 percent of the rock consists of grains smaller than 0.05 mm. A few coarser fragments up to 4 mm in major diameter are also present. A definite foliation is visible microscopically in the sheared aggregates of quartz, feldspar, iron oxides, etc. There is also a pair of cleavages obliquely intersecting the foliation at low angles. Pervasive fine-grained sericite and chlorite have replaced much of the original plagioclase and mafic minerals. It is not clear whether some of the sericitization was pre-shearing, but some of it is definitely later since it occupies late fractures. There also are some late stage epidote, sphene and chlorite. Copper stains are present on the hand specimen. It is probable that the recrystallization here is largely hydrothermal rather than dynamometomorphic.

The occurrence of this almost glassy appearing cataclasite is restricted to the prospect pit and no significance other than its existence has been recognized so far. But the development of a nearly pseudo-tachylitic rock testifies to the local intensity of shearing in the granodiorite, presumably during the Laramide deformation.

Origin

The Johnny Lyon pluton originated from the quiet intrusive emplacement of a large, slightly discordant body of granodioritic magma into the Pinal schist, after the regional deformation of the latter was essentially complete. There is only slight evidence of primary flow foliation, which the deep weathering of the granodiorite unfortunately tends to obliterate. From the orientation of scattered small dark tabular schist inclusions and occasionally of the biotite plates, hornblende prisms and tabular plagioclase a steep flow foliation approximately parallel to the contact can sometimes be recognized. Some of the alignment among the larger metasedimentary inclusions may also reflect this flow direction.

That the composition of the magma was originally granodioritic and was not strongly modified by reaction is clear from the nature of the effects on its inclusions and contacts. Among the several types of inclusions already described, only the amphibolite inclusions show strong reaction effects and the compositional changes are predominantly in the direction of modification of the inclusions toward more acidic rocks. The quantity of hybrid magma produced is minute compared to the mass of the granodiorite and it is confined to the immediate vicinity of the basic inclusions. The metarhyolite (rhyodacite) inclusions show every indication of textural recrystallization in a system near compositional equilibrium. The metasedimentary hornfels inclusions and contact zones, while undergoing considerable recrystallization and reconstitution, show only slight and very localized evidences of metasomatism, principally addition of potassium from the magma. The slight zoning of the pluton with biotite preponderant over hornblende in the vicinity of the intrusive contact may reflect zome alumina contamination of the magma, but it might equally well reflect a local internal differentiation within the pluton. As has already been noted, the contacts between granodiorite and schist are sharply defined to within less than an inch in most exposures. There is no textural evidence suggesting assimilation, except possibly in scattered local injections of typical granodiorite along the marginal planar structures of the schist.

The mechanism of emplacement is not clear. Proponents of stoping might consider the numerous scattered small inclusions in the granodiorite significant, but volumetrically these constitute much less than one percent of the mass. Most of the blocks would have to have been removed physically from the visible scene, at least, before they reached a reactive environment. Forcible emplacement, i.e. under the drive of orogenic stress, is not recorded by deformational evidence in the schist that it would be reasonable to expect. The granodiorite itself shows no strong evidence of forceful flowage into place such as is common in syntectonic bodies.

Fusion in place at the base of the geosynclinal prism would be a reasonable source for the magma. But the metamorphic rank of the rock at the present site of the body shows the schist was clearly never subjected to the geothermal gradients necessary to produce such effects at this level. Metasomatists would fine little structural, textural or compositional comfort in the geological relations.

The passive nature of the emplacement suggests a regional stress pattern with a minimum horizontal compressive stress, in which space was provided for the introduction of the magma without too much resistance, possibly under a gravity drive. The forces of the Mazatzal deformation must have been greatly diminished or modified. An upward direction of relief is normally to be expected, but with the limited information on the shape of the pluton and the internal flowage, other directional relations of stress cannot be assumed.

A rotational reconstruction of the post-granodiorite pre-Cambrian shear zones to a pre-Apache group attitude, reorients the shear zones that now strike N. 10° E. and dip 60° W. to a strike of N. 5° E. and a dip of 85° E. Thistrend is oblique to the earlier structural trends of the schist and results in the intersections of the easternmost shear zone with the intrusive contact. The reconstructed surfaces are essentially vertical and the apparent sense of movement is left lateral on the easternmost fault. Shearing is so intense along the zones, as reflected in the local flaser gneisses, that they may well be wrench faults (E. M. Anderson, 1951, p. 15) rather than simple normal faults.

The existence of the post-intrusive shears might be used as evidence for a renewal of the Mazatzal force system. A wrench fault set of N. 10° E. orientation with left lateral movement could result from compression along a N. 20° W. line. The lack of any independent evidence on this point limits further speculation.

Age and correlation

The granodiorite of the Johnny Lyon Hills is but one of many large bodies of post-kinematic granitic rocks in Arizona which are truncated in erosional unconformity by the Apache group or its equivalent. The great mass of the Oracle granite at the north end of the Santa Catalina Mountains; the Madera diorite (actually a quartz diorite to granodiorite) and Ruin granite of the Globe region, and unnamed granite and granodiorite plutons in the upper Tonto Creek basin, the Grand Canyon, Morenci, and elsewhere are all potential equivalents. So are large igneous bodies at Jerome, Bagdad and Chloride. All of these bodies appear to be members of an episode of batholith emplacement at the end of the Mazatzal Revolution.

Positive demonstration of equivalent ages must depend on radioactive dating methods. Two Larsen (1952) method age determinations on zircon separates from the Johnny Lyon granodiorite yielded apparent ages of 815 and 615 million years. The average value of 715 million years is about the minimum age compatible with the geologic relations in the area.

Recent unpublished work by G. Tilton and others (D. Gottfried, personal communication) on the isotopic composition of the lead in fine-grained zircons from several pre-Cambrian rocks indicates that some radiogenic lead may be lost from these minerals. This effect would result in Larsen method measurements in which the apparent age of the granites would be lower than the actual age.

In the case of the Johnny Lyon granodiorite, it is possible that the complex alteration history of the igneous body is responsible for some post-crystallization chemical modification of the zircons. Although the samples from which the zircons were separated were the freshest available, they were not completely free from some alteration effects that could have been deuteric or much younger. If some younger secondary effects were imposed, it is probable (but not necessary) that they would be in the direction of lead removal, and would therefore also tend to reduce the apparent age of the intrusive.

Upper Pre-Cambrian System

Apache group

The Apache group was first described by Ransome (1903) from the well-exposed section on the west face of the Apache Mountains, 10 miles north of Globe, Arizona. Resting unconformably on a pre-Cambrian crystalline complex, the group consists of seven distinct formations with a total thickness of about 1,000 feet in the most complete exposures. Numerous diabase sills invade these formations, particularly the lower ones.

The Apache group rocks in the Johnny Lyon Hills and the Little Dragoon Mountains are the most southerly exposures of the group known. Here, too, the group rests unconformably on old pre-Cambrian rocks. In the Johnny Lyon Hills, only the two lowest formations recognized by Ransome, the basal Scanlan conglomerate and the overlying Pioneer shale, are present. They are associated with a diabase sill. The presence in the Little Dragoons of some of the higher Apache group formations indicates that they were probably present in the Johnny Lyon Hills area and were removed by pre-middle Cambrian erosion.

Scanlan conglomerate

The basal formation of the Apache group is the Scanlan conglomerate. It was named by Ransome (1903) for Scanlan Pass just east of Barnes Peak in the Globe quadrangle. It is described as one to six feet of subrounded quartz pebbles and occasional schist fragments in a sandy matrix of potash feldspar and quartz. It rests on a surface cut on both Pinal schist and granite.

The Scanlan conglomerate in the Johnny Lyon Hills consists of a series of thin pebble conglomerate horizons, 1 to 6 inches thick, and scattered pebbles in a predominant matrix of feldspathic quartzite (fig. 44). This pebbly quartzite grades stratigraphically upward into similar quartzite beds in which pebbles are rare or absent in the Pioneer shale. Locally the entire quartzite section at the base of the Apache group may be free of pebbles and the Scanlan conglomerate as defined is not present. The maximum thickness measured for the conglomeratic quartzite is 25 feet. The conglomerates are not always to be found in the very basal bed of the formation.

The pebbles are angular to subrounded and consist principally of vitreous white and pink quartz, with less abundant fragments of gray schist and quartzite. They vary in size from 10 to 75 mm averaging about 25 mm. Neither the abundance of pebbles nor their composition appears to be a function of whether the conglomerates rest on granite or schist.

The matrix quartzite consists of gray to pink-gray, medium- to coarse-grained quartz with about 5 to 20 percent pink and white feldspar. It is medium to thick-bedded, with some cross-bedding.

The basal unconformable contact of the Scanlan conglomerate is usually partly concealed by debris from the overlying rocks, but the extreme regularity and lack of relief of this surface is striking. No conspicuous channels have been noted. It would be difficult to demonstrate as much as 5 feet of local relief in a distance of 100 yards. Where the granodiorite is the underlying rock, its upper one or two feet are commonly somewhat darkened by iron and manganese oxide stains. It appears to be as well consolidated as the rest of the granodiorite but it has lost the sharpness of definition in its igneous texture. Scattered quartz pebbles (fig. 45) indicate that this is the indurated remnant of the regolith which covered the old erosion surface prior to the deposition of the Apache group. The Pinal schist at the base of the Scanlan conglomerate commonly shows a darkening in color sometimes to a depth of tens of feet, but no evidence of an old soil mantle has been noted.

Pioneer shale

The Pioneer shale was named for the exposures at Pioneer, an old mining camp south of Globe, Arizona, by Ransome (1903). It was described as dark reddish-brown arenaceous shales, thin-bedded, with characteristic small, round or elliptical, buff-colored spots; a few fine-grained quartzites are intercalated. Ransome (1916, p. 136) has remarked that elsewhere the Pioneer shale generally contains basal arkosic quartzites ranging from 15 to 175 feet in thickness.

In the Johnny Lyon Hills area the Pioneer shale is coextensive with the Paleozoic section. It emerges from under the alluvium west of Kelsey Peak and except for fault offsets, crops out continuously southward to the vicinity of Lechugilla Hill. It also appears in thrust plates and thrust slices in Thompson Wash, on Sheep Camp Ridge, and on Keith Peak. The topographic expression of the combined Scanlan conglomerate and Pioneer shale usually consists of low ridges rising above the Johnny Lyon granodiorite or the Pinal schist. Where a considerable interval of diabase separates the Apache group from the

Figure 44. Scanlan conglomerate at the base of Apache group. The thin zones of angular white pebbles in feldspathic quartzite are the most common lithology of this stratigraphic unit in the Johnny Lyon Hills area.

Figure 45. The contact at the base of the Scanlan conglomerate where it rests upon the Johnny Lyon granodiorite. The old regolith on the pre-Scanlan erosion surface has been indurated until it is difficult to distinguish from the underlying altered but mechanically undisturbed granodiorite. Commonly the appearance of angular quartz fragments (at the level of the hammer in the photograph) is the first reliable indication of the transition from granodiorite to arkosic.material.

Figure 44

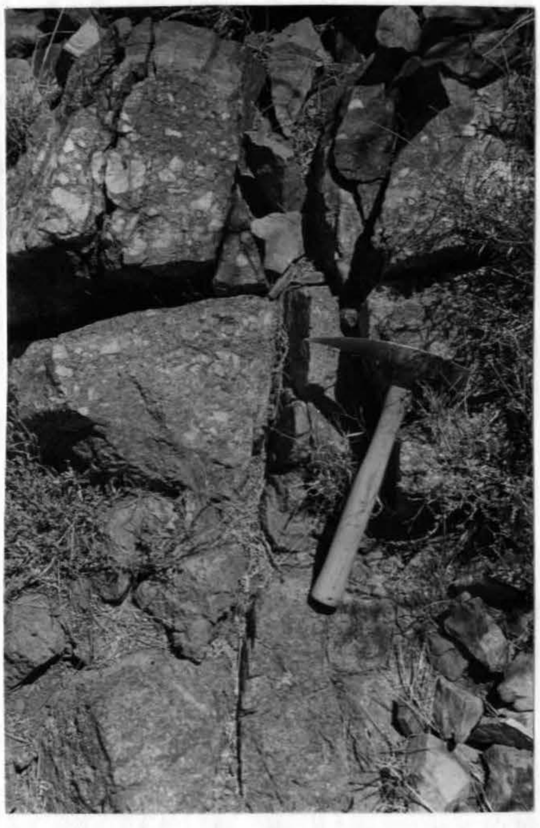


Figure 45

Bolsa quartzite as in the Rattlesnake Ridge area, the tilted quartzites of the Scanlan conglomerate and basal Pioneer shale form hogbacks on which the upper Pioneer shale is exposed on the dip slope. Where the diabase is thin or absent, the overlying Bolsa quartzites dominate the local topography.

Lithologically, the Pioneer shale consists of two units: (1) basal arkosic quartzites, and (2) overlying argillites. The basal quartzites are medium to coarse-grained, feldspathic to arkosic, and are indistinguishable from the Scanlan conglomerate quartzites, except for the pebbles in the latter. The argillite unit, for which the name shale has been employed, contains thin bedded, well indurated mudstones, siltstones and rare thin quartzites. The argillites are typically purple and brown, more rarely yellow, tan and gray, and may be characterized by distinctive color spots of two types. One type is small, 1/4 to 1 inch in diameter, oval or round, buff to white, and appears to have been formed by reduction and removal of iron around a small nucleus. The second type is black, round or elongate parallel to the bedding, 1/4 to 1/2 inch in diameter or width, and up to 1 to 2 inches long (fig. 46). This type appears to be a manganese oxide stain. Both of these color markings are three dimensional and are not confined to outcrop surfaces.

The Pioneer shale is generally uniform over the area mapped. It varies somewhat in thickness, 300 to 325 feet, because the upper contact is in part determined by the intrusive diabase and in part unconformable against the Bolsa quartzite. The variable abundance of the congomerates forming the Scanlan conglomerate also affects the apparent thickness by varying the thickness of quartzites assigned to the basal

Figure 46. Dense argillite of the upper part of the Pioneer shale showing the distinctive black manganese oxide (?) spots which characterize most of the beds in this part of the formation.

Figure 46

Pioneer shale. A description of a section of Scanlan conglomerate and Pioneer shale, west of Lechugilla Hill is given on page 205.

The Scanlan conglomerate and Pioneer shale have been mapped as a single unit because of their gradational relationship and because of the very slight thickness of the Scanlan conglomerate. They are interpreted as representing a single episode of continuous sedimentation in a sea transgressing across a remarkably regular plain of erosion which truncated the older crystalline complex. The conglomerates and quartzites are the littoral equivalents which pass upward into the neritic shales. The feldspathic character of the quartzites reflects the granite-rich parent terrane rather than the stable shelf environment in which the sediments were formed.

On the basis of the lithologic similarity and the geologic relations, these two formations are correlated with the Apache group of the Globe region. They are unfossiliferous and are dated in this area as older than middle Cambrian fossils from the Abrigo formation. The intervening Bolsa quartzite in the map area also lacks fossils.

The group is separated by deformation, intrusion and erosion from the older Pinal schist. Ransome (1903, pp. 38-39, 1916, p. 164) originally believed the Apache group to be Cambrian because of lithologic similarities between the Mescal limestone and the Abrigo limestone. Darton (1925, p. 36) argued for the correlation of part of the Troy quartzite and all of the underlying formations of the Globe area, with the Grand Canyon Series, presumably younger pre-Cambrian in age. Subsequently, he (1932) proposed to restrict the term Apache group to the pre-Troy formations and Ransome (1932, pp. 5-6) accepted this as the most reasonable classification. Subsequent workers (Stoyanow, 1936, McKee, 1951) have followed the practice of tentatively placing the Apache group in the upper pre-Cambrian.

The thickness of the Scanlan-Pioneer beds in the Johnny Lyon Hills is as great as any thickness reported in central and southern Arizona. Cooper's work (1950b) in the Little Dragoon Mountains has shown that all of the Apache group units which have been preserved after the pre-Bolsa erosion there, are comparable in thickness to analogous units described by Ransome and others in central Arizona. The strong lithologic similarities of the various units argue for no great difference in source areas and sedimentary environments. It seems reasonable that the southern margins of deposition in Arizona in late pre-Cambrian time may have been some distance south of the Johnny Lyon Hills-Little Dragoon Mountains area. Post-Apache erosion has given these outcrops their present outlying relationship.

APACHE GROUP SECTIONS

Scanlan Conglomerate - Pioneer Shale

Section measured in NE. 1/4, sec. 10, T. 15 S., R. 21 E.

	Thickness
Bolsa quartzite	
1. Dark brown, coarse-grained sandstone with pebble conglomerate interbeds	3 feet
Apache group	
Pioneer shale	
2. Dense, siliceous, thin-bedded argillites with uncommon fine-grained quartzites. Color commonly purple and brown, but also mottled green, gray and tan. Distinctive black manganese spots 1/8 to 1/2 inch in diameter, and zones 1/4 to 1/2 inch thick laterally extensive parallel to the bedding	244 feet
1. Quartzites, gray, medium-grained to fine-grained, vitreous, feldspathic, thin to medium-bedded, rare angular pebbles of white and pink quartz . .	39 feet
	283 feet
Scanlan conglomerate	
1. Quartzites with conglomerate interbeds. Quartzites are gray to brown, vitreous, medium to coarse-grained, well sorted, to medium-bedded, feldspathic in variable degree. Conglomerates form thin interbeds, 1 to 6 inches thick, of angular pebbles of white and pink quartz, quartzite and schist. Pebbles are up to 1 to 2 inches in diameter and rest in matrix of quartzite . . .	25 feet
Pinal schist	
1. Gray sericite schists and metagraywackes in angular unconformity.	

Diabase sheet

A persistent sheet of diabase rests on the Pioneer shale throughout the northern half of the Johnny Lyon Hills area. It is 250 feet in thickness in the latitude of Kelsey Peak and, except for structural duplication, thins southward until it disappears in the latitude of Mesa Tank. In the southern half of the area it appears sporadically at the same horizon but never attains a thickness of more than 75 feet. The diabase is found also as thrust slices, both in the Johnny Lyon Hills, and in the vicinity of the American mine in the northwestern corner of the map area.

The topographic expression of the diabase is usually a recessive swale, or a minor valley between the more resistant Pioneer shale and Bolsa quartzite. Debris from the latter formation tends to obscure the outcrop areas and the contacts of the diabase commonly cannot be located within 10 to 20 feet.

The diabase is a fine to medium-grained gray-green rock in the freshest exposures, but deep weathering has produced granular disintegration and a dark red-brown soil. The characteristic ophitic texture can generally be recognized in the disintegrated particles of diabase in the soil.

Petrographic examination of a sample from one of the less weathered outcrops reveals that although the original ophitic texture is well preserved, the plagioclase has been almost completely altered to kaolinite, calcite, and gibbsite(?). Most of the original pyroxene has been replaced pseudomorphously by chlorite, calcite and iron oxide dust, but a few relics can be identified as augite. Brown biotite, altered partly to chlorite, abundant magnetite or ilmenite, now partly altered to limonite, and minor apatite and zircon complete the mineralogy.

The pervasive alteration cannot be attributed entirely to the recent weathering history. Where exposures of the upper few feet of diabase underlying the Bolsa quartzite are visible, an ancient weathering profile of pre-Bolsa age is revealed. The gray-green diabase becomes increasingly iron-stained until it is deep red-brown in color. The diabasic texture becomes less pronounced and the granules of disintegration pass successively to a massive hematite cemented material and then to a fissile hematite-rich shale three inches to one foot in thickness (fig. 47). Resting directly on this shale are iron-oxide-rich basal conglomerates and quartzites of the Bolsa.

The lower contact of the diabase is not often seen. The texture appears to be finer grained close to the Pioneer shale but no chill zone has been recognized. There are no megascopic effects of contact metamorphism in the uppermost beds of the Pioneer.

The only major lateral variation in the character of the diabase within the map area is in its thickness. Inasmuch as the upper surface is clearly an erosion surface, it cannot be determined whether the thickness fluctuations are original or superimposed. Nor is it possible to demonstrate locally whether the diabase is intrusive or extrusive. The texture is sufficiently coarse to support the hypothesis of hypabyssal emplacement, but no unequivocal evidence for intrusion has been recognized. No feeder system has been found in the area. In the Little Dragoon Mountains, Cooper (1950b) has found two diabase sills present in the upper part of the Pioneer shale, just below the Barnes

Figure 47. Fissile hematite-rich shale at the top of the diabase under the basal Bolsa quartzite. This shale formed from a lateritic regolith which developed on the erosion surface of the diabase prior to the deposition of the Bolsa quartzite.

Figure 48. Joint block of Bolsa quartzite showing the typical color banding both parallel and oblique to the bedding.

Figure 47

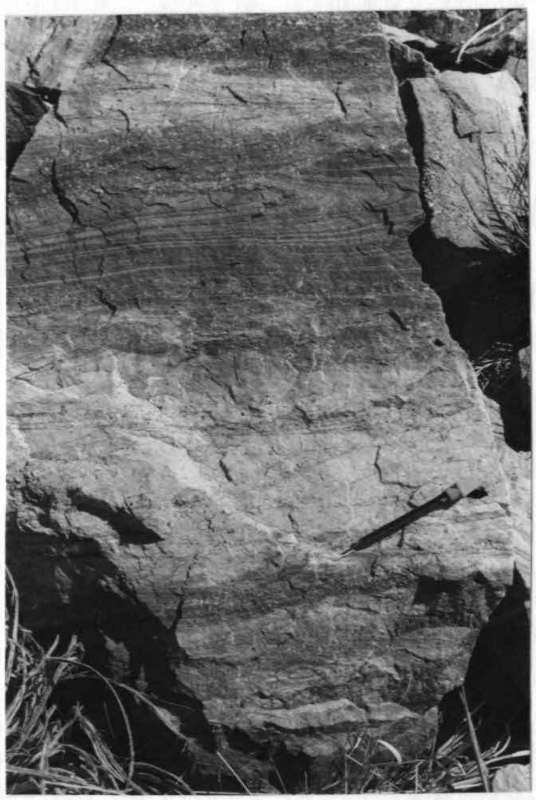


Figure 48

conglomerate of the Apache group. Intrusive evidence there includes contact metamorphic effects, small diabase apophyses into the Barnes conglomerate, and upper chilled selvages. Cooper attributes the constant stratigraphic position of the diabase to the relatively greater competence of the overlying conglomerates and quartzites, which caused the sills to spread out below them.

The age of the diabase in the Johnny Lyon Hills area can be placed as younger than the Pioneer shale which it overlies, and older than the middle Cambrian(?) Bolsa quartzite which rests unconformably on it. It has been tentatively called upper pre-Cambrian and is correlated with those diabases of Central Arizona which Darton (1925, p. 34) describes as unconformably overlain by the Troy quartzite. Much of the central Arizona diabase is clearly younger than the Troy, and Darton's age assignment has been questioned by some geologists, but the pre-middle Cambrian age of the diabase in the Johnny Lyon Hills and the Little Dragoon Mountains seems certain.

Cambrian System

Bolsa quartzite

The type locality for the Bolsa quartzite was established by Ransome (1904, p. 28) in Bolsa Canyon west of Bisbee. The formation was described as 430 feet of thick-bedded vitreous grits and quartzites, cross-bedded, feldspathic in the lower beds, with a persistent basal conglomerate of pebbles of white quartz 6 inches to one foot thick. The formation rests with great angular unconformity on the Pinal schist and is conformably overlain by the Abrigo limestone. The Bolsa quartzite has subsequently been recognized at Tombstone, in the Dragoon Mountains, and elsewhere.

The Bolsa quartzite of the Johnny Lyon Hills region crops out almost continuously as a resistant ridge from the northwest corner of the map area to Lechugilla Hill. It forms prominent cliffs and ledges on Keith Peak and is the resistant "backbone" of Sheep Camp Ridge. As abundant slices, the resistant quartzites commonly emphasize the traces of some of the major thrust faults.

The Bolsa quartzite is characterized by three major zones of lithology. The lower zone consists of dark brown to tan coarse-grained quartzites and granule conglomerates, with pebble conglomerate beds appearing throughout the zone. The middle zone consists of white and tan, fine to medium-grained vitreous quartzites. The upper zone consists of brown quartzites with interbedded thin olive-brown fissile shales. This upper zone represents a gradational transition from the lower quartzites to the overlying shales of the base of the Abrigo formation. The quartzites commonly show distinctive color banding (fig. 48) with alternating light and dark bands both parallel and oblique to the bedding and cross-bedding. This color banding, the gritty and pebbly texture, and the lack of feldspar usually serve to identify the Bolsa quartzites where they are found in fault slices. A stratigraphic section of the Bolsa quartzite and underlying diabase is given on pages 214-215.

The base of the Bolsa quartzite rests upon the erosional unconformity which truncates the diabase and the Pioneer shale. The composition, size, and roundness of the pebbles in the conglomerates strongly suggest reworked Barnes conglomerate pebbles as their source. On the west side of Keith Peak the basal conglomerates of the Bolsa formation contain numerous fragments of Pioneer shale. Nowhere in this area have fragments of diabase been found included in these conglomerates, but the deep weathering and ready decay of the diabase provide a reasonable explanation for this lack. There is evidence of a very slight angular discordance between the Bolsa strata and the underlying Apache group beds which will be discussed in the structural section of this paper.

The upper contact of the Bolsa quartzite has been taken as the top of the highest quartzite, 1 foot or more thick, for mapping purposes. This arbitrary choice was necessary because of the lithologic gradation between the Bolsa and the Abrigo formations.

The thickness of the formation varies from 400 to 480 feet where measured and may be even greater where the diabase has been stripped completely away. The quartzites may show considerable tectonic thinning where they had been involved in some of the thrusting.

There is no fossil evidence for the age of the Bolsa quartzite in the Johnny Lyon Hills. This is also true of the Bolsa in its type locality, where Ransome (1904, p. 30) placed the formation in the middle Cambrian because of its completely gradational relation with the overlying Abrigo formation. Correlation of the Johnny Lyon section with the Bisbee Bolsa section is based on the strong similarities of lithology and their common relationship to the Abrigo formation. The Bolsa can also be correlated with the Troy quartzite of the Globe region on the basis of lithologic similarities and the geologic relations to the underlying Apache group. Darton (1925, pp. 36, 256) pointed out there the important erosional unconformity between the

Troy and the underlying Apache group to which it had been originally assigned. He also recognized a thin fossiliferous zone equivalent to the Abrigo formation resting immediately upon the top of the Troy.

The presence of conglomerates and orthoquartzites in the basal Paleozoic formation throughout much of Arizona, records the first of the Paleozoic marine transgressions. The Bolsa sediments were laid down on an erosion surface of locally gentle, yet recognizable relief. They are apparently littoral deposits, as indicated by the conglomerates, cross-bedding, and relatively well-sorted orthoquartzites. The presence of strong iron oxide cement in the lowermost units reflects the lateritic soil profile in the underlying diabase. Indeed, much of the hematite which is characteristic of the basal sandstones of the Cambrian formations of southern Arizona and New Mexico may have been derived from the diabases in the Apache group (or its stratigraphic equivalent elsewhere) as a result of deep pre-Paleozoic weathering and erosion.

DIABASE-BOLSA QUARTZITE SECTION

Section measured in SE. 1/4, sec. 10, T. 15 S., R. 21 E.

	Thickness
Abrigo formation	
Fissile olive shales and thin brown sandstone.	
Bolsa quartzite	
5. Covered (stream bottom), may conceal fault.	10 feet
4. Quartzites with interbedded shales. Quartzites, brown, stained black on upper surfaces, medium-grained, vitreous to granular, beds 1' to 3' thick. Shales, yellow-brown to olive brown, fissile, somewhat sandy, generally 2" to 1' thick, increasing in abundance toward top of unit.	34 feet
3. Quartzites, white to tan with some color banding, fine to medium-grained quartz, vitreous, thick-bedded. Some worm boring casts.	189 feet
2. Quartzites, dark brown to tan, commonly showing alternating light and dark color banding parallel to and crosscutting bedding. Medium to coarse-grained quartz, scattered quartz granules and granule horizons. Vitreous, medium- to thick-bedded. Casts of worm borings.	195 feet
1. Interbedded quartzites and pebble conglomerates, dark chocolate brown at base to medium brown at top, with some mottling and color banding of diffusion (?) origin. Medium to thick-bedded with 1" to 1' thick pebble conglomerates occurring at 1' to 2' intervals throughout unit. Quartzites are coarse-grained with abundant granules, subangular to subrounded, principally quartz with some magnetite. Silica is principal cement with iron oxides increasingly important toward the base. Some cross-bedding. Conglomerates, pebbles of white, gray, and pink quartz and quartzite, 5 - 50 mm. diameter, well rounded, in quartzite matrix.	52 feet
	480 feet

Diabase

1. Altered diabase, partly covered by talus of Bolsa quartzite. Gray-green, fine grained, ophitic texture, weathering producing granular disintegration. Grades upward to 2' to 3' of dark red-brown, fissile, hematite-chlorite-clay (?) zone showing occasional remnants of ophitic texture. Strongly suggests deep weathering horizon of pre-Bolsa age. . . . . 23 feet

Pioneer shale

Tan and purple argillites, thin to medium-bedded.

Abrigo formation

Ransome (1904, pp. 30-33) proposed the name, Abrigo limestone, for a section of thin-bedded, cherty limestones, carrying middle Cambrian fossils, which crops out in Abrigo Canyon three miles southwest of Bisbee. The formation is underlain by the Bolsa quartzite and overlain disconformably by limestones of Devonian age. The name has been extended subsequently to rocks exposed in the Tombstone district (Ransome, 1916), the Dragoon Mountains (Gilluly, U. S. Geol. Survey Prof. Paper in preparation), and many other parts of southern Arizona. Major facies changes occur regionally within the formation however, and the equivalent rocks have been given the less restrictive name, Abrigo formation.

In the Little Dragoon Mountains and in the Johnny Lyon Hills, this formation contains less than fifty percent limestones. J. R. Cooper (1950a, b) has made a detailed study of the Abrigo formation in the Little Dragoon Mountains. The formation contains the principal ore horizons in the Johnson Camp mining district on the east side of the range. Cooper subdivided the Abrigo into three members containing a total of 10 units. Some part or all of each of these units may be recognized in the Johnny Lyon Hills area.

The exposures of the Abrigo formation extend more or less continuously from the northwest corner of the map area, southeast to Lechugilla Hill. They are prominent on Sheep Camp Ridge and Keith Peak where the upper carbonate units form cliffs and ledges 20 to 100 feet high. Elsewhere the topographic expression is in flanking outcrop on ridges, such as Rattlesnake Ridge, which are held up at the crest by the more massive and resistant Escabrosa limestone.

Within the Johnny Lyon Hills area, the three members may be summarized as follows:

Lower member - Shales, olive, fissile with subordinate thin dolomites and sandstones in lower part, and with thin gray limestones commonly interbedded in the upper part. The unit is capped by medium-grained gray orthoquartzites, cross-bedded. Total thickness of the unit is 400 feet. Johnson Camp unit no. 1.

Middle member - Limestones with minor shales, thin-bedded, nodular, laminated with silt and sand, horizons with numerous intraformational limestone pebble conglomerates (fig. 49). Some limy sandstones. Total thickness of the unit is about 175 to 200 feet. Johnson Camp units nos. 2-5.

Upper member - Sandy dolomites, with some sandstones and limestones. Dolomites are laminated, glauconitic and may grade laterally into sandstones and limestones. A white quartzite, one to two feet thick frequently appears at the top. Total thickness of the unit is about 100 to 150 feet. Johnson Camp units nos. 6-10. Detailed sections are given on pages 227-233.

The gradational lower boundary of the formation has been discussed. The upper boundary is generally sharply defined between underlying quartzite or limestone, and the overlying massive Martin formation dolomites. Where neither quartzite nor limestone appears at the top, the distinction between the dolomites of the Abrigo and the Martin, can be made usually on the basis of the laminated, clastic-rich character of the former, and the massive weathering characteristics of the latter. In small outcrops, however, the distinction may be difficult.

Figure 49. Typical intraformational conglomerate in the Abrigo formation consisting of tabular fragments of light gray and brown limestones and sandy limestones in a gray limestone matrix.

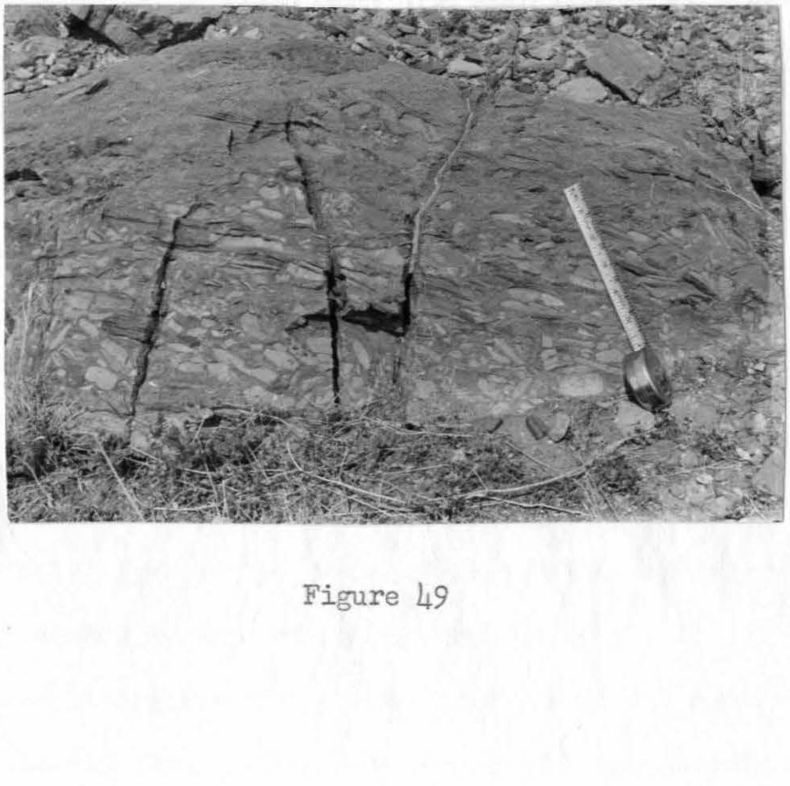


Figure 49

Several interesting lateral variations in the lithology of the Abrigo formation can be seen in the Johnny Lyon Hills area. The gray cross-bedded quartzite unit at the top of the lower member appears in the northern part of the map area as about 50 feet of thick, ledge making beds. This unit thins toward the south and on Lechugilla Hill consists of 10 feet of thin to medium-bedded quartzites. On Sheep Camp Ridge, the unit is only about six feet thick. In its exposures on the west and south sides of Keith Peak the unit thins from six feet of interbedded thin quartzites and green shales to about two feet of flaggy quartzites and calcareous sandstones in abundant green shales. It is interesting to note that there is very little evidence of this unit in the Little Dragoon Mountains to the southeast.

The ratio of limy sandstones to sandy and silty limestones in the middle member increases northward. North of the Willcox-Cascabel road, these sandstones have dark brown to black weathered surfaces which make a distinctive color band on the west flank of Rattlesnake Ridge and the ridges to the north. The clastic content does not exceed 50 percent of the member, however.

Within the upper member, there appears, in all exposures north of the Willcox-Cascabel road, a sequence of fossiliferous limestone beds on top of the sandy dolomites. The thickness is about 50 feet, and the beds are characteristically pinkish-gray to pink, coarsely crystalline, glauconitic, thin to medium bedded. South of the road these limestone beds become mottled with yellow dolomite spots and zones which both parallel and cross-cut the bedding, and appear in all of the beds. Within less than two miles, in the latitude of the

Mesa Tank, the dolomite is completely pervasive. All the evidence observed points to lateral gradation. Nowhere in the southern Johnny Lyon Hills have any limestones been observed in the upper member.

The quartzite or sandstone which appears at the very top of the Abrigo in the Keith Peak and Lechugilla Hills sections, is not seen north of the Willcox-Cascabel road. An atypical limestone bed does appear sporadically in that position and has been mapped in the Abrigo formation. It varies from 0 to 10 feet thick, is blue-gray, massive, and finely crystalline. It rests on the typical thin-bedded pink-gray limestones described above. It sometimes contains in its lower portion a very coarse intraformational conglomerate made up of fragments of the pink limestone which are only slightly dislocated from the underlying beds. This gray limestone is overlain by typical basal Martin dolomite. No fossils have been found and its age and relation to the major disconformity at the base of the Martin formation are not known.

A total thickness of the Abrigo formation in the Johnny Lyon Hills area varies from 740 feet to 800 feet. Ransome (1904) measured 770 feet in the Bisbee area. Cooper (1950b) reports 685 feet in the Little Dragoon Mountains. Tectonic activity has locally thickened or thinned various parts of the Abrigo. For example, the exposures on the north slope of Keith Peak contain beds representative of all three members, but the total thickness is only about 175 feet. Bedding plane faults are apparently common but locally unrecognizable in the lower member.

The Abrigo formation includes beds of both middle and late Cambrian age. A. R. Palmer (personal communication) of the U. S.

Geological Survey reports the following fossils among collections from the sections measured on Lechugilla Hill.

Lechugilla Hill - Sec. 11, T. 15 S., R. 21 E.

Upper Cambrian

Aphelaspis zone	JLA-6	Middle member - 269 feet above the top of the quartzite marker bed. *Aphelaspis* sp.
Crepicephalus zone	JLA-5	Middle member - 235 feet above the top of the quartzite marker bed. *Crepicephalus* sp. *Llanoaspis* sp. *Maryvillia* sp. *Tricrepicephalus* sp.
Cedaria zone	JLA-4	Middle member - 129 feet above the top of the quartzite marker bed. *Coosia* sp. *Genevievella* sp. *Tricrepicephalus* sp.
	JLA-3	Middle member - 73 feet above the top of the quartzite marker bed. *Arapahoia* sp. *Cedaria* sp. *Kormagnostus* sp. *Millardia* sp. *Semnocephalus* sp.
	JLA-2	Middle member - 12 feet above the top of the quartzite marker bed. *Cedaria* sp. *Kormagnostus* sp. *Meteoraspis* sp. *Semnocephalus* sp.

Middle Cambrian

JLA-1 Lower member - 25 feet below the top of the quartzite marker bed.

Ehmania sp.

Fossils from two localities in the middle member on Keith Peak are according to Palmer:

JLA-8 Middle member - 49 feet above the quartzite marker bed.

Cedaria sp.
Coosella? sp.
Kormagnostus sp.

Cedaria zone

JLA-7 Middle member - $17\frac{1}{2}$ feet above the quartzite marker bed.

Kormagnostus sp.
Semnocephalus sp.

No fossils were found in the upper or dolomitic member at these localities. However, collections made where the pink crystalline limestones were present in the upper members yielded the following faunules:

NE. 1/4, sec. 27, T. 14 S., R. 21 E.

Ptychaspis zone

Upper member - 10 feet below the base of the Martin formation.

Idahoia sp.
Drumaspis sp.

NE. 1/4, sec. 21, T. 14 S., R. 21 E.

Elvinia zone

Upper member - about 10 feet below the base of the Martin formation.

Camaraspis sp.
Dellea sp.
Elvinia sp.
Irvingella sp.
Kinbladia sp.
Linnarssonella sp.
Pseudoagnostus sp.

According to Palmer, "Representatives of possibly two late Middle Cambrian zones and the Cedaria, Crepicephalus, and Asphelaspis zones of Dresbachion age (early Upper Cambrian) and the Elvinia and Ptychaspis zones of Franconian age (medial Upper Cambrian) are present."

The type locality of the Abrigo has been re-examined by Stoyanow (1936, pp. 466-472) and he has restricted the formation name to the part of the originally described beds that contains a Crepichephalus-Hesperaspis fauna. On the basis of detailed studies in southeastern Arizona, Stoyanow has introduced a number of new formational names, some of them for different lithologic facies of units containing the same faunal zones.

In mapping in the Johnny Lyon Hills area, the original sense of Ransome's Abrigo has been retained. Facies transitions visible within the area partly clarify the relations between a number of the formations established by Stoyanow. It is clear that the quartzite at the top of the lower member is the Southern Belle quartzite of the Santa Catalina Mountains (Stoyanow, 1936, p. 476), and that this is the southern limit of that formation. The section below the quartzite in the Johnny Lyon Hills is lithologically similar to, and probably equivalent to the Santa Catalina formation. The shales and limestones underlying this quartzite in the Johnny Lyon Hills have great lithologic and faunal similarity to the two lower members and perhaps the lowest part of the upper member of the Cochise formation of the Whetstone Mountains (Stoyanow, 1936, p. 466). A lithology very similar to most of the upper member of the Cochise is found above the quartzite zone. Therefore, the equivalence of the top of the Cochise formation with the top of the Southern Belle quartzite suggested by

Stoyanow (1936, p. 482), cannot be accepted. The Crepicephalus fauna first appears more than 100 feet above the quartzite in the Johnny Lyon Hills. Therefore, a considerable section is older than Stoyanow's restricted "Abrigo fm.", is younger than the Southern Belle quartzite and is characterized by Cedaria fauna. Either a new formation must be suggested or a re-evaluation of Stoyanow's designations must be made. Greater attention to lithologic as well as faunal facies changes would probably be rewarding.

The pink limestones at top of the upper member in the northern Johnny Lyon Hills are lithologically identical with the Rincon limestone of the Whetstone Mountains (Stoyanow, 1936, p. 471). They contain a younger fauna, however, than Stoyanow (1942, pp. 1262-1263) was able to recognize in the Whetstone Mountains. The transition of these pink limestones to dolomites has already been described. These dolomites in the southern part of the Johnny Lyon Hills have a two foot quartzite parting bed at the top. In this and in the Ptychaspis faunal assemblage of the equivalent pink limestones they are similar to the Copper Queen limestone (Stoyanow, 1936, pp. 469-470) of the Bisbee Area. The distribution of beds containing this fauna is wider than Stoyanow (1936, p. 469; 1942, p. 1263) believed and there may be much more in common between the Rincon and Copper Queen limestones, than was formerly supposed.

The decrease of muddy clastics and the increase of clean quartz-carbonate rock with decreasing age suggests an increasing stability in the shelf environment of deposition of the Abrigo formation. The marine environment must have been quite shallow, as the numerous intraformational conglomerates and crossbedded silt and sand seams testify to the numerous disturbances of the bottom by wave action. The abundant glauconite in the upper members also supports this interpretation and suggests numerous hiatuses during the deposition (Grim, 1953, p. 353).

ABRIGO FORMATION SECTION

Rattlesnake Ridge

NE. 1/4, sec. 21, R. 21 E., T. 14 S.

	Thickness
Martin formation	
Dolomites, gray, "elephant hide" texture.	
Abrigo formation	
10. Sandy limestones, gray to distinct pinkish-gray in upper part, carries, glauconite, beds 1' to 2' thick many thin sandy layers, flat pebble intraformational conglomerates, abundant trilobite fragments.	47 feet
9. Sandy dolomites, yellowish-gray to tan, beds 1' to 2' thick, several beds of white quartzite, glauconite. Breccia zone in this interval.	65 feet
8. Limestones, gray, many silty bands some of which show cross-bedding, beds 1' to 2' thick.	61 feet
7. Sandstones with some limestones. Sandstone weathers reddish-brown, limy matrix. Limestone gray, intraformational conglomerate.	18 feet
6. Limestones, gray, beds 6" to 1', much intraformational conglomerate, some sandy and silty layers which weather reddish-brown.	98 feet
5. Quartzites, light gray, fine to coarse-grained thick-bedded, cross-bedded, some glauconite (?) in lower 10 feet.	45 feet
4. Shale with interbeds of thin sandstone and limestone. Shale, olive, fissile. Sandstones 2" thick. Limestones, gray, abundant intraformational limestone pebble conglomerates, beds up to 1' thick. . .	75 feet
3. Covered.	124 feet
2. Shale with interbeds of sandstone, limestone, and some dolomite. Shale olive, fissile. Sandstone, tan, limy, 2" beds. Limestone, gray, up to 1 1/2' thick. One dolomite bed, 1' thick at top of unit. Unit may be duplicated by faulting.	233 feet

1. Covered. . . . . 47 feet

813 feet

Bolsa quartzite

Quartzites and sandstones, poorly exposed.

ABRIGO FORMATION SECTION

Lechugilla Hill

NE. 1/4, sec. 10, NW. 1/4, sec. 11, T. 15 S., R. 21 E.

Thickness

Martin formation

Dolomites, tan, thick bedded, "elephant hide" surface texture.

Abrigo formation

13. Sandy dolomites, sandstones and quartzites. Dolomites, tan to dark brown, microcrystalline, with disseminated sand and silt in base, massive, grading upward into tan and brown thin-bedded dolomitic sandstones and quartzites. Quartz sand grains vary from very fine to very coarse. Clastic content is quite variable both vertically and laterally throughout this unit. . . 57 feet

12. Silty dolomites, tan, similar to dolomites in unit no. 11, but lacking the abundant clastics, except as thin, 1/4" to 2" continuous silty partings. Beds are 6" to 1' thick, and contain a few pebble intraformational conglomerates. . . 39 feet

11. Sandy dolomites with interbedded sandstones. Dolomites, tan to brown, microcrystalline to medium crystalline, with continuous silty and sandy partings, glauconite. Sandstones, brown, fine to medium-grained in beds 6" to 2' thick, cross-bedded, dolomitic, occasionally quartzitic, predominant in the upper 10 feet of the unit . . 47 feet

10. Sandy limestones with abundant intraformational pebble conglomerates, both continuous and discontinuous thin silt and sand partings up to 3" thick. Limestone, gray-brown, medium to coarsely crystalline, ferruginous, glauconitic, numerous fossiliferous horizons . . . . 51 feet

Fossil locality JLA #6, 4 feet below top of unit 10.

Fossil locality JLA #5, 23 feet above base of unit 10.

9. Interbedded limy sandstones and sandy limestones. Sandstones, brown, medium to fine-grained, occasionally quartzitic, regularly bedded 3" - 2' thick,

invariably give acid test for carbonates. Limestone, gray brown, weathering limonitic, medium to coarsely crystalline, with scattered zones of fossil fragments, some discontinuous partings of silt and sand. . . . . 54 feet

8. Limestone, gray to pink-brown, with prominent continuous silt and fine sand partings 1/10" to 1/2" thick, microcrystalline to coarsely crystalline, some intraformational conglomerates, glauconitic, thin-bedded 1" to 6", nodular. . . . . 36 feet

Fossil locality JLA #4 is 7 feet above the base of unit 8.

7. Interbedded limestones and shales. Limestones texturally similar to limestones of no. 6, somewhat more nodular, thin-bedded 1" - 4" thick. Shales, gray to olive green, calcareous, micaceous. . 79 feet

Fossil locality JLA #3 is 32 feet above base of unit no. 7.

6. Limestones, gray mottled with tan silt partings, microcrystalline to medium crystalline, scattered intraformational limestone conglomerates, glauconitic, beds 2" - 1 1/2', abundant trilobite fragments. Sporadic thin, nodular, olive green calcareous shales, 1" to 4" thick. . . . . 41 feet

Fossil locality JLA #2 is 12 feet above base of unit 6.

5. Quartzites, gray to gray-brown weathering brown, medium-grained, quartz with scattered magnetite which leaves weathering pits, beds 1" to 1 1/2', cross-bedded. Somewhat fractured and brecciated. . . 10 feet

4. Alternating thin-bedded shales, sandstones, limestones in that order of abundance. Shales, variegated in color as in unit no. 2, fissile, micaceous. Sandstones, fine-grained to medium-grained, variable from quartzitic to calcareous, thin-bedded 1" - 6", uncommonly cross-bedded. Limestones, gray mottled with yellow, brown, red, finely crystalline, silty and/or sandy, thickness 2" to 3", sometimes contains limestone pebble intraformational conglomerates, glauconitic, ferruginous. . . . . 95 feet

Fossil locality JLA #1 is 15 feet below the top of unit no. 4.

3. Covered. . . . . 41 feet

2. Shales with interbedded sandstones. Shales predominant, variegated red-brown, yellow-brown, olive green, quite fissile, slightly calcareous, in intervals of 1" to 1'. Sandstones, red-brown, fine to very fine-grained, ferruginous, micaceous, thin-bedded, nodular. . . . . 19 feet

1. Covered, gully bottom. Probably contains a fault . . 17 feet

586 feet

Bolsa quartzite

Quartzites, dark brown to maroon, medium-grained, thick-bedded.

ABRIGO FORMATION SECTION

Keith Peak

Section measured in SE. 1/4, sec. 20, T. 15 S., R. 21 E.

	Thickness
Martin formation	
Dolomites, tan, massive, "elephant-hide" weathering texture.	
Abrigo formation	
13. Quartzites and dolomites. Quartzites, white, silicified, up to 1' thick but varying laterally and upwards into orange, sandy dolomite.	2 feet
12. Sandy dolomites with basal quartzite. Dolomites, brown, massive-weathering with thin sandy laminae. Basal quartzite is white, medium- to coarse-grained, 0 to 2' thick, varying laterally and upwards into sandy dolomite.	8 feet
11. Sandy dolomites, tan, microcrystalline, coarse-grained sand partings, medium bedded.	30 feet
10. Sandy dolomites and sandstones. Dolomites, tan, sandy with some cross-bedding, beds 6" to 2' thick. Sandstones, gray, medium-grained, often quartzitic, 6" to 2' thick, distributed throughout unit. A dense porcellaneous light-gray, thin shale rarely present	42 feet
9. Limestones, gray-brown to brown, medium crystalline, numerous limestone pebble conglomerates, beds 2" - 2' thick, discontinuous silty and sandy partings 1" to 3" thick which uncommonly show cross-bedding .	46 feet
8. Silty limestones and limy sandstones, massive-weathering and representing an increase of clastics content so that 1 - 2' thick beds of cross-bedded limy dark brown sandstone are abundant. Limestones, rusty brown, similar in texture to those in unit 7 .	35 feet
7. Limestones, massive-weathering but laminated parallel to bedding with thin 1/4" to 2", continuous, irregular partings of silt and sand. Gray to light brown of silt and sand. Gray to light brown mottled with pink and orange, locally dolomitic spots and bands, microcrystalline to coarsely crystalline, some intraformational pebble conglomerates. Rare, thin, brown and	

pink shale beds, usually less than 1' thick. Silt partings, brown, increase in abundance and thickness in upper part of unit. . . . . 175 feet

Fossil localities JLA no. 8, 5 1/2 feet above the base, and JLA no. 9, 37 feet above the base of unit no. 7.

6. Shales with interbedded limestones. Shales similar to those in unit no. 5, indurated with almost a slaty parting. Uncommon thin, brown limestones 3" thick, limonitic mottling, continuous silty partings, pebble intraformational conglomerates. . . . . 12 feet

5. Quartzites with interbedded shales. Quartzites, gray-brown, medium to coarse-grained, beds 1/2" to 1' thick, cross-bedded. Shales, olive, well indurated, micaceous. 6 feet

4. Interbedded shales and sandstones, partly covered in upper 40 feet. Shales, olive green, fissile. Sandstones, brown, medium-grained, micaceous, flaggy. . . . . 108 feet

3. Limestones, gray with orange-brown to red-brown silty partings, microcrystalline to finely crystalline, thin-bedded. Some subordinate nodular, limy shale interbeds. Upper 10 feet very silty and sandy. 44 feet

2. Interbedded limestones, sandstones and shales. Limestones, brown to gray with rusty mottling, flaggy to nodular, some intraformational conglomerates. Sandstones, brown, fine-grained, very thin-bedded, micaceous. Shales similar to those in unit no. 1. . 116 feet

1. Shales with interbedded sandstones and dolomites. Shales are red-brown, sandy, micaceous, fissile to nodular, somewhat limy. Sandstones are brown, fine to medium-grained, thin-bedded 1" to 3", rarely cross-bedded, limy. Dolomites, brown, nodular to flaggy, silty and sandy, thin-bedded. . . . . 120 feet

744 feet

Bolsa quartzite

Quartzite, brown, 1' thick.

Devonian System

Martin formation

Ransome (1904, p. 33) gave the name, Martin limestone, to about 340 feet of dark gray, fine-grained limestones with a few pink calcareous shales, which are well exposed on Mt. Martin, southwest of Bisbee. The formation contained Upper Devonian fossils and was limited disconformably by the Abrigo formation below and the Escabrosa limestone above. Stoyanow (1936, p. 486) called the Martin limestone the standard Upper Devonian formation of southeastern Arizona. He has restricted the formation, however, by recognizing at least two other formations in the Upper Devonian elsewhere in the region. These include the Picacho de Calera formation and the Lower Ouray formation. In this report no subdivision of the Upper Devonian beds is undertaken. The word formation has been substituted for limestone in the formational name. In the Johnny Lyon Hills and the Little Dragoon Mountains the Martin formation consists of dolomites, shales, and a few quartzites.

The Martin formation is exposed continuously from the northwest corner of the map area, southeast to the vicinity of the thrusting in cross-section line C-C'. It is there overlapped by alluvium and reappears to the south on low hills projecting above the cover as on Lechugilla Hill. It is exposed on the northeast corner of Sheep Camp Ridge and on Keith Peak, as well as in a number of thrust slices.

The dolomites of the Martin formation generally form ledges and low cliffs on the slopes of ridges maintained by the resistant Escabrosa limestone. The shale zones form conspicuous recessive swales which may be traced for hundreds of yards without rock exposures.

The lithology of the formation is quite constant throughout the Johnny Lyon Hills area. It consists of four major units: (1) a basal dolomite, gray to tan, microcrystalline, a few sand grains, and a distinctive, weathering texture like wrinkled elephant-hide; (2) a recessive-weathering clastic zone of pink-brown shales, thin dolomites and a few quartzites; (3) a thick massive dolomite, medium-gray, microcrystalline with numerous stylolites; (4) a swale-forming, usually covered, unit of fissile pink shales. Two sections are given on pages 237-238.

In general, the dolomite members are easily distinguished by the presence of the intervening pink-brown clastic unit. In small fault blocks, however, the lower gray dolomites of the Escabrosa are indistinguishable from the 'stylolite' dolomite, and the sandy tan beds of the 'elephant-hide' are very similar to some beds high in the Abrigo formation.

The Martin formation is completely parallel with the underlying Abrigo formation. Despite the absence of representatives of at least two and one-half lower Paleozoic systems no evidence of reworking of the top of the Abrigo has been noted unless the upper one foot quartzite originated in this fashion.

The thickness of the Martin formation varies from 205 to 240 feet and seems to represent cumulative variations of all the members rather than any individual member. This compares with 220 to 270 feet in the Little Dragoon Mountains (Cooper, 1950), 230 feet in the Tombstone area, (Gilluly, in preparation), and 340 feet at the type locality.

Although no major fossil collections of the Devonian rocks have been made by the author, Cooper has collected extensively both in the Little Dragoon Mountains and the Johnny Lyon Hills. This suite has been studied by G. Arthur Cooper of the U. S. National Museum who has confirmed the correlation of the local Martin formation with part of the Upper Devonian. It has not been possible in the Johnny Lyon Hills area however, to recognized Stoyanow's Lower Ouray or Picacho de Calera formations although Stoyanow (1942, p. 1271) says the Lower Ouray is present in the Little Dragoon Mountains. The thin anomalous blue-gray limestone which appears sporadically at the top of the Abrigo formation on Rattlesnake Ridge and which in mapping has been assigned to that formation, lithologically resembles units of the Picacho de Calero formation and may be equivalent to it. The upper shale unit of the Martin formation in the Little Dragoons contains fish teeth and hence the equivalent shale unit in the Johnny Lyon Hills may also represent the Lower Ouray formation.

In addition to the lesser thickness, the Johnny Lyon Hills Devonian section differs from the type locality in its increased clastic content and its dolomitization. This is in keeping with the trend toward an increasingly arenaceous facies in central Arizona, perhaps reflecting the influence of Mazatzal land, whose existence Stoyanow (1936, p. 494) has proposed.

MARTIN FORMATION SECTION

Rattlesnake Ridge

NE. 1/4, sec. 21, SE. 1/4, sec. 16, T. 14 S., R. 21 E.

	Thickness
Escabrosa limestone	
Dolomites, french gray, medium to thick-bedded, smooth weathering.	
Martin formation	
5. Partly covered, some outcrops of buff sandstone and shale.	33 feet
4. Dolomites, french gray, microcrystalline, beds 2' to 4', stylolite seams, silty in lower portion.	90 feet
3. Quartzites, brown, grade laterally into brown silty dolomites, ledgemaker.	6 feet
2. Partly covered, fissile red shales and red limy sandstones.	63 feet
1. Dolomites, dark gray to light gray, finely crystalline, minor silty material and scattered quartz sandgrains, thick beds. Rare limestone interbeds. .	45 feet
	237 feet
Abrigo formation	
Limestone, pinkish-gray, coarsely crystalline, fossiliferous, glauconitic.	

MARTIN FORMATION SECTION

Keith Peak

NW. 1/4, sec. 11, T. 15 S., R. 21 E.

	Thickness
Escabrosa limestone	
Dolomites, tan, thick-bedded.	
Martin formation	
5. Mostly covered, some pink shale. Makes recessive swale on topography.	27 feet
4. Dolomites, gray, microcrystalline to sublithographic, massive beds except for thin beds in lower 2 feet. Scattered coarsely crystalline calcite nodules, irregular shapes, limonite stained, 1/2" to 2" in diameter, rimmed by white silica to give "geode" appearance. Contains a number of fossiliferous zones, some partly silicified. Scattered small cherts.	86 feet
3. Sandy dolomites and quartzites, grade vertically and laterally into each other, beds 1' to 2' thick. Quartzites, gray to brown, fine-grained to very fine-grained, showing occasional white silicification bands parallel to bedding 1" thick. Dolomites, tan to brown, scattered silt and sand grains.	10 feet
2. Shales and interbedded dolomites. Shales, yellow-brown to pinkish-brown, fissile. Dolomites, tan silty, 3" to 2' thick, in upper part of unit. Makes recessive swale.	52 feet
1. Dolomite, tan in lower part to gray in upper part, very finely crystalline, massive except for a 10' interval of thin sandy and silty laminae in the middle of the unit. Weathers to an etched "elephant hide" surface. Scattered coarse calcite nodules, irregularly shaped, bordered and stained by limonite, 1/2" to 1 1/2" in diameter, in upper part of unit. .	31 feet
	206 feet
Abrigo formation	
Quartzite, white, coarse-grained, 2' thick bed.	

Mississippian System

During the writing of this manuscript the U. S. Geological Survey adopted systemic status for the Mississippian and Pennsylvanian rocks. Inasmuch as the map drafting was completed while Carboniferous was still the accepted systemic name for that stratigraphic interval, the principal plates still carry the old designations. References in the text will, however, conform to the new Survey practise in this regard.

Escabrosa limestone

Escabrosa Ridge, southwest of Bisbee, contains a section of thick-bedded crinoidal limestones. To these topographically resistant white to dark gray beds, Ransome (1904, p. 42) gave the name Escabrosa limestone. He estimated their average thickness at about 750 feet. G. H. Girty, who described Ransome's fossil collections from the Escabrosa, placed the formation in the Kinderhook and Osage series (Ransome, 1904, p. 46).

In the Johnny Lyon Hills the Escabrosa limestone is physiographically the most impressive of the sedimentary formations. It forms the crest of the long line of Paleozoic hogback ridges extending from the north edge of the map area southward to Lechugilla Hill. In brecciated form, it provides the massive cliffs crowning Javelina Hill. Its massive lower dolomites cap the principal ridges of Keith Peak and sustain part of the northern heights of Sheep Camp Ridge. It also occurs less prominently in a number of the underlying thrust plates and slices.

In the Johnny Lyon Hills area, the Escabrosa consists of approximately two-thirds limestone and one-third dolomite. It is almost completely free of clastics. The limestones are usually in massive beds, medium to coarsely crystalline, rich in crinoid fragments and, in restricted zones, in chert. The dolomites constitute the lower 160 to 180 feet and the top 15 to 25 feet and are occasionally interbedded in the middle of the section. They are gray to tan, microcrystalline and somewhat cherty. Silicified horn and colonial corals appear in both types of carbonate beds. Coarse, abundant chert appears in the upper half of the formation in the form of loaves and pods up to six feet long and one foot thick. It occurs only as small, sparsely scattered nodules in the lower half. However, a characteristic blue-black chert zone, brown weathering with associated silicified horn corals appears repeatedly in the upper 15 feet of the lower dolomites.

The only clastics observed in the section are two thin lenses of silty carbonate less than fifty feet long and 2 feet thick, observed in the lower dolomites, about a mile southeast of Keith Peak.

Some mention should be made here of a tectonic breccia made up almost entirely of Escabrosa limestone which occupies a considerable area on Javelina Hill and is exposed intermittently in windows in the alluvium farther south. The breccia is an erosion remnant of a major thrust plate, the greatest exposed thickness of which is 400 to 500 feet. The Black Prince formation contributes 50 to 75 feet and the upper 400 feet of Escabrosa limestone apparently supplies the rest.

The breccia contains angular fragments of limestone, dolomite, and chert ranging from less than 1/4 inch in diameter up to blocks four and five feet in diameter. Fragments of rock types underlying the breccia plate are very uncommon within the breccia. The fragments are intimately bound together by an abundant matrix of finely milled carbonate ranging from coarsely crystalline to microcrystalline. The larger blocks, however, contain their bedding structures, cherts and fossils undisturbed. The texture of the more coarsely crystalline carbonate in the matrix is inherited. There is no evidence of recrystallization in any of the carbonate material except for the strong cohesiveness of the brecciated aggregate nor of plastic flowage in any of the larger blocks. Except within the coarser fragments there is no evidence of bedding in the lower 100-250 feet of the breccia (figs. 50, 51). Higher in the thrust plate it is possible to recognize a lateral lithologic continuity suggesting the bedding despite pervasive brecciation. In particular, the basal maroon shale of the Black Prince formation has been thinned, mixed with limestone and dolomite fragments and literally squirted into the surrounding breccia. But it is possible to follow its brilliant trace continuously, or nearly so, over Javelina Hill (fig. 64).

The massive lower part of the breccia now forms resistant cliffs 25 to 75 feet high (fig. 51). The classic klippe (fig. 69) northeast of Javelina Hill clearly shows the lack of bedding. The principal structures within the lower breccia are irregular stringers of chert fragments, and vertical to near vertical joints which have a northerly trend. These features will be discussed at greater length in a consideration of the tectonic history of this breccia.

The Escabrosa limestone is very constant lithologically within the Johnny Lyon Hills area. Although the thickness varies from 600

Figure 50. Limestone-chert breccia in the thrust plate on Javelina Hill. The stringers of chert fragments have been etched into relief by solution of the surrounding carbonate material.

Figure 51. Massive cliffs of Escabrosa limestone breccia on the east side of Javelina Hill in which no evidence of the original bedding is visible.

Figure 50

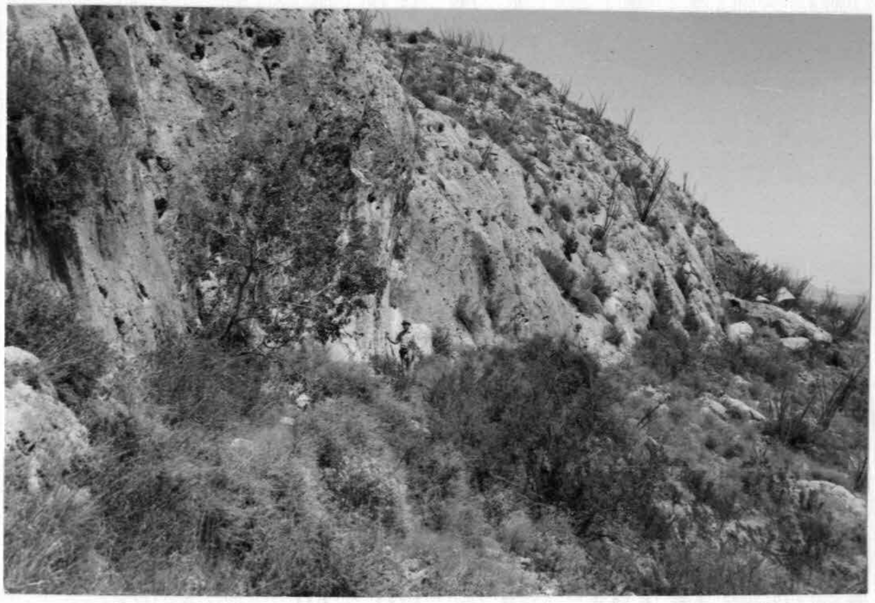


Figure 51

to 700 feet it is a variation distributed among all of the distinctive zones within the formation.

The dolomites of the Escabrosa are difficult to distinguish in small fault blocks from those of the Martin formation, unless some of the characteristic coarse Escabrosa chert is present. The Escabrosa limestones are usually readily recognized by their massive crinoidal character, coarse cherts, and lack of shale interbeds. Again, the distinction may be lost among fault slices containing certain Black Prince or unfossiliferous Horquilla limestones which are individually quite similar to some of the Escabrosa beds.

The lower contact with the Martin formation is a disconformity since apparently neither youngest Devonian or oldest Mississippian faunas are present. There is no visible evidence of erosion and the location of the contact has been arbitrarily placed at the top of the highest Martin shale. The upper contact of the Escabrosa is placed at the base of a maroon shale in the Black Prince formation. The highest Escabrosa bed is invariably a buff-yellow dolomite, and it is apparently conformable with the overlying shale.

Faunal collections made by Cooper (1950b) in the Little Dragoon Mountains have been examined by J. S. Williams of the U. S. Geological Survey. He has stated that the "fauna ranges from upper Kinderhook or lower Osage, possibly into the lower Meramec." This is in close correspondence with the Escabrosa at the type locality. The only significant difference in the local formation as compared to the Bisbee exposures is the presence of about 30 percent dolomite in the Johnny Lyon Hills section.

ESCABROSA LIMESTONE SECTION

Rattlesnake Ridge

NE. 1/4, sec. 16, T. 14 S., R. 21 E.

		Thickness
Black Prince formation		
	Shales, dark red, partly covered.	
Escabrosa limestone		
14.	Dolomites, light tannish-gray, finely crystalline, cherty.	26 feet
13.	Limestones, light gray, scattered nodules of chert.	70 feet
12.	Dolomites, light gray, sparse nodules and lenses of chert.	9 feet
11.	Limestones, light gray, beds 2' to 3', a few scattered nodules of chert.	52 feet
10.	Dolomites, light gray, finely crystalline, cherty with abundant banded lenses and irregular pods of light gray to blue gray chert.	18 feet
9.	Limestones, light gray, beds 3" to 2'	51 feet
8.	Limestones, light gray, thin-bedded 1 to 2', cherty with nodules and lenses white to bluish in color. .	17 feet
7.	Limestones, gray, massive cliff-maker.	51 feet
6.	Limestones, light blue-gray, finely crystalline, thin-bedded 2" to 1', some stylolite seams "geodes", slightly dolomitic near top of unit.	32 feet
5.	Limestones, light gray, massive, beds to 12'. . . .	61 feet
4.	Limestones, light blue-gray, fine crystalline, basal bed 5' thick, upper beds 1" to 1' thick with faint pinkish cast.	29 feet
3.	Dolomites, light gray, beds 1' to 3', nodules and lenses of blue-black cherts, "geodes".	55 feet
2.	Dolomites, gray, thick bedded, fossiliferous with horn corals, "geodes", two breccia zones in this interval.	67 feet

1. Dolomites, gray, microcrystalline, calcite-quartz "geodes", beds 1' to 3'. . . . . 56 feet

594 feet

Martin formation

Shales, red, limy, partly covered.

ESCABROSA LIMESTONE SECTION

Keith Peak

SE. 1/4, sec. 28, T. 15 S., R. 21 E.

	Thickness
Black Prince Formation	
Purple shales with bedded, coarse, greenish-white chert nodules.	
Escabrosa limestone	
11. Interbedded cherty limestones and dolomites, capped by a 3' tan dolomite.	22 feet
10. Limestones, gray, thick beds 6' to 8', cherty in massive loaves and pods.	17 feet
9. Dolomites, tan, microcrystalline, beds 2' to 4' . . .	14 feet
8. Limestone, gray, crinoidal, beds 4' to 6', large chert pods in top 5'.	43 feet
7. Interbedded cherty limestones and dolomites, Dolomites more common in lower half of unit, with chert which is in large loaves and bands up to 6' long and 1' to 2' thick, commonly irregular in shape. Beds 2' to 4' thick.	34 feet
6. Limestone, dark gray, crinoidal, beds 4' to 6' thick, chert in lower 10 feet	60 feet
5. Dolomites, cherty, light gray to gray, beds 2' to 4' thick, cherts are white to gray, occasionally transect bedding.	73 feet
4. Limestones, gray to dark gray, coarsely crystalline, crinoidal fragments, thick-bedded. Lower 15' has large chert loaves and sheets up to 8" thick and 4 feet long.	64 feet
3. Limestones and a few interbedded dolomites. Limestones, dark gray, coarse grained, crinoidal beds 3 - 5' thick, cherty with silicified fossils, some "geodes". Dolomites, light gray, abundant cherts and "geodes".	208 feet
2. Dolomites, gray with occasional tan beds, micro-	

crystalline to medium crystalline, beds 2 - 4' thick. Scattered "geodes". Upper 15 feet has small black cherts, brown silicified horn corals. . . . . 144 feet

1. Dolomites, tan, microcrystalline, medium to thick-bedded, a few scattered calcite-silica "geodes". . . 21 feet

700 feet

Martin formation

Pink, fissile shales.

Mississippian(?) or Pennsylvanian(?) System

Black Prince limestone

The Black Prince limestone was named by J. R. Cooper (1950a) from exposures near the Black Prince mine at Johnson Camp on the east side of the Little Dragoon Mountains. It is described in a section measured in the nearby Gunnison Hills as containing: (1) a maroon basal shale unit, 17 feet thick, containing chert nodules and a 6 inch sedimentary breccia with angular chert pebbles; and (2) a limestone unit, 102 feet thick, of gray to pinkish limestones with scarce chert nodules.

The Black Prince formation crops out continuously from the northwest corner of the map area to just south of the Willcox-Cascabel road, except where cut out by faulting or covered by alluvium. It reappears to the south within the thrust plates forming Javelina Hill and Keith Peak. It is generally unimpressive topographically, forming part of the dip slope of the Escabrosa hogbacks with the shale unit a smooth swale between ribbed carbonate outcrops. On the northwest ridge of Javelina Hill the tectonic breccia of the Black Prince limestones forms a crowning scarp 30 to 50 feet high similar to the cliffs formed by the Escabrosa limestone breccias.

In the Johnny Lyon Hills area, the Black Prince formation contains two major units as in the type section; lower shales and upper limestones. The lower shale unit has a distinctive maroon color mottled with light green spots. It is moderately fissile and generally contains bedded chert nodules up to 1 foot in diameter and 4 inches thick. The large cherts are usually greenish white, but small chert nodules are commonly white to a flame orange. The latter are sometimes found as pseudomorphic replacements of hexacorals. These colorful and resistant nodules weather out and form a residual gravel on the outcrops. A number of outcrops of the shale carry distinctive pebble conglomerate beds. The pebbles are angular to rounded jasper and chert fragments 1/4 to 1 inch in diameter in a variable matrix which consists of fine-grained silica, calcite and argillaceous matter. The conglomerate beds may range from 6 inches to 3 feet in thickness. An excellent exposure of the shale and conglomerates may be seen in the shaft of the Jack Pot mine in the overturned section south of the junction of Thompson Wash and Tres Alamos Wash.

The limestone unit of the Black Prince formation is thick-bedded at the base to medium-bedded at the top. The limestones are generally medium to coarsely crystalline, and may locally be oolitic. The limestones vary from dark gray to mottled gray and black (fig. 52) with bright tints of yellow, pink and green. The mottled beds when present serve to distinguish the formation from the drab gray but texturally similar beds of the Escabrosa where no other ready distinction is possible. Chert is present in small scattered nodules. A section of the Black Prince formation is described on page 254.

In the tectonic breccia on Javelina Hill the limestone unit of the Black Prince formation has responded in the same way as the Escabrosa limestones. There is the same wide range of fragment size in a finely milled matrix. The variegated color of the limestone and presence of fragments of the characteristic maroon shale usually identify it. The shale was more plastic in its response and it can be found in isolated squeezed pods and lenses wholly surrounded by

Figure 52. Dark gray and black mottlings in a gray limestone of the Black Prince formation. This mottling aids in distinguishing Black Prince from Escabrosa limestones in small blocks in fault breccias.

Figure 52

limestone clasts. Generally, there is sufficient continuity to the shale despite thinning and thickening, to permit it to be mapped as a zone (fig.69). The squirted segregates of shale rarely are found more than 15 or 20 feet from this continuous zone.

The thickness of the Black Prince formation is constant in the Johnny Lyon Hills area, except for tectonic variations. The shale unit is 25 to 30 feet thick, the limestone unit 140 to 150 feet with a typical total thickness of 170 or 175 feet. The lower contact is placed at the base of the shale, which rests on a tan dolomite. The upper contact is at the base of a shale zone which rests with apparent conformity on the Black Prince limestone unit. This shale is assigned to the Horquilla formation although fusulinids, the oldest distinctive Horquilla fossils, are generally not found below the overlying limestone beds.

The lithologic identity of the beds of the Black Prince limestone in the Johnny Lyon Hills and the Gunnison Hills is clear and there is no doubt about this correlation. The fauna which has been collected from the formation is meager and the formation has been tentatively assigned to Upper Mississippian although Lower Pennsylvanian fauna may be included (Gilluly et al, 1954, p. 15). The formation may be permissively but not conclusively correlated with the Paradise formation (Stoyanow, 1936, p. 508) in the Chiricahua Mountains. Elsewhere in southeastern Arizona, it may well be equivalent to an undifferentiated thin-bedded limestone sequence in the upper Escabrosa limestone.

BLACK PRINCE FORMATION SECTION

Rattlesnake Ridge

NE. 1/4, sec. 16, T. 14 S., R. 21 E.

	Thickness
Horquilla formation	
Mostly covered, some shale float.	
Black Prince limestone	
2. Limestones, light gray, with some pinkish mottling, medium to coarsely crystalline, beds 2' to 4' thick, sparse small chert nodules.	141 feet
1. Shales, partly covered, red to maroon with green mottling, with chert nodules, a few thin nodular limestones. Chert is unusual orange and white, often replaces hexacorals.	27 feet
	168 feet
Escabrosa limestone	
Dolomites, tan-gray, microcrystalline, nodules of chert.	

Pennsylvanian System

Naco group

Ransome (1904, pp. 44-46) gave the Naco limestone its name for the Naco Hills, near the western edge of the Bisbee quadrangle, which are composed of light gray limestones. He described the unit as being at least 1,500 feet and probably more than 3,000 feet thick, and containing thin pink shale interbeds which were useful in distinction from the conformably underlying Escabrosa limestone. G. H. Girty described a fauna then called (Ransome, 1904, p. 54) Carboniferous but which has been found subsequently to be partly Permian in age. The U. S. Geological Survey (Gilluly et al, 1954) has given group status to the original Naco, and has subdivided it into a number of new formations. Within the Johnny Lyon Hills area, the two lowest formations, the basal Horquilla and part of the overlying Earp formation, are present.

Horquilla formation

Gilluly (1954, p. 16) gave this name to the basal formation of the Naco group for the exposures on Horquilla Peak in the Tombstone Hills. It is described as 1,000 feet of thin-bedded gray limestones with a few thicker ledge-making beds and a few reddish-weathering shaly limestones. The common presence of abundant small fusulinids is a distinctive feature of the formation.

In the Johnny Lyon Hills area, the Horquilla formation crops out more or less continuously from Kelsey Canyon on the north to the vicinity of the Willcox-Cascabel road at the south end of Rattlesnake

Ridge. It reappears from under the alluvium farther south in thrust plates exposed on the east and south flanks of Javelina Hill and east of Keith Peak. Although topographically not as prominent as the Escabrosa limestone, its alternation of thin-bedded shales and limestones with thicker ledge-making limestones presents a characteristic ribbed weathering surface. Kelsey Peak, the highest topographic point in the northern half of the area, is composed entirely of the Horquilla formation. The topographic prominence of the formation at this point is the indirect result of the structural complications which duplicated Horquilla beds without exposing the more resistant Escabrosa limestones.

The outcrops of the Horquilla formation reveal a thick section of alternating limestones and calcareous shales with uncommon dolomites and calcareous siltstones. The limestones are light gray to blue-gray with black mottling, fine to coarsely crystalline, in beds ranging from three inches to eight feet thick. Chert is common, usually blue-black, weathering rusty brown, but also white, gray and in certain zones a brick red. The nodules of chert are rarely more than a foot long and two to three inches thick, in contrast to the much larger chert nodules of the Escabrosa limestone. The limestones are very fossiliferous with abundant fusulinids, brachiopods and gastropods. Crinoid fragments are common but do not form thick coquinoid accumulations as in the Escabrosa limestone.

The shales are either pink or olive-green, fissile, calcareous, and generally form thin interbeds two inches to two or three feet thick, between limestones. Exceptionally, as in the basal unfossiliferous zone the shale intervals may reach a thickness of 40 feet.

Tan siltstones appear sporadically among the shales. They are generally flaggy, calcareous and topographically nonresistant.

Dolomites, light gray or tan, microcrystalline, thin to thick-bedded, and silty, are also uncommonly present in the section.

The presence of fusulinids (*Fusulina* sp., *Triticites* sp.) has been the principal criterion for distinguishing small exposures of the Horquilla beds from the older Paleozoic limestones.

The lower contact of the formation has been placed at the base of a 30 to 40 foot shale unit which apparently rests conformably on the limestones of the Black Prince formation. In most examinations, diagnostic Pennsylvanian fossils (fusulinids) have not been found below the first limestones *above* the shale. On the east flank of Keith Peak, however, thin flaggy limestones within the lower 10 feet of the basal shales carry recognizable fusulinids.

The contact of the Horquilla formation with the overlying Earp formation is preserved only within the core of an overturned syncline southeast of Javelina Hill. This contact is defined as that horizon above which shales and red siltstones are more abundant than carbonate beds. This is solely a lithologic distinction and no important faunal break has been recognized here.

More commonly, the upper beds of the Horquilla formation have been eroded and the remaining beds are unconformably overlain by Cretaceous(?) or younger rocks.

Although both the base and the top of the formation are exposed within the Johnny Lyon Hills area, structural complications and alluvial cover have prevented the measurement of a complete section. The best estimates indicate at least 1,500 feet of total thickness but this might well be in error by several hundred feet. In the only complete section examined in the Dragoon quadrangle, J. R. Cooper (in Gilluly, 1954, p. 18) measured 1,595 feet of Horquilla beds in the Gunnison Hills.

J. S. Williams (in Gilluly et al, 1954, p. 34) concluded that the Horquilla formation as mapped "contains beds ranging in age from post-Morrow Pennsylvanian to middle late Pennsylvanian." Beds of Morrow age also may be present, but the faunal evidence is not sufficient to confirm this.

Earp formation

The Earp formation was given its name by Gilluly (1954, p. 18) from the exposures on Earp Hill, southeast of Tombstone. He defined the formation as embracing that part of the Naco group containing most of the clastic deposits. The base was taken where the shaly limestones and reddish shales became dominant over the more massive limestones. The top was placed immediately above the highest "orange dolomite" in a section of interbedded limestones and those vivid dolomites.

Cooper (in Gilluly, 1954, p. 21) measured an excellent section of the Earp formation in the Gunnison Hills in the southeastern part of the Dragoon quadrangle. He recognized two members separated by a distinctive heterogeneous conglomerate, which he pointed out, marks an abrupt change in the character of the formation. The lower member contains abundant fusulinids in light colored limestones, whereas the dark gray limestones of the upper member contain a poorly preserved gastropod-cephalopod fauna in which no fusulinids have been found.

Shales, siltstones, sandstones and shaly limestones are abundant in both members.

Within the Johnny Lyon Hills area, only one locality has revealed Earp formation beds. They are found in the core of an overturned syncline in one of the thrust plates southeast of Javelina Hill. The beds are complicated by isoclinal drag folding and by faulting and it is difficult to determine the thickness of beds exposed. At least 300 feet and perhaps as much as 500 to 600 feet of beds are exposed.

The shale-rich composition of the Earp formation renders it topographically recessive. This exposure is in a swale surrounded by low ridges of Horquilla limestone and it owes its existence to rather recent removal of alluvium which once overlapped this area. The section is dominantly clastic with red and green shales, some dark-brown-weathering thin-bedded siltstones and sandstones, a conglomerate and a number of thin-to medium-bedded limestones. The limestones are light colored with tints of green, yellow, or pink. Fusulinids are abundant throughout and appear to be large *Triticites* sp.

The conglomerate appears at the edge of the alluvium and cannot be traced for more than 250 feet before fault offsets appear which displace it back under the alluvium. The structural relations indicate it is very close to the stratigraphic top of the revealed section. It is a heterogeneous bed, one to two feet thick, containing pebbles of chert, jasper and limestone, in a brown, silty dolomite matrix. It appears to be lithologically very similar to the distinctive conglomerate, whose base is used as the contact between lower and upper members of the Earp formation.

The lower contact is readily placed at an abrupt transition from the thick limestones of the Horquilla formation to the clastics described above. The upper contact is hidden by the overlapping alluvium.

All of the Earp formation mapped in this area has been assigned to the lower member as defined by Cooper. If the conglomerate described above corresponds to the marker conglomerate at the base of the upper member in the Gunnison Hills, not more than 20 to 40 feet of upper member may be included. Unfortunately, there is not enough exposure of the beds overlying the conglomerate to be certain of the correlation. The total surface area affected would not be more than a few hundred square feet.

Williams (Gilluly et al, 1954, p. 38) has concluded that the age of the Earp ranges from middle late Pennsylvanian to and including beds of Wolfcamp (Permian?) age. Since the Earp formation exposed in the Johnny Lyon Hills represents only the lower part of the formation, it is probably almost all, if not entirely, Pennsylvanian in age. The Virgil-Wolfcamp boundary is not known to be marked by any unusual lithologic change and may be either above or below the distinctive intraformational conglomerate in the section near Tres Alamos Wash.

It has not been possible to identify any higher units of the Naco group in the map area. These upper formations probably occur under the alluvium.

The visible part of the group appears to represent a more or less continuous sequence of deposits in a shallow marine basin where alternating chemical and clastic deposits accumulated. No major breaks are visible in the section and the conglomerate horizon is considered to be intraformation in character.

Triassic or Jurassic System

Walnut Gap volcanics

The Walnut Gap volcanics were originally described by J. R. Cooper (1950b) from outcrops on the northeast side of Walnut Gap in the Gunnison Hills in the Dragoon quadrangle. They rest unconformably on the Naco group, there, and are overlain unconformably by the Glance conglomerate. They consist principally of purple and red tuffs, breccias and volcanic conglomerates containing altered fragments of andesite. A few feet of conglomerate with interbedded tuff and sandstone occur at the base. No fossils have been found in these rocks.

In the northwest corner of the map area (see cross-section A-A'), there are local exposures of a series of andesitic breccias and conglomerates which are very similar to the volcanics of Walnut gap. These beds are overlain by Glance conglomerate and alluvium. The contact with the Glance conglomerate is poorly exposed and although it is interpreted as sedimentary may actually be a fault. The relation to the underlying units is concealed by thrust faults which bring pre-Cambrian rocks in contact with the volcanic sediments, and locally overturn them.

The clastic beds are poorly bedded to massive and consist of fine-grained tuffs and coarser breccias with fragments up to three or four inches in diameter. These fragments are usually angular, lithic clasts consisting of variable proportions of altered plagioclase, hornblende(?), and rare quartz phenocrysts up to 3 to 4 mm in diameter, in a brown, red-brown, or purple aphanitic groundmass. The matrix in which the fragments are imbedded is typically bright red-brown or magenta in color. Petrographic examination reveals that the matrix color reflects a pervasive hematite content. The plagioclases are largely, but not completely, albitized with some formation of calcite and clay minerals. The former ferromagnesian minerals have been replaced by an alteration suite of iron oxide dust, silica, clay minerals and traces of chlorite. They usually have a conspicuous corona of magnetite dust.

Uncommonly, rounded pebble and cobble conglomerate beds appear among the breccias. The pebbles are generally volcanic but some limestone and chert is also present.

On the basis of lithologic similarity and the interpreted sedimentary contact with the overlying Glance conglomerate, these pyroclastics are correlated with the Walnut Gap volcanics. Their age in the map area, is known only as pre-Glance conglomerate and probably post-Naco group on the basis of limestone and chert fragments. If the conglomerate is truly Glance then the volcanics are pre-lower Cretaceous and post-Permian. Lacking any other evidence, the formation is called Triassic or Jurassic in age as Cooper has done at the type locality in Walnut Gap.

Cretaceous System

Bisbee group

Dumble (1902) gave the name "Bisbee beds", to a thick section of clastic and carbonate strata of Cretaceous age, near Bisbee. Ransome (1904, p. 56) used the term Bisbee group for the same beds and recognized four formations; the basal Glance conglomerate, the Morita formation, the Mural limestone, and the Cintura formation. The Mural limestone thins and apparently pinches out northward in the Mule Mountains. In its absence there is no ready means for distinguishing between the Morita and Cintura formations. Cooper (1950) has combined them and thus recognizes two mappable formations in the Bisbee group in the Dragoon quadrangle, the Glance conglomerate and the Morita-Cintura formations undifferentiated. The correlation with the type Bisbee is made chiefly on the basis of lithologic resemblances and geologic relations. Cooper has found petrified wood of a type present in both Lower and Upper Cretaceous series, whereas Stanton (in Ransome, 1904, pp. 70-73) and Stoyanow (1949, p. 6) have been able to limit the Mural limestone, at least, to the Lower Cretaceous series. No fossils have been found in the Johnny Lyon Hills area.

Both within the Johnny Lyon Hills and the Little Dragoon Mountains, the formations of the Bisbee group have been involved in the Laramide thrusting. They in turn have been intruded, cross-cut, and metamorphosed during the igneous cycle represented by the Texas canyon quartz monzonite stock in the southern part of the Dragoon quadrangle.

Glance conglomerate

The Glance conglomerate received its name for the exposures near the Glance mine, southeast of Bisbee. It is apparently of local derivation and in the Bisbee area, consists of fragments of underlying and nearby formations. Thus schist and granite pebbles and boulders are locally found, according to Ransome (1904, p. 59);

but for the most part, the conglomerate consists of limestone. It is well indurated with a reddish sandy matrix and fairly distinct bedding. Its thickness varies from 0 to 600 feet.

In the Johnny Lyon Hills area, conglomerates occurring at two different localities have been assigned to the Glance. One locality, a half-mile northwest of the American mine, is just off the edge of the quadrangle. It occurs there in low ridges and rests unconformably on less resistant Walnut Gap pyroclastics. The other locality is on the south side of Kelsey Canyon, just north of Kelsey Peak. The conglomerate there rests unconformably on the Horquilla formation.

At both localities, the conglomerate consists of pebbles, cobbles and boulders of limestone, chert and to a lesser extent, shale and sandstone in a red calcareous sand matrix. The limestone fragments predominate and are generally angular to subrounded. They may be as large as two to three feet in diameter, but average six inches. Fine-grained matrix material generally constitutes less than 25 percent of the rock. The induration is so excellent that fragments of Glance conglomerate generally break through the original boulders rather than around them. Uncommon sandstone interbeds permit the measurement of attitudes.

The exposures northwest of the American mine are overlain by Tertiary and Quaternary alluvium. The Kelsey Canyon exposures are overlain by a thick section of Threelinks conglomerate containing boulders of Glance conglomerate and volcanic fragments. The contact relations are obscured but are interpreted as probably faulted in part.

Only minimum estimates of the thickness of the Glance conglomerates are possible. They probably exceed several hundred feet in both localities and these figures reflect the local erosion preceding the deposition of the overlying Tertiary beds.

No fossils have been found in either location. Correlation is based on lithology and geologic relations, and is therefore tentative. Emphasis is placed on the strong induration, the lack of volcanic fragments and the relation to the underlying rocks.

Morita-Cintura formations

Ransome (1904, pp. 63-65, 68, 69) described the type Morita and Cintura formations near Bisbee as consisting of red and tawny sandstone, occasionally quartzitic, and sparse thin gray limestones.

On the margin of this map area, exposed in limited outcrops surrounded by the alluvium about a quarter of a mile west of the American mine, is a series of fractured red indurated shales, red quartzites, and red conglomerates. They underlie thrust plates of Naco group limestone. They have no counterpart in the Paleozoic sequence, and they are better sorted and more indurated than any clastic beds known in the Tertiary formations.

A tentative assignment to the Morita-Cintura formation has been made on the basis of lithologic similarities alone. It is quite possible that these beds may represent undifferentiated upper Cretaceous sediments such as are reported farther north in the San Pedro valley. (L. A. Heindl, personal communication).

Cretaceous(?) or Tertiary(?) Systems

Lamprophyre sheets and dikes

In the southern part of the Johnny Lyon Hills area, the Paleozoic and older rocks involved in structures of pre-Cambrian to Mesozoic age have been invaded by swarms of dark dike rocks in several conspicuous structural sets. Some of the individual dikes and sheets can be followed for three miles or more, crosscutting almost all major structural features in their path. They are so numerous as to make it impractical to map them all. In general, only the larger and more conspicuous bodies are shown on the map. Most of the lamprophyres shown north of Sheep Camp Ridge in plate I, were taken from the patterns visible on aerial photographs, with scattered ground checks to determine the composition and attitudes of the dikes.

In the field, many varieties of lamprophyre can be recognized on the basis of composition and texture. Two particular textural types are so recurrent that they have been distinguished from the others in mapping. One of these is olive-green to gray-green, porphyritic with 20 to 25 percent dark prismatic phenocrysts showing good amphibole outlines, varying from 1 mm to 2 mm long. Fragmental inclusions of dark-green mafic rock up to 5 cm in diameter are common. Small white phenocrysts of plagioclase up to 2 mm are much less common. The groundmass is gray-green, microcrystalline, and sparsely amygdaloidal. The phenocrysts usually show strong flow orientation parallel to the dike walls. Locally this texture will undergo a transition to a variolitic type of nodular texture.

Petrographic examination of the "porphyritic" lamprophyre reveals that the amphibole phenocrysts are invariably altered to chlorite-epidote-carbonate intergrowths. The groundmass is an intergrowth, predominantly of albite in grains 0.1 to 0.2 mm in diameter, but containing, also, chlorite, epidote, magnetite octahedrons, sericite, and traces of apatite and zircon. If the rock was ever crystallized free of alteration minerals it would have had about 60 percent sodic plagioclase and 40 percent amphibole. However, the low temperature mineral suite is so characteristic of the rock type wherever it is found throughout the southern part of the map area, that it is difficult to accept it as anything but a deuteric phase essential to the rock. At best, it may be said this rock had spessartite (Johannsen, family 2212D) affinities.

The second textural type of lamprophyre which has been distinguished is a medium to coarse grained, hypidiomorphic inequigranular rock, dark green in color. In hand specimen prismatic dark-green amphibole from 3 to 10 mm long is randomly oriented in a background of white plagioclase feldspar. Chilled margins are common on this type of dike, but there is also considerable internal variation in grain size.

Petrographically, this rock, in its least altered form, consists of a relatively simple "diorite" mineralogy comprising about 40 percent hornblende, 5 percent augite and 55 percent feldspar. The amphibole is typically euhedral (fig. 53) and pleochroic from a slightly ruddy olive-brown (X); to olive-brown (Y) to pale yellow (Z). $Z \wedge C = 17^{\circ}$, (-) $2V = 80^{\circ}$(est.). A little green hornblende is usually present. The pyroxene is colorless and probably diopsidic. The

Figure 53. Photomicrograph. "Diorite" lamprophyre with prismatic hornblende and albitic plagioclase crowded with coarse sericite, epidote and calcite. Crossed nicols. Mag. x 26 diameters. Spec. L-104.

Figure 54. A foundered block of limestone in the thick "diorite" lamprophyre which crosses the Abrigo formation just south of the top of Keith Peak. Reaction of the calcium carbonate with the magma helped produce unusually coarse hybrid textures.

Figure 53

Figure 54

feldspar is predominantly twinned plagioclase (Ab_{90-95}). A little perthite and antiperthite may be present. The important accessories are abundant sphene, apatite and ore minerals. This rock, too, is a spessartite in character but appears to differ from the "porphyritic" lamprophyre in higher TiO_2 (in the sphene and probably in the hornblende) and K_2O content, as well as in texture. Locally the rock becomes a hornblendite with 90 percent or more amphibole. Abundant alteration in the "diorite" lamprophyre is the rule rather than the exception but the common presence of 20 to 40 percent chlorite, carbonate, epidote and sericite does not mask its characteristic texture.

Little will be said of the many other lamprophyric types found in the area. Profound conversion to low temperature mineralogies is characteristic of them, and specimens which are essentially equal parts of chlorite and calcite are not uncommon.

The distribution of the various types is more or less systematic. The "porphyritic" lamprophyres form a zone of sheets and dikes which parallels on the northwest with some overlap, the entire pre-Cambrian rhyolite porphyry sheet zone in the Pinal schist. It maintains this general position despite the offsets of the rhyolite zone, and at the same time clearly transects many of the thrust faults in its path. Dikes maintain their prevalent N. 45° E. trend while cutting across the Paleozoic formations on Keith Peak. Individual sheets are up to 20 feet thick and show considerable flow banding. Xenoliths of granodiorite and basic rocks up to 1 foot in diameter are occasionally observed.

The "diorite" lamprophyre forms the thickest and most impressive single lamprophyre dike in the area. This dike is first seen in the Pinal schist just east of the lowest thrust fault on the east side of Keith Peak. It then trends three miles S. 65° W. in a path which intersects at least four major thrust faults. It is seemingly independent of all structural trends from pre-Cambrian to Laramide which it traverses. Just west of Keith Peak, this dike cuts across a dike of the "porphyritic" lamprophyre establishing their age relation, at least locally.

This 45 foot wide "diorite" dike, where it intersects the Abrigo formation high on the west side of Keith Peak, created a contact metamorphic zone 50 to 150 feet wide on either side. The calcareous shales and thin limestone interbeds below the Abrigo quartzite marker bed are converted to hornfels containing up to 80 percent epidote and clinozoisite with lesser quantities of recrystallized calcite, quartz, albite and microcline. The silty limestones above the quartzite marker bed are converted to grossularite-bearing marbles with epidote and clinozoisite replacing the silt seams. Spectacular hybrid textures (Fig. 54) developed within the diorite as blocks of the limestone and argillaceous rocks foundered and reacted in the magma. Crystals of hornblende, actinolite and tremolite up to 6 inches long and an inch thick are developed in coarse fringes about some of the xenoliths.

A similar hybrid "diorite" and contact metamorphic zone is developed in the Abrigo formation in the saddle between the two lobes of north Sheep Camp Ridge. But aside from these two localities no other contact metamorphic effects are conspicuous.

"Diorite" lamprophyre is found in a generally NNW-trending set of dikes at a number of places in the Johnny Lyon granodiorite pluton.

One swarm seems to have issued forth from the great N 65° E. dike as it crossed the rocks in the Catclaw Hills. A second swarm which appears west and northwest of Sheep Camp Ridge is rather flat dipping with an average dip of about 45 degrees to the east. A third swarm is exposed on The Mesa with irregular trends but prevailing easterly dips of 40 to 50 degrees. Dikes of this last group transect the north-south shear zones of the granodiorite, with no evidence of unusual alteration. Many of the "diorite" dikes attain thicknesses of 40 feet and uncommonly as much as 75 feet.

The absolute age of these major lamprophyre types cannot be determined from the relations in the Johnny Lyon Hills. These dikes are clearly younger than the major thrust faults and the large normal fault on Keith Peak. They are in turn older than the large northeast trending rhyolite dike which crosses "diorite" lamprophyres at a number of points southwest of Sheep Camp Ridge.

While mapping in the Sheep Basin area of the southwestern Little Dragoon Mountains, the author observed important lamprophyre dikes which were texturally identical with both the normal and hornblendite varieties of the "diorite" type in the Johnny Lyon Hills. Examination of thin sections of samples collected by J. R. Cooper elsewhere in the Little Dragoon Mountains, as well as of these specimens suggests a strong similarity. The amphibole in the dikes from the Little Dragoon Mountains is one of the more titaniferous red-brown varieties, whereas sphene is perhaps more abundant in the "diorite" of the Johnny Lyon Hills.

Much less commonly, dikes with the texture of the "porphyritic" lamprophyres were also observed in the Sheep Basin area.

In Sheep Basin, the lamprophyre dikes occupy a post-thrusting, post-normal faulting position in the geologic history. They are also younger than the Texas Canyon quartz monzonite and most but not all of its associated aplites and pegmatites. A rhyolite dike rock much like that in the Johnny Lyon Hills truncates Texas Canyon aplites but is not seen in contact with the lamprophyres. On the basis of the lithologic similarity and of the comparable positions in the sequence of geologic events, the "diorite" and the "porphyritic" dikes are considered to be lamprophyric representatives in the Johnny Lyon Hills, of the Texas Canyon quartz monzonite intrusive episode in the Little Dragoon Mountains. This places them as late Cretaceous(?) or early Tertiary(?) in age.

Most of the many unclassified lamprophyres appear to be of the same generation, and may well be merely textural and alterational variants of one of the described types. It has not been possible to establish whether any pre-Cambrian lamprophyres are present in the granodiorite or Pinal schist, although they could reasonably be expected. If they are present, they are certainly subordinate in number to the younger dikes.

In general, the lamprophyres are free from younger deformational effects. However, prospect pits have been developed on all types of lamprophyre dikes in the granodiorite which show local shearing and post-shearing mineralization.

Tertiary and Quaternary Systems

The Tertiary and Quaternary rocks of the Johnny Lyon Hills area include indurated conglomerates, a volcanic sequence, and thick alluvial accumulations which were derived from these volcanics and from the accelerated erosion of the older rocks after the Laramide deformation. In contrast to the older rocks, these formations are entirely non-marine and show great compositional variations laterally because of the local nature of the basins of deposition. Except for limited lacustrine deposits, they are poorly sorted. They are composed principally of fanglomerates and coarse fluviatile conglomerates and sandstones.

The relative ages of the various units have been inferred entirely from local and regional geologic relations. No Tertiary fossils have been found in this area, and only a few have been found in the entire San Pedro basin. The locally derived nature of the sediments prevents positive lithologic correlation with the known fossil localities.

Threelinks conglomerate

The name Threelinks conglomerate has been proposed for a series of bouldery beds which crop out in the Steele Hills (the type locality) in the eastern part of the Dragoon quadrangle and in Kelsey Canyon. The Threelinks Ranch which includes more than half of the quadrangle, and on which the outcrops are found is the source of the name. In both localities the Threelinks conglomerate rests unconformably on Cretaceous rocks. It is overlain in turn by flows and tuffs of the

Galiuro volcanics, in a nearly parallel relation. In the Steele Hills, flows are found interbedded in the formation but none has been found below the visible top of the exposures in Kelsey Canyon.

In the exposures at the northeast foot of Kelsey Peak, the Threelinks conglomerate is composed of subangular to rounded cobbles and boulders of Paleozoic limestones, dolomites and quartzites as well as fragments of Glance conglomerate. Volcanic fragments, identical in color and texture with the Walnut Gap pyroclastics are scattered throughout. Schist and granite fragments are rarely present. The boulders may reach, commonly, one foot, and unusually two feet in diameter. In contrast to the Glance conglomerate, there are many poorly sorted sandstone beds, and sandy matrix is abundant in the conglomerates. The rocks are moderately but unevenly indurated so that locally they will maintain fairly steep slopes.

No fossils have been found in the Threelinks conglomerate. It is post-Glance and also post-Laramide deformation in age. It is pre-Galiuro(?) volcanics but these volcanics are also undated. Its age may be Eocene(?) to Pliocene(?).

Galiuro volcanics

W. P. Blake (1902, p. 546) gave the name "Galiuro rhyolite" to the volcanic rocks of the Galiuro Mountains. This range and the Winchester Mountains, which are its southeastward projection are the topographic axes of a great volcanic pile some seventy-five miles long and fifteen miles wide. The southernmost extensions of this pile reach into the northern edge of the Dragoon quadrangle, in the vicinity of Kelsey Canyon and in the Winchester Mountains foothills.

Within the quadrangle, it is clear that (1) there are a number of mappable units within this volcanic suite and (2) only a small fraction of the total Galiuro Mountains volcanic section appears in the southern extensions. It is proposed therefore to adopt the name, Galiuro volcanics for the entire pile and to recognize the locally mappable units as some of the members.

In general, the Galiuro volcanics are interbedded flows, tuffs, breccias, and conglomerates derived from the volcanic rocks. In the Kelsey Canyon section, it is possible to recognize four members representing flows and clastics. These members are (1) a basal andesite flow member, (2) an overlying quartz latite flow member, (3) a conglomerate member and (4) a rhyolite tuff member, which is the highest unit locally exposed. Tertiary and Quaternary alluvium blankets the rest of the formation within the map area.

Andesite member

The lowest map unit of the Galiuro formation has been called the andesite member. It is a series of flows extruded on a surface of the Threelinks conglomerate. The contact is well exposed on both sides of Kelsey Canyon. The andesite is only moderately resistant and despite the youthful incision of Kelsey Canyon, tends to form steep slopes rather than the cliffs characteristic of the overlying quartz latite member. Although no detailed measurement has been attempted, the indicated map thickness of andesite is about 200 feet.

In hand specimen, the andesite is characterized by a striking porphyritic texture. Large, tabular, yellow to pale brown plagioclase euhedrons, 5 to 25 mm in major dimension and up to 10 or 15 mm in lesser dimension are set in an aphanitic, brown to dark brown, matrix. The plagioclase commonly shows Carlsbad twins in reflection. Much less conspicuous are scattered black phenocrysts of pyroxene and magnetite up to 5 mm in diameter.

Microscopic examination of several specimens reveals a considerable variation in texture and in composition. The estimated average original composition is:

Phenocrysts		
	Plagioclase	25 percent
	Pyroxenes	8-10
	Ores	1
	Apatite	1/2
Groundmass		65

The large phenocrysts of plagioclase are present throughout; zoned from cores of An_{50-60} to rims of An_{30-40}, euhedral with conspicuous albite and Carlsbad twinning (fig. 55). The pyroxenes are augite and hypersthene, in anhedral phenocrysts up to 5 mm in diameter. Magnetite and apatite are the conspicuous accessory minerals.

The groundmass ranges from hypohyaline to completely crystallized. Where devitrification is incomplete abundant microlites of plagioclase, An_{25} to An_{30}, minute grains of augite and magnetite, generally less than 0.2 mm in diameter, and crystallite-rich brown glass make up the groundmass. Where devitrification is complete, the groundmass consists principally of anhedral equant grains of plagioclase, 0.1 to 0.3 mm in diameter. Many of these equant grains consist of stubby subhedrons of sodic oligoclase with an irregular, but optically oriented rim of albite. In most cases it is possible to determine

Figure 55. Photomicrograph. Andesite member of the Galiuro volcanics showing a typical, coarse zoned and twinned andesine phenocryst with several smaller phenocrysts in a groundmass of microcrystalline plagioclase and pyroxene. The narrow fringe with high illumination around the large phenocryst is albite. Crossed nicols. Mag. x 26 diameters. Spec. L-310.

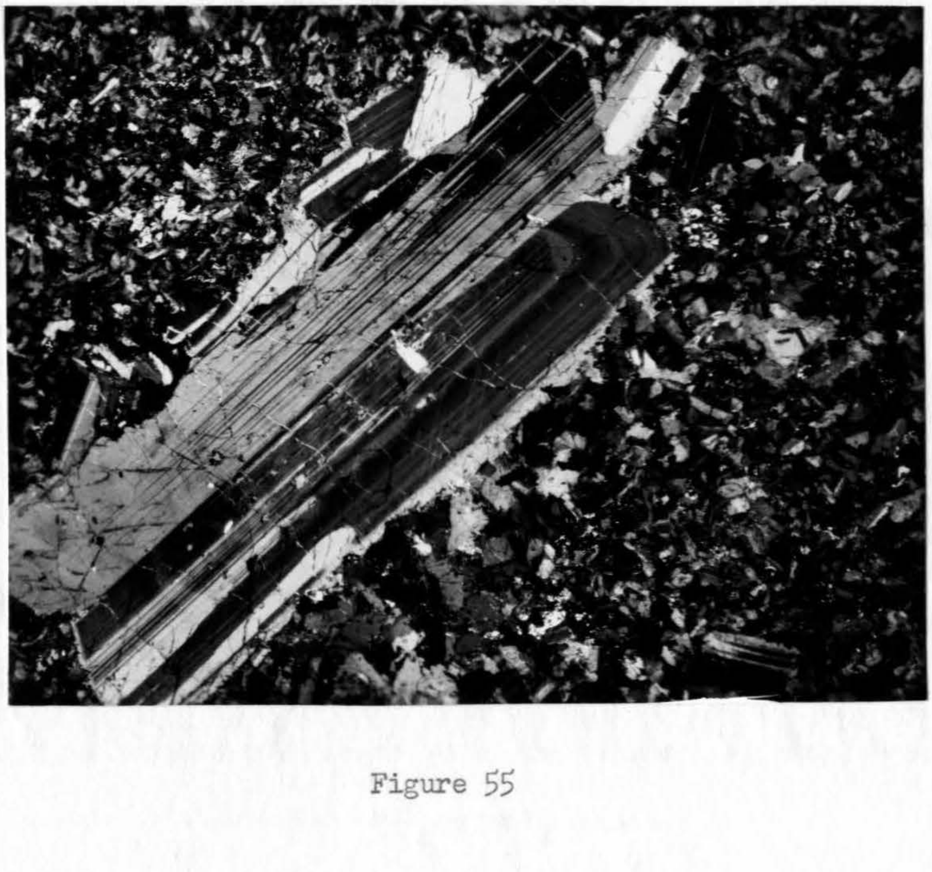


Figure 55

only that the index of refraction of the microcrystalline plagioclase is less than that of balsam. In addition to this plagioclase, the groundmass contains abundant minute needles, a few of which can be identified as apatite.

In the thin-sections where albite is abundant in the groundmass apparently as an overgrowth on the microlites, the phenocrysts are also surrounded by narrow albitic margins. Replacement textures of albite penetrating the andesine or labradorite are common. The albite may represent as much as 20 percent of the rock. The average composition of all of the original feldspar neglecting albitization was probably An_{40} to An_{45}; which is the basis for identifying the rock as an andesite. The significance of the albitization is not fully understood. Rapid quenching in a subaerial environment argues against late stage crystallization effects. The plagioclase shows no other alteration effects, but the pyroxenes are very commonly at least partly altered to a fine-grained chlorite and hematite mixture. This may be an associated product with the albite, of a hydrothermal alteration history.

The recessive topographic expression prevents satisfactory exposure of the contacts of this member. From the abrupt textural and compositional differences compared to the adjacent volcanic member, the andesite is interpreted as a separate flow.

Quartz latite member

The cliff-forming quartz latite member appears to be largely a single flow resting conformably on the andesite member. On the north side of Kelsey Canyon it has been separated into 2 areas of outcrop as a result of block faulting and erosion. There is no single unfaulted exposure of the entire member so that the thickness can only be estimated at about 250 feet.

At the base of the quartz latite member, and mapped with it because it is only 15 to 20 feet thick is a locally weathered vitrophyre. It is recessive in outcrop, and good exposures are seen only where recent stream action has removed the debris from the overlying units.

A thin section examination of the freshest specimen of vitrophyre obtained gave the following estimated composition:

Phenocrysts	
Plagioclase	35 percent
Augite	5
Ores	1
Apatite	tr
Quartz	tr
Glassy groundmass	60

The plagioclase phenocrysts range from 0.1 to 4 mm in diameter and from euhedrons to nearly completely resorbed residuals. Good zoned crystals indicate ranges of An_{40-45} near the core to An_{30} at the rim. Some of the grains show a zoning reversal at the core. The augite is anhedral and sometimes forms inclusions in the feldspar. It alters to chlorite, clay(?) and limonite. The glassy matrix has innumerable crystallites and rare microlites of plagioclase. It is fractured with some suggestions of a perlitic pattern. It contains many planar amygdules, stretched out and with devitrification of the walls and fillings of albite-quartz(?) crystals. This rock is tentatively called an andesite vitrophyre although it may be more silicic.

In outcrop, the quartz latite flow is a porphyritic, amygdaloidal brown rock with pronounced pink-brown and medium brown narrow flow-banding. Feldspar phenocrysts up to 4 mm, mafic minerals altered to limonite and the abundant partly filled amygdules are surrounded by the aphanitic flow-banded matrix. In the highest one to 5 feet of the flow, a single locality of abundant geodes, generally completely filled with opaline and chalcedonic silica, was found on the north side of Kelsey Canyon. The geodes are one to three inches in diameter, rarely reaching five inches. They do not contain quality agate, but present an attractive milky blue contrast to the deep red altered matrix in which they are found.

Petrographic examination yielded the following estimated original composition:

Phenocrysts	
Plagioclase	30 percent
Pyroxene	1/2
Quartz	3
Biotite	tr
Ores	1
Groundmass	65

The plagioclase phenocrysts show all stages of resorption from euhedrons to disintegrated residuals. They are zoned with cores of An_{40} and rims of An_{30}. A number of grains show considerable albitization. The quartz exists as a few highly resorbed phenocrysts. Most of the pyroxene has been altered pseudomorphously to aggregates of iron oxide, clay and calcite with distinctive coronas of iron oxide (fig. 56). In one instance a brown biotite was observed as a reaction

Figure 56. Photomicrograph. Quartz latite member of the Galiuro volcanics. The zoned oligoclase, the magnetite pseudomorphs which form coronas around residual pyroxene, the hypohyalline groundmass and numerous vesicules are typical of this member. Partial lining of the vesicules with quartz and albite druses is also common. Plain polarized light. Mag. x 26 diameters. Spec. L-309b.

Figure 56b. Same field, crossed nicols.

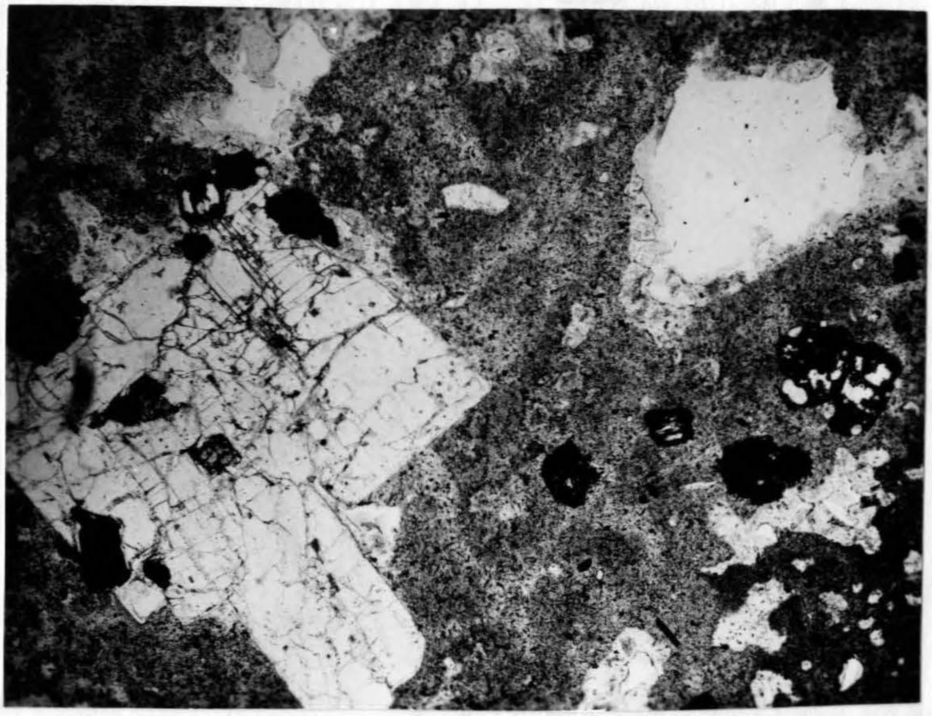


Figure 56a

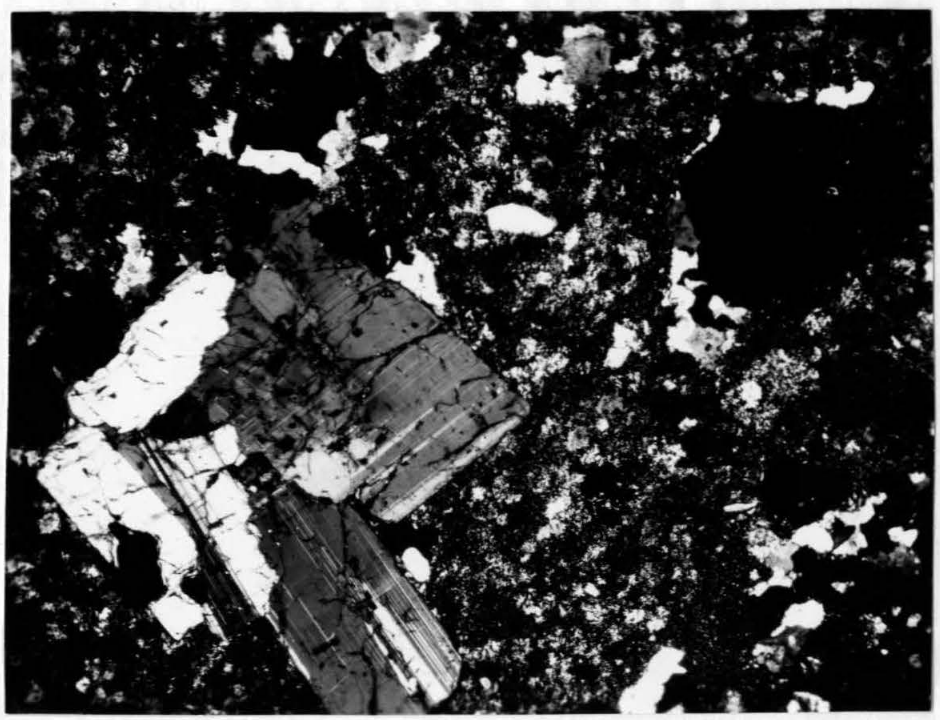


Figure 56b

product of the pyroxene. The small residuals of pyroxene have been tentatively called augite(?). Numerous apatite needles are present. The groundmass is hypohyaline and the devitrification is more complete in the brown flow bands than in the pink-brown bands. The numerous vesicles and amygdules are found within the glass or between phenocryst surfaces and the glass. The filling typically consists of zoned subhedral quartz and albite with superimposed fine grained calcite. The shapes of the amygdules are commonly elongated parallel to the flow banding and show evidence of distortion during the final stages of flow.

The field name quartz latite would appear to be a misnomer, if the phenocrystic composition is the basis of classification. Andesite would be more appropriate. However the resorption and albitization of the plagioclase, the presence of biotite reacting from the pyroxene and the albite and quartz in the amygdules suggest that the groundmass may be both more silicic and alkali-rich than the phenocrysts indicate.

Conglomerate member

The conglomerate member rests unconformably on the quartz-latite flow in most exposures but in two limited outcrops it is found resting upon the andesite member. The conglomerate member is composed predominantly of volcanic conglomerate and sandstone but the upper part also contains pyroclastic tuff beds and waterlaid sediments. The subangular to rounded pebbles, cobbles and boulders up to one foot in diameter are principally volcanic fragments. The underlying andesite member and quartz latite member are represented as well as many volcanic rock types not seen within the map area. In the upper 75 feet of the member, thin-bedded fine-grained tuffaceous water-laid sediments are interbedded with a few thick-bedded vitric tuffs. The tuffs contain angular fragments of red and brown volcanic rock up to two inches in diameter in a buff to yellow matrix of pumiceous glass fragments. Capping the member is massive yellow vitric tuff 20 to 30 feet thick, which appears to be gradational to the overlying rhyolite tuff member.

The conglomerate member is well indurated and the stream in Kelsey Canyon and its tributaries have steep cutbanks in which the unit is well exposed. The total thickness of the member varies considerably but at least 500 feet of beds are present on the south side of Kelsey Canyon.

No fossils have been found in this member, but it would appear to be an attractive hunting ground for fossils which might supply dates within the interval of accumulation of the Galiuro volcanics.

Rhyolite tuff member

The most easterly exposures of the Galiuro volcanics in Kelsey Canyon reveal a medium brown, dense, tuff-breccia containing crystal fragments of feldspar and quartz, and abundant lithic volcanic fragments up to several inches in diameter. This rhyolite tuff has a gradational relation to the underlying yellow vitric tuff which caps the conglomerate member. The rhyolite tuff differs lithologically from that pumiceous tuff in its dense brown aphanitic groundmass.

In the limited exposures, the top of the rhyolite tuff member is concealed under the overlapping alluvium. An estimated 150 feet of the member is exposed on the north side of the canyon. Lack of bedding structures prevents precise measurement.

Petrographic examination indicates that the dense matrix is a welded tuff (fig. 57). The original glass shards, although now largely devitrified, are well preserved in outline. Plastic flowage has removed all porosity except for a few vesicles which are now filled with quartz and albite. The individual shards were deformed around the crystals and lithic fragments in response to the compacting pressures. The devitrification patterns are developed commonly normal to the shard surfaces, but radiating spherulitic patterns are also present.

The crystal fragments include grains of quartz showing various resorption textures: plagioclase which is twinned and zoned, averaging about An_{30}; sanidine which is simply twinned; and reacted and altered mafic minerals which may include hornblende(?). Magnetite, zircon and apatite are recognizable accessories.

The lithic fragments represent a wide range of textures and compositions, from fine-grained andesite or basalt, to quartz-rich porphyritic textures. Most of the rock types are not recognized as flows within the map area, a characteristic this tuff member shares with the underlying conglomerate member.

Rhyolite dikes

The youngest intrusive rock recognized in the Johnny Lyon Hills area is rhyolite that forms a series of en echelon dikes which can be followed from The Mesa (NW$\frac{1}{4}$, sec. 9, T. 15 S., R. 21 E.) over three

Figure 57. Photomicrograph. Rhyolite tuff member of the Galiuro volcanics displaying a striking welded tuff texture. The original glass shards have been compacted and plastically deformed as they adjusted to each other and to the more rigid phenocrysts and fragments of diverse volcanic rock types included in the tuff. Devitrification of the glass is only partial. Plain polarized light. Mag. x 26 diameters. Spec. L-308.

Figure 57

miles S. 40° W. to the alluvial cover at the west edge of the map area. Over this distance, the nearly vertical dikes of the series transect all rocks, including lamprophyres, and structures in their path, and are not offset by any later structures. The dikes increase continuously in thickness to a maximum of 100 feet near the edge of the map area. A number of apparent offsets are visible in the dikes southwest of Sheep Camp Ridge, but the geologic relations in the field suggest that the zones of weakness followed by the dikes had suffered prior structural offset and that the intruding rhyolite accepted these offsets as it met them. No shearing or any other internal evidence of faulting has been recognized in these rhyolites.

The rhyolite is a light gray to purple-brown porphyritic-aphanitic rock. It is usually strongly flow-banded and jointed in flat plates parallel to the flow banding. The composition averages 10 percent quartz phenocrysts, 10 percent sanidine phenocrysts and 80 percent groundmass. The quartz phenocrysts range from 1/2 to 3 mm in diameter and show strong resorption forms. The feldspar phenocrysts are anhedral to subhedral, 1 to 2 mm in diameter, twinned according to the Carlsbad and invariably strongly altered to sericite. The groundmass is a microcrystalline intergrowth of quartz and potash feldspar, with little or no plagioclase present. No mafic minerals are recognized, but the pervasive alteration of the groundmass to sericite (or kaolinite), may obscure some. Rare zircon grains have been noted. Calcite, limonite, and manganese-oxide dendrites are other secondary minerals.

Its position as younger than the thrusting and lamprophyre dikes makes this rock younger than any igneous rocks in the map area, except possibly the Galiuro volcanics to which it is not spatially related. However, the texture reveals the very shallow depth of emplacement of this rock and it may well have been a feeder dike for flows of the same generation as those to the north.

Dikes of similar composition and texture cut aplite of the Texas Canyon quartz monzonite in roadcuts in SE$\frac{1}{4}$, sec. 30, T. 16 S., R. 22 E., on state highway 84, at the west end of Texas Canyon.

Alluvium

Alluvial deposits of late Tertiary(?) and Quaternary age overlap unconformably and nearly surround the elongate outcrop area of older rocks of the Johnny Lyon Hills area. On the west flank, the irregular edge of the basin deposits of the San Pedro River valley approximately coincides with the edge of the map area. On the east, the thick accumulation of alluvial fill underlying the present Tres Alamos Wash separates the Johnny Lyon Hills area from the Little Dragoon Mountains to the southeast and the Winchester Mountains to the northeast. These two belts coalesce in the south and only in the north do exposures of the older rocks extend out of the map area for any considerable distance.

The alluvial deposits include coarse, poorly sorted fanglomerates, fluviatile conglomerates and sands, and finer-grained lacustrine sediments. They vary from older well-indurated rocks standing in vertical cliffs 20 to 60 feet high (fig. 2), to the unconsolidated gravels, sands, and silts currently being scoured and filled in Tres Alamos Wash and Kelsey Canyon.

The older rocks of the eastern alluvial belt consist of marginal fanglomerates derived from the Paleozoic bedrock ridges on which they rest and a broad band of fluviatile conglomerates of more diverse derivation and greater transportation in fills in the Tres Alamos Wash basin. The fanglomerates are generally very coarse with boulders of Paleozoic limestones and quartzites, Apache group formations and less commonly, Pinal schist, up to four feet in diameter. These fragments are angular and are embedded in a poorly sorted pink sandy matrix with a strong calcium carbonate cement. The stratification is very crude and bedding attitudes when visible suggest original dips of two to five degrees. From the south end of Rattlesnake Ridge to the vicinity of Lechugilla Hills this narrow marginal belt is much finer grained for it consists principally of disintegrated Johnny Lyon granodiorite swept from The Mesa.

The main body of alluvium underlying Allen's Flat and Tres Alamos Wash is much more heterogeneous in the rock types represented. Abundant cobbles and boulders of volcanics, varying from basalt to rhyolite, subrounded to rounded, and up to two feet in diameter have been transported from the area north of Kelsey Canyon and from the Winchester Mountains. Coarse slabs of the foliated metamorphic rocks of the Pinal schist including metagraywackes, metarhyolites and greenstones have been carried down from the western slopes of the Little Dragoon Mountains. Granitic rock types from both recognized and unrecognized terranes are less commonly encountered. All of the familiar Paleozoic and younger pre-Cambrian types are present. Sandy and silty interbeds are flat-lying and indicate that there has been no significant tilting of these sediments.

To the south and southwest of the Johnny Lyon Hills these conglomerates grade laterally into fine-grained, unconsolidated pink and buff sands, silts, and clays of lacustrine origin. Pebble conglomerates are commonly intercalated in these moderate to well-bedded deposits. Scattered crystals of gypsum and horizons of white calcareous nodules are less common. The lake beds are not conspicuous in outcrop because the beds are mantled with a veneer of lag gravels which give the slopes a false conglomeratic appearance. The topographic expression is more subdued and rounded than is characteristic of the steep walled arroyos and ridges of the better indurated conglomerates.

The edge of the western belt of alluvium is characterized by partly stripped old gravels with a predominance of coarse fragments and gruss derived from the Johnny Lyon granodiorite. These are generally stained red-brown, although locally the boulders take on a gray-greenish cast. West of Sheep Camp Ridge, boulders up to six feet in diameter are not uncommon. Subordinate quantities of Pinal schist, Paleozoic, and Mesozoic sedimentary rocks and lamprophyre dike rocks are also present in the conglomerates. A calcareous cement provides moderate induration but continuing disintegration of the prevalent granodiorite prevents this alluvium from being as resistant to erosion as the fanglomerates and conglomerates in Tres Alamos Wash. It is difficult in some places to draw a sharp line between the transported but re-consolidated gruss at the alluvial edge and the deeply decayed granite of the present surface.

The present channels and flood plains of Tres Alamos Wash and Kelsey Canyon as well as their major tributaries contain unconsolidated sands, silts, and gravels, which are in part derived by reworking of the older alluvium and in part by the continued degradation of the older rocks. They are apparently surficial and do not represent any appreciable quantity of the total alluvium.

The surface on which the older alluvium was accumulated varies from one of considerable dissection and relief on the east and south sides of the Johnny Lyon Hills, to a surface of very low relief and little dissection on the San Pedro River slope. In the latter area, the inner alluvial edge apparently consists of older pediment gravels developed in an earlier geomorphic interval.

Renewed dissection and stripping is the rule both in the direct drainage to the San Pedro River and in the drainage of its major local tributary, Tres Alamos Wash. This has produced numerous isolated caps of older alluvium resting on ridges and slopes high in the Johnny Lyon Hills and on the bedrock surfaces surrounding them. It is clear that the local lateral extent and depth of alluvium was once much greater than it is at present.

No accurate figure can be given for the maximum thicknesses of alluvium presently surrounding the Johnny Lyon Hills. At least two wells in Tres Alamos Wash are reported to have been drilled over 400 feet, without encountering bedrock. Local relief and geologic relations clearly indicate widespread thicknesses of 150 to 250 feet in Allen's Flat and Tres Alamos Wash. Dissection in the immediate vicinity of the San Pedro River has revealed cliffs of conglomerates and sand several hundred feet high, and wells up to 1,500 feet deep have been drilled entirely in alluvium. Within the map area the probable thickness of alluvium on the San Pedro Valley slope probably never exceeds 50 feet and is generally much less.

Kirk Bryan (unpublished report, U. S. Geological Survey) has applied the name Gila conglomerate to the older conglomerates and lake beds which fill the San Pedro River valley and its major tributaries. He found general geologic relationships in these sedimentary rocks similar to those in the type locality on the Gila River where G. K. Gilbert (1875) first proposed the formation name. Discovery of vertebrate fossils by Bryan at two sites in the San Pedro River valley enabled Gidley (1923, 1926) to place the upper part of the alluvial deposits at the respective localities in the middle or upper Pliocene. One of the sites is two miles south of Benson and only 10 miles from the southern edge of the Johnny Lyon Hills map area. The geologic environment, in a lateral transition zone between lacustrine deposits and fanglomerates, is very similar to the sedimentary relations immediately south of the Johnny Lyon Hills.

Knechtel (1937) has described the Gila conglomerate in the Gila River valley and San Simon basin, and fossils which he found there were called quivalent to, or possibly slightly younger than the fossils of the Benson collecting site. On this basis, the correlation of the San Pedro River deposits with the Gila conglomerate seems permissible. Unfortunately, the lithology of the valley fill is so variable locally in its aspects and the time interval represented is so uncertain that it is considered premature to assign specific formational status to various parts of the late Tertiary(?) and Quaternary alluvial deposits in the Johnny Lyon Hills.

STRUCTURE OF THE JOHNNY LYON HILLS AREA

General

The structure of the Johnny Lyon Hills is susceptible of a two-fold historical subdivision; (1) the older pre-Apache group structural features, and (2) the younger post-Apache group structures. Spatially, of course, these structures are not separable and it is necessary in any discussion of the structure that this fact be kept constantly in mind.

The earliest and most important group of the older pre-Cambrian structural features was developed during the Mazatzal Revolution and gave the Pinal schist its strong northeast-trending steep-dipping structural orientation. This episode was followed by the post-kinematic emplacement of the Johnny Lyon pluton whose structural character was influenced in part by the pre-existing grain of the country rock. The last of the older pre-Cambrian structures to develop was the suite of north-northeast to north-trending shear zones which are found principally within the granodiorite, but which also offset the schist-granodiorite contact. The relations evolved in these three structural episodes have been discussed in the earlier sections describing the implicated rocks and they will be referred to in the following sections only as they are involved with the younger structures.

The post-Apache group structures cannot be subdivided quite so simply. Major thrust faults and associated structures can be demonstrated to be at least as young as post-Pennsylvanian, in most cases, and near the American mine they are post-Lower Cretaceous. The exposures of Mesozoic formations are too limited to permit the dating of any post-Paleozoic and pre-Cretaceous structures which may be present. All of the thrust structures are correlated therefore with the Laramide orogeny. Subsequent faulting probably occurred intermittently through Tertiary and Pleistocene time in this region. The dearth of paleontologic evidence for the age of the Mesozoic and Cenozoic rocks of the region makes it impossible to establish anything but a sequential chronology, with little known of the absolute age of the various episodes.

The following discussion will be organized primarily on a geographical basis, and secondarily on the types of structures in each area. The faulted and folded area between Tres Alamos Wash and Sheep Camp Ridge and Keith Peak constitute one geographical unit. West and southwest of Keith Peak are the structures in the vicinity of the Catclaw Hills. The great tilted and faulted rib of sedimentary rocks extending northwest from Lechugilla Hill to Kelsey Peak is another unit. The Cretaceous(?) and younger rocks of Kelsey Canyon may be grouped together. The great thrust slices in the vicinity of the American mine, in the northwest corner of the map area, form an independent geographical unit.

Within each of these areas, the structural descriptions will be discussed on the basis of low angle faults (dip less than 40°), high angle faults (dip greater than 40°), and folds.

Structures from Tres Alamos Wash to Keith Peak

Low angle faults

Major low angle faults characterize this entire area, for the Paleozoic rocks form an overlapping series of continuous and discontinuous plates, stacked up to three or four deep on the underlying Pinal schist. At the northeast end of the zone, Javelina Hill is composed of one of these stacks. Additional stacking is partially revealed by stripping of the alluvium between Javelina Hill and Keith Peak. The southeast side of Keith Peak also displays some of this overlapping arrangement.

The highest thrust fault on Javelina Hill underlies the breccia-plate of Escabrosa and Black Prince formations. This plate (structure sections D-D', E-E', G-G') overrides rocks ranging from the Pinal schist to the Horquilla formation. Its brecciated character distinguishes it from all other plates.

A classic klippe of breccia resting on Pinal schist forms an isolated topographic knob off the northeast corner of the main part of the breccia plate (figs. 58-60). A continuous trace outlines a block about one mile long north-south, and a half-mile wide, east-west. The trace may be followed discontinuously for another half mile southward on the southwest side of Javelina Hill because of deep dissection of the overlying alluvium. The fault surface has a general dip to the south but is sufficiently undulating to give local dips in all quadrants (see figs. 58, 60, 61). One of the most surprising characteristics of this fault is the very thin sheared zone between the breccia and the schist. It is always less than one foot

Figure 58. Javelina Hill seen from a distance of about one mile to the northwest. The basal limestone breccia of the thrust plate which caps the hill forms the nearly vertical cliffs circling the brow of the hill. The undulating character of the sole fault is evident in this photograph. Pinal schist is the underlying formation.

Figure 59. The klippe and northeast corner of the thrust plate on Javelina Hill in which Escabrosa limestone breccia rests on Pinal schist. View from the northwest.

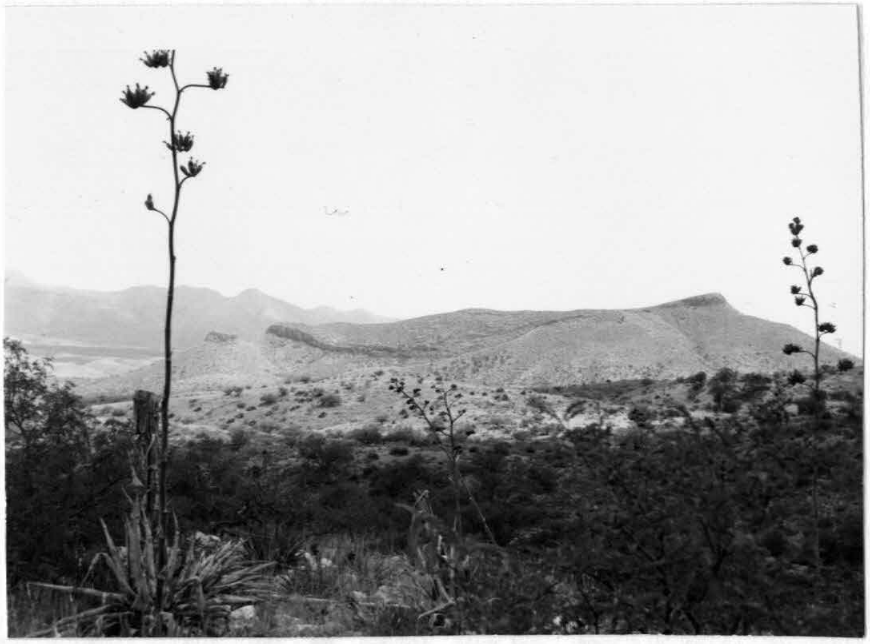


Figure 58

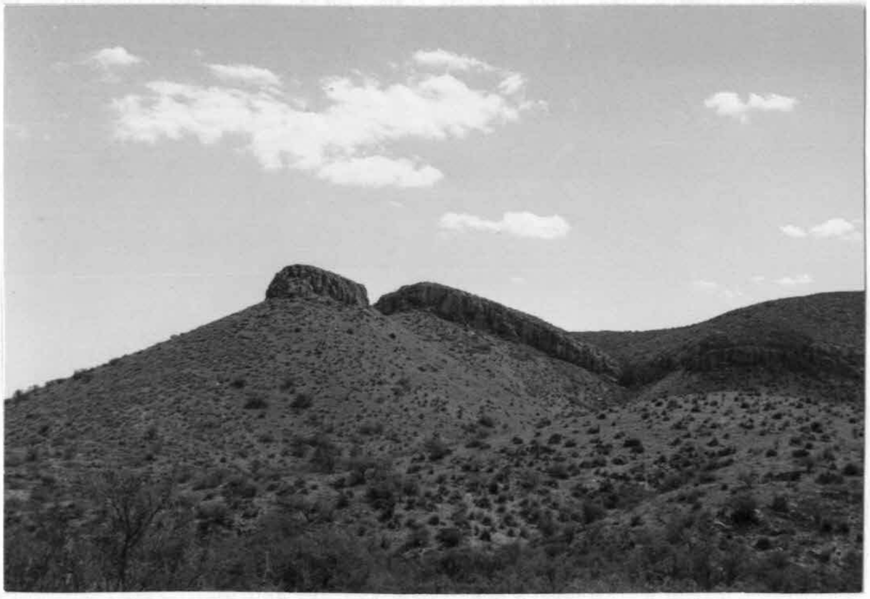


Figure 59

Figure 60. Javelina Hill seen from Tres Alamos Wash to the northeast. In this view, the Escabrosa breccia plate lies not only on Pinal schist but on underlying slices and plates ranging from Abrigo formation to Horquilla formation.

Figure 61. Javelina Hill viewed from the west. In this view the cliffs of the breccia plate are in Black Prince formation high on the left, and in Escabrosa formation on the right. The sole fault is exposed at the base of the cliffs at a number of points in the photograph. Pinal schist is the underlying formation except for a thin plate of Apache group and Cambrian formations at the right.

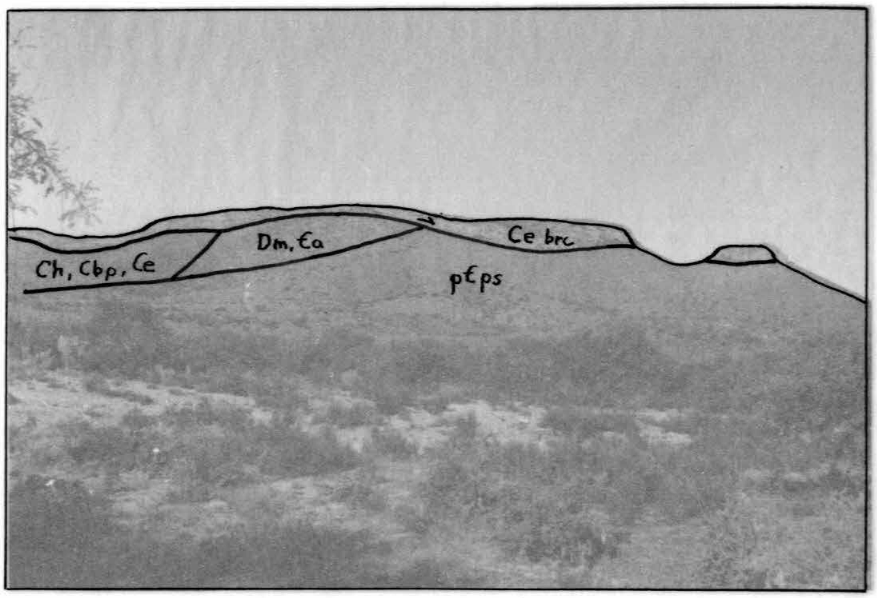


Figure 60

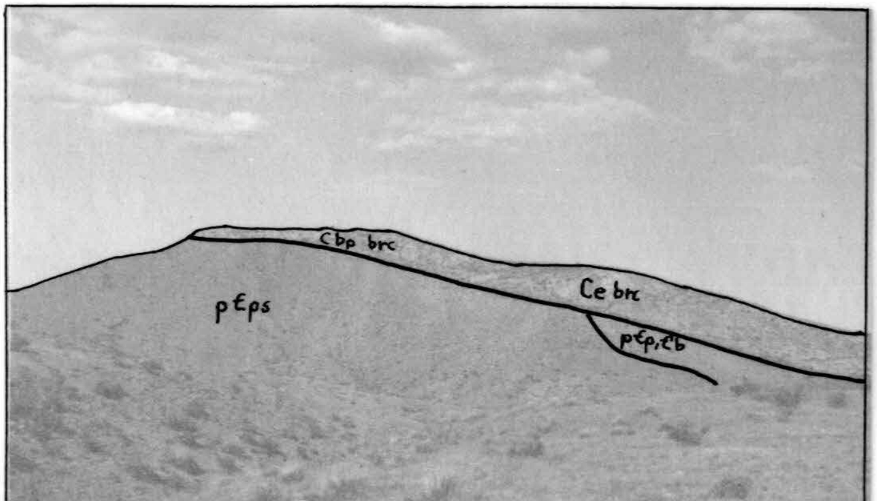


Figure 61

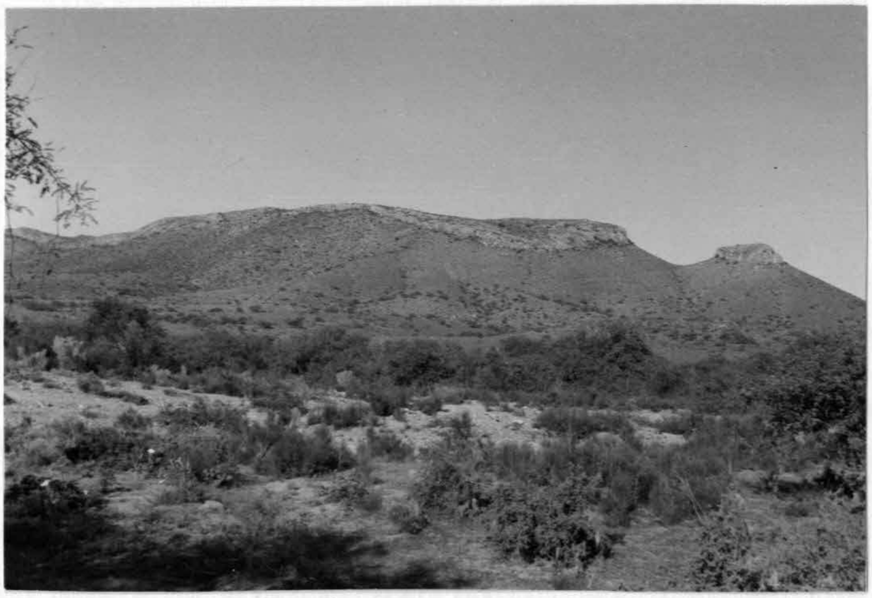


Figure 60

Figure 61

thick, and is composed entirely of schist fragments. The depth of local deformation of the schist is confined to a few feet. Between Javelina Hill and the alluvium of Tres Alamos Wash, several plates are exposed which underly the breccia plate (structure sections F-F', G-G'). The highest of these plates has the greatest exposure, and contains an overturned, synclinal fold of the Horquilla formation with Earp formation beds exposed in the core. Outcrops of a nearly continuous and overturned section of rocks along the west bank of Tres Alamos Wash indicate the fold, and hence the plate, extends a half mile south of the junction of Thompson Wash and Tres Alamos Wash. The sole fault of this plate is exposed for about 1,500 feet and dips 30°-35° SSW. Underlying this large plate is a limited exposure of a section of east dipping Escabrosa to Horquilla strata. This section is bounded on the north by an east-trending fault whose dip cannot be measured directly, but appears to be to the south. Since this fault brings the Carboniferous section against the Pinal schist, this fault is interpreted as a thrust. A steep fault of comparable displacement would be expected to have introduced major offsets in the older pre-Cambrian rocks west of Javelina Hill. Such offsets do not exist. A triangular block of Martin and upper Abrigo formations crops out between this fault, the breccia plate and the Pinal schist, and it is probably in slice relation to the overlying faults (see fig. 60).

On the west side of Javelina Hill, the Thompson Wash drainage has been superimposed and incised on a wedge of Apache group and Cambrian rocks within a plate resting on the Pinal schist. The beds dip southeast and east. The formational sequence within the plate is a nearly normal one for a depositional relation to the schist and no stratigraphic displacement is indicated. However, a major shear zone at the base, the absence of the Scanlan conglomerate, great reductions in the thickness of each of the stratigraphic units and pervasive fracturing and brecciation belie the apparently normal stratigraphic relation and indicate that this is also a fault plate.

The Javelina Hill breccia plate is well exposed as it crosses Thompson Wash, resting on lower Abrigo limestones and shale of the lower plate. On the low ridge west of the wash, a plate of Horquilla strata intervenes.

In the general topographic depression between Javelina Hill and Keith Peak, the exposures are limited to windows stripped clear in the overlying alluvium. The relations are interpreted in plate I, and in section E-E'. The available exposures indicate that the lowest slices and plates are derived from the Apache group and lower Paleozoic beds; that an intervening plate is principally Horquilla formation; and that the overlying plate is again the breccia plate. On the east side of Keith Peak two major low angle faults are exposed (see section E-E'). The higher fault underlies a thin irregular plate of rocks from the Escabrosa, Black Prince and Horquilla formations. This fault is an irregular surface varying in dip from 36° E. to nearly horizontal. The beds strike N. 40° W. in this plate. They steepen in dip from 40° E. to the vertical and finally are overturned at 75° W. At the southern end of the exposures of the plate, dissection of the alluvium has revealed an overlying Escabrosa breccia mass thrust upon it. Underneath this plate are highly deformed beds of the main mass of Keith Peak, ranging from the upper Abrigo formation to the Horquilla formation.

The lowest fault on the east side of Keith Peak is a thrust which underlies all of Keith Peak and Sheep Camp Ridge (structure sections D-D', E-E', H-H', J-J', K-K', L-L', M-M', N-N'). Its trace can be followed almost continuously from the alluvium in the NE$\frac{1}{4}$, sec. 21, T. 15 S., R. 21 E., northwestward two and a half miles around the north end of Sheep Camp Ridge (figs. 62-63). Above the thrust are rocks ranging from Pinal schist and granodiorite to Horquilla formation. This plate rests on the Pinal schist under Keith Peak and on granodiorite under Sheep Camp Ridge. The sole dips southwestward at angles ranging from five to twenty degrees along most of the trace. At the northwestern extremity of Sheep Camp Ridge, the sole attitude reverses and dips 26° E. The trace is marked by a continuous zone of slices and blocks from every formation in the plate, with sheared Bolsa quartzite commonly forming prominent resistant slices up to 1,000 feet in outcrop length.

About one and a half miles south-southeast of Keith Peak in the SW$\frac{1}{4}$, sec. 28, T. 15 S., R. 21 E., a limited exposure shows a low angle fault in which Escabrosa limestones and older rocks are thrust upon the Bolsa quartzites. The strike of the fault appears to swing from south to east within 500 feet of exposed length.

An attempt at correlation of the low-angle faults which appear on the east side of Keith Peak and Sheep Camp Ridge with those farther to the east is shown in figure 64. The persistent relation of a lowest plate containing Apache group and Cambrian formations, an intermediate block containing Carboniferous strata, and an overlying plate

Figure 62. Sheep Camp Ridge viewed from the east. The trace of the basal thrust fault underlies the low knobs (Bolsa quartzite slices) at the base of the ridge on the left and gradually rises as it trends northward (to the right.) At the right end of the ridge as viewed the trace is halfway up the slope of the ridge, with nearly vertical Escabrosa limestone resting on Johnny Lyon granodiorite.

Figure 63. The north end of Sheep Camp Ridge viewed from the northwest. The vertical beds on the right are Bolsa quartzite, the saddle is in the Abrigo shales and the section on the left includes upper Abrigo, Martin and Escabrosa strata. Johnny Lyon granodiorite is the underlying rock. A conspicuous slice of Bolsa quartzite under the shales of the Abrigo formation indicates the position of the thrust fault.

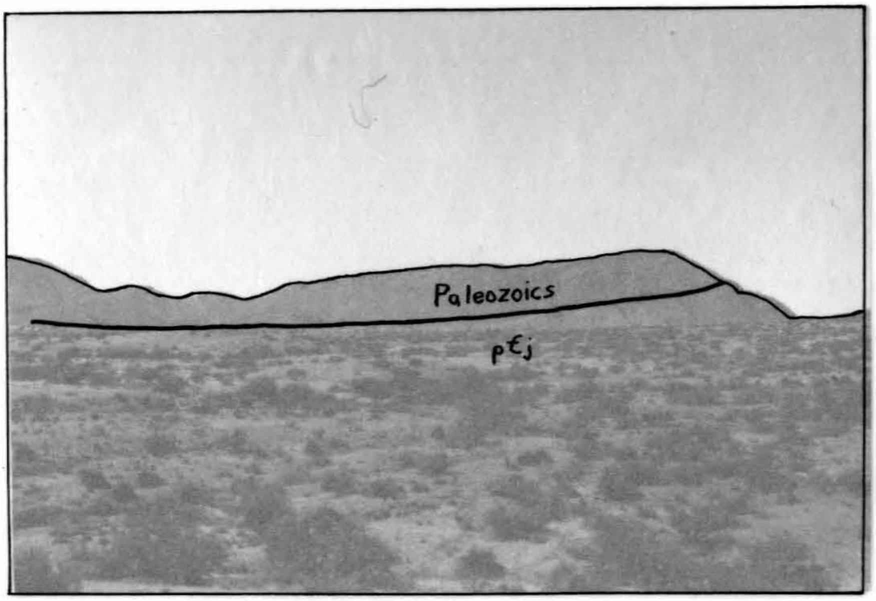


Figure 62

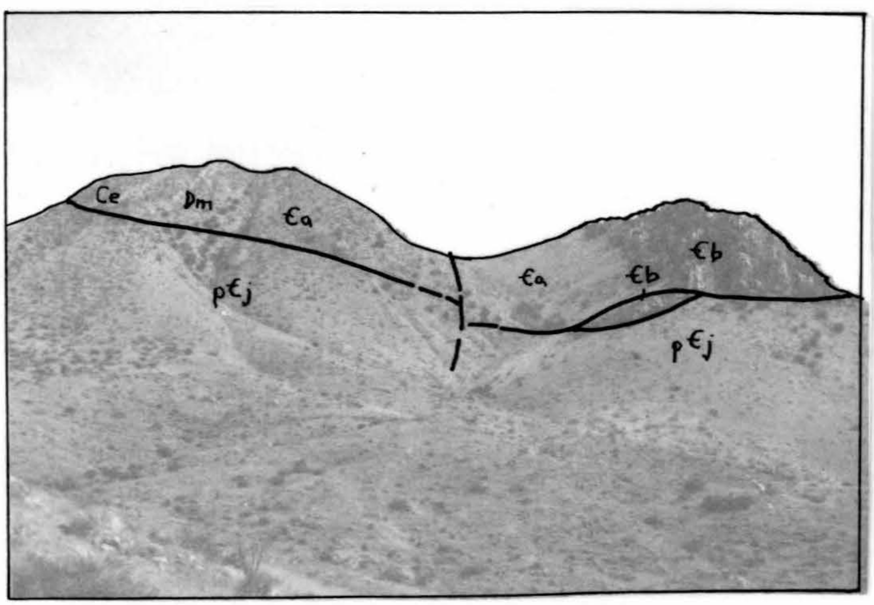


Figure 63

Figure 62

Figure 63

of Escabrosa-Black Prince limestone breccia is the basis for the correlation. The correlations do not necessarily imply that each group of faults underlies a continuous plate at present, for this clearly is not the general case. The spatial sequence is more significant in suggesting possible contemporaneity of plate development during thrusting.

High angle faults

A great number of high angle faults of both small and large displacements occur entirely within the various thrust plates. Only a few important steep faults offset the plates. The former type may represent structures older than the associated thrust which have been truncated by the limiting thrust faults, or they may represent faults developed within the thrust plates after thrusting was initiated.

Many of the small faults on Keith Peak, on the east side of Sheep Camp Ridge and in the plates underlying Javelina Hill appear to be local tear faults by which the interiors of the plates have adjusted to local differential resistance along the thrust planes.

On the northeast side of Keith Peak are a number of north-trending faults dipping steeply to the east with both normal and reverse apparent movements. These faults terminate abruptly against the thrust surface on the north. To the south most of them terminate against an unusual east-west hinge fault which in turn is truncated by a large north-south steep fault.

The aforementioned hinge fault dips south at 70°-75° and has a maximum stratigraphic displacement of about 300 feet at its eastern end. Horquilla formation is downdropped against Escabrosa

Figure 64. Sketch map showing possible correlations among the thrust plates of Keith Peak and Sheep Camp Ridge and the area to the east. These correlations are based on the formational composition of the plates and do not indicate present continuity.

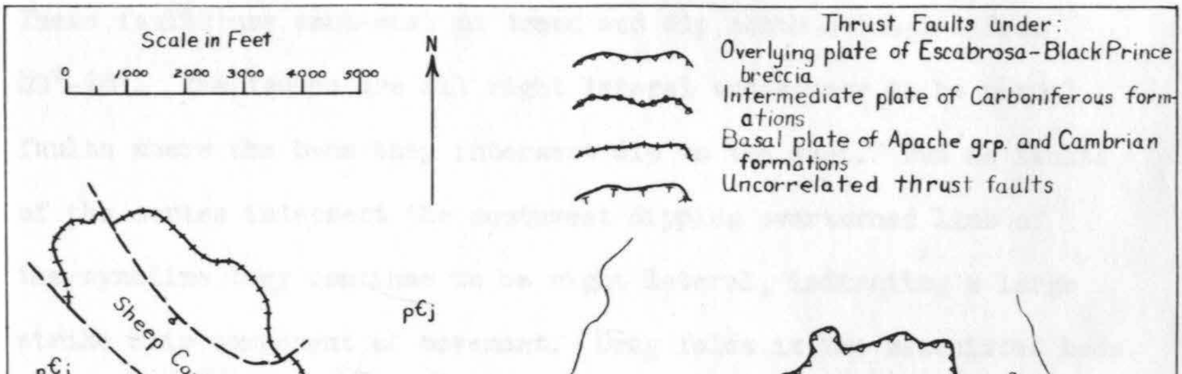

Scale in Feet
0 1000 2000 3000 4000 5000
N
Thrust Faults under:
Overlying plate of Escabrosa-Black Prince breccia
Intermediate plate of Carboniferous formations
Basal plate of Apache grp and Cambrian formations
Uncorrelated thrust faults
Sheep Camp Ridge
p€j
p€j
p€j
p€j
p€ps
p€ps
p€ps
Javelina Hill
Keith Peak

Figure 64

limestone in a normal sense. As the fault is followed westward toward the crest of Keith Peak the stratigraphic displacement decreases rapidly and the fault appears to die out shortly before reaching the top.

An interesting series of fairly steep faults is found within the Horquilla-Earp plate on the southeast side of Javelina Hill. These faults are east-west in trend and dip south at angles from 40°-70°. The faults are all right lateral and appear to be normal faults where the beds they intersect dip to the east. But as faults of the series intersect the southwest dipping overturned limb of the syncline they continue to be right lateral, indicating a large strike slip component of movement. Drag folds in the associated beds with axes generally plunging steeply to the east also indicate lateral movement on these faults.

Major high angle faults which offset the thrust faults are uncommon. However, a N. 30° W.-trending normal fault whose trace can be followed for about three miles, offsets the great plate which composes Keith Peak, and then bounds the southwest side of the Sheep Camp Ridge block (sec. D-D', E-E', fig. 65). This fault dips 50°-60° E. and has an apparent stratigraphic displacment of more than 800 feet on the northwest side of Keith Peak. However, local thinning of the formations prior to this faulting has exaggerated the minimum displacement which is actually about 500 feet including drag offsets.

On the northwest crest of Keith Peak (fig. 66), the fault develops subsidiary branches which can be followed until they enter the underlying schist where they are not conspicuous. The fault which

Figure 65. The west side of Sheep Camp Ridge with Bolsa quartzite on the skyline. A major normal fault which offsets the thrust fault under the ridge is only partly exposed under talus high on the slope. Johnny Lyon granodiorite is exposed west of the fault.

Figure 66. The north side of Keith Peak with the M. M. Keith ranch house visible in the valley. The trace of the major east-dipping normal fault crosses the slope obliquely from upper right to lower left. The thrust fault trace separating the Pinal schist from the granodiorite appears near the floor of the valley on the left and swings around the ranch house in a ninety degree are to pass out of view in the right foreground.

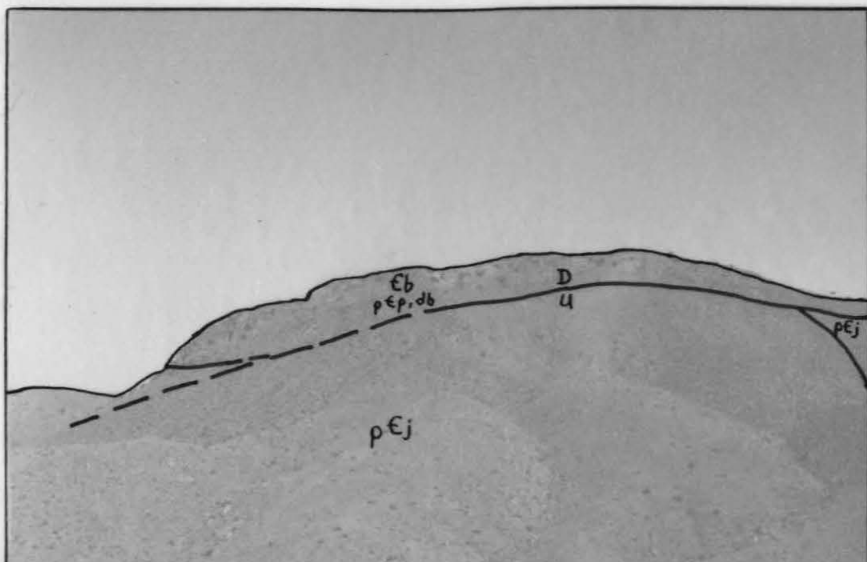


Figure 65

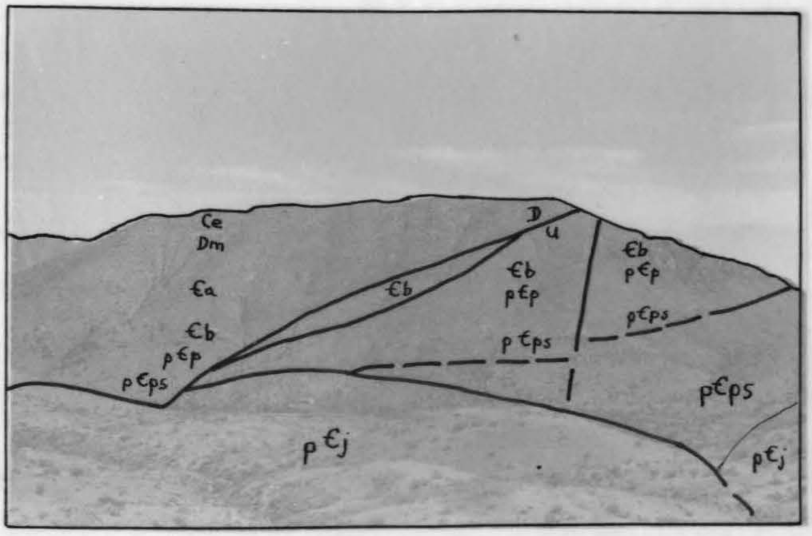


Figure 66

Figure 65

Figure 66

has a number of fairly large horses in its zone, can be followed readily on Keith Peak as long as it is oblique to the bedding. On the south side of Keith Peak, however, it becomes first a strike fault and then close to a bedding plane fault in the Abrigo formation. As a result its stratigraphic displacement almost disappears and it is difficult to follow until it passes obliquely into the Martin formation just before disappearing under the alluvium. At the opposite end of its trace, northwest of Sheep Camp Ridge, the fault separates granodiorite in the plate from underlying granodiorite, and is almost completely concealed by talus from Sheep Camp Ridge. When the fault trace passes entirely into the underlying granodiorite, it cannot be distinguished.

A smaller northwest-trending steep fault of reverse movement offsets the trace of the thrust under the northern end of Sheep Camp Ridge. The actual fault zone, which is nearly bedding plane in the Abrigo formation, is difficult to follow in the upper plate. The offset is about 200 feet but is largely concealed by talus.

In Thompson Wash, southwest of Javelina Hill, the Pioneer-Bolsa quartzite contact is marked by a conspicuous basal conglomerate in the Bolsa. The conglomerate is offset 10 to 40 feet by small normal faults trending N. 30° W. and dipping steeply east. These appear to be younger than the thrust at the base.

Folds

Within some of the larger thrust plates, dislocated portions of large folds can be recognized. Although it cannot be demonstrated for all the plates, the undulation of some of the best exposed fault surfaces appears to reflect the original irregularities of the surface and not subsequent folding. The internal fold structures therefore have not been developed post-thrusting. One conspicuous exception however is a group of drag effects associated with the large post-thrusting normal fault on the west side of Sheep Camp Ridge and Keith Peak. These effects include local reversals in the attitudes of major thrust faults.

Keith Peak represents one of the most prominent fold structures. Topographically the crown of the peak consists of three ridges trending northeast, east and south-southeast from the very top. All three ridges are maintained by the massive lower beds of the Escabrosa limestone. On the northeast ridge the underlying beds strike northeast to east and dip about 30° S. As the beds pass under the top of the peak, they swing to a northerly strike and dip 25° E. Passing into the south-southeast ridge they change to a northwest strike dipping northeastward at increasingly steep angles until they become steeply overturned just before disappearing under the alluvium of Tres Alamos Wash.

The general form of the Keith Peak fold is synclinal, open, and plunging to the east-southeast. The hinge fault between the northeast and east ridges is responsible for some complications in the cores of the fold. Whether the overturning of the beds south of Keith Peak is related to the same fold incident as the main mass of the hill is not clear.

Southeast of Javelina Hill a major fold has been developed in a plate containing exposed beds of upper Paleozoic formations (sec. G-G'). A north-striking limb of beds of the Horquilla formation is exposed between Javelina Hill and Tres Alamos Wash. This limb dips east and steepens as it is followed southward until the beds overturn and form a southeast-striking inverted limb which dips about 45° SW. In the core of the fold are tightly folded shales and thin limestones of the lower Earp formation. These subordinate folds have inclined axial planes (striking S. 85° E., dipping 45° S.), axial plane cleavage (fig. 67) and axes plunging southeast at about 30°. The southwest dipping overturned limb includes a section of about 2,500 feet of beds ranging from the Earp formation down to the upper Martin(?) formation. Right lateral faults with large strike slip components of movement offset the core of the fold, displacing the overturned limb somewhat westward of its original position.

Some of the large plates have relatively undisturbed sections and show simpler changes in attitude which may reflect earlier participation in large folds, or which may represent distortion during thrusting. For example, the Sheep Camp Ridge section is essentially homoclinal, but the dip of the Bolsa quartzite steepens from an average of 40° NE. at the southeast end of the ridge to about 80° NE. at the northwest end. The attitude of the beds also tends to steepen from southwest to northeast in any transverse section (K-K', for example) across the ridge. This is probably related to drag effects on the bounding normal fault on the southwest side of the ridge. A somewhat similar change of attitude is found in the thin plate of Escabrosa to Horquilla beds on the east side of Keith Peak, but there is no younger fault to which to relate the effect.

Figure 67. Siltstone and limestone outcrops in the Earp formation in the core of the overturned syncline on the southeast side of Javelina Hill, displaying a cleavage which is axial plane to the folding in orientation.

Figure 67

Miscellaneous structural features

A number of interesting structural features do not fall into the previous categories. The lithology of the cataclastic breccia plate on Javelina Hill has already been described (pp. 240-241). A striking joint pattern is exposed along the margins of the plate and in the klippe, where erosion has stripped the overlying less brecciated portions. The joint pattern is grossly expressed in the vertical jointing in the massive cliffs of the northern edge of the plate (fig. 68) and the klippe (fig. 69 and see also fig. 59). On the upper surfaces of the plate, solution by meteoric waters has etched out the incipient joint pattern and shown it to be very pervasive (fig. 70). The joints are incipient in the sense that most of them show no visible separation between opposite walls, but only a greater tendency for solution. However, when coarse blocks do develop, their bounding surfaces parallel the incipient joint set. It is possible to map this joint pattern continuously around the margins of the plate and the distribution of joint attitudes is shown in figure 71. The average attitude of the joints is approximately due north and about vertical. The joints are best developed in the finest breccia; indeed they do not cut most of the coarser fragments in the breccia. Sometimes the joints show a flow divergence and convergence about the large pieces. When a joint is found to be developed in a fragment it does not offset the contacts or internal structures; nor do the joints show any offset of the planar aggregates or chert breccia which they traverse. The fine-grained portion of the limestone breccia is now as dense as any of the fragments, with a bonding strength apparently

Figure 68. Vertical jointing in the cliff of Escabrosa limestone breccia at the base of the thrust plate at the northeast corner of Javelina Hill. The cliffs are approximately 60 feet high at this point.

Figure 69. Vertical jointing on the south side of the klippe of limestone breccia near the northeast corner of Javelina Hill. The smooth lower slope is developed on exposed Pinal schist.

Figure 68

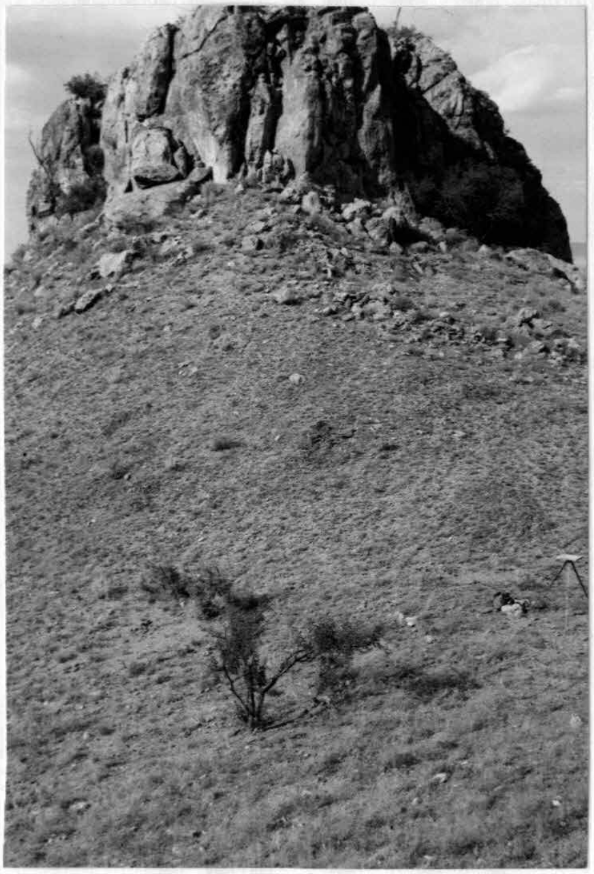


Figure 69

Figure 70. A horizontal surface at the top of the klippe of limestone breccia (see figure 69) showing the pervasive pattern of joints etched out by groundwater solution.

Figure 70

Figure 71. A map of the joint pattern visible on the margins of the limestone breccia plate on Javelina Hill in sec. 15, T. 15 S., R. 21 E. The mapped distribution of the basal shale of the Black Prince formation in the plate is also shown.

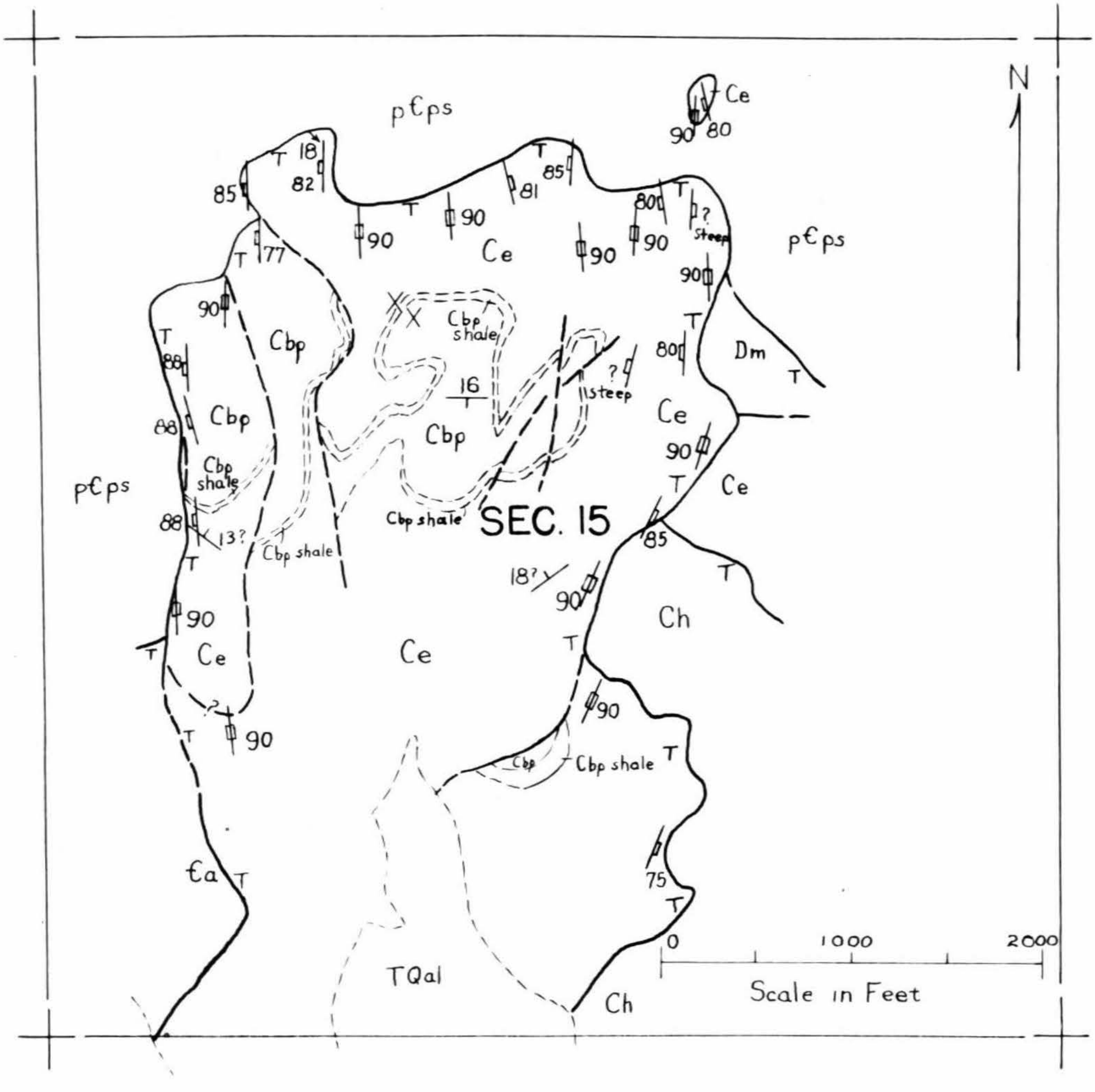

N
p€ps
Ce
90
80
18
82
85
T
81
90
77
Ce
Cbp
Cbp shale
16
Cbp
steep
Dm
80
Ce
Cbp
Cbp shale
p€ps
88
13?
Cbp shale
SEC. 15
85
18?
Ch
Ce
Ce
€a
75
TQal
Ch
0
1000
2000
Scale in Feet

Figure 71

as great as the internal strength of the individual clasts. Hand specimens are broken out with difficulty, and the fracture surfaces truncate carbonate and chert fragments alike. It is unlikely therefore, that the joints have developed since cessation of plastic movement or the joints would be as common in the coarse fragments as in the comminuted material. But if the joints were formed as shear phenomena at a time of plastic movement then they must be incipient and must record the very closing episode, otherwise displacements of the chert breccia strings where the joints intersect them would be common.

Another interesting structural phenomenon is the member by member attenuation of the various formations in some of the plates. On the north side of Keith Peak where every formation is represented from the Apache group to the lower part of the Escabrosa limestone, a section normally more than 1,900 feet thick has been reduced to about 750 feet. The greatest thinning occurred in the Abrigo formation, but even the massive Bolsa quartzite has lost nearly half its thickness. Both flowage and non-componental shearing along numerous surfaces nearly parallel to the bedding appear to have been the reducing mechanisms. The thinning on the north slope is in contrast to the normal thickness of the sections exposed on the southwest flank of the peak.

A similar example of tectonic thinning is nicely exposed in the narrow gap cut by Thompson Wash in the plate of Apache group and Cambrian rocks which it crosses. The Pioneer shale, the Bolsa quartzite and part of the Abrigo formation all have lost more than half of their original thickness.

Structures West of Keith Peak and Sheep Camp Ridge

Low angle faults

The great thrust dipping southwest under Sheep Camp Ridge and Keith Peak is offset by a younger, normal N. 30° W. fault which raised the western block some 500 feet higher than the eastern block. As a result the thrust fault trace reappears west of Sheep Camp Ridge. The thrust passing west under the ridge has been cutting down the section so that both Pinal schist and granodiorite appear in the western flank of the Sheep Camp Ridge plate, but <u>east</u> of the normal fault. As a result, it is to be expected that the exposures of the same thrust <u>west</u> of the normal fault will probably be between schist and granodiorite or wholly within one of these two types of rock.

The granodiorite-schist contact west of the normal fault appears about 300 yards east of the M. M. Keith ranch house, a few feet south and above the ravine floor (fig. 66). The contact can be traced for nearly three-quarters of a mile in a crude semicircle west and northwest. Along its entire length it possesses a marked zone of shear and cataclasis. The crushing is shared both by the granite and schist which lose their older textures. There is no evidence of contact metamorphism until the zone approaches an intersection with a normal intrusive contact in the schist, more than a quarter of a mile west of the ranch house. The shear zone passes northwest into the granodiorite (fig. 72) where fortunately it can be followed continuously for another quarter of a mile. The fault contact dips southwestward at angles of 25°-30° except in the vicinity of the intersection with the

Figure 72. Sheared Johnny Lyon granodiorite in the thrust fault zone more than a quarter of a mile northwest of the Keith ranch house.

Figure 72

normal fault where it is dragged around to the south or southeast.

As the fault zone extends into the granodiorite its strongly sheared character is weakened as it approaches the junction of Gold Mine Ridge and Sheep Camp Ridge. The exact trace of the zone is not known in this area; the trace shown on plate I was drawn through a number of possibly related sheared granodiorite exposures, which fall on a reasonable projection of the fault attitude on the topography.

On the north side of Gold Mine Ridge are a number of features which probably mark the same zone. These features include a number of conspicuous flat plates of breccia derived from various Paleozoic formations and resting on or in the granodiorite. The highest of these breccia plates is truncated by the normal fault on Sheep Camp Ridge. Its exposure is about fifty feet wide and more than 150 feet long. It is composed of coarse angular breccia fragments of altered dolomite from the Abrigo and Martin formations (fig. 73). It appears to be a slice within the granodiorite and a conspicuous shear zone trends west downslope in the igneous rock from the mass of breccia. A number of additional masses of breccia ranging from Bolsa quartzite to Escabrosa limestones appear in a curving line for a half mile west of the first mass. Some of them rest on the granodiorite; others are within the granodiorite (fig. 74) and at least one is transected by a lamprophyre dike. Along this line at a number of points the granodiorite is sheared, and on the projection of the zone still farther west there is an impressive 50 to 100 feet thick, south dipping shear zone which can be followed for more than two thousand feet on the north side of Gold Mine Ridge before talus conceals it.

Figure 73. Altered dolomite and limestone breccia derived from the Abrigo and Martin formations in a large slice within the granodiorite on the southwest slope of Sheep Camp Ridge. The ocotillo stalks in the upper right are about one inch in diameter and may be used for scale.

Figure 74. The contact between a large limestone-dolomite breccia mass and the enclosing granodiorite on the southwest slope of Sheep Camp Ridge. The geology pick marks the contact between the breccia on the right and sheared and weathered granodiorite (light colored patches) on the left.

Figure 73

Figure 74

There is little doubt that this is also part of the thrust which underlies Sheep Camp Ridge, and that the various masses of breccia now wholly in the Johnny Lyon granodiorite were slices torn from the forward part of the upper plate. The granodiorite exposures in the vicinity of the Keith ranch house are part of a fenster which is completely surrounded by the thrust plate.

Another low angle fault, of indeterminate displacement, appears at a number of points along the foot of the Apache group section on the west side of Keith Peak. It dips eastward and cannot be followed readily in the schist. At a number of points it slices out the Scanlan conglomerate and the lower part of the Pioneer shale. Several high angle faults terminate against this thrust.

A prospecting tunnel has been driven through this low angle fault. Located in the SW$\frac{1}{4}$, sec. 20, T. 15 S., R. 21 E., the tunnel entered the Pinal schist about 150 feet west and 50 feet west below the surface exposure of the fault on a bearing of N. 72° E. At 230 feet it encountered a ten foot thick shear zone in the schist above which lies Pioneer shale on a fault surface striking N. 1° W. and dipping 29° E. The Scanlan conglomerate and the basal quartzite of the Pioneer formation are missing.

This east-dipping fault shows no important apparent displacement of the pre-Cambrian rhyolite porphyry zone and is considered to be subordinate and perhaps conjugate to the principal west-dipping thrust fault under Keith Peak.

In the Catclaw Hills the traces of a pair of low angle major faults with opposite dips approach within 200 yards of each other

(NE$\frac{1}{4}$, sec. 30, T. 15 S., R. 21 E.). Both faults have general northwest-southeast trends and are quite sinuous in pattern. These two faults are the boundaries of block IV in the Pinal schist as designated in figure 27. The faults are entirely in the Pinal schist and Johnny Lyon granodiorite and the age of the faulting must be inferred from indirect relationships.

The northeastern fault of the pair is first seen in the schist in windows through the alluvium on the east side of Dry Tank Wash in section 29. It trends west-northwest across the wash, where the schist-granodiorite contact is exposed in the footwall. At this point the fault zone is silicified and an excellent exposure yields a dip of 31° NNE. The silicified zone consists of six inches to one foot of brecciated and recemented white quartz resting on sheared, fissile granodiorite. Coarse slickensiding is oriented parallel to the dip. The fault continues to trend west-northwest for half a mile before swinging to north-northwest. The change in trend is due in part to the topography and in part to a change in attitude. The northwestern part of the fault dips more easterly at angles up to 45 degrees. Several good exposures of the fault surface, usually silicified, display near dip-slip slickensiding. Where the fault passes into the granodiorite beyond the intrusive contact on the hanging wall side, it is difficult to follow for there are several major shear zones in the intrusive which may singly or collectively represent the fault extension. The probable trend shown represents an impressive shear zone on a reasonable projection of the last fault attitude observed.

This fault shows a left lateral displacement of the intrusive contact of more than 4,000 feet, and of the rhyolite porphyry and mica rhyolite sheet zones of about 2,500 feet. The fault has many characteristics of a thrust, with good evidence of dip slip movement. As shown in structure section E-E', this fault may be an exposure of the major thrust which passes under Keith Peak or it may merely intersect it in an indeterminate relation.

The most southwesterly low angle fault can be traced continuously for a distance of more than two miles. It appears in the schist from under the alluvium, about 1,200 feet west of Dry Tank Wash, in the NE$\frac{1}{4}$, sec. 32, T. 15 S., R. 21 E. It then trends about N. 40° W. for a mile and a half, along an irregular path marked by numerous large slices. The dip varies from 25° to 40° to the southwest, averaging about 35°, with dip-slip slickensiding noted at several points. Among the slices in the schist in the SE$\frac{1}{4}$, sec. 30, is a lens of granodiorite about 900 feet long and 50 feet thick. As the fault passes the schist-granodiorite contact in the footwall, it encloses a large slice of schist with a little granodiorite, nearly completely in the igneous rock (section E-E'). This slice is of particular interest because it contains a portion of a rhyolite porphyry sheet.

Upon reaching the crest of one of the Catclaw Hills, the trend of this thrust zone abruptly changes to west-southwest and for about one-half mile is marked by about 300 feet of severely crushed igneous rock (section I-I'). This cataclasite contains a wide variety of crushed textures and is as dense and tough as the undeformed granodiorite. The fault disappears under the alluvium near the edge of the map area in sec. 25, T. 15 S., R. 20 E.

The displacement of the rhyolite porphyry zone by this fault is only a few hundred feet, right lateral, and the mica rhyolite zone shows little displacement if any, in the same direction. The contact appears to have been displaced more than a thousand feet in a right lateral direction but this discrepancy is clearly due to the rather low dip (about 35°S.) of the intrusive contact relative to the steep dip of the rhyolite zones on either side of the fault. None of these apparent displacements is sufficient to account for the size of the large granodiorite slice wholly in schist, or of the schist slice wholly in granodiorite. A much greater displacement is necessary to account for the large slices even with the most favorable configuration of the schist-granodiorite contact. Such a large movement must have been oriented in a direction close to the strike of the rhyolite zones (N. 65° E.) and the intrusive contact to produce the small apparent displacement of these features.

Not only the size of the slices but the reversed relationships of granodiorite and schist as slices in each other implies a special direction of movement. This movement would have to have been close to the strike of the intrusive contact in order to take advantage of whatever irregularities of configuration existed in the contact to provide the schist slice within the granodiorite and at the same time introduce a granodiorite slice completely into the schist. Movement in a direction more normal to the strike of the contact would be much less likely to produce either of the observed relations.

The effects of this fault on the older structures and textures in the Pinal schist through which it passes are greater than faulting effects observed elsewhere in the schist. Generally, there is a right lateral drag of the bedding and foliation in the schist and of the rhyolite porphyry sheets into a position nearly parallel with the fault. Within 25 feet of the fault and within the schist slices, a new fracture cleavage is developed which is essentially parallel to the fault. A number of small folds are developed in the footwall whose axes generally plunge S. 40°-60° W. at 20°-30°, which places them in the class of a lineation features in the Sander coordinate system. In the actual fault zone both cataclasis and recrystallization are evident in varying degrees.

The possible relation of the opposed faults to each other is of interest. One possibility, of course, is that they are parts of an originally continuous fault separated now only by a fortuitous pattern of erosion. Even if an abrupt knick in the attitude of such a fault plane is accepted, this would not account for the discrepancies in the orientation and position of the rhyolite sheet zones as they are projected toward each other from blocks III and V (fig. 27).

A second possibility is that the overlying plates originally were one thrust plate which was imbricated during thrusting, and that block V overrode block III with a slightly different orientation of movement. Such an interpretation would explain the origin of the large schist slice in the granodiorite, and would also explain the presence of the rhyolite porphyry sheet in the slice. This sheet at present lies on the projection of the rhyolite porphyry zone in block III. The surface measurements of the attitudes of these thrust faults do not lend readily to such an interpretation (see sec. E-E'), but then the surface attitudes may not be representative of the general attitude at depth of one or either of these faults.

A third possibility with many alternatives is that these faults are not immediately related to their structural development, except as independent faulting responses to the same general period of compression. The first two possibilities would allow these thrusts to be correlated directly or indirectly with the thrust under Sheep Camp Ridge and Keith Peak and argue for a single major thrust west of these hills. No positive conclusion can be reached because of the inability to follow these fault zones with certainty as they extend into the granodiorite mass.

A number of low angle shear zones appear entirely in the Johnny Lyon granodiorite west and southwest of Sheep Camp Ridge. They are impressive in their development of cataclastic textures in the igneous rock, but there is no stratigraphic basis for estimating the magnitude of faulting which produced these zones. They cannot be followed readily because of the deep weathering of the granodiorite; or because of concealment by younger alluvium and by talus; or because of the common and disconcerting phenomenon of wide shear zones abruptly losing their width and conspicuous shearing effects over a very short distance. By analogy with faults which can be seen to extend into rocks other than the granodiorite, some of these zones undoubtedly represent major faults which additional work might delineate.

A northwest-trending fault zone dipping 35°-40° NE., which can be followed for three-quarters of a mile in the granodiorite in $S\frac{1}{2}$, sec. 19, $N\frac{1}{2}$, sec. 30, west of the Catclaw Hills, is an example. This zone which is five to ten feet of crushed rock, separates a large area of granodiorite with abundant schist inclusions, aplite bodies, and fault structures on the southwest from granodiorite which is essentially free of these features on the northeast. The zone finally disappears under the alluvium at the edge of the map area. The possibility that this fault may be the true extension of the northeast-dipping thrust of the Catclaw Hills must be considered. However, considerable efforts to evaluate this in the field could not establish a sufficient basis to make the correlation.

High angle faults

Few high angle faults are known west of Keith Peak and Sheep Camp Ridge. A few right lateral faults trending north-northwest and nearly vertical offset the granodiorite-schist contact in block IV in the Catclaw Hills. These may be related to the right lateral apparent movement on the thrust under block V.

Within the granodiorite, there are a number of impressive high angle shear zones, which like their low angle counterparts are difficult to evaluate. One of these zones trends north-northwest in secs. 18, 19, T. 15 S., R. 21 E., and is nearly vertical from the pattern of the trace on the topography. The zone is twenty to twenty-five feet wide, is injected by lamprophyre, and is locally silicified and contains irregular masses of limonitic carbonate. To the west of the fault the granodiorite is characterized by abundant similarly oriented ribs of Pinal schist with numerous thin aplite dikes. To the east the granite is free of these features. The west side of the fault is apparently down dropped for the ribs of the schist are probably remnants of roof pendants, and concentration of aplites is characteristic of much of the contact zone of the granodiorite.

West of the Catclaw Hills (in the SE$\frac{1}{4}$, sec. 24, NE$\frac{1}{4}$, sec. 25), two north-northeast-trending, sub-parallel major shear zones which convert the granodiorite to a foliated gneiss can be followed for distances of two thousand feet or more. They dip steeply to the west and at places have been strongly silicified. The more easterly of the pair is truncated on the north by the northeast-dipping low angle (40°) fault mentioned on page 338. Both zones are still well defined as they leave the map area or disappear under the alluvium, to the southwest.

Folds

No important younger fold structures have been recognized in the Gold Mine Ridge-Catclaw Hills area. With the exception of minor folds developed in the schist near the thrust faults, the deformation has been largely by fracturing.

Directions of Movement on the Thrust Faults in the Southern Johnny Lyon Hills

Recognition of the numerous low angle faults in the belt between Lechugilla Hill and the Catclaw Hills gives rise to an additional series of problems, the first of which is the direction of movement on the various faults. A natural initial tendency is to look down dip for the direction from which thrusting came. But the examples of clear-cut reversals of dip are sufficiently numerous to make one wary of such simplifications. Evidence must be considered for each fault, for it is not implicit that what is true for one thrust is true for all the others.

In the Catclaw Hills the two major low angle faults dip in opposite directions. It has already been argued from the evidence of the size of the slices, the spatial distribution of rock types among the slices, and the small apparent offsets of the intrusive contacts and rhyolite zones that the movement of the southwest-dipping fault must have been along a line nearly parallel to the intrusive contact and the rhyolite sheet zones which trend approximately N. 65° E. The following evidence bears on the sense of movement, i.e. whether movement came from the southwest or the northeast. The southwestward dip of the fault zone although fairly consistent throughout the exposed length is in itself not conclusive evidence.

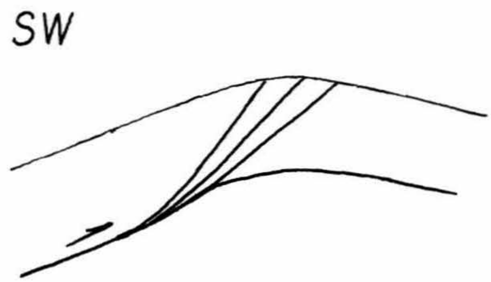
The right lateral drag on many features both above and below the fault indicates that if the movement came from the southwest it was from a bearing more to the south (S. 55° W.?) than S. 65° W., while if it was from the northeast it came from a bearing more to the east (N. 75° E. ?) than N. 65° E. If the movement came from the northeast, this fault zone must have an equivalent fault zone to the northeast from which it has been separated by erosion and/or faulting. The possibility that the other major low angle fault in the Catclaw Hills is the same fault has already been considered (page 337). The distribution of rhyolite porphyry in both upper plates (blocks III and V) and in one of the slices under block V does not favor movement from the northeast. If the Catclaw Hill faults are correlated with the great thrust under Sheep Camp Ridge and Keith Peak as originally a single fault, then a considerable weight of direct evidence for movement from the southwest would pertain to the former faults. The only other possible site of an equivalent fault zone would be a concealed one underneath block III (fig. 27). No independent evidence exists for such a relation.

Movement along the fault from the southwest, of course, would not require any other trace than its known exposure.

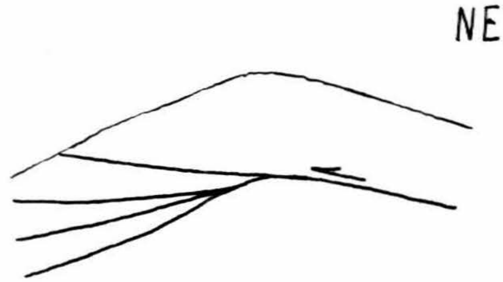
Movement from the northeast along the line indicated also could not supply the large granodiorite slice from that direction as indicated by the position of the intrusive contact in block IV. Movement from the southwest is not favored by an obvious source for the slice either. However, possible changes in the trend of the intrusive contact concealed beneath block V that might provide a source are, at least, not disproven.

The origin of the large schist slice in the granodiorite is more readily explained by assuming movement from the southwest. The intrusive contact in the upper plate, as revealed by the topography and faulting has a low dip to the south. The granite exposed in the upper plate directly above the schist slice is a thin, tabular mass whose shape was determined by the low dips of the overlying intrusive contact and the underlying thrust fault. Fortuitous erosion has stripped much but not all of the overlying schist. The schist slice, itself, cannot have been derived from the nearby schist in the overlying plate because the rhyolite porphyry sheet in the slice is out of position with respect to the rhyolite zone in the plate. The simplest explanation is the possibility already discussed (page 337) in which block V overrode a southwestward extension of block III from the southwest, incorporating a slice of the latter in its zone.

Where the fault zone consists of several distinguishable faults, and where the topography or the exposures indicate the attitudes of the several fault surfaces, the more southwestern faults are steeper than the others. This relation (structure section E-E') and figure 75a suggests movement from the southwest, whereas the shear slice pattern for a block moving from the northeast which here is faulted down dip would be expected to resemble figure 75b.



a.



b.

Figure 75

Several small low angle faults in the upper plate one-half mile to a mile southwest of the major fault zone offset individual rhyolite sheets with small right lateral displacements and locally suggest up-dip thrusting. This probably reflects the prevailing stress pattern in the plate.

The new cleavage developed in the schist adjacent to the fault zone dips to the southwest at angles of 30°-40° which is as steep or steeper than nearby fault attitudes. Such a cleavage is more compatible with a shear pattern in which the upper plate moves up dip.

The small folds in the schist just below the thrust zone suggest a-lineation features, parallel to the direction of thrust movement. Their average trend of about S. 50° W. is better attributed to movement from the southwest than from the northeast in explaining the right lateral offsets. The slickensides observed do not directly provide a sense of movement, but their average plunge bearing is about S. 50°-60° W. and is compatible with movement from the southwest in terms of the right lateral offsets.

From the foregoing details, it is reasonable to conclude that the movement of block V on its southwest dipping sole fault was probably from the southwest.

The northeast-dipping fault in the Catclaw Hills has less evidence which can be brought to bear on the direction of movement. The left lateral displacement of the granodiorite contact and the rhyolite porphyry zone restrict the source of the movement to an arc of less than 180 degrees from about S. 30° W. through S. to about N. 45° E. The closer the line of movement was to the present N. 35° E. trend of the rhyolite porphyry zone and the intrusive contact in block III, the greater the displacement must have been. The slickensiding on the fault surface plunges nearly down dip, in a northeasterly direction, indicating that at least part of the movement was close to the N. 35° E. trend. Direct evidence for the sense of movement on this fault was scarce. No slices or persistent drag effects are visible. This fault did not develop conspicuous associated cleavage or new folds, and the shear patterns visible in the fault zone are ambiguous. If this fault is the fault underlying Keith Peak and Sheep Camp Ridge then the following arguments also apply to it.

The Keith Peak-Sheep Camp Ridge fault, including that portion west of the large normal fault, has many features which may reflect direction and sense of movement. The general trend of the sedimentary formations in the tilted rib of Sheep Camp Ridge and the fold on Keith Peak suggest northeast-southwest compression. The gradual overturning of the Escabrosa formation as it trends southeast from Keith Peak, suggests active forces and block overriding from the southwest. The distribution of masses of Paleozoic breccias in the granodiorite west of Sheep Camp Ridge suggests fragments torn from the upper plate as it moved from southwest to northeast. The cleavages developed in the slices of various formations in the fault zone, dip southwest at angles usually greater than the dip of the fault. Rare drag folds in the Abrigo shales at the north end of Sheep Camp Ridge also suggest movement from the southwest. The right lateral offset of the intrusive contact by more than 2,000 feet, with a possible slight offset of the rhyolite porphyry zone in the same direction might appear to be satisfied with movement from any part of a southeasterly semi-circle between S. 30° W. and N. 70°-50° E. However, the great displacement indicated from other evidence requires again that the line of movement has been very close to the strike of the rhyolite zone in order to produce such a small apparent displacement. If the average trend of the rhyolite zone is about N. 45° E., then the direction and sense of movement must have been approximately <u>toward</u> N. 40° E.

The pattern of distribution of slices on the north and east sides of Sheep Camp Ridge and Keith Peak gives somewhat conflicting evidence. At the north end of Sheep Camp Ridge all of the slices in the sole of the thrust are distributed to the east of the corresponding formations in the present erosional remnant of the plate. Figure 63, a view of Sheep Camp Ridge from the northwest shows a large slice of Bolsa quartzite underlying Abrigo formation in the upper plate, and just east of the Bolsa quartzite in the plate. The simplest interpretation would involve a movement from east to west. However, the tilted Paleozoic rib which is now Sheep Camp Ridge is not the entire original plate, but only an erosional remnant of it. Evidence of this lies in some of the slices. Limestones containing Pennsylvanian fusulinids are found in the thrust zone where it rests on the inclusion of Pinal schist in the granodiorite in the NE$\frac{1}{4}$, sec. 17. No Pennsylvanian formations are present in the upper plate at this time, but their former presence must be accepted. In addition, many blocks of Martin and Escabrosa beds now are exposed in the thrust zone in positions south of the projected trends of the corresponding formations in the upper plate. These would argue for the simplest interpretation of thrusting from the south or west. It is quite possible that in the original plate the stratigraphic section was duplicated one or more times and that the present distribution of slices therefore should not be referred at all to the corresponding formations as they are now exposed in the residual plate.

In summarizing all of the evidence for the net direction of movement of this major thrust, the weight of evidence favors a southwesterly source. However, the possibility of a subsequent lesser southeasterly movement on the same fault, will be considered in later discussions.

Before considering the thrust faults east of Keith Peak, brief reference should be made to the thrust fault, with limited exposures one and a half miles south-southeast of Keith Peak, in the SW$\frac{1}{4}$, sec. 28. The right lateral displacement of younger beds (Escabrosa) over older beds (Bolsa) would be satisfied by thrusting from a direction more easterly than the trend of the beds which is about S. 25° E. The slices in the fault zone are from intermediate formations, and are therefore compatible with this interpretation.

The thin plate of Carboniferous formations low on the east side of Keith Peak, has a very undulating sole fault generally dipping to the east and south. Within the plate, the northwest-striking strata steepen northeastward from a 35° NE. dip to an overturned 75° SW. dip. This is independent of the attitude of the sole fault and may reflect pre-faulting folding due to a northeast-southwest compression. At the north end of the Horquilla formation exposed in this plate, about 75 feet from the basal fault, limestone beds which are nearly vertical and striking N. 15° E. have developed a coarse fracture cleavage which strikes N. 70° W. and dips about 60° S. The cleavage may be interpreted as a shear phenomenon indicating movement from the south-southwest. If this plate was torn from the underlying large Keith Peak plate, then movement from the south-southwest would be compatible with the present distribution of formations in both plates. It should be pointed out, however, that the change in trend from northwest to northeast, of the beds close to the basal fault, suggests a drag due to movement from the east or southeast. Slickensides on the sole fault plunge 40° E. down dip in an exposure on the west side of the mass.

The fault under the Upper pre-Cambrian-Cambrian plate exposed in Thompson Wash west of Javelina Hill dips southeast and the overlying formations dip in the same general direction. The apparently normal stratigraphic relation might be developed reasonably by thrusting a block from a southern extension of the homoclinal section exposed in Lechugilla Hill, toward the northwest. The block is torn by several steep north-northwest trending, left lateral faults which do not extend into the underlying schist. These faults also suggest thrusting from the southeast, but they may be effects superimposed on the plate by the overriding Javelina Hill thrust.

The brecciated plate on Javelina Hill in its present erosion defined distribution gives the visual impression of riding up and over the other plates from the south. What evidence is available does not conflict with this fortuitous impression. The distribution of the Black Prince formation on the plate suggests several low angle shear surfaces within the plate on which successively higher sections of the breccia were thrust northward over the lower part of the breccia. The Escabrosa breccia southeast of Keith Peak, which overrides Black Prince formation in a lower plate, has apparently dragged northward or northeastward an underlying breccia phase derived from the Black Prince formation, for a distance of 500 feet or more.

The joint pattern mapped in the cataclastic breccia in the lower parts of the Javelina Hill plate (fig. 71), may yield information on the direction of final movement, if correctly interpreted. Without knowing the original thickness of the plate, it is reasonable to speculate that the breccia was at the base of a thicker more or less continuous section (as reflected by the much less deformed Black Prince shale in the thick center of the present remnant). Field and microscopic observations have confirmed that recrystallization is confined only to the renewal of bonds in the tectonically milled breccia. It may therefore be visualized as a plastic mass of rotating coarse fragments and fine powder; the "ball-bearings" or "lubricant", as you will, on which the higher rock moved. Within this mass, differential resistance from the underlying surface might have set up incipient shear planes related to the direction of flow, which constantly merged and reformed. The final aspect of this shear pattern could have been "frozen-in", and subsequently etched out during weathering.

Whether the present trend of the joints is actually parallel to the direction of movement or perhaps oblique to it at an acute angle, cannot be said with certainty but an hypothetical stress pattern which may explain the joint attitudes can be put forward. E. M. Anderson (1951, p. 15) postulates a system of stresses to account for wrench faults which may apply here. Figure 76, taken from Anderson, shows the pattern of stresses.

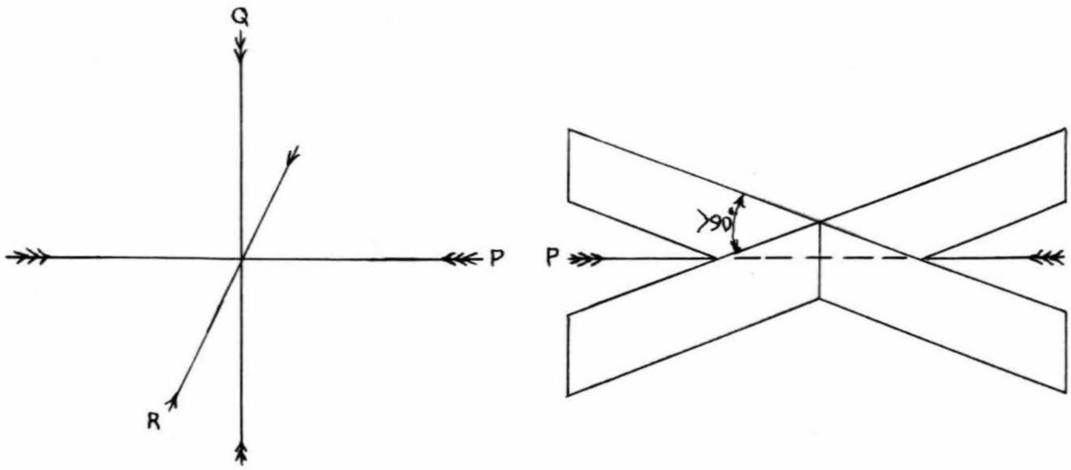


Figure 76

The maximum pressure, P, is horizontal, i.e. from the direction of thrusting, while the minimum pressure, R, is also horizontal but at right angles to the maximum pressure. The intermediate direction is vertical, presumably because of the weight of the overlying rock. The planes of maximum shearing stress are vertical and inclined at 45° to the directions of P and R. Actual failure will develop along vertical planes forming more acute angles with P. Ideally, a conjugate set of planes should form, but only one direction may commonly be developed as in the breccia plate.

If the preceding stress analysis is applicable then the average north-south strike of the joints implies movement along an approximate trend either N. 30° W. or N. 30° E. for this plate, with no indication of the sense of movement.

Of the plates exposed east and southeast of Javelina Hill the higher blocks contain younger formations. Such a relation can be developed by displacing successive slices of a tilted block (as is exposed in Lechugilla Hill) in a direction opposite to the direction of tilting (from east to west in this case).

The fault on which Horquilla beds are thrust over Escabrosa and Black Prince strata, dips 36° SW, and shows strong dip slip slickensiding. The overturned syncline in this plate with its subordinate folds and axial plane cleavage must have originated from southwest-northeast compression, but the east-west transecting faults are apparently wrench faults in which the south block moved west suggesting a principal stress along southeast-northwest lines.

It should be clear from the preceding discussions, that all of the evidence for thrusting in the southern Johnny Lyon Hills area points to or is compatible with movement from somewhere in the southern half of the azimuth. The apparent conflict between southwest and southeast indications may be resolvable. Much evidence including the folding and displacement of pre-Cambrian structures argues for a major compression along southwest-northeast lines. The evidence for movement from the southeast is generally found in the higher plates and is superimposed on the plates which appear to have been compressed already along southwest-northeast lines. There is good evidence elsewhere in the map area that southeasterly and easterly forces were at work in this same general episode. A sequential relation, in which local conditions caused a change in orientation of the principal stress may be the answer.

Magnitude of Thrust Fault Displacements

On all of the thrust faults only minimum values for the displacements can be determined. The largest stratigraphic displacements indicated are found in those plates where Horquilla formation rests on Pinal schist or granodiorite. These displacements would be considerably greater than 2,500 feet, depending upon what parts of the Pennsylvanian section and the Pinal schist are involved.

Another minimal value can be obtained from the size of slices in zones where the upper and lower rock is different from that of the slice and assuming that the slice dimensions parallel to the fault planes are approximately equal. A slice of schist nearly half a mile long is exposed in granodiorite in the southwestern Catclaw Hills fault. Slices nearly a thousand feet long are found in the zone under Sheep Camp Ridge. The block of Martin and Abrigo strata under the northeast corner of Javalina Hill is also nearly a thousand feet long.

Offsets of older structural features such as the intrusive contact of the granodiorite and the pre-Cambrian rhyolite sheet zones suggest minimum displacements up to half a mile.

The Paleozoic breccia masses in the granodiorite west of Sheep Camp Ridge require displacements up to 4,000 feet to restore them to the nearest exposures of the corresponding formations in that plate.

The Javelina Hill breccia plate, resting on younger rocks over much of its length must have a minimum displacement of its entire continuously exposed length which is about one mile. If the correlations under the alluvium with the masses of limestone breccia exposed to the southwest are accepted, then another half mile of displacement must be added.

The surrounding and overlapping alluvium does not permit determination of the sources or root zones from which these plates might have been derived. But from the discussions about the individual thrust plates, it should be clear that the actual displacements must have been on the order of miles or perhaps even tens of miles, rather than fractions of a mile and that the roots of many of these faults lie a considerable distance outside of the map area.

The Lechugilla Hill-Rattlesnake Ridge-
Kelsey Peak Structural Belt

A long eastward-dipping belt of Upper pre-Cambrian and Paleozoic rocks is exposed in a series of ridges and valleys extending from Tres Alamos Wash south of Lechugilla Hill, to the northwest corner of the map area, a distance of nearly ten miles. The trend of the belt swings, by a number of fault dislocations, from about N. 10° W. at the south end to N. 50° W, northwest of Kelsey Peak. This section rests in angular unconformity on the Pinal schist and the Johnny Lyon granodiorite. To the east it is overlapped by the alluvium of Allen's Flat and Tres Alamos Wash, except in the vicinity of Kelsey Canyon where intervening Mesozoic(?) and Tertiary rocks are exposed.

Within the belt, the formations are essentially parallel except for a very slight discordance at the erosional unconformity between the Upper pre-Cambrian diabase sheet and the Middle Cambrian Bolsa quartzite. Systematic comparison of the dips in the Pioneer shale with the attitude of the overlying Bolsa quartzite, reveals that on the average the Pioneer shale dips 2°-5° more steeply eastward than does the quartzite. This relation holds true despite the fact that the average dip of the whole section steepens from nearly 40° at the south end of the belt to nearly 60° in the latitude of Kelsey Peak. A slight angular unconformity is also suggested by the increase in the diabase thickness as it trends northward under the unconformity. This thickening is the only significant effect of the post-Apache group unconformity on the structural character of the section.

The entire belt has been disjointed by several large low angle faults and a great many steep faults of which only the more important are shown in plate I. As far north as Kelsey Peak the present trend of the belt is the resultant of the strikes of the beds and the consistently right lateral offsets of several different sets of faults. For example, the average strike of the beds in the belt between Tres Alamos Wash and the thrust faults in sec. 27, T. 15 S., R. 21 E., is N. 30° W., but the gross trend of the belt over the same distance averages N. 10° W. with a slight undulation. North of this thrust zone, the overall trend is N. 35° W. for the next mile whereas the beds strike N. 55° W.

Low angle faults

At least four zones of low angle faulting intersect and offset the stratified rocks in a right lateral direction.

The most southerly of these fault zones is exposed about two and a half miles north-northwest of Lechugilla Hill. This zone consists generally of two faults (sec. C-C') trending about N. 80° E. with considerable topographic deviations, and dipping 6°-14° to the south. The overall apparent horizontal displacement is right lateral, and more than 1,000 feet in magnitude, with Escabrosa limestones thrust upon Abrigo dolomites, Abrigo shales thrust upon the Pinal schist, and so forth. The plate between the two faults is only about 100 to 150 feet thick and consists principally of dragged and locally overturned Abrigo strata. Just before the faults pass eastward under the alluvium, some thin masses of Escabrosa limestone, considerably brecciated, appear in the zone.

Although the thrust zone must clearly intersect the granodiorite-Pinal schist contact a few hundred yards to the southwest, an offset has not been recognized. Exposures are not good, and it must be assumed that fortuitous irregularities in the trend of the contact have tended to conceal the effects of any offset that was developed. Although the fault cannot be followed through the granite, it is interesting to note the apparent termination of two nearby alteration bands in the intrusive at about this latitude. Furthermore, the western alteration band nearly two miles away displays a right lateral displacement of the same magnitude, by a south-dipping fault. There are possible indications therefore of the existence of this fault to the west.

The direction of displacement on these thrusts is northwestward for the right lateral displacement could not have been achieved unless the direction was more westerly than the trend of the formations. This is also confirmed by the nature of the drag folds and tear faults in the slices. The stratigraphic displacement of about 800 feet is clearly minimal for even a S. 80° E. source would have required nearly 2,000 feet of movement to create this displacement. Thrusting from S. 40° E. would require more than a mile of movement to offset the formations to the same degree.

A mile to the north and less than a half-mile south of the Willcox-Cascabel road, another series of south-dipping low angle faults is in imbricate relation. They are apparently part of a zone of thrusting which has been offset by a large N. 30° E. normal fault dipping steeply to the southeast. The overall apparent horizontal displacement on this thrusting zone is right lateral and about 800 feet. Again the evidence points to thrusting from the southeast and the actual displacements may have been much larger than the apparent displacement.

A more prominent low angle fault appears about a mile northwest of where the Willcox-Cascabel road crosses the Pioneer shale. This fault trends about east-west and dips 40° to the SSE (sec. B-B'). The apparent horizontal displacement of the Pioneer shale is about 1,500 feet, but much of this displacement is contributed by several closely spaced, high angle faults north of the thrust fault, which are concealed by the latter before they intersect the Pioneer shale. A more accurate indication of the apparent displacement may be obtained from the offset of higher horizons, such as the Abrigo quartzite marker bed or the base of the Martin formation. About 400 feet of right lateral offset is indicated. The fault cannot be traced in the intrusive to the west and is offset by a normal fault and lost in the Horquilla strata on the east. The displacements on this zone are responsible for the offset of the entire pattern of northwest trending ridges which are maintained by the basal Pioneer formation, the Bolsa quartzite and the Escabrosa limestone. (See sec. 16, T. 14 S., R. 21 E. in plate IV.)

About a quarter of a mile south of the preceding fault, a smaller low angle fault is present on the crest and dip slope of Rattlesnake Ridge. It offsets the Carboniferous strata nearly 400 feet on the dip slope, but a stratigraphic displacement of only 175 feet is involved. Its gentle southerly dip (about 15^{o}) and right lateral displacement mark it as a member of the same series as the other low angle faults in this belt.

At the north end of Rattlesnake Ridge, a series of north to northeast trending segments of at least two large low angle fault traces is offset by younger, steep NNW trending faults. The low angle faults dip more southeasterly than those farther south and the strike appears to be about N. 45^{o} E. Most of the fault traces appear on rather steep southwest-dipping topographic slopes which accounts for the divergence between trend and strike.

At least two, and probably three, different sets of younger steep faults have complicated the fault pattern to such a degree that it is not possible to correlate the segments with certainty. The fault zone enters the strata from the granodiorite southwest of Kelsey Peak trending generally north, and swings by virtue of topography and fault offsets around the north side of the Peak. Upon entering the Horquilla formation, the faults are lost because of additional structural complications and a lack of dependable marker beds in these strata.

The apparent horizontal displacement of stratigraphic horizons on the largest of the faults is variable because of some formational thinning, but a minimum value of 700 feet in a right lateral direction is reasonable.

The direction of displacement on the low angle faults in the vicinity of Kelsey Peak must also be more from the east than the trends of the formations in order to produce the right lateral displacements. Since the bedding has swung into an average S. 50° E. trend in this latitude, this would suggest a more easterly direction of movement than on the faults to the south.

An indication that the directions of movement may be more easterly the farther north the fault occurs, comes from an incompletely known fault zone in the extreme northwest corner of the map area. This zone is partly exposed on the west face of the northeast dipping Paleozoic section, south of Kelsey Canyon in sec. 6, T. 14 S., R. 21 E. Its trace is very sinuous and offset by younger faults. Slopewash conceals most of its length, and the interpreted pattern may well be part of several faults. The one attitude (58° N.) obtained on the fault is steeper than the trend of the fault trace suggests, but a reverse movement in which a northeasterly block rides up toward the southwest is implied along its entire length. Parts of the stratigraphic section including the entire Black Prince formation are cut out at various points. This requires that, in general, the northeast dip of the fault should be less steep than the dip of the beds which averages 40°-45° NE. in most of the section affected. The measured attitude may owe its anomalous orientation to the influence of drag on the fault plane by the adjacent transverse fault.

High angle faults

The blocks into which the Lechugilla Hill-Kelsey Peak belt is divided by the larger low angle faults, are further disjointed by several sets of high angle faults. Most of these faults have relatively small displacements but they are so numerous as to have important cumulative effects on the structure. The steep faults generally appear to be contemporaneous with or younger than the thrust faults.

In the block between Lechugilla Hill and the thrust fault shown in structure section C-C', two principal sets of faults appear. Both sets show predominant right lateral displacements. The older set generally trends N. 80° W. to S. 85° W. and dips steeply southward. The younger set trends N. 45° E. to N. 65° E., also dipping south but apparently at somewhat lower angles. Unfortunately, the exposures generally do not provide enough opportunities to measure attitudes and thus distinguish the sets more completely. The older set is in general characterized by somewhat larger stratigraphic displacements, up to 300 feet, whereas the largest faults in the younger set do not exceed 100 feet.

Most of the faults apparently lose their displacements in the Pinal schist to the west. Only a few offsets of the schist-granodiorite intrusive contact have been observed and these apparently correspond to the older fault set. It is also worth noting that the trend and attitude of the younger faults are essentially parallel to the foliation of the underlying Pinal schist.

In the block between structure section C-C', and the east-trending thrust fault in the $S\frac{1}{2}$, sec. 16, two sets of steep faults are recognized, also. An older set trends N. 70°-80° W., but with several transverse faults changing into strike faults of more northerly trend, in the shale units of the Abrigo and Martin formations. These northwest-trending faults dip generally steeply south when oblique to the strike of the beds, but may become parallel to the bedding when they turn into the shales. The stratigraphic displacement on most of these faults is right lateral and may amount to 300 feet. A N. 50° W. bedding plane fault apparently offsets the trace of the thrust fault at the north end of this block, about 500 feet horizontally. A few faults of the same trend south of the Willcox-Cascabel road turn into strike faults in the lower Abrigo formation.

The more numerous younger faults are in a set trending from N. 30° E. to N. 60° E. and dipping southeast at 50°-60°. They offset many of the older steep faults, and, uncommonly, some of the low angle faults. It is a predominantly right lateral set, but occasionally individual faults are obliquely intersected by what appears to be complementary left lateral faults of about the same displacement. The stratigraphic displacement is generally less than fifty feet, but appears to be about 150 feet in the large fault which truncates the thrusts in the center of this block.

The two sets of steep right lateral faults are present in Rattlesnake Ridge north to the low-angle fault under Kelsey Peak but they are joined in increasing numbers by east-west trending left lateral faults dipping steeply to the north. Faults of the left lateral set offset the thrust fault but are in turn offset by right lateral northeast trending faults.

In the vicinity of Kelsey Peak and to the north, at least four sets of steep faults, all younger than the thrust faults, are present. The oldest steep faults are east-west to N. 80° W. and nearly vertical, with left lateral stratigraphic displacements up to 300 feet or more. These faults are best exposed in sec. 6.

The next younger set trends about N. 35 E. and is vertical to north-dipping. There are only a few faults of this set but they have stratigraphic displacements up to 900 feet and are responsible for major offsets of the Paleozoic ridges in sec. 5 and 6. They also offset the Glance(?) conglomerate on the south side of Kelsey Canyon.

Probably younger than the large left lateral northeast faults are right lateral faults trending due north to N. 15° E. and dipping steeply to the east. They have small displacements, usually under 100 feet, but are quite numerous.

The youngest high angle faults trend N. 65°-70° W. and have large right lateral displacements. They dip vertically to 80° S. and are associated with considerable drag folding where they intersect the Horquilla strata. The largest of these faults offsets the section southwest of Kelsey Peak (section A-A') as well as older faults, with an apparent horizontal displacement of more than 1,700 feet. The stratigraphic displacement is more than a thousand feet, and when combined with the displacement on the adjacent lesser faults of the set, brings Escabrosa limestone opposite pre-Cambrian diabase. The fault is responsible for the topographic re-entrant at the north end of Rattlesnake Ridge. It passes under the alluvium of Allen's

Flat to the southeast. Northwest of Kelsey Peak it also passes under the alluvium. In the SW$\frac{1}{4}$, sec. 6, a small window in the alluvium reveals granite within 50 feet of Bolsa quartzite, implying the presence of a large fault which may be the same one.

Two more faults of the N. 65° W. set appear high on the north side of Kelsey Peak. They are apparently responsible for an elongate series of folds with nearly horizontal axes which suggest they are normal faults on which the southwest block is downdropped. This is compatible, of course, with the right lateral apparent displacement. These faults intersect the low angle faults to the northwest and are lost in the bedding in that complicated area.

Still another fault of similar trend and offset duplicates the Pioneer shale and diabase just west of the north end of Rattlesnake Ridge. This fault disappears in the granite under the alluvium to the northwest, and turns into the diabase on the southeast. In the latter direction, it would be expected to offset the thrust fault in its path but such an offset is not clear. Unfortunately, the deeply decayed diabase has as poor a lithology in which to study faulting as the Abrigo shales on the opposite side of the thrust fault. The thrust fault may be offset, but not to any great degree. If it is not, then this northwest trending fault is older than the thrust and must represent a different generation of faulting.

In most of the Lechugilla Hill-Kelsey Peak belt, the normal faulting can be directly dated only as post-Pennsylvanian and pre-alluvium. Northwest of Kelsey Peak one of the fault sets younger than the thrusting and intermediate in the fault sequence does offset Glance(?) conglomerate, and if the age assignment of the latter is correct, these faults are post-Lower Cretaceous. The same faults do not appear to offset the Threelinks conglomerate.

Lamprophyre sills in the basal Horquilla formation along Rattlesnake Ridge are offset by the younger northeast trending right lateral faults. If these lamprophyres are of the same origin as most of the lamprophyres in the Dragoon quadrangle (i.e. related to the Texas Canyon quartz monzonite), then the younger fault set is post-Early Tertiary(?). It is also distinctly younger than the age of the thrusting in the southern Johnny Lyon Hills area.

Folds

This long belt of stratified rocks is singularly free of folds, for such an extensive deformation record. Even the broad changes in the attitude of the homocline seem to be largely due to cumulative changes by fault displacement. Perhaps the only major fold feature is the homocline itself. The term, homocline, can be used only for beds in restricted areas, for inevitably changes will occur in the attitude of the beds, if considered over a large enough area. The question is then raised, does the present tilted section reflect part of a major regional fold with a core of older crystalline rocks? The answer can only come from a regional examination of the structure, and further consideration must be deferred at this time.

The only local folding in the northern Johnny Lyon Hills to which attention has been called is that associated with west-northwest faulting in the Horquilla formation in the vicinity of Kelsey Peaks. These folds represent deviations from the prevailing attitude of the section that are best interpreted as drag folds on the faults.

On the downdropped, or southwest side of the faults, the normally northeast-dipping beds are dragged up into a southwest-dipping position forming a syncline. On the northeast or upthrown side of the faults, the beds near the fault are dragged down into a southwest dip forming an anticline. Between the two faults, folds are present but are more complex in pattern. In all cases the fold axes appear to be close to horizontal, which is compatible with the normal fault interpretation.

The Horquilla formation in the extreme northwest corner of the map area shows a change in the attitude of the beds indicating a fold. It has not been mapped in detail, particularly north of the map area, so no attempt at interpretation can be made.

The Structures of Kelsey Canyon

At the extreme north edge of the map area, is the topographic feature called Kelsey Canyon. This steep-walled valley not only represents a major new drainage for the area, but divides the Mesozoic(?) and Paleozoic rocks to the south from the Tertiary volcanic and sedimentary rocks to the north.

The most prominent structures in Kelsey Canyon are steep faults which divide the Threelinks conglomerate and the various members of the Galiuro volcanics into a number of fault blocks (sec. A-A'). The most prominent set is a generally north-trending group of normal and reverse faults exposed on the north side of the canyon, in sec. 4. The intervening blocks between the faults have been raised or lowered distances up to several hundred feet, with some consequent drag and distortion of the blocks. In general, all of the blocks are tilted eastward and the blocks to the east contain exposures of the younger units of the section.

Less prominent but more important is an older fault trending N. 80° W., close to the floor of the canyon in sec. 4. This fault, which is offset at several points by younger faults, dips from 69° N.-81°S. and has dropped the north block down. It separates the Galiuro andesite member from the Threelinks conglomerate over part of its length and the andesite member from the quartz latite member over the rest of its length. The displacement appears to be at least several hundred feet.

On the southwest side of Kelsey canyon the steeply dipping Glance(?) conglomerate is believed to be in fault contact with more gently dipping Threelinks conglomerate. The surface exposures are not good enough to permit positive recognition of the fault but its trend is believed to be about N. 60° W. Its existence is inferred from the general difference in attitude of the two formations and from local suggestions of steepening by drag in the Threelinks conglomerate. It may be a member of the N. 65° W. set exposed on the southwest side of the Paleozoic ridge but opposite in displacement. The steepening in the Threelinks conglomerate beds suggests that the north side is downdropped.

Structures on The River Slope, North of The American Mine

Stripping of the alluvium on the erosion surface called The River Slope is currently active in the drainage in the northwest corner of the map area. Because of this stripping, major structures involving the granodiorite, schist and younger rocks are exposed in a small area north of the American mine.

A series of generally north-trending, arcuate, low angle faults, dipping to the east can be followed intermittently for nearly a mile (sec. A-A'). The most easterly of the faults enters the quadrangle trending N. 45° E. but swings north and northwest before disappearing under an alluvial cap. The fault zone separates the granodiorite on the east from a large block (about 700 feet wide) of Pinal schist with intrusions of granodiorite, and deformed Pioneer shale and diabase on the west. In at least one part of the block the Apache group is in sedimentary contact with the schist but is overturned to the northeast. There are a number of small slices of quartzite, probably Bolsa, along the eastern fault.

Southwest of the American mine, a poor exposure gave an apparent dip of 47° SE. on this fault zone. A lower angle of dip is indicated by relations at the American mine (fig. 77) about 300 feet east of the fault. The mine is now abandoned and the only accessible working is an inclined shaft in the granodiorite, driven S. 68° E. at a 55° angle. The shaft is now flooded ninety feet below the collar, and only granodiorite is exposed to this depth. As the granodiorite becomes increasingly sheared with depth and the last waste added to the dump is Pioneer shale, it is apparent the prospect was driven through the low angle fault. As diagrammed in a sketched cross-section (fig. 78) this would indicate a lower dip than the measured 47°, even if the workings are much deeper than the accessible part.

On the west side of this large pre-Cambrian block is a series of closely spaced faults which also enter the map area from the south,

Figure 77. View looking east across The River Slope surface of the Johnny Lyon granodiorite to Rattlesnake Ridge in the background. The American mine (arrow), in the middle foreground, is 300 feet east of a major thrust fault cropping out on the opposite bank of the arroyo in the foreground. The photograph was taken from a topographic rise on a resistant Bolsa quartzite fault slice just west on the edge of the map area.

Figure 77

Figure 78. Sketched cross-section of the inferred structural relations at the American mine.

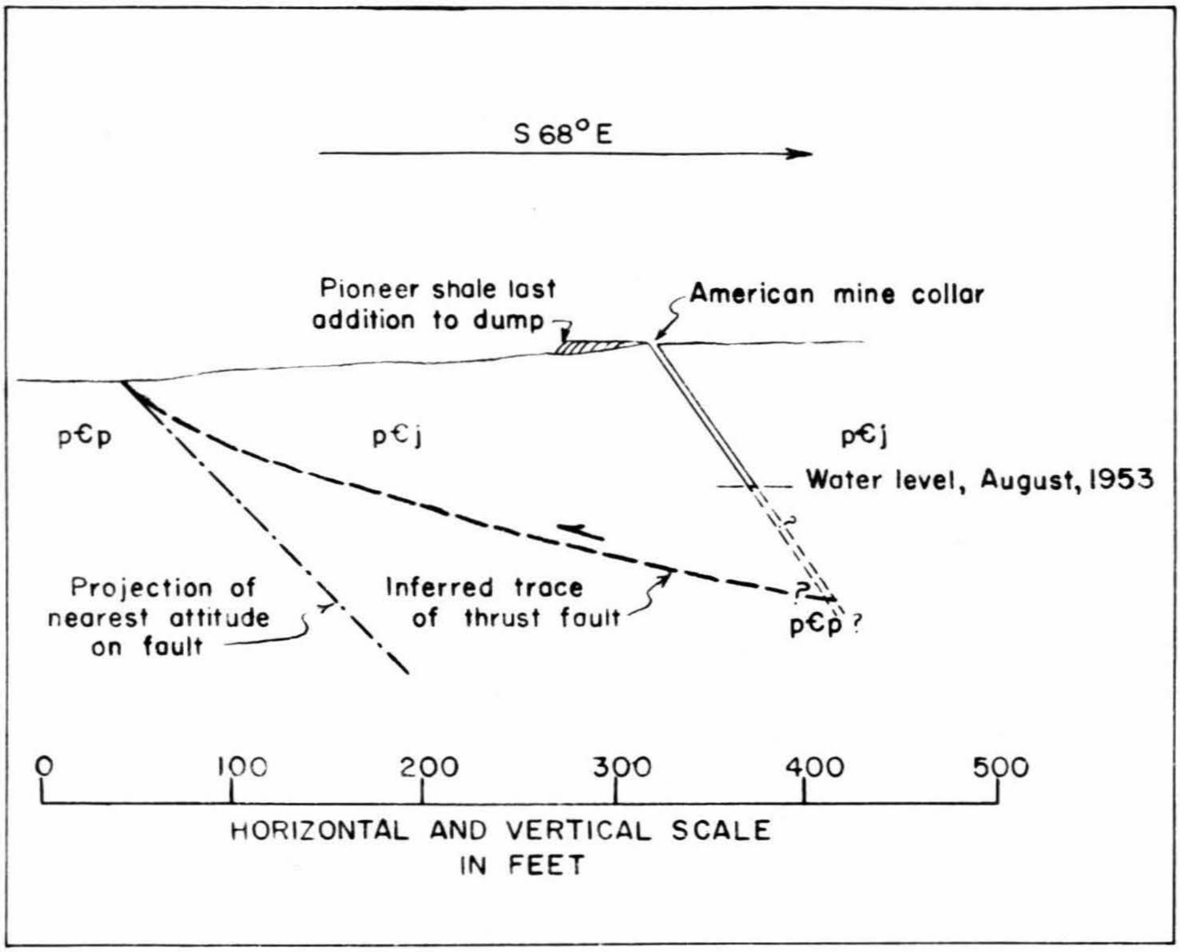

S 68° E
Pioneer shale last addition to dump
American mine collar
p€p
p€j
p€j
Water level, August, 1953
Projection of nearest attitude on fault
Inferred trace of thrust fault
p€p ?
0
100
200
300
400
500
HORIZONTAL AND VERTICAL SCALE IN FEET

Figure 78

trending northeast and then swinging northwest. These faults also dip eastward, with one measured attitude at the north end indicating a dip of 37° NE. These faults include slices of Pioneer shale, diabase, and a Naco group limestone which is probably from the Horquilla formation.

On the west edge of the map area is a thick section of the Walnut Gap formation and Glance conglomerate, striking north-northwest and dipping to the east-northeast, apparently overturned. This section apparently underlies the western low angle faults described above.

Off the map area, a quarter of a mile west of the American mine, partly exposed plates of Naco group limestones, apparently klippen, rest on red quartzites, shales and conglomerates which are assigned to the Morita-Cintura formations of the Bisbee group. The alluvium conceals most of the significant relations, but an overthrust relation is clear.

The entire series of faults and fault blocks give good indications of thrusting from the east. The evidence, in addition to the prevailing dip, includes the sequence of slices in which successively older formations overlie younger rocks from west to east. The overturning of the Mesozoic rocks also suggests compression along east-west lines with the east block overriding the western strata.

Structural Significance of the Tertiary Dikes

The lamprophyre dike swarms are useful indicators of structural conditions at the time of their intrusion. E. M. Anderson (1951, pp. 22-27) has pointed out that dikes must be tension phenomena in origin and that for deep-seated dikes at least, one cannot call upon pre-existing horizontal tensions in the surrounding rocks to explain their presence. An indirect tension must be derived, therefore, from the relation between the magmatic pressure and the opposing pressures in the wall rock. Anderson proposed that the intrusive magma would, if the hydrostatic pressures exceeded a principal pressure normal to a minute cleft in the rock on the walls of a magma chamber, propagate itself from the cleft by a wedging action in the plane normal to the principal pressure. Since two of the principal stresses in the crust are normally horizontal, most dikes are nearly vertical. However, pre-existing planes which are sufficiently close to normal to the lesser of the principal pressures may sometimes be invaded. It is a corollary of the discussion that dikes will not form normal to the maximum principal stress in a region undergoing crustal compression.

The lamprophyre dikes of the Johnny Lyon Hills are separable into several sets as has already been noted (pp. 266-273). The oldest set is apparently the 'porphyritic' lamprophyre set of N. 45° E. trend which follows the bedding and foliation in the Pinal schist, but also observes the same trend independent of various surrounding structures in Keith Peak, and in cross cutting several major thrust zones. Compression from the southeast must have subsided prior to their emplacement.

The great 'diorite' dike of Keith Peak transects all earlier structures, along a vertical plane which shows no evidence of faulting and for which there are no companion structures. This N. 65° E. plane must truly represent the path of least resistance, if so many sub-parallel structures in the schist are avoided. At the time of its emplacement, therefore, the minimum principal stress was presumably oriented S. 25° E. in the horizontal direction.

The other swarms of 'diorite' lamprophyres are found principally in the granodiorite where their trends are north to north-northwest, and they dip consistently eastward at an average of about 45°. Their apparent connection to the N. 65° E. dike as well as their composition suggests their simultaneity. The orientation of the swarms in the granite is nearly normal to the source(?) dike and is inclined at such an angle as to indicate that the vertical principal stress and the east-northeast principal stress were also less than the hydrostatic pressure on the lamprophyric magma. The development of the great dike may have contributed to favorable intrusive conditions for the other dikes, by locally changing the state of stress in its vicinity (E. M. Anderson, 1951, pp. 50-53). For much of its length it is 30 to 50 feet thick and its emplacement undoubtedly influenced the local conditions.

Pre-existing structures (e.g. joints) may have helped determine the orientation of the dike swarms in the granite also. No attempt to map the fracture patterns in the intrusive has been made because of their complexity and poor exposures, but it may be safe to conclude, nevertheless, that at the time of injection of the lamprophyre dikes, orogenic crustal compression in the area had essentially disappeared. The hydrostatic pressure on the magma chamber was the maximum pressure of the region, and was presumably equal to the vertical principal stress.

The location and origin of the lamprophyric magma chamber cannot be deduced from the available data. Presumably related to the Texas Canyon Quartz monzonite, the source of the magmatic pressures probably originated in common with that large body.

Tertiary rhyolite dikes form an en echelon series that enters the map area west of the Catclaw Hills and trends N. 40° W. about four miles across Sheep Camp Ridge, to a point in the granodiorite where the last dike disappears. The dikes are thickest to the southwest and thin gradually to their point of disappearance to the northeast. The rhyolite textures and structures suggest a shallow depth of emplacement, and they may have served as feeder dikes for flows of the Galiuro formation.

These dikes transect many but not all structures in their path. They crossed the major faults of Sheep Camp Ridge but accepted offsets along pre-existing faults farther west. For example, northwest of the Catclaw Hills, the rhyolite dikes are apparently offset by several faults (plate I), but at the same time the dikes clearly transect a series of 'diorite' lamprophyre dikes. One of the same faults is transected farther south by the major northeast-trending 'diorite' dike of the area. At the points of apparent fault offset, the rhyolite dikes show no evidence of mechanical deformation, although the adjacent rock is usually sheared in the fault zone. It would appear therefore that at least in part the dikes followed pre-existing planes of weakness which were offset by faulting prior to the dike injection.

Not all of the en echelon character of the series can be explained in this way, for the field relations show that most of apparent offsets of the dikes in the series have no relation to recognizable transverse structures. Whether the en echelon effect is the result of a regional horizontal stress couple which produced an en echelon pattern of tension fractures into which the rhyolite was injected, or whether the dike en echelons were developed above a single dike at greater depth due to a change in stress directions at different levels in the crust in the manner suggested by E. M. Anderson (1951, pp. 55-56) can only be speculated.

Structures in the Tertiary and Quaternary Alluvium

The great thicknesses of alluvium which lap upon the older rocks of the Johnny Lyon Hills have been examined in detail on the margins to determine the relations to the underlying rocks. Rapid reconnaissances of the Allen's Flat–Tres Alamos Wash areas have been made in order to assure mapping of all windows in the alluvium which reveal older rocks. At the same time some general observations on the lithology and structure of the alluvium were made. The lithology has already been discussed (pp. 291-293), and there is little to add on the structure.

No faults which were followed in the Galiuro volcanics or older rocks of the map area were found to offset the alluvium. In general, the attitudes within the conglomerates and sand beds are so close to the horizontal that any deviations may be ascribed to initial dip. Some broad warping may have occurred and is even suggested in aerial photographs of the lacustrine beds south of the Johnny Lyon Hills. However, the degree of warping, if any, is too gentle and the reference planes are too indefinite to confirm on the ground without much more work than has been done.

Examination of aerial photographs of the alluvium has revealed a number of linear features, some of which are delineated by vegetation and the others by changes in the soil colors. Ground checks of a number of these features have in all cases but one failed to confirm faulting. A single exception is a series of sheared exposures etched out by erosion in the NW$\frac{1}{4}$, sec. 3, north of Kelsey Canyon. The shearing trends about N. 30° W. out of the map area and dips quite steeply. It has not been possible to demonstrate any appreciable offsets within the map area and the feature is not shown on the map.

Summary of Post-Apache Group Structures

With the possible exception of the slight pre-Middle Cambrian tilting of the Apache group, no Paleozoic deformational effects have been recognized in the rocks of the Johnny Lyon Hills area.

Only in the vicinity of the American mine, and in Kelsey Canyon, are there exposed rocks considered to be Mesozoic in age. These are directly involved in thrusting and high angle faulting along with the Paleozoic section. It is considered probable, therefore, that all of the major structures visible in the area are post-Bisbee group in age.

Among the oldest structures involving the Paleozoic formations are some of the high angle faults which are wholly within the various thrust plates and which appear to be more or less unrelated to their present structural environment. However, where the record of deformation is so obviously intense and complex, they may well have formed during an episode only slightly earlier in the same orogeny as the thrust faults.

The earliest major structures of the post-Lower Cretaceous deformation were folds and low-angle faults which broke the folds and included parts of them in thrust plates. All of the folds exposed in the plates of the southern Johnny Lyon Hills were apparently deformed by a northeast-southwest compression. There is also considerable evidence of movements of some of the thrust plates from the southwest toward the northeast.

The largest structural feature in the area, the great tilted section of stratified rocks from Lechugilla Hill north to beyond Kelsey Peak, was developed in a great fold(?) at this early stage. The tilted block included not only the younger section but apparently all of the pre-Cambrian crystallines now visible beneath them. The structural homogeneity of the Pinal schist belt argues against any flexure which involved only part of the schist exposed in the Johnny Lyon Hills. Further, the orientation of the schist as a structural member was probably so close to the direction from which the compression came, (i.e. the southwest) that failure by faulting was much more probable than by flexure. The great block of granodiorite buttressed by the schist on the south and east must have played a major role in determining the orientation of the younger structures.

While many of the thrust faults involving the 'basement' rocks do appear to have come from the southwest, there is additional evidence of thrusting from the south and southeast which was superimposed on some of the already developed plates, and which may well have been responsible for the highest (and youngest?) plate on Javelina Hill. Thrusting from the southeast is recorded throughout the Lechugilla Hill-Kelsey Peak structural member, seemingly becoming more easterly in source as it was recorded farther north. And in the

American mine vicinity, major thrusting from the east is strongly indicated.

Steep faulting seems to have been generally younger than the low angle faulting. On the basis of attitude and direction of apparent displacement, both the older N. 70° W. set and the younger N. 45° E. set in the tilted section south of Kelsey Peak can be interpreted as younger normal faults. However, it is also possible to interpret the N. 70° W. set of faults, apparently quite steep, as a wrench fault set related to a compression from the approximate direction S. 40° E. This is the same direction from which the thrusting in this area apparently came. Unfortunately there are almost no direct observations on such phenomena as slickensides or drag folding associated with this set of faults by which such an interpretation might be confirmed. Possibly, the much greater average displacement on the faults of this set reflects such an origin.

The N. 70° W. right lateral set does not appear northwest of Kelsey Peak. Instead two prominent sets of left lateral faults dominate the older steep faulting. The relation of these sets to the steep faults of the south is not clear. They may be part of an earlier pattern developed during compression from the southwest, or they may reflect some local rather than regional complication in the structure.

In this same status is the large N. 30° W. left lateral normal fault of Keith Peak-Sheep Camp Ridge. There are no indications that this fault is a product of compression. It strongly suggests that the southwest compressional forces had disappeared prior to its formation which is also prior to the injection of the lamprophyre dikes of early Tertiary(?) age.

Another set of faults which appear to be normal are the younger right lateral faults of the Lechugilla Hill-Kelsey Peak belt. These faults, which trend N. 30°-60° E. and dip 50°-60° SE. along most of the belt, show slickensiding close to dip slip. Their orientation is such that they may well be relaxation phenomena following the cessation of the southeast compression. Probably in the same class are the numerous small faults northwest of Kelsey Peak trending due north to N. 15° E. Their more northerly orientation may reflect earlier compression from a more easterly direction which has already been suggested from other evidence. These young 'relaxation' faults are apparently younger than lamprophyre sills in the Paleozoic section. If these are early Tertiary(?) lamprophyres, then there is a further basis for separating these faults in time from the older N. 70° W. (wrench?) faults.

The youngest important faults in the Johnny Lyon Hills area south of Kelsey Canyon, are the N. 65°-70° W. right lateral faults near Kelsey Peak. These faults truncate faults of all the other sets, but no direct relation to the lamprophyres is known. If the steep faults of similar trend but opposite displacement in the floor of Kelsey Canyon represent the same episode of faulting, then these faults are younger than the Threelinks conglomerates and the Galiuro volcanics.

The north-trending block faults within the Galiuro volcanics are apparently independent of the patterns in the older rocks to the south and west.

It is apparent that the 'grain' of the older rocks in the Johnny Lyon Hills has not been imposed on most of the younger structures.

The important role the basement rocks played was not in failure along old structural planes in response to the Laramide compressional forces. They apparently served as a rigid structural member which rotated as a massive unit and about which the regional pattern was modified locally. Much more might be said in this regard if the overall size and shape of the Johnny Lyon granodiorite pluton were better known. It would also be important to know what external influence was exerted by the presence of other massifs. For example, the Tungsten King granite exposed for several square miles southeast of the map area, on the west side of the Little Dragoons, might conceivably have been a massive impediment to the regional crustal deformation and thus diverted thrust movements toward the Johnny Lyon Hills.

Relation to Regional Structures

In southeastern Arizona, the major post-Paleozoic structural episode is generally correlated with the Laramide revolution, although it is clear that considerable tectonic activity continued through Cenozoic time. The assumed Laramide age is based on the fact that the very thick section of Comanchean rocks of the Bisbee group has been intimately involved in the orogeny along with the Paleozoic strata. Upper Cretaceous beds are rare (Stoyanow, 1949, pp. 58-60; McKee, 1951, p. 497) or unrecognized, and hence have not been a general basis for dating the deformation.

The lithologic character of the units in the Comanchean section, particularly the coarse boulders of the Glance conglomerate at the base, indicates that some crustal disturbance must have developed after the Paleozoic and prior to the Comanchean. McKee (1951, p. 496) considered it likely that a general period of uplift, probably early in the Cretaceous, was responsible for the conglomerates. A few faults, particularly the Dividend fault and associated structures at Bisbee (Ransome, 1904, p. 42), have been recognized which cut Paleozoic beds and not Cretaceous strata. Gilluly (1941) has reported the presence of post-Paleozoic, pre-Cretaceous intrusions in the Dragoon Mountains. These are the principal symptoms of early and middle Mesozoic regional unrest.

The Laramide orogeny produced folding and overthrusting in many other areas of the region. Work elsewhere in the Dragoon quadrangle by Cooper and his co-workers has shown thrusting to be present along the entire west side of the range from South Camp (sec. 24, T. 15 S., R. 22 E.) south to Sheep Basin. Thrusting was definitely from the southwest in some cases, and possibly in all cases. The rocks involved range from Pinal schist to Bisbee group, and following the thrusting, high angle faulting of large displacements transected the thrust plates. The Texas Canyon quartz monzonite and related aplites and lamprophyres invaded and metamorphosed many of the thrust and normally faulted blocks. In the Steele Hills in the northeastern part of the quadrangle, Cooper found a thick section of Morita-Cintura formations in folds trending northwest and partly overturned toward the northeast.

Gilluly (1941, 1945) reported northwest trending overthrusts of great displacement in the Dragoon Mountains to the southeast, some of which must enter the Dragoon quadrangle. The overriding blocks came from west and southwest. East of the Dragoon Mountains, Gilluly reported a band of Comanchean strata, 4 miles across the strike, overturned and dipping at low angles to the west.

On the southwest flanks of the Rincon Mountains, west of the map area, work by Moore, Tolman and others (Moore, et al, 1949) has outlined a great thrust plate carrying Paleozoic, Cretaceous and early Tertiary(?) strata as well as granite, up on to the crystallines of the range. Farther north, early Tertiary(?) alluvium is thrust from the south upon the granites of the Santa Catalina Mountains. Still farther west, Brown (1949) described overthrusting from the west in the Tucson Mountains.

The general uniformity of the evidence cited so far for the direction of regional compression is perhaps slightly misleading. Observations and interpretations at many other sites of Laramide compression in southeastern Arizona give a somewhat less consistent pattern of thrusting.

Northeast of the Dragoon quadrangle, Ross (1925, p. 46) reported post-Cretaceous thrusting from the east, and northwest trending folds. Southeast, in the Swisshelm Mountains, Galbraith and Loring (1951) reported thrusting from the east, and north-northwest trending folds. In the Mule Mountains, Gilluly (1941) reported thrusting from north to south. In the Bisbee district, Ransome (1904, pp. 85-104) and others have described northwest trending fold axes and thrusting from the southwest developed in the Laramide part of the structural history.

In the Huachuca Mountains, Wilson (1951, p. 47) quoting the work of C. O. Alexis and R. H. Weber, reports prevailing fold axes and thrust faults striking northwest, and with thrusting from the north-east. In the Santa Rita Mountains, Schrader (1915) reported over-thrusting at Helvetia from east to west. In the Empire Mountains, Galbraith (1949) reported major thrusting from the southeast.

The wide discrepancies noted in the directions of thrusting reported in the various districts tend to dilute a picture of regional structural uniformity. But although the reported directions of active thrusting nearly box the compass, the prevailing trend of northwest-southeast fold axes is clear. So it appears quite probable that a regional compression along southwest-northeast lines is real (Wilson, 1949).

To attribute the divergence in interpretations of thrusting in the various districts solely to errors of judgement or to lack of observable critical relations, would not only be uncharitable, but unrealistic. In a region where new structures have developed nearly at right angles to the structural pattern of the older underlying rocks, and where the older rocks include massive plutons of granitic rocks, some disruptions of the regional pattern are to be expected. The crystalline massifs cannot be expected to flow and fold as readily as the overlying sedimentary strata. They must respond as their strength, mass and shape permit , and these factors will inevitably set up local patterns of differential stresses affecting the overlying and surrounding weaker rocks. Resultant structural failures would inevitably include deviations from a systematic regional pattern similar to those observed in this region.

Following the cessation of the Laramide compressions, granitic rocks which correspond to the Texas Canyon quartz monzonite, presumably early Tertiary in age, were emplaced throughout the region in numerous bodies both large and small.

Faulting continued throughout Tertiary time in the region, principally in the form of northwest trending steep normal faults. To these faults are generally attributed the present topographic trends of the Basin and Range province. They must share the responsibility however, with the earlier northwest-trending compressional features of Laramide age within the ranges which control the topography in many areas where younger faults cannot be demonstrated.

RESUMÉ OF THE GEOLOGIC HISTORY OF THE JOHNNY LYON HILLS AREA

There are no records of the geological history of the area during most of the time interval known geologically as the older pre-Cambrian. Probably rather late in this interval, the local crust was deformed into part of a great geosynclinal basin.

Tens of thousands of feet of graywackes, shales, conglomerates, and submarine volcanic flows, now known as the Pinal schist, were poured into the basin as it developed and were deposited at depths generally below the marine wave base. The sources of the sediments included both syngenetic volcanic products and positive areas of crystalline rocks, of unknown distribution but probably lying to the south. Turbidity currents may have been the important transporting mechanism, for hundreds of coarse graywacke beds are characterized by graded bedding and by rhythmic alternation with fine-grained pelitic beds.

After these deposits were accumulated, numerous rhyolite porphyry bodies were injected into them, in part in a widespread zone of thin sheets parallel to the bedding, and in part in larger stocks and plugs.

A great orogeny (the Mazatzal Revolution) deformed the strata and associated rhyolite porphyry along directions of compression trending northwest-southeast. The section was distorted into tight folds ranging in amplitude from inches to miles and generally overturned to the northwest, with fold axes plunging to the east. The rocks of the section were subjected to general dynamic regional metamorphism of the rank of the greenschist facies.

Following the deformation, and probably after a period of minor injection of mica rhyolite sheets and dikes, a great pluton of granodiorite (Johnny Lyon) was intruded into the Pinal schist. This pluton produced a considerable halo of contact metamorphism in the invaded Pinal schist, modifying some of the earlier products of regional metamorphism. The granodiorite locally reacted with inclusions of basic volcanics to form minor hybrid phases. Numerous small pegmatites and aplites were injected near the contact with the neighboring schist.

At some time following the crystallization of the granodiorite, long, steep, north-trending shear zones developed in the igneous body and in the adjacent schist. These shear zones subsequently served as loci for wide hydrothermal alteration bands in the granodiorite.

By late in pre-Cambrian time, the complex of older pre-Cambrian rocks was truncated by a remarkably smooth erosion surface (Ep-Archean) on which no topographic reflection of the earlier mountain-building processes remained.

The erosion surface was transgressed by shallow marine waters in which were deposited the unfossiliferous strata of the Apache group. Shortly thereafter, a thick continuous sheet or sheets of coarse diabase was intruded concordantly into the Apache group section. Following this igneous activity came a period of emergence and broad warping of the crust, during which a new period of erosion stripped off much of the Apache group and part of the diabase.

By middle Cambrian time, the area had again been submerged under shallow seas and a middle and upper Cambrian section ranging from basal conglomerate and sandstones (Bolsa quartzite) through shales and carbonate rocks (Abrigo formation) was deposited on an erosion surface (Ep-Algonkian) of low to moderate relief.

The interval from latest Cambrian time through Ordovician and Silurian to late Devonian time is not recorded by deposits in the Johnny Lyon Hills. Elsewhere in southern Arizona some Ordovician strata have been found but if originally present here, they were removed by pre-Middle Devonian erosion.

It is clear that there was little or no crustal unrest during this long interval for the Upper Devonian section of thick dolomites and shale interbeds was deposited essentially parallel to the underlying beds of the Abrigo formation. Following another, shorter period of non-deposition the massive carbonate beds of the Escabrosa limestone were formed by both chemical precipitation and mechanical accumulation of thick coquinas of crinoid stem fragments, in early Mississippian time. After another interval of non-deposition the basal shale and overlying limestones of the Black Prince formation were deposited in late Mississippian or early Pennsylvanian time. Following another apparent disconformity, the great thickness of fossiliferous carbonate rocks and clastic sediments now represented by the Naco group was deposited in shallow seas during the Pennsylvanian and Permian periods. Throughout the entire Paleozoic era crustal stability was one of the most prominent geological characteristics of the region.

Most of the Mesozoic era is unrecorded. Following the deposition of the Naco group there was a long interval of emergence in the

Triassic and Jurassic periods during which the only rocks formed and preserved were the rarely observed volcanic fragmental beds of the Walnut Gap formation. Some crustal disturbance must have occurred in this interval because the lowest beds of the lower Cretaceous section are coarse boulder conglomerates, derived principally from the Paleozoic strata and lying unconformably upon the Walnut Gap and Horquilla formations. Upon this basal Glance conglomerate was deposited an indeterminate thickness of continental sandstones and shales of the higher formations of the Bisbee group.

The combined Paleozoic and Mesozoic strata received their most important deformation during the Laramide orogeny of late Cretaceous and/or early Tertiary time. During a general crustal compression along northeast-southwest axes, the heretofore undisturbed strata were thrown into great folds, and were broken into numerous thin plates which were generally but not invariably overthrust toward the northeast. The intersections of the prevailing Laramide trends with the older pre-Cambrian structures at nearly right angles, and with the large masses of pre-Cambrian granitic rocks, introduced many complexities into the general structural pattern. At this time, for example, the entire pre-Cambrian core of the Johnny Lyon Hills was rotated more than 40 degrees about a north-northwest trending horizontal axis. This rotation reoriented only slightly the already inverted limbs of tight folds, but overturned some of the steeply plunging pre-Cambrian fold axes. Locally some cataclastic and retrogressive metamorphic effects were imposed by the mechanical deformation.

Following a period of high angle faulting and relaxation of the regional compressive stresses, the area was invaded by swarms of lamprophyre dikes, some with the thicknesses up to 100 feet and traceable for three miles or more. These dikes, which produced local contact metamorphic effects, are apparently consanguinous with the large Texas Canyon quartz monzonite stock in the southern Little Dragoon Mountains and similar intrusive bodies elsewhere in southern Arizona. Some associated hydrothermal activity produced alteration and traces of mineralization in the older rocks.

For Tertiary time the unfossiliferous sedimentary record includes only a sequence of thick alluvial conglomerates (Three-links conglomerate) which was followed by major volcanic activity (Galiuro volcanics). The volcanism was accompanied and followed by intermittent steep faulting. These steep faults, particularly the larger northwest-trending sets, combined with the earlier Laramide structural axes to set up the present physiographic pattern of basins and ranges characteristic of the region.

Within the earlier formed basins, later Tertiary and Quaternary alluvium accumulated to great thicknesses, principally as fanglomerates and fluviatile conglomerates but also as lacustrine deposits of considerable extent. Interbedded volcanics are common in nearby areas and may be present but concealed in the map area. This basin-filling alluvium, generally assigned to the Gila conglomerate, was partially indurated, faulted and tilted, and has been bevelled, dissected, and reworked with considerable vigor by erosion processes to the present time.

GROUND WATER AND ECONOMIC GEOLOGY

Introduction

Southeastern Arizona, where the Johnny Lyon Hills are located, is a region whose economic life has been particularly dependent on two natural resources, water supply and metalliferous ore deposits. The availability of water controlled the early growth of the cattle industry, and the more recent agricultural expansions in cotton and feed crops. The rich mining districts of Bisbee, Tombstone, Superior, Globe-Miami, Ray, Clifton-Morenci, and many lesser areas made metal mining more responsible than any other single factor for drawing population to the region. Continued dependence of the economy on these resources requires that any areal geological study in the region contain some evaluation of the potential ground water and mineral resources of the area under study.

In the Johnny Lyon Hills area, there is only one industry, cattle-raising. The grasslands moistened by the summer rains, and the water withdrawn from ground water reservoirs or trapped by earthen dams from surface runoff, provide sustenance for a considerable number of cattle. The resident ranchers are careful in general, to avoid overgrazing and make strenuous efforts to utilize their available water supplies as efficiently as possible. It is clear, however, that development of water supplies is the limiting factor in ranching expansion.

Although traces of metallic mineralization are found at numerous places in the Johnny Lyon Hills, and although evidences of prospecting efforts are even more numerous, there are no records of mineral production from the area. Local ranchers recall tales of limited gold discovery on Gold Mine Ridge, but it has not been possible to substantiate these reports. A number of extensive prospects have been developed with some exploratory underground workings up to several hundred feet long. More often than not, there is no remaining evidence of whatever distinctive minerals, rock coloration or alteration excited the exploration.

Ground Water Resources

The presence of significant ground water reserves depends upon the existence of suitable bodies of reservoir rocks, located where conditions for recharging these rocks are as favorable as those conditions which withdraw water from the reservoirs. The rocks of the Johnny Lyon Hills area may be subdivided into several groups on the basis of their potential hydrologic value: (1) the pre-Cambrian crystalline rocks, (2) the upper pre-Cambrian, Paleozoic and Mesozoic stratified rocks, (3) the older Tertiary conglomerates and volcanics, (4) the late Tertiary and Quaternary consolidated alluvium and (5) the Recent alluvial fill in the present stream courses.

The older pre-Cambrian crystalline rocks are generally unfavorable sites for water storage. Although they do present large surfaces on The River Slope and The Mesa where considerable surface runoff has an opportunity to percolate down into the rocks, the permeability and porosity of the rocks are generally too low. Only in those areas where faulting and jointing have been extensively developed is there any possibility of appreciable storage. Such situations are not always predictable but the major north trending shear zones in the granodiorite where unsilicified, are possible sites, especially those low on The Mesa drainage. Another potential area for exploration is in the fractured granodiorite east of the thrust faults on the northwest edge of the map area. The water standing in the shaft of the American mine suggests that perhaps the east-dipping faults may serve as subsurface dams to ground water underflow.

Several wells have been drilled in the granodiorite and have shown evidences of deep weathering, fracturing and even subterranean cavities to depths of 600 and 700 feet. A well in the SW$\frac{1}{4}$, sec. 19, T. 14 S., R. 21 E. wholly in the granodiorite produces about three gallons per minute from a water level of 270 feet, in a hole 644 feet deep (Heindl, 1952, Table 15, well #D-14-21, 19 cac).

The stratified older rocks are also generally poor sources for ground water. They are too well indurated and cemented to have any appreciable storage capacity and they are rarely exposed under conditions favoring intraformational recharge. If sufficient fracture porosity was developed during the structural history of the formations, they may be minor sources of water. One such source is exploited by a well in the SW$\frac{1}{4}$, sec. 22, T. 14 S., R. 21 E., just north of the Willcox-Cascabel road as the road crosses the gap south of Rattlesnake Ridge. The well, collared in the lower shale member of the Abrigo formation, was drilled to a depth of 705 feet and developed a little water in the fractured sandstones and quartzites in the top(?) of the Bolsa. The water level is reported at 640 feet and the discharge is only about a gallon per minute under favorable conditions.

Little exploration of the older Tertiary conglomerates and volcanic rocks has been made. In Kelsey Canyon, other sources of water have been available. Some of the interstratified conglomerates and porous tuffs of the Galiuro volcanics might be investigated for aquiferic possibilities. The volcanic members themselves are too impervious to be given much direct consideration.

The Tertiary and Quaternary alluvium is the most important source of ground water in the area. In Allen's Flat and in Tres Alamos Wash the coarse conglomerates and sands although fairly well consolidated have considerable porosity and permeability. Most of the ground water underflow in the Tres Alamos Wash drainage must move through the relatively narrow gap between the southern Johnny Lyon Hills and the Little Dragoon Mountains. Considering the size of the recharging basin and the depth of alluvium at this point it is not surprising that water has been developed. A well at the Deepwell ranch house in the NW$\frac{1}{4}$, sec. 1, T. 15 S., R. 21 E., at the eastern edge of the map area is 160 feet deep entirely in alluvium and has water at 145 feet. A well in Tres Alamos Wash, a half-mile south of the Jack Pot Mine, is 300 feet deep in alluvium with water level reported at 290 feet. These wells provide year around water for several hundred head of cattle.

Other wells with an appreciable yield of water have been drilled in the same formation to the north. At the former Bar X Ranch (plate IV), now headquarters for the Threelinks Ranch, a 300 foot well has water level reported at 240 feet. Still farther north, on the Kelsey Canyon-Tres Alamos Wash divide in the NW$\frac{1}{4}$, sec. 11, T. 14 S., R. 21 E., a 415 foot well is reported to have water standing at the 300 foot level.

The sites of all these wells are along topographic low points of the present Tres Alamos Wash drainage. This topographic axis does not coincide with the center of the alluviated trough over much of its length, however. Therefore wells drilled along it may very well be missing the main flow of ground water through the Tres Alamos trough. Wells developed somewhat farther east (a quarter to a half mile) of the present bed of the wash east of Keith Peak, might develop greater yields than those already in existence. This factor should offset the expense of slightly higher well collar elevations.

The recent alluvial fills in the main washes are the most rapidly recharged, if relatively small, reservoirs. Small subsurface check dams in the coarse sand and gravels locally hold back subsurface runoff, giving it an opportunity to recharge the ground water table in the vicinity of shallow wells. A well drilled to a depth of 100 feet at the Keith Ranch, has a few feet of water standing at the bottom of the hole which is recharged by a small check dam in the ravine which flows east between Sheep Camp Ridge and Keith Peak. In Thompson Wash on the west side of Javelina Hill a small concrete dam was constructed at a narrows in the channel. This dam was rapidly filled to the brim by arkosic sands derived from the gruss of the Johnny Lyon granodiorite. The porous sand reservoir is tapped by a pipe through the dam and will supply water for several months after a good rain in the drainage. Several other sites exist where similar arrangements would be profitable.

Hydrothermal Mineralization and Economic Geology

There is good evidence for more than one period of hydrothermal activity in the Johnny Lyon Hills area. The existence of pre-Cambrian shear zones with hydrothermal alteration in the Johnny Lyon granodiorite has been mentioned already. In the discussion of the great extent of the zones, the type of alteration and the evidence for the age of the zones have been described. In general, the hydrothermal mineralogy of the zones displays few or no traces of metallic ore minerals, although a few prospect pits have been dug in the zone.

In the same discussion, the possibility of renewed hydrothermal activity along these zones in Tertiary time was also mentioned. A number of younger veins intersect lamprophyres (which may be Tertiary) which in turn transect the older shear zones. These veins commonly trend due east to N. 75° E. and dip 25°-50° south (plate I, sec. 29, T. 14 S., R. 21 E.). Mineralogically they are composed principally of brown carbonate, opaline quartz and limonite boxworks. Less commonly, white calcite and traces of malachite, chrysocolla and chalcocite are found.

Similar veins not spatially associated with the older shear zones have been found at many points throughout the granodiorite. On the north side of Gold Mine Ridge they occupy fractures in the major south-dipping shear zone which is part of a Laramide thrust fault. Northwest of Sheep Camp Ridge (SE$\frac{1}{4}$, sec. 12, T. 15 S., R. 20 E.), two prospects have been developed extensively on similar veins up to three feet thick in sheared granite. The veins trend due east and dip 40°-50° to the south, but do not show more than one or two hundred feet of continuity. Small piles of altered granodiorite and vein material showing considerable copper stain have been abandoned on the dumps.

Another typical vein type in the granodiorite consists of massive, milky to opaline, irregular quartz veins a few inches to one or two feet thick, with occasional vugs and open fractures lined with nearly clear comb quartz. Traces of galena, chalcopyrite, pyrite, specularite, malachite, chalcocite and limonite are visible, but the veins are very short and the ore minerals are not abundant. The vein set generally trends N. 70°-80° E. dipping steeply to the south or vertically. A number of prospects have been opened on these veins northeast of Sheep Camp Ridge in sec. 8 and 9. Similar veins are accompanied by vertical north-trending quartz veins of the same composition in the vicinity of Gold Mine Ridge. At a number of places these veins cut lamprophyre dikes, and are therefore probably Tertiary in age.

Considering the complicated and extensive fracture patterns developed during the Laramide orogeny, relatively few of the major faults of that general period are mineralized. Both of the large low angle faults in the Catclaw Hills have been silicified extensively at various points, but although many prospect pits have been dug, only one or two show traces of metallic mineralization. The large N. 30° W.-trending normal fault on the west side of Sheep Camp Ridge is occupied by a one to five foot thick east-dipping vein for more than 400 feet of its length. The vein material is a limonitic brown, microgranular carbonate, with variable amounts of quartz, clay minerals and sericite. Scattered limonite pseudomorphs after pyrite are sometimes present. Sheared and altered granodiorite is also present in variable amounts. No ore minerals have been found.

The long prospecting tunnel in the Pinal schist and Pioneer shale on the west side of Keith Peak (p. 333) also shows only slight traces of copper staining in the dump material, with no traces visible in the workings. This tunnel was apparently driven with the intention of intersecting at depth a weakly mineralized fault and lamprophyre zone in the overlying Bolsa quartzite, but the goal was never reached.

One of the most extensive areas of alteration of the granodiorite is a broad ill-defined band of extensive specularite development trending north-northeast against the thrust faults in the northwest corner of the map area. The band is up to a mile long and 750 feet wide. In it the granodiorite is locally sheeted with thin veins of quartz and calcite less than 200 feet long, trending about N. 25° E. and dipping 60°-65° to the southeast. The specularite occurs not only in the quartz veins, but as veinlets and as a replacement of the ferromagnesian minerals in the granodiorite, in plates up to 1-2 cm in diameter. In addition, the veins locally carry white pocket calcite, brown vein carbonate, traces of pyrite, chalcopyrite, chalcocite, oxidized copper minerals, and, uncommonly, small pockets of white fluorite and tabular barite.

Numerous prospect pits and the American mine, one of the most extensive workings in the area, are located in this zone. At the mine, at present, only a flooded inclined shaft, directed S. 68° E. at 55°, can be followed for about 90 feet, but the size of the dump suggests a much larger development. The last material deposited on the dump is quartzite and red-brown siltstone of the Pioneer shale indicating the workings crossed a major fault structure (see pl. I and fig. 78). The dump material shows only traces of valuable ore minerals.

Northeast of the American mine, a zone of large lenses of quartz and silicified granodiorite trends N. 70° E. for about a mile. This zone appears to be pre-Cambrian in age and is truncated on the west by the thrusting. Individual lenses are up to 1,000 feet long and 100 feet thick and dip north at average dips of about 50°. No valuable minerals have been observed in this zone.

Within the various thrust plates numerous prospect pits have been dug. In general the Carboniferous formations, particularly the Escabrosa limestone, carry more indications of hydrothermal mineralization than the other stratified rocks.

On Keith Peak, scattered irregular fractures in the Escabrosa limestone carry thin veinlets of opaline silica with traces of pyrite, galena and chalcopyrite. On the main ridge trending southeast from the top of Keith Peak a small mine, Tip Top #1, has been opened about 80 feet above the base of the Escabrosa limestone. About 150 feet of irregular workings on two levels follow narrow, porous breccia zones which generally trend northeast but ramify in all directions. These zones are generally four inches wide or less and contain fragments of limestone and dolomite in a matrix of coarse white calcite and quartz. Malachite, chrysocolla, limonite and copper pitch are the principal metallic minerals, but traces of primary chalcopyrite, bornite and pyrite are also visible. On a small bench on the slope west of the mine portal, the owner J. J. Wien, has stockpiled about a ton of low grade oxidized copper ore.

Northeast of the Tip Top #1, in a steep gully in the SW$\frac{1}{4}$, sec.

21, an unnamed prospecting tunnel is driven 175 feet north-northwest, into the basal Escabrosa limestone toward the large N. 65° E. trending 'diorite' lamprophyre. The exploratory work was abandoned after passing through the dike, and no visible evidence of mineralization remains anywhere in the working. Prospect pits showing minor mineralization along the surface outcrop of the dike were the apparent source of interest in this effort.

On the west side of Tres Alamos Wash, a short distance south of the junction with Thompson Wash, a considerable number of prospects have been developed in the overturned Carboniferous section. The most extensive of these is the Jack Pot mine, which is only partly accessible at present. The inclined entry shaft is in the basal shale member of the Black Prince formation. It descends nearly one hundred feet S. 31° W. at 41°, which is nearly down the dip of the bedding and its footwall is the overturned base of a conglomerate bed. The excavation was made in the soft maroon shales with interbedded cherts stratigraphically below the conglomerate. At the base of the shaft, workings can be seen trending to the west and southwest, which probably connect with a number of vertical shafts to the west in the overlying Escabrosa limestone. Only a few traces of copper stain are visible in the dump material. Some of the other prospects nearby show traces of malachite and considerable red jasper in irregular lenses.

About 800 feet southwest of the Jack Pot mine, a number of prospects in the basal Escabrosa and upper Martin formations are on a set of numerous, steep, vuggy, milky quartz veinlets trending due north to N 5° E. Extensive silicification has taken place both in the basal tan dolomite of the Escabrosa and in the highest shale of the Martin. This silica is chalcedonic, white to brown, and dispersed throughout are malachite, chrysocolla, chalcocite, limonite and considerable brown carbonate.

On the crest of Javelina Hill, several prospects have been dug on showings of malachite, limonite and copper pitch in the sheared basal shale of the Black Prince formation and carbonate rocks above and below the shale member.

Throughout the rest of the Johnny Lyon Hills area intensive prospecting has left typical scars, but rarely is evidence of significant mineralization visible.

A summary of the hydrothermal history of the Johnny Lyon Hills area must acknowledge the widespread hydrothermal activity, both pre-Cambrian and late Cretaceous or early Tertiary. The principal effects are visible in the alteration of the existing rocks rather than in the introduction of ore deposits. Traces of ore minerals are found in many places, but there is little evidence on which to base suggestions for a profitable exploration program. Detailed studies of alteration distribution in the granodiorite, combined with geochemical prospecting might provide a focal point for exploration. The evidence of mineralization in the overturned Carboniferous section on the west side of Tres Alamos Wash is increasing as the section disappears south under the alluvium. Possibly, geophysical methods of prospecting might disclose the presence of appreciable buried sulfide bodies under the cover. On the basis of visible indications throughout the area, however, no great confidence can be placed in the productivity of such efforts.

Anderson, C. A. (1951) Older pre-Cambrian structure in Arizona, Geol. Soc. Am., Bull., Vol. 62, p. 1331-1346.

Anderson, E. M. (1951) The dynamics of faulting, and dyke formation with applications to Britain, 2nd ed., Oliver and Boyd, Edinburgh and London.

Bailey, E. B. (1930) New light on sedimentation and tectonics, Geol. Mag., Vol. 67, p. 77-92.

________ (1936) Sedimentation in relation to tectonics, Bull. G. S. A., Vol. 47, p. 1713-1726.

Barker, F. (1954) Pre-Cambrian and Tertiary geology of the Los Tablos quadrangle, New Mexico, Calif. Inst. Tech., Ph.D. dissertation (unpublished).

Blake, W. P. (1883) The Silver King mine, Eng. and Min. Jour., Vol. 35, p. 238-239, 254-256.

Brown, W. H. (1939) Tucson Mountains, an Arizona Basin Range type, Geol. Soc. Am. Bull., Vol. 50, p. 697-760.

Bryan, K. (1923) Erosion and sedimentation in the Papago country, Arizona, with a sketch of the geology, U. S. Geol. Survey Bull. 730-B, p. 37-65.

________ (1925a) The Papago country, Arizona, U. S. Geol. Survey W. S. Bull. 499.

________ (1925b) The date of channel trenching (arroyo cutting) in the arid southwest, Science, new series, Vol. 62, p. 342.

________ (1926) The San Pedro Valley, Arizona and the geographic cycle (abstract) Geol. Soc. Am. Bull., Vol. 37, p. 170.

Bryan, K., Smith, G. E. P., and Waring, G. A. (1934) Geology and water resources of the San Pedro River Valley. U. S. Geol. Survey, unpublished manuscript, on open file.

Campbell, I. and Maxson, J. H. (1933) Some observations on the Archean metamorphics of the Grand Canyon, Proc. Nat. Acad. Sci., Vol. 19, p. 806-809.

Chayes, Felix (1949) A simple point counter for thin-section analysis, Am. Mineral., Vol. 34, p. 1-11.

Cooper, J. R. (1950a) Johnson Camp area, Cochise County, Arizona, Univ. Arizona, Ariz. Bur. Mines, Bull. 156, p. 30-39.

________ (1950b) Geology and ore deposits of the Johnson area, Arizona, U. S. Geol. Survey, unpublished manuscript.

Dapples, E. C., Krumbein, W. C., and Sloss, L. L. (1953) Petrographic and lithologic attributes of sandstones, Jour. Geol., Vol. 61, p. 291-316.

Darton, N. H. (1925) A resume of Arizona geology, Univ. Ariz., Ariz. Bur. Mines, Bull. 119.

________ (1932) Algonkian strata of Arizona and west Texas (abstract), Geol. Soc. Am., Bull., Vol. 43, p. 123.

________ (1933) Guidebook of the western United States-Part F, Southern Pacific Lines, U. S. Geol. Survey Bull. 845.

Darton, N. Y., Lausen, C. D., and Wilson, E. D. (1924) Geologic map of the state of Arizona, scale 1:500,000, Ariz. Bur. Mines, in cooperation with the U. S. Geol. Survey.

Davis, W. M. (1938) Sheetfloods and streamfloods, Geol. Soc. Am. Bull., Vol. 49, p. 1337-1416.

Dumble, E. T. (1902) Notes on the geology of southeastern Arizona, Am. Inst. Min. Engrs. Trans., Vol. 31, p. 696-715.

Ehlers, E. G. (1953) An investigation of the stability relations of the Al-Fe members of the epidote group, Jour. Geol., Vol. 61, no. 3, p. 231-251.

Fairbairn, H. W. (1949) Structural petrology of deformed rocks, Addison-Wesley Press, Inc., Cambridge, Mass.

Fenneman, N. M. (1931) Physiography of the western United States, McGraw-Hill Co., New York.

Folk, R. L. (1954) The distinction between grain size and mineral composition in sedimentary rock nomenclature, Jour. Geol., Vol. 62, p. 344-359.

Galbraith, F. W. (1949) Thrust faulting in the Empire Mountains, southeastern Arizona, (abstract) Geol. Soc. Am. Bull., Vol. 60, p. 1889-1890.

Galbraith, F. W. and Loring, W. B. (1951) Swisshelm district, Univ. Arizona, Ariz. Bur. Mines Bull. 158, p. 30-36.

Gastil, R. G. (1953) The geology of the eastern half of the Diamond Butte quadrangle, Gila County, Arizona, Unpublished thesis for Ph.D., Univ. Calif. (Berkeley).

________ (1954) Late pre-Cambrian volcanism in southeastern Arizona, Am. Jour. Sci., Vol. 252, p. 436-440.

Gidley, J. W. (1923) Preliminary report on fossil invertebrates of the San Pedro Valley, Arizona, U. S. Geol. Survey, Prof. Paper 131, p. 119-131.

Gidley, J. W. (1926) Fossil Proboscidea and Edentata of the San Pedro Valley, Arizona, U. S. Geol. Survey, Prof. Paper 140, p. 83-93.

Gilbert, G. K. (1875) U. S. Geog. and Geol. Survey 100th Mer., Vol. 3, p. 540-541.

Gilluly, J. (1941) Thrust faulting in the Dragoon Mountains, Ariz. (abstract), Geol. Soc. Am. Bull., Vol. 52, p. 1949.

_________ (1945) Emplacement of the Uncle Sam porphyry, Tombstone, Arizona, Am. Jour. Sci., Vol. 243, p. 643-666.

_________ Geology of central Cochise County, Arizona, U. S. Geol. Survey, Prof. Paper, in preparation.

Gilluly, J., Cooper, J. R., and Williams, J. S. (1954) Late Paleozoic stratigraphy of central Cochise County, Arizona, U. S. Geol. Survey, Prof. Paper, 266.

Griggs, D. (1937) A theory of mountain building, Am. Jour. Sci., Vol. 237, p. 611-650.

Grim, R. E. (1953) Clay mineralogy, McGraw-Hill Book Co., New York.

Grout, F. F. (1932) Petrography and petrology, McGraw-Hill Book Co., New York.

Heindl, L. A. (1952) Upper and Lower San Pedro basins. In "Ground-water in the Gila River basin and adjacent areas, Arizona (a summary)", U. S. Geol. Survey, Open File Report.

Hinds, N. E. A. (1936) I. Ep-Archean and Ep-Algonkian intervals in western North America, p. 1-52, II. Uncompahgran and Beltian deposits in western North America, Carnegie Inst. Wash. Publ. 463, p. 53-136.

_________ (1938) Pre-Cambrian Arizona revolution in western North America, Am. Jour. Sci., 5th Series, Vol. 35, p. 445-449.

Howard, A. D. (1942) Pediment passes and the pediment problem, Jour. Geomorph., Vol. 5, p. 3-31, 95-136.

Jagger, T. A., Jr., and Palache, C. (1905) Bradshaw Mountains folio, U. S. Geol. Survey, Folio 126.

Jahns, R. H. (1946) Mica deposits of the Petaca district, Rio Arriba County, New Mexico, New Mexico Bur. Mines Bull. 25.

_________ (1952) Pegmatite deposits of the White Picacho district, Maricopa and Yavapai Counties, Arizona, Univ. Ariz., Ariz. Bur. Mines, Bull. 162.

Johannsen, A., A descriptive petrography of the igneous rocks, Vol. I, 2nd ed. (1939); Vol. II, 1st ed. (1932); Vol. III, 1st ed. (1937), Vol. IV, 1st ed. (1938), Univ. Chicago Press, Chicago, Ill.

Johnson, D. W. (1932a) Rock fans of arid regions, Am. Jour. Sci., 5th ser., Vol. 23, p. 389-420.

________ (1932b) Rock planes of arid regions, Geogr. Rev., Vol. 22, p. 656-665.

Jones, O. T. (1938) On the evaluation of a geosyncline, Geol. Soc. London Proc., Vol. 94, p. LXII-LXVI.

Just, Evan (1937) Geology and economic features of the pegmatites of Taos and Rio Arriba Counties, New Mexico, New Mexico Bur. Mines, Bull. 13.

Kearney, T. H. and Peebles, R. H. (1951) Arizona flora, Univ. of Calif. Press, Berkeley.

Kelley, V. C. and Silver, C. (1952) Geology of the Caballo Mountains, Univ. New Mexico, Publ. in Geol., No. 4.

Kuenen, Ph. H. (1950) Marine geology, John Wiley, New York.

King, P. B. and Flawn, P. T. (1953) Geology and mineral deposits of pre-Cambrian rocks of the Van Horn area, Texas, Univ. Texas, Publ. 5301.

Knechtel, M. W. (1937) Geology and ground water resources of the valley of the Gila River and San Simon Creek, Graham County, Arizona, U. S. Geol. Survey, Water Supply Paper 976.

Knopf, A. (1948) The geosynclinal theory, Geol. Soc. Am. Bull., Vol. 59, p. 649-670.

Knopf, E. B. (1931) Retrogressive metamorphism and phyllonitization, Pt. I, Am. Jour. Sci., 5th series, Vol. 21, p. 1-27.

________ and Ingerson, E. (1938) Structural petrology, Geol. Soc. Am. Mem. No. 6.

Krumbein, W. C. and Sloss, L. L. (1951) Stratigraphy and sedimentation, W. H. Freeman and Co., San Francisco.

Krynine, P. D. (1948) The megascopic study and field classification of sedimentary rocks, Jour. Geol. Vol. 56, p. 130-165.

Larsen, E. S., Jr., Keevil, N. B. and Harrison, H. C. (1952) Method for determining the age of igneous rocks using the accessory minerals. Geol. Soc. Am. Bull., Vol. 63, p. 1045-1052.

Lawson, A. C. (1915) The epigene profiles of the desert, Univ. of Calif., Dept. of Geol. Bull., Vol. 9, p. 23-48.

Lindgren, W. (1905) The copper deposits of the Clifton-Morenci district, Arizona, U. S. Geol. Survey, Prof. Paper 43.

________ (1926) Ore deposits of the Jerome and Bradshaw Mountains quadrangles, Arizona, U. S. Geol. Survey Bull. 782.

Lyell, Charles (1837) Principles of geology, 5th ed., Vol. II, London.

McKee, E. D. (1951) Sedimentary basins of Arizona and adjoining areas, Geol. Soc. Am. Bull., Vol. 62, p. 481-506.

Moore, B. N., Tolman, C. F. (with contributions by Butler, B. S. and Hernon, R. M.) (1949) Geology of the Tucson quadrangle Arizona, U. S. Geol. Survey, Open File Rept., on file at the Arizona Bur. Mines, Tucson.

Noble, L. F. and Hunter, J. F. (1917) A reconnaissance of the Archean complex of the Granite Gorge, Grand Canyon, Arizona, U. S. Geol. Survey, Prof. Paper 98, p. 95-113.

Peterson, N. P. (1951) Geology and ore deposits of the Castle Dome area, Gila County, Arizona, U. S. Geol. Survey Bull. 971.

________ (1954) Geology of the Globe quadrangle, Arizona, U. S. Geol. Survey, Geol. Quad. Map 411.

Pettijohn, F. J. (1943) Archean sedimentation, Geol. Soc. Am. Bull., Vol. 54, p. 925-972.

________ (1949) Sedimentary rocks, Harper and Bros., New York.

________ (1954) Classification of sandstones, Jour. Geol., Vol. 62, p. 360-365.

Ransome, F. L. (1903) Geology of the Globe district, Arizona, U. S. Geol. Survey, Prof. Paper 12.

________ (1904) Geology and ore deposits of the Bisbee quadrangle, Arizona, U. S. Geol. Survey, Prof. Paper 21.

________ (1915) Quicksilver deposits of the Mazatzal Range, Arizona, U. S. Geol. Survey, Bull. 620, p. 111-128.

________ (1916) Some Paleozoic sections in Arizona and their correlation, U. S. Geol. Survey, Prof. Paper 98, p. 133-166.

________ (1919) The copper deposits of Ray and Miami, Arizona, U. S. Geol. Survey, Prof. Paper 115.

Ransome, F. L. (1932) General geology and summary of ore deposits in "Ore deposits of the Southwest", 16th Internat. Geol. Cong., United States (1933), Guidebook 14, Excursion C-1.

Reiche, P. (1949) Geology of the Manzanita and north Manzano Mountains, New Mexico, Geol. Soc. Amer. Bull., Vol. 60, p. 1183-1212.

Schrader, F. C. (1909) Mineral deposits of the Cerbat Range, Black Mountains and Grand Wash Cliffs, Mohave County, Arizona, U. S. Geol. Survey, Bull. 397.

_________ (1915) Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona, U. S. Geol. Survey Bull. 582.

Schuchert, C. (1923) Sites and nature of the North American geosynclines, Geol. Soc. Am. Bull., Vol. 34, p. 151-230.

Shrock, R. R. (1948) Sequence in layered rocks, McGraw-Hill Book Co., New York.

Smith, H. V. (1930) The climate of Arizona, Univ. of Ariz. Coll. of Agr. Bull. 130.

Stark, J. T. and Dapples, E. C. (1946) Geology of the Los Pinos Mountains, New Mexico, Geol. Soc. Am. Bull., Vol. 57, p. 1121-1172.

Steinmann, G. (1905) Geol. Beobacht in den Alpen. II Die Schardtsche Ueberfaltungsteorie und die geologische Bedeutung der Tiefseeabsatze und der ophiolithschen Massengesteine. Bericht Naturforsch Gesell, Freiburg, Vol. 16, p. 18.

Stoyanow, A. (1936) Correlation of Arizona Paleozoic formations, Geol. Soc. Am., Bull., Vol. 47, p. 459-540.

_________ (1942) Paleozoic paleogeography of Arizona, Geol. Soc. Am. Bull., Vol. 53, p. 1255-1282.

_________ (1949) Lower Cretaceous stratigraphy in southeastern Arizona, Geol. Soc. Am. Mem. 38.

Taliaferro, N. L. (1943) Franciscan Knoxville problem, Am. Assoc. Pet. Geolog., Vol. 27, p. 109-219.

Thomas, B. E. (1949) Ore deposits of the Wallapai district, Arizona, Econ. Geol., Vol. 44, p. 663-705.

Turner, F. J. (1948) Mineralogical and structural evolution of the metamorphic rocks, Geol. Soc. Am., Mem. 30.

_________ and Verhoogen, J. (1951) Igneous and metamorphic petrology, McGraw-Hill, New York.

Tyrrell, C. W. (1933) Greenstones and greywackes, C. R. Reunion Intern. pour l'Etude du Pre-Cambrien (1931), p. 24-26.

Twenhofel, W. H. (1939) Principles of sedimentation, 1st ed., McGraw-Hill Book Co., New York.

Williams, H., Turner, F. J., and Gilbert, C. M. (1954) Petrography, W. H. Freeman and Co., San Francisco, Calif.

Wilson, E. D. (1939) Pre-Cambrian Mazatzal revolution in central Arizona, Geol. Soc. Am. Bull., Vol. 50, p. 113-1164.

_________ (1949) Structure in Arizona (abstract), Geol. Soc. Am. Bull., Vol. 60, p. 1929.

_________ (1951) Huachuca Mountains, Univ. Ariz., Ariz. Bur. Mines Bull. 158, p. 36-40.