GEOLOGY OF THE PINE VALLEY MOUNTAINS, UTAH

by

EARL FERGUSON COOK

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Approved by J. Hoover Mackin

Department Geology

Date May 21, 1954

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Date: May 4, 1954

We have carefully read the thesis entitled Geology of the Pine Valley Mountains, Utah submitted by Earl Ferguson Cook in partial fulfillment of the requirements of the Doctorate Degree and recommend its acceptance. In support of this recommendation we present the following joint statement of evaluation to be filed with the thesis.

Mr. Cook's thesis deals with the geology of a rugged desert range in southwestern Utah. His geologic map, covering an area of about 500 square miles on a 1/31,250 scale, shows the areal distribution of 28 separate units of sedimentary and volcanic rock ranging in age from Late Paleozoic to Recent, and five intrusive bodies of monzonite porphyry. The field work occupied about seven months spread over three summer seasons. Because no base map was available, Cook laid down his geologic lines on air photos, and later transferred them to a planimetric map constructed from a semi-controlled air photo mosaic. The extent of his library work, in connection with various problems of the area, is indicated by a list of about 80 references cited in the text.

Mackin visited the area twice while the work was in progress, and field checked the final map. The accuracy of the map corresponds with the scale, and Cook's interpretation of the geologic relations, while not in some cases "the last word", is entirely acceptable to the thesis committee. The thesis will probably be published in its entirety, and will result in at least one special paper.

Outstanding original contributions are:-
The working out of the structural history of a key area in a transitional zone between the Colorado Plateau on the east and the Basin Range Province on the west.
A demonstration that the Pine Valley Mountains intrusion, one of the largest of its type in the West, is floored by sedimentary rock. This is an important contribution to our knowledge of the Tertiary porphyry intrusions of the Colorado Plateau and the Basin Range Province.
The mapping of a complex sequence of Tertiary volcanic rocks, most of which are unusual types of special interest to students of volcanism.

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by

EARL FERGUSON COOK

The Pine Valley Mountains of southwest Utah lie in a zone which is structurally transitional between the Basin and Range and the Colorado Plateau provinces. The mountains are largely composed of a deroofed monzonite porphyry laccolith which has an exposed extent of 70 square miles and a maximum remaining thickness of 3,000 feet. The concordant base of the laccolith is exposed or thinly covered by talus for 25 miles.

The decipherable history of the Pine Valley Mountains begins with a long period of marine and continental deposition, with intermittent emergence and erosion, but without folding. Sometime in the late Jurassic or early Cretaceous, the region was moderately warped and Upper Jurassic rocks were beveled by erosion. Geosynclinal or foreland trough sedimentation began in the early Late Cretaceous with the deposition of a basal conglomerate followed by a thick accumulation of shale and sandstone.

Near the close of Montana time the area was uplifted; two folds developed along northeast axes, became overturned

toward the east, and possibly broke into thrusts of small displacement. The numerous orogenic pulsations recorded in the thick Cretaceous and Tertiary sediments of central Utah apparently did not affect the Pine Valley Mountains area. The absence of evidence of movement within the Upper Cretaceous rocks and within the overlying Claron formation (the basal part of which may also be of Upper Cretaceous age) closely brackets the main Laramide movement.

After the Laramide folds were planed off by erosion, the quartzite conglomerate and lacustrine limestone of the Claron formation were deposited. Claron deposition was closely followed by an extended series of volcanic eruptions which produced rhyolite and dacite ignimbrites; welded tuff-breccia; andesite, latite, and dacite flows and breccia; mudflow deposits; and minor air-fall tuff and intercalated sediments. Several unconformities within the volcanics, some of them marked by deposits of lacustrine limestone and quartzite gravel, may record either orogenic disturbances or periods of great intrusive folding. Although the Pine Valley laccolith postdates this Early(?) Tertiary volcanic sequence, other intrusions in the area may be older and may have been associated with the earlier folding in the volcanics.

Closely following the formation of the volcanic rocks, the Pine Valley intrusion spread laterally between the Claron formation and the overlying volcanics. The intrusion moved in

as a half-crystalline mush in which some gravitative settling of the mafic constituents took place before solidification of the rest magma. A thin zone about 1,200 feet above the base of the laccolith apparently remained partially liquid longer than the rest and suffered the most intense deuteric alteration during final consolidation. A roughly horizontal color banding in the laccolith is believed to be due partly to gravitational crystal fractionation and partly to differential deuteric alteration.

During the Quaternary, deep erosion, stimulated by spasmodic uplift along block faults (accompanied by widespread thin basalt flows), has stripped the cover from the Pine Valley laccolith. Because of its resistance to erosion, the laccolith now stands high above its less resistant sedimentary pedestal.

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GEOLOGY OF THE PINE VALLEY MOUNTAINS, UTAH

INTRODUCTION

Present Investigation

Objectives

The igneous mass capping the Pine Valley Mountains in southwestern Utah (map, Fig. 1) was recognized as an intrusive body by Mackin (personal communication) during reconnaissance in connection with the geologic mapping of the Iron Springs district. In that district the upper parts of three laccoliths are exposed, but no portion of a floor of any of the bodies has been found (Mackin, 1947a, p. 16). Consequently the fact that the concordant base of the Pine Valley Mountains intrusion is exposed or thinly covered by talus for about twenty-five miles suggested that an investigation of this body and the surrounding sedimentary and volcanic rocks which constitute its structural setting might supplement the existing knowledge of the intrusive bodies of southwestern Utah.

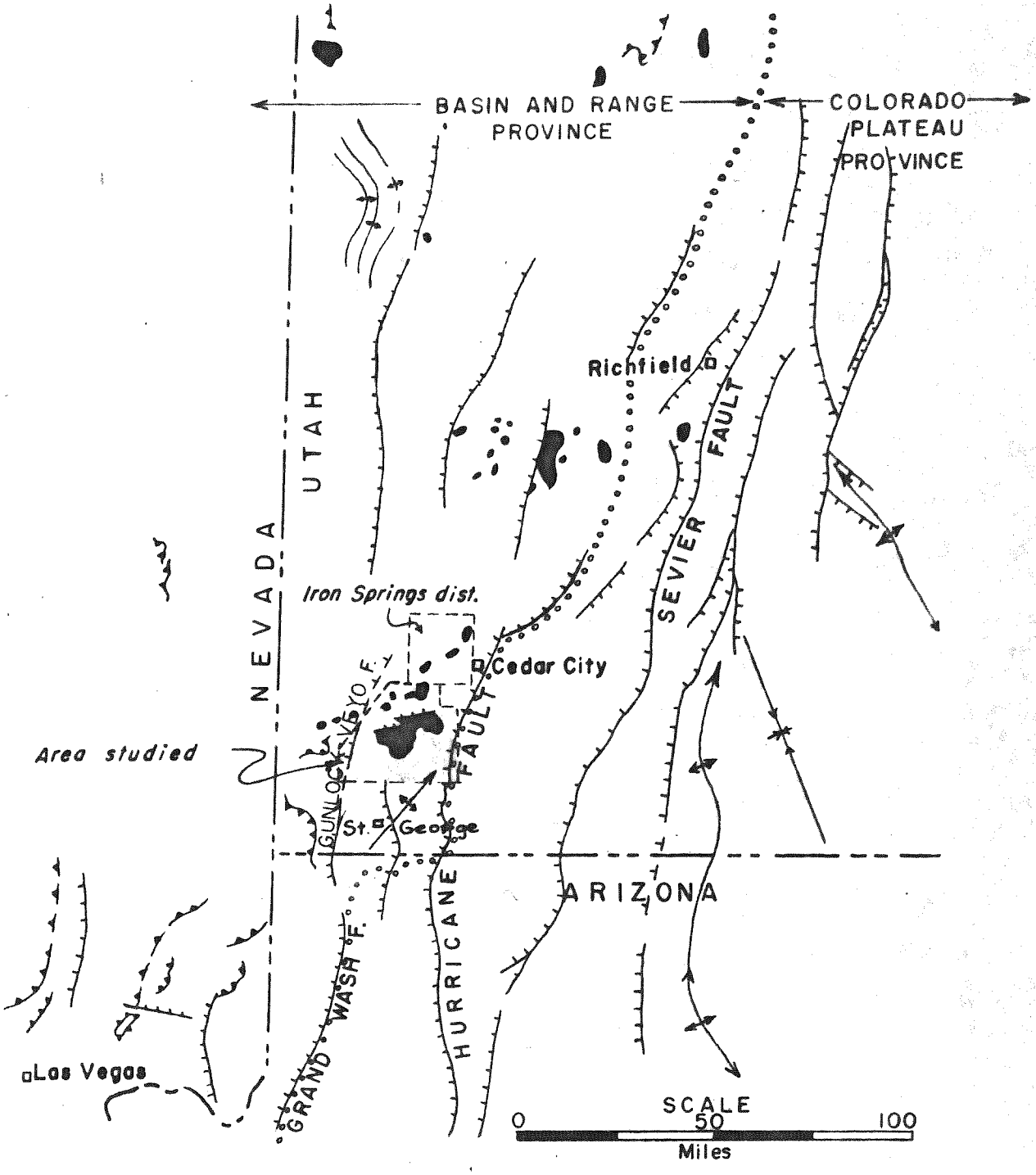


FIG. 1 MAP SHOWING LOCATION OF AREA STUDIED AND THE REGIONAL STRUCTURAL SETTING. Data from Tectonic Map of the United States.

It became evident, with the progress of mapping, that an understanding of the structural relationships required an extension of the limits of the area to include a portion of the Gunlock fault on the west and part of the Hurricane fault on the east. The study thus covers the width of a zone which is structurally transitional between the Basin and Range province and the Colorado Plateau province.

Field work

Field mapping was carried on during the summers of 1951, 1952, and 1953. A network of foot traverses covered most of the area; the geology between traverses was done by photogeology. Contact prints of air photos were used in field mapping; at the close of each field season data were transferred from the photos to photomosaics.

Photogeology

Most of the contacts and faults shown on the geologic map were plotted by stereoscopic study of air photos, based upon spot field observations during traverses across structure. The solid-line contacts and faults represent, to a large extent, traces which have been determined accurately within the limits of photogeologic interpretation, but which have not been walked out.

Photogeology proved most useful in the bedded sedimentary rocks of the southern part of the map area, more

difficultly usable and less accurate in the volcanic sequence of the northern Pine Valley Mountains, and of relatively little use in the intrusive rocks.

Attitudes of bedded rocks (and of platy parting in igneous rocks) were visually estimated under the stereoscope. The photogeologic attitude symbols shown in the map explanation illustrate one of the limitations of the technique: high dips cannot be estimated nearly so accurately as low dips. Thus one attitude symbol includes dips of one to three degrees, whereas another covers the range of 45 to 89 degrees; it is just as easy (or difficult) to estimate a dip accurately in the one range as the other. Few dips in the Pine Valley Mountains area exceed 45 degrees; consequently, most of the dips fall within the field of greater accuracy of the method. Many photogeologic estimates were checked in the field during this study and it is felt that 90 per cent of the photogeologically estimated dips should fall within the range indicated.

Base maps

Semi-controlled photomosaics of the Soil Conservation Service, enlarged to a scale of two inches equals one mile, were used as planimetric base for most of the area. The photomosaics, especially in areas of high relief, contain inherent planimetric errors, but are good enough for reconnaissance

mapping. In the northern portion of the map, between 37° 30' N. and 37° 35' N. latitude, topographic sheets of the U. S. Geological Survey were available.

Vertical control for construction of profiles in the area south of 37° 30' N. was obtained by spot Paulin altimeter readings, tied to a bench mark both morning and night, and corrected by means of a daily variation curve constructed by making hourly observations at a fixed point during several days. Elevations obtained in this manner are probably accurate to within 50 feet.

Previous Geologic Investigation in This and Adjacent Areas

The early surveys

The first geologist in southwestern Utah was A. R. Marvine who, traveling for the Wheeler Survey, noted (1875, p. 136) that in the Hurricane Cliffs near Toquerville, rising abruptly from a basalt-floored valley,

> are the edges of several thousand feet of sedimentary strata, which, dipping at first gently away from their exposed edges, and acquiring, in a succession of abrupt steps, the various members of the overlying geological series, stretch eastward to the Rocky Mountains and form the great Colorado Plateau.

In the following year, 1872, G. K. Gilbert, also with the Wheeler Survey, recognized (1875, p. 59) the transitional geologic character of the area:

> ....in the vicinity of Cedar City....the Tertiary passes....to the Iron Mountain and Pine Valley Ranges. Throughout this region....there is a graduated mingling of characters, completely bridging over the interval from the plateaus on one side to the ranges on the other.

E. E. Howell, working through this area again for the Wheeler Survey in 1872 and 1873, stated the same thought as follows (1875, p. 231):

> There is such a gradation of the range into the plateau system, along their line of intersection in Southern Utah, that it is impossible to draw a line which shall have all the range structure on one side and all plateau on the other.

Howell also published the first geological description of the Pine Valley Mountains (1875, p. 254):

> These mountains, which owe their existence to a heavy bed of trachyte that protected them while the surrounding country was being denuded away, are flanked on the west, south, and east by a belt of basaltic craters, the latest of which are perfect in form, although made up of loose scoriaceous materials, and are as yet uncovered with vegetation.

C. E. Dutton, who joined the Powell Survey in 1875, described (1882, p. 37) the Pine Valley Mountains as seen from a point on the Hurricane Cliffs:

> To the southwestward are the sierras of the Basin Province, and quite near to us there rises a short but quite lofty range of veritable mountains, contrasting powerfully with the flat crestlines and mesas which lie to the south and east. It is the Pine Valley range, and though its absolute altitude above the sea is smaller than many other ranges of the West, yet since their bases are comparatively low the mountain masses themselves are very high.

Dutton, in his Tertiary History of the Grand Canyon District

(1882), published two geologic maps covering a portion of the Pine Valley Mountains area (Atlas Sheet II at a scale of 1:1,000,000 and Atlas Sheet XX at a scale of 1:250,000). Atlas Sheet II shows the Pine Valley Mountains to consist largely of "Trachyte, rhyolite, and andesite" undifferentiated; Sheet XX indicates the main mass to be "trachyte and rhyolite" and shows no andesite. The topographic base of Sheet XX is today, almost 75 years later, the best topographic map available of the Pine Valley Mountains.

Dutton believed (1880, p. 23) that differential uplift of the western margin of the Colorado Plateau produced the Hurricane and Grand Wash faults and that, in the latitude of the Pine Valley Mountains, the uplift was mainly on the Hurricane fault.

Until 1904 these reconnaissance reports were all the recorded geologic knowledge of southwest Utah. Virtually no geologic work was done in the Pine Valley Mountains during the early surveys.

Studies of restricted areas

The first geologic investigation of a restricted area in southwest Utah was made by Huntington and Goldthwait who spent six weeks of the summer of 1902 studying the southeastern flank of the Pine Valley Mountains and the adjacent portion of the Hurricane fault. In addition to confirming, on

physiographic evidence, Dutton's conclusions about differential uplift of the plateau country and the areas to the west, Huntington and Goldthwait (1904; 1905) demonstrated that there were two main periods of movement on the Hurricane fault, separated by a long interfault erosion cycle.

In the first report dealing primarily with the economic geology of southwest Utah, Lee (1907) described the Iron County coal field and included a description of the coal beds in the Harmony field in the northeastern part of the Pine Valley Mountains. Two years later, in a report on the coal fields of southern Utah, Richardson (1909) gave a more detailed description of the Harmony field.

A major geologic investigation in an area adjacent to the Pine Valley Mountains was carried out in the early years of this century by Leith and Harder (1908), who studied and mapped the Iron Springs district (Fig. 1). Apparently Leith and Harder were the first geologists to study the igneous rocks west of the Hurricane fault; they mapped the intrusive bodies of the Iron Springs district as andesite laccoliths and called the extrusive rocks "latitic lavas and associated pyroclastics".

The geology of the Bull Valley district, which appears to be similar to that of the nearby Pine Valley Mountains, was outlined by Wells (1938) who separated the extrusive rocks of the district into an older group of flows (largely porphyritic latites) and a younger group of rudely stratified pyroclastics.

In the Bull Valley Mountains, according to Wells, intrusion of monzonite porphyry and deformation were synchronous with the accumulation of the volcanics, which show progressive unconformity.

The transitional nature of the structure between the Gunlock and Hurricane faults was well brought out by the mapping of Dobbin (1939) in the St. George basin and vicinity. Dobbin regarded the igneous rock capping the southern Pine Valley Mountains as trachyte.

The evolution of the Hurricane fault zone in the region east of the Pine Valley Mountains was described by Gardner (1941) who recognized three periods of faulting (two Tertiary, one Quaternary). Gardner, who was the first to map the Hurricane zone in detail, referred to the igneous rock of this part of the Pine Valley Mountains as Miocene(?) latite lavas.

The first detailed general geologic study of an area near the Pine Valley Mountains was started in 1942 by Mackin in the Iron Springs district. Results of this investigation which are significant in relation to the geology of the Pine Valley Mountains are:

(1) mapping of zones within the intrusive bodies on the basis of joint types and degree of endomorphic alteration (Mackin, 1947a).

(2) demonstration that the joint types and patterns are related to direction and kind of intrusive flow

(Mackin, 1947a, pp. 33-40; 1947b).

(3) summation of evidence that some of the interior intrusive rock was emplaced by a late intrusive surge (Mackin, 1947a, pp. 19-21).

(4) proof that the intrusions all followed the same stratigraphic horizon, although they probably range in shape from a laccolith with peripheral faults (bysmalith?) to a "bulgy sill" (Mackin, 1947a).

(5) recognition that the lower units of the extrusive sequence are welded tuffs (Mackin and Nelson, 1950).

(6) demonstration of the outward migration of iron during endomorphic alteration of the intrusive bodies (Mackin and Switzer, 1948) and of at least one of the welded tuff units (Mackin, 1952).

Recent geologic work in and near the Pine Valley Mountains includes Proctor's investigation (1949; 1952) of the Silver Reef mining district; Bissell's correlation (1952) of the Cretaceous and Tertiary sedimentary rocks of southwest Utah; and Neighbor's outline (1952) of the geology of the structure of a portion of the eastern foothills of the Pine Valley Mountains.

Acknowledgments

Dr. J. H. Mackin suggested the area, directed the investigation, and critically reviewed the map and text. The California Company, through Mr. James Kinzer, kindly loaned a complete set of air photos of the area. The Columbia Iron Mining Company made available the logs and cores of two diamond drill holes in the northern part of the area. The Sun Oil Company allowed the use of the sample log of the exploratory well drilled in 1951 west of Pintura.

OUTLINE OF GEOLOGIC RELATIONS

A sequence of sedimentary rocks about 11,500 feet in thickness, ranging in age from Pennsylvanian(?) to Eocene, has been measured within the map area. Overlying the sediments is a succession of volcanic rocks and minor intercalated sediments, aggregating over 6,000 feet in thickness (Fig. 2).

The decipherable history of the Pine Valley Mountain area begins with a long period of marine and continental deposition, with intermittent emergence and erosion, but without folding. Sometime in the late Jurassic or early Cretaceous, the region was moderately warped and Upper Jurassic rocks were beveled by erosion. Geosynclinal or foreland trough sedimentation began in the early Late Cretaceous with the deposition of a basal conglomerate followed by a thick accumulation of shale and sandstone. This type of deposition was interrupted once by uplift about the end of Colorado time. Renewed sedimentation began, probably in Montana time, with the spreading of the basal conglomerate of the Kaiparowits formation, apparently recording an orogenic pulsation to the westward.

Following the deposition of the Kaiparowits formation the Pine Valley area was uplifted, two folds were developed

along northeast axes, became overturned toward the east and locally broke into thrusts of relatively small displacement. This, the major folding of the area, in all likelihood took place within the late Cretaceous.

The numerous orogenic pulsations recorded in the thick Cretaceous and Tertiary sediments of central Utah (Spieker, 1946; 1949) apparently did not affect this southwest Utah area. The absence of evidence of movement within the Upper Cretaceous rocks and within the overlying Claron formation closely brackets the main Laramide movement in this area, even though it is uncertain whether the basal Claron is Upper Cretaceous or Eocene.

After the Laramide folds had been planed off by erosion, renewed uplift west of the Pine Valley area sent the basal Claron conglomerate spreading eastward over the truncated Mesozoic formations. Deposition of the lacustrine limestones and sandstones of the Claron was followed by a short interval of uplift and local crustal disturbance before the first volcanic rocks were laid down. Explosive volcanism had started shortly before the close of Claron time; that episode was the prologue to a series of eruptions which formed welded tuffs, lava flows and mudflows, and a variety of pyroclastic rocks. These volcanic rocks, because they contain Claron-type sediments at several horizons, are tentatively considered to be early Tertiary.

Numerous unconformities within the volcanics, some of them marked by deposits of lacustrine limestone and quartzite gravel, may record either orogenic disturbances or periods of great intrusive folding--probably the latter. In the surface rocks of today, folding due to intrusion is a common feature. Although the Pine Valley laccolith postdates the Tertiary volcanic sequence, other intrusions in the area may be older and may have been associated with the earlier folding in the volcanics.

Closely following the formation of the volcanic rocks, the Pine Valley Mountains intrusion, at least 3,000 feet thick, spread laterally between the Claron formation and the overlying volcanics. To the north the possibly contemporaneous Stoddard Mountain laccolith intruded at a horizon low in the Upper Cretaceous section. The intrusive rock is a monzonite porphyry, similar both lithologically and mineralogically to the extrusive rocks which are in the rhyolite-latite composition range. Most of the igneous rocks, both intrusive and extrusive, contain a high percentage of intratelluric crystals.

Folding during or shortly after intrusion produced an asymmetrical anticline in the Hurricane fault zone. Whether this folding was the result of compression or of collapse due to withdrawal of enormous amounts of magma (or both) is not clear.

During the Quaternary, deep erosion, stimulated by

spasmodic uplift along block faults, has stripped much of the cover from the Stoddard intrusion and entirely deroofed the Pine Valley laccolith (Fig. 3). Because of its resistance to erosion, the latter intrusion now stands high above its less resistant sedimentary pedestal (Fig. 4). Hogbacks of sedimentary rock, conspicuous outliers of basalt, and a gravel-veneered partial pediment lie between the mountains and the Hurricane Cliffs on the east (Fig. 5).

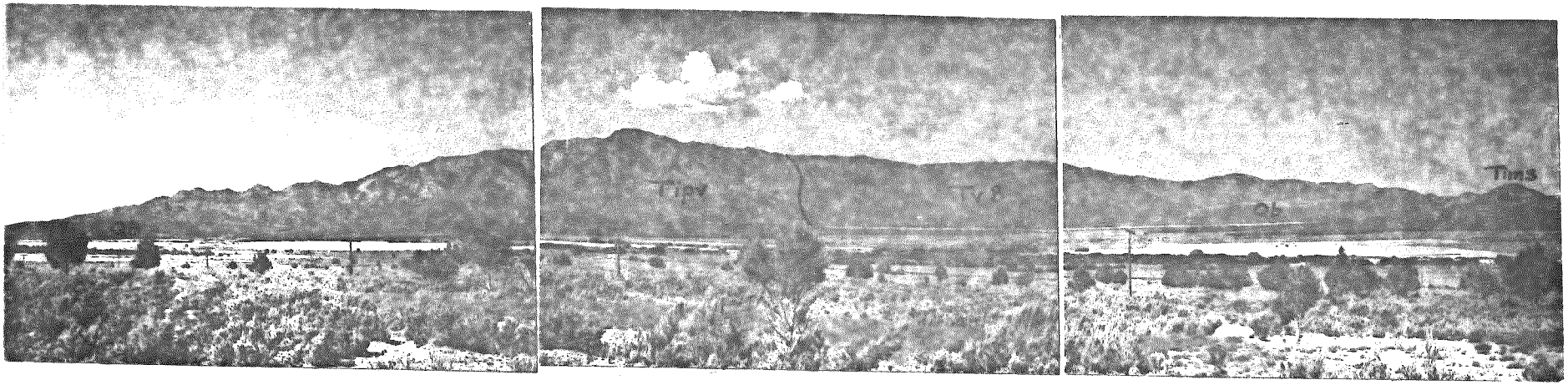


Fig. 3 The northern part of the Pine Valley Mountains. Looking southwest across the alluvial plain of the upper Ash Creek drainage. Pine Valley laccolith (Tipv) on the left, Stoddard laccolith (Tims) on the right; Tv 8 - "platy porphyry"; Qb - Quaternary basalt.

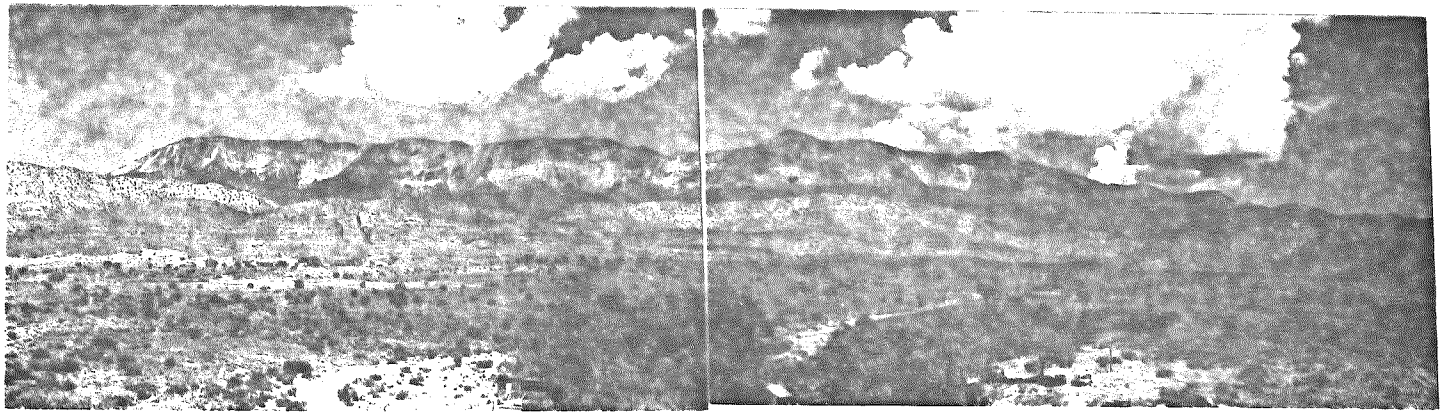


Fig. 4 The deroofed Pine Valley laccolith above its less-resistant sedimentary pedestal. From Silver Reef, looking northwest. The light-toned, resistant rock in the middleground is the Navajo sandstone.

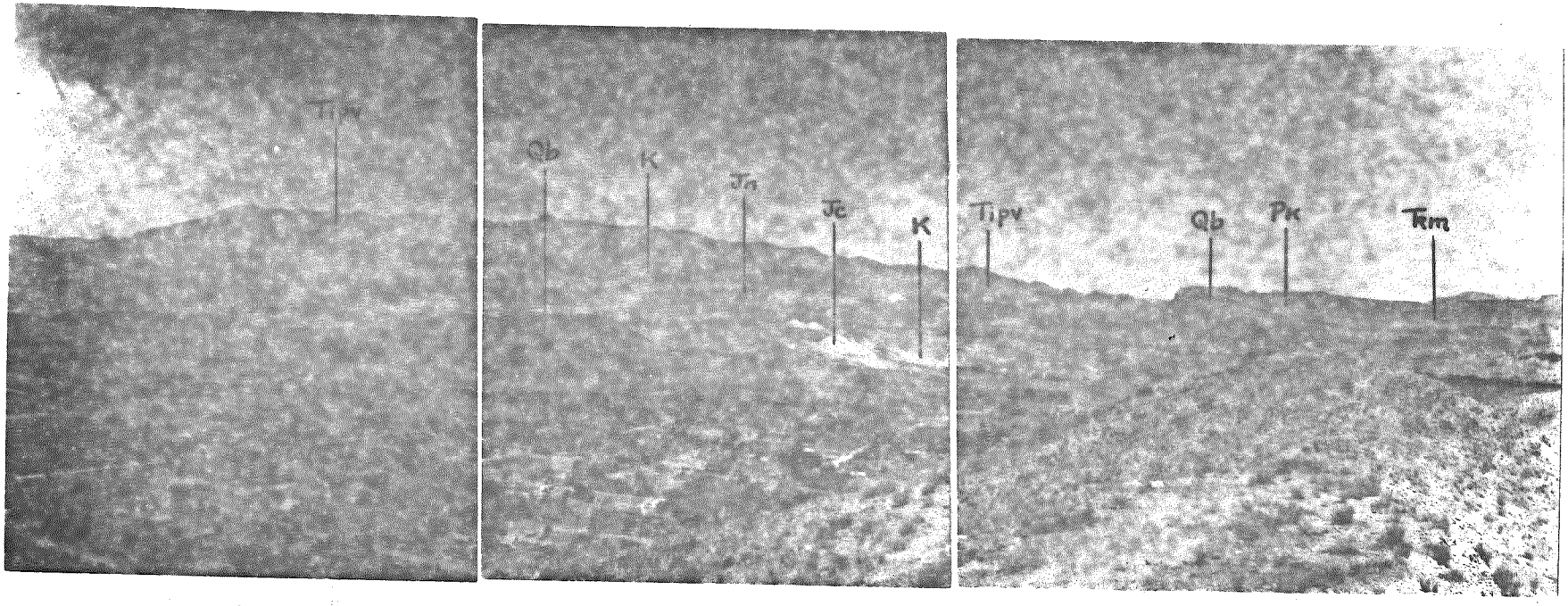


Fig. 5 The Pine Valley Mountains from the Hurricane Cliffs, looking northwest across the town of Hurricane. Pk-Kaibab limestone; Trm-Moenkopi formation; Jn-Navajo sandstone; Jc-Carmel formation; K-Upper Cretaceous formations; Tc-Claron formation; Tipv-Pine Valley laccolith; Qb-Quaternary basalt.

SEDIMENTARY ROCKS

Pennsylvanian(?) - Permian Formations

Coconino(?) sandstone (Csc)

The lowest stratigraphic unit in the map area is represented by 500 feet of white to buff sandstone which outcrops in the lower part of the Hurricane fault scarp east of Pintura and north of Toquerville. This sandstone is massive, cross-bedded, medium-grained and well-sorted, and is composed almost entirely of quartz grains with some calcareous cement. The upper part appears lighter in color than the lower, which contains some pale red-brown bands. Most of the rock is characterized by uniformly distributed, small yellowish-brown spots of iron oxide. The massive uniformity and weak cementation cause the sandstone to weather in subrounded cliffs below the harder, rougher Kaibab limestone.

Nowhere in the map area is the full unit exposed, but in the Beaver Dam Mountains, a few miles southwest of the map area, Reeside and Bassler (1922, p. 77) measured 1,420 feet of massive, pale yellow sandstone containing brown specks of iron oxide, overlain by the Kaibab limestone and underlain by the Redwall limestone. They referred the sandstone to the "Coconino and Supai formations." In the Virgin Narrows,

southwest of St. George, the same authors (1922, p. 76) measured 1,535 feet of this sandstone, but divided it into an upper 45 feet of "Coconino sandstone(?)" and a lower 1,490 feet of "Supai formation(?)."

In the Grand Canyon area, the three units which underlie the Kaibab limestone are, in descending order: the white, cross-bedded Coconino sandstone; the red Hermit shale; and the brick-red sandstone and shale of the Supai formation. Northward the Hermit disappears, the Coconino becomes yellowish, and the red Supai sandstone and shale appear to change into massive yellow to buff sandstone from which the Coconino is not separable.

In the Beaver Dam Mountains, Reber (1952, p. 104) measured 1,800 feet of "Supai-Coconino" underlain by Pennsylvanian Callville limestone. The California Company well five miles south of St. George penetrated 1,850 feet of calcareous sandstone assigned to the "Permian Coconino" and underlain by "Permian Pakoon limestone and dolomite" (Campbell, 1952, p. 88). McNair (1951, p. 515) has shown that the Pakoon and Callville limestones wedge out (Pakoon) and tongue out (Callville) southeastward. It thus appears that the Coconino(?) sandstone of this report is a distinct lithologic unit which occupies the stratigraphic position of the Supai-Hermit-Coconino sequence of the Grand Canyon section.

If the limestone underlying the "Coconino" sandstone

in the California Company well was correctly identified as Pakoon, the Coconino(?) sandstone of the Pine Valley Mountains area is probably Permian, for the Pakoon in the North Grand Wash Cliffs contains Lower Permian fusulinids (McNair, 1951, p. 525). On the other hand, the Supai formation of the Grand Canyon is, at least in part Pennsylvanian and, if the lower part of the Coconino(?) sandstone is the lateral equivalent of the Supai, the Coconino(?) is also in part Pennsylvanian.

Permian Formations

Kaibab limestone (Pk)

Conformably overlying the Coconino(?) sandstone is 800 feet of hard, gray, massive, cherty, fossiliferous limestone in two thick beds separated by gypsum. This is the Kaibab limestone and it caps the Hurricane Ledge east of Ash Creek Valley, in places composing the entire scarp. In this area the upper massive limestone is about 350 feet thick, the intermediate anhydrite or gypsum unit is 150 feet thick, and the lower limestone is 300 feet thick (stratigraphic section 1). The basal 50 feet of the Kaibab is sandy.

The two limestone members of the Kaibab are cliff-formers, whereas the intermediate gypsum member is a slope-former. The limestones weather to rough-textured, dark gray ridges and cliffs, into which transverse valleys are sharply notched.

The Kaibab thickens southwestward. In the San Rafael swell of central Utah it is but a few feet thick; on the rim of the Grand Canyon at Bass Trail, 562 feet; along the Hurricane Cliffs, 800 feet; in the Beaver Dam Mountains, 1,000 feet (Reber, 1952, p. 105); and five miles south of St. George, 1,050 feet (Campbell, 1952, p. 88).

The Kaibab contains abundant fossils which indicate its age to be Leonardian (McKee, 1952, p. 54).

Triassic Formations

Moenkopi formation (Trm)

The Moenkopi formation, which disconformably overlies the Kaibab limestone, is one of the conspicuous units of the region. Its soft chocolate and red sandy shales form the riser of one of the giant steps of the plateau province, being the slope-maker between the plateaus developed on the Kaibab below and the Shinarump above.

The Moenkopi appears only along the eastern edge of the map area--on the back slope of the Hurricane escarpment and locally on the downthrown block in the Toquerville area. It has an extensive outcrop along the Virgin anticline south of the Silver Reef area, as well as in the plateau province east of the Hurricane fault.

The six stratigraphic subdivisions of the Moenkopi recognized by Gregory (1950a, p. 31; 1950b, p. 60) in the

plateau country can readily be differentiated in the log of the Pintura well (stratigraphic section 1) where the formation is 1,774 feet thick. The Moenkopi is composed largely of thin-bedded, gray-green, red, and chocolate gypsiferous sandy shales with a prominent limestone unit (Virgin limestone member) in the lower part. The shales form valleys and slopes in which the Virgin limestone member appears as a ridge or ledge.

The Moenkopi formation thickens southwestward. Gregory and Williams (Gregory 1950a, pp. 95-96) measured 1,080 feet of Moenkopi about six miles south of Kanarraville, near the northeast corner of the present map area. The formation increases in thickness to nearly 1,800 feet in the Pintura-Virgin City area, to 2,035 feet in the Harrisburg dome of the Virgin anticline south of Silver Reef (Reeside and Bassler, 1922, p. 66) and to 2,100 feet in the Beaver Dam Mountains (Reber, 1952, p. 105).

Although the Virgin limestone member is abundantly fossiliferous, the Lower Triassic age of the Moenkopi was not established until about 1920, when Walcott's original age determinations on the Moenkopi fossils were revised by Shimer and by Girty (Gregory, 1950b, p. 62).

The lower part of the Moenkopi formation records both shallow-water marine and continental deposition. Progressive retreat of the sea in late Moenkopi time resulted in terrestrial conditions which continued throughout the rest of the Triassic.

Shinarump conglomerate (Trs)

The thin, resistant Shinarump conglomerate forms a pronounced ridge or ledge above the chocolate and red slopes of the Moenkopi. It outcrops in the map area only near Toquerville, on the downthrown side of the Hurricane fault.

The Shinarump in this area is a light gray to reddish brown, fine to coarse sandstone, locally grading into lenticular pebble conglomerates near the base; it is rudely bedded and contains silicified wood. The pebbles are largely quartz, quartzite, and chert, with a matrix of sand and some ferruginous cement.

The only place within the map area where the thickness of the Shinarump has been measured is in the Pintura well, where 184 feet of sandstone and conglomerate is assigned to this formation. Proctor reports 115 feet of Shinarump in the Harrisburg dome a few miles south of Silver Reef.

The age of the Shinarump is determined only by its stratigraphic position. It lies disconformably on the Lower Triassic Moenkopi formation and grades upward into the Upper Triassic Chinle formation; consequently, it may be Lower, Middle, or Upper Triassic, or it may straddle either one or both of the intra-Triassic series boundaries.

Chinle formation (Trc)

The Chinle formation is exposed in the vicinity of

Silver Reef where it has been folded and faulted around the crest of the northward-plunging Virgin anticline. The soft sandstones and shales of the formation form wide flat valleys and talus-covered slopes beneath the overlying massive Navajo sandstone. The monotony of the shale valley is broken by a ridge of the resistant white Silver Reef sandstone, which occurs about in the middle of the formation. In the Silver Reef area this sandstone contained silver minerals, mainly cerargyrite in fossil wood. Silicified logs and wood fragments are locally abundant in the lower part of the formation.

Proctor (1949, pp. 12-13) gives a detailed description of the Chinle of the Silver Reef area, where it consists of 1,100 feet of alternating sandstones and shales with two thin beds of cherty limestone. Proctor subdivides the formation as follows (Units 5 and 6 are the Silver Reef sandstone):

		Thickness (feet)
Navajo sandstone		
Chinle formation		
7.	Red shale and sandstone with some white sandstone	400 plus
6.	Lavender to purple sandstone	35
5.	Buff to white sandstone	65
4.	Red sandstone and shale	310
3.	Purplish to bluish-gray shales with banded chert	10-15
2.	White arkosic sandstone	5-15
1.	Dark red shales and minor interbedded red sandstones	265
Shinarump conglomerate		

Some of the upper sandstone members in the Silver Reef area may prove to be equivalent in age to the Wingate sandstone and perhaps to the Kayenta formation (Thomas, 1952, p. 58). The top of the Chinle must be drawn arbitrarily. West of Silver Reef the soft-bedded sandstones of the Chinle grade upward into massive, resistant, rudely bedded red sandstone and then a soft section of red shaly sandstone before reaching the massive, cross-bedded sandstone of the Navajo. These transition beds which are 100 feet thick in the Silver Reef area, can be traced without break southwestward to St. George and thence northwestward for several miles. In the mapping the topographic break at the base of the massive bedded sandstone was used as the formational contact; the transition beds, therefore, were included in the Navajo sandstone.

The Chinle apparently increases in thickness northward or northwestward; the upper sandstone member provides most of the increase. Reeside and Bassler (1922, p. 73) measured 995 feet of Chinle near Virgin City; Proctor's subdivisions are recognizable in the Virgin City section. Reber reports 1,030 feet of Chinle in the Beaver Dam Mountains (1952, p. 105). The Pintura well passed through 1,380 feet of Chinle. Along the Hurricane fault 18 miles south of Cedar City, near the northeast corner of this map area, Gregory measured 1,359 feet of Chinle (1950a, pp. 94-95) and one mile east of Cedar City Thomas and Taylor (1946, p. 20) report 1,950 feet of the

formation.

The Chinle has been assigned to the Upper Triassic on good fossil evidence (Reeside and Bassler, 1922, p. 68).

Jurassic(?) Formations

Navajo sandstone (Jn)

The most prominent formation in southern Utah is the Navajo sandstone which forms the walls of Zion Canyon and the flaming red Kolob Buttes of Zion National Monument just east of the Pine Valley Mountains. This massive cross-bedded sandstone outcrops in a broad west-dipping hogback along the eastern foothills of the Pine Valley Mountains. In the southwest between Diamond Valley and Gunlock, the Navajo forms a broad dip slope, inclined gently northeast; this outcrop is cut off westward by the Gunlock fault.

The Navajo overlies the Chinle formation conformably and gradationally. In the plateau country the Kayenta formation and the Wingate sandstone underlie the Navajo and all three together form the Glen Canyon group. Although the Navajo is the only recognizable member of this group in the map area, its basal beds may be time equivalents of the Kayenta-Wingate section. Some geologists believe that the Navajo sandstone of southwestern Utah is the time equivalent of the entire Glen Canyon group (Williams, 1952, p. 63).

The description of the Navajo sandstone near Kanarraville

by Gregory and Williams (1947, p. 229) would apply for the Pine Valley Mountains area:

> The outstanding lithologic features of the Navajo sandstone are general uniformity of grain, cross-bedding and massiveness. In most places, however thick, it is one homogeneous indivisible stratum composed chiefly of round grains of translucent quartz averaging about 0.15 millimeter in diameter, cemented by iron and lime....Cross-bedding is universal and remarkably variable....In places its lower part is stratified and cross-bedding laminae are inconspicuous.

The Navajo sandstone varies greatly in thickness and color. At Cedar City, it is 1,100 feet thick (Thomas and Taylor, 1946, p. 20; Gregory, 1950a, p. 81); east of the Hurricane Cliffs near Kanarraville, the thickness is 1,500 feet (Gregory, 1950a, p. 94) to 1,800 feet (Williams, 1952, p. 65); at Zion Park, 2,280 feet (Gregory, 1950b, p. 83); in the Beaver Dam Mountains, 2,200 feet (Reber, 1952, p. 106). In southwestern Utah, then, the Navajo appears to thicken southward, instead of westward as it does from Colorado to Zion Park. The thickness in the map area probably averages 2,000 feet.

The color is predominantly red, although in the map area the upper part is white to light brown; but just east of the area the Navajo of the Kolob Buttes is bright orange-red from bottom to top. In Snow Canyon two miles south of Diamond Valley, red and white wedges interfinger, roughly parallel to the dip of the formation. This color difference led Huntington

and Goldthwait (1904, p. 203) to define two formations, the Colob sandstone for the upper white portion and the Kanab sandstone for the lower red part; these are probably the White Cliff sandstone and Vermilion Cliff sandstone of Dutton and earlier authors. Tangential cross-bedding is especially striking in the upper portion. However, the boundary between red and white has no definite position and may vary within a short distance from the middle to the top of the sandstone. Gregory (1950b, pp. 88-89) presents evidence that the white sandstone has been formed by leaching of the ferruginous coating of the quartz grains. On the other hand, the Sun Oil Company used the color break in mapping the Pintura structure, and perhaps locally the boundary may be consistent enough for use in structural interpretation. The color of the upper part in the map area is white, gray, buff, pale brown, and pinkish; in the lower part it is orange-red, brick red, and red-brown.

Major vertical joints in the Navajo are several hundred feet apart and are traceable for miles, especially in the Zion Park area where they control drainage and help shape the almost vertical, smooth canyon walls and cliff faces which rise above the Chinle slopes.

In a small exposure, the cross-bedding in the upper Navajo, being on a large scale, appears to be normal bedding. Several places were studied where buff to light brown, coarse to medium well-sorted, quartz sandstone appears in thin,

distinct, parallel beds. Only study of large outcrops shows that no reliance can be placed on attitudes in such material.

Dutton (1880, p. 152) believed that the Navajo sands were deposited in the sea as near-shore deltaic deposits spread from a Mesozoic highland to the west. Today the Navajo is believed by most geologists to be a continental deposit, largely aeolian. Gregory thought (1950a, p. 39) that the Navajo in southwestern Utah lies "near the edge of an ancient interior basin where sediments deposited by streams were but slightly rearranged by wind."

The Navajo in Utah contains no fossils and its tentative age assignment to the Jurassic is based on stratigraphic position. Williams (1952, p. 63) believes that the lower part of the Glen Canyon group, represented here by the Navajo, may be Triassic.

Upper Jurassic Formations

Carmel formation (Jc)

In the map area, the San Rafael group of the plateau section is represented only by the Carmel formation and the Entrada sandstone. The Carmel outcrops in a broad arc around the southern part of the Pine Valley Mountains. The contact with the subjacent Navajo is accentuated by differential erosion, a long dip slope leading down to the less resistant, thin bedded Carmel. Thin, ledge-forming limestones in the

middle and upper part of the Carmel support steep slopes beneath.

The Carmel appears to overlie the Navajo conformably, but the cross-bedding of the Navajo is sharply truncated by a surface of erosion on which the basal Carmel, composed to a large extent of reworked Navajo, rests, indicating a disconformable relationship. On the east flank of the Pine Valley Mountains the Carmel can be subdivided into three units: lowermost is a group of soft red sandstones, gypsiferous shales and gypsum about 225 feet thick; in the middle is 150 feet of gray and brown arenaceous limestone; and uppermost is 250 feet of platy, argillaceous gray limestone, making a total thickness of 675 feet (stratigraphic sections 2 and 3). In Diamond Valley, the Carmel is only about 480 feet thick (stratigraphic section 4). The thinning takes place in the upper two members.

The basal unit of the Carmel, 195 to 230 feet thick in measured sections (2, 3, and 4) is composed of gypsiferous shale and gypsum overlying red friable sandstones which probably represent Navajo sandstone reworked by the wave action of the advancing Carmel sea. This unit is well-developed in the Zion Park region where Gregory called it the Temple Cap member of the Navajo sandstone (1950b, p. 89). Williams (1952, p. 65) points out that this unit is characteristic of the base of the Carmel, not only in southwestern Utah but elsewhere and Gregory

seems to be the only geologist who has assigned it to the Navajo.

The two upper units of the Carmel are not everywhere distinguishable. In the Diamond Valley section, for example, brown fossiliferous limestones extend from the basal member to the top of the formation without the development of the gray to white argillaceous limestone which is characteristic of the upper unit on the east side of the mountains.

On a regional scale, the Carmel formation increases in thickness westward and includes an increasing amount of limestone. The age, established by abundant fossils, the most notable of which is Pentacrinus asteriscus, is Upper Jurassic. The fossiliferous zones are generally in the upper third of the formation. In most places the arenaceous beds are grouped in the middle of the formation (Gregory, 1950b, p. 94). The Carmel formation is the record of an advancing sea which, having filled the low places in the Navajo surface with sands and evaporites, deposited shallow-water sandy limestone and, later, deeper-water muddy limestone.

Baker, Dane and Reeside (1936, p. 7) say the upper boundary of the formation is transitional and arbitrary at most places. This is certainly not true in the Pine Valley Mountains where the break is sharp between the Carmel limestone and the overlying soft sandstone or shale of the Entrada or the basal conglomerate and sandstone of the Cretaceous.

Entrada sandstone (Je)

Overlying the Carmel formation is the Entrada sandstone which appears as a narrow band of soft rocks, commonly covered by talus, on both sides of the Pine Valley Mountains. It wedges out southeastward-near Leeds Creek on the eastern side of the mountains, and at the southern end of Diamond Valley.

The maximum thickness of the formation in this area, about 150 feet, is exposed northwest of Pintura, where the Entrada consists of extremely friable, red-chocolate and greenish-white sandstone which erodes more readily than the Carmel, causing a dip slope to form on that formation.

In Diamond Valley the Entrada is principally shale, as it is also near Gunlock; this led Baker and his associates to correlate the upper part of the Diamond Valley Entrada with the Curtis formation of the plateau section. The basal unit of the Diamond Valley Entrada which consists of 45 feet of greenish-gray sandy shale and platy sandstone, is overlain by 55 feet of brick-red shale containing some thin white limestones, and then by 40 feet of gray mudstone, above which lie Cretaceous sandstones. This section fits the observed facies change in the Entrada, from terrestrial cross-bedded sandstone east of the Paria River to bedded gypsiferous sandstones with intercalated lenticular gypsiferous and calcareous shales in the Zion Park region (Gregory, 1950a, p. 40; 1950b, p. 127).

The change in color from red to gray and greenish may represent change from terrestrial to marine deposition in the Pine Valley Mountains area.

On the other hand, the Curtis formation in southwest Utah is lithologically quite different from the Diamond Valley Entrada; in Zion Park, for example, it is composed of gypsum and a fossiliferous limestone conglomerate which forms a mesa cap (Gregory, 1950b, p. 96). Elsewhere in southwestern Utah the Curtis is composed of gypsum, gypsiferous sandstone and argillaceous limestone (Williams, 1952, p. 67). It seems unlikely that any of the strata mapped as Entrada in Diamond Valley represent the Curtis formation.

The Entrada thins southward throughout Utah, but becomes finer-grained westward, indicating that part or all of the thinning is due to erosional truncation following uplift in the south, before the overlying formations were laid down.

No fossils have been found in the Entrada of southwestern Utah but its age is well established by its position, in the plateau province, between the fossiliferous Carmel and Curtis formations, both of Upper Jurassic age.

Upper Cretaceous Formations

General statement

A broad belt of gray Upper Cretaceous rocks, sharply contrasted in color with the pink rocks above and the white

and red rocks below, outcrop over a large part of the map area. Although it almost surrounds Stoddard Mountain, forms the floor of the breached anticlinal valley west of Page Ranch, and appears as a thick member of the sedimentary pile underlying the Pine Valley Mountains, the Cretaceous is still not a dominant feature of the landscape. Colors are predominantly gray and yellow-brown; the lower and upper parts of the section form brush-covered, undistinguished slopes, while the thicker, middle part of the section produces a subdued, laminated, ledge-and-slope topography with no eye-catching features.

Over the map area, there is a marked facies change in the Cretaceous rocks. On the east side of the Pine Valley Mountains, four units of the Cretaceous are rather easily distinguished and correlated with the plateau Cretaceous. A basal unit, zero to 80 feet thick, of sandstone and conglomerate overlies the Entrada sandstone (in places, the Carmel) unconformably and is correlated with the Dakota(?) sandstone of the plateau. This unit grades upward into an 800-foot section of alternating thin sandstones and shales, identifiable as the Tropic formation. Gradationally overlying the Tropic is an 1800-foot thick sequence of alternating thick sandstones and shales, recognizable as the unseparated Straight Cliffs and Wahweap sandstones of the plateau. Disconformably above the Straight Cliffs and Wahweap sandstones is another, softer, formation about 1,200 feet thick, consisting largely of soft

sandstones above a basal conglomerate; it is correlated with the Kaiparowits formation of the plateau section. Westward these units acquire an increasing percentage of sandstones and the lithologic characteristics of the individual formations become more alike, so that, near the south end of the Pine Valley Mountains it is no longer possible to map separate formations within the Cretaceous.

The Cretaceous rocks exposed near Diamond Valley were measured by Reeside and Bassler (1922, p. 77). Above their "Cretaceous(?) variegated shale" (which has been mapped as Entrada in this paper) they show 883 feet of "Cretaceous(?) sandstone" overlain by 1,500 feet of "Tertiary(?) sandstone", which in turn is capped by a basalt flow.

This section was remeasured by the author (stratigraphic section 4). The Cretaceous exposed in Diamond Valley and Alger Gulch is about 3,850 feet thick, the same as on the eastern flank of the mountain, and is overlain by 500 feet of the Eocene Claron formation, capped in places by Quaternary basalt, but elsewhere by the Pine Valley intrusive porphyry.

The section, except for an offset of a few hundred feet across a basalt cover, is continuous, although exposures in Alger Gulch are poor. At the head of the gulch and across the divide to the south the full thickness of Claron is exposed, about 500 feet. Just to the east, however, is a fault upthrown on the east which raises the section several hundred

feet; viewed from the south it appears that the pink band of Claron is indeed 1,500 feet thick.

The Upper Cretaceous rocks underlying the Pine Valley Mountains and near Gunlock have a total thickness of nearly 4,000 feet. In places, however, they have been greatly thinned or even completely removed by erosion prior to the deposition of the overlying Claron formation.

In the adjoining Iron Springs district, the "Pinto sandstone" of Leith and Harder (1908) has recently been separated into the Iron Springs formation of probable Upper Cretaceous age and the "Entrada" formation of probable Jurassic age (Mackin, 1947a, p. 8). The Iron Springs formation is apparently equivalent to the Upper Cretaceous section of the Pine Valley Mountains.

Dakota(?) sandstone (Kd)

The basal sandstone and conglomerate of the Upper Cretaceous, the Dakota(?) sandstone of the Colorado Plateau, appears as a discontinuous sheet of variable thickness unconformably overlying the Entrada sandstone and shale, and, along the southern and southeastern foothills of the Pine Valley Mountains, rests on the Carmel formation.

The Dakota(?) sandstone in the Pine Valley Mountains area, is composed of gray, poorly sorted conglomerate containing lenses of yellow-brown sandstone. Subrounded chert and quartzite

pebbles are a persistent component; black limestone fragments are locally abundant. Only a small percentage of the pebbles are over two inches, the maximum being about four inches. The matrix is calcareous sand. The formation disappears in places and a medium-grained sandstone rests directly on the Entrada. On the other hand, the Dakota(?) thickens to 80 feet in the Gunlock area. Along the southeastern side of the Pine Valley Mountains the formation is 20 to 30 feet thick.

The Dakota(?) is essentially a basal conglomerate of the Tropic formation and as such is probably also Colorado in age.

Tropic formation (Kt)

The Tropic formation is recognizable on the eastern flank of the Pine Valley Mountains. A section about 800 feet thick of alternating shales and thin sandstones, with some coal beds, it grades downward into the Dakota(?) sandstone and upward into the Straight Cliffs sandstone. East of the map area, the upper contact is commonly easy to draw because of the sudden appearance of a massive sandstone, sometimes conglomeratic, above a dominantly shale section. In the map area, however, the Tropic has acquired a more arenaceous character, especially in its upper part, and the contact with the overlying Straight Cliffs-Wahweap section is gradational and somewhat arbitrary. No single stratigraphic horizon can be

followed any great distance. However, the Tropic is a mappable unit on the east side of the Pine Valley Mountains, distinguished by its bulk lithology and a fossiliferous bed at or near its top. The sandstones of the Straight Cliffs and Wahweap are thicker, more yellowish and cross-bedded than the Tropic sandstones. The base of the Tropic must also be drawn arbitrarily.

The Tropic outcrops in a band around Stoddard Mountain. That the Cretaceous rocks in contact with the Stoddard Mountain intrusive are part of the Tropic formation is indicated by lithology, stratigraphy, and fossils. West of the Hurricane fault only the Tropic section of the Cretaceous includes much shale; the section in Pace Canyon (stratigraphic section 8), just east of the Stoddard intrusive, contains abundant shale. Moreover, Gregory (1950b, p. 192) notes that, in the Zion Park region, although all the Cretaceous formations contain coal beds, only in the Tropic is there coal thick enough for mining and in places as many as six beds occur within the Tropic; several coal beds are found in the Pace Canyon section.

Most of the coal in the Tropic of the plateau country is in the lower part of the formation, from 100 to 300 feet above the Dakota(?) sandstone (Gregory 1950b, p. 192) and near the lowest prominent fossiliferous layer; this is probably the sandy fossiliferous limestone near the lowest (stratigraphically) coal seams in Pace Canyon. In the plateau section a thin limestone containing the turreted gastropod Turritella is commonly

found 50 to 150 feet above the coal section; a single specimen of Turritella Sp. was found in the upper part of the Pace Canyon Cretaceous section. Furthermore, the Tropic is the only Cretaceous unit in this area which contains limestone.

Both east and west of Stoddard Mountain, the Tropic section of carbonaceous and calcareous shales and thin sandstones passes upward (stratigraphically) and outward (from the intrusive body) into thicker, more massive, yellow brown sandstones, probably representing the Straight Cliffs sandstone.

The soft beds in the Tropic formation are red, grape, and chocolate silty shales and blue-gray to lavender siltstones; the ledge-formers are white to buff, fine-grained massive sandstones one to five feet thick, which become yellower and show cross-bedding near the top of the formation. The shales are mainly marine and contain fossils of Colorado age.

At Gunlock and Diamond Valley there is no coal and practically no shale in the strata which are probably equivalent to the Tropic, the section consisting of medium to coarse sandstone and minor conglomerate.

Straight Cliffs and Wahweap sandstones (Ksw)

The Tropic formation grades upward into a thick sequence of sandy shale and lignite beds alternating with massive, resistant, buff sandstones. This unit, about 1,800 feet thick on the southeast side of the Pine Valley Mountains, is

correlated with the Straight Cliffs and Wahweap sandstones of the plateau section. No basis for separation of the two units was found. The sandstone beds, which form a conspicuously laminated topography, are as much as 40 feet thick, but beds five to 15 feet thick are most common. Most of the sandstones are lenticular and cross-bedded. Traced westward from the Kaiparowits Plateau marine beds constitute a decreasing part of the formations (Gregory, 1950a, p. 50) and this is true in the Pine Valley Mountains area also. The Straight Cliffs and Wahweap sandstones of the plateau section, as indicated later, deposited in Colorado time.

Kaiparowits formation (Kk)

The Straight Cliffs and Wahweap sandstones are overlain disconformably by the Kaiparowits formation, 1,200 feet thick. The plane of disconformity is uneven but the beds above and below are substantially parallel. The basal conglomerate apparently varies greatly in thickness, being about 50 feet thick in the Dixie Forest Camp section (stratigraphic section 3) and not thick enough to be recognizable in the Diamond Valley and Gunlock sections (4 and 5). Gregory (1950b, p. 108) mentions that the basal Kaiparowits conglomerate varies from one to 40 feet in thickness in the Zion Park region. The conglomerate is composed chiefly of rounded pebbles and cobbles of gray, white, and red quartzite, quartz, and black chert, from a quarter of

an inch to six inches in diameter.

There are no prominent ledge-formers in the Kaiparowits formation and the weakly cemented sandstones disintegrate into light-colored sandy slopes. Therefore the formation is readily distinguishable by photogeology from those above and below it. Its exposures lack the benches and steps formed by the projecting ledges common to the other Cretaceous formations. The dominant rock is thin-bedded, weakly cemented quartzose sandstone, buff to white in color, with some red shales near the base of the formation.

Some of the sand is fine to medium-grained, well-rounded and well-sorted but many cross-bedded lenses of angular, coarse sand appear in the lower part of the formation. Iron concretions in the form of balls, cakes, and hollow tubes are common; concentric iron rings are found in the sandstone, sawed blocks of which produce the "picture rock" of southern Utah. Westward, the Kaiparowits becomes more gritty and conglomeratic. Above the basal conglomerate, the fragments in the conglomerate lenses consist of buff sandstone, chert, black limestone, jasperoid silica, and quartz; there is little or no quartzite. No fossils were found in the Pine Valley Kaiparowits but on the plateau it contains a fresh-water and terrestrial fauna of Montana age. Richardson (1927, pp. 467-8) discussed the age relations of the Cretaceous formations on Colob Terrace and concluded that a lower group (Tropic, Straight Cliffs and Wahweap) was of Colorado

age, "above which lie several hundred feet of buff sandstone and shale of Montana age" (Kaiparowits).

Upper Cretaceous(?) - Tertiary Formations

Claron formation (Tc)

Unconformably overlying formations from the Kaiparowits down to the Navajo sandstone is the Claron formation. In most places, the Claron is a sequence of freshwater limestones with subordinate calcareous sandstone and shale above a basal quartzite cobble conglomerate. The beds of the Claron vary greatly in composition, texture, and color. The general color of the unweathered limestone is pale red, yellow, or gray, but weathering produces a strong pink tone, especially in the lower part of the formation. The upper part of the formation is commonly gray to white. Within the map area, the Claron varies from zero to 1,000 feet in thickness, the average being about 500 feet.

The Claron strata form the Pink Cliffs of southwestern Utah and have been assigned by common usage to the Wasatch formation, although exact correlation with known beds of that formation has not been established. For this reason and because Spieker has shown (1946) that the unit formerly called Wasatch in central Utah is actually a composite of several unconformable formations, the name Claron, applied by Leith and Harder (1908, pp. 41-43) to the Iron Springs equivalent of the plateau

At the base of the Pine Valley Mountains the Claron forms a pink band about 500 feet thick (stratigraphic sections 4, 6, 7), consisting largely of sandy lacustrine limestones and an iron-stained basal conglomerate 30-80 feet thick. In the Hurricane fault zone northwest of Pintura, the Claron beneath the Pine Valley intrusive porphyry abruptly thickens to about 700 feet, but in an exposure two miles south of Pintura it is again only 450-500 feet thick. The Claron is exposed on the east side of Pace Canyon and in the Comanche Creek area northwest of New Harmony. It forms part of the rimrock on both sides of the valley west of Page Ranch. The Claron outcrops near the town of Central and again northwest of Gunlock.

In the Pine Valley Mountains the three facies or subdivisions can be recognized. A ledge-forming gray limestone near the base of the upper, white limestone unit was mapped as a key bed on the southeast side of the Pine Valley Mountains. Although the limestones become more arenaceous on the west side of the mountains, the three facies can still be distinguished in the area between the south end of the mountains and Central. Farther west, however, in the Gunlock section, (only six miles west of a section still dominantly calcareous) no limestone is left and the Claron consists of 959 feet of pebble, cobble, and boulder conglomerate and subordinate sandstone (Fig. 6).

Variations in thickness of the Claron are believed to represent southeastward depositional thinning as well as

post-Claron, pre-Quichapa erosion.

In several places, a white calcareous tuff with black euhedral flakes of biotite outcrops 30 to 50 feet below the top of the Claron. The tuff, five to 30 feet thick, is overlain by white limestone. It does not appear in the Claron beneath the Pine Valley laccolith, except in the thick Leap Creek section.

The Claron is non-marine and contains sparse freshwater and terrestrial fossils. The formation is generally considered to be of lacustrine and fluvial origin. Bissell (1952, p. 73) believes that the Claron may be of Laramie age in its lower part and Eocene in the upper portion. This suggestion may be based on Spieker's studies (1946) in central Utah which have shown that the lower part of the unit formerly called Wasatch is late Cretaceous. No evidence has been found in the Pine Valley Mountains by which the precise age of the Claron could be determined. Its tentative assignment to the late Upper Cretaceous (Laramian) - Eocene interval is based upon lithologic similarity with the Wasatch of the Colorado Plateau sections.

Upper Tertiary(?) Formations

Parunuweap(?) formation (Tp?)

Conformably beneath the titled basalt cap of Bald Hill, northwest of New Harmony, is a sequence of poorly sorted,

bedded, poorly consolidated sands and gravels about 200 feet thick. The sediments are white to gray and are dominantly of volcanic origin, having apparently been derived from erosion of the Tertiary volcanic rocks which they overlie with angular unconformity. Pebbles and sparse cobbles of quartzite are the only rounded constituents of the dominantly angular detrital material. The beds, ranging in thickness from a few inches to two or three feet, dip 12 degrees southeast.

The strata at Bald Hill are tentatively correlated with the Parunuweap formation (Gregory, 1945). Other exposures in the area, too small to be mapped (Fig. 7), may also represent this formation.

The Parunuweap formation is loosely defined by Gregory and it is sometimes difficult to decide how to distinguish this formation from the overlying high-level gravels or boulder alluvium.

Gregory reported (1950a, pp. 68-71) that the Parunuweap underlies the oldest Quaternary basalts, that it postdates the major pre-Quaternary movements on the Hurricane fault and antedates the known Quaternary movement. These criteria are difficult to apply. In the first place, basalt extrusion in this area was intermittent over a long period of time; some of the basalt postdates all movement on the Hurricane fault. Secondly, in some places boulder alluvium underlying basalt is identical in character with boulder alluvium resting on the

basalt; in this case, the basalt is not a good formational boundary. Finally, some of the boulder alluvium (herein mapped as high-level gravels) antedates the latest Hurricane movement and is itself displaced by faulting.

In the Pine Valley Mountains area, the Parunuweap(?) can be restricted to a mappable unit on the basis of lithology and structure. It rests with marked angular unconformity on all older rocks. The upper limit of the formation is a surface of unconformity which represents a period of folding, faulting, and erosion prior to the deposition of the overlying boulder alluvium. The Parunuweap(?) sediments are finer and better bedded than the boulder alluvium (Fig. 7). The boulders in the upper formation are almost entirely of Pine Valley porphyry; although fragments of this porphyry are locally abundant in the Parunuweap(?), they are much smaller.

The relationship between the Parunuweap(?) and the high-level gravels can be seen in an exposure one mile west of Pintura (Fig. 8). The Parunuweap(?) here consists of gray, pale green, and red, bedded, loosely coherent sands, which have been faulted and eroded before the high level gravels were laid down. The gravels are rudely bedded and poorly sorted, containing rounded to subrounded boulders of Pine Valley porphyry and smaller angular to subrounded fragments of sandstone, conglomerate, and quartzite. Later faulting has displaced the gravels which are overlain by finer, Recent alluvium.

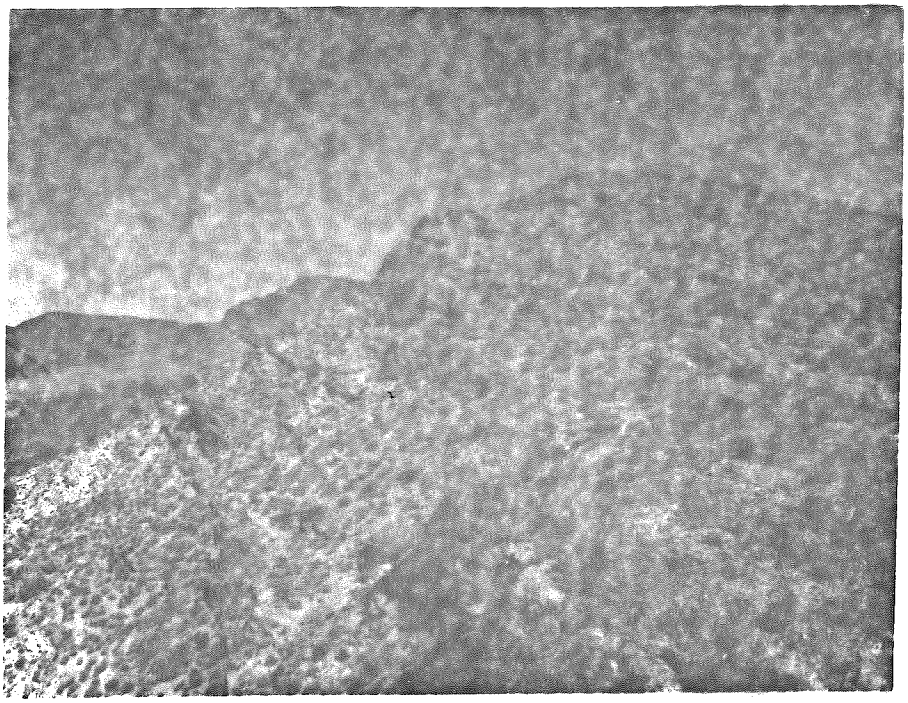


Fig. 6 Lower part of Claron formation (Tc) near Gunlock. Westward (in the distance) the formation consists of about 1000 feet of red conglomerates. The Upper Cretaceous rocks (K) are mainly medium-grained sandstones.

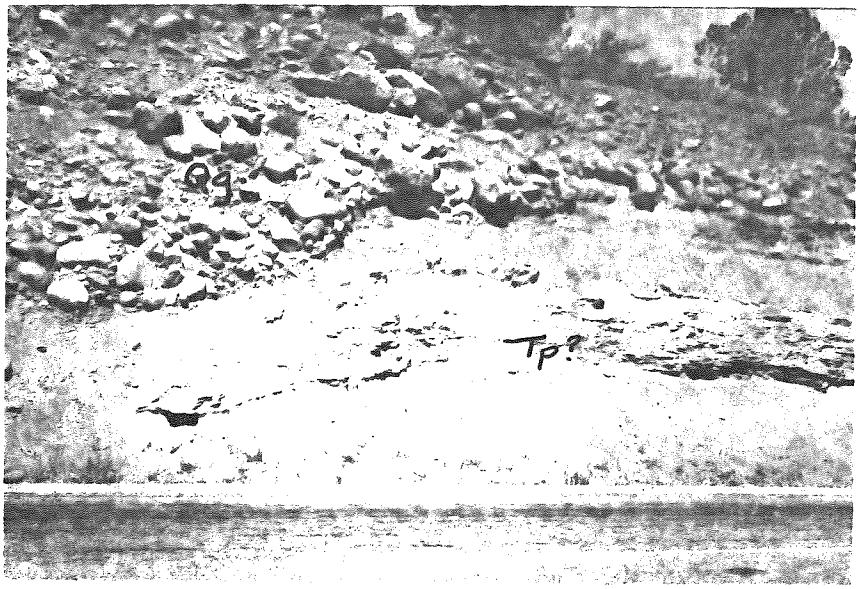


Fig. 7 Parunuweap (?) formation (Tp?) overlain by high-level gravel (Qg) in highway cut two miles south of Pintura.

Fine-grained, bedded, consolidated sediments of Parunuweap(?) are locally exposed beneath a surficial mantle in the area between New Harmony and the Hurricane Cliffs. In one locality (Fig. 9) silty shale and friable sandstone has been folded, faulted, eroded and overlain unconformably by silty sand; draped over this fine-grained sequence is a mantle, several feet thick, of unbedded alluvium containing quartzite cobbles, Cretaceous sandstone slabs, and fragments of Claron limestone, welded tuff, and basalt.

In the Pine Valley Mountains area, the Parunuweap(?) sediments, which locally have a calcareous cement, appear to have been deposited under conditions of semi-aridity. It appears that the moderate folding and faulting which marked the close of Parunuweap(?) time was approximately coincident not only with the beginning of basalt extrusion but also with uplift and/or climatic change which started deposition of the coarse boulder alluvium.

Following Gregory (1945) the Parunuweap(?) is tentatively assigned to the Pliocene. Some exposures which Gregory called Parunuweap were included by Thomas and Taylor (1946) in their "Pleistocene(?) fanglomerate terraces".

Quaternary Formations

High-level gravels (Qg)

The sheet of vegetation-covered gravel which slopes

away from the Pine Valley Mountains towards the Ash Creek and Virgin River Valleys thins and divides outward from the mountain. As far as six miles from the mountain base it contains occasional boulders of Pine Valley porphyry up to 20 feet in diameter. Near the mountain the gravel, probably in great part deposited under conditions different from those of today, is being reworked by hillwash and stream action. These thick and irregular deposits grade away from the mountain into sloping gravel terraces and isolated terrace remnants. The high-level gravels are probably nowhere over two hundred feet thick; remnants in the Silver Reef area are as much as 50 feet thick. Poor sorting, lack of bedding, and dominance of intrusive porphyry boulders are everywhere striking. The smaller boulders are of sandstone and quartzite conglomerate with an interstitial filling of sand and silt.

The high-level gravels rest on a partially developed pediment above which rise hills of resistant rocks such as the Navajo sandstone. Present-day streams have dissected and largely destroyed the outer part of this boulder mantle, cutting canyons which in places are 200 feet below the gravel-capped partial pediment.

Extrusion of basalt appears to have continued throughout the deposition of the high-level gravels. Locally as much as 50 feet of boulder alluvium is capped by basalt; in other places high-level gravels rest on basalt.

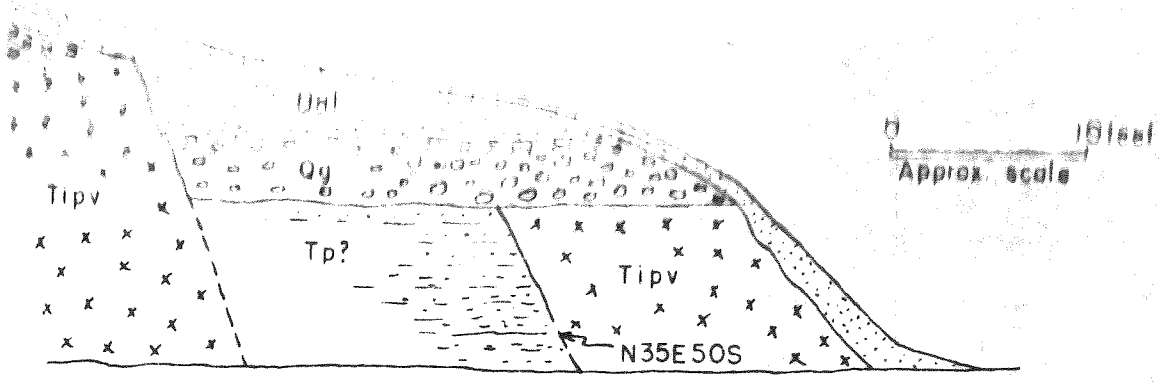


FIG.8 Sketch of outcrop showing post-Parunuweap(?)(Tp?), pre-high level gravels(Qg) faulting, and post-high level gravels faulting. Qal-alluvium; Tipv—Pine Valley monzonite porphyry. One mile west of Pintura.

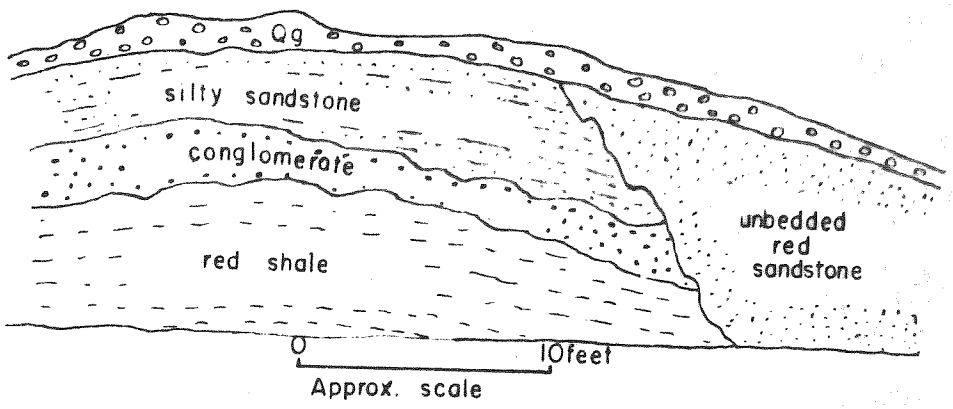


FIG. 9 Sketch of outcrop of folded Parunuweap(?) sediments overlain by a lag mantle of high-level gravels. About two miles east of New Harmony.

These gravels are the Boulder Alluvium of Gardner (1941, p. 243) and Proctor (1949, pp. 37-40). Proctor recognizes two levels of the boulder alluvium and thinks that it was deposited by streams and possibly mudflows coming off the Pine Valley Mountains during the Wisconsin stage of the Pleistocene epoch. Outliers of the higher-level boulder alluvium suggest a period of at least 100 feet of erosion before the lower terrace material was deposited and 60 feet or more has been eroded since the deposition of the lower-level boulder alluvium.

The high-level gravels, as mapped in this investigation, probably range in age from Pleistocene to Recent. Thomas and Taylor (1946, p. 33) noted similar material in Cedar City and Parowan Valleys which they mapped as fanglomerate terraces.

Alluvium (Qal), hillwash (Qhw), and landslide material (Qls)

Alluvial material deposited by the present streams is areally insignificant and consists of sand, silt, and gravel, the composition being influenced strongly by the underlying and nearby rocks. Ash Creek, Pinto Creek and the Santa Clara river have locally deposited alluvium wide enough to map.

Accumulations of angular, unsorted and unstratified material in steeply sloping piles at the foot of rapidly eroding scarps have been mapped as hillwash, material carried to its present position by a combination of hillwash,

sheetflood, rockfalls and small landslides. These accumulations typically occur at the base of fault scarps such as the Hurricane Ledge north of Toquerville.

Only one area of landslide material was mapped, about three or four miles northwest of Silver Reef, where a hill capped by basal Cretaceous has been undermined by sapping of the Carmel at the base, resulting in a landslide covering several acres.

Stratigraphic Sections

1. Section in Pintura well of Sun Oil Company, 2 miles west of Pintura; constructed from study of the well log of the Denver Sample Log Company.

	Thickness (feet)
Navajo sandstone:	
Fine to coarse, gray to orange red, well-rounded sandstone	1160 plus
Chinle formation:	
Alternating bands of brick red to purple red shale and gray, red, and purple-red sandstone ..	540
Silver Reef sandstone member. Gray, pale purple, orange-brown sandstone	100
Gray-buff to red-purple sandstone and interbedded gray to purple and red shale	190
Chocolate, red, and purple shale with some gypsum and minor interbedded red sandstone	165
Pale, purple-gray limestone	10
Calcareous shale	43
Sandy to conglomeratic pale purple limestone ...	22
Variegated sandy and conglomeratic shale and fine calcareous sandstone	310
Thickness of Chinle formation - - - - - - -	1180

	Thickness (feet)
Shinarump conglomerate:	
Fine to coarse, gray to purple sandstone, conglomeratic in the lower part. A few gray shale stringers	184
Moenkopi formation:	
Upper red member. Chocolate, red, gray and gray-green shale and siltstone with, near the base, interbedded gypsum and gypsiferous shale	574
Shnabkaib member. Gray, green and pink gypsum and gypsiferous shale	355
Middle red member. Red to brown, sandy, calcareous and gypsiferous shale and siltstone .	387
Virgin limestone member. Gray silty limestone .	54
Lower red member. Red to chocolate, sandy gypsiferous shale	302
Timpoweap member. Gray sandy limestone, reddish-brown and gray-green gypsiferous sandy shale; conglomeratic limestone at the base	102
Thickness of Moenkopi formation - - - - - -	1774
Kaibab limestone:	
Gray crystalline, cherty, fossiliferous limestone	348
Gray anhydrite	150
Gray to buff crystalline limestone, lower 50 feet sandy	294
Thickness of Kaibab limestone - - - - - - -	792
Coconino(?) sandstone:	
Gray to buff, fine to medium sandstone with some red streaks	206
Total depth of well - - - - - - - - - -	5496

2. Section near Danish Ranch, about three miles west of Silver Reef.

Dakota(?) sandstone

Unconformity

	Thickness (feet)
Carmel formation:	
Limestone, light gray, platy argillaceous subconchoidal fracture	135
Limestone, brown, massive, fossiliferous; ledge-former	25
Limestone, gray to buff	40
Limestone, cream to gray brown; ledge-former	30
Limestone, buff, platy	20
Limestone, gray, silty	10
Limestone, buff, silty, platy (1/8" to 1/4" beds)	20
Limestone, gray; ledge-former	03
Limestone, buff, platy, silty	15
"Temple Cap" member:	
Gypsum, weathers dark brown, massive	10
Shale, gray-green, purple, red; fissile; forms slope	60
Sandstone, gray, fine, poorly sorted, quartzose	02
Sandstone, red, soft	05
Shale, greenish-gray, sandy, gypsiferous	25
Sandstone, brick-red, soft, coarse	15
Shale, gray-green, sandy, soft, gypsiferous	05
Sandstone, brick-red to gray	33
Sandstone, gray to greenish-gray, medium to coarse, quartzose, gypsiferous	35

	Thickness (feet)
Sandstone, brick-red	25
Sandstone, medium to coarse, buff to red	15
Thickness of Carmel formation - - - - - - -	528
Disconformity	
Navajo sandstone, 11° dip slope	2000 plus or minus

3. Section on the east flank of the Pine Valley Mountains, west of Pintura and passing near Dixie Forest Camp.

	Thickness (feet)
Pine Valley laccolith	
Intrusive contact	
Claron formation:	
Limestone, white to red, sandy	18
Sandstone, pink to red, calcareous	12
Conglomerate, pink to white, calcareous, including small pebbles of limestone and sandstone ...	3
Covered; probably white to red limestone, calcareous sandstone, and some conglomerate with black limestone pebbles	35
Covered; probably white to pink limestone	10
Covered; probably calcareous conglomerate with sandstone and quartzite pebbles	10
Covered; probably white to pink limestone	15
Limestone, bluish-white, locally conglomeratic .	53
Covered; probably red limestone	12
Limestone, pale blue, locally conglomeratic; forms ledge	47
Grit, maroon and red, calcareous	3
Covered; probably white and pink limestone with some gray limestone conglomerate	35

	Thickness (feet)
Covered; probably pale blue and pink limestone	40
Limestone, pink to brick-red, and calcareous pebble conglomerate	47
Limestone, bluish-maroon, soft	40
Quartzite pebble to cobble conglomerate	80
Thickness of Claron formation - - - - - - -	460

Unconformity

Kaiparowits formation:

At top, buff sandstones with grit and channel conglomerate; below this, a generally soft sequence of buff sandstones with prominent iron concretions, fine white sandstones, pebble conglomerates, and minor silty limestone; at base, cross-bedded, massive, cavernous-weathering buff sandstone	960 plus or minus
Shale, red, silty	20
Sandstone, buff, medium-grained	20
Shale, red, silty, friable	60
Sandstone, buff to white	20
Quartzite cobble conglomerate	60
Sandstone, red soft	20
Quartzite pebble to cobble conglomerate	20
Sandstone, red, soft	20
Thickness of Kaiparowits formation - - - - -	1200 plus or minus

	Thickness (feet)
Disconformity	
Straight Cliffs and Wahweap sandstones: Alternating massive, medium to coarse, buff sandstones 10 to 40 feet thick, and blue-gray shales 10 to 30 feet thick	1800 plus or minus
Tropic formation: Sandstone, dark brown, fossiliferous; forms ledge	20
Covered; probably soft sandstone; forms slope ..	20
Sandstone, yellow-brown; forms ledge	20
Covered; probably red to gray sandy shale	25
Sandstone, yellow-brown; forms ledge	20
Covered; probably red-purple sandy shale	25
Sandstone, yellow-brown, locally cross-bedded ..	25
Covered; probably soft siltstone, buff to lavender	105
Sandstone, yellow-brown	3
Shale, blue-gray, sandy	3
Sandstone, yellow-brown	2
Shale, red, sandy	5
Sandstone, fine to medium, gray, reddish, and yellow-brown	48
Covered; probably red, lavender, and gray silty shale	37
Sandstone, cream, fine-grained, poorly bedded; forms ledge	20
Covered; probably lavender and gray-blue silty shale	45

	Thickness (feet)
Sandstone, buff, fine-grained, massive	8
Covered; probably purple to buff siltstone	15
Sandstone, yellow-brown, medium-grained, locally cross-bedded	10
Covered; probably red and gray silty shale	5
Sandstone, buff, fine-grained; forms ledge	10
Covered; probably red and chocolate shale	55
Sandstone, buff, fine-grained, massive; forms ledge	20
Mudstone, lavender and gray-blue; forms slope ..	120
Sandstone, cream, fine-grained, massive	3
Siltstone, dark gray	17
Sandstone, white to cream, thin-bedded, fine-grained	15
Covered; probably red-brown, red-chocolate, and purple silty shales	70
Thickness of Tropic formation - - - - - - -	771
Dakota(?) sandstone: Conglomerate of quartzite, chert, and black limestone pebbles in a matrix of calcareous sandstone	20
Unconformity	
Entrada sandstone: Extremely friable red-chocolate and greenish-white sandstone with a few beds of hard white to red-brown sandstone to two feet thick	140
Carmel formation: Limestone, gray to buff, platy to subconchoidal fracture	200 plus or minus

	Thickness (feet)
Sandstone, calcareous, and sandy limestone, gray to buff	101
Sandstone, brown, calcareous, fossiliferous	5
Limestone, gray, much of it sandy or silty	176
"Temple Cap" member:	
Sandstone, purplish, calcareous, fine-grained, and sandy limestone	17
Limestone, gray to pale lavender, argillaceous .	44
Mudstone, soft sandstone, and sandy limestone ..	26
Sandstone, red-brown, soft, fine-grained, poorly sorted	108
Thickness of Carmel formation - - - - - - -	677 plus or minus

Disconformity

Navajo sandstone

4. Section from Diamond Valley east up Alger Gulch, 11-12 miles north of St. George, Utah.

	Thickness (feet)
Dixie basalt	
Unconformity	
Claron formation:	
Red calcareous sandstone and sandy limestones above a 30-foot conglomerate containing many black limestone pebbles and quartzite cobbles to five inches	475 plus or minus
Unconformity	
Cretaceous rocks, undifferentiated:	
Sandstone, red, white, fine-grained, soft	440 plus or minus
Sandstone, dark-brown, medium-grained, platy ...	7

	Thickness (feet)
Sandstone, some red layers to 8 feet thick, but mainly massive buff and yellow-brown, cross-bedded sandstone with some thin sandy shales and gray sandstone near the base.....	2800 plus or minus
Sandstone, in beds three to eight feet thick, red, gray, and brown, medium-grained; dark brown iron concretions in lenses three feet thick	40
Sandstone, buff, cross-bedded, medium to coarse; forms ledge	27
Sandstone, alternating dark brown with limonite concretions and soft red sandstone, five-15 feet thick; three-foot gray shale at top	80
Sandstone, brown, cross-bedded; forms ledge	30
Sandstone, buff to brown, cross-bedded, medium-grained, poorly sorted, thin to medium-bedded ..	108
Sandstone, white to buff, cross-bedded, medium-grained, in beds 4 to 20 feet thick, more cross-bedded and poorly sorted toward the top; forms cliff	147
Sandstone, buff to red-brown, cross-bedded, contains iron concretions	35
Sandstone, pale gray, fine-grained; some blue sandy shale	10
Sandstone, buff, weathers dark brown, cross-bedded, hard; forms ledge	5
Sandstone, gray to dark brown, fine-grained, soft; forms ledge	100
Sandstone, gray, quartzose, medium-grained, cross-bedded, hard	6
Sandstone, white to gray, calcareous, fine-grained	47

	Thickness (feet)
Sandstone, argillaceous, gray; some thin gray calcareous shale layers	5
Sandstone, white, fine-grained, quartzose; lower five feet forms ledge	30
Thickness of Cretaceous rocks undifferentiated - - - - - - - - - - - - - - -	3917 plus or minus
Unconformity	
Entrada sandstone:	
Shale, gray	40
Shale, brick-red with some thin layers of white limestone	55
Shale, greenish-gray, sandy, and platy siltstone	45
Thickness of Entrada sandstone - - - - - - -	140
Carmel formation:	
Limestone, brown, platy, locally well rippled; Pentacrinus and Ostrea	2
Shale and platy limestone, gray; some oolitic, some sandy	145
Limestone, gray-brown, dense, platy	5
Limestone, light gray, laminated, dense	20
Limestone, gray, soft and earthy	35
Limestone, gray, dense, hard; breaks with conchoidal fracture	15
Limestone, gray, soft and earthy	10
Limestone, gray, dense, hard; conchoidal fracture	10
Limestone, gray, thin-bedded; alternating hard and soft beds	15

	Thickness (feet)
"Temple Cap" member:	
Gypsum, with some blue-gray shale	20
Shale, gray, calcareous	15
Limestone, gray, dense, hard	5
Shale, greenish-gray, gypsiferous	15
Shale, brick-red, silty	5
Gypsum	10
Shale, brick-red, silty, gypsiferous	50
Covered; probably red sandstone	100 plus or minus
Thickness of Carmel formation - - - - - - -	477 plus or minus

Disconformity

Navajo sandstone

5. Section measured just west of the town of Gunlock, Utah.

Tv-1 Ignimbrite

Disconformity

Claron formation:

Covered; probably gray calcareous conglomerate with rounded quartzite to 24 inches; gray to buff sandstone and limestone fragments to 18 inches; some petrified wood	100
Conglomerate, red; 6 to 8-inch rounded quartzite, limestone, and sandstone; upper 20 feet is a calcareous red grit	100
Sandstone, pale red, conglomeratic and calcareous	20
Conglomerate, with limestone boulders to 14 inches and occasional rounded quartzite to 7 inches	105

	Thickness (feet)
Covered; probably conglomerate	60
Conglomerate, pale red; contains yellow-brown slabs of fine calcareous sandstone to 6 inches, many black and blue-gray limestone pebbles and cobbles, dark gray fossiliferous limestone boulders to 15 inches and yellow-brown sandstone slabs to 15 inches	120
Sandstone, red calcareous, medium-grained, well-bedded	20
Conglomerate, brown to gray; contains limestone, sandstone, and subordinate quartzite to 9 inches; 50 per cent of the material is limestone; some black limestone fragments to seven inches	90
Sandstone, red, medium-grained, soft	10
Conglomerate, red, with cobbles to 8 inches; forms slope	30
Conglomerate, brown, containing sandstone and grit lenses; sandstone, limestone, and quartzite pebbles and cobbles; about 15 per cent of the material is dark limestone; sandstone fragments are dominant; forms cliff	115
Sandstone, gray to dark red, fine-grained	40
Sandstone, brown, cross-bedded, conglomeratic, calcareous	3
Siltstone, red, soft	18
Conglomerate, pink, poorly sorted; contains sandstone lenses; most of the material is subrounded quartzite to 8 inches; some sandstone slabs to 14 inches; black limestone pebbles; forms ledge .	18
Sandstone, buff to gray, coarse cross-bedded; gets coarser upward with scattered pebble lenses	60
Sandstone, red, medium-grained, with thin gray quartz sand layers; cross-bedded and poorly cemented	20

	Thickness (feet)
Sandstone, gray to red, fine-grained, calcareous, soft	15
Conglomerate, gray with irregular red staining, poorly sorted; contains boulders to ten inches, the largest being sandstone; smaller cobbles and pebbles are sandstone, limestone and quartzite; only about 5% of material is quartzite; no bedding; a few sand lenses; contains sandstone from the unit below	15
Thickness of Claron formation - - - - - - -	959

Unconformity

Cretaceous rocks undifferentiated:

Upper part is white, buff, and red, fine to medium sandstone with some dark brown calcareous sandstone and some soft purple silt; lower, the beds thicken, ranging from 20 to 50 feet and the sandstone beds are buff, coarse-grained, cross-bedded, alternating with soft reddish sandstones and silty shale; one brown gritty limestone layer occurs about 1000 feet below the top; in the upper part of the lower half of the unit, buff to yellow-brown sandstones 20 to 40 feet thick alternate with gray and variegated shale layers 10 to 15 feet thick; near the bottom of the Cretaceous, the sandstones become gray to white and the shale breaks are thicker. At the base is 50 feet of Dakota(?) sandstone, containing pebbles to 6 inches, although most are less than 3 inches, largely of black limestone and quartzite	3850 plus or minus

Unconformity

Entrada sandstone:

Shale, gray	0-15
Shale, red, silty	30
Shale, gray-blue to greenish	70
Thickness of Entrada sandstone - - - - - -	100-115

	Thickness (feet)
Carmel formation:	
Tan sandy limestone with Pentacrinus columnals	

6. Section at headwaters of Cottonwood Creek, between the West Fork and the Middle Fork.

Pine Valley laccolith	
Intrusive contact	
Claron formation:	
Blue-gray friable limestone	105
White, massive limestone; ledge-former	20
Blue-gray and red, thin-bedded limestone; weathers pink; forms ledges and slopes	175
Gray conglomerate and sandstone; contains quartzite pebbles and flattish black limestone fragments	35
Disconformity	
Blue-gray, arenaceous limestone; stains reddish, fractures easily	15
Massive gray conglomerate; occasional quartzite cobbles, mainly pebbles; interbedded gray lenticular quartzitic sandstone; ledge-former ..	20
Disconformity(?)	
Soft, white to yellow-brown sandstone	18
Quartzite pebble conglomerate	02
White, fine sandstone and gray-green to red-brown sandy shale	05
Purplish limestone; minor blue shale	05
Blue and red shale, and white, fine sandstone, well-bedded	10
Red and blue-gray shale	15

	Thickness (feet)
Gray conglomerate and white, medium to coarse sandstone	35
Thickness of Claron formation - - - - - - -	460

Unconformity

Kaiparowits formation: Cream to buff medium sandstone.

7. Section at headwaters of Cottonwood Creek, above the east fork.

Pine Valley laccolith

Intrusive contact

Claron formation:

Mudstone, gray-green, slightly calcareous.....	03
Limestone, white to red, friable.....	35
Pebble conglomerate, light pink.....	05
Limestone, blue-gray to red; slope-former.....	65
Limestone, dark blue-gray, two-foot beds; ledge former.....	15
Limestone, blue-gray and pink, some red shale; slope.....	130
Sandstone, dark gray, calcareous, locally conglomeratic.....	05
Limestone, white to vermilion with some dark red shale; slope-former.....	73
Limestone, blue-gray, well-bedded, gritty; ledge-former.....	12
Limestone, gray to pink, sandy, locally conglomeratic with some orange-brown to dark red shale.....	75
Conglomerate, pink, poorly sorted, unstratified; formed of pebbles and cobbles of quartzite to six inches, with some sandstone, chert, jasperoid	

	Thickness (feet)
quartz, and altered igneous rocks in a coarse quartz sand matrix. Middle 15 feet of section consists of calcareous sandstone with conglomerate lenses	45
Shale, red-brown to deep purple	15
Limestone, blue-gray; forms ledge	05
Covered; probably gray to pink limestone and quartzite conglomerate	50 plus or minus
Thickness of Claron formation - - - - - - -	533 plus or minus

Unconformity

Kaiparowits formation

8. Pace Canyon Section;
Measured one-half mile north of Kelsey Deer Camp

Alluvium in Pace Creek Channel

Tropic formation:	
Sandstone, gray, soft, with thin beds of yellow-brown sandstone	50 plus
Sandstone, yellow-brown, resistant, dips 80° east	10
Sandstone, gray to red, soft	40
Sandstone, yellow-brown, resistant; overturned, dips 40° west	04
Sandstone, gray, yellow-brown and red, soft	30
Sandstone, mustard yellow, calcareous, forms ridge; overturned, dips 45° west	05
Covered; probably sandy shale	20
Sandstone, yellow-brown; overturned, dips 60° west	02

	Thickness (feet)
Shale, red, sandy, and thin yellow-brown sandstone beds	90
Sandstone, dark yellow-brown; resistant, overturned, dips 75° west	05
Sandstone, yellow-brown and red, soft	50
Covered; probably shale with some thin sandstone beds	130
Shale, gray to black, carbonaceous	60
Sandstone, gray to orange-brown; overturned, dips 60° west	20
Shale, gray and buff	20
Coquina; mostly clam and oyster shells in dark gray calcareous matrix; ledge; overturned, dips 48° west	08
Coal	05
Shale, gray to black, sandy, carbonaceous	20 plus
Thickness of Tropic formation measured - - -	569 plus

Intrusive contact

Stoddard Mountain porphyry.

IGNEOUS ROCKS

Extrusive Rocks

General statement

A thickness of several thousand feet of pyroclastic rocks and flows, in several unconformable groups, lying above the Claron formation in the northern part of the Pine Valley Mountains attests to the intensity and length of the Tertiary volcanism. North of a line connecting Central and New Harmony, most of the surface rocks of the map area are volcanic; south of that line, the rocks are mainly sedimentary and intrusive.

Almost without exception, the pyroclastic rocks of the Pine Valley Mountains are well indurated and stand in cliffs. In order of increasing hardness and resistance to erosion, the pyroclastic rocks of the area may be classified as tuffs, breccias, bedded tuff-breccias and ignimbrites.

Types of volcanic rocks in the area

Ignimbrite

Pyroclastic rocks indurated by partial fusion of glass shards or by pneumatolytic recrystallization have been variously called welded tuffs, ignimbrites and tuff-flows. Fenner (1948, p. 883) would like to restrict the term welded tuff to those

rocks in which there has been softening and union by heat and proposes the term tuff-flow to include all indurated tuffaceous rocks in which the induration is a primary feature caused by heat, pneumatolysis, or both.

As commonly used, ignimbrite means the deposit of "burning clouds" (Gilbert, 1938, p. 1853) even if only partially or moderately welded (Mackin, 1952, p. 1337), although Marshall, who originally proposed the term, thought (1935, p. 323) that the temperature of such deposits would be high enough to cause welding. In this thesis, the term is applied only to tuffs and tuff-breccias which are partly to completely welded, and not to unwelded tuffs and tuff-breccias, although some of the unwelded tuff-breccias may have had a nuée ardente origin.

The ignimbrites of the Pine Valley Mountains vary from pink, crystal-vitric, rhyolite ignimbrite with prominent lithic fragments to brown, crystal, dacite ignimbrite which looks like an intrusive rock. Each ignimbrite contains broken and corroded intratelluric crystals; except in two or three vitric units, such crystals comprise 40 to 75 per cent of the rock. The groundmass is glassy, commonly partly devitrified. In the more vitroclastic units, the glass shards are flattened around and between the large crystals in a compaction structure; the shards themselves are drawn out and flattened. Other units which lack a vitroclastic groundmass may have irregular,

lenticular cavities around which the groundmass is devitrified into an aggregate of tridymite and orthoclase(?); these cavities represent either decomposed glass fragments or, more likely, envelopes of entrapped gas which endomorphically altered the adjacent groundmass to a crystalline aggregate.

The Wentworth and Williams (1932) classification of pyroclastic rocks is followed in this thesis and has been extended to cover ignimbrites. In terms of this classification, the ignimbrites of the Pine Valley Mountains range from vitric to crystal; most, however, fall in the crystal-vitric category.

There is no bedding and no sorting of either crystals or lithic fragments. The more or less complete crystals average about two to four millimeters in diameter. In some units lithic fragments of rather uniform maximum size are distributed evenly throughout the rock; in other units, there may be a wholly irregular variation in size and quantity of lithic fragments. Variation in size range and percentage of lithic fragments is usually vertical, not lateral.

Judged by the intratelluric crystals the ignimbrites of the Pine Valley Mountains are all andesites and trachytes; however, the glass of the groundmass has a silica content (based on index of refraction) of 65 to 70 per cent and so the ignimbrites are actually dacitic to rhyolitic in total composition.

Each tuff unit apparently represents one eruption; most

units have black glass at the base, locally brecciated, and have no other black glass, breccia, or evidence of anything but simultaneous formation throughout the entire thickness of the unit, which may be as much as 700 feet.

A persistent accidental element in the ignimbrites is quartzite, in rounded pebbles and cobbles. Each pebble is isolated; although there are no accumulations of quartzite, certain of the welded tuffs contain it more abundantly than others. The quartzite probably represents surface gravel swept up and incorporated into the swiftly moving, turbulent gas cloud in which each tuff unit had its beginning.

Field relations and evidence of extension of at least some of the tuff units into and through the Iron Springs district (Mackin and Nelson, 1950) indicate that each ignimbrite was laid down with fairly uniform thickness over an area vastly greater than that of the Pine Valley Mountains. Variation in thickness of a unit within the area is probably due more to irregularity of the surface on which the ignimbrite was deposited and to subsequent erosion than to depositional thinning away from the source of the eruption.

The origin of ignimbrites or welded tuffs in general, and of the type exposed in the Pine Valley Mountains in particular (great lateral extent, uniform thickness and lithology), is a matter of considerable speculation. Most of the authors who have treated this subject favor the nuée ardente or "burning

cloud" hypothesis, that is, that the units were formed from an incandescent, rapidly expanding, highly mobile magmatic gas cloud which, erupting from one or several fissures simultaneously, carries with it fragments of intratelluric crystals from the exploding magma, as well as rock fragments picked up in the vent or from the ground surface by the fast-moving, turbulent cloud.

This and other concepts of origin have been discussed by Lacroix (1930), Mansfield and Ross (1935), Marshall (1935), Gilbert (1938), and Fenner (1948).

Bedded tuff-breccia

After the ignimbrites, the next most abundant pyroclastic rock of the Pine Valley Mountains is bedded (unwelded) tuff-breccia. Rudely bedded with two to twenty feet between stratification planes, the tuff-breccia contains angular to subangular blocks of igneous rocks to six feet in diameter and broken quartzite pebbles and cobbles, set completely at random in an abundant, friable, sand matrix of broken feldspar and biotite crystals and interstitial ash.

There is no sorting or stratification of the material visible other than the thick bedding. Large, angular blocks may be found anywhere within the tuff-breccia, and no compaction structures are noticeable in their vicinity. The rock, although standing in cliffs, is friable under the fingers and breaks

around its constituent particles.

Features of the tuff-breccia which must be explained by any hypothesis of origin are:

1. The utter lack of sorting and small-scale stratification.
2. The thick, rude bedding; the planes of separation are apparently continuous, but there is no vertical gradation of the material between planes.
3. The fact that the tuff-breccia fills depressions in a rough topography formed on folded and faulted older volcanic rocks; the tuff-breccia rests directly upon these older rocks.
4. An apparent upward gradation, in one locality, from a partially welded tuff-breccia without bedding into the less-indurated, bedded tuff-breccia.
5. The heterogeneity, subangularity, and great size range of the lithic fragments.
6. The presence of broken quartzite as an accidental constitutent.
7. The slightly calcareous nature of the matrix.
8. The gross composition: lithic and pumice fragments make up about half the rock; mineral crystals, largely of feldspar and euhedral biotite, are abundant.

Deposition in running water is ruled out because of the

lack of sorting and fine stratification. Lacustrine deposition of the products of a tremendous explosion is not the answer, for there are no lacustrine sediments at the base of the tuff-breccia; neither would lacustrine deposition explain the thick bedding.

The bedding is also evidence against an air-fall origin; furthermore, the deposit should be better sorted than it is, were it the product of the free fall through air of volcanic ejecta. Finally the quartzite pebbles scattered through the tuff-breccia appear to preclude an air-fall origin.

There remains to be considered the gradational series of phenomena whose end members are, on the one hand, a volcanic mudflow, and on the other, a nuée ardente not hot enough to produce a welded deposit. Curiously, authors have made little or no attempt to describe or distinguish the deposits made by the different kinds of flows represented in this series, but have concerned themselves largely with the flow phenomena--with some conspicuous differences of opinion on flow mechanism and composition, even regarding historic, observed flows. For example, the flows which descended the flanks of Mont Pélé in 1902 have been ascribed to torrential rains which followed the eruption of volcanic dust and ashes (Sharpe, 1938, p. 60); to the ejection of crater lakes, the waters of which carried heated boulders in a "flood of boiling mud" (Curtis, 1903, p. 204); and to repeated blasts of superheated steam carrying

vast quantities of glowing ash and blocks, described as nuées ardentes and avalanches incandescentes (Lacroix, 1930, p. 458).

Based on examples observed during the West Indian eruptions of 1902, Lacroix (1930) distinguished three types of flow, each of which involves a gas-solid mixture, the gas being predominantly water vapor: (1) nuées ardentes péléennes d'explosion dirigée, whose movement is caused largely by explosive propulsion, involving the violent release of gas from a magma; (2) nuées ardentes d'avalanche or avalanches incandescentes, products of a weaker explosion, which move mainly under their own weight, their mobility being due to "that strange mixture of solid material and high-temperature gas"; and (3) nuées ardentes d'explosion vulcaniennes, caused by the ejection of a crater lake during an eruption and the turning of its water into steam by hot ejecta. The last-named flows are equivalent to the "lahars" of Java (Scrivenor, 1929, pp. 433-434).

Lacroix (1930, p. 464) briefly described the lahar deposits of St. Vincent and contrasted them with the nuée ardente péléennes and glowing avalanche deposits of Mont Pélé. Although all the deposits are unstratified and petrographically heterogeneous, the lahar deposits differ from the others as follows: (1) the maximum dimensions of the fragments are "infinitely smaller", the deposit being 90 per cent fine cinders and sand; (2) the volcanic blocks are distributed

par essaims (by swarms); and (3) there is an absence of the "secondary fumaroles" characteristic of the Péléan deposits.

If the tuff-breccia of the Pine Valley Mountains was formed as a result of torrential rains (or rapidly melting snow) which produced mudflows on slopes mantled with loose volcanic material, the tuff-breccia (which should then probably be called volcanic fanglomerate) should have, apart from composition, the characteristics of a normal mudflow deposit. As Blackwelder points out (1928, p. 465), mudflow deposits are beds of unsorted and unstratified material, commonly containing blocky boulders; the mudflow itself slides or glides over the surface, shearing off but not readily incorporating objects in its path. Although mudflows have, in some localities, occurred with some regularity and are superimposed one upon another (Chawner, 1935, p. 256) mudflow deposits are more commonly succeeded upward by streamflood deposits lying in channels on the mudflow material (Blackwelder, 1928, p. 472). Blissenbach reports (1954, p. 186) that individual mudflow deposits range in thickness from one foot to 15 or 20 feet. According to the same author (p. 178), "a striking peculiarity of sheetfloods is their shortness in distance as well as in time of their flows" (Sheetfloods produce the blanket-shaped mudflow deposits). Although the tuff-breccia of the Pine Valley Mountains is unsorted and unstratified between its bedding planes, the scarcity of intercalated streamflood deposits and

the ubiquity (but not abundance) of sedimentary material probably incorporated en route suggests that it was not formed by successive sheetfloods.

The pumice fragments in the tuff-breccia show that an explosion preceded or accompanied its formation, for no pumice deposits from which the flows might have picked up material have been found in the area. The broken quartzite inclusions, unless torn from the volcanic vent, were probably incorporated into the flows from surface gravels; if so, a somewhat turbulent mass spreading rapidly from the vent seems indicated. The absence of endomorphic cavities (Lacroix's "secondary fumaroles"?) and welding shows that the temperature of formation was not that of a nuée ardente, at least not of the first two types distinguished by Lacroix. On the other hand, the Pine Valley Mountains tuff-breccia appears to have a larger average particle size than the lahar (nuée ardente d'explosion vulcanienne) deposits described by Lacroix (1930, p. 464) and the larger included blocks are not distributed "in swarms". The upward gradation, seen in one locality, from a loosely welded tuff-breccia into the unwelded, bedded tuff-breccia suggests a decrease in temperature of successive flows and the possibility of formation from low-temperature nuées ardentes.

In conclusion, the evidence indicates the tuff-breccia was deposited by a series of rapidly moving, widely spreading flows of gas (possibly steam) and solid particles, in which the

temperature was below that required for welding. This type of flow can more logically be called a lahar (if the crater-lake origin of the steam can be ignored in the definition, for there is no evidence in the Pine Valley Mountains suggesting either the existence or non-existence of crater lakes during the formation of the tuff-breccia) than a "glowing avalanche", because the particles were probably not incandescent.

Breccia and tuff

Black to olive-brown andesite breccia and intertonguing or gradational flow-rock in thicknesses up to 500 feet are exposed in the northwestern Pine Valley Mountains. The breccia is monolithic and, in the thicker sections, contains angular blocks to 20 feet in diameter. Locally the breccia grades laterally into jointed flow-rock; in such places, the brecciation may have been caused by an explosion of gas (or water) trapped beneath the flow.

Pale gray dacite porphyry forms an extensive breccia at one horizon in the volcanic sequence. Unwelded, air-fall tuff forms a minor part of the volcanic rocks of the area. It is well-sorted, biotitic, and light-colored; one unit is calcareous and was probably deposited in shallow lacustrine water.

Lava flows

Lava flows of the Pine Valley Mountains include stony red dacite(?); light gray dacite porphyry, locally porous and "shardy"; olive brown to black andesite; and dark gray to black basalt. Except for the basalts, which cover extensive areas around the Pine Valley Mountains, the unbrecciated flows are a small portion of the extrusive rocks of the area. Strangely enough, however, many of the fragments in the ignimbrites and bedded tuff-breccias appear to be of flow origin.

"Platy porphyry"

The higher part of the northern Pine Valley Mountains consists of latite (or quartz latite) porphyry whose outstanding characteristic is a conspicuous platy parting which, from a distance, looks like bedding. Except for a basal chilled phase, the rock is lithologically uniform throughout its thickness of 2,000 feet. The rock is mineralogically and texturally similar to the intrusive monzonite porphyry of the Pine Valley laccolith. Although the "platy porphyry" has been mapped as an extrusive rock, the rock may actually be intrusive.

Quichapa group

Distribution and stratigraphic relations

The Quichapa group, named by Mackin (personal

communication) from exposures in Quichapa Canyon of the Harmony Hills, is represented in the Pine Valley Mountains by three ignimbrite units, each with distinctive characteristics which makes it easily traceable in the field. Caution must be exercised in the identification of units in isolated outcrops, however, for another and apparently younger group of welded tuffs contains two units lithologically identical with the two lower units of the Quichapa group.

In the Pine Valley Mountains the thickness of the group ranges from zero to about 1,600 feet, the variation being due largely to the unconformity at the top of the group. The Quichapa group has an extensive outcrop within the map area; it forms the cliffs which partially enclose the valleys west and south of Page Ranch, outcrops in Comanche Canyon and in the vicinity of The Dairy, forms the basal portion of the mountains which rise on both sides of the Santa Clara Valley between Pine Valley and Central, and overlies the conglomeratic Claron in the Gunlock area.

The base of the group is a disconformity. Indeed, in most exposures the lowermost welded tuff appears to overlie the Claron formation conformably. In the northern part of the Iron Springs district, however, several volcanic units not found in the Pine Valley Mountains sections form the lower part of the Quichapa group (Mackin, personal communication); these units, which thin and disappear southward, represent a hiatus between

the Claron and the Quichapa of the Pine Valley Mountains. Evidence, not only of nondeposition, but of erosion following crustal disturbance, is found in the distribution of the upper Claron biotitic tuff. This tuff was laid down on a regular, horizontal surface and probably formed as a continuous thin blanket over the entire region. Its disappearance from the thinning Claron section in the vicinity of Pine Valley and its absence beneath the Pine Valley laccolith (except in Leap Creek) are believed to be due to post-Claron, pre-Quichapa differential uplift and erosion.

The Quichapa group is limited upward by an unconformity marked in several localities by lenses of white limestone and loosely compacted gravel. In other places, where the contact with the succeeding tuff appears gradational, the overlying tuff contains abundant quartzite pebbles, probably swept from the erosion surface and incorporated in a nuée ardente.

The Quichapa group has been recognized in exposures many miles from the Pine Valley Mountains (Mackin, personal communication); the source or sources of the eruptions which formed it is not known.

Tv-1 ignimbrite

The lowermost unit of the Quichapa group, the Tv-1 ignimbrite, ranges in thickness from less than one hundred feet just east of Stoddard Mountain (and again near Pine Valley) to

about 800 feet near Pinto Peak. The thinning near Stoddard Mountain is accompanied by a more abrupt thinning of the Claron, which is there represented only by a thin conglomerate which locally pinches out. From this, it is inferred that post-Claron, pre-Quichapa uplift (probably along a northeast-southwest axis) caused partial to complete removal of the Claron by erosion, leaving a low ridge in the Stoddard Mountain area, over which the Tv-1 ignimbrite was deposited. Some of the thinning of the Tv-1 may also be due to post-Tv-1, pre-Tv-2 erosion. Just north of the town of Pine Valley, Tv-1 less than 100 feet thick is overlain disconformably by the basal black glass of the Tv-2 ignimbrite. Furthermore, in the hills about three miles southeast of Central, the Tv-1 is locally overlain by gray calcareous grit and a little lacustrine limestone. It thus appears that a disconformity exists between the two lower members of the Quichapa. West of Page Ranch the Tv-1 ignimbrite is underlain by a dense, red latite(?) flow, which appears to thicken toward the northwest. Its maximum thickness in the area mapped is about 40 feet.

Although the hard, dense rocks of the Tv-1 ignimbrite weather a pale red-brown, the fresh rock surface is a pale red-violet. Sparsely scattered through the rock are angular red latite(?) fragments, averaging under 10 millimeters in diameter. Lithic fragments make up only five to ten per cent of the tuff, but are a striking feature of the smooth surfaces

along which the rock breaks (Figs. 10, 11); none of the fragments are larger than 15 centimeters in diameter and the great majority are under five millimeters. The stony groundmass contains abundant feldspar and biotite crystals one to two millimeters in diameter.

Five to twenty feet of black glass at the base of the unit also contains the angular red fragments. In this glass, a planar compaction structure consisting of flattened white lenticles is common. Above the glassy base, the Tv-1 ignimbrite is remarkably uniform both vertically and laterally; the only deviations from the norm in the Pine Valley Mountains involve, in one locality, a change in color to gray with a faint pinkish tinge and, in another place, an increase in biotite. A small percentage increase in biotite can greatly alter the megascopic appearance of a low-biotite tuff. Endomorphic cavities and flattened white inclusions are sparingly present in the normal rock. Under the microscope, the Tv-1 ignimbrite is found to have the following composition:

Lithic fragments, not identified	5-10%
Groundmass, glassy, partially devitrified; vitroclastic and compaction structures; index of refraction, 1.51	30-55%
Crystals and crystal fragments	40-70%

The crystals are identified as follows:

Sanidine, euhedral; partially resorbed	65%
Plagioclase, zoned; oligoclase andesine	25-30%
Biotite, strongly pleochroic	1- 5%
Hornblende, euhedral; highly altered	1%
Magnetite, largely secondary	1- 2%
Apatite	1%
Sphene	less than 1%



Fig. 10 Tv-1 ignimbrite. Angular red dacite (?) inclusions in a pale red-violet, crystal-vitric groundmass. Note clean fracture across fragments.

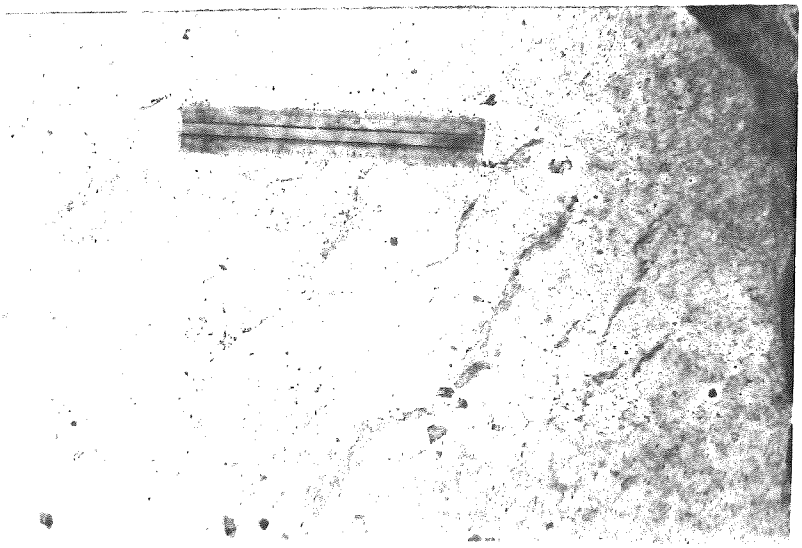


Fig. 11 Tv-1 ignimbrite. Devitrification aureoles surrounding accidental fragments.



Fig. 12 Photomicrograph of basal glass of the Tv-1 ignimbrite. Note the broken and corroded sanidine crystals. Plane light, 21.5x.

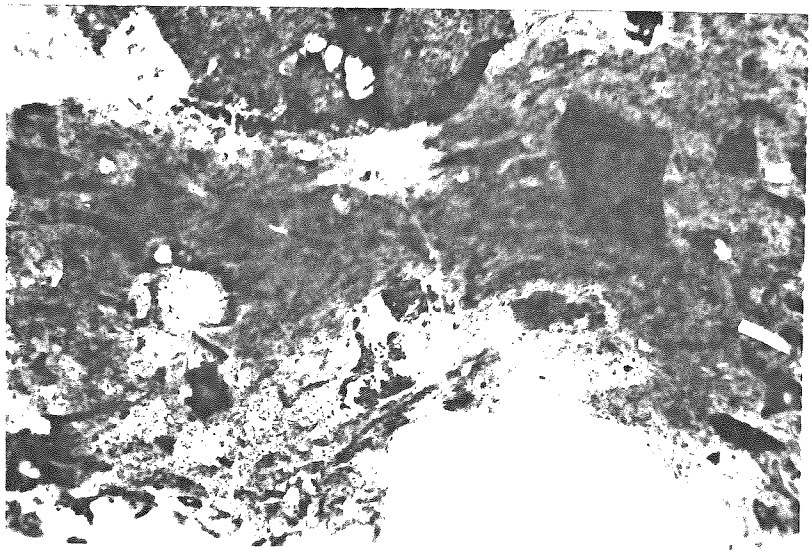


Fig. 13 Photomicrograph showing vitroclastic compaction structure in the Tv-1 ignimbrite. Plane light, 35x.

Nearly all of the crystals of sanidine and plagioclase are broken; and many are partially resorbed (Fig. 12); crystal fragments range in size from two millimeters down to the crystal dust which is distributed throughout the groundmass. Except for biotite, the original mafic minerals are almost completely altered to magnetite, limonite, and hematite; the biotite itself is considerably altered.

The groundmass is partially devitrified glass, locally containing shards, aligned and bent down under and between crystals in a vitroclastic compaction structure (Fig. 13). The sparse lenticular vugs are lined with microlites, probably representing devitrified glass.

The rock is a crystal-vitric rhyolite ignimbrite.

Tv-2 ignimbrite

Disconformably overlying the Tv-1 ignimbrite is another rhyolite ignimbrite. This formation has a rather uniform thickness in the Pine Valley Mountains, averaging about 180 feet. Above a basal black glass ten to twenty feet thick is a strongly foliated, pale red section and this grades upward into a hard, structureless, pale lavender rock at the top of the unit. The basal glass is jet black and contains as much as 25 per cent white, feldspar crystals, as well as sparse angular red lithic fragments. The foliated unit has a brick-red vitric groundmass containing numerous thin, parallel white

lenticles (Figs. 14, 15) up to six inches long and one inch thick. Locally these lenticles comprise as much as 40 per cent of the rock. The lenticles commonly are vuggy.

The microscope shows the lenticles to be composed of finely crystalline material, in which tridymite can be identified and orthoclase is likely present. Microscopically, the lenticles do not have nearly as sharp boundaries as they appear to have megascopically (Fig. 16); whether a lenticle represents a devitrified flattened pumice fragment or a flattened cyst of entrapped gas which caused pneumatolytic crystallization is a moot question.

Crystals of feldspar to four millimeters in length and sparse, copper-colored biotite about one millimeter in diameter comprise 25 per cent of the foliated rock. The feldspar consists of broken and corroded crystals of plagioclase and sanidine, in approximately equal amounts. The plagioclase is oligoclase-andesine and contains scattered inclusions of biotite and apatite. Almost all of the sanidine shows Carlsbad twinning and some of it contains plagioclase inclusions. The glassy groundmass is dark with hematite dust (which gives the rock its color), has a fluidal structure (Fig. 17) and a refractive index between 1.50 and 1.51. Recognizable glass shards are scarce, probably because most of them have been fused and drawn out into the fluidal structure. There are no lithic fragments.

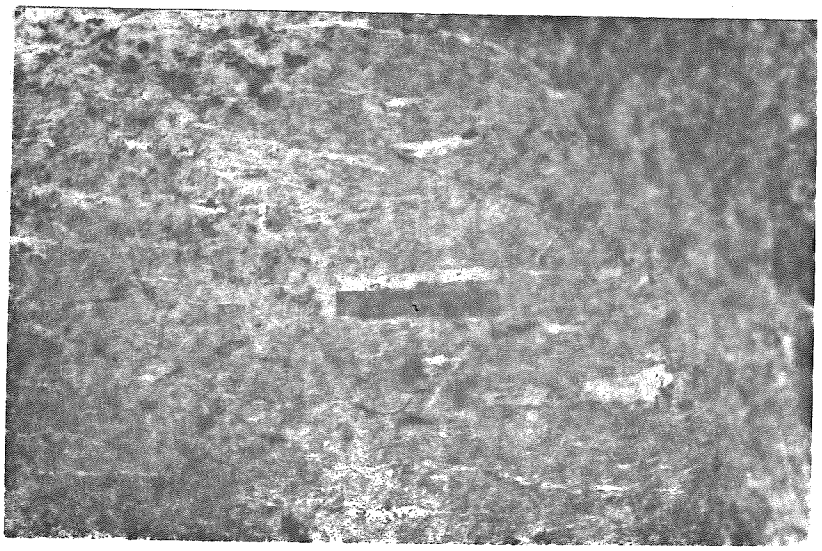


Fig. 14 Outcrop of the Tv-2 ignimbrite near The Dairy. Parallel white lenticles are set in a brick-red vitric groundmass. Scale is six inches long.

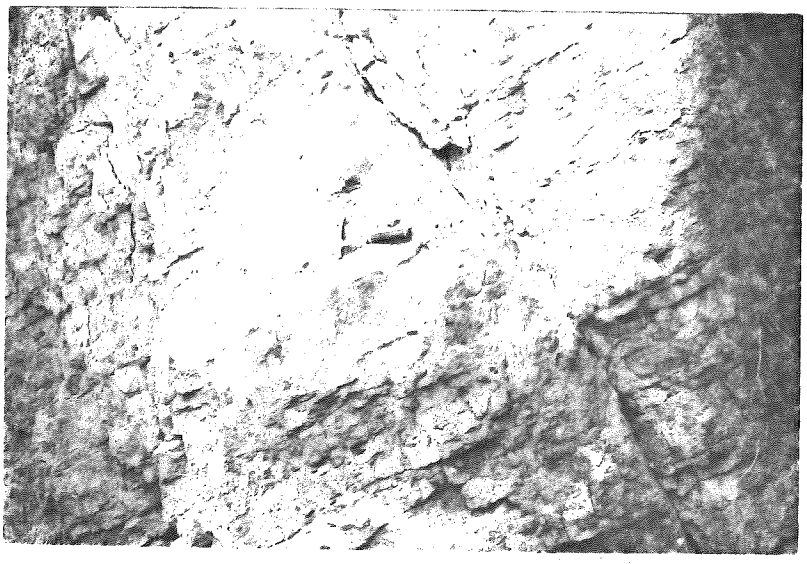


Fig. 15 Outcrop of Tv-2 ignimbrite in Comanche Canyon. The dip of the formation is shown by the white lenticles inclined down to the left. The hammer gives the scale.

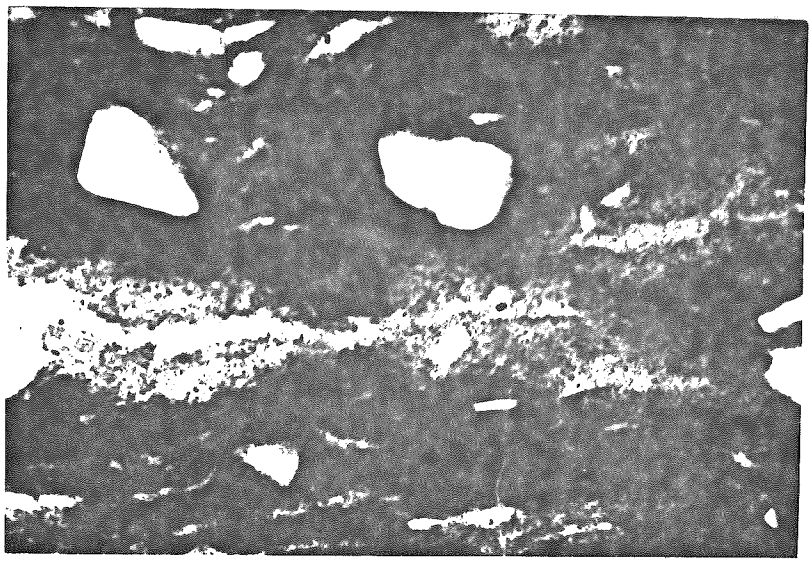


Fig. 16 Photomicrograph of the foliated unit of the Tv-2 ignimbrite. Note gradational boundaries of devitrification lenticles. Plane light, 35x.

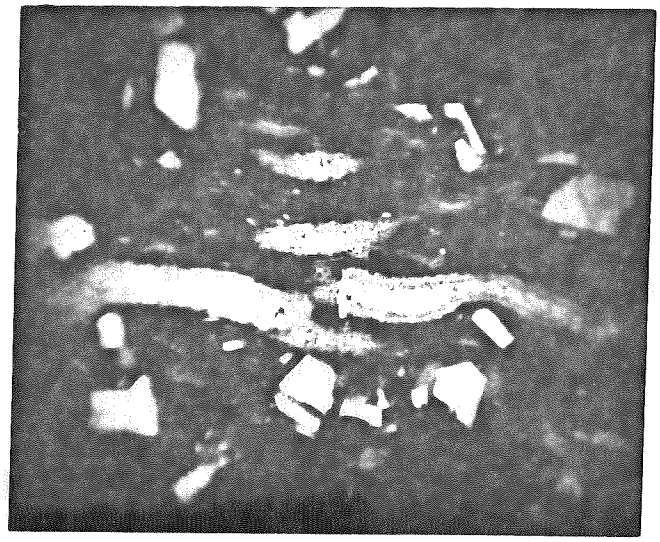


Fig. 17 Photomicrograph of foliated Tv-2 ignimbrite, showing devitrification lenticles. Plane light, 11x.

Most of the larger crystals of the foliated rock are enclosed in finely crystalline reaction rims, a feature rare in the other welded tuffs. Biotite composes two to five per cent of the rock, augite and magnetite each about one per cent, and apatite, under one per cent.

The upper, pale lavender portion of this ignimbrite (not over 40 feet thick in any outcrop) has no megascopic structure; it contains about 15 per cent broken crystals of feldspar to about four millimeters in length and sparse bronze biotite in a cryptocrystalline (devitrified) groundmass. In this rock sanidine appears to be more abundant than plagioclase and the index of refraction of the sparse groundmass glass is near 1.50. The unit as a whole is a vitric rhyolite ignimbrite.

Tv-3 ignimbrite

Apparently there was no erosion of the Tv-2 ignimbrite before the deposition of the overlying Tv-3 ignimbrite. In the Pine Valley Mountains, the maximum thickness of this unit is about 550 feet. The Tv-3 ignimbrite is unconformably overlain by the Rencher formation but is nowhere cut out by it; however, higher unconformities in the volcanic section do truncate the Tv-3 in Grassy Flat Canyon, on Atchinson Mountain, and in Comanche Canyon.

Sixty to 80 per cent of the rock is composed of crystals and crystal fragments, about one-fourth of which are biotite flakes. Lithic fragments to about four inches in diameter are sparingly distributed and inconspicuous. A hand specimen without accidental fragments closely resembles an intrusive igneous rock--a biotite diorite.

A fresh surface is red-brown or purplish brown. The ignimbrite weathers to brown or dark brown, rough-textured cliffs. Locally the weathered surface has elongated parallel depressions one to two inches long and one-half to one inch deep. This tendency increases upward and the upper part of the Tv-3 is, in most places, a "pockmarked" tuff in which the depressions are larger and more irregular. The pockmarked tuff is less resistant to erosion than the lower part of the formation and locally contains ragged essential (cognate) lithic fragments.

The basal black glass of the Tv-3 ignimbrite is as much as 35 feet thick and contains 60 to 70 per cent crystals and crystal fragments. The feldspars have a maximum length of four millimeters and the biotite flakes average about one millimeter in diameter; the crystals in the basal glass are the same size as those in the rest of the formation. In the welded tuffs the biotite seldom appears in books, but is in flakes. Because of the abundance of white feldspar crystals, the Tv-3 basal glass appears dark gray instead of shiny black.

Except for the basal glass, the Tv-3 ignimbrite is only moderately welded.

The average composition of the crystalline material in the Tv-3 ignimbrite is about as follows:

Plagioclase (andesine-labradorite)	60%
Biotite, red-brown	25%
Orthoclase	10%
Hornblende	1-3%
Augite	0-3%
Magnetite, mostly secondary	2%
Apatite	less than 1%

The plagioclase crystals are broken and corroded (Fig. 18). Some of the hornblende is euhedral and some has formed as an alteration product of augite (probably before deposition of the ignimbrite). The position of former euhedral hornblende is commonly occupied by limonite fringed with fine-grained magnetite (Fig. 19); this is a post-depositional change. The glassy groundmass is only locally and partially devitrified; the resulting microlites are either arranged in a subparallel flow or compaction structure or are bundled together in microlite sheaves. No shards were seen in the sections examined.

The glass of the groundmass has an index of refraction just under 1.51 and the rock is a crystal dacite ignimbrite.

Rencher formation (Tv-4 and Tv-4a)

A complex assemblage of ignimbrite, breccia, air-fall tuff, bedded tuff-breccia, volcanic sandstone, and lenticular

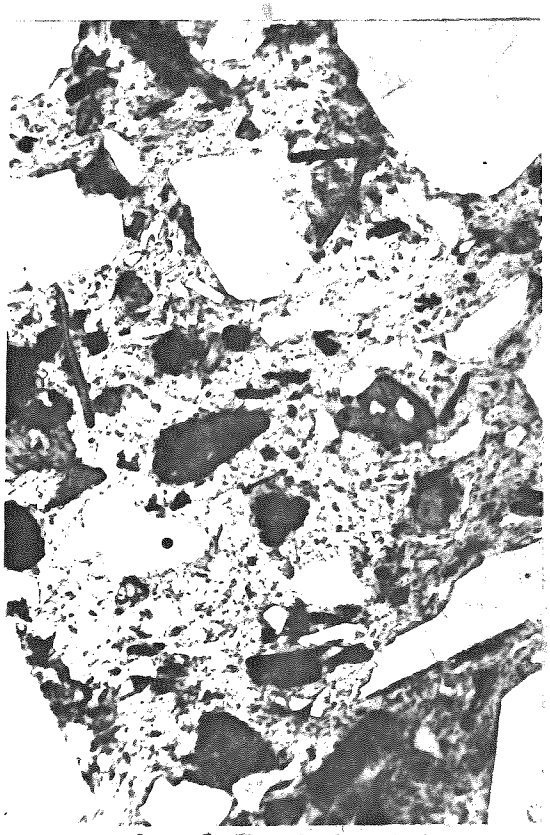


Fig. 18 Photomicrograph of Tv-3 ignimbrite. Broken and partially resorbed crystals in a vitroclastic, moderately welded groundmass. Plane light, 35x.

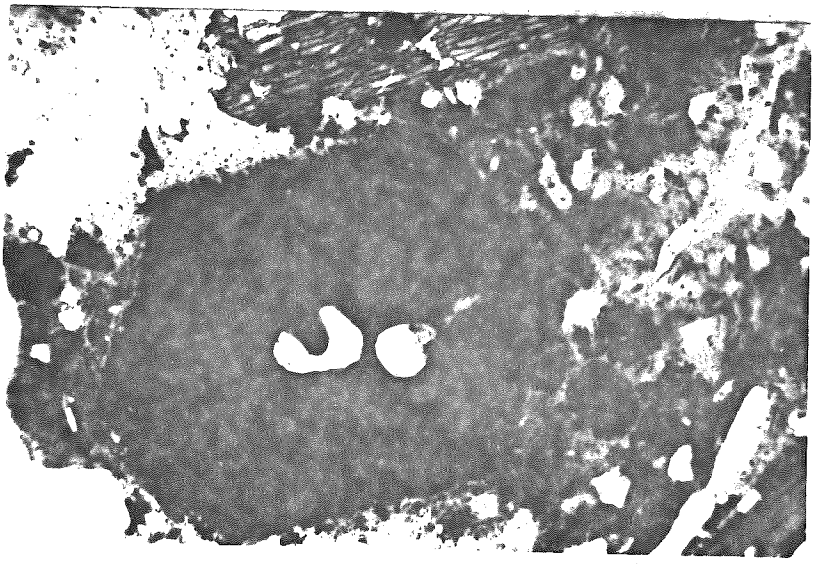


Fig. 19 Photomicrograph of Tv-3 ignimbrite. Note limonite pseudomorphic after hornblende, fringed with magnetite. Devitrified groundmass. Plane light, 35x.

limestone and conglomerate, overlies the Quichapa group unconformably. These rocks are here grouped as the Rencher formation. The formation is well exposed in the vicinity of Rencher Ranch at the north end of Grass Valley.

The lower members of the Rencher formation apparently fill depressions on the surface of the folded and eroded Quichapa. In the vicinity of Pinto Spring the base of the Rencher formation is marked by red conglomerate (containing slabs of Cretaceous sandstone and quartzite cobbles), calcareous sandstone, and white lacustrine limestone. Overlying these basal units or resting directly upon the Quichapa group where the basal units are absent is, in most places, a gray to tan biotitic ignimbrite containing quartzite pebbles in such abundance that the unit was mapped in the field as the "pebble tuff" (Fig. 20). It is rudely bedded in some localities (Fig. 21) and under the microscope (medium to high power) shows vitroclastic structure. Fragments of other ignimbrites as well as quartzite pebbles (many of them broken) can be found throughout the unit. In most places angular fragments of red flow-rock are abundant and, locally, pumice fragments are an important constituent. On the average, lithic fragments comprise about 15 per cent of the pebble tuff. In places the unit is even more conspicuously pockmarked (Fig. 22) than the upper part of the Tv-3 ignimbrite.

The pebble tuff is crystal-vitric dacite ignimbrite,

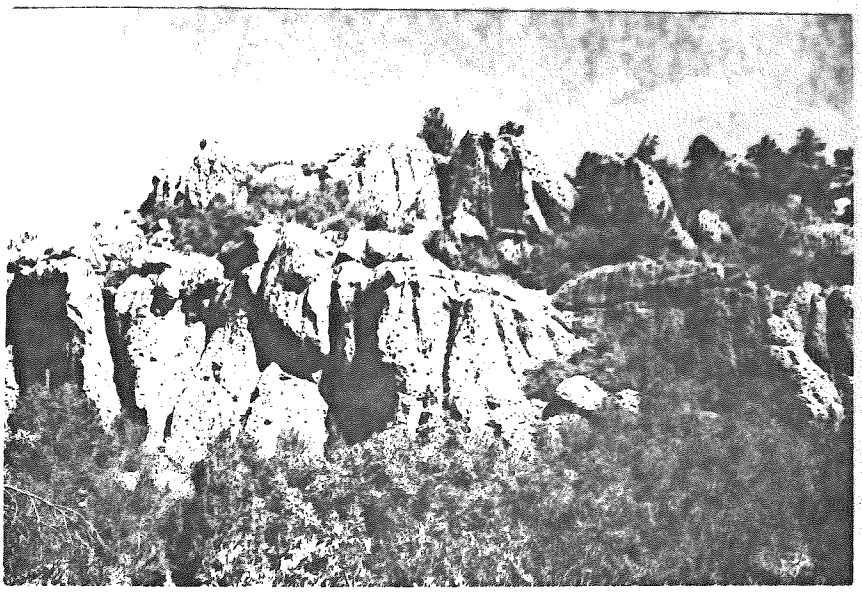


Fig. 20 "Pebble tuff" ignimbrite of the Rencher formation in Comanche Canyon. The weathering forms are characteristic.

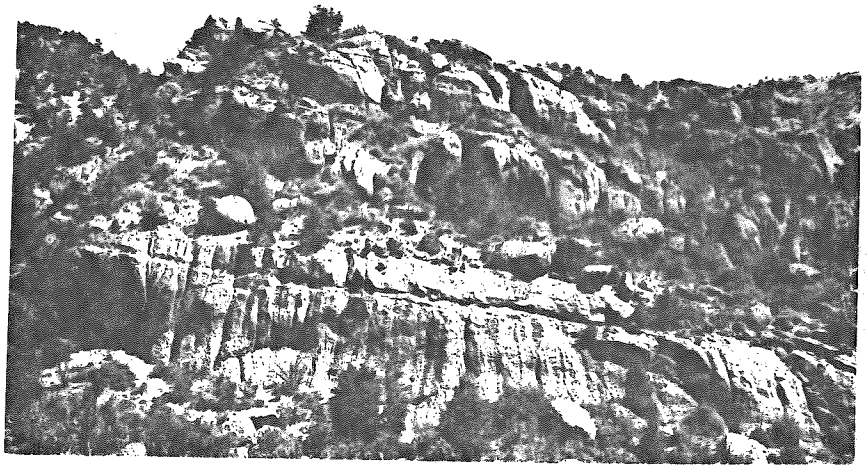


Fig. 21 Rudely bedded "pebble tuff" ignimbrite of the Rencher formation in Comanche Canyon.



Fig. 22 Pockmarked phase of the "pebble tuff" ignimbrite of the Rencher formation, about one mile north of Pinto Spring.

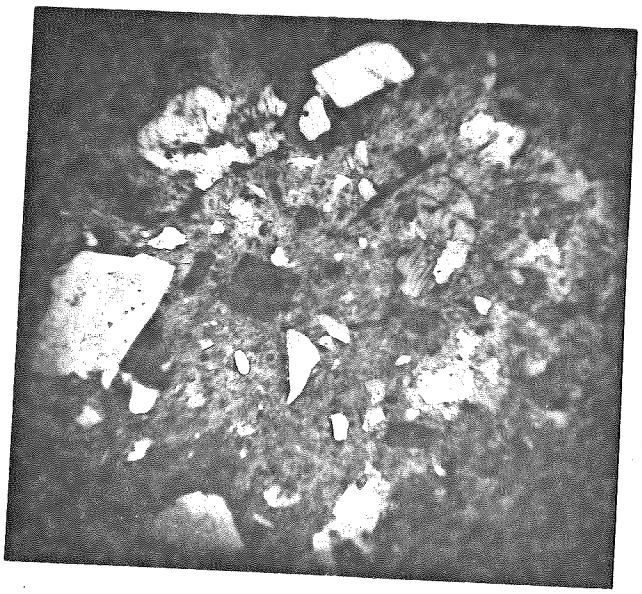


Fig. 23 Photomicrograph of the "pebble tuff" ignimbrite of the Rencher formation. The large lithic fragment in the upper part of the picture is an accidental ignimbrite inclusion. Plane light, 22x.

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being composed of approximately equal amounts of fractured crystals (down to dust-size particles) and glassy groundmass (Fig. 23) with a refractive index of about 1.50. Of the crystals, 70 per cent are andesine, about 15 per cent are orthoclase, eight per cent are biotite, and five per cent are hornblende. Secondary magnetite forms not over two per cent of the rock. As in all the ignimbrites of this area, there is a size gap between the large fractured crystals which (in this tuff) average about one millimeter in diameter and the smaller fragments which average perhaps one-fifth to one-tenth millimeter in diameter. The smaller fragments would thus appear to be developed by attrition, representing edges and corners of intratelluric crystals knocked off during their turbulent transport.

At the type locality the pebble tuff grades upward into a poorly bedded, unsorted tuff-breccia which in turn gives way to a white massive, structureless, biotitic tuff. Elsewhere (e.g., at the south end of Grass Valley, or in the mountain northwest of Page Ranch) the pebble tuff grades upward directly into the white compact tuff. The white tuff forms conspicuous outcrops in Grass Valley (Figs. 24, 25). All these rocks, from the pebble tuff through the tuff-breccia to the soft white tuff, appear to be products of a nuée ardente type of eruption. Vugs lined with microscopic crystals are scarce in the pebble tuff, but are abundant in the welded tuff-breccia. The latter

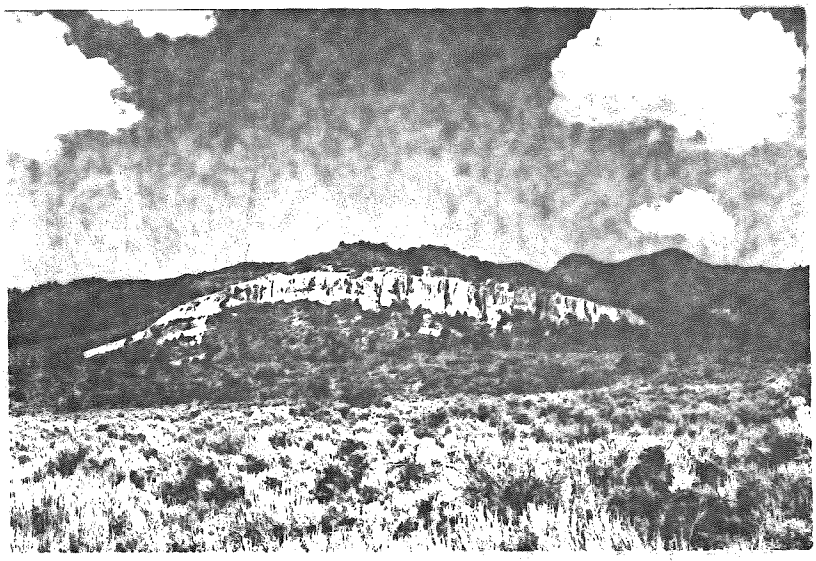


Fig. 24 Soft white biotitic tuff of the Rencher formation. East side of Grass Valley.



Fig. 25 Outcrop of the white, compact tuff of the Rencher formation. Near north end of Grass Valley.

is a rough-textured, red-brown rock containing a heterogeneous assortment of lithic fragments in a vitric-crystal groundmass highly charged with crystal dust. Crystal composition is similar to that of the pebble tuff--dacitic. The white tuff, which is not welded, is locally pinkish; its lithic fragment content is rather low in the white variety (0-10%), higher in the pinkish rock (10-20%).

In the vicinity of The Dairy and outcropping as far east as Paradise is a unit of the Rencher formation characterized by gray blocks (with a bluish cast) consisting largely of crystals held together by porous glass. This breccia unit is thickest just south of The Dairy where it includes irregular solid masses of cognate rock. This "blue breccia" appears to be the result of the eruption of a frothy lava containing intratelluric crystals. In some places the groundmass consists entirely of subparallel plates of glass in an open meshwork; the structure, however, is fluidal and not vitroclastic (Figs. 26, 27). Elsewhere the groundmass is dense glass, not at all devitrified but showing faint flow lines around the corners of crystals. In both light and dense varieties crystals and crystal fragments compose about 40 per cent of the rock and abundant tiny angular crystal fragments are scattered throughout the groundmass; their average composition is:

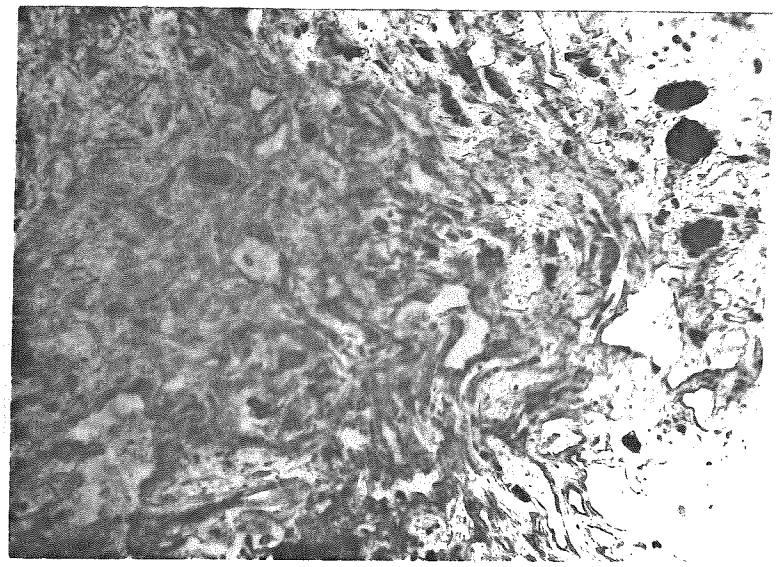


Fig. 26 Photomicrograph of porous dacite porphyry from "blue breccia" of the Rencher formation. Structure is fluidal, not vitroclastic. Plane light, 55x.

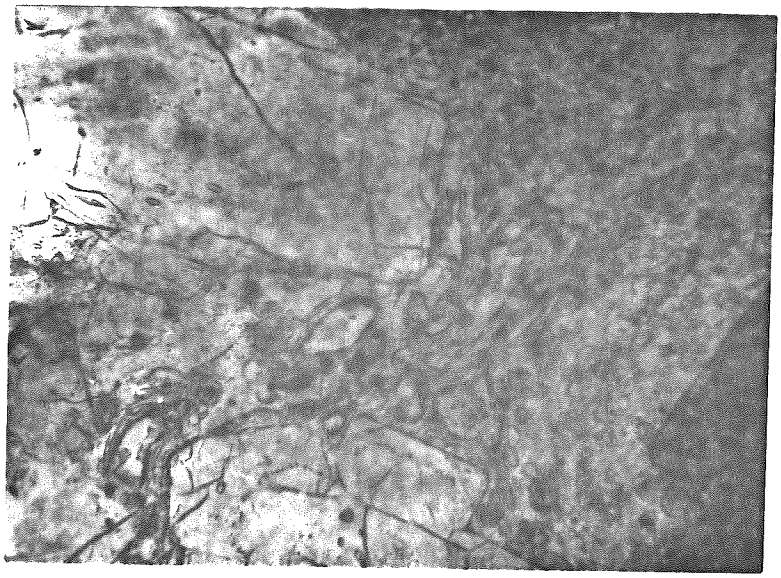


Fig. 27 Photomicrograph of dacite porphyry from breccia in the Rencher formation. Intratelluric crystals in a porous, fluidal groundmass. Plane light, 55x.

Plagioclase (andesine)	65%
Hornblende; largely basaltic hornblende in euhedral crystals up to 6 mm.	15-20%
Biotite, red-brown to almost black	10-15%
Augite	2- 5%
Magnetite	2- 5%

There is neither hematite nor limonite in the rock. The larger crystals average about two millimeters in diameter. The index of refraction of the groundmass glass is about 1.505. The composition of the rock is that of a dacite porphyry. In the thicker part of the breccia (probably not more than 100 feet thick) south of The Dairy the blocks are as much as 12 feet in diameter and all the material appears essential. The unit thins eastward and near Paradise "blue" blocks to eight feet in diameter lie in an unsorted matrix containing blocks of "pebble tuff" to three feet in diameter as well as numerous pebbles and cobbles of quartzite; in the Paradise area the unit appears to be a mudflow breccia.

The relation of the dacite porphyry breccia to the white biotitic tuff is imperfectly known. In some places the white tuff appears to grade upward into the dacite breccia; on the other hand the fact that the breccia, from place to place, rests variously on the Tv-3 ignimbrite, the "pebble tuff", and the welded tuff-breccia suggests either: (1) that all the subjacent units of the Rencher formation are limited by the edges of local basins in which they were deposited, or (2) that the base of the breccia is an unconformity. The first

hypothesis is certainly true in part, but not enough is known to rule out the second.

In six localities a volcanic sandstone was found unconformably overlying either the dacite porphyry breccia or the bedded, welded tuff-breccia (Fig. 28). The white tuff and this volcanic sandstone appear to be mutually exclusive in the sections measured. The volcanic sandstone is gray to white, well-bedded, laminated, locally cross-bedded (Fig. 29) and is composed of fairly well-sorted, angular to subangular grains as follows (in the one section studied):

Plagioclase	45%
Orthoclase (sanidine)	20%
Detrital glass	10-15%
Biotite	10-12%
Magnetite	5- 8%
Hornblende	5- 7%

Above the dacite breccia and the volcanic sandstone, and locally resting on the white tuff is a monolithic breccia (Tv-4a) composed of subangular fragments (averaging first-size, but locally large blocks) of a hard, red-brown lithoidal latite(?). Around Grass Valley this breccia is strongly cemented and stands in cliffs above the soft white tuff. In some localities, other breccias appear to be intertongued with the latitic(?) breccia. In a few places, the latite(?) is overlain by unbroken rock of the same composition. In Comanche Canyon (Fig. 30) and in a small outcrop near Pinto Spring, this breccia unit is overlain by soft, white bedded tuff containing

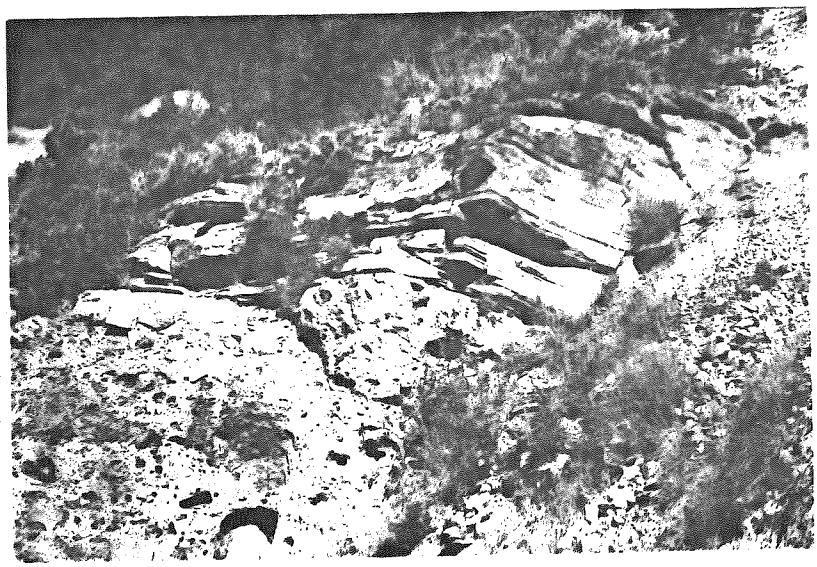


Fig. 28 Rencher formation. Volcanic sandstone overlying welded tuff-breccia about two miles south of The Dairy.



Fig. 29 Rencher formation. Three attitudes in cross-bedded volcanic sandstone near Pinto Spring.

numerous lithic fragments.

Maximum thickness of the Rencher formation is about 600 feet.

Grassy Flat Canyon formation (Tv-5)

In Grassy Flat Canyon and the area northwest and west of Pine Valley a formation which includes a thin andesite flow and two ignimbrites above basal white limestone overlies with angular unconformity all of the older extrusive rocks. One mile northwest of The Dairy the basal limestone of this formation, here named the Grassy Flat Canyon formation, rests on Claron limestone--all the intermediate volcanics having been truncated by the unconformity. The maximum thickness exposed in the map area is about 1,000 feet. The two ignimbrites are almost identical in appearance to the two lower ignimbrites of the Quichapa group and occur in the same order--a foliated vitric rhyolite ignimbrite overlying a rhyolite ignimbrite with prominent orange-red lithic fragments. To further complicate matters, the basal limestone strongly resembles the white limestone of the upper part of the Claron formation. The presence of an amygdaloidal andesite flow between the limestone and the lower ignimbrite is the only difference, in the sections examined, between the Grassy Flat Canyon formation and the Quichapa group; however, in the Iron Springs district, there is commonly a flow at this horizon (Mackin, personal

communication). There is a possibility of a thrust fault in the upper Claron in the Iron Springs district (Mackin, personal communication), but for the time being, the Pine Valley Mountains stratigraphic sequence is based on the presence of an unconformity at the base of the Grassy Flat Canyon formation.

The basal limestone attains a maximum thickness of 100 feet and is well exposed near the crest of the divide at the north end of Grass Valley. The color is dominantly white with some pale pink bands; the bedding is thin but irregular; and the rock is hard, dense, and pure.

The flow which, in all outcrops examined, overlies the limestone is a dull black augite andesite with sparse but prominent, ovate, gray amygdules, plagioclase phenocrysts to ten millimeters in length, and augite to four millimeters in diameter. The andesite contains scattered vesicles averaging about three millimeters in length, a minority of which are filled with crumbly gray material.

Under the microscope, the andesite is seen to consist of 50 per cent phenocrysts, about equally augite and plagioclase, and 50 per cent groundmass, which is largely felted plagioclase with interstitial glass and some augite. The glass has a refractive index of 1.525. The rock contains three to four per cent magnetite, mostly in the groundmass. The augite

is euhedral to subhedral and contains abundant inclusions, most of which are glass. The plagioclase phenocrysts are euhedral and also contain inclusions, in peripheral or zonal arrangement. Although the andesite appears to be uniform throughout, in its thickest section (about 50 feet) lenses of limestone appear, suggesting that the unit locally may be a composite of two or more flows.

In Grassy Flat Canyon, the andesite flow is overlain by two feet of volcanic sandstone and five feet of soft white ashy tuff; these thin units are surmounted by the basal glass (15 feet thick) of a thick (up to 700 feet) vitric-crystal rhyolite ignimbrite which breaks in a clean fracture revealing a red-violet surface in which are set small, angular orange-red lithic fragments. Crystals of feldspar and biotite under two millimeters in diameter, together with the lithic fragments, constitute about 30 per cent of the rock. The groundmass is turbid with hematite and magnetite and is largely devitrified. A few shards can be seen under the microscope--bent under the corners of crystals. Most of the shards apparently have recrystallized. There are small lenticular areas of finely crystalline material; microlite sheaves are common in the groundmass (Fig. 31). The crystals, corroded and badly broken, are largely sanidine (70%) and andesine (30%).

A unit similar to the Tv-2 ignimbrite overlies the

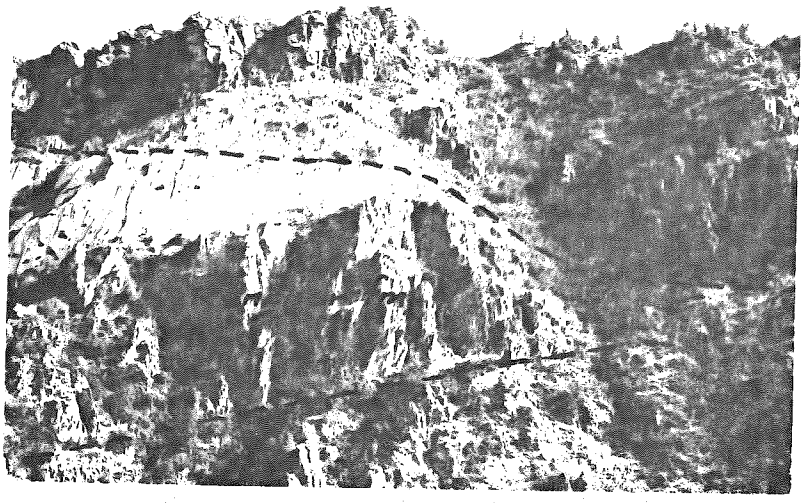


Fig. 30 Rencher formation above Quichapa group and below "platy porphyry". South wall of Comanche Canyon.

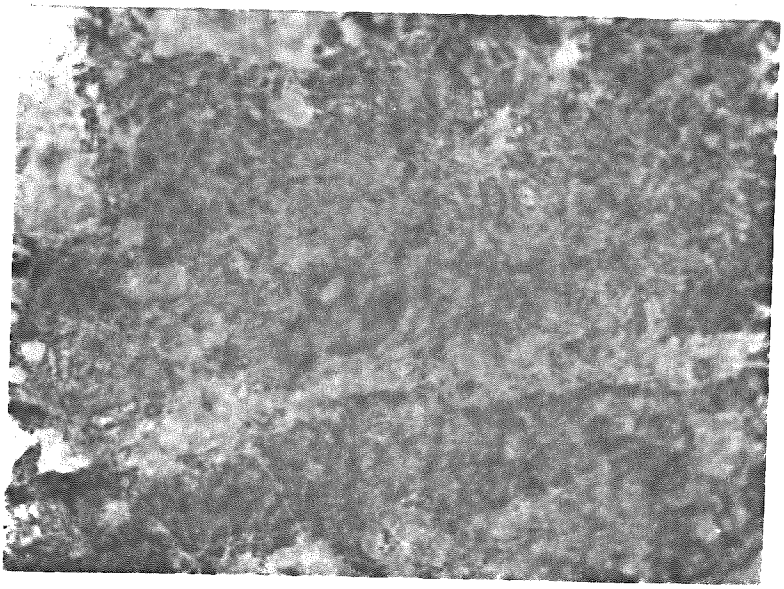


Fig. 31 Photomicrograph of vitric rhyolite ignimbrite member (Tv-5c) of the Grassy Flat Canyon formation. Sheave structure in devitrified groundmass. Plane light, 85x.

red-violet ignimbrite. This unit, where well-exposed, has a maximum thickness of about 150 feet. In these exposures it is truncated by an unconformity; consequently, its original thickness is unknown. In several outcrops, the characteristic white patches of devitrified glass are rounded, not flattened as in the Tv-2 ignimbrite. The rock is a vitric-crystal rhyolite ignimbrite, containing about 35 per cent crystals and 15 per cent white devitrified glass (and holes) in a brick-red, stony groundmass. The crystals are principally feldspar with minor biotite and hornblende.

Although the lower ignimbrite (Tv-5c) contains fewer crystals than the Tv-1 ignimbrite and the upper ignimbrite (Tv-5d) appears to have less foliation than the Tv-2 ignimbrite, these lithologic differences could be lateral gradational changes in the same rock units brought together by thrust faulting.

The outcrops on the east side of Grass Valley tentatively correlated with the Grassy Flat Canyon formation are poorly exposed; this map unit may include rocks of the Rencher formation and the Atchinson formation. North and west of Grass Valley the Grassy Flat Canyon formation is unconformably overlain by the Atchinson formation.

Atchinson formation (Tv-6a and Tv-6)

West of a line connecting Pinto Spring with Pine Valley,

an erosion surface cutting across the Rencher and Grassy Flat Canyon formations is overlain by the Atchinson formation. In most places the basal unit of this formation, named for the excellent exposures on Atchinson Mountain, is a black breccia composed of angular blocks of augite andesite lava (Fig. 32). In Atchinson Mountain this breccia unit is about 500 feet thick and grades irregularly into unbroken flow-rock; on the west side of Grassy Flat the unit seems to be represented entirely by solid lava. Locally at the base of the andesite are found a little white limestone and red sandstone gravel.

The andesite is finely vesicular and has a porosity as high as 30 per cent. Small phenocrysts (most are below three millimeters) comprise 30 to 50 per cent of the rock and consist mainly of andesine and subordinate augite set in a hyalopilitic groundmass of felted feldspar microlites and glass. The andesine phenocrysts are abundantly charged with glass inclusions. Magnetite makes up five to ten per cent of the rock.

The andesite breccia, in most places monolithic, locally contains fragments of each of the members of the Grassy Flat Canyon formation as well as lenses of gray volcanic sandstone possibly derived from erosion of the Rencher formation. Many of the blocks in the breccia weather yellow-brown and appear to be from a different eruption than the black fragments--although both are augite andesite. On the

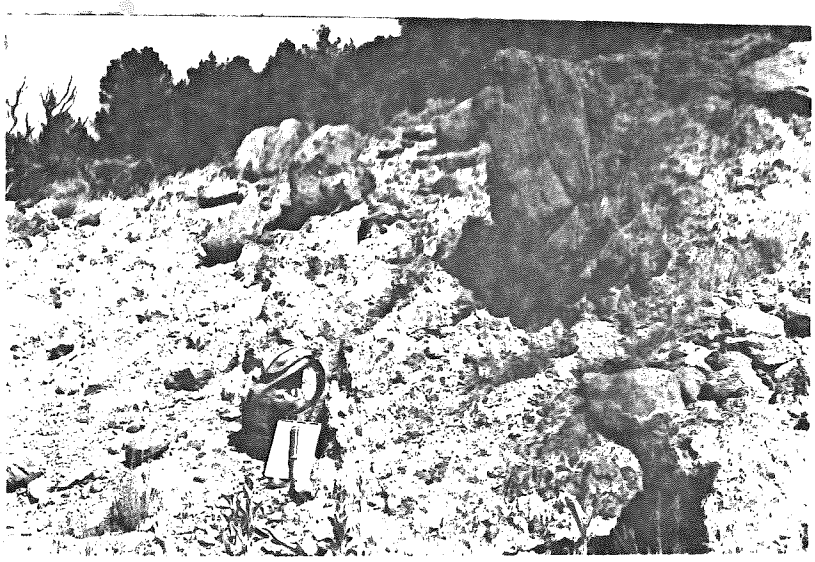


Fig. 32 Black andesite breccia of Atchinson formation.

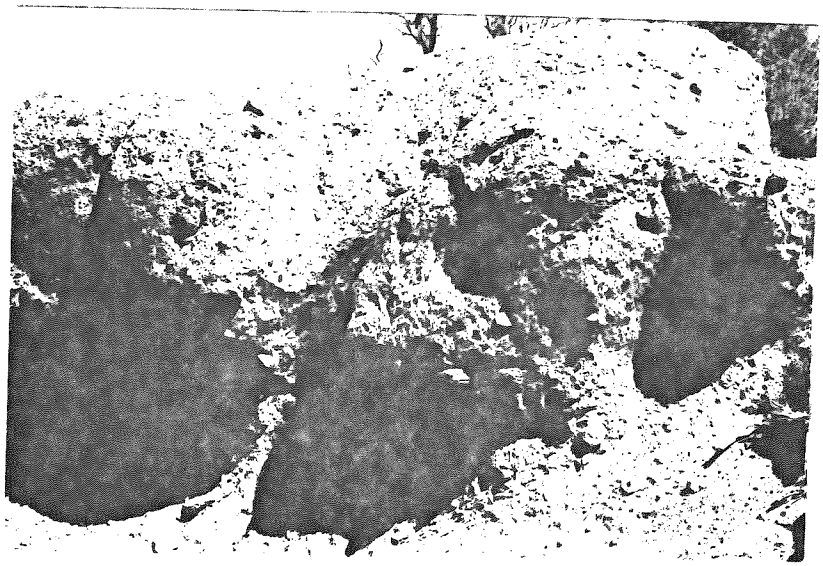


Fig. 33 Tuff-breccia (Tv-6a) mapped as part of the Atchinson formation; on the south side of Grassy Flat Canyon.

north side of Grassy Flat Canyon and farther north (near Pinto) a thin red flow and breccia underlie the andesite breccia.

Overlying the black andesite breccia is a red to red-brown monolithic breccia. This is a lithoidal rock containing feldspar and biotite. No thin sections of it were studied.

On the south side of Grassy Flat Canyon, between the Grassy Flat Canyon formation and the andesite breccia is a unit of tuff-breccia (Fig. 33) which has, on the basis of structure and stratigraphy, been included with the Atchinson formation although its lithology is similar to that of part of the Rencher formation.

Page Ranch formation (Tv-7)

The Page Ranch formation, named for exposures capping the mountain northwest of Page Ranch, has a maximum thickness of at least 600 feet and appears to consist of two units, a lower, bedded tuff-breccia (well exposed in the cliffs above Pinto Spring) and an upper, crystal biotite dacite ignimbrite. This upper unit may prove to be a separate formation. It does not appear above the lower member in the Pinto Spring area, nor in the area north of New Harmony; furthermore, in the area west of Grassy Flat and in Atchinson Mountain, the ignimbrite unit is not underlain by bedded tuff-breccia. Only in the mountain northwest of Page Ranch, then, are the two units

together; here they appear to be conformable.

In Atchinson Mountain the ignimbrite unit rests on welded tuff-breccia which may be equivalent to the bedded tuff-breccia or may be, as mapped, part of the Atchinson formation. In this locality, the Page Ranch ignimbrite is overlain by basalt.

The bedded tuff-breccia rests unconformably on the Atchinson formation in the Grassy Flat Canyon area, on the Rencher formation in the Pinto Spring and Page Ranch areas, and on the Rencher formation, the Quichapa group and the Claron formation in the area north of New Harmony. It is overlain unconformably in the Pinto Spring area by the "platy porphyry" and south of Grassy Flat Canyon by basalt.

The bedded tuff-breccia is a gray to gray-brown, poorly bedded, rough-textured rock which contains occasional subangular boulders to six feet in diameter in a matrix of smaller lithic fragments and broken mineral crystals. Although friable, the tuff-breccia is resistant to erosion and weathers to rounded cliffs (Fig. 34). Thick, rough bedding is seen in completely unsorted material (Fig. 35). The thinnest and best bedding is developed in finer material (Fig. 36), but even here sorting is poor and angular boulders are randomly scattered through the rock.

The lithic fragments are heterogeneous, angular to subangular, consisting largely of extrusive igneous rocks.

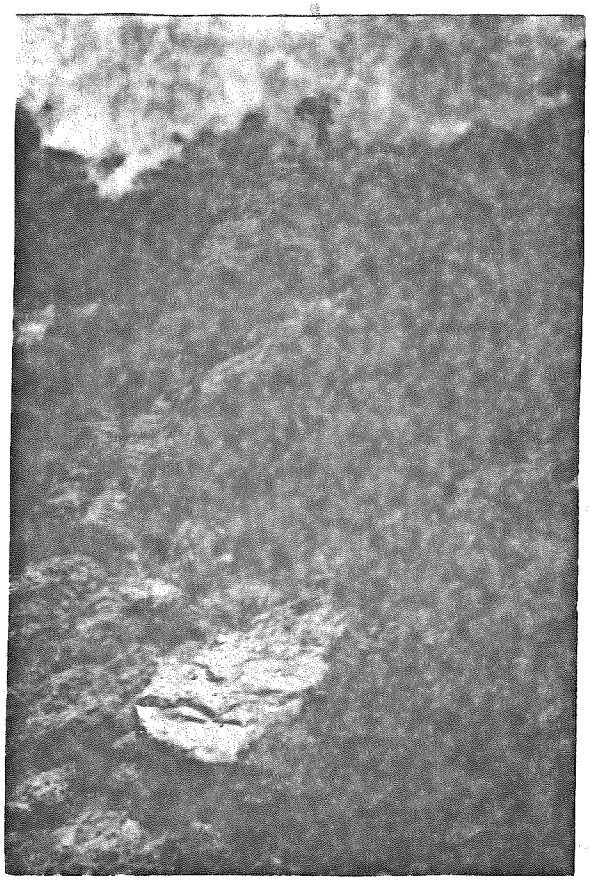


Fig. 34 The bedded tuff-breccia unit of the Page Ranch formation, near Pinto Spring.

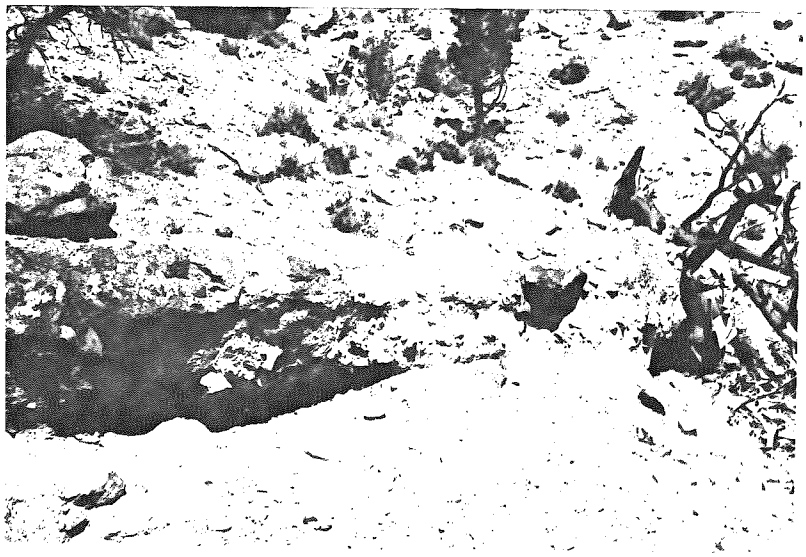


Fig. 35 Bedded tuff-breccia of the Page Ranch formation, two miles northwest of Page Ranch. Note sub-angular block almost as thick as the bedding.

Locally, quartzite pebbles and cobbles are abundant; many of them are broken. Pumiceous inclusions are common in the unit northwest of Page Ranch. The groundmass of the tuff-breccia is everywhere sparsely speckled with biotite flakes. The biotite flakes have random orientation. In fact, there is no lamination (except for the rude bedding) in any of the outcrops examined. In some exposures, the fine gray interstitial material is calcareous. The bedded tuff-breccia is believed to be the result of a series of hot mudflows (lahars) or rather cool nuées ardentes.

The upper unit of the Page Ranch formation is a crystal-vitric to crystal, biotite dacite ignimbrite, moderately welded, gray-brown to purplish-brown, containing sparse lithic fragments. The rock strongly resembles specimens of the Tv-3 ignimbrite of the Quichapa group. The lighter-colored specimens are light in weight, somewhat porous, slightly pockmarked on the surface, and contain small pumiceous fragments. The heavier specimens contain abundant feldspar in crystals one to three millimeters in diameter, much biotite in flakes and books (a rare feature in the ignimbrites of the Pine Valley Mountains), and considerable hornblende. Neither lineation nor foliation is apparent. No thin sections of the rock were studied; it is named a dacite ignimbrite because of the visible lithic fragments, the hardness and coherence of the rock, the resemblance to the Tv-3 ignimbrite, and the index

of refraction of the glass in the groundmass (1.51).

"Platy porphyry" (Tv-8 and Tv-8a)

The upper portions of the northern Pine Valley Mountains are composed of a peculiar porphyritic rock characterized by a platy parting which looks, from a distance, like sedimentary bedding (Fig. 37). The parting planes are more closely spaced near the base of the formation. Differential erosion accentuates the impression of bedding (Figs. 38, 39). The parting planes are discontinuous (Fig. 40) and apparently reflect a planar flow structure. This flow structure is only faintly visible in the ordinary gray to red-purple rock (Fig. 40) but becomes more apparent in the dark gray glassy rock at the base of the formation (Fig. 41). The parting planes are from one inch to several feet apart and are more widely spaced in the upper part of the formation.

The rock is an augite-biotite latite porphyry, hard and heavy, with a rough fracture surface. It varies in color from dark gray to red-purple. Phenocrysts, which under the microscope are seen to be intratelluric crystals, comprise 60 per cent of the rock. Plagioclase crystals up to ten millimeters long, with a roughly parallel orientation, constitute about three-fourths of the crystals; most of the feldspar crystals are one to five millimeters long. The crystals of augite and flakes of biotite are one to two millimeters in

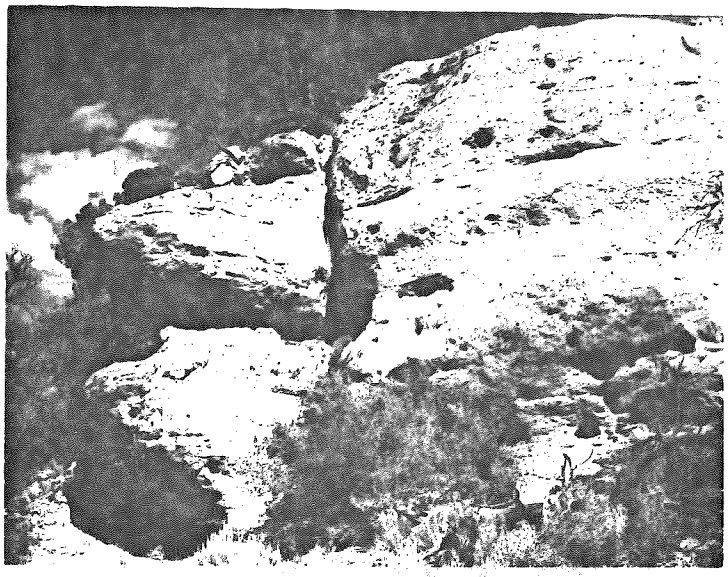


Fig. 36 Bedded tuff-breccia of the Page Ranch formation, one mile west of Pinto Spring.



Fig. 37 "Platy porphyry" (Tv-8), two miles southwest of New Harmony.

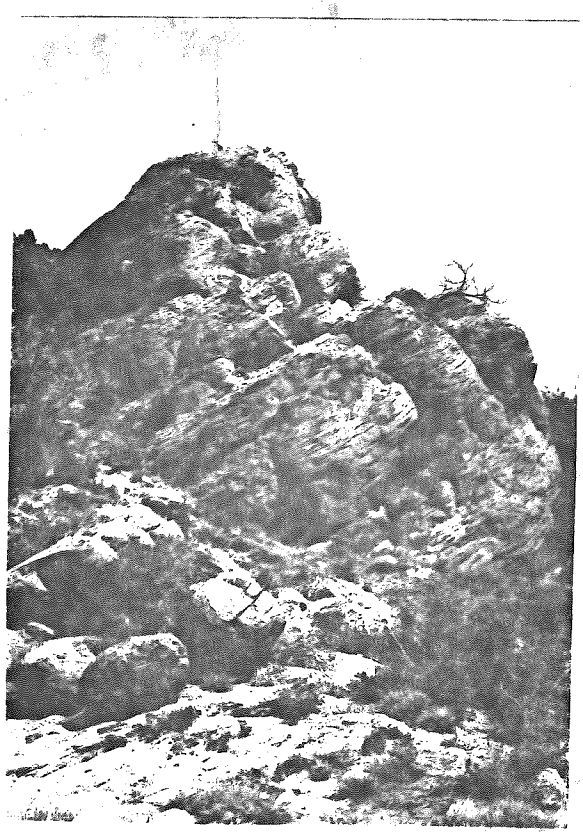


Fig. 38 Differential erosion of "platy porphyry" (Tv-8). South of Big Water in northern Pine Valley Mountains.

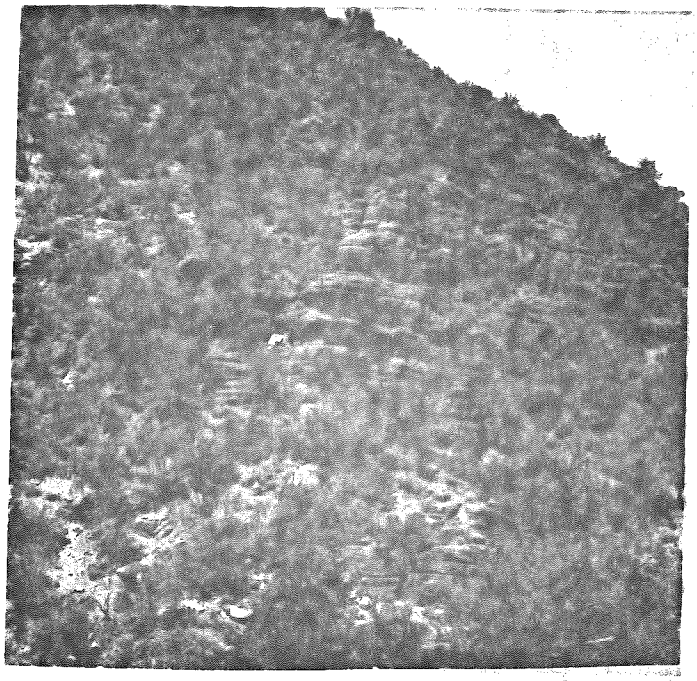


Fig. 39 The "platy porphyry" (Tv-8). Differential erosion in Main Canyon, southwest of New Harmony.



Fig. 40 Platy structure in latite porphyry (Tv-8). Outcrop two miles southwest of New Harmony. Note discontinuity of parting; also flow structure parallel to the parting. Pack gives scale.



Fig. 41 Flow structure and platy parting in basal glass unit (Tv-8a) of "platy porphyry" (Tv-8). About two miles southeast of Paradise.

diameter. Megascopically, the groundmass is stony throughout most of the formation, glassy near the base.

Above the basal glass, the "platy porphyry" appears to have a rather uniform composition. The crystal portion of the rock (60 per cent) is made up as follows:

Plagioclase (calcic andesine)	65-75%
Augite	15-25%
Biotite	5-10%
Magnetite	5-15%

Hypersthene was found in some of the sections and there is a small amount of apatite in all sections. The plagioclase is euhedral and microfractured. Much of it is zoned and many crystals contain glass inclusions (Fig. 42). The larger and more elongate feldspars are subparallel (Fig. 43). In the groundmass are many angular fragments of feldspar. Augite and biotite are greatly altered to magnetite. Most of the magnetite appears to be the result of deuteric alteration, but some of it is euhedral and is probably a primary constituent.

The groundmass is cryptocrystalline to glassy. The index of refraction of the glass is about 1.51. This is equivalent to a silica content of about 68 per cent; the groundmass, therefore, has a composition equivalent to that of a quartz latite. Assuming that the groundmass, where cryptocrystalline, is entirely feldspar and quartz, the proportion of quartz is probably not much over 10 per cent in the groundmass or five per cent in the rock as a whole. For



Fig. 42 Photomicrograph of "platy porphyry". Note glass inclusions in feldspar. Plane light, 18x.



Fig. 43 Photomicrograph of "platy porphyry". Note alignment of feldspar crystals. Plane light, 18x.

this reason, and because the groundmass feldspar is assumed to be largely orthoclase (as it is in the similar rock of the Pine Valley laccolith), the rock is called a latite porphyry, although a chemical analysis might indicate enough free silica to warrant its assignment to the quartz latite group.

In the upper part of the formation, microlitic lenticles in which tridymite is identifiable parallel planar orientation of the feldspars; megascopically, these lenticles appear as irregular subparallel gray streaks. As the platiness diminishes in the higher parts of the formation, little vugs lined with glass become apparent; the porosity due to these small cavities is estimated at five to ten per cent. No lithic fragments were seen in the formation.

The platy structure, so uniformly planar and parallel throughout most of the formation, and so obviously an expression of flow structure, is locally modified by the development of one of the following structures: (1) "cross-bedding"; (2) "log" structure; (3) recumbent folding.

The "cross-bedding" (Fig. 44), like the platy structure appears to be a function of the internal rock structure. At several localities a thickening of the rock between adjacent partings was observed (Fig. 45). This feature may represent not only planar orientation of feldspar crystals, but actual sorting of crystals. Such a sorting, parallel to the feldspar orientation, was noted in one section (Fig. 46). The sorting,



Fig. 44 "Cross-bedding" in latite porphyry (Tv-8). Two miles south of Paradise on Big Water road.

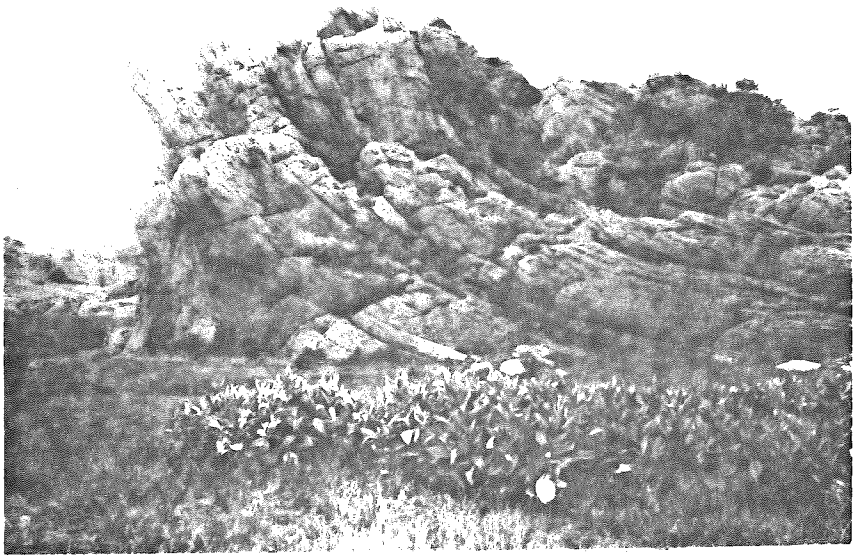


Fig. 45 Non-parallelism in folded platy structure at White Rocks Reservoir. "Platy porphyry" (Tv-8).

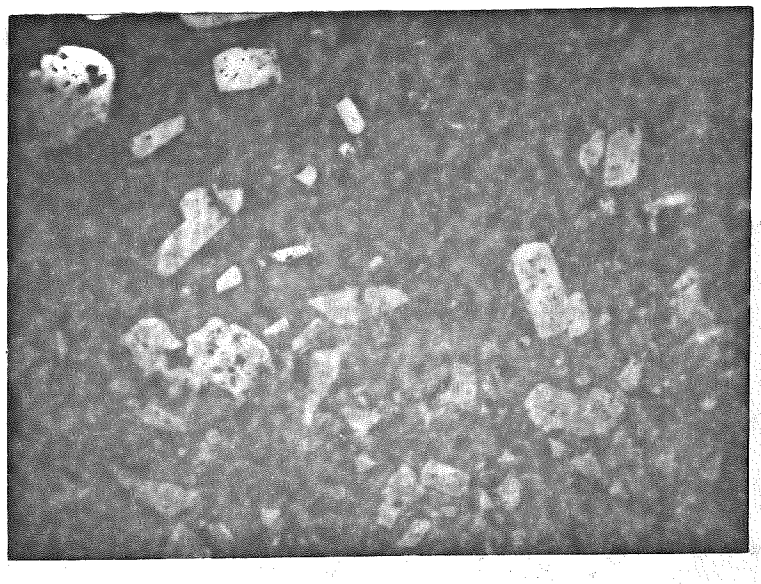


Fig. 46 Photomicrograph of "platy porphyry" (Tv-8). Small feldspar crystal fragments are concentrated in a band which is parallel to the orientation of large feldspar crystals. Plane light, 18x.

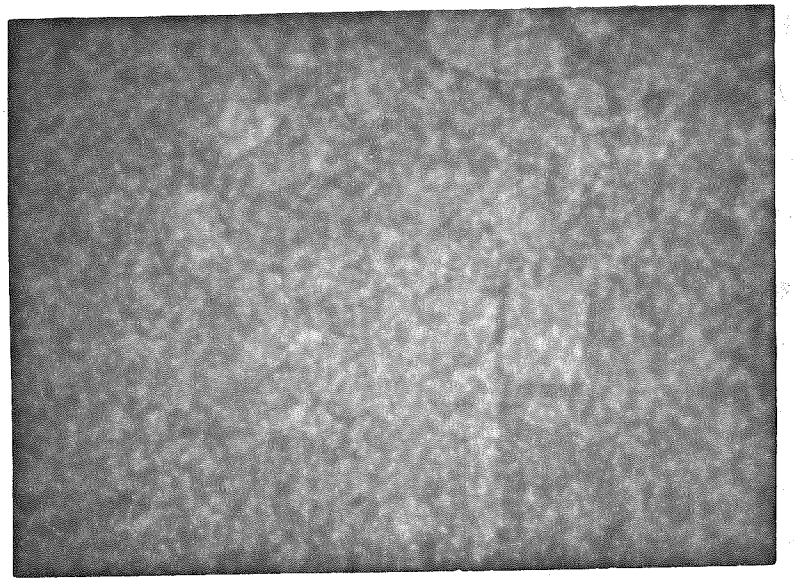


Fig. 47 Photomicrograph of "log" structure in "platy porphyry" (Tv-8) in Mill Canyon. Note irregular band of microlites skirting a feldspar crystal in glassy groundmass. Plane light, 18x.

like the feldspar orientation, probably produced a flat, parallel foliation which was distorted by late differential movement within the cooling mass.

In Mill Canyon (Fig. 48) and in Comanche Canyon (Fig. 49) the regular platy structure locally changes to a rolling, irregular structure which makes a weathered outcrop appear to be made up of knotty logs piled one upon the other. The change from platy to "log" structure resembles the structural change in a moving liquid passing from laminar to turbulent flow. The mobile magmatic fluid, heavily loaded with intratelluric crystals, may have developed turbulent flow over irregularities in the depositional surface. The preservation of such structure, however, demands such an instantaneous consolidation of the mass, that some alternative explanation seems necessary. Rotation or "rolling" of partially consolidated, plastic lava on axes transverse to the direction of movement of overlying flowing lava appears to be the most logical hypothesis. The weight and movement of the flowing lava may have, through friction, disturbed lava which had already come to rest but which was still plastic and contained entrapped volatile material. The latite in the Mill Canyon outcrop contains grayish streaks which, under the microscope, are seen to be composed of finely crystalline material. This crystalline material grades into the cryptocrystalline to glassy groundmass, but one of the bands continues entirely across the section

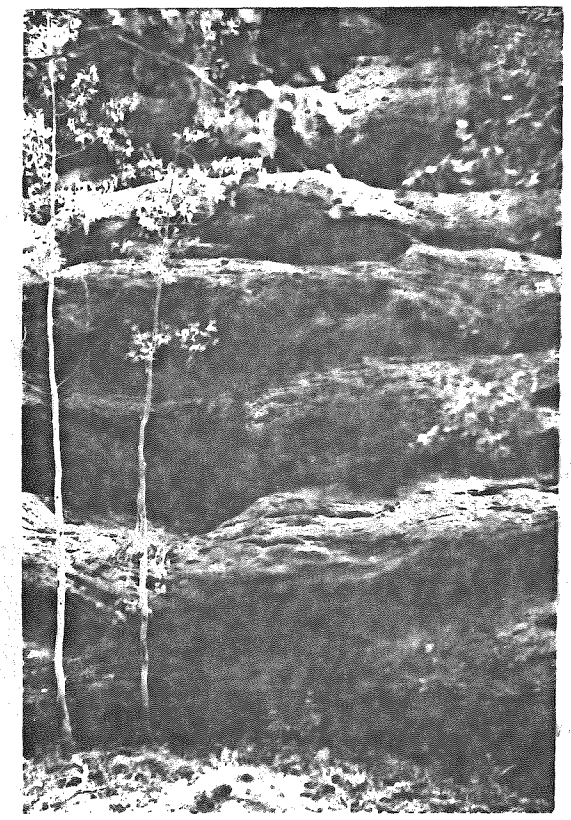


Fig. 48 "Log" structure in latite porphyry (Tv-8). In Mill Canyon about three miles east of Grass Valley.

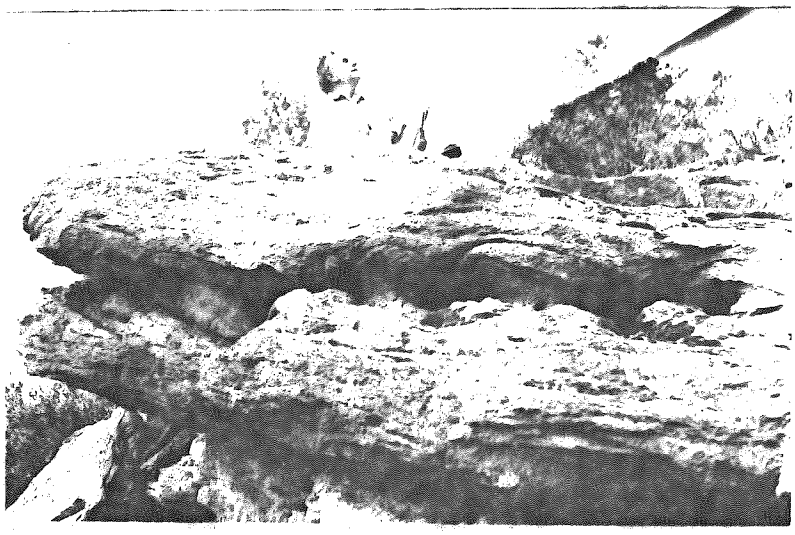


Fig. 49 Irregular platy or modified "log" structure in latite porphyry (Tv-8). In Comanche Canyon.

examined (Fig. 47), curving to skirt the edges of some of the larger crystals and passing through other crystals. Apparently the rock was internally fractured when the lava had ceased flowing but was still capable of movement; deuteric recrystallization (probably pneumatolytic) took place along these late fractures. Thus, the "log" structure appears to have developed during the deuteric alteration phase of consolidation and is not a frozen fluidal structure.

A structure which looks like recumbent folding is locally developed in the latite porphyry (Fig. 50). This is believed to have developed as another, more spectacular, effect of the friction produced by fluid lava moving across motionless plastic latite. It is, then, a peculiar form of drag folding.

Toward the base, the "platy porphyry" contains a decreasing percentage of augite and an increasing proportion of hornblende. The basal glass unit, which locally grades into a breccia, contains white feldspar crystals as much as 11 millimeters in length, set in a jet-black, glassy groundmass (Fig. 51). Under the microscope, flow structure is apparent (Fig. 52). Forty to 50 per cent of the rock is composed of crystals. The groundmass is glass, and is but slightly devitrified. The mineral composition varies considerably; for example, in some sections hornblende is the most abundant mafic, in other sections no hornblende is found. In the several sections studied, percentage ranges are as follows:

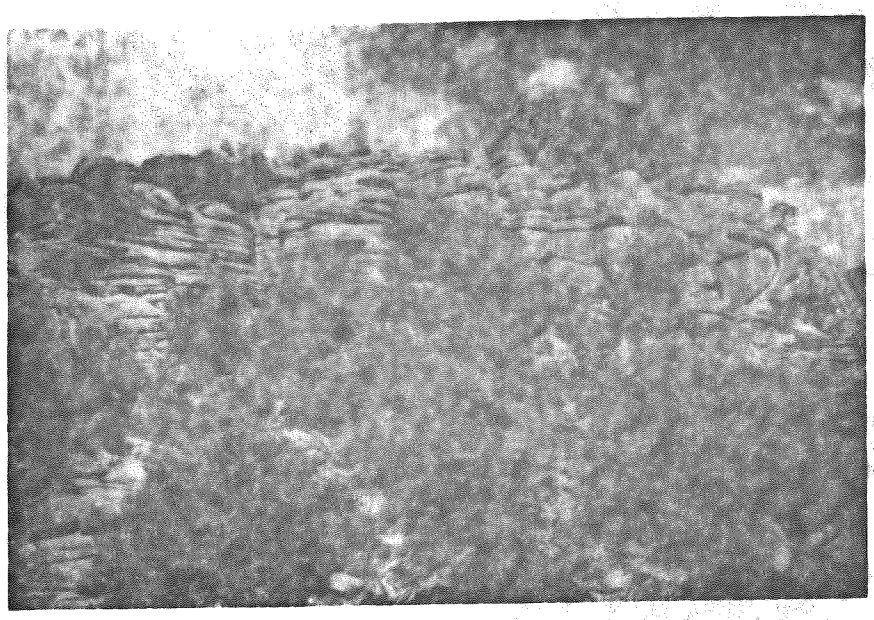


Fig. 50 Recumbent folding in latite porphyry (Tv-8) near Big Water. Believed to be the result of dragging of plastic lava by overlying fluid lava.

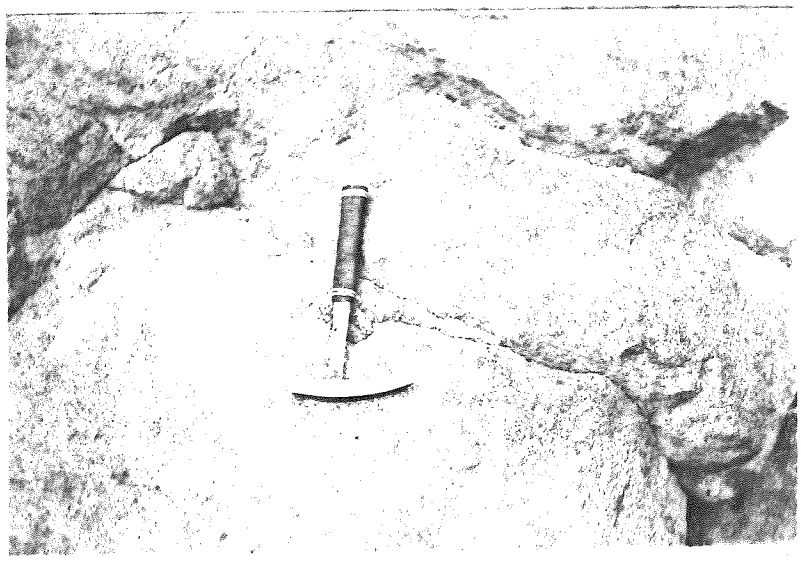


Fig. 51 Basal glass unit (Tv-8a) of the "platy porphyry". In Comanche Canyon.

Plagioclase (calcic andesine)	50-60%
Augite	5-25%
Biotite, strongly pleochroic	10-25%
Hornblende, brown	0-15%
Magnetite	2-10%

The plagioclase crystals average three to four millimeters in length and are euhedral and fractured; glass inclusions in a zonal arrangement are common. The mafic minerals are somewhat altered to magnetite; augite is more altered than the other minerals. The hornblende is euhedral. There are some plagioclase-augite-hornblende glomerocrysts which look like fragments torn from a medium-grained diorite. The groundmass is glassy and contains abundant specks of magnetite as well as some feldspar crystal fragments and many acicular to lath-like microlites. Spherulites of irregular shape are sparsely distributed; locally there are a few small vugs.

In the upper part of the basal glass is a band of gray rock containing many vugs in a meshwork of small glass tabulae. Also an augite latite porphyry, this phase of the "platy porphyry" resembles the rock of the "blue breccia" member of the Rencher formation. The basal glass unit ranges from ten to about 150 feet in thickness, averaging about 50 feet. In the 2,000 feet of "platy porphyry" which lies above this, black glass porphyry and breccia are rarely met with and seem to be restricted to the southern part of the formation--from Mill Canyon south to the Pine Valley laccolith.

If the "platy porphyry" is an extrusive rock, it is

puzzling that the formation has no outliers. At the north end of Grass Valley, for example, a great thickness of "platy porphyry" is exposed east of the road, but there is none to the west, beneath the Quaternary or late Tertiary basalt. Erosion of all but the piled-up central mass of lava may have removed the outer portions of the original deposit, or the extrusion may have been limited to a topographic basin. On the other hand, the absence of outliers and the lithologic uniformity through 2,000 feet suggest that the "platy porphyry" may be an intrusive rock. For the time being, the formation has been mapped as extrusive for the following reasons:

1. No structures which could be attributed to intrusion of the porphyry have been found at the base or margins of the mass.
2. The basal contact of the "platy porphyry" is interpreted as an unconformity; in the hills south of Gardner Ranch, limestone float was found at the base of the formation.
3. The basal glass is as much as 150 feet thick, whereas glass at the base of the Pine Valley laccolith is either absent or, at most, a few feet thick.
4. If the mass is intrusive, it is difficult to see what could have been the cover: the only known younger rocks are mudflow breccia, intermontane sediments, basalt, and alluvium; except for the

thin basalts, these rocks are of quite local distribution.

Much of the original bulk of the "platy porphyry" has been removed by erosion. The Pliocene(?) Parumuweap(?) formation in Bald Hill rests on a rough erosion surface developed in part on the basal glass of the "platy porphyry"; a great thickness of latite must have been removed before Parunuweap(?) time.

On the south, the platy latite porphyry has been intruded by the monzonite porphyry of the Pine Valley laccolith. Along the contact (an intrusive fault) the two rocks are almost impossible to tell apart. Megascopically, the main criterion of distinction is the platy structure of the latite (Fig. 53). Microscopically, rocks from opposite sides of the intrusive contact show considerable difference in texture, but none in mineralogic composition. Both are augite-biotite latite or monzonite porphyries and contain about the same proportion of phenocrysts. The groundmass in the platy rock (Fig. 54), however, is glassy, only partially cryptocrystalline, whereas the groundmass of the intrusive porphyry (Fig. 55) is cryptocrystalline to microgranular. The intrusive porphyry groundmass contains a considerable amount of small crystal fragments, but the percentage of such fragments is much greater in the platy porphyry.



Fig. 52 Photomicrograph of basal glass unit (Tv-8a) of "platy porphyry". Note the fluidal structure in the arrangement of microlites. Plane light, 51x.



Fig. 53 Photomicrograph of porous phase of basal "platy porphyry" (Tv-8a). Note resemblance to dacite porphyry of Rencher formation. Plane light, 35x.

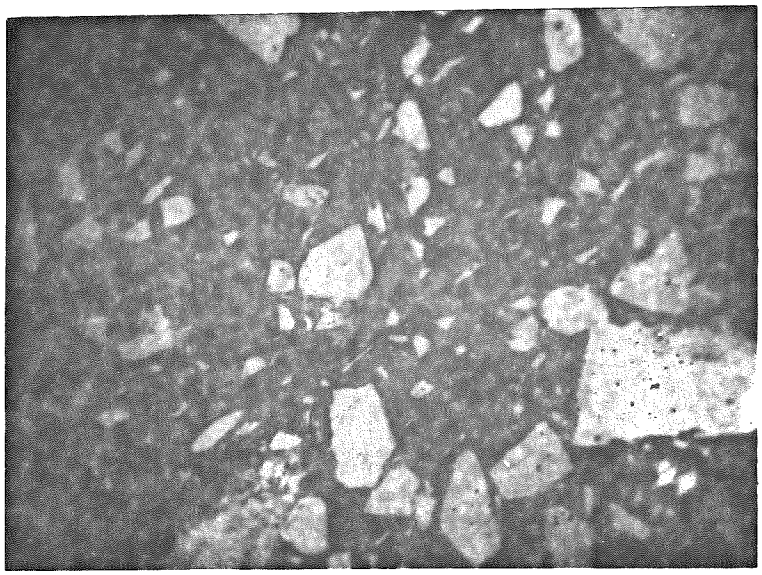


Fig. 54 Photomicrograph of "platy porphyry" near contact with Pine Valley laccolith. Note abundant small crystal fragments in glassy groundmass. Plane light, 20x.

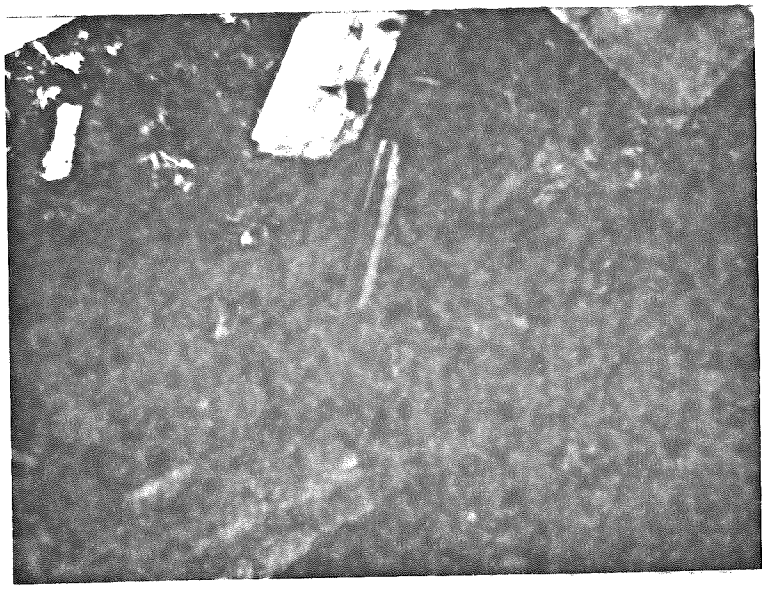


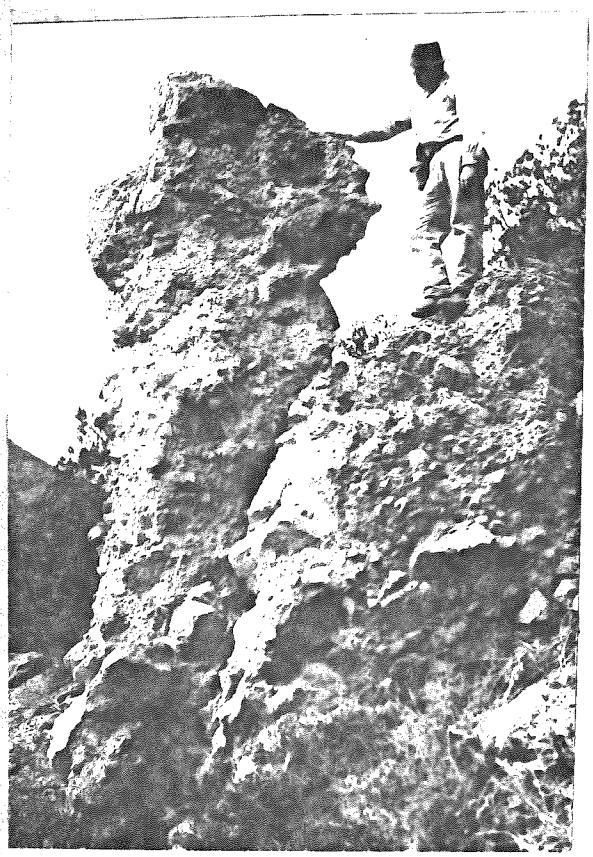
Fig. 55 Photomicrograph of Pine Valley intrusive porphyry near contact with "platy porphyry". Note microgranular groundmass and small number of crystal fragments. Crossed nicols, 31x.

Stoddard breccia (Ts-9)

Exposed in small patches on the east side of Stoddard Mountain is the Stoddard breccia. The breccia consists of angular to subangular blocks of all sizes up to five feet in diameter, in a poorly cemented matrix (Fig. 56). There appear to be two breccia units, differing principally in the dominant color of the fragments. Near Comanche Creek the lower unit is dominantly brown, the upper, gray; about two miles north of Comanche Canyon the lower unit is olive to yellow-brown, the upper is red-brown. From a distance, both units are seen to have rough bedding.

At least 25 per cent of the blocks in each unit are dense monzonite porphyry from the Stoddard Mountain laccolith. Locally the breccia is monolithic, made up entirely of such fragments. In other places the majority of the fragments are gray, porous boulders which, under the microscope, are seen to be merocrystalline to microgranular, porphyritic, biotite-augite monzonite. There is no flow or compaction structure in the gray rock; the ten to 15 per cent porosity is due to miarolitic cavities. The crystals and crystal fragments, which comprise about 50 per cent of the rock, are mainly andesine, with subordinate augite, biotite, and highly altered hornblende.

Despite considerable differences in color and density, the rocks composing the Stoddard breccia appear to have come from the Stoddard laccolith. The breccia rests on a rough



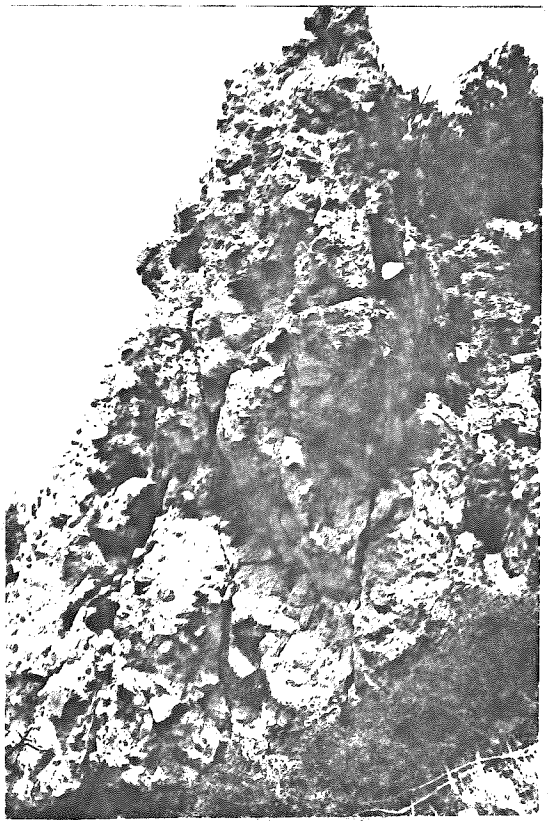




Fig. 56 Outcrops of Stoddard breccia (Ts) about three miles northwest of New Harmony.

erosion surface which not only cuts across the older volcanics but across the Stoddard laccolith itself. In fact, the breccia was deposited on a surface not much different from the present surface. It filled valleys and probably made islands out of some of the higher knobs of the Stoddard laccolith. The breccia was certainly much more extensive than its present outcrops, which are mere remnants capping interfluve divides and clinging to valley sides.

The Stoddard breccia appears to be the result of mudflows which originated inside the peripheral shell of Stoddard Mountain. Many of the rocks in the breccia are from a zone of great deuteric alteration. The rude bedding and poor sorting indicate a mudflow origin. The deposit could as well be called a fanglomerate as a mudflow breccia.

The Stoddard breccia, which rests on the deeply eroded Stoddard laccolith, is tentatively regarded as late Tertiary in age. On the other hand, no evidence was found which would be against a Pleistocene age. The Stoddard breccia may be a Pleistocene fanglomerate formed under proglacial climatic conditions.

Guide Meridian volcanics (Tv-x)

Like the Stoddard breccia, the Guide Meridian volcanics appear to have been deposited on a surface little different from the present erosion surface. These volcanic rocks

apparently filled a valley which descended to the south from Atchinson Mountain along the line of the Pine Valley Guide Meridian, two to three miles northeast of the present village of Central. Two units make up the Guide Meridian volcanics: (1) a lower, massive, hard, cliff-forming, pale brown rock 50 to 100 feet thick, principally composed of glass tabulae, overlain by (2) denser, heavier, porphyritic lithoidal lava at least 200 feet thick. The lower unit has a flow structure similar to that of the "platy porphyry"; the parting planes are closely spaced, they are folded, and they show the "cross-bedding" described in the "platy porphyry". The illusion of sedimentary bedding is striking.

Under the microscope, the two units are seen to be identical in composition, although not in structure: both are porphyritic hornblende dacites. The lower unit has a porous, fluidal structure (Fig. 57) in a glassy, partially devitrified groundmass. The upper unit has a structureless glassy groundmass, not at all devitrified (Fig. 58).

In both units, phenocrysts up to nine millimeters in diameter make up 10 to 15 per cent of the rock, small crystals 25 to 30 per cent, and groundmass (including cavities) 60 per cent. The crystals are as follows:

Andesine-labradorite, zoned, with numerous glass and microlite inclusions	60%
Hornblende, largely euhedral	25-30%
Biotite, red-brown, strongly pleochroic	5-10%
Magnetite	5%
Augite	1- 2%

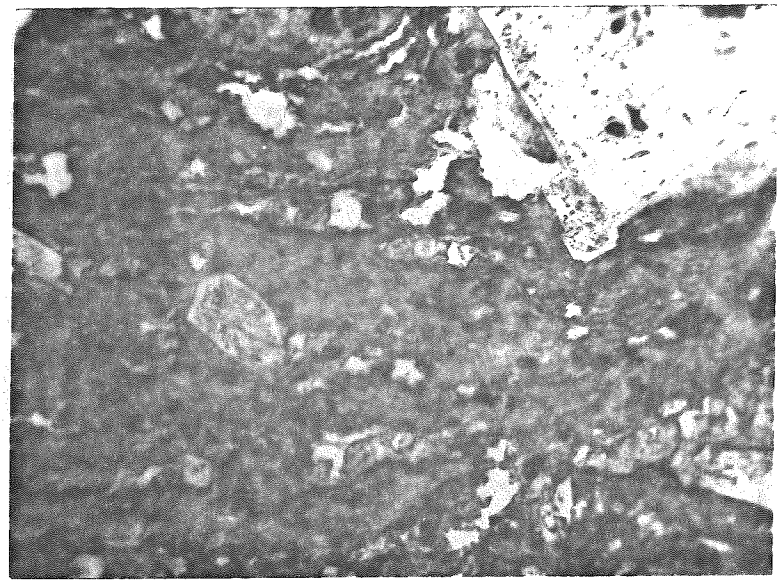


Fig. 57 Photomicrograph of porous flow at base of Guide Meridian volcanics. Aligned lenticular cavities in glassy groundmass highly charged with microlites. Numerous inclusions in feldspar phenocrysts. Plane light, 31x.

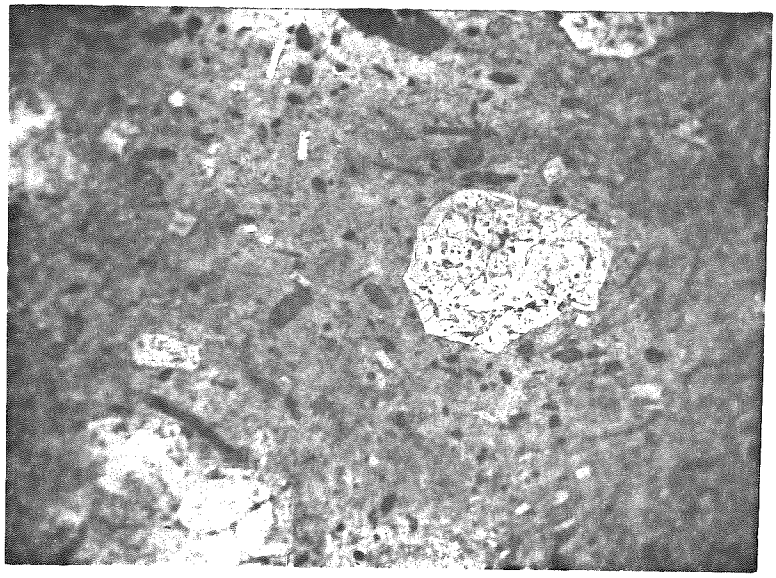


Fig. 58 Photomicrograph of lithoidal flow which forms main part of Guide Meridian volcanics. Plane light, 20x.

Glomero-phenocrysts of zoned plagioclase, hornblende, and magnetite are found, as well as cumulo-phenocrysts of plagioclase. The glass of the groundmass, highly charged with microlites, has a refractive index of 1.505. The rock of both units is a hornblende dacite; the lower unit is apparently a basal phase of the upper.

The Guide Meridian volcanics are tentatively assigned to the Late Tertiary, but may be Quaternary, for they were extruded onto a topography similar to that of the present.

Basalt (Qb)

Thin basalt flows and basaltic cinder cones are a prominent feature of the low-lying areas east, south and west of the Pine Valley Mountains. Howell (1875, p. 254) noted that:

> The valley of the Santa Clara has been flooded with basaltic lava for eight or ten miles below the Pine Valley settlement, filling up the channel of the River, which has carved for itself a new course, partly by the side of the lava stream and partly canyoning through it. Farther down the Santa Clara another stream of lava has flowed from the southern end of Diamond Valley, nearly to St. George. Over the vent from which this issued another fine cinder cone has been formed.

Howell's description is of some of the more recent basalt extrusions in this area. Clearly, basalt has been erupted intermittently over a long time, each successive extrusion coming out on a surface with a little more relief. The oldest basalt rests concordantly on Tertiary volcanics and

sediments; its remnants form small mesa-caps on Atchinson Mountain, on the hills east and west of Grassy Flat, and on Bald Hill. The later basalts, on the other hand, lie with strong discordance on all the older rocks.

The thickest basalt is in Black Ridge, north of Pintura; in Leap Creek, eight flows are visible and the maximum thickness in this locality is at least 200 feet. Most of the basalt, however, is in thin sheets and outliers; the average thickness is about 50 feet.

The oldest basalt, which may be Tertiary in age, is dark gray, finely vesicular and platy (Fig. 59); under the microscope, this rock is seen to have some augite phenocrysts (0.5 to 1.0 millimeter) set in a hyalopilitic to trachytic groundmass which contains labradorite laths. There is some olivine in greatly altered anhedra. Magnetite is abundant in the groundmass and may form over ten per cent of the rock.

The younger basalt is jet black, has an irregular blocky fracture, and is vesicular only near the tops of individual flows. Columnar structure is locally well developed.

The cones commonly are formed of stratified cinders (Fig. 60) piled up on a low lava mound. Most of the cinders are vesicular and scoriaceous basalt fragments under three inches in diameter. Some of the fragments, however, are blocks up to two feet or more across. The youngest cones have so perfectly retained their form and have so little vegetation on

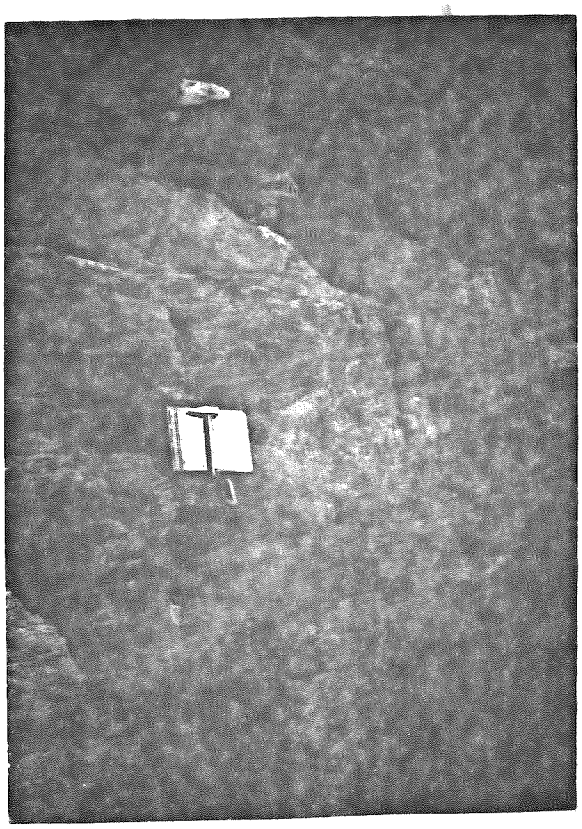


Fig. 59 Outcrop of older basalt, showing platy and vesicular structures. On hill between Grass Valley and Grassy Flat.

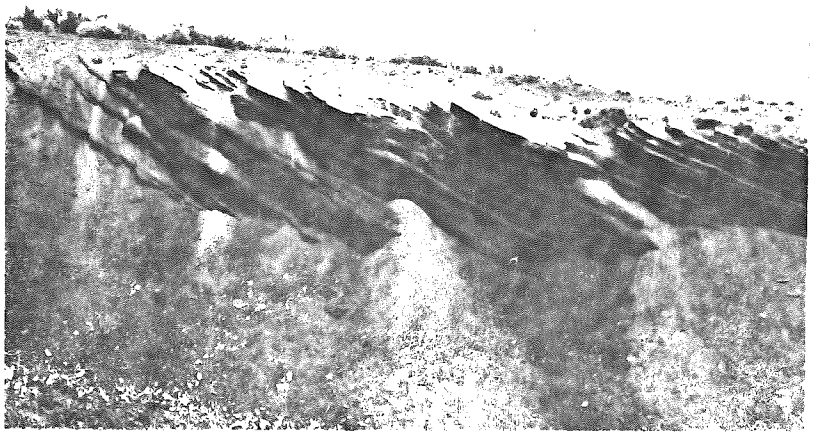


Fig. 60 Bedded cinders and ash in side of basaltic cinder cone on west side of Grass Valley.

them that they must be Recent in age.

Intrusive Rocks

Distribution and form of intrusions

There are five intrusions within the map area, ranging in size from about 40 acres to 70 square miles. On the geologic map separate symbols are used for each of the five. Structural evidence and field observation indicate that the intrusive bodies have in general made room for themselves by uplift and upfaulting of the roofing rocks. The bodies are laccoliths of irregular shape.

The largest and best exposed of the five intrusive bodies is that of the Pine Valley laccolith, which forms the main mass of the Pine Valley Mountains. The next largest, exposed in nearly circular outcrop, is the Stoddard laccolith, which is connected, on the surface, with the smaller Paradise body and, beneath the surface, with a small intrusive area north of Pinto Peak. The smallest intrusion is exposed just south of The Dairy; this also may be part of a large intrusive body from which the Pinto Peak and Stoddard bodies rise like bosses on a batholith.

Petrography

The rock in all five areas is monzonite porphyry. All the rocks contain about 50 per cent phenocrysts in a

cryptocrystalline, microgranular, or fine-grained groundmass. Much orthoclase and some quartz are found in the finely crystalline groundmass. The majority of the phenocrysts in each case are of andesine-labradorite (Ab_5 An_5). Magnetite is abundant in all sections studied, averaging about 5 per cent of the rock.

Despite the apparent consanguinity of the rocks in these five outcrops, there is a difference in the mafic constituents of the rocks exposed in the four northern areas as compared with the porphyry of the Pine Valley laccolith. Whereas the Pine Valley rock contains no hornblende, specimens from The Dairy, Pinto Peak, Paradise, and Stoddard intrusives contain as much as 15 per cent of hornblende phenocrysts. Moreover, 15 to 25 per cent of the phenocrysts in the Pine Valley porphyry are augite (and hypersthene); in the northern outcrops augite is absent or comprises, at most, ten per cent of the phenocrysts. Average compositions of rocks from the different areas are given below:

<u>The Dairy</u>

Groundmass, cryptocrystalline		40%
Phenocrysts:		55%
Calcic andesine, 1-8 mm long	75%	
Biotite, 1-2 mm diameter	15-20%	
Hornblende, 1-13 mm long; much altered	5-10%	
Augite	1%	
Magnetite		5%

Pinto Peak

Groundmass, cryptocrystalline		55%
Phenocrysts:		40%
Andesine, euhedral, microfractured; 1-3 mm	75%	
Biotite, strongly pleochroic; avg.1 mm.	15%	
Hornblende, euhedral; 1-4 mm	10%	
Magnetite, mainly secondary		5%

Paradise

Groundmass, microgranular		45%
Phenocrysts:		50%
Andesine-labradorite, 1-5 mm	65%	
Biotite, bronze-colored; 1-2 mm	15%	
Hornblende, some basaltic; highly altered	10%	
Augite and hypersthene	10%	
Magnetite		5%

Stoddard

Groundmass, fine-grained		50%
Phenocrysts:		45%
Plagioclase, 1-8 mm	65%	
Biotite, 1-2 mm	15%	
Hornblende, much altered, 1-4 mm	15%	
Augite	5%	
Magnetite		5%

Pine Valley

Groundmass, cryptocrystalline to fine-grained		45%
Phenocrysts:		50%
Andesine-labradorite, 1-15 mm	70%	
Augite and hypersthene	20%	
Biotite	10%	
Magnetite		5%

The mineralogic compositions given above are estimates based upon study of thin sections and hand specimens. The

magnetite is both primary and secondary and occurs both in the groundmass and among the phenocrysts. Most of it apparently is a product of the deuteric alteration of mafic minerals (Fig. 62).

Peripheral zoning is prominent in the eastern part of the Stoddard laccolith, with a zone of deuteric alteration forming a valley about 2,000 feet from the margin of the body (Fig. 61). Roughly horizontal zoning is apparent on cliff faces of the Pine Valley laccolith and this has been studied in some detail.

Zoning in the Pine Valley laccolith

The strongly jointed basal part of the Pine Valley laccolith (Figs. 65, 67) forms vertical cliffs above the weak Claron limestone. The maximum remaining thickness of the de-roofed intrusive body is 3,000 feet and its outcrop covers 70 square miles. The basal contact is exposed or thinly covered by talus for about 25 miles.

The rock of the laccolith is a monzonite porphyry (Fig. 63). Phenocrysts of andesine-labradorite (Ab_5 An_5), augite, hypersthene, and biotite (in order of decreasing abundance) make up about half the rock; the much finer-grained groundmass apparently consists mostly of orthoclase with some quartz. Unlike the phenocrysts, which although ranging from 4 to 15 millimeters in length do not vary much in average size

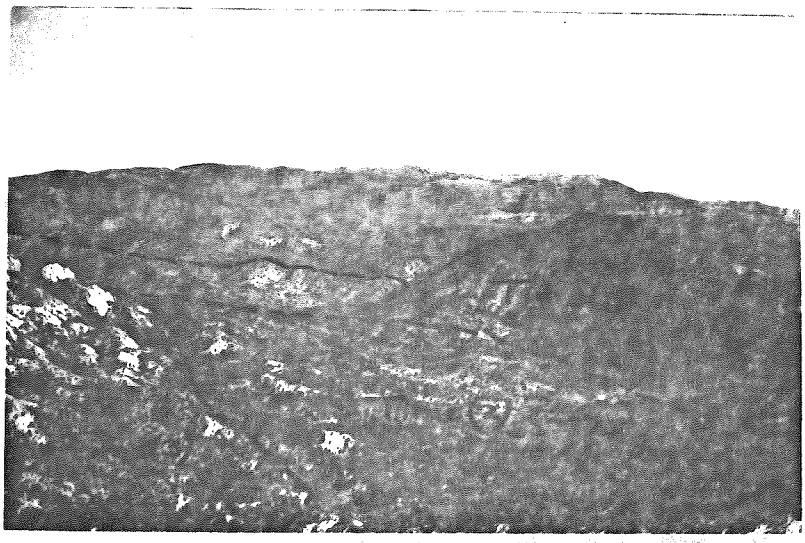


Fig. 61 Peripheral zoning in eastern part of Stoddard laccolith. Tims(1) is resistant, red-brown, peripheral shell. Tims(2) is zone of deuteric alteration and brecciation; rock is red, gray, or greenish with considerable porosity. Tims (3) is gray, hard, inner core.

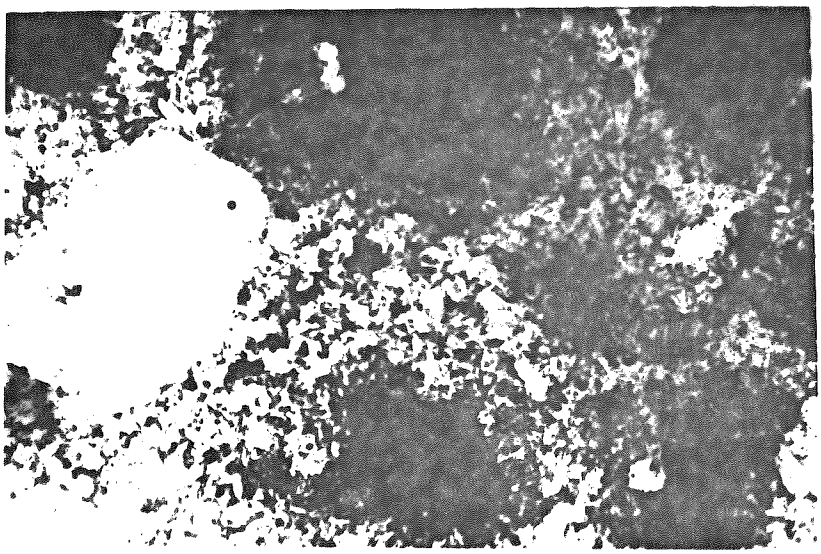


Fig. 62 Photomicrograph of monzonite porphyry from zone of deuteric alteration, Stoddard laccolith. Note development of abundant magnetite and cavities at the expense of mafic minerals. Plane light, 25x.

throughout the laccolith, the groundmass is coarser-grained higher in the body than near the base. The phenocrysts of plagioclase and augite are micro-fractured, and many of the plagioclase crystals are partially resorbed. Many of the augite and biotite crystals are greatly altered, only magnetite and hematite stains remaining in some cases. Magnetite is scattered in small grains throughout the groundmass, but is especially abundant wherever the mafics have been destroyed (Fig. 64).

On any extensive vertical exposure, the intrusive body shows roughly horizontal gradational color bands; these bands are best seen on the steep southeast face of the laccolith. These color zones may, for convenience of discussion, be divided into (from bottom to top): a thin "dark brown zone", 50-250 feet thick; a "brown zone" 750-1,150 feet thick; a central "white zone" 100-350 feet thick; and an upper "purple zone" at least 1,600 feet thick. These color designations are generalizations and represent the bulk visual impact of each zone from a distance.

The basal "dark brown zone" has a pseudocolumnar structure due to intersecting vertical joint sets (Figs. 65, 67). The contact, grossly concordant with the bedding of the Claron formation, is a surface of small relief; little irregular igneous apophyses with phenocrysts as large as higher in the laccolith extend downward into the lacustrine

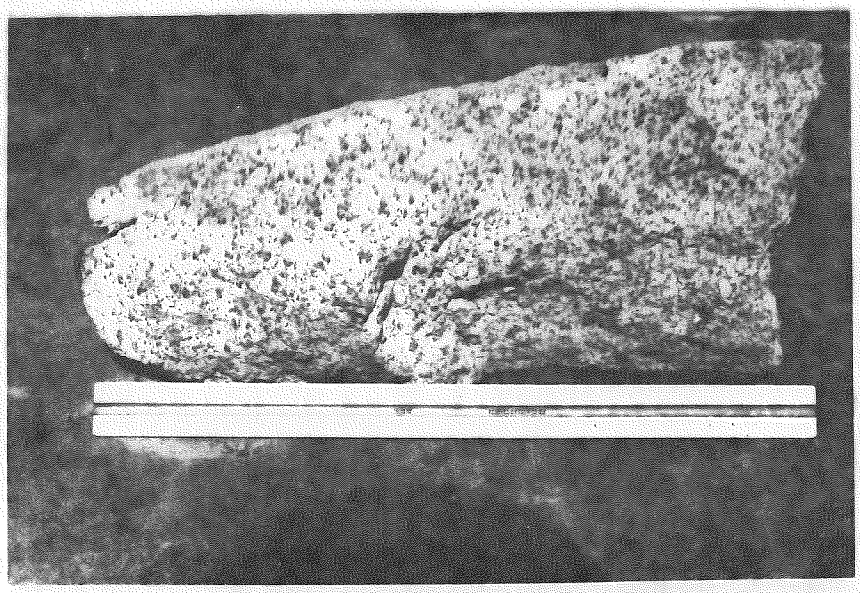


Fig. 63 Photograph of monzonite porphyry from the Pine Valley laccolith.

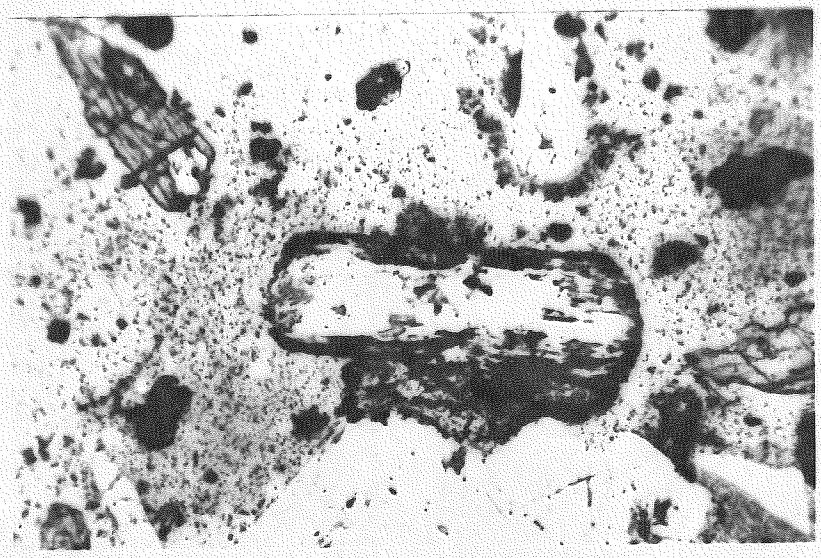


Fig. 64 Photomicrograph of deuterically altered Pine Valley monzonite porphyry of the "white zone". Note abundance of secondary magnetite. Plane light, 20x.

limestone of the Claron as much as 12 inches (Figs. 66, 69, 70). As far as can be determined, the basal contact follows approximately the same horizon wherever seen: the top of the Claron formation.

The basal zone grades rapidly upward into the slightly less resistant but much thicker "brown zone", greatly fractured by vertical joints. The rather uniform reddish-brown color is the color of a weathering rind which is cut through by the deeper canyons, revealing an olive-gray fresh surface. Except on the steepest parts of the cliff face, the top of the brown zone is marked by a rough craggy bench (Fig. 72).

For a distance of about five feet downward from the contact the limestone is a pale green (whereas normally it is pinkish); except for the color change and a slight baking within a foot of the contact (Fig. 68), there are no signs of metamorphism. The "dark brown zone" is the most resistant of the four zones and stands up as a cliff everywhere it is exposed. Locally near the base there is a faint planar flow structure and in one place large-scale protoclastic structure is exposed. The groundmass in this zone is cryptocrystalline to glassy (Fig. 71); the glass has an index of refraction between 1.495 and 1.500, indicating a rhyolitic composition. Broken crystals of andesine-labradorite, augite, hypersthene, and biotite rest against the base, showing that they are intratelluric. For a variable distance below the laccolith floor,

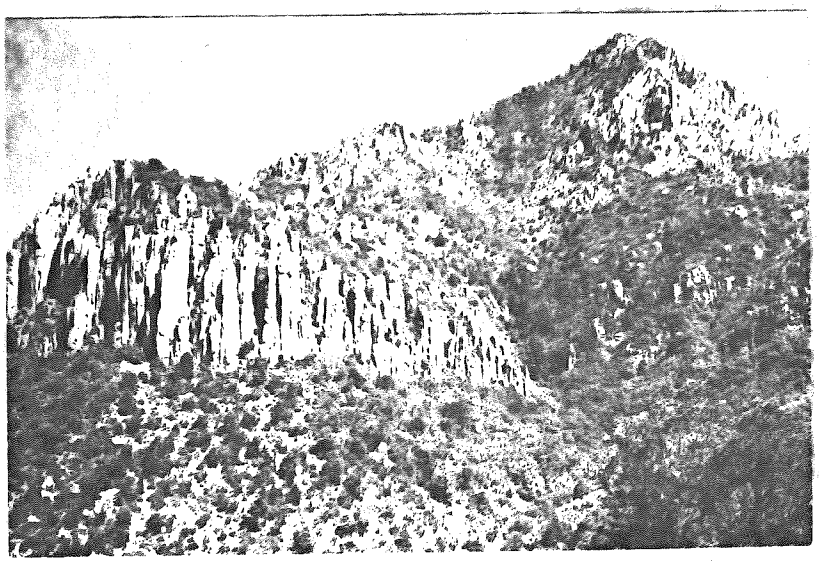


Fig. 65 Pseudocolumnar structure in basal "dark brown zone" of the Pine Valley laccolith.

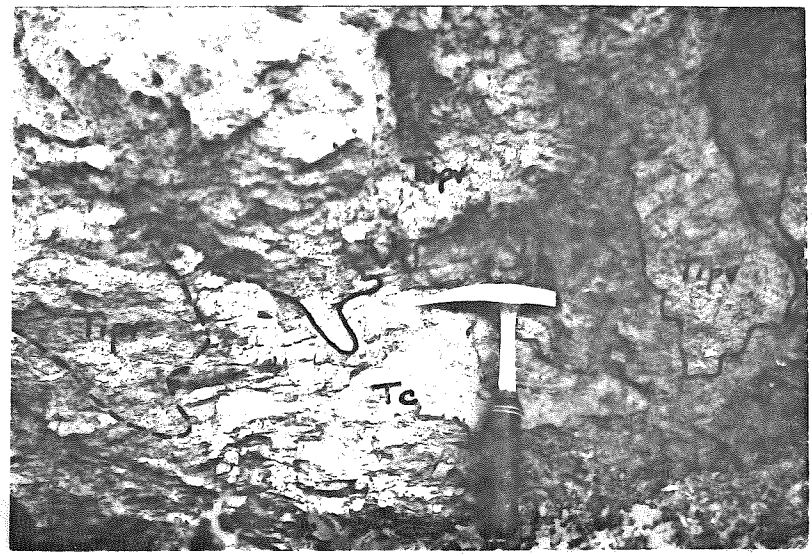


Fig. 66 Detail of base of Pine Valley laccolith, exposed in Leap Creek, near Peter's Leap.

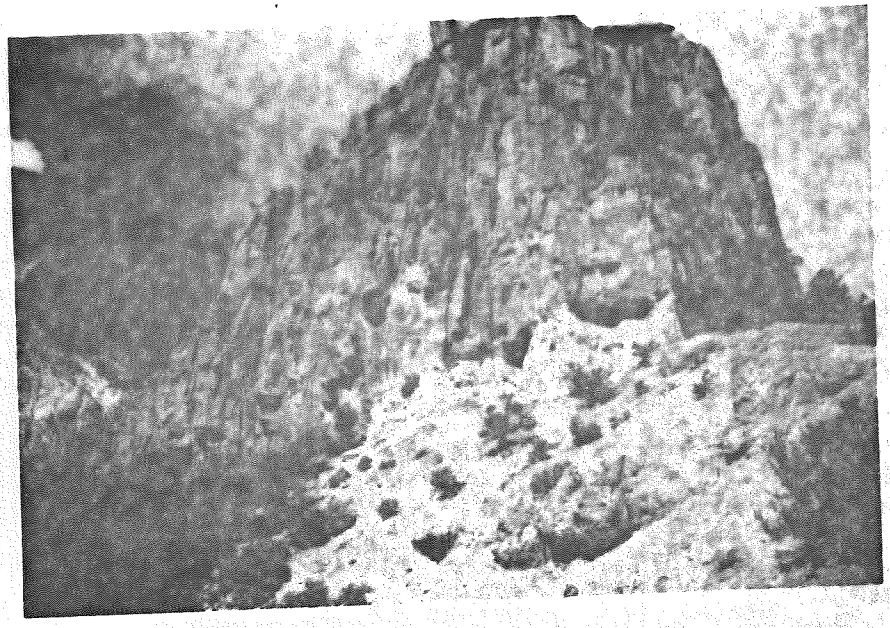


Fig. 67 Base of Pine Valley laccolith exposed near the headwaters of Cottonwood Creek. Note pseudo-columnar structure in "dark brown zone".

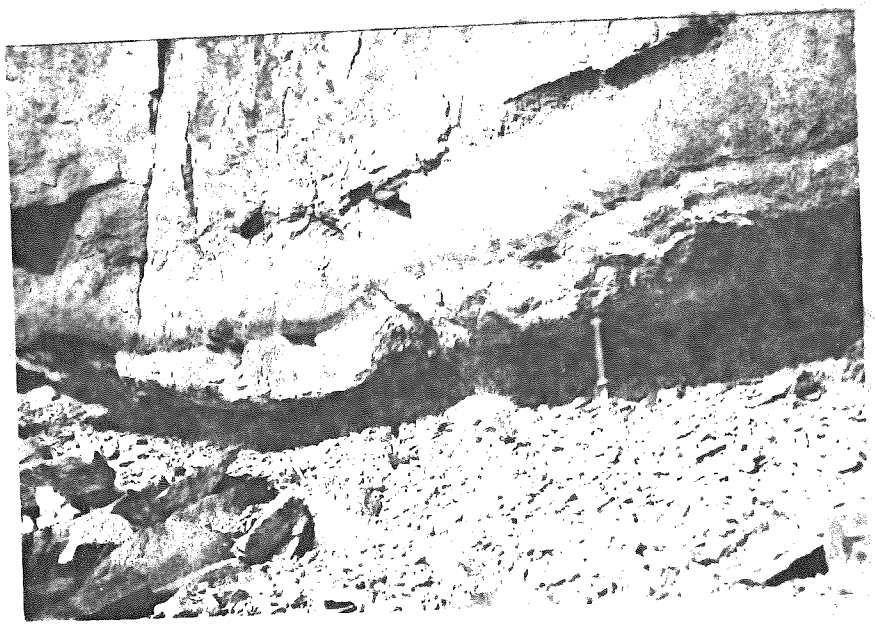


Fig. 68 Base of Pine Valley laccolith near headwaters of Cottonwood Creek. Baked Claron limestone overlain by thin, dark, chilled border of basal "dark brown zone".

commonly about ten millimeters (Fig. 69), these intratelluric crystals have been mechanically mixed with the calcareous sediment of the Claron formation. The base of the igneous mass locally has a thin, dark, chilled border (Fig. 68) in which the phenocrysts are just as large, and more numerous, than in higher parts of the body.

Despite an apparent concentration of mafic minerals near the base of the laccolith, the greatest specific gravity in the zone is found near the middle and top (Fig. 78), about one hundred feet above the base. Near the base, the mafic minerals make up about 25 per cent of the rock; near the top of the dark brown zone, they form about 15 per cent of the rock. These estimates are from thin section study and do not include magnetite. An explanation for the apparent anomaly between mafic content and specific gravity may be that magnetite is less abundant near the base than higher; thin sections appear to bear this out, for the microgranular groundmass of a specimen taken 100 feet above the base is seen to be much more highly charged with fine-grained magnetite than the cryptocrystalline groundmass of the basal rock. In addition to abundant magnetite, specimens from the upper part of the zone contain considerable disseminated chlorite.

Throughout most of the brown zone the rock contains about 15 per cent of intratelluric mafics, greatly altered to magnetite and chlorite--which mark the positions of vanished

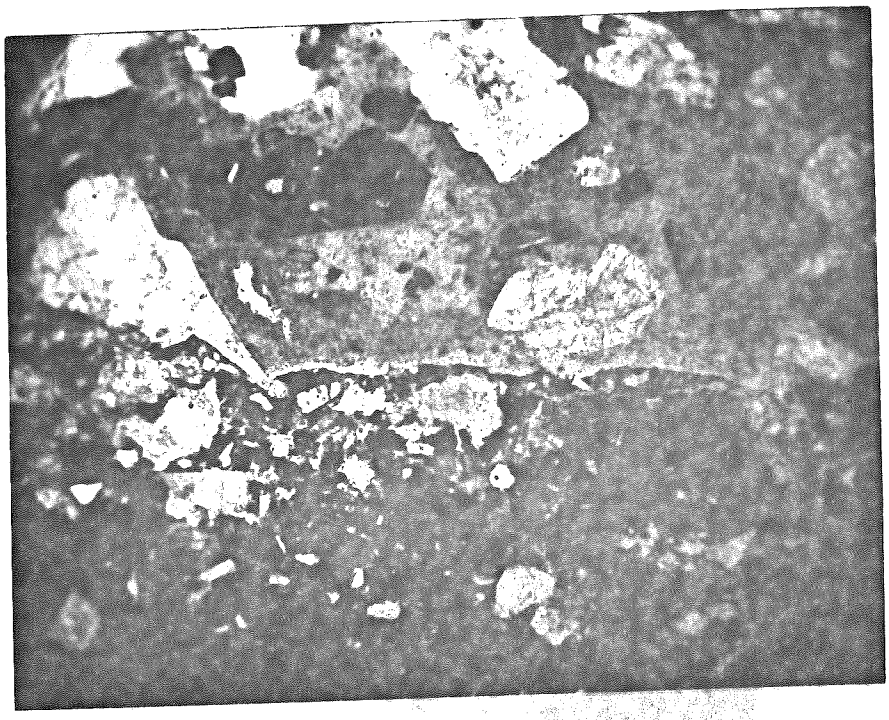


Fig. 69 Photomicrograph of basal contact of Pine Valley laccolith with the Claron formation. Note broken intratelluric crystal in porphyry at contact, cryptocrystalline groundmass of porphyry and igneous minerals in Claron formation. Plane light, 20x.

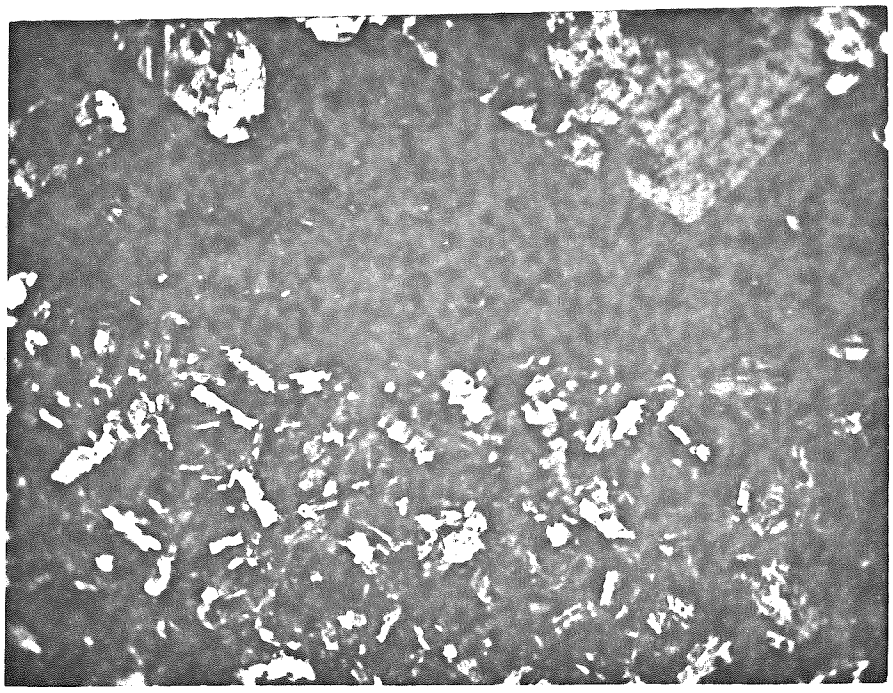


Fig. 70 Photomicrograph of basal contact of Pine Valley laccolith with the Claron formation. Crossed nicols, 20x.



Fig. 71 Photomicrograph of rock from "dark brown zone" of Pine Valley laccolith. Plane light, 14x.

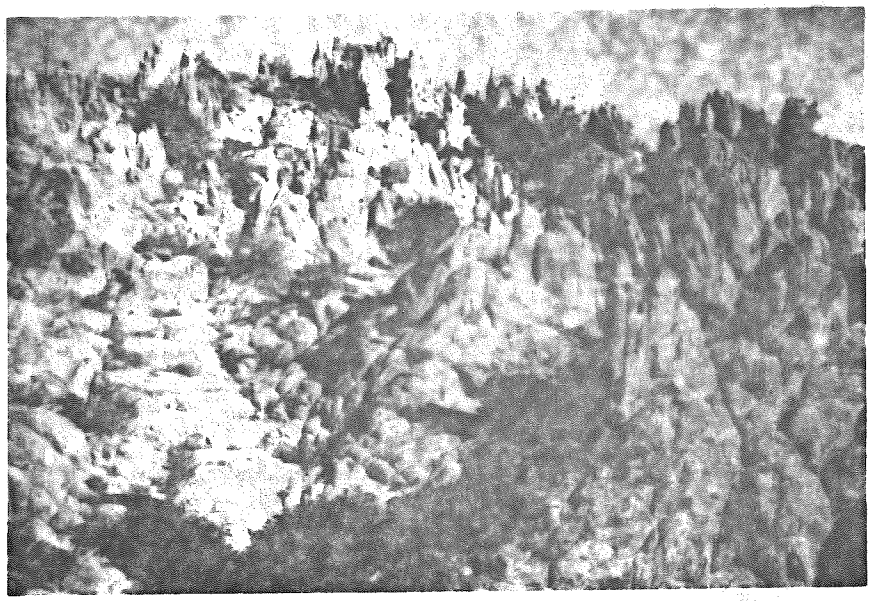


Fig. 72 Rough, craggy bench at top of "brown zone" of Pine Valley laccolith.

biotite crystals, form irregular rims and embayments on augite and hypersthene, and are abundantly distributed through the microgranular groundmass. Near the top of the zone, an increase in specific gravity (Fig. 78) is accompanied by an increase in chlorite, an increase in mafics to about 25 per cent, and--most notably--by an increase in magnetite which occurs along numerous cracks in feldspar crystals as well as in the groundmass and in altered mafics. From the upper part of the brown zone to the basal part of the purple zone, a prominent feature (under the microscope) is this migrating magnetite, filling cracks in the groundmass as well as in intratelluric crystals (Fig. 76).

Above the bench at the top of the brown zone appears the gray, commonly porous and crumbly, rock of the "white zone" (Fig. 77). Rock of this zone has numerous cavities (Fig. 73) and a bleached appearance which makes it appear white from a distance. The white zone rock contains few mafic minerals, some specimens having as little as five per cent. In consequence --although there is considerable magnetite, possibly as high as ten per cent--the rock has a low powder specific gravity (Fig. 78) and, due to miarolitic porosity, an even lower bulk specific gravity. The intratelluric feldspars have alkalic reaction rims. The groundmass is coarser and more irregularly grained than elsewhere in the laccolith; little lenses and veinlets of quartz occur in the groundmass; magnetite veinlets

cut through both groundmass and phenocrysts; much of the groundmass contains poorly defined granophyric (or micropegmatitic) intergrowths.

The contact between the white zone and the overlying "purple zone" is gradational but locally it appears sharp. However, even in hand specimen it can be seen that this sharp contact is not intrusive but is an alteration boundary; the color contact cuts across feldspar phenocrysts without disturbing them. Under the microscope, the contact is difficult to define (Fig. 74); the only change appears to be an increase in turbidity in the groundmass of the purple rock. The purple zone rock has a pale reddish-purple groundmass and is much less jointed than the two lowermost zones--in fact, incipient jointing is often seen, marked by alined, elongate weathering depressions.

Although the intratelluric mafic phenocrysts throughout the purple zone have undergone considerable deuteric alteration, their outlines (especially near the base of the zone) are euhedral--which is not the case with the mafics of the three lower zones. Except at the base of the zone, where there is a slight increase, the mafic minerals form a rather consistent 10 to 15 per cent of the purple zone rock. Above the basal part of the zone the groundmass is generally cryptocrystalline and there is no migrating magnetite along cracks (Fig. 75); at the base of the zone, however, the groundmass is coarser and

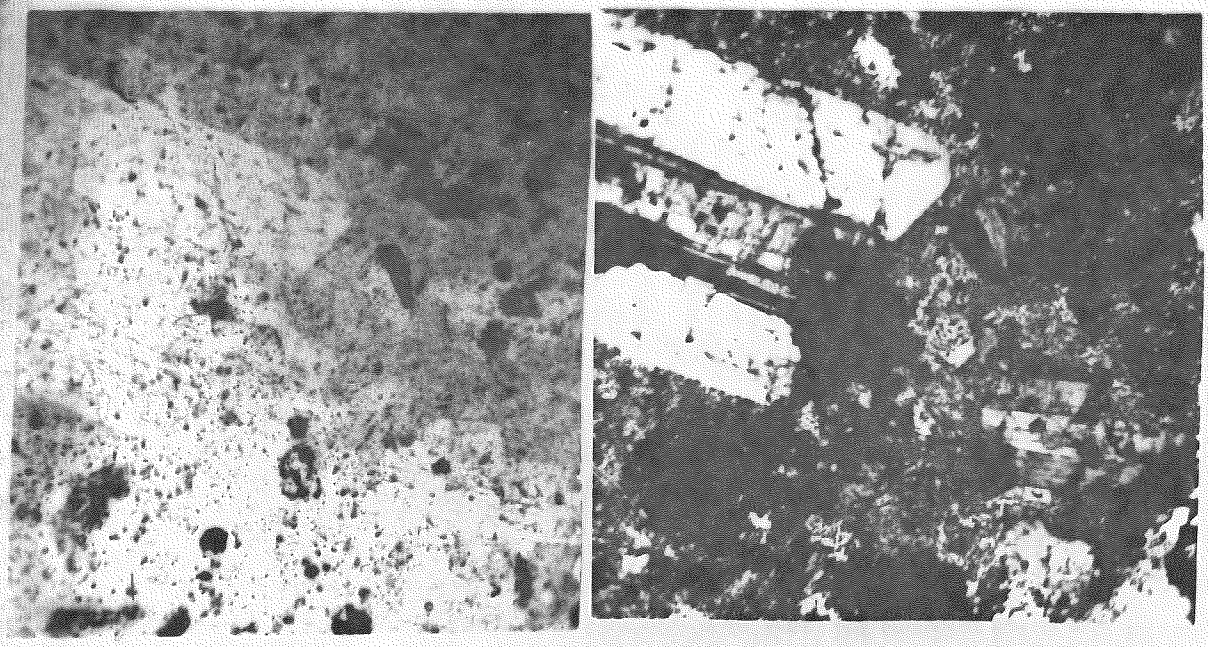


Fig. 73 Photomicrographs of deuterically altered rock of "white zone" of Pine Valley laccolith. Miarolitic porosity is nine per cent. Plane light on the left, crossed nicols on the right; 20x.

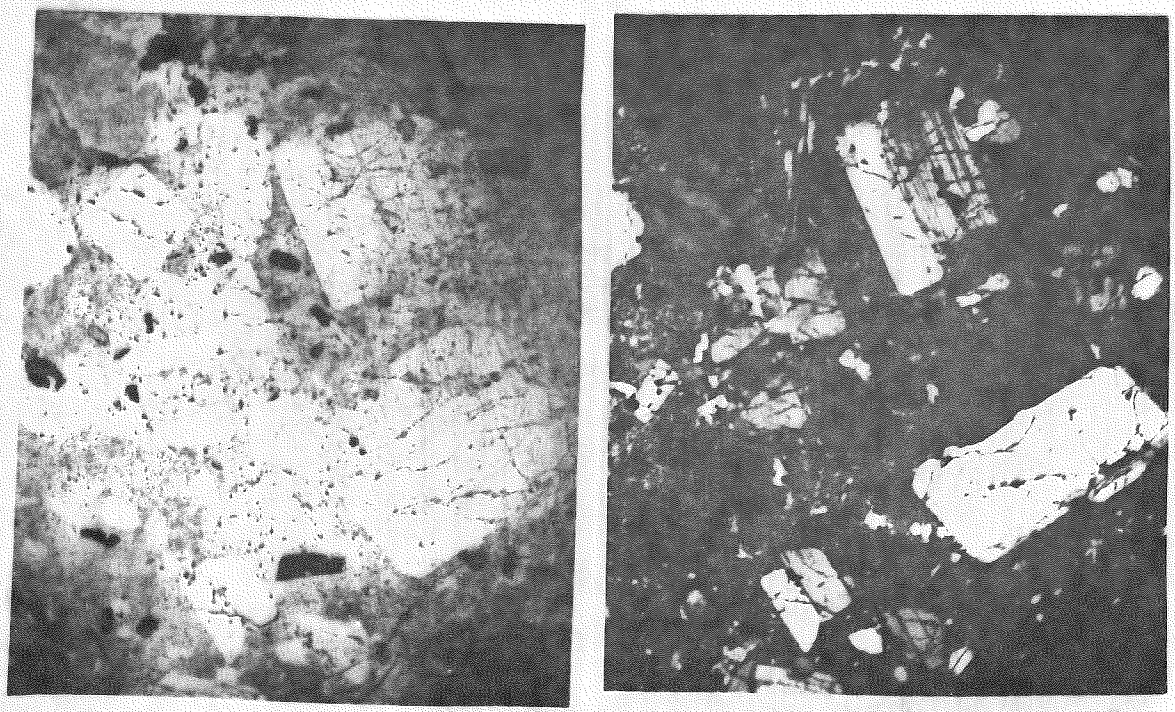


Fig. 74 Photomicrographs of contact between "white zone" and overlying "purple zone". Plane light on the left, crossed nicols on the right; 15x.

some magnetite does occur in microfractures.

In an effort to determine the cause of these color bands or zones, a number of bulk and powder specific gravity determinations were made. The two types of determinations, bulk and powder, were made on each specimen to isolate and quantitatively determine the effect of porosity. A diagram (Fig. 77) has been constructed, representing the southeast face of the Pine Valley Mountains, with the vertical scale exaggerated ten times. Positions where specimens were obtained, the corresponding powder specific gravities, schematic profiles at four different places along the mountain front, and the extent of the four color bands are shown.

Composite density curves (Fig. 78) have been drawn (a) for Sections A and B of Fig. 77, (b) for Sections C and D, and (c) for all four sections--this latter accomplished by an upward shift of 150 feet of most of the second curve in order that the zones match. In other words, all determinations on which the final composite curve is based are shown in their proper position relative to zonal boundaries but some of them are not in the correct position relative to the base of the intrusion. A composite porosity curve has also been constructed. Per cent porosity was calculated by dividing the difference between the bulk and powder specific gravities by the powder specific gravity and multiplying by 100.

The curves based on powder specific gravities show a

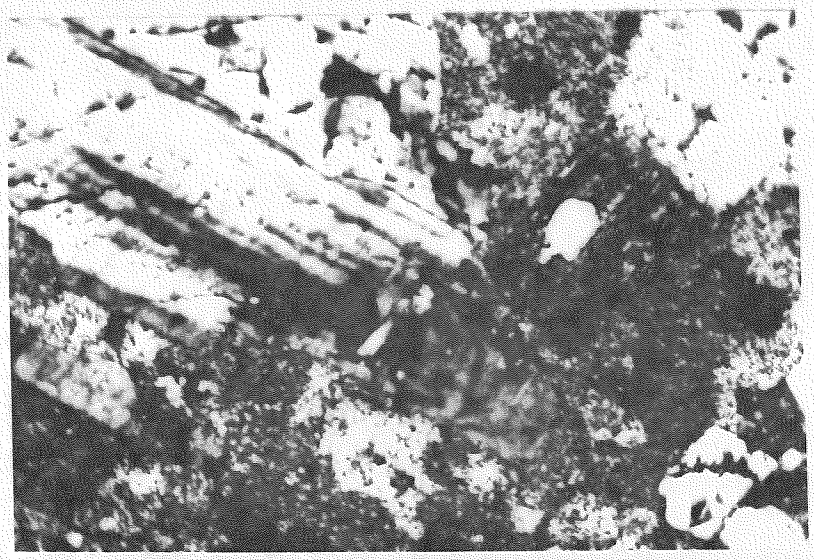


Fig. 75 Photomicrograph of typical "purple zone" rock from Pine Valley laccolith. Crossed nicols, 15x.

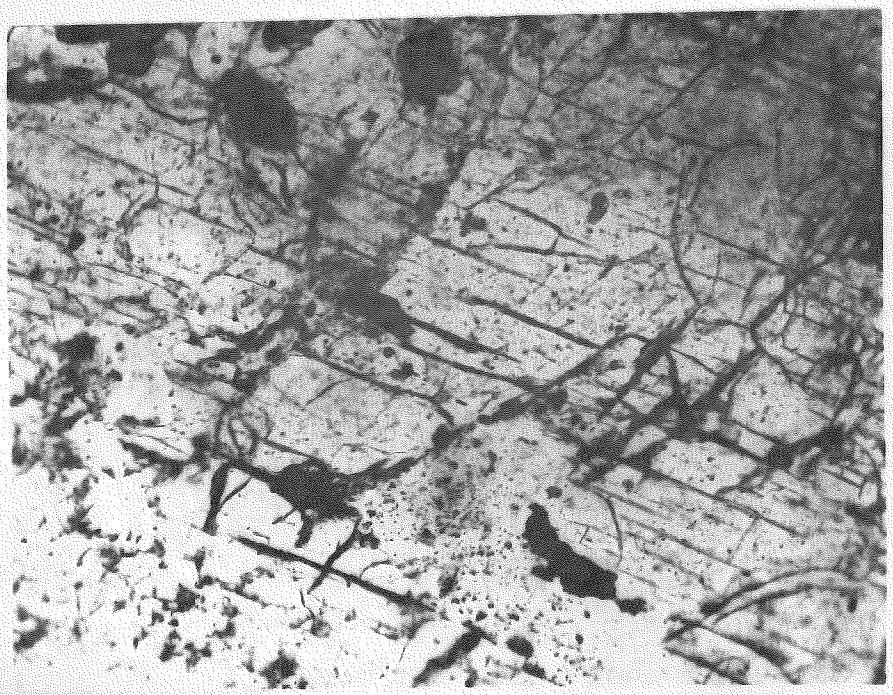


Fig. 76 Photomicrograph showing deuteric magnetite migrating along cracks in feldspar. In upper part of "white zone". Plane light, 88x.

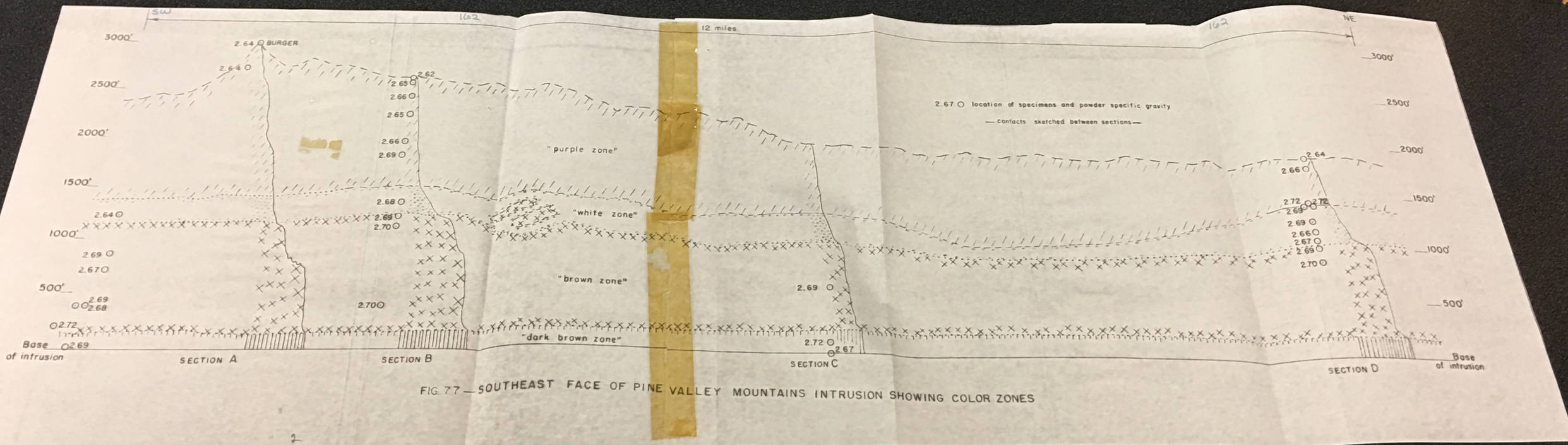


FIG. 77 — SOUTHEAST FACE OF PINE VALLEY MOUNTAINS INTRUSION SHOWING COLOR ZONES

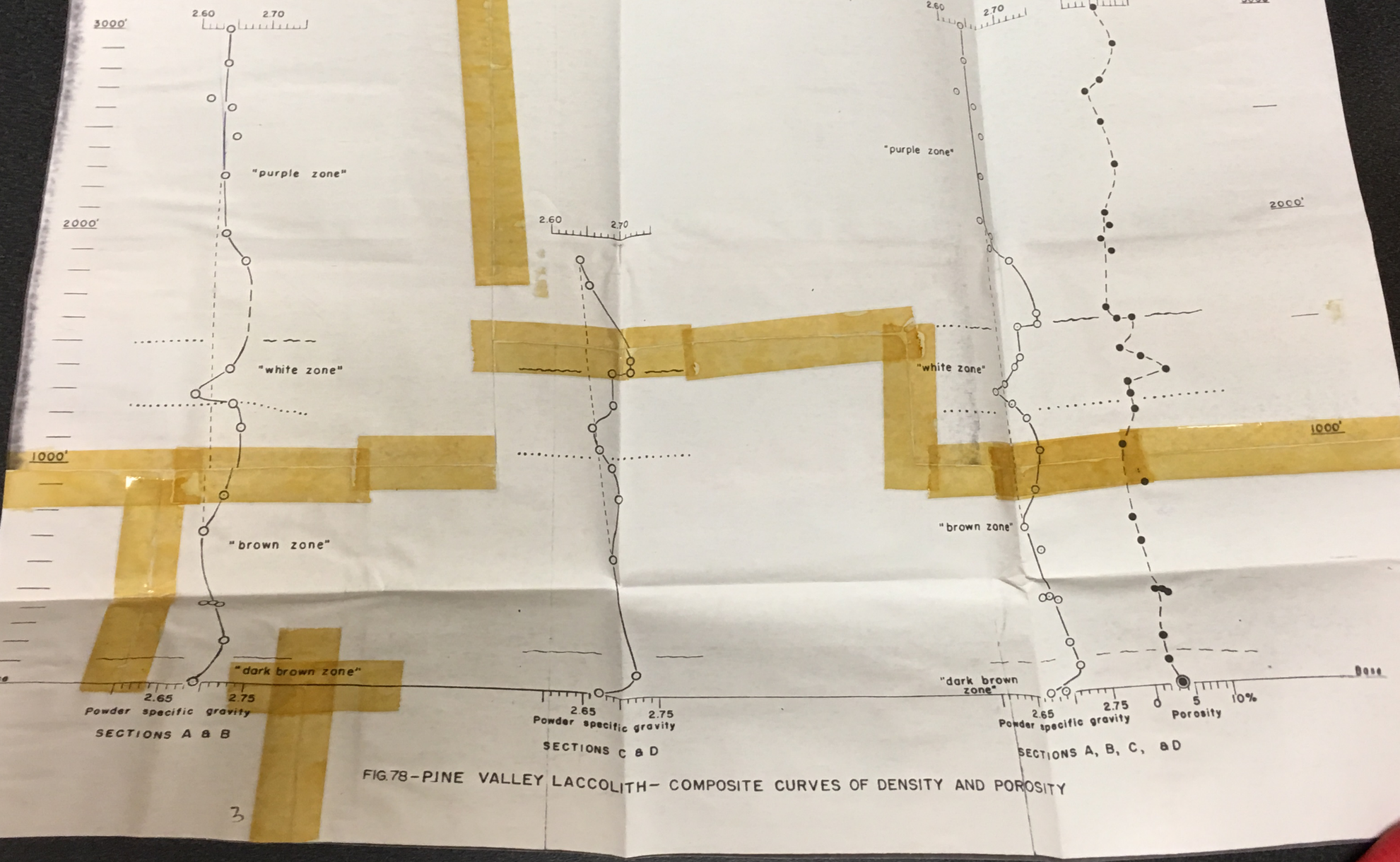


FIG. 78 – PINE VALLEY LACCOLITH – COMPOSITE CURVES OF DENSITY AND POROSITY

FIGURE 2

GENERALIZED SECTION OF THE ROCK FORMATIONS OF THE PINE VALLEY MOUNTAINS, UTAH

System	Series	Formation	Lithology	Thickness (feet)
QUATERNARY	RECENT	Alluvium, hillwash, landslides	Sand, silt, gravel; talus, landslide blocks	0-200
		unconformity		
	PLEISTOCENE	High-level gravels	Coarse, poorly sorted gravel	0-200
	PLIOCENE(?)	Basalt	Basalt	0-200
		unconformity		
		Parunuweap(?) formation	Silt, sand, fine gravel, locally cemented	0-200
		relations unknown		
		Guide Meridian volcanics / Stoddard breccia	Porphyritic hornblende dacite / Mudflow breccia	0-200
		unconformity		
		"Platy porphyry"	Augite-biotite latite porphyry with well-developed platy parting. May be intrusive. Basal glass 10-150' thick	500+ / 0-150
		unconformity		
		Page Ranch formation	A crystal, biotite dacite ignimbrite, moderately welded, overlying bedded tuff-breccia of possible lahar origin	2000+
		unconformity		
		Atchinson formation	Rudely bedded breccia overlying augite andesite flows and breccia. Locally, at the base, tuff-breccia	0-600
TERTIARY		unconformity		
		Grassy Flat Canyon formation	Vitric-crystal rhyolite ignimbrite, foliated	0-500
			Vitric-crystal rhyolite ignimbrite with lithic fragments	0-150
			Augite andesite lava, amygdaloidal	0-700
		unconformity or thrust fault	Lacustrine limestone	0-50
		Rencher formation	Latite breccia at top, minor air-fall tuff; volcanic sandstone; dacite porphyry breccia; bedded, welded tuff-breccia; biotite ignimbrite, poorly welded; crystal-vitric dacite ignimbrite containing quartzite pebbles; basal conglomerate, limestone	0-100
		unconformity		
		Quichapa grp. Tv-2	Crystal biotite dacite ignimbrite	0-600
		disconformity	Vitric rhyolite ignimbrite, foliated	0-550
		Tv-1		0-180
		disconformity	Crystal-vitric rhyolite ignimbrite with lithic fragments	0-800
	EOCENE	Claron formation	Lacustrine limestone with, near the top, a bed of biotite tuff, and near base, black ls. pebble cong.	0-1000
			Calcareous sandstone and sandy limestone	
	LARAMIAN	unconformity	Quartzite cobble conglomerate and sandstone	
	MONTANAN	Kaiparowits formation	Soft sandstone, much of it cross-bedded and conglomeratic. Iron concretions common. At the base, silty shale and quartzite cobble conglomerate.	0-1200
		disconformity		
CRETACEOUS	UPPER CRETACEOUS	Wahweap and Straight Cliffs sandstones	Sandy shale and lignite alternating with massive, cross-bedded sandstone in beds 5-40 feet thick.	0-1800
	COLORADOAN	Tropic formation	Alternating silty shales and thin sandstones with some coal beds. Becomes more arenaceous westward.	0-800
		Dakota(?) sandstone	Poorly sorted, pebble conglomerate with sandstone lenses	0-80
		unconformity		
JURASSIC(?)		Entrada sandstone	Friable sandstone, grading westward into shale with minor sandstone and limestone	0-150
	UPPER JURASSIC		Platy argillaceous limestone	
		Carmel formation	Soft sandstone, gypsiferous shale, and gypsum	0-675
		disconformity		
		Navajo sandstone	Cross-bedded sandstone. At the base, shaly sandstone and rudely bedded sandstone.	1800-2200
TRIASSIC	UPPER TRIASSIC	Chinle formation	Variegated sandstone and shale. Two thin beds of cherty limestone. Near the middle a prominent sandstone ledge (Silver Reef sandstone). In lower half, shales and sandstones containing fossil wood.	1000-1380
		Shinarump conglomerate	Coarse-grained to conglomeratic sandstone, irregularly bedded	115-184
		disconformity		
	LOWER TRIASSIC	Moenkopi formation	Thin-bedded gypsiferous and calcareous sandstone. Bed of fossiliferous marine limestone in lower half (Virgin limestone member).	1100-2000
		disconformity		
PERMIAN & PENNSYLVANIAN(?)	LOWER PERMIAN	Kaibab limestone	Two thick beds of fossiliferous limestone separated by 150 feet of gypsum	800
	LOWER PERMIAN & U. PENN (?)	Coconino sandstone(?)	Cross-bedded, well-sorted quartz sandstone	500+

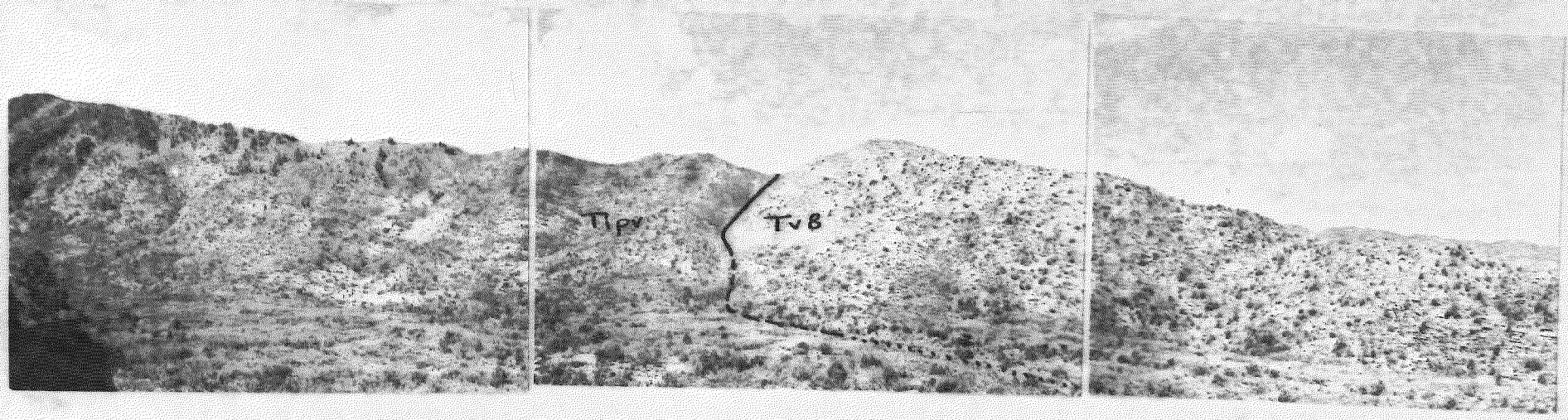


Fig. 80 Contact between Pine Valley laccolith (Tipv) and "platy porphyry" (Tv-8) about two miles southwest of New Harmony. The contact, which here dips south, under the intrusion, is revealed by change in structure and tone of the rocks, as well as by a topographic depression.

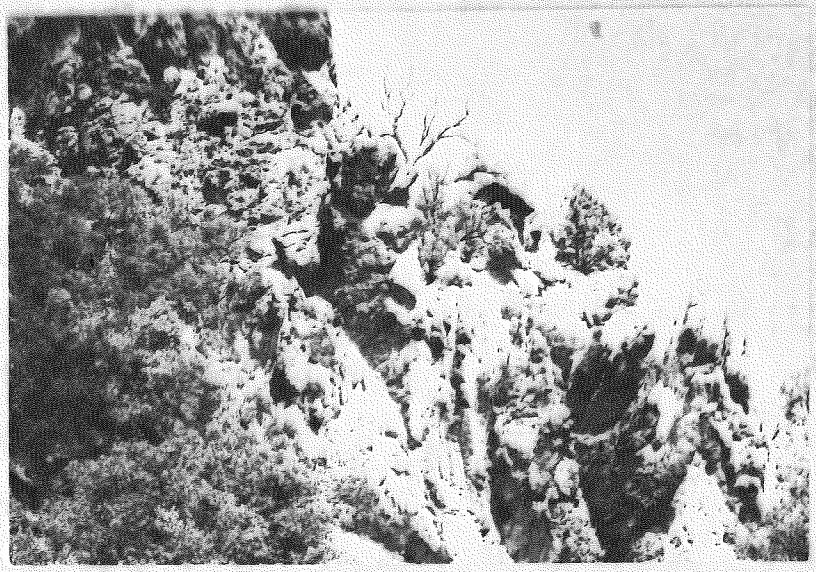


Fig. 81 Detail of platy latite porphyry near contact with Pine Valley laccolith southwest of New Harmony. Contact is in the gully at the right. Upturned platy rock contains some sandstone fragments and smashed quartzite boulders. Rock on left is a black, porphyritic, glassy breccia.



Fig. 82 Contact between "platy porphyry" (Tv-8) and Pine Valley intrusive porphyry (Tipv) in gully about two miles southwest of New Harmony. Hammer rests on intrusive breccia.

found anywhere in that formation. In the gravel mantle of the small pediment which descends toward the northeast from this outcrop were found pebbles and cobbles of quartzite and fragments of yellow-brown sandstone, although the nearest known exposure which might yield such material is almost three miles to the north and not in the same drainage. These observations suggest that the base of the "platy porphyry" is near the surface southwest of New Harmony.

In only one place along the northern contact of the laccolith was any projecting offshoot of the intrusive porphyry found. This occurrence is about four miles southeast of Central (see geologic map, Sheet 1). Here a tongue-like sill of monzonite porphyry projects from the main body some distance above its base and lies concordantly on extrusive rock of the Atchinson formation (Fig. 85). Along most of its northern contact the magma of the laccolith apparently rose past the upturned edges of the volcanic sequence. In the locality southeast of Central, on the other hand, the volcanic strata dip southward into the laccolith and the formational contacts were available avenues of protrusion for the magma.

Structural features of special interest

Little flow structure and no columnar jointing can be seen in the porphyry, although a system of vertical joints does

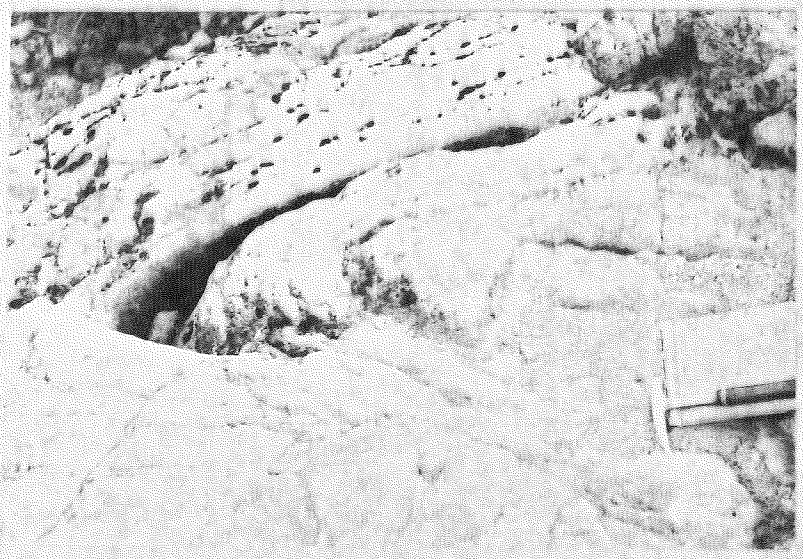


Fig. 83 Tightly folded platy latite porphyry near contact with Pine Valley laccolith. Outcrop southwest of New Harmony.

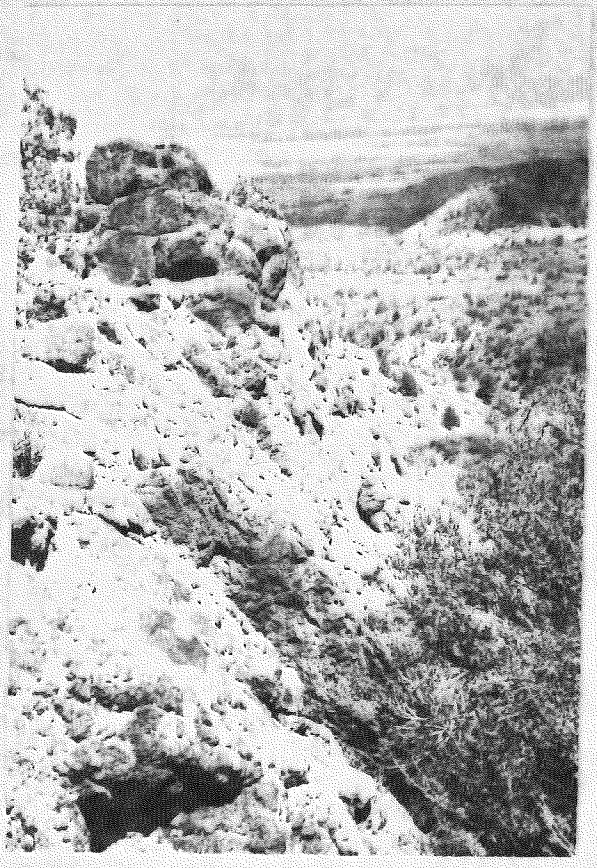


Fig. 84 Black glass breccia (Tv-8a?) dipping southward along northern contact of Pine Valley laccolith. About two miles southwest of New Harmony.

produce a pseudocolumnar structure in basal portions of the mass.

The monzonite is porphyritic even in the smallest apophyses; only the groundmass shows a decrease in grain size near the base. Protoclastic structure in the basal part of the porphyry was seen in one locality.

The argillaceous limestone underlying the laccolith is baked and broken for several feet away from the contact. In several exposures it appears that the limestone in the contact zone has been decarbonatized and turned green, but there are no "contact" minerals. Secondary calcite is locally abundant in the lower few inches of the monzonite.

Original extent and shape of body

The original extent of the Pine Valley laccolith is largely a matter of surmise. It was limited on the north by the intrusive fault contact which has been mapped from New Harmony to a point about three miles southeast of Central. Unless it changed its horizon of intrusion, the laccolith did not extend beyond Gunlock on the west, for the Tv-1 ignimbrite overlies the Claron formation in that locality. The eastward and southward limits are unknown; erosion has removed all the evidence in those directions.

Because the roof of the laccolith has been removed by erosion, the assumption of previous laccolithic form rests

upon the evidence of the concordant base, the remaining thickness of the body, and the intrusive faults which limit it on the north. The pertinent facts and inferences are:

1. The body has a remaining thickness of 3,000 feet, an areal extent of 70 square miles, and a maximum horizontal dimension of over 20 miles.
2. The base is concordant with the underlying sedimentary rocks. The intrusion followed a stratigraphic horizon at or very near the top of the Claron formation.
3. The body is limited by intrusive faults on the north and may have been similarly bounded in the other directions.
4. Because the base is concordant and there has been no assimilation, it may be inferred that the upper surface of the Pine Valley body was essentially concordant.

To call such a body a laccolith is to apply the term loosely. But to restrict the term to completely concordant, igloo-shaped intrusions would mean that the word laccolith could rarely be used. Billings (1942, p. 272) applies a form-ratio to distinguish between a thick sill and a laccolith: the longest horizontal dimension of a laccolith must be less than ten times its greatest thickness; otherwise, the body is a sill. This criterion, applied to the Pine Valley intrusion, would

require an improbable initial thickness of at least two miles. Also, the discordant periphery is characteristic of a bysmalith, not a laccolith *sensu strictu*.

Despite these objections, it seems more in line with common usage to call the body a laccolith than a sill.

Horizon of intrusion

The Claron formation beneath the laccolith has a remarkably uniform thickness of 460 feet in most of the sections measured.

Knowledge of the much thicker Claron sections in the Iron Springs district (1,000 feet) (Mackin, 1947a, p. 8), on the Markagunt Plateau (over 1,300 feet) (Gregory, 1950a, p. 78), and even within the map area at Gunlock (959 feet), leads one to suspect that the Pine Valley intrusion spread along a horizon within the Claron formation. Detailed examination at two localities suggests however, that the intrusion, at these places, came between the top of the Claron formation and the base of the overlying volcanic sequence. At each place the base of the laccolith and the base of the extrusive sequence appear at the same elevation on opposite sides of the intrusive fault contact, with the Claron formation passing unbroken and unchanged in thickness beneath the contact (see cross-section, Fig. 87).

Stratigraphic study of the Claron in this area leads

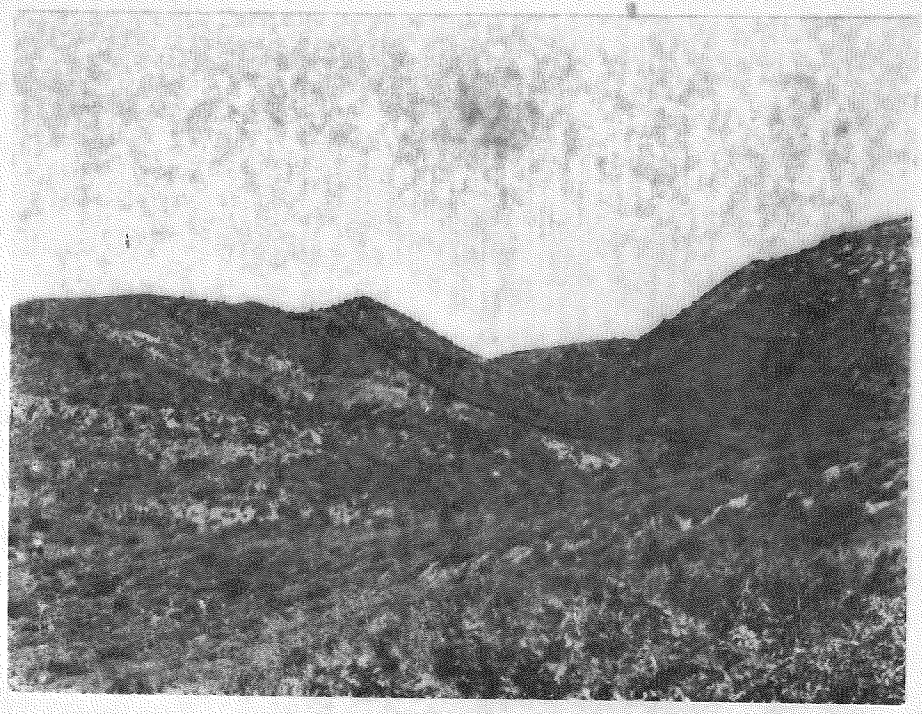


Fig. 85 Sill projecting northward from Pine Valley laccolith (Tipv) and concordantly overlying rocks of the Atchinson formation (Tv-6). Exposure four miles southeast of Central.

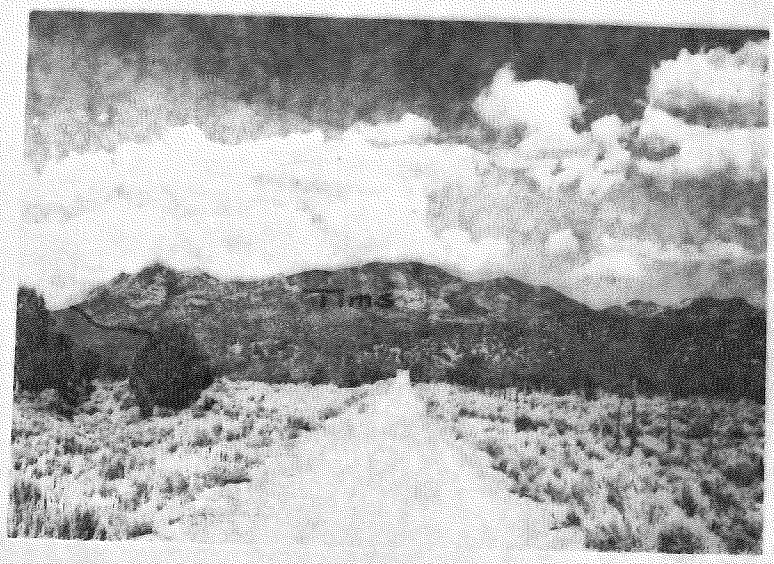


Fig. 86 Stoddard Mountain laccolith (Tims). Looking east.

to the same conclusion, that the intrusion came at the top of the formation, and indicates that the southward thinning of the formation is, in large measure, depositional thinning, but is partially due to post-Claron, pre-Quichapa erosion.

The threefold subdivision of the Claron can be recognized beneath the laccolith, indicating that all or most of the formation is present. Additional stratigraphic evidence is found in the southward thinning of the Claron, which shows that a thickness of about 500 feet could be normal for the area covered by the laccolith.

Cover of laccolith

These relationships suggest that the cover under which the laccolith intruded was entirely volcanic. But how thick was this cover? The minimum must be about three thousand feet, else the magma would have broken through the cover along the peripheral faults. We cannot total the maximum, or even the average, thicknesses of the several volcanic formations and say that is the probable thickness of the cover, for there is direct evidence that much of the earlier volcanic pile had been eroded away by the time the platy latite porphyry was extruded. The maximum remaining thickness of platy latite is about 2,000 feet. This seems an inadequate cover; on the other hand, if the platy rock was once much thicker than it now is--say three or four times as thick--it must have had a correspondingly

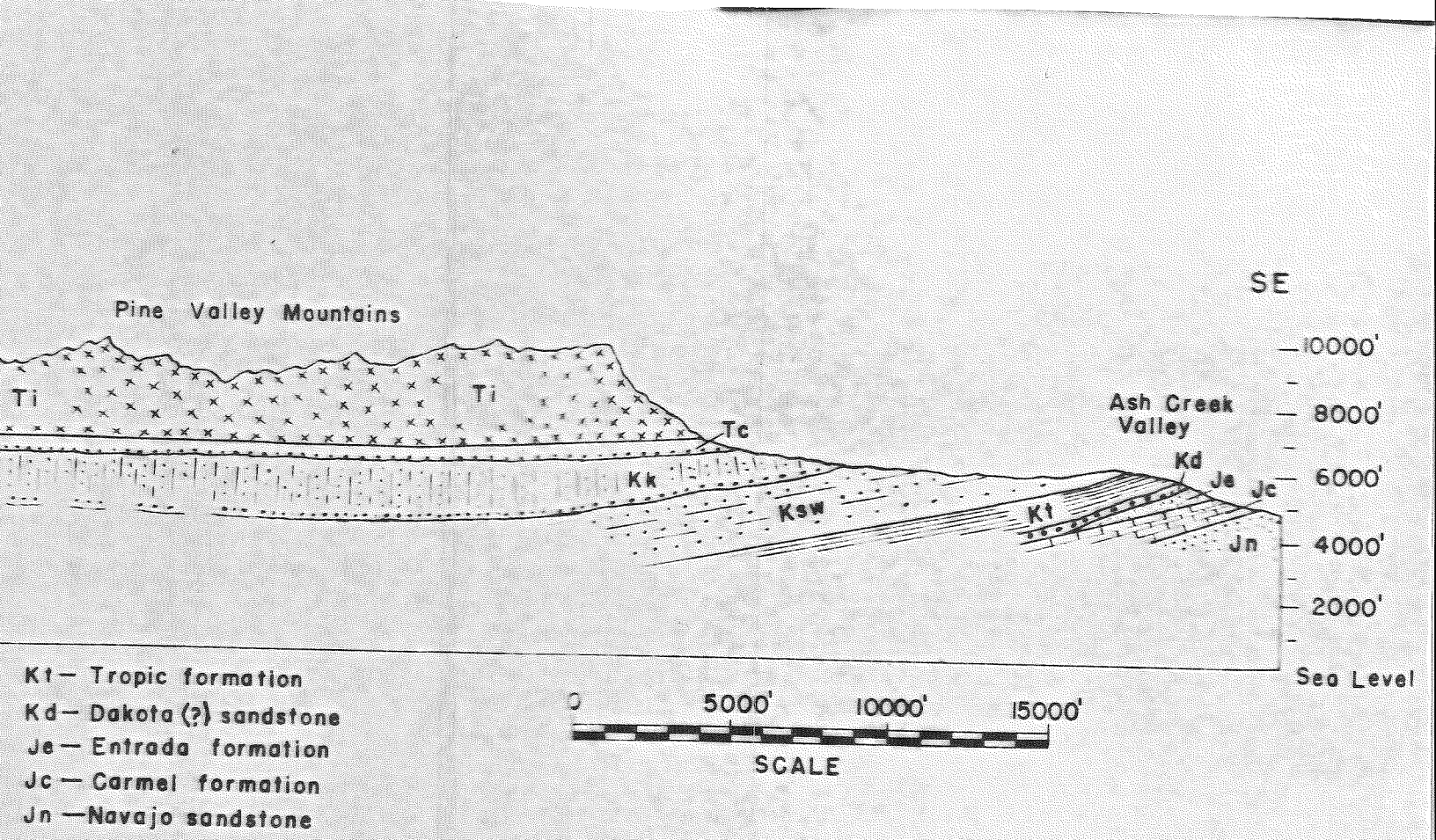


FIG. 87-SECTION THROUGH PINE VALLEY LACCOLITH

downward increase in density from 2.62 to 2.72, with an abrupt decrease in the basal part of the intrusion. This picture is modified by a low-density indentation of the curves in the "white zone" and two high-density bulges, one above, the other below the "white zone".

The porosity curve shows a maximum porosity of four per cent in the two lower zones, increasing to a maximum of nine per cent in the "white zone", decreasing abruptly to two or three per cent in the lower part of the "purple zone", then increasing irregularly upward.

In seeking an explanation of the zoning in the Pine Valley laccolith, four possibilities must be considered:

(1) separate intrusions;

(2) differentiation within a single intrusion;

(3) differential deuteric alteration;

(4) some combination of the above.

The first possibility, that the zoning is due to separate and distinct intrusions, is eliminated by the absence of intrusive contacts within the body; all zonal "contacts" are gradational. However, the possibility still remains that some of the zoning may represent original magmatic differences in the intrusion, from level to level, and that these may be related to pulses within the period of emplacement. The origin of the zoning involves this question, and differentiation, and deuteric alteration; the actual problem is the evaluation of

the relative importance of these factors. Much more work is needed for a definitive answer. The discussion to follow merely outlines what seem to be the most likely hypothesis at this stage in the study.

Except for the irregularities associated with the white zone, the density curves appear to represent a single intrusion in which a progressive increase in specific gravity, from near the top to near the bottom, took place before consolidation. The intratelluric phenocrysts show that the magma must have moved in as a mush, already partially crystallized. This, plus the simplicity of the mineral suite throughout the laccolith, rules out immiscible liquid separation as a means of differentiation. Settling of heavier crystals due to gravity, aided perhaps by convection currents, appears to explain the major portion of the density curve. Estimated mafic content, based upon thin-section examination, varies more or less directly with the specific gravity--except in two parts of the body: in the basal dark brown zone, and at the base of the purple zone.

In the dark brown zone, the percentage of mafic minerals increases toward the base, but the specific gravity falls. Inasmuch as there is comparatively little deuteric alteration in specimens from the base of the zone, but much alteration in rock from the upper part of the zone, it appears that the upper part of the zone remained fluid after the basal

portion solidified. The concentration of mafic minerals (principally augite and hypersthene) on the laccolith floor shows that some gravitative settling of the heavier crystals took place during and shortly after intrusion and that the basal rind was probably not "quenched", although it did solidify before much deuteric alteration could take place. That the upper part of the dark brown zone now has a greater specific gravity despite a lower percentage of mafic minerals appears to be due to a higher content of magnetite, most of which is distributed in fine grains throughout the groundmass. This magnetite is probably primary and, because of its fine grain size, was able to sift down through the crystal mesh of the partially liquid magma and concentrate in a layer above the solidified basal portion of the laccolith. A possible indication that the intratelluric mafics, because of their large size, found it difficult to settle through the crystal mesh is the concentration of mafics near the top of the brown zone, with a resulting upward increase of density in this portion of the laccolith. That this is not a unique situation is shown by the upward increase in density in the lower part of the Shonkin Sag laccolith, Montana (Barksdale, 1937, p. 341) which was interpreted by Hurlbut (1939, pp. 1109-1110) as due to close packing of crystals settling from above.

The relatively thin white zone has both the lowest mafic content and the greatest deuteric alteration of any zone in the

laccolith. Apparently this zone remained molten longer and most of the mafic crystals settled out into the upper part of the brown zone. The settling-out of heavy minerals from the white zone may have been facilitated by decreasing viscosity of the remaining liquid due to enrichment in volatiles. This concentration of volatiles and the resulting high pressure would probably, as Barksdale points out, writing of Shonkin Sag (1952, pp. 714, 716), "temporarily offset the effect of temperature drop" and the residual liquid might be present for a long period. The entrapped volatiles probably account for the high porosity of the white zone as well as for the occurrence of magnetite along cracks, both in the groundmass and in phenocrysts. This magnetite, because of its occurrence in cross-cutting veinlets, must have been mobilized after consolidation of the white zone. The occurrence of such veinlets is confined to the white zone and adjacent portions of the purple zone above and the brown zone below. Destruction of mafics and resultant bleaching of the rock is much more pronounced in the white zone than in the lower portion of the purple zone or the upper part of the brown zone; consequently, the veinlets of magnetite in these layers adjacent to the white zone seem to indicate an addition derived from the white zone, possibly propelled outward from that zone by high vapor pressure. Release of iron by deuteric decay of mafics in a similar rock has been demonstrated by Mackin (1947, p. 45;

also Mackin and Nelson, 1948, p. 1339) in the Iron Springs district.

Concentration of mafics settled from the white zone and addition of some late-stage deuteric magnetite from that zone accounts for the bulge in the density curve at the top of the brown zone. The upward migration of magnetite from the white zone provides at least a partial explanation of the density curve bulge at the base of the purple zone. On the other hand, this density bulge seems to be in part due to an increase in mafic percentage; no explanation of this anomaly is known at present. In fact, the general downward increase in density within the purple zone is anomalous when compared with the density curves of the Shonkin Sag laccolith (Barksdale, 1937, p. 341) which is regarded as a classic example of gravity differentiation. A partial answer may be that the purple zone of the Pine Valley laccolith consolidated more rapidly, after some initial differential settling of the heavy minerals, than the analogous zone (upper shonkinite) at Shonkin Sag, thus preserving a normal downward increase in density; at Shonkin Sag, on the other hand, slow downward consolidation of the upper layer allowed progressive impoverishment in heavy minerals of the still molten portion of the layer.

Although the upper boundary of the white zone is a sharp color break, no evidence was found of the auto-injection which is a feature of similar horizons in the Shonkin Sag

(Hurlbut, 1939, p. 1110; Barksdale, 1952, p. 706) and in the Three Peaks laccolith of the Iron Springs district (Mackin, 1947, p. 21). Selvaged joints, one-half to one-third of which carry crusts and veins of magnetite, are prominent in the Iron Springs laccoliths (Mackin, 1947, pp. 22-25) and are believed by Mackin (1947, p. 60) to have provided channels for the outward migration of magnetite deuterically released from the rock adjacent to the joints. No such selvaged joints were found in the Pine Valley laccolith. They may have existed in the now-eroded portion of the body, but they did not extend into the white zone; therefore, deuterically released magnetite from this zone, although possibly in a gas phase under great pressure, was largely unable to escape and was redeposited in microfractures within the white zone and the immediately adjacent portions of the overlying and underlying zones. Mackin indicates (1947, p. 61) that a late intrusive surge which produced fractures and displacements on earlier bulges and faults appears to have been a critical factor in the origin and migration of iron-rich emanations in the Iron Springs laccoliths. The Pine Valley body appears to have been a flat, tabular intrusion without marginal bulges (at least, along the portion of the margin still available for inspection). Furthermore, there was apparently no late intrusive surge. Consequently, there was no great migration of iron compounds from any part of the laccolith now visible; the Pine Valley intrusion may have

been largely "wasted" magma (Mackin, 1947, p. 60).

In summary, the history of the Pine Valley intrusion is believed to be as follows: the intrusion moved in as a semi-liquid mass heavily charged with intratelluric crystals of plagioclase, augite, hypersthene, and biotite in a more acidic rest magma. After a short period of differential gravitative settling of these crystals, a basal rind solidified. In the remainder of the magma deuteric alteration of the mafic minerals occurred. The larger crystals by this time, due to increasing viscosity of the cooling mass, were probably incapable of further sorting, either by gravity or convection. Convection probably was never an important agent of differentiation in the body; Osborne and Roberts (1931, p. 350) point out that high viscosity in such a mass precludes convection and leaves crystal settling as the probable agent of differentiation.

During the end stages of consolidation deuteric alteration, although active throughout the whole intrusion, was concentrated in a relatively thin zone 1,200-1,600 feet above the base of the intrusion. This central rock represents the last portion of the mass to crystallize. Here the residual magma, enriched in volatiles, may have remained molten because of the rise in pressure. At any rate, a large part of the mafic minerals had settled out by the time the magma of the white zone finally crystallized. Upon consolidation, the entrapped

volatiles produced considerable porosity and caused some of the iron to migrate along minute cracks; some of this migrating iron was apparently sweated out of the white zone and re-deposited both above and below the zone.

The explanation for the color zones seems to lie mainly in varying mafic content of the rock, which in turn depends partly upon gravitative settling of the heavier minerals in the magma and partly upon the intensity of deuteric alteration of the original mafics. Secondary magnetite locally prevents a direct correlation of density with rock color; for example, secondary magnetite has a considerable effect on the bulgy portions of the density curves, but no effect on rock color.

Study of the early fracture patterns and flow structure throughout the Pine Valley laccolith would undoubtedly clarify the history of the intrusion, but were not felt to be important enough in a reconnaissance survey to warrant the great amount of time necessary to collect the data. Mackin's work in the Iron Springs district (1947), for example, shows that the direction of intrusion and shape of the top of the body can be inferred from study of joint patterns. In any extension of this work, heavy mineral separations and chemical analyses should be used to supplement the density curves and microscopic evidence.

The intrusive history was not studied in the other intrusions. Concentric zoning is a striking feature of the

eastern part of the Stoddard laccolith; the Stoddard exposures are excellent and a study of joint patterns, density, porosity, and heavy mineral variations within the body would be under no handicap other than available time. One of the problems on which a study of the Stoddard body might throw some light is: What controls the position of the end-stage magma, the residuum which produced the white zone of the Pine Valley laccolith? In the Pine Valley and Shonkin Sag laccoliths, for instance, the residual zone is located about midway between bottom and top of the body (if we infer that the top of the Pine Valley laccolith was not far above the present eroded surface); on the other hand, in a thick sill in western Oregon (Roberts, 1953, p. 46), the residual zone is just below the upper surface. In all three bodies, the zone is approximately horizontal. In the Stoddard body, however, the residual zone appears to be discontinuous and to parallel the steeply dipping upper surface of the laccolith, lying about 2,000 feet inside the periphery.

STRUCTURAL GEOLOGY

Structural Relations of Intrusive Bodies

Pine Valley laccolith

Evidence of intrusion

Earlier authors (Howell, 1875, p. 254; Dutton, 1882, Atlas Sheets II and XX; Dobbin, 1939, p. 121; Gardner, 1941, p. 259) have regarded the thick mass of igneous rock which forms the main bulk of the Pine Valley Mountains (Fig. 79) as extrusive. Three lines of evidence demonstrate that the igneous body is an intrusion. These lines of evidence are: (1) the absence of evidence of extrusion; (2) the intrusive nature of the basal contact; and (3) the intrusive fault character of the lateral contact of the body.

Within the great porphyritic body, 3,000 feet thick, no significant change in structure or lithology was noted, except for areas of deuteric alteration, and neither intrusive nor extrusive contacts were seen. There is no evidence of an erosion surface beneath the porphyry, such as might be expected had the rock been emplaced as a flow. The concentration of intratelluric crystals at the base of the body shows that even

See p 52 fig 66

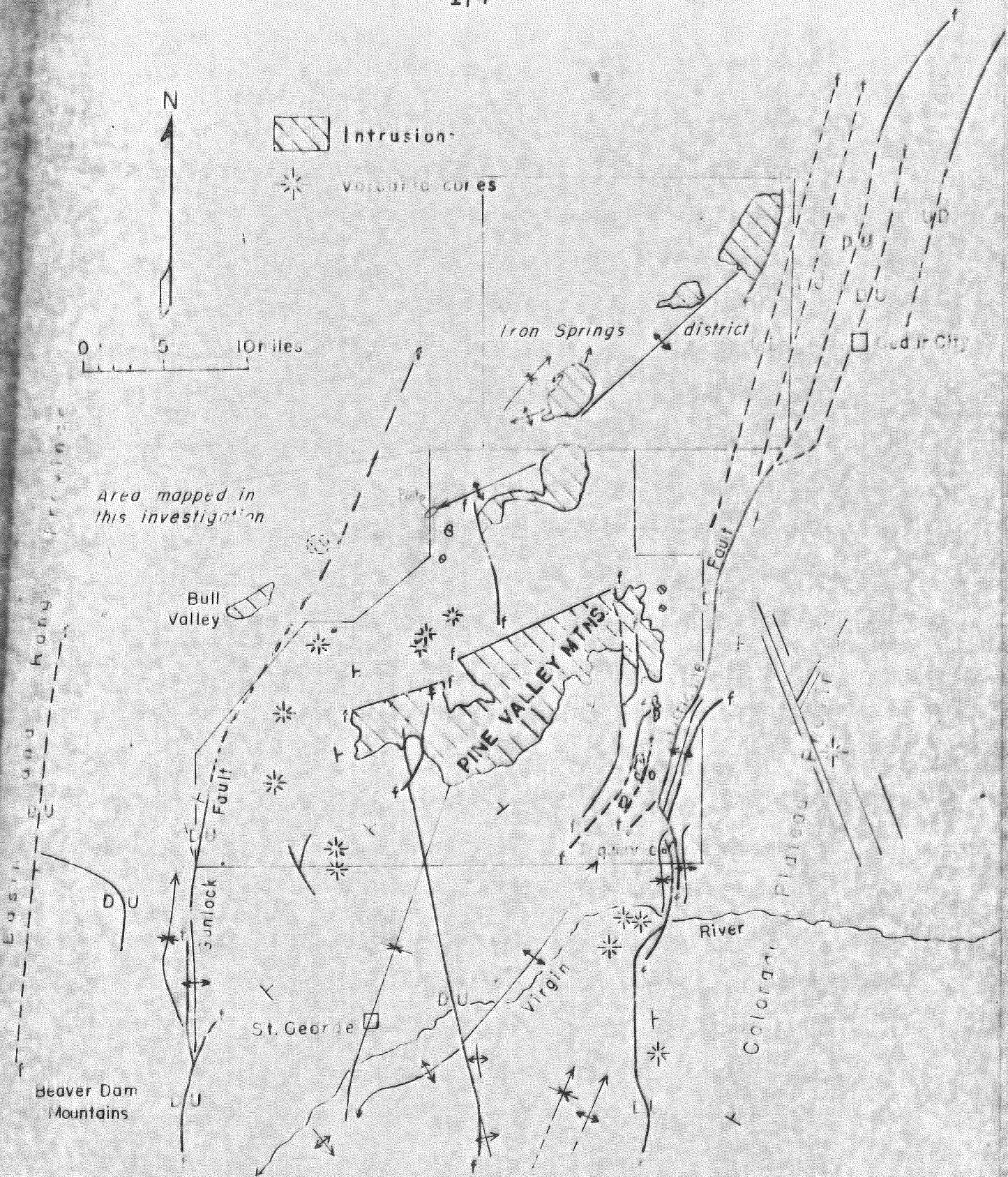


Fig. 79 SOME STRUCTURAL FEATURES OF THE PINE VALLEY MTNS. AND VICINITY

the lowest part of the mass was not quenched as it probably would have been had it flowed onto an erosion surface.

Although in general following one horizon, in detail the basal contact is far from planar; small, intricately branching, porphyritic apophyses reach into the limestone several inches away from the main contact. This irregularity, as well as the absence of glass, breccia, chalcedony, and erosion surface criteria, some of which normally accompany the basal contact of a flow, suggests that the contact is intrusive.

On the north and northwest, the Pine Valley monzonite porphyry is in intrusive fault contact with members of the volcanic sequence, from the Quichapa group to the "platy porphyry". The intrusive faults, of course, do not displace the underlying sediments; two places are known where the Claron formation can be seen to pass, unbroken and apparently unchanged in thickness, from a position beneath the laccolith to a position beneath the Quichapa group. These localities are: (1) on the north side of Pine Valley, northeast about one mile from the town of the same name; and (2) on the end of the west spur of the Pine Valley Mountains, about three miles southeast of Central. At the first locality, sharply upturned and brecciated rock of the Tv-1 and Tv-2 ignimbrites lies against the monzonite; at the second locality, the volcanics dip gently toward the intrusive, but the actual contact is obscured by talus and vegetation.

Where the monzonite porphyry lies against the remarkably similar "platy porphyry" the contact is difficult to map; it was determined largely by observation of the platy structure in the latite. It was found that outcrops showing this structure terminated southward along a straight line, marked in at least three places by springs; at several places along this line the platy structure shows that the latite has been folded and broken.

At a locality about two miles southwest of New Harmony, where the northern fault contact appears to dip under the intrusive body (Fig. 80), the platy structure in the latite dips gently away from the laccolith except within a few feet of the contact, where it becomes sharply upturned and broken (Figs. 81, 82). Locally near the contact the platy rock has been tightly folded (Fig. 83), as if it had been plastic at the time of intrusive faulting; however, there is recumbent folding elsewhere in the "platy porphyry" not related to intrusion and thus the structure mentioned here may not have been caused by intrusion. A tightly cemented breccia containing porphyritic black glassy blocks forms a south-dipping ridge along part of the contact (Fig. 84); it may represent an overturned portion of the basal glass (Tv-8a) of the platy latite.

In one outcrop along the contact a few sandstone fragments and smashed quartzite boulders were found in the platy latite (Fig. 81). These are the only lithic fragments

extensive outcrop which today should be indicated by outliers. If we assume that the platy latite was once 3,000 feet thick, the estimated thickness of cover would be about 4,500 feet, for there is about 1,500 feet of volcanic rocks exposed between the top of the Claron and the base of the platy latite along the northern contact of the laccolith.

This reasoning has been outlined to indicate that the cover may have been several thousand feet thick.

Date of intrusion

The Pine Valley intrusion post-dates all the acidic extrusives of the area, except perhaps the Guide Meridian volcanics with which it is not in contact. The laccolith is probably more or less contemporaneous with the platy porphyry. The platy porphyry is likely closer in age to the underlying rocks than to the Pliocene(?) and Quaternary rocks which locally overlie it, because the unconformity beneath the latite is less pronounced than the one above and because of the occurrence of Claron-type limestone at or near the base of the latite. Although there exists no basis for definite dating of the volcanics, it seems probable that most of the volcanic sequence is early Tertiary and that the platy porphyry and the Pine Valley intrusion are either early or middle Tertiary in age.

Stoddard laccolith

The exposed part of the Stoddard laccolith is a dissected dome-shaped mountain (Fig. 86) of nearly circular plan (see geologic map, Sheet 2). Except on the south where it has apparently intruded the lower parts of the volcanic sequence the Stoddard body is in more or less concordant contact with sharply upturned and overturned shales and sandstones of the Upper Cretaceous Tropic formation. The base of the body does not outcrop and the laccolithic form is inferred from the generally concordant upper contact.

Core-drilling in the anticlinal valley west of Stoddard Mountain has revealed monzonite porphyry of Stoddard type at a depth of less than 600 feet below the surface. The overlying rocks appear to represent the Tropic formation. This evidence strongly suggests that anticline is an intrusive structure, overlying a westward extension of the Stoddard intrusion. The small, discordant, Pinto Peak intrusion, on the south side of the anticlinal valley, is probably connected at a depth to the large Stoddard intrusion.

Cores from the drill-holes show a sharp contact between the intrusive rock and the overlying sediments, and a striking lack of change in either rock near the contact (Fig. 88). These are characteristic features of the intrusive contacts of the region.

Structure around Stoddard laccolith outcrop

The Upper Cretaceous rocks around the outcrop of the Stoddard laccolith are sharply upturned, locally overturned and complexly faulted. The most complicated structure is exposed in Pace Canyon, east of the laccolith. In this area, a thick Claron section, tightly folded, steeply dipping and faulted, is apparently truncated by the overlying Quichapa group. Whether the contact is an unconformity representing disturbance in post-Claron, pre-Quichapa time, or is a flat thrust fault, is not definitely known. However, the basal portion of the Quichapa group in Pace Canyon is much brecciated, suggesting that the contact is a fault.

Paradise intrusive body

The intrusion whose base and top are both exposed in the area called Paradise appears to be an offshoot of the Stoddard laccolith, a satellite which sprang from the discordant southern portion of the main Stoddard body and intruded along a horizon within the Rencher formation. The Paradise intrusion is confined to a structural basin developed on the south flank of the Stoddard-Pinto intrusive anticline. It is limited on the west by a high-angle fault which apparently formed a barrier to further westward movement of magma. The bowl shape of the Paradise intrusion is the classic laccolith form inverted.

The Paradise body intruded at the highest stratigraphic

horizon of any of the intrusions of the area, and thus probably had the least cover. As indicated on the geologic map (Sheet 2), the major part of the Rencher formation and the entire Atchinson formation appear to be missing in the Paradise area. The Paradise intrusion is overlain directly by bedded tuff-breccia of the Page Ranch formation and by the "platy porphyry". The upper part of the Page Ranch formation also is missing. There appear to have been two periods of non-deposition or erosion in the Paradise area, whose effect was to considerably reduce the thickness of the volcanic sequence above the basal part of Rencher formation. The "platy porphyry" appears to have been the main part of the cover of the Paradise intrusion; the thickness of this cover is a matter of conjecture, but it seems hardly probable that it exceeded 2,000-3,000 feet.

Pinto Peak intrusive body

As previously mentioned, the intrusive porphyry which outcrops northeast of Pinto Peak is probably a discordant projection of the greater Stoddard intrusive body. The Pinto Peak porphyry has intruded across the Claron formation and into the Quichapa group volcanics.

The Dairy intrusive body

From The Dairy to Pinto, Pinto Creek follows an anticlinal valley transverse to the Stoddard-Pinto anticline. Just

south of The Dairy, where this anticline plunges southward beneath a thick volcanic sequence, is a small (about 40 acres) area of intrusive porphyry which appears to be part of a much larger body underlying the anticlinal valley and, possibly, connecting with the Stoddard intrusive.

Tectonic Structures

Structural setting

In southwestern Utah the transition from Colorado Plateau structure on the east to Basin Range structure on the west is accomplished largely within a fault block lying west of the Hurricane fault (Fig. 79). In this block, a segment of which was mapped during the present investigation, are several intrusive masses injected into moderately folded and block-faulted sedimentary and volcanic rocks. The largest of these intrusions is the Pine Valley laccolith.

The western part of the Colorado Plateau province is a group of high plateaus cut in flat-lying sedimentary rocks. These plateaus, descending in great steps toward the south, are cut by a few long northerly trending faults. Dutton, Gilbert, Marvine, Davis, Huntington and Goldthwait, all speak of the fact that the great faults of the plateau region, which at present determine the major features of the topography, follow the lines of older monoclinal flextures that dip east.

The eastern part of the Basin and Range province,

inadequately mapped except in a few localities, appears to be characterized by thrust faults--some of which were active in the Cenozoic era--and steeply tilted fault blocks.

The transition zone apparently has no post-Laramide thrusts, and folding and tilting are moderate; thus it differs from the Basin and Range province. On the other hand, the transition zone contains asymmetrical and even overturned and thrust-faulted Laramide anticlines, which the plateau province does not.

Two structural trends intersect in the Pine Valley Mountains segment of transition area (Fig. 79). A well-defined set of structures, developed during the Laramide orogeny in an older zone of demarcation between foreland to the east and geosyncline to the west, trends northeasterly and is shown by aligned intrusions, folds, and faults; the second, developed during the Tertiary, is expressed principally by north-south faults. The later movements in the area have followed both structural trends; an example is the Hurricane fault, which follows a Laramide anticline for part of its length, then leaves the Laramide structure abruptly to take the Tertiary trend southward into Arizona.

The major structural features of the transition zone are the broad shallow syncline in which the Pine Valley laccolith rests, two Laramide anticlines broken and obscured by faults (except for the Virgin anticline which is a

twenty-mile segment of one of these two folds), several laccolithic intrusive bodies with outcrops smaller than the 70 square miles of the Pine Valley laccolith, and a number of steeply dipping faults, several of which are closely grouped in the Hurricane fault zone.

A striking feature of the intrusive masses of the transition zone is their proclivity for following a stratigraphic horizon. The Three Peaks, Granite Mountain and Iron Mountain (all in the Iron Springs district) intruded along a single horizon in the Jurassic Carmel formation (Mackin, 1947a); the concordant contact of the Stoddard laccolith is near the base of the Upper Cretaceous section; and the Pine Valley intrusion moved in at or near the top of the Upper Cretaceous(?) -Eocene Claron formation.

The Pine Valley segment of the transition zone is bounded on the west by the Gunlock and Veyo faults and on the east by the Hurricane fault. The Hurricane is actually a fault zone up to five miles wide paralleling a truncated Laramide anticline which was overlain unconformably by Tertiary sediments and volcanics before the development of the present belt of steeply dipping parallel faults which slice the rocks into long, narrow fault blocks (Fig. 90).

Hurricane fault zone

Description

The Hurricane fault, which forms the eastern boundary

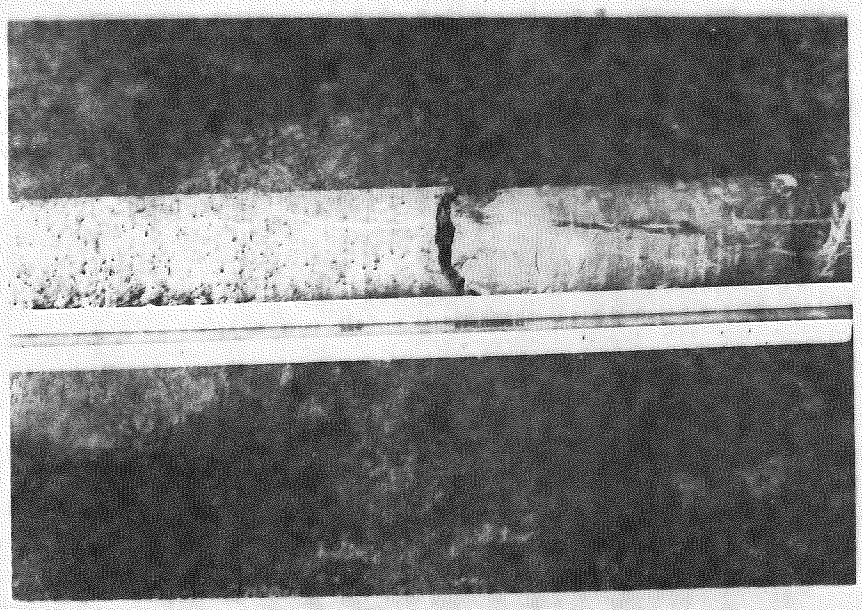


Fig. 88 Portion of core from Dixon No. 1 drill-hole, about three miles southwest of Page Ranch. Core broke along contact of intrusive monzonite porphyry with calcareous shale of the Tropic formation. Note secondary calcite in both rocks.

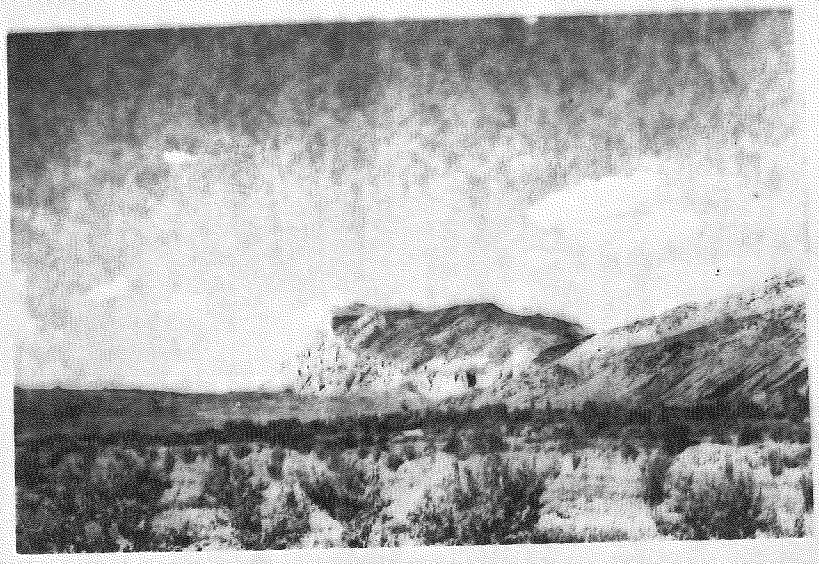
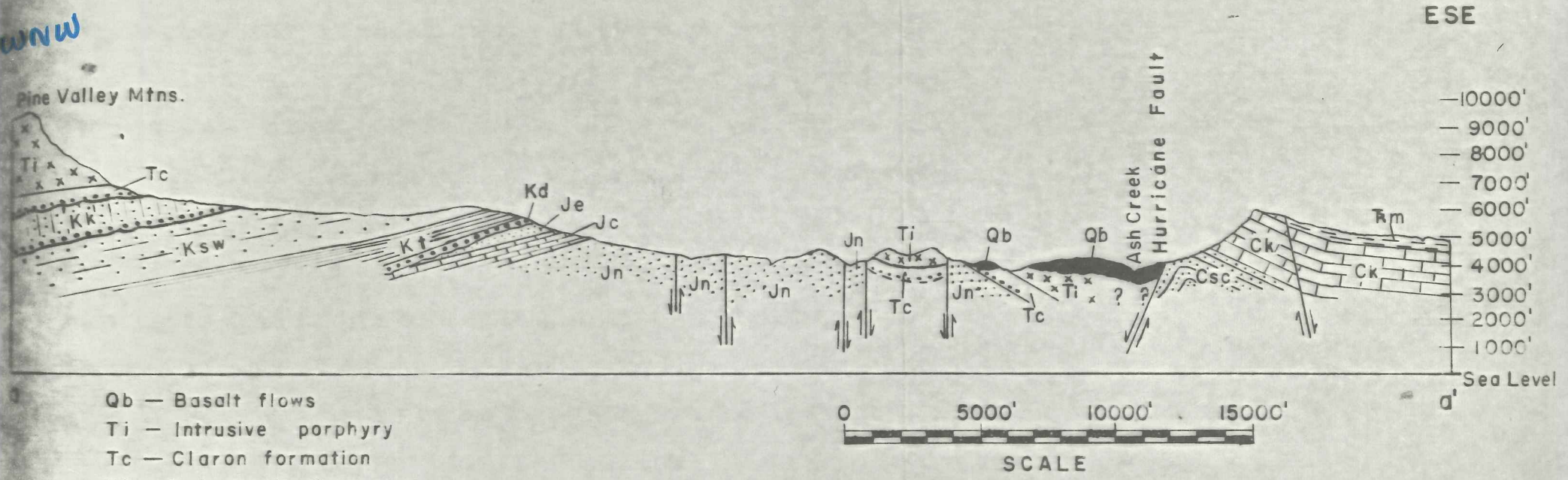


Fig. 89 Hurricane ledge north of Toquerville. Louderbacks of horizontal basalt resting on east-dipping sedimentary beds. The Hurricane fault turns the "corner" shown in the middle distance and cuts across part of a Laramide fold.

195 - Fig. 90



Qb — Basalt flows
Ti — Intrusive porphyry
Tc — Claron formation
Kk — Kaiparowits formation
Ksw — Straight Cliffs and Wahweap sandstones
Kt — Tropic formation
Kd — Dakota(?) sandstone
Je — Entrada formation
Jc — Carmel formation
Jn — Navajo sandstone

Trm — Moenkopi formation
Ck — Kaibab limestone
Csc — Coconino(?) sandstone

Fig. 90 — SECTION ACROSS ASH CREEK VALLEY SHOWING HURRICANE FAULT ZONE

of the southwest Utah structural transition zone, is marked by a high, west-facing escarpment, known as the Hurricane Ledge or the Hurricane Cliffs. Gardner (1952, p. 16) summarizes the evidence that this is a true fault scarp. Huntington and Goldthwait (1904) showed that the most recent displacement, so strikingly evidenced by the horizontal basalt remnants (louderbacks) on the upthrown side (Figs. 89, 91), represents the lesser of two periods of faulting which were separated by a long inter-fault erosion cycle.

North of Anderson Ranch the Hurricane escarpment is over 1,500 feet high; the exposed Permian and Triassic beds in the upthrown block dip eastward, away from the scarp, steeply at first, then flatten out in the valley of LaVerkin Creek, east of which the beds are horizontal (Fig. 92). For several miles the frontal portion of the ledge is an asymmetrical anticline. Northward, the east dip of the beds forming the backslope of the ledge continues to increase; in the vicinity of Kanarraville (about ten miles northeast of New Harmony) these beds are overturned. Gregory and Williams (1947) regard these east-dipping strata in the Hurricane Cliffs as the east flank of an asymmetrical, locally overturned, Laramide anticline, along which the Hurricane fault later formed, more or less parallel to the axial plane; they named this ancestral Hurricane anticline the Kanarra fold.

About a mile northeast of Anderson Ranch the Hurricane

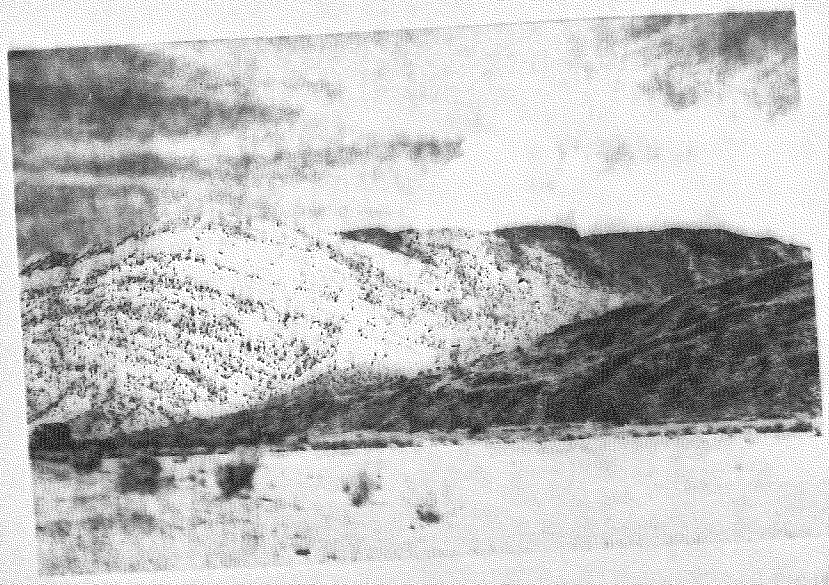


Fig. 91 Hurricane Ledge near Anderson Ranch. The louder-backs on the skyline are probably displaced portions of the basalt in the right foreground. The two fault scarps shown here represent the two dominant structural trends of the area.

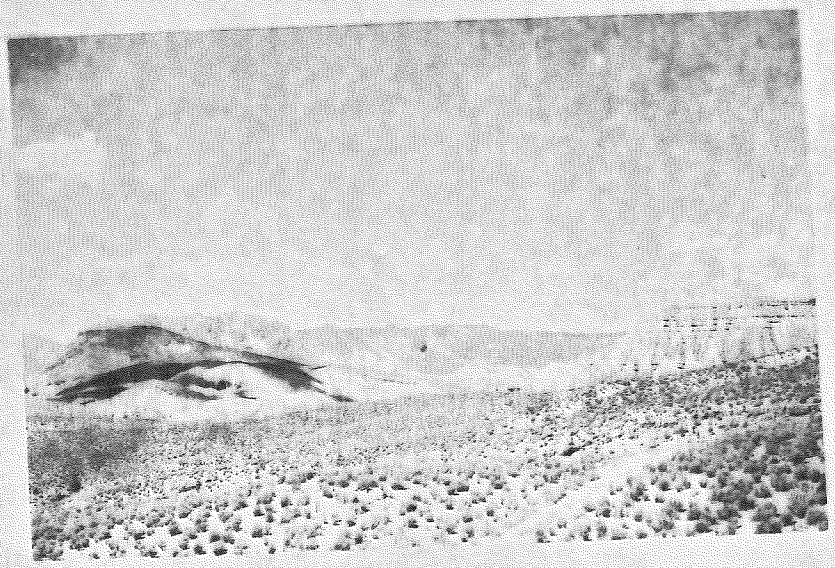


Fig. 92 The backslope of the Hurricane Ledge. Looking north, up the valley of LaVerkin Creek.

Ledge forms a massive corner (Fig. 91), caused by an abrupt change in direction of the Hurricane fault. After following the Laramide fold southwesterly for many miles, the fault veers to the south and cuts across this structure. Southward from this corner the ledge is lower and less well-defined. As might be expected, at the corner there is a southward projection of the Laramide trend in a fault which forms a low scarp just east of Anderson Ranch (Fig. 91).

The rocks of the downthrown side are, in most places along the fault trace, concealed by alluvium and hillwash. In the hill east of Toquerville, Triassic rocks and overlying basalt dip steeply west, away from the fault. A few miles south of Toquerville the Virgin River crosses the fault and Moenkopie beds can be seen in the downthrown block, also dipping steeply away from the fault. In both localities, as well as near the base of the Ledge east of Pintura, portions of the fault plane (or one of the fault planes in a fault zone) can be seen. The dip, as seen in these three localities, ranges from 60 to 75 degrees west.

In the Pintura area the Claron formation, on the downthrown side, dips toward the fault at angles of 30 to 40 degrees. There is no evidence, however, that the formations which underlie the Claron in this vicinity also dip toward the fault as shown by Gardner in his structure section across Ash Creek Valley (1952, p. 19).

North of the Anderson Ranch "corner", a belt about five miles wide of northerly trending high-angle faults and minor cross-faults lies west of the Hurricane Ledge. This fault zone can be traced southwesterly into the Silver Reef district, where it dies out. It extends northward through the Harmony Hills into Cedar City Valley and beyond. Of the several faults which make up this zone in Ash Creek Valley, only one, the easternmost, turns at the "corner" and heads south past Toquerville.

History of the Hurricane zone

Huntington and Goldthwait (1904; 1905) as well as Gardner (1941; 1952) have discussed in detail the evolution of the Hurricane fault.

Huntington and Goldthwait mapped the Tertiary and Mesozoic sedimentary rocks west of Ash Creek Valley as a conformable sequence folded into a large anticline. They separated the Navajo sandstone into two units on the basis of a color change and recognized the upper, white unit on both sides of what they thought was an anticlinal axis, because of the obvious reversal of dip in the overlying Tertiary (Claron) sediments. In 1951 geologists of the Sun Oil Company, after two weeks of plane-table mapping in the area west of Pintura, also decided to accept the color break in the Navajo as a structural criterion. Huntington and Goldthwait believed that two

Laramide anticlines had formed in the Ash Creek Valley area, the more easterly of the two being the more compressed and later breaking to form the Hurricane fault.

Gardner correctly mapped the angular unconformity between the Claron and the underlying Mesozoic rocks, but also believed that two anticlines had formed in this area in the late Cretaceous or early Eocene. His restored cross-section (1952, p. 19) shows a broad western anticline (the Pintura fold) and a more compressed eastern anticline (the Kanarra fold of Gregory and Williams).

Close examination of the map published by Gardner or of the map in this thesis will reveal no data from which two folds can be inferred across Ash Creek Valley. The Pintura fold, as a Laramide structure, probably does not exist.

If the Navajo sandstone had normal bedding the question would have long since been settled; but the Navajo cross-bedding is useless in determining the attitude of the formation. However, the attitude of the contact between the Navajo and the overlying Carmel formation can be used. The easternmost exposure of this contact in the area under discussion is in the Leap Creek drainage, about three miles northwest of Pintura. In this locality the exposures are excellent and there is no question about the structural relations: The Navajo-Carmel contact dips 10 to 15 degrees northwest and is truncated by the base of the Claron formation, dipping 35 degrees

east (see geologic map, Sheet 2). Not only is there no reversal of dip on the Navajo-Carmel contact, but when its pre-Claron attitude is restored by rotating 35 degrees to the west, it is found that the dip here after the Laramide folding must have been about 45 degrees west--in a spot through which the crest of the Laramide Pintura fold is supposed to have passed.

West of the Hurricane scarp, in the Pintura area, there are no outcrops of east-dipping pre-Claron formations--unless the color change in the Navajo does represent a stratigraphic horizon. Gregory, who may have looked at more Navajo than any living geologist, has this to say about the Navajo color break (1950b, pp. 87-8):

> ....the boundary between these great expanses of red and white has no definite position....Local changes in color are even more conspicuous. Most of the cliff and flat-land outcrops display sheets, patches, and circular dots of one color above, below, or side by side with those of another color....Regional surveys and detailed observations show that the color of the Navajo has no stratigraphic significance....Though in many places the planes that separate colors are horizontal, they rarely conform to the bedding.

The evidence supports the postulate of but one Laramide anticline across Ash Creek Valley, the axis of which was about the line of the present Hurricane fault. The Virgin anticline is regarded as a southward extension of this fold. When one stands on the Harrisburg dome of the Virgin anticline and looks northeast along the axis of that structure to the Hurricane

ledge, the east-dipping beds in the ledge are seen to represent the broken and uplifted east flank of the Virgin anticline.

Tertiary folding, perhaps contemporaneous with the intrusion of the Pine Valley laccolith, produced a broad anticline west of the Hurricane scarp and may even have reversed the dip of the truncated Mesozoic strata in the west limb of the Laramide Kanarra fold. If so, the axis of the fold in the Mesozoic rocks lies to the east of the axis in the Tertiary rocks.

The probable evolution of the Hurricane fault zone in the Pintura area is outlined in the four sections of Figs. 93 and 94.

Although in Section 2 of Fig. 93 the Laramide fold is shown as unbroken in Claron time, indirect evidence suggests that this fold may have broken into a reverse or thrust fault. In the Kanarraville area, for example, to get the present structural relations without Laramide thrust faulting would necessitate a tightly compressed, overturned anticline like that envisaged by Huntington and Goldthwait (1904, p. 233, Fig. 8). That this type of fold could develop at a shallow depth in a sequence containing the massive Navajo sandstone seems highly improbable. More likely, a fault like that pictured by Mackin in an analogous structural situation in the Iron Springs district (1947a, Fig. 4) developed along this ancestral Hurricane fold; unlike the Iron Springs example, the

ledge, the east-dipping beds in the ledge are seen to represent the broken and uplifted east flank of the Virgin anticline.

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Hurricane thrust involved the Navajo and subjacent rocks.

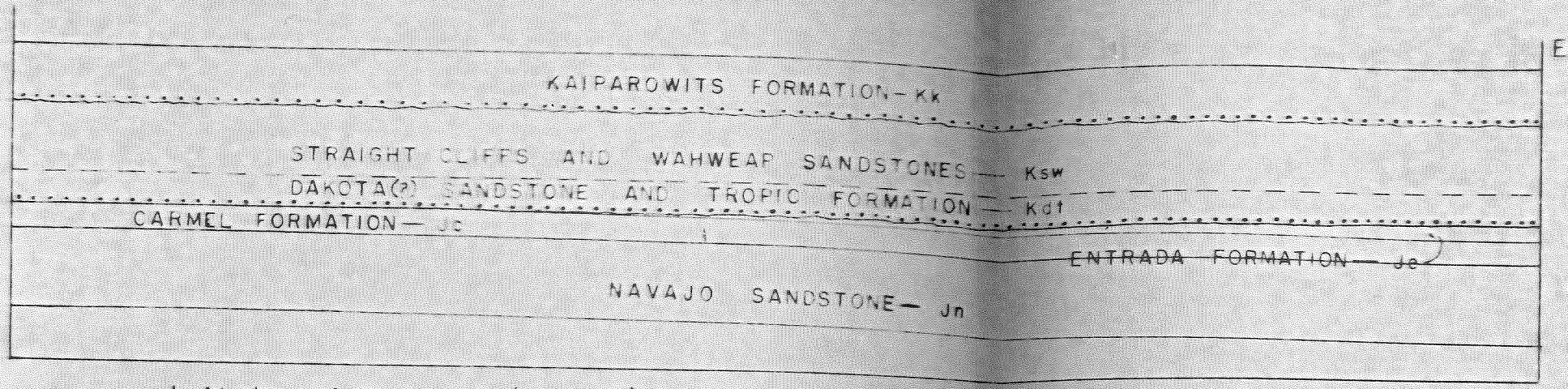
The Kanarra fold was planed off by erosion before deposition of the Claron formation (Section 2, Fig. 93). The normal movement on the Hurricane fault may have started with the post-Claron, pre-Quichapa disturbance, which produced the thick Leap Creek Claron section through repetition of beds by faulting and protection of the uppermost Claron beds from erosion.

Although small-scale displacements probably took place in the Hurricane zone during the extrusion of the Tertiary volcanics, the major displacement seems to have occurred contemporaneously with or shortly after the period of platy flow-rock extrusion and laccolithic intrusion (Section 3, Fig. 94). This conclusion is based on the following data:

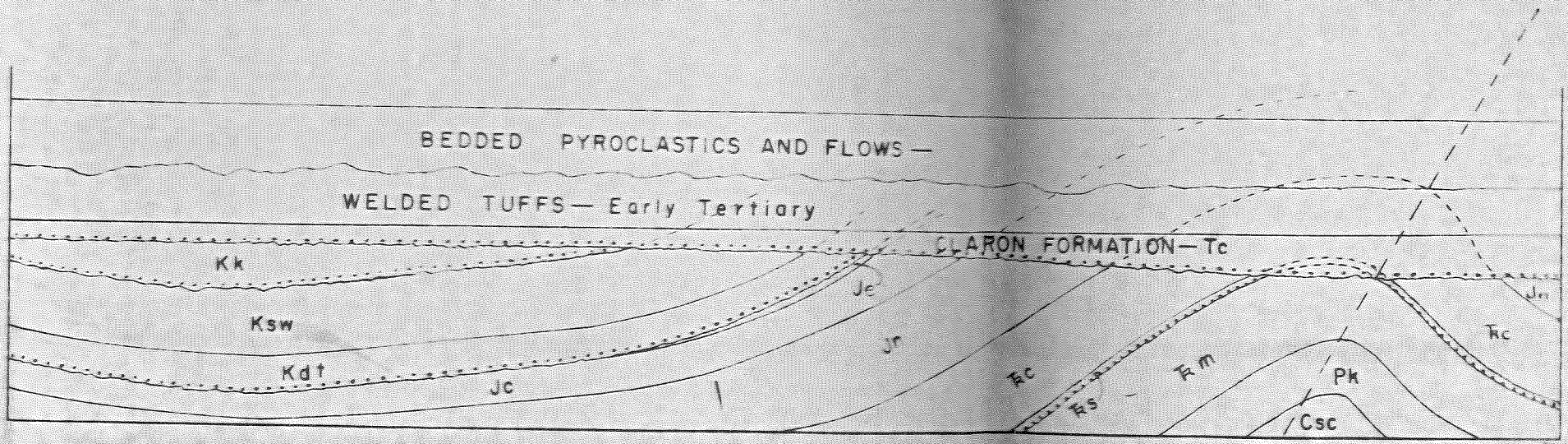
1. The base of the Pine Valley laccolith, even within the Hurricane fault zone, is concordant on the Claron and dips at an equally high angle toward the main fault.
2. The Tertiary tuffs are widespread on the Markagunt plateau northeast of the Pine Valley Mountains (Mackin, personal communication), but rock of the Pine Valley intrusive porphyry type has not been reported there.
3. The Pine Valley laccolith and the related platy flows represent the most recent large-scale

204 - Fig. 93

FIG. 93- RESTORED SECTIONS ACROSS ASH CREEK VALLEY



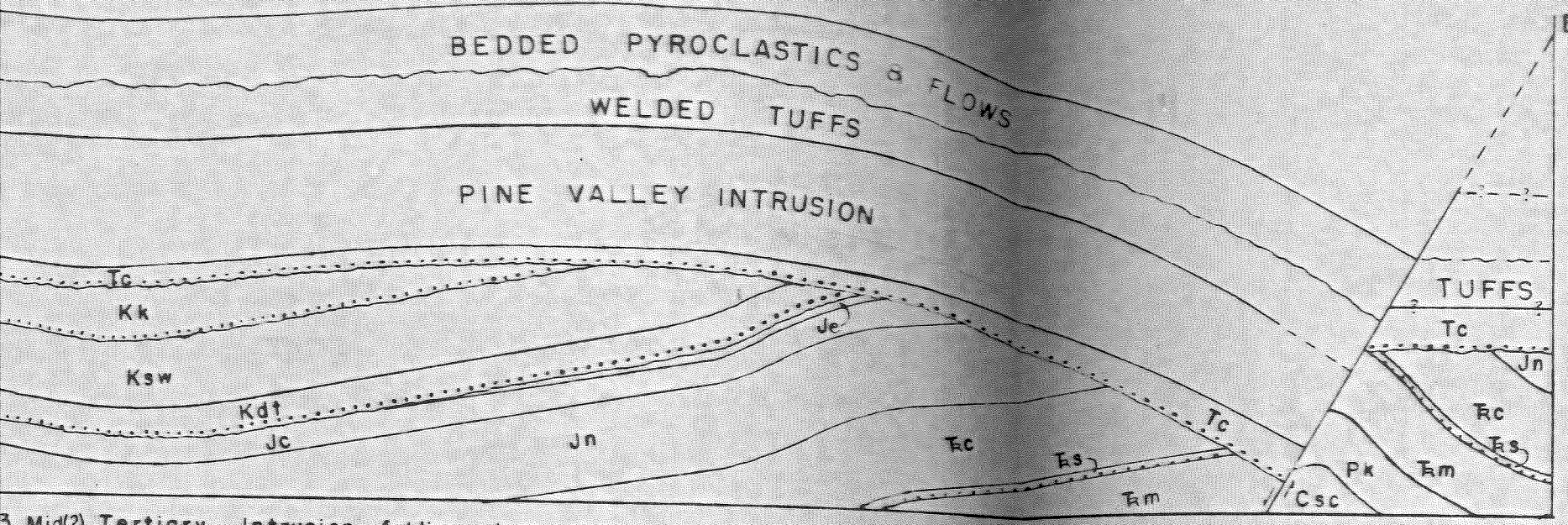
1. At close of Kaiparowits (Laramie?) time, before folding



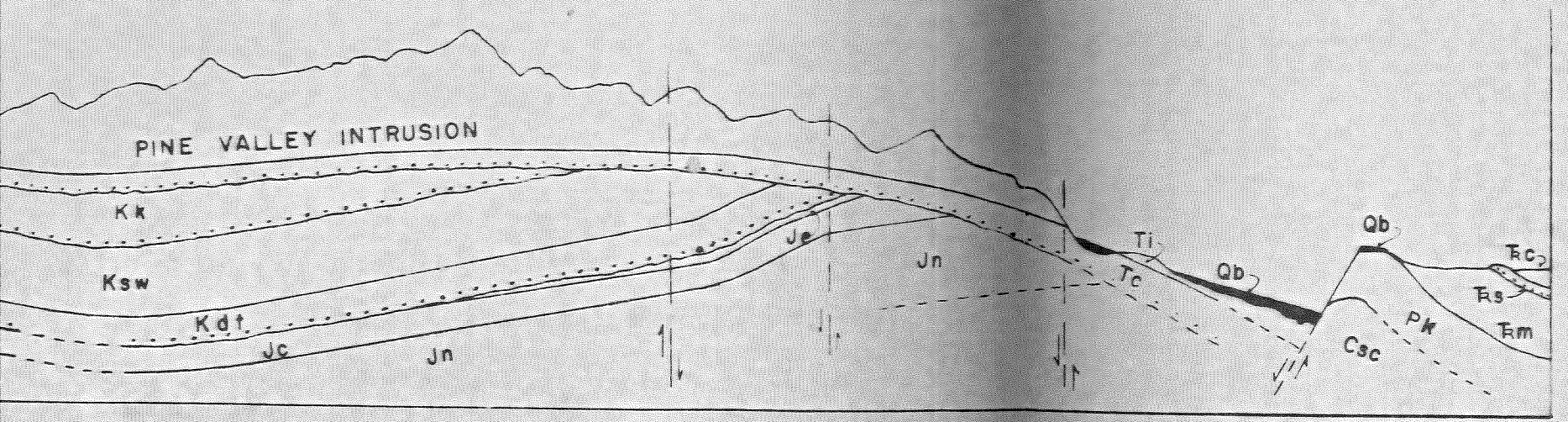
2. Early or Middle Tertiary, after beveling of Laramide folds and deposition of Claron plus volcanics.

FIG. 94- RESTORED SECTIONS ACROSS ASH CREEK VALLEY

205 - Fig. 94



3. Mid(?)-Tertiary. Intrusion, folding, development of Hurricane fault.



4. Present. Composite section with displacement and tilting along minor faults of the Hurricane zone not shown.

movement of magma from depth; the basalt flows, although widespread, represent considerably less magma.

From these facts, it may be inferred that the pyroclastic rocks spread far to the eastward across the trace of the Hurricane fault, whereas the later latite extrusion and monzonite intrusion were largely limited to an area west of the fault. Previous displacement on the main fault may have made it easier for magma to spread westward, even by intrusion, than to surmount a scarp or intrude under the thicker cover of the upthrown block. As suggested by Gardner (1941, p. 259) the pronounced sag to the east of the Claron formation in the Hurricane zone may be due to the removal of a vast amount of magma from beneath the zone; the occurrence of the Pine Valley laccolith and the consanguineous lava opposite the area where this sag is most pronounced seems to support Gardner's speculation.

Most of the minor faults of the Hurricane zone in Ash Creek Valley break and displace the intrusive porphyry. The virtual absence of scarps along these faults indicates that they originated before the later (post-basalt) Hurricane faulting.

Following this faulting the area, as Huntington and Goldthwait (1904) showed, was reduced to low relief by erosion. A low fault scarp remained on the resistant Kaibab limestone

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to have been formed at the same time as the late Hurricane movement.

Whether the earlier and greater Hurricane displacements occurred as normal or thrust movements cannot be conclusively determined in the Ash Creek Valley area. The locally sharp westward downbending of Kaibab strata in the upthrown block and the eastward upbending of Moenkopi and Shinarump beds in the downthrown block were produced mainly during the early faulting, for the basalt which is the indicator of the late faulting shows little bending near the fault (except in Toquerville Hill). If these westward-dipping bent strata parallel the early fault plane, the early movement must have been normal. On the other hand, the bending could presumably have been produced by thrust movement.

Displacement

The vertical displacement along the Hurricane fault is difficult to estimate because of the confusing effects of the Laramide structure, local drag folding, the "sag" of the downthrown block, and the absence on the upthrown side (near the fault) of the Claron formation.

At the three localities in or near the map area where rocks of the downthrown block beneath the alluvium and basalt can be seen in contact with the fault, these rocks are dipping steeply (60°-75°) west, paralleling the dip of the fault plane.

This is opposite to the in-dipping attitude recorded by early observers as more or less characteristic of the large faults of the region, but is similar to the attitude of the downthrown strata along most of the Sevier fault, the next large fracture to the east. In each of the three localities (at the Virgin River, in Toquerville Hill, and east of Pintura) the visible downthrown beds are of the Moenkopi formation and in each case they abut against Kaibab limestone on the upthrown side. The stratigraphic separation can most accurately be estimated in Toquerville Hill where the Shinarump conglomerate, capping the hill, is a stratigraphic marker on the downthrown side. The stratigraphic throw here is about 2,500 feet.

In the Pintura area, the effect of drag in the footwall block and sag in the downthrown block is to make the shift much greater than the slip. The shift in this area is estimated at 5,000 to 10,000 feet, whereas the slip along the main fault plane is not greater than 4,000 feet anywhere between the Virgin River and Cedar City--and probably averages close to 2,000 feet.

Pine Valley syncline

The Pine Valley laccolith rests in the broad, shallow northward-plunging Pine Valley syncline. Huntington and Goldthwait (1904) suggested that this syncline may have developed contemporaneously with the formation of the igneous rock.

However, the Cretaceous rocks immediately beneath the Claron formation appear to dip into the syncline at slightly greater angles than the Claron and the syncline disappears southward at about the same latitude at which the more or less parallel Virgin anticline dies out; these facts suggest that the Pine Valley syncline started as a Laramide downwarp which was further depressed during the intrusion of the Pine Valley laccolith.

Iron Springs Gap anticline

The Upper Cretaceous rocks, the Claron formation, and the Tv-1 ignimbrite all thin toward a northeast line bisecting the Stoddard laccolith (at least, the outcrop of the laccolith) and this line probably represents an extension of the Iron Springs Gap anticline, the name given by Mackin (personal communication) to an isoclinal Laramide fold in the Iron Springs district (Mackin, 1947a, p. 12). The Iron Springs Gap anticline was beveled by pre-Claron erosion (Mackin, 1947a, p. 12) as was the Kanarra fold. Evidence in the Iron Springs district suggests "slight renewed arching" in post-Claron time (Mackin, 1947a, p. 12); this post-Claron deformation may account for the thinning of the Claron (by erosion) and of the Tv-1 ignimbrite (by deposition over a ridge).

Gunlock-Veyo fault set

The western margin of the Pine Valley Mountains segment

of the transition block is marked by a set of en echelon, subparallel faults along which the Basin and Range country to the west has subsided. The main member of this fault set in the south is the Gunlock fault; northward, the Veyo fault, which starts out within the uplifted block, becomes the dominant and marginal fault. The Veyo fault is largely obscured by basalt flows.

The en echelon nature of the set is another expression of the intersecting structural trends of the area, the attempt by a Cenozoic structure to more or less conform to the older Laramide lines. Here, though, there was no Laramide anticline and the struggle between the two trends is not as clear-cut as in the Hurricane zone.

GEOMORPHOLOGY

Introduction

The general geomorphic history of southwestern Utah and the physiographic features and processes peculiar to the region have been adequately treated in previous publications (Powell, 1875; Dutton, 1880, 1882; Huntington and Goldthwait, 1904, 1905; Gregory, 1950b); consequently, the present discussion will be limited to physiographic features of the Pine Valley Mountains area which have a particular bearing on the geologic history of the area.

Evidence of Recent Vertical Movement

Huntington and Goldthwait (1904) concluded that the latest vertical movement of the transition block was upward, although not as great as the upward movement of the plateau country to the east. In other words, they visualized differential uplift of the plateau margin, the transition block rising above the Basin and Range country but lagging behind the main plateau. This conclusion was based on the combination of mature and youthful topography found in the transition block, a combination which to them represented the

mature topography of the Hurricane interfault cycle (during which their "Mohave peneplain" was developed over the Grand Canyon district) and the youthful topography of the present canyon cycle. They contrasted this combined youthful-mature landscape with the dominantly youthful topography of the plateau country, where the interfault topography has largely been destroyed as a consequence of great uplift. Dutton appears to have reached a similar conclusion, for he states (1880, p. 23) that "since the Eocene, the High Plateaus have risen from 10,000 to 12,000 feet, while the adjoining Basin areas have risen from 5,000 to 6,000."

Gardner (1941, p. 259), on the other hand, suggests that the most recent movement of this transition block has been downward, while the country to the east remained stationary. He bases this suggestion on the absence of important alluvial deposits, especially in Ash Creek Valley, such as characterize the Basin and Range country, as well as on the comparative youthfulness of Ash Creek Valley as compared to the valley of La Verkin Creek. Gardner apparently believes that the transition block was elevated above the Basin and Range country before the Miocene(?) Muddy Creek formation was deposited in the basins of that region and that, later, presumably in the Quaternary, the block sagged below the level of the plateau country. The sagging block was hinged to the Shivwits Plateau by the monoclinal flexure near the Arizona border.

Although the latest displacement along the Hurricane fault, ranging from zero near Mt. Trumbull in Arizona to 1,500 feet near Toquerville, shows that the transition block is a northward extension of the Shivwits which sagged relative to the upthrown block on the east (Gardner, 1952, p. 17), the evidence supports the conclusion of Huntington and Goldthwait that the apparent sag is a matter of differential uplift. The considerations which lead to this conclusion are as follows:

(1) The longitudinal profile of the Virgin River

This profile (Gregory, 1950b, p. 157) has two prominent oversteepened portions, one immediately east of the Grand Wash Cliffs, the other just east of the Hurricane Ledge. As the steep portion east of the Hurricane is obviously related to the recent displacement, so is the other steep stretch related to recent movement along the Grand Wash fault. Base-level for the Virgin River has presumably remained relatively stable during the Quaternary. Therefore the two abnormal sections of the profile record absolute differential uplift of the transition block and the plateau country. Had the transition block actually sagged, with the plateau block remaining stationary, as Gardner suggests, oversteepening in the Virgin profile east of the Hurricane Ledge would have started, but its development should have been arrested by

aggradation on the sagged block. Instead of aggrading its downthrown section, the Virgin has sawed a considerable gorge immediately west of the Hurricane Ledge. Furthermore, had absolute downward movement taken place, there should be no steepening of the Virgin profile near the Grand Wash Cliffs--unless the Basin and Range country subsided at the same time, an hypothesis disproven by the recent incision of the Virgin River hundreds of feet into old basin fill in its lower reaches.

(2) Dissected pediments During the Hurricane interfault cycle the Pine Valley area was not reduced to a peneplain. A fringing pediment was developed from which long narrow embayments sloped up toward the mountains between low spurs and hogback remnants. Pediment formation was interrupted by a period of aggradation, perhaps induced by climatic change. Boulder alluvium spread outward from the mountains and covered the pediment. Today, remnants of this pediment are found beneath a gravel veneer, a lava cap, or both. The pediment, which has been dissected to depths of about 200 feet by the present streams (Fig. 95), probably developed under conditions of semi-aridity. A climatic swing back to semi-aridity following the period of aggradation would merely have exhumed the pediment,

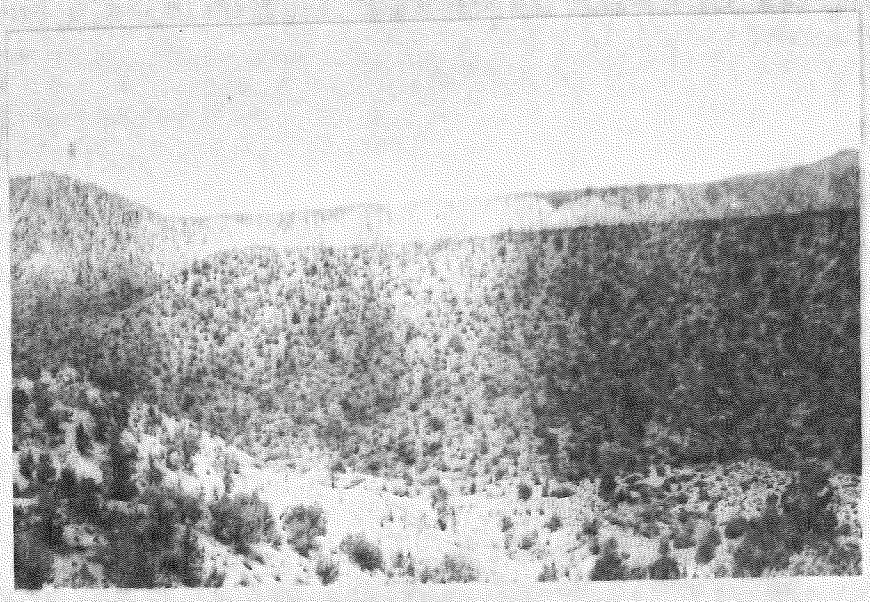


Fig. 95 Gravel-veneered pediment remnants on southeast side of Pine Valley Mountains. Present streams have cut 200 feet below the pediment, but in places are still flowing on it.

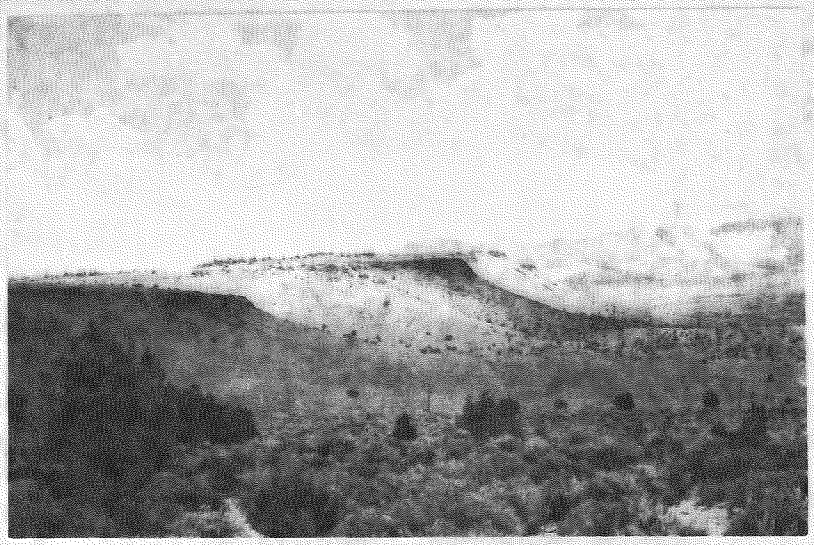


Fig. 96 Lava-capped ridge, representing old stream channel, elevated and preserved by differential erosion.

not dissected it. Base-level remaining stationary, uplift is indicated.

(3) Basalt flow levels Many of the later basalt flows came in thin ribbons down stream channels. With continued uplift, the sediments on both sides wore down faster than the sediments under the lava-protected channels, leaving sinuous lava-capped ridges (Fig. 96) above the present lowlands. In one locality near St. George and another near Veyo (Fig. 97) successive flows are found at successively lower elevations, recording continued erosion and intermittent extrusion. At the occurrence near St. George, which is in the lowest part of the transition block, the highest flow appears to have been poured out onto the mature surface of the Hurricane interfault cycle. The successively lower flows, most of which rest on bedrock, seem to indicate Quaternary uplift of the transition block. Had the block subsided, we would expect to find successive flows piled one upon the other or upon thick alluvium.

(4) Warped Bonneville shoreline Gilbert in his monograph on Lake Bonneville (1890, pp. 408, 415, 418) recorded the results of aneroid observations made along the supposed southern shore of that lake, immediately northwest of the Pine Valley Mountains. His data show that the shoreline was strongly upwarped toward the

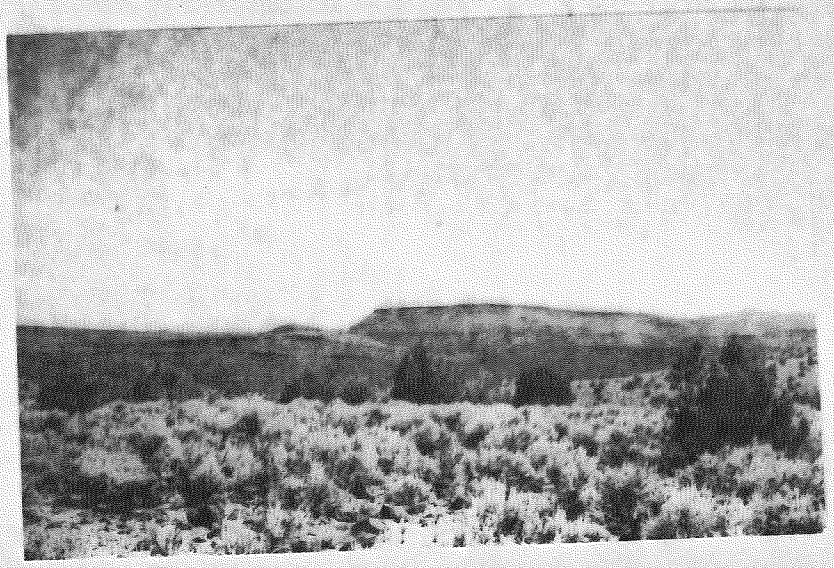


Fig. 97 Remnants of successive lava flows east of Veyo. The lower flows are younger and record continuing erosion.

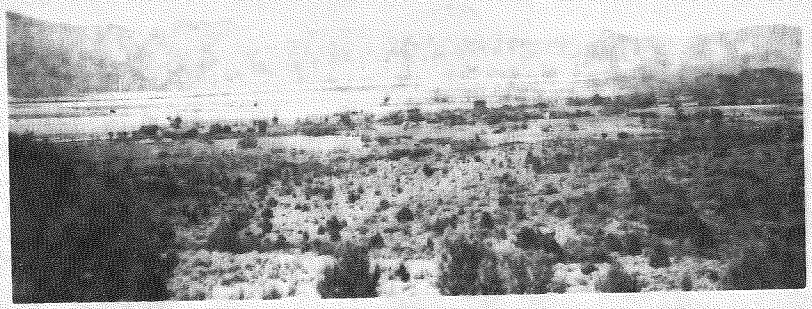


Fig. 98 Broad valley at the headwaters of Ash Creek, just south of Great Basin rim. Looking east toward Hurricane Ledge and Kolob Buttes from New Harmony.

south. Although it seems questionable that a Bonneville shoreline can be recognized in this area, the report agrees with the conclusion that the Quaternary vertical movement in the Pine Valley Mountains has been uplift, not subsidence.

Drainage Reversals Near Kanarraville

A cursory study of the Pliocene(?) to Recent sediments exposed in the vicinity of the low divide which, near Kanarraville, separates the Great Basin from the Colorado drainage, reveals evidence of drainage reversals, the significance of which is not known.

The Pliocene(?) Parunuweap(?) sediments in the wide valley east of New Harmony contain calcareous red sands and silts which appear to have come from the Harmony Hills to the north, where the exposed Claron formation is the nearest source of such material. The drainage then was southward. These sediments, laid down before the latest Hurricane displacement are overlain by boulder alluvium containing abundant boulders of Pine Valley porphyry. Similar material is found north of the present divide, at the east end of the Harmony Hills (Mackin, personal communication), indicating that the drainage was northward through this gap during the period of boulder aggradation (Pleistocene?), a reversal of Parunuweap(?) drainage. Today the drainage is again reversed, intermittent

streams flowing southward over a broad plain (Fig. 98) which is only beginning to be dissected as Ash Creek erodes headward into it.

Lack of Evidence of Glaciation

Because moraines are found at elevations as low as 8,500 feet in the plateau country to the east, some evidence of glaciation was expected in the higher parts of the Pine Valley Mountains. However, little or no evidence of glaciation was found. There are no cirques, no U-shaped valleys, and no definite moraines. A few low ridges of angular boulders extend down the steep west slope of Burger Peak, but these appear to be boulder streams formed under proglacial climatic conditions, and not morainal material.

Origin of Pine Valley

One of the results of Quaternary basalt extrusion was the formation of Pine Valley. The lava which flowed down the valley of the Santa Clara River above Central issued from a north-south fissure just west of the present settlement of Pine Valley. Over this fissure a long ridge of basalt was built up, which dammed the Santa Clara River. Sediments quickly filled the valley above the dam and a broad fertile plain was formed, in sharp contrast to the rugged, rocky country below the lava ridge. Grass Valley and Grassy Flat

were formed at the same time, because of the damming of smaller valleys by lava spreading from the north end of the ridge.

Cinder Cones

Low-lying areas around the southern part of the Pine Valley Mountains are surmounted, in a number of places, by cinder cones. The most recent are two in Diamond Valley (Fig. 99), the larger of which Howell described (1875, p. 254):

> It is a perfect cone, 300 or 400 feet in height, and about 400 feet in diameter at the top, with a regularly formed crater, 75 feet to 100 feet deep. A few small streams of lava have issued from the same vent, but none have extended more than a quarter of a mile.

The perfection of this cone has lately been destroyed. Men, seeking ready sized material for road metal, have breached the regular crater wall by bulldozer. The cone is unmarked by natural agencies of erosion and vegetation has gained only a foothold on its flanks.

The highest cone of the area (Fig. 100) stands as a prominent landmark about one mile south of Veyo. Its crater has been breached in one place by erosion and its slopes are covered with sagebrush.

The cones appear to mark the position of faults, which parallel but are subordinate to the major dislocations of the area. As Dutton remarked (1880, p. 62) in speaking of the relationship between the volcanic cones and the major faults



Fig. 99 Recent cinder cones in Diamond Valley.



Fig. 100 Cinder cone surmounting lava mound, about one mile south of Veyo.

of the region:

> In a great majority of cases the vents stand near the faults, but the curious part of it is that they break forth almost always upon the lifted and very rarely upon the thrown side of the fault.

ECONOMIC GEOLOGY

Coal

Harmony field

The Harmony coal field lies along the eastern margin of the Stoddard laccolith about four miles north of New Harmony. The field is now inactive. The main workings, which consist of several surface pits, one inclined shaft 40 feet deep, and one adit about 180 feet long, lie within a few hundred yards, north and south, of a cabin known as Kelsey Deer Camp, on the dirt road which connects Page Ranch with New Harmony.

The coal here occurs in at least six seams within the Upper Cretaceous Tropic formation. A stratigraphic section of the exposed Cretaceous beds west of Pace Creek is given in the chapter on sedimentary rocks. The beds are steeply dipping and near the laccolith are overturned; the strike of the strata parallels the broadly curved intrusive contact. The principal coal seam lies near the intrusive body and, as a consequence of intrusion, has been crushed and faulted (Fig. 101), mixed with shaly material, and metamorphosed to semi-anthracite.



Fig. 101 Detail of thin, faulted coal seams at inactive mine near Kelsey Deer Camp. Looking south; Stoddard laccolith about 30 feet west. Width of picture about 15 feet.

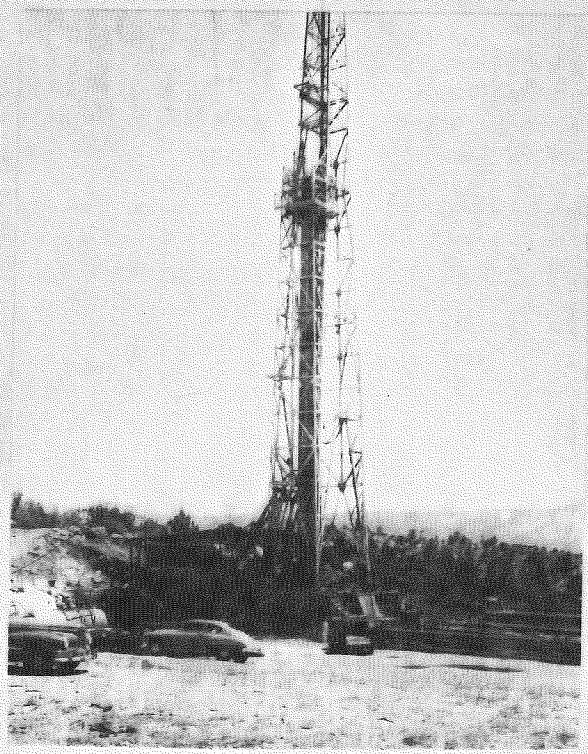


Fig. 102 Drilling Pintura No. 1 well of Sun Oil Company in July, 1951. Kolob Buttes in far distance.

The Harmony coal field has been described by Lee (1907) and Richardson (1909). Neither investigator was able to correlate the coal-bearing section with any known coal horizons in the Kolob Plateau, although both recognized that the Harmony beds represented the lower part of the Upper Cretaceous section. Lee reported the following fossils:

Ostrea sp.
Cyrena securis Meek?
Corbula nematophora Meek
Glauconia coalvillensis (Meek)
Chemnitzia? sp.
Planorbis

Richardson (1909, pp. 386-387) described the New Harmony coal as follows:

> The coal in the Harmony field is deep black in color and has a brilliant luster. It breaks both with a semiconchoidal and a cubical fracture, and is fairly hard, though it can be crushed in the hands. The coal is streaked with seams of bone and shale in intimate association, and, at least locally, much foreign matter is present. Films of iron pyrite occur, irregularly disseminated. The coal burns with but little smoke and with a faint blue flame.
>
> The analyses show an extremely high percentage of ash, ranging from 22.89 to 33.96 per cent in air-dried samples. These high values are due to the intimate association of shale and foreign matter with the coal....If by washing or other means the product of this field can be put on the market with a much lower percentage of ash....The Harmony coal will rank as a high-grade fuel. The high ash content is the cause of the low heating values.

The principal mine in the coal field is about 600 feet south of Kelsey Deer Camp, in the NE¼ SW¼ Sec. 32, T. 37 S., R.13W., Salt Lake Meridian. An adit about 180 feet long follows southward the seam nearest the intrusive porphyry.

The coal seam, displaced and crushed by faulting, pinches and swells, ranging from eight inches to four feet in width. At the end of the adit a stope goes up about 15 feet; here the coal, interspersed with thin stringers of shale and apparently repeated by faulting, is four to seven feet wide.

At a point 100 feet south of the portal, a channel sample was taken across the seam which here is 2.0 feet wide and contains no shaly partings. The seam at the point of sampling strikes N.10° W., dips about 65° east, and is greatly sheared. Both hanging and foot walls are dark gray shale. Through the courtesy of Mr. Paul Averitt, U. S. Geological Survey, the sample was analyzed by the U. S. Bureau of Mines. The results are given below, together with an analysis of coal from the same bed, published by Richardson (1909, p. 388).

As Received	Cook Per cent	Richardson Per cent
Moisture	5.7	8.21
Volatile matter	13.3	4.41
Fixed carbon	45.3	58.02
Ash	35.7	29.36
Sulphur	2.8	2.28
British Thermal units	7690	8908

Grant Ranch field

Over a distance of one half-mile, just northwest of the lower Grant Ranch, at least six prospect pits have been dug on a coal seam six to ten feet wide which strikes N. 25° W., dips 30° west, and parallels the intrusive contact of the Stoddard

laccolith, which lies 200 feet to the east.

All the pits are caved, there are no fresh outcrops, and the coal in the dumps is considerably weathered. The coal is black, has a shiny to dull luster, and an irregular blocky fracture. It is intimately associated with carbonaceous shale.

No fossils were found at this locality, but the lithology of the beds in which the coal is found is that of the Tropic formation. A measured section is given below:

	Thickness (feet)
Dark shales and thin buff sandstones ...	100 plus
Dark brown sandy limestone	2
Gray calcareous sandstone	2
Coal and carbonaceous shale	10
Hard gray shale	2
Gray calcareous sandstone and shale	15
Carbonaceous shale	4
Gray shale with beds of buff to white sandstone 1-3 feet thick	80
White, fine sandstone	10
Gray to black shale	35
Stoddard laccolith	
Total	260 plus

Silver - Uranium

An area of about two square miles near Leeds produced nearly $8,000,000 in the ten years following the discovery, in 1875, of silver ore in the sandstone which became known as the Silver Reef. Where the sandstone contained fossil plants it was especially rich; one petrified log yielded 17,000 ounces

Minerals containing copper, vanadium, and uranium are associated with the silver minerals. The mines are now inactive.

Proctor gives a detailed account of the geology of the deposits; his theory of their origin is as follows (1949, p. 1):

> It is believed that the metals in the Silver Reef sandstone were primary constituents of original volcanic tuffs in the Chinle formation. These metals were dissolved and/or mechanically transported by streams which were eroding the tuffaceous sediments. They were deposited with the sandstones and shales of the Silver Reef area. Further concentration of the metals in the Silver Reef sandstone was (1) by solution in circulating ground waters and (2) by precipitation because of contact with entombed plant debris and associated bacteria.

Ground Water

The most valuable mineral resource in the Pine Valley Mountains is water. The greatly jointed Pine Valley laccolith is a vast water reservoir. Meltwater from the heavy winter snows seeps into the laccolith along joints and is discharged in springs at the base of the intrusive body, above the relatively impermeable Claron limestone. Springs are absent on cliff faces of the monzonite porphyry, but are numerous at the foot of the mountain. Water from springs at the southern end of the main mountain mass is piped to St. George for municipal supply. Other springs feed creeks whose waters, if they get far enough away from the mountain, are diverted for irrigation and consumption; Leeds Creek is an example of such a stream. The Santa Clara River is fed largely by springs

which issue from the base of the laccolith in the Pine Valley area.

Water seeps are rare in the high parts of the Pine Valley Mountains except along the northern edge of the laccolith. There the intrusive fault contact is marked by a number of springs which help feed streams on both sides of the mountains.

The top of the limestone layer which marks the base of the Grassy Flat Canyon formation east of Grass Valley is also a locus of springs. The principal creek entering Grass Valley heads in Reservoir Canyon at a spring which comes out of the ground along the intrusive fault, but the flow of this stream is greatly augmented in the two miles before it reaches the valley by springs issuing from the canyon sides, above the Grassy Flat Canyon limestone.

Surface runoff is an unimportant, but sometimes troublesome, part of the water resources of the area. Most of the water used is derived from effluent seepage. Such seepage is usually found in one of the following places:

(1) at the base of the Pine Valley laccolith, and/or

(2) above a layer of limestone, or

(3) on a fault trace.

Exploration for Iron and Oil

Although the intrusive bodies of this area have a high iron content, none of it appears to have escaped to form ore bodies. Two vertical diamond drill holes were sunk in 1952 southwest of Page Ranch on the basis of a magnetic anomaly. Monzonite porphyry was encountered in both holes, but no iron ore. Apparently the magnetite in the monzonite was the cause of the anomaly.

In 1951 an exploratory well was drilled by the Sun Oil Company about three miles west of Pintura (Fig. 102). The well was abandoned at a depth of 5,546 feet, in the Coconino(?) sandstone. Oil exploration in the region is largely due to the discovery, in 1907, of the Virgin oil field, about seven miles east of Toquerville. This field has produced a little oil from the basal limestones of the Moenkopi formation. Exploration west of the Hurricane fault, mainly in the St. George district, has been unsuccessful.

BIBLIOGRAPHY

Baker, A. A., Dane, C. H., and Reeside, J. B. (1936) Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado, U. S. Geol. Survey, Prof. Paper 183.

Barksdale, J. D. (1937) The Shonkin Sag laccolith, Am. Jour. Sci., 5th ser., vol. 33, pp. 321-359.

_____ (1953) The pegmatite layer in the Shonkin Sag laccolith, Montana, Am. Jour. Sci., vol. 250, pp. 705-720.

Billings, M. P. (1942) Structural geology, New York, Prentice-Hall.

Bissell, H. J. (1952) Geology of the Cretaceous and Tertiary sedimentary rocks of the Utah-Arizona-Nevada corner, Guidebook Geol. Utah, no. 7, pp. 69-78.

Blackwelder, E. (1928) Mudflow as a geologic agent in semiarid mountains, Geol. Soc. Am. Bull., vol. 39, pp. 465-483.

Blissenbach, E. (1954) Geology of alluvial fans in semiarid regions, Geol. Soc. Am. Bull., vol. 65, pp. 175-190.

Campbell, G. S. (1952) Bloomington dome, Washington County, Utah, summary article, Guidebook Geol. Utah, no. 7, pp. 86-89.

Chawner, W. D. (1935) Alluvial fan flooding. The Montrose, California, flood of 1934, Geog. Rev., vol. 25, pp. 255-263.

Curtis, G. C. (1903) Secondary phenomena of the West Indian volcanic eruptions of 1902, Jour. Geol., vol. 11, pp. 199-215.

Dobbin, C. E. (1939) Geologic structure of the St. George district, Washington County, Utah, Amer. Assoc. Pet. Geol. Bull., vol. 23, pp. 121-144.

Dutton, C. E. (1880) Report on the geology of the high plateaus of Utah, U. S. Geog. and Geol. Survey Rocky Mountain Region.

_____ (1882) Tertiary history of the Grand Canyon district, U. S. Geol. Survey, Mon. 2.

Fenner, C. N. (1948) Incandescent tuff flows in southern Peru, Geol. Soc. Am. Bull., vol. 59, pp. 879-893.

Gardner, L. S. (1941) The Hurricane fault in southwestern Utah and northwestern Arizona, Am. Jour. Sci., vol. 239, pp. 241-260.

_____ (1952) The Hurricane fault, Guidebook Geol. Utah, no. 7, pp. 15-21.

Gilbert, C. M. (1938) Welded tuff in eastern California, Geol. Soc. Am. Bull., vol. 49, pp. 1829-1862.

Gilbert, G. K. (1875) Report on the geology of portions of Nevada, Utah, California, and Arizona examined in the years 1871 and 1872, U. S. Geog. Surveys W. 100th Mer. Rept., vol. 3.

_____ (1890) Lake Bonneville, U. S. Geol. Survey, Mon. 1.

Gregory, H. E. (1945) Post-Wasatch Tertiary formations in southwestern Utah, Jour. Geol., vol. 53, pp. 105-115.

_____ (1950a) Geology of eastern Iron County, Utah, Utah Geol. and Min. Survey, Bull. 37.

_____ (1950b) Geology and geography of the Zion Park region, Utah and Arizona, U. S. Geol. Survey, Prof. Paper 220.

_____ and Williams, N. C. (1947) Zion National Monument, Utah, Geol. Soc. Am. Bull., vol. 58, pp. 211-244.

Howell, E. E. (1875) Report on the geology of portions of Utah, Nevada, Arizona, and New Mexico examined in the years 1872 and 1873, U. S. Geog. Surveys W. 100th Mer. Rept., vol. 3.

Huntington, E., and Goldthwait, J. W. (1904) The Hurricane fault in the Toquerville district, Utah, Harvard Coll. Mus. Camp. Zoology Bull., vol. 42, pp. 199-259.

_____ (1905) The Hurricane fault in southwestern Utah, Jour. Geol., vol. 11, pp. 46-63.

Hurlbut, C. S. (1939) Igneous rocks of the Highwood Mountains, Montana, Part I. The laccoliths, Geol. Soc. Am. Bull., vol. 50., pp. 1043-1112.

Lacroix, A. (1930) Remarques sur les matériaux de projection des volcans et sur la genèse des roches pyroclastiques qu'ils constituent, Livre Jubilaire du Centenaire de la Société Géologique de France, Paris.

Lee, W. T. (1907) The Iron County coal field, Utah, U. S. Geol. Survey, Bull. 316, pp. 359-375.

Leith, C. K., and Harder, E. C. (1908) Iron ores of the Iron Springs district, Utah, U. S. Geol. Survey, Bull. 338.

Mackin, J. H. (1947a) Some structural features of the intrusions of the Iron Springs district, Utah, Guidebook Geol. Utah, no. 2.

_____ (1947b) Joint patterns in the Three Peaks laccolith. Iron Springs district, Utah (abstract), Geol. Soc. Am. Bull., vol. 58, p. 1255.

_____ (1952) Hematite veinlets in an ignimbrite in the Iron Springs district, southwestern Utah (abstract), Geol. Soc. Am. Bull., vol. 63, pp. 1337-8.

Mackin, J. H. and Nelson, W. H. (1950) Early Tertiary welded tuffs in the Iron Springs district, Utah (abstract), Geol. Soc. Am. Bull., vol. 61, p. 1528.

Mackin, J. H. and Switzer, G. (1948) Origin of mineralizing emanations in the Iron Springs district, southwestern Utah (abstract), Geol. Soc. Am. Bull., vol. 59, p. 1339.

Mansfield, G. R., and Ross, C. S. (1935) Welded rhyolitic tuffs in southeastern Idaho, Am. Geophysical Union, Tr., 16th annual meeting, pp. 308-321.

Marshall, P. (1935) Acid rocks of the Taupo-Rotorua volcanic district, Roy. Soc. New Zealand Trans. and Proc., vol. 64, pp. 323-366.

Marvine, A. R. (1875) Report on the geology of a route from St. George, Utah, to Gila River, Arizona, examined in 1871, U. S. Geog. Surveys W. 100th Mer. Rept., vol. 3,, pt. 2, pp. 189-225.

McKee, E. D. (1952) Uppermost Paleozoic strata of northwestern Arizona and southwestern Utah, Guidebook Geol. Utah, no. 7, pp. 52-55.

McNair, A. H. (1951) Paleozoic stratigraphy of part of northwestern Arizona, Amer. Assoc. Pet. Geol. Bull., vol. 35, pp. 503-541.

Neighbor, F. (1952) Geology of the Pintura structure, Washington County, Utah, Guidebook Geol. Utah, no. 7, pp. 79-80.

Osborne, F. F., and Roberts, E. J. (1931) Differentiation in the Shonkin Sag laccolith, Montana, Am. Jour. Sci., 5th ser., vol. 22, pp. 331-353.

Powell, J. W. (1875) Exploration of the Colorado River of the West and its tributaries explored in 1869, 1870, 1871, and 1872 under the direction of the Secretary of the Smithsonian Institution, Washington, Govt. Printing Office.

Proctor, P. D. (1949) Geology of the Harrisburg (Silver Reef) mining district, Washington County, Utah, Ph. D. thesis, University of Indiana.

_____ (1952) Silver Reef area, Washington County, Utah. Guidebook Geol. Utah, no. 7, pp. 90-91.

Reber, S. J. (1952) Stratigraphy and structure of the south-central and northern Beaver Dam Mountains, Utah, Guidebook Geol. Utah, no. 7, pp. 101-103.

Reeside, J. B., and Bassler, H. (1922) Stratigraphic sections in southwestern Utah and northwestern Arizona, U. S. Geol. Survey, Prof. Paper 129, pp. 53-77.

Richardson, G. B. (1909) The Harmony, Colob and Kanab coal fields, southern Utah, U. S. Geol. Survey, Bull. 341, pp. 379-400.

_____ (1927) The Upper Cretaceous section of the Colob Plateau, southwest Utah, Wash. Acad. Sci. Jour., vol. 17, pp. 466-468.

Roberts, A. E. (1953) A petrographic study of the intrusive at Marys Peak, Benton County, Oregon, Northwest Science, vol. 27, pp. 43-60.

Scrivenor, J. B. (1929) The mudstreams ("Lahars") of Gunong Keloet in Java, Geol. Mag., vol. 66, pp. 433-434.

Sharpe, C. F. S. (1938) Landslides and related phenomena, New York, Columbia Univ. Press.

Spieker, E. M. (1946) Late Mesozoic and Early Cenozoic history of central Utah, U. S. Geol. Survey, Prof. Paper 205-D, pp. 117-161.

_____ (1949) The transition between the Colorado Plateaus and the Great Basin in central Utah, Guidebook Geol. Utah, No. 4.

Thomas, H. E. (1952) Triassic stratigraphy of southwestern Utah, Guidebook Geol. Utah, no. 7, pp. 56-60.

Thomas, H. E., and Taylor, G. H. (1946) Geology and groundwater resources of Cedar City and Parowan valleys, Iron County, Utah, U. S. Geol. Survey, Water Supply Paper 993, p. 210.

Wells, F. G. (1938) Origin of iron ore deposits in the Bull Valley and Iron Springs districts, Utah, Econ. Geol., vol. 33, pp. 477-507.

Wentworth, C. K., and Williams, H. (1932) The classification and terminology of the pyroclastic rocks, Natl. Research Council Bull., no. 89, Rept of Comm. on Sedimentation, 1930-32, pp. 19-53.

Williams, N. C. (1952) Jurassic stratigraphy of southwestern Utah, Guidebook Geol. Utah, no. 7, pp. 61-68.

VITA

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			unconformity	
TERTIARY		Atchinson formation	Rudely bedded breccia overlying augite andesite flows and breccia. Locally, at the base, tuff-breccia.	0-500
			unconformity	
		Grassy Flat Canyon formation	Vitric-crystal rhyolite ignimbrite, foliated	0-150
			Vitric-crystal rhyolite ignimbrite with lithic fragments	0-700
			Augite andesite lava, amygdaloidal	0-50
			Lacustrine limestone	0-100
			unconformity or thrust fault	
		Rencher formation	Latite breccia at top; minor air-fall tuff; volcanic sandstone; dacite porphyry breccia; bedded, welded tuff-breccia; biotite ignimbrite, poorly welded; crystal-vitric dacite ignimbrite containing quartzite pebbles; basal conglomerate, limestone	0-600
			unconformity	
		Quichapa group Tv-3	Crystal biotite dacite ignimbrite	0-550
		Tv-2	Vitric rhyolite ignimbrite, foliated	0-180
		disconformity		
		Tv-1	Crystal-vitric rhyolite ignimbrite with lithic fragments	0-800
		disconformity		
	EOCENE	Claron formation	Lacustrine limestone with, near the top, a bed of biotite tuff, and near base, black ls. pebble cong.	0-1000
			Calcareous sandstone and sandy limestone	
	LARAMIAN		Quartzite cobble conglomerate and sandstone	
			unconformity	
	MONTANAN	Kaiparowits formation	Soft sandstone, much of it cross-bedded and conglomeratic. Iron concretions common. At the base, silty shale and quartzite cobble conglomerate.	0-1200
			disconformity	
CRETACEOUS	UPPER CRETACEOUS	Wahweap and Straight Cliffs sandstones	Sandy shale and lignite alternating with massive, cross-bedded sandstone in beds 5-40 feet thick.	0-1800