THE PORCUPINE MOUNTAIN "RED ROCK"

Thesis for the Degree of M. S.

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Robert Emerson Thaden

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This is to certify that the

thesis entitled

"The Porcupine Mountain Redrock"

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Robert E. Thaden

has been accepted towards fulfillment
of the requirements for

Master's degree in geology

B. T. Sandefur

Major professor

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THE PORCUPINE MOUNTAIN "RED ROCK"

by

Robert Emerson Thaden

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THE PORCUPINE MOUNTAIN "RED ROCK"

INTRODUCTION

Geography

<u>Location and Extent of Area</u>: The Porcupine Mountains are located in northwestern Ontonagon County, Michigan (pl. 1). They comprise an arcuate ridge and highland topography which is convex to the northwest and parallels the southern shore of Lake Superior from a point a few kilometers west of Silver City to the eastern edge of Gogebic County.

<u>Culture</u>: One good highway, Michigan State Highway M-107, enters the area. Following the southern shore of Lake Superior from the east, it extends up the northern ridge of the mountains and terminates at a point just north of the western end of Carp Lake. This point is approximately 36.3 kilometers west of the city of Ontonagon. Other than this one good road, the region is practically devoid of permanent cultural features.

This does not imply, however, that the region has been deserted. There are evidences of prehistoric mining operations for copper carried on by the Indians long before white men entered the area, and since the United States government acquired this part of the Northwest Territories from the Mississippi and Lake Superior Chippewa Indians by treaty on October 4, 1842 (A. G. Ruthven, 1906, p. 19), the natural resources have been persistently exploited by white men.

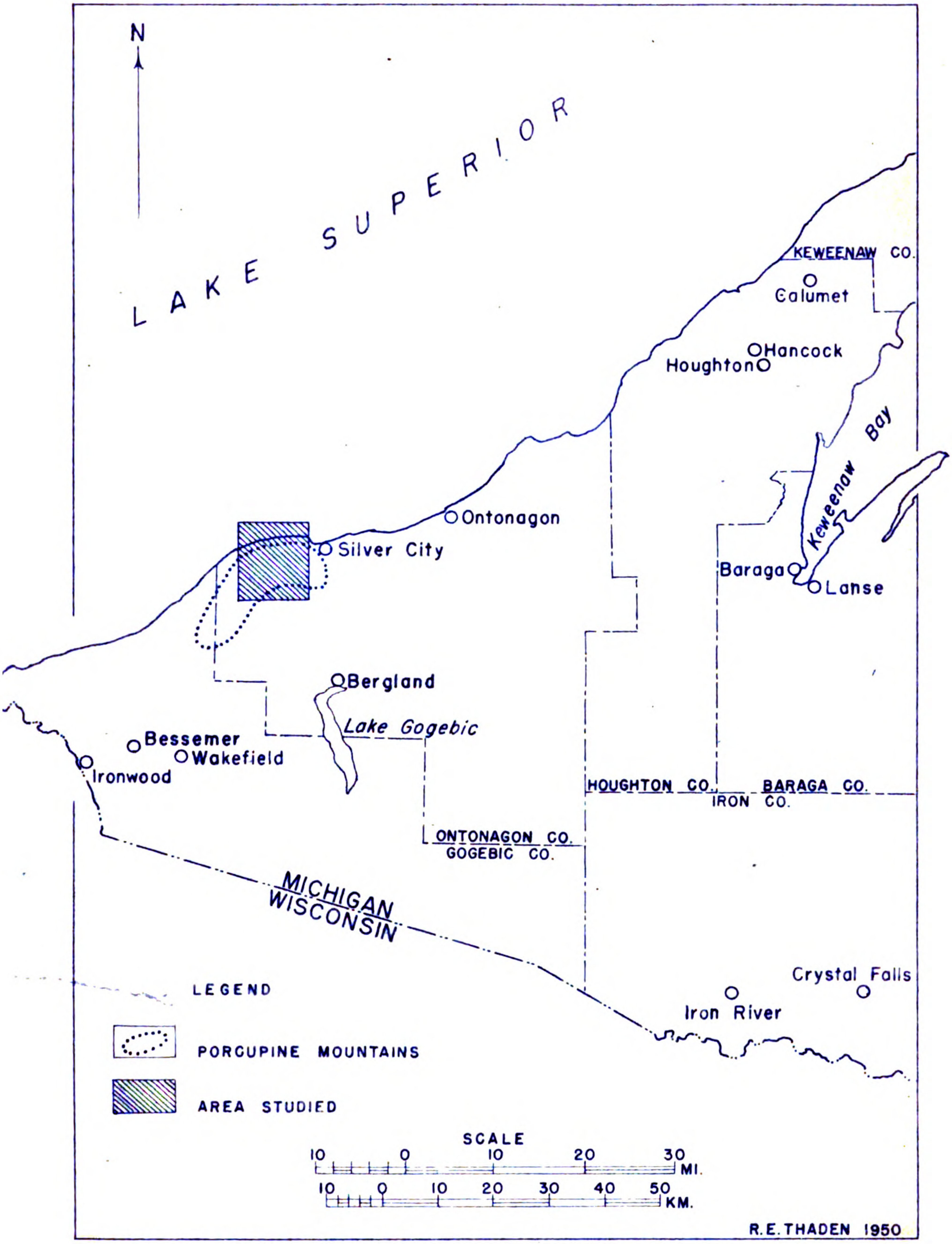
After copper was discovered in extrusive basic flows farther north on Keweenaw Peninsula, any such rocks were considered indicative of the presence of valuable copper lodes. Identification of this type of rock in the Porcupine Mountains led to the organization of many companies and to the sinking of many shafts in the northern part of the region. However, the copper deposits were narrow and lean, and by the end of 1848, according to Foster and Whitney, most of the mines had closed down and the majority of the miners had gone elsewhere (J. W. Foster and J. D. Whitney, 1850, p. 80). Logging, trapping and deep sea fishing have been the principal means of livelihood since that time.

Because the region is heavily forested and contains few settlements, there is an abundance of wild game. In an effort to preserve for the future the primitive character of the region, the virgin stands of maple and hemlock, and the wide variety of floral and faunal representatives, nearly one hundred square miles have been set aside by the state of Michigan as a wilderness state park.

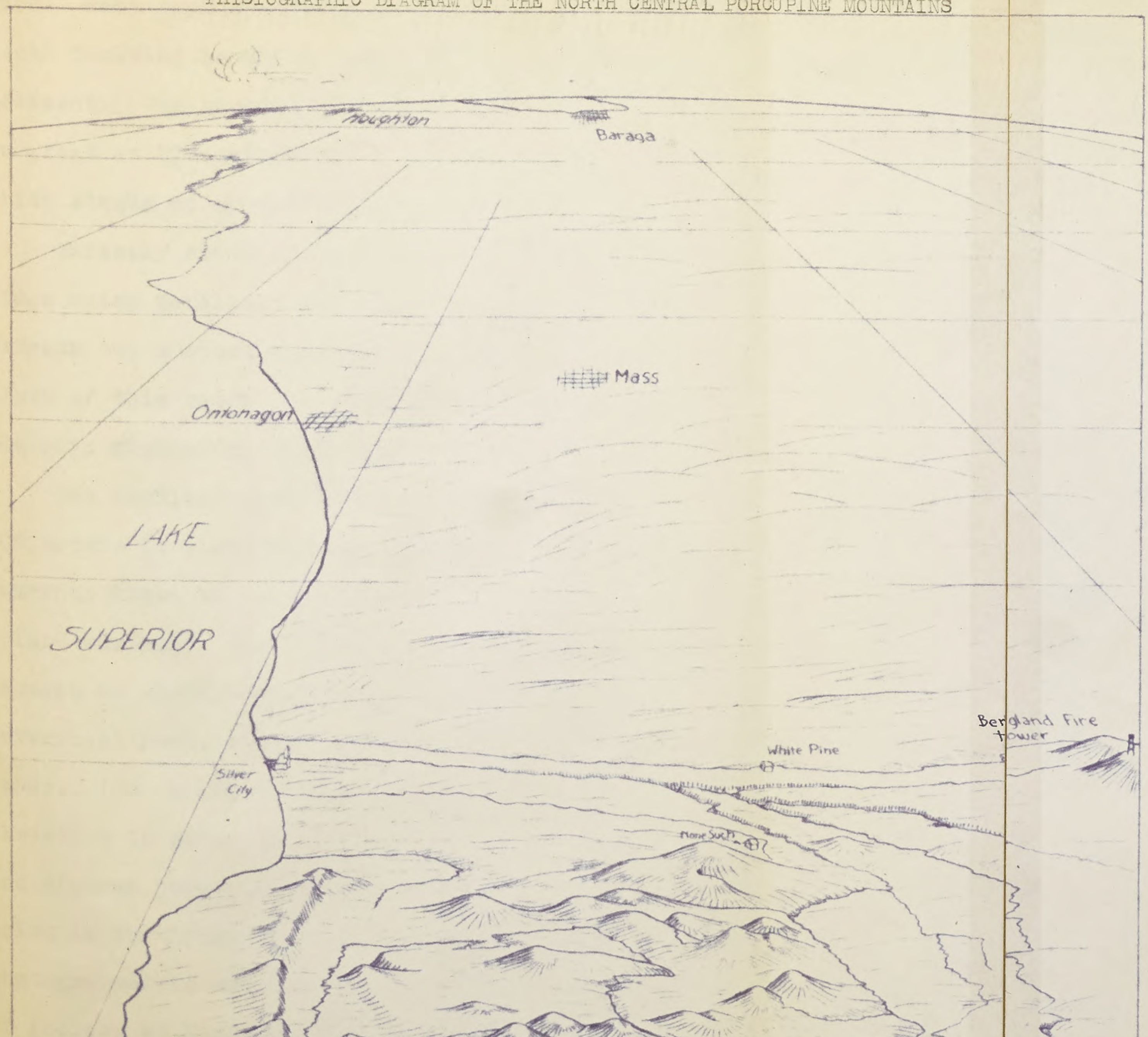
Topography: Elevated masses of pre-Cambrian rock comprise the main topographic features of the region. In the north is an elongate ridge which slopes with decreasing steepness to the north until it finally disappears under Lake Superior (pl. 2). The south side of this ridge is in many places a precipitous cliff rising 100 to 150 meters above the valley of the Carp River. Although the ridge extends for many miles, it becomes lower to the east and to

PLATE I

INDEX MAP SHOWING LOCATION OF THE PORCUPINE MOUNTAINS



PHYSIOGRAPHIC DIAGRAM OF THE NORTH CENTRAL PORCUPINE MOUNTAINS



west of Carp Lake and is interrupted in many places by wind gaps. Many gaps apparently developed as a result of north-south faulting in which there was very little vertical movement. The highest points on the ridge are at elevations as great as 275 meters above the level of Lake Superior, which stands at an elevation of 183.5 meters.

Directly south of Carp Lake is another, and lower, ridge which parallels the southern shore of the lake and extends but a short distance beyond either end. To the south of this ridge, in a valley between the ridge and the main highlands, flows Scott's Creek.

The highland area is a plateau averaging approximately 500 meters in elevation and sloping gently to the south. Numerous knobs up to 110 meters in height rise from this upland surface. The Michigan Department of Conservation records an elevation of 617 meters (2,023 feet) for Government Peak, a knob in the northern part of the highlands. (On charts of the United States Lake Survey, this elevation is given as 2,022.19 feet.) This is, allegedly, the highest point in Michigan and, incidently, the highest point in the Lakes States. However, recent field and photogrammetric work by Dr. W. A. Kelly of the department of geology at Michigan State College has established that the elevation of Government Peak is but little over 565 meters (1,860 feet) and that a prominence approximately 1.5 kilometers south of Little Carp Lake, with an elevation of nearly 600 meters (1,970 feet), is the highest point in the Porcupine Mountains and, probably, in Michigan (W. A. Kelly, personal communication).

The highland area is abruptly terminated on the south by a broad and concave valley in which flow the Little Iron and Iron rivers.

Drainage: Draining the major portion of the Porcupine Mountains are five streams. Union River on the east is a rather small stream, although one of its sources is Union Spring, one of the largest in Michigan and, according to F. E. Wright (1905, p. 41), flowing at a rate greater than 750,000 gallons (2,750 kiloliters) per day.

The Little Iron and Iron rivers occupy the broad valley south of the mountains and most of their tributaries head on the dissected southern slopes of the highland area. They are required to flow around the southern and eastern sides of the highland in an annular drainage pattern before entering Lake Superior east of the mountains.

Little Carp River and Carp River both originate in the highlands, flow through the lakes of the same names, and by circuitous routes drain northwestward into Lake Superior. (Although the United States Board of Geographic Names still lists these lakes as Carp Lake and Little Carp Lake, the Michigan Department of Conservation, in deference to esthetic tourists, no doubt, has unofficially renamed them Lake of the Clouds and Mirror Lake respectively.)

The highland surface is relatively impermeable and, being rather flat, retains meteoric water as swamps. These are breeding places for innumerable infamous "Michigan mosquitoes" and are the sources of the rivers. Springs, which are numerous at low elevations in the region, and which are thought to rise along fault planes (F. E. Wright, 1905, p. 39), are also probably fed by the swamp waters.

The proximity of the region to Lake Superior, the prevalence of westerly winds, and the elevated nature of the region combine to produce a positive precipitation anomaly (A. H. Eichmeier, personal communication). Most of the precipitation falls on the western part of the mountains; the eastern part is in the rain shadow.

Geomorphology

The presently extant topographic features of the Porcupine Mountains are relatively permanent. The flat highland area is probably a peneplain developed during Cambrian time after subsidence of the orogenic activity of the Killarney Revolution. Van Hise (1896, pp. 57-59) even considers base leveling taking place during a time extending to the Cretaceous. Monadnocks, such as Government Peak and the unnamed eminent hill south of Little Carp Lake, were preserved on this surface.

Geologists generally believe that fluctuating Paleozoic seas alternately covered and uncovered the area. Sediments were deposited, were removed, and were redeposited. Finally Pleistocene glaciers advanced over the mountains, eroding, sculpturing, and dropping erratics as large as 4 x 7 x 10 meters on the upland surface. The ice occupied river valleys which had been established, in many cases, parallel to the strike of beds, widening, flattening, and probably partially filling them with glacial debris.

A strong shoreline of glacial Lake Duluth is developed at 355.1 meters on the northern slope of the northern ridge, where highway M-107 follows it for more than 4 kilometers. Although the position on the northern side of the main highland mass to the south is not readily identifiable in the field, it can be seen clearly on aerial photographs by a distinct change in flora. Careful observation on the ground discloses a thin linear zone of maple occupying the old beach, bounded on either side by hemlock forest.

Shore features of glacial Lake Algonquin at an elevation of 250 meters and glacial Lake Nipissing at an elevation of 187.7 meters are well developed, marked by steep banks as high as 10 meters. While the various lake stages were evolving, the ridges in the northern part of the region were, successively, offshore islands, points of land on the seaward side of elongate bays, and, finally, ridges as developed at present.

The rapid succession of glacial lakes at lower elevations was probably responsible for development of youthful geomorphic characteristics in the lower reaches of the Carp and Little Carp rivers. It was, in effect, a rejuvination of the rivers, although incision of the streams has not yet affected the mature upper parts of their courses.

Other interesting geomorphic features are cirques. Located along the southern edge of the highland area, they were first identified by W. A. Kelly (personal communication). Whether the cirques developed at the advent, or at the decline of Pleistocene glaciation is not known, and although they are small they are, nevertheless, present -- the first known in Michigan.

Stream capture and change in direction of flow of many streams is evident. Since there is no divide between Carp River and the north branch of Union River, it is highly possible that Carp River once flowed in the opposite direction, occupying its present course only after recession of the glaciers and opening of a new and lower outlet to the west. In the southern part of the area, tributaries of Little Iron River have beheaded several tributaries of Little Carp River. Although conjectural, the rapid southward tilting of the whole region may be aiding stream piracy by streams flowing to the south, the gradients of these, and consequently their eroding powers, increasing while the gradients of northward draining streams are reduced.

The effects of tilting can also be seen along the shore of Lake Superior. Angular outcrops of rock project from the water offshore; large masses of boulders are piled on the beaches; and the area between the glacial Lake Nipissing shoreline and the present shoreline is, in most places, a swamp. By these and other features, a typically submergent coastline is evident.

General Geology and Previous Investigations

Stratigraphy: The rocks cropping out in the Porcupine Mountain region belong to the Keweenawan series, upper Proterozoic era. Lowest in the series is the "red rock", which comprises the central highland region. Its origin, manner of emplacement, and position within the geologic column have been controversial issues for more than a hundred years.

Dr. Douglas Houghton (1841, pp. 487-490), observing Keweenawan rocks as early as 1841, termed them "greenstone". He specifically included basic flows and sandstone conglomerates, but whether he also meant to include the acid rocks does not appear. It is questionable whether Houghton ever saw the "red rock".

Bela Hubbard (1850, p. 837), reporting on his field work in 1845, mentions an "imperfect sienitic granite" on Keweenaw Peninsula, evidently referring to an acid porphyry. Although he thought, in 1845, that the basic flows were "dykes", as did Houghton, he changed his mind the following year while at work in the Porcupine Mountains. He mentions (idem., pp. 886-887),

> "...regularly disposed and alternating beds of greenstone and amygdaloid... [which] ...give an appearance of stratification to the mass."

With regard to the "red rock" he says,

> "Associated, however, with the greenstone and amygdaloid of that country, appears an argillaceous and silincous [siliceous?] rock, which, though we have classed it among the trap rocks, is very distinguishable from all the other varieties of trap, and is therefore entitled to a separate description. This rock occurs in

belts, alternating with those which make up the mass of the Porcupine ranges, and possibly may be regarded as a volcanic mud, altered and hardened by its vicinity to rocks of igneous origin."

He thus hints at an igneous origin for the "red rock" and goes on to describe it,

"It has been already mentioned, that, alternating with the several rocks that compose the Porcupine Mountains is a hard rock of red color, fine grained, and sub-slaty in structure. It is evidently trappose in character, but is at the same time quite argillaceous, and sufficiently siliceous to strike fire under the hammer. Its color varies from a light to a dark brick red."

Dr. C. T. Jackson (1849, pp. 399, 400, 414), J. D. Whitney (1849, p. 728; 1850, p. 64), and J. W. Foster (1850, p. 64) were of the opinion that the acid rocks of Keweenaw Peninsula were sandstones, indurated and granitized by the associated basic traps. Dr. Jackson (1849, p. 661) thought those in the Porcupine Mountains might be volcanic in origin. Thomas MacFarlane (1866, p. 142) considered the acid rocks to be eruptive.

R. D. Irving, in "The Copper-Bearing Rocks of Lake Superior", U. S. Geol. Survey Mon. 5, 1883, and with T. C. Chamberlain in U. S. Geol. Survey Bull. 23, 1885, fails to mention the bedded nature of the "red rock" but does conclude (1883, p. 150) that the Porcupine Mountains,

"...owe their existence in all probability to a fold, the porphyry of the central portions being one of the usual embedded masses laid bare by subsequent denudation."

Later, however, Butler and Burbank (1929, p. 170), came to the conclusion that,

> "The structure of the region is probably due to the intrusion of an igneous mass of later age than any of the rocks in which deposits of copper and silver are found [Nonesuch shale] ...All known features connected with this particular part of the region [White Pine Mine] point to the production of the structural features by the intrusion of the igneous core of the Porcupine Mountains and the doming up and outward thrusting of the rocks that were invaded."

A. C. Lane, in "The Keweenawan Series of Michigan", published as part of the Mich. Geol. Survey Ann. Rept. for 1909, vacillated on succeeding pages from one view to another but for the most part embraced the intrusive school of thought. As late as 1936 the Michigan Geological Survey (1936, centennial map) considered the "red rock" as intrusive, but thought it was pre-Keweenawan in age. The rock it was supposed to have intruded is not known to the writer.

The "red rock", being of principal interest in this paper, has been dwelt upon at some length, and long quotations from Bela Hubbard were introduced because he, as one of the earliest workers in the region, held essentially the same views as are brought out in this thesis.

Overlying the "red rock" are basic lava flows and flow breccias, interbedded with sandstone breccias and conglomerates containing abundant "red rock" and basic flow fragments. The base of this unit is primarily thin basic flows which cap the northern part of the "red rock" area and, weathering slowly, maintains a steep north-facing slope.

Next above these basic flows is a thick sedimentary formation whose lower portion is predominantly sandstone conglomerate; the upper portion is predominantly sandstone. The well indurated upper portion forms the ridge south of Carp Lake and extends up the precipitous southern face of the northern ridge to a point just below the crest.

Capping the northern ridge are the "Lake Shore traps." They are a small number of basic amygdaloidal lava flows with no interbedded conglomerate. Weathering less rapidly than the underlying sandstone, these flows hold up the crest of the ridge.

The "Outer conglomerate" and the Nonesuch shale, respectively, overlie the "Lake Shore traps" and represent the youngest rocks in this area. The "Outer conglomerate" has recently been renamed the Porcupine Mountain sandstone (El Khalidi, 1950, p. 16) in the Porcupine Mountain area. Due to its relatively non-conglomeratic nature and to the facts that, although lying directly above the "Lake Shore traps" as does the "Outer conglomerate" in other areas, and although similar in lithic character, it may not be a temporally identical formation.

The Nonesuch shale does not crop out in the northern part of the region. It does, however, with steep dips to the south, abut the "red rock" on the south. Other formations were apparently faulted out.

A good geologic section was made by Gordon (1906, pl. XXXII) along the Black River west of the Porcupine

Mountains. Since the formations vary in thickness from place to place, or are not continuous throughout the length of the peninsula, other sections of Keweenawan rocks, many of which are derived from inspection of drill cores, are too distant, too general, or too limited in stratigraphic extent to be of use here.

The writer has, therefore, constructed a section based upon average dips observed in the field and upon photogrammetric measurements in the laboratory. An attempt is made to correlate this section with that of Gordon and to identify the various lithologic units with the several groups generally recognized in the Keweenawan series. The section (table 1), is normal to the strike and passes through a point 100 meters west of Carp Lake.

Structure: Lake Superior fills a large synclinorium formed, it is thought (W. O. Hotchkiss, 1923, pp. 669-678), by collapse of the earth's crust caused by the removal of large quantities of magma. Keweenaw Peninsula and the Porcupine Mountains are on the southeastern limb of this synclinorium and the dips of formations are, in general, homoclinal to the north. On the northwestern limb, rocks similar in age and lithologic character to those cropping out on Keweenaw Peninsula are exposed on Isle Royale and in northeastern Minnesota.

The Porcupine Mountains present a singular structure in this region. As mentioned before, it is generally thought to be a fold, truncated by erosion, and exposing older rocks

TABLE 1

IDENTIFICATION AND CORRELATION OF KEWEENAWAN ROCKS

Gordon†		Thaden		
Black River section	Thickness	Porcupine Mountains section	Thickness	Possible correlation
Freda sandstone	-----		-----	Freda sandstone
Nonesuch shale	500		-----	Nonesuch shale
Outer conglomerate	5,000	Sandstone and conglomerate. Upper portion dips under Lake Superior.	2,000	Outer conglomerate# (Porcupine Mountain sandstone)*
Lake Shore traps	500	Basic flows. No sandstone or conglomerate.	370	Lake Shore traps‡
conglomerate	350	Sandstone with conglomerate grading down to conglomerate with sandstone.	1,885	Great conglomerate‡
mixed eruptives and sediments	5,500	Conglomerate grading down to eruptives.	490	Ashbed group ?*
total	5,850	total	2,375	
felsite	450	"Red rock"	?	

*H. H. El Khalidi, 1959, p. 16.
†W. C. Gordon, 1906, pl. XXXII.
#Identified in the Porcupine Mountains as such by C. R. Van Hise and C. K. Leith, 1911, p. 385.
‡Idem., pl. XXVIII.
*According to A. C. Lane (1911, p. 624), the Ashbed group is exposed in Sec. 33, T. 51 N., R. 42 W. (46° 46' N., 89° 39' W.).

Note: It is highly probable that some duplication of beds has taken place in both sections due to longitudinal faulting.

at the surface, although quite a number of geologists hold to a theory of igneous intrusion and subsequent uncovering of the intrusive rock to explain the observed quaquaversally dipping strata.

A complete chronologic bibliography of reports by the men mentioned in this section, and of other works bearing on the Keweenawan, may be found in "The Copper-Bearing Rocks of Lake Superior", U. S. Geol. Survey Mon. 5, 1883, by R. D. Irving, on pages 14-23 inclusive.

Bibliographies of general works on the Lake Superior region are contained in "The Geology of the Lake Superior Region", U.S. Geol. Survey Mon. 52, pp. 74-84, 1911, by C. R. Van Hise and C. K. Leith, and in "The Copper Deposits of Michigan", U. S. Geol. Survey Prof. Paper,144, pp. 3-14, 1929, by B. S. Butler and W. S. Burbank.

DEFINITION OF THE PROBLEM

The geology of the Porcupine Mountains is not well known. The structure and stratigraphy have never been satisfactorily solved, nor has careful identification of several rock types been made. Hence, "red rock" and other noncommittal and ambiguous, if descriptive, terms have come into general, and almost exclusive use when reference is made to the Porcupine Mountains.

The efforts of this investigation are directed toward solving some unanswered problems and of elucidating several poorly understood phenomena in the Porcupine Mountains.

Since the so-called "red rock" is almost unknown geologically, and since additional information on the problems relating to it might be applied to other areas of Keweenawan rocks resulting in, (1) a better understanding of the structure there and, (2) the discovery of new ore bodies of copper and silver, the "red rock" is the formation treated in this thesis. The following major problems are considered:

(1) An attempt is made to interpret the mode of origin and manner of emplacement of the "red rock".

(2) An attempt is made to determine the percentages of the various minerals present in the "red rock" and to classify the "red rock" according to some standard system which will allow a satisfactory identification using the analytical data available.

(3) An attempt is made to determine the attitude of the "red rock", to correlate its various exposures, and to define its relation to adjacent strata (i. e., its position within the geologic column).

(4) An attempt is made to determine the forces which have acted upon the "red rock" and to interpret their effect upon it and upon the surrounding region.

FIELD PROCEDURE

The field work was done during June, July, and August of 1949. A base camp was established along highway M-107 near the east entrance to the state park. From this location the origins of several routes into the "red rock" area could be reached by automobile.

It is possible to drive, for instance, to the end of highway M-107 and to enter the hinterland just west of Carp Lake. Likewise, the area can be entered approximately 4 kilometers east of Carp Lake by walking up the course of the Carp River. On the east, the "red rock" area can be entered from any point along Nonesuch road or from innumerable logging trails, impassable for automobiles, which parallel the main highland mass on the southeast.

Vertical aerial photographs at a scale of approximately 1:20,000 were carried in the field. Outcrops, swamps, faults, dikes, strikes and dips, and other information was plotted on them. Localities of interest were also plotted on them and numbered. Under corresponding numbers in the field notebook, pertinent data were recorded.

No attempt was made to run straight line traverses as the scarcity of outcrops made this impractical. However, all major streams were followed, all knobs and ridges were visited, and swamps, where there was likelihood of outcrops, were traversed. It is believed that all of the larger outcrops and most of the smaller ones were studied.

Attempts were made to obtain fresh rock specimens. These were oriented and suitably marked before being removed from the outcrop. Compass readings were taken on foliation, lineation, and on fracturing wherever they were identified. In addition, the bearings of linear elements, such as stream courses and ridges with truncated sides, were obtained.

Other features, such as changes in flora, orientation of streams and roads, geomorphic features, and attitude of adjacent rocks were recorded. Compass traverses and diagrams were made of particularly interesting or well exposed areas and structures.

A resumé of each days observations was made at night and previously held theories and partially solved problems were appropriately revised.

TERMINOLOGY

Most terms of vague or ambiguous meaning (e. g., melaphyre, felsite, dolerite), and those of various definition, are avoided in this paper. The contextual definition of those which are used is given below:

Crystalline - crystals visible to the naked eye

Entoölitic - mineral matter projecting toward a common point, line, or plane

Eutaxitic - banded; parallel arrangement of textures or minerals in extrusive rocks; flow banding

Exogenetic - apart from the main mass, as volcanic dust

Extoölitic - mineral matter projecting from a common point, line, or plane

"Kainoblastic" - Gr., kainos, new or recent, and blastos, sprout or shoot. Introduced as descriptive or metamorphic structures and textures in general

Microcryptocrystalline - crystals which appear very small under the microscope; in general, less than three microns

"Planiolite" - L., planus, level, and Gr., lite, equivalent to lith, from lithos, of stone. Introduced as descriptive of spheriolitic structures oriented with respect to a plane (cf., spheriolite, axiolite)

Structure - megascopic features of a hand specimen; also major features of, or in, a rock body

Texture - microscopic features of, or in, a rock

PETROLOGY, PETROGRAPHY, AND MINERALOGICAL ANALYSES

Preliminary to an attempt to interpret the mode of origin, the manner of emplacement, and the attitude of the "red rock", the criteria upon which such interpretation is based must be defined and their value as criteria must be demonstrated.

The criteria are, obviously, the megascopic and microscopic structures and textures developed in the rock, both contemporaneous with, and after, its deposition. Therefore, a complete examination and description of the rock in the field, in hand specimen, and under the microscope is necessary.

Since the genesis of the described rock was not observed, only on the basis of comparison with published works, written by experts, and describing rocks of similar character but of known origins, can interpretation of its formation and structure be made.

Petrology of the "Red Rock"

Hand specimens, oriented with respect to north, to the horizontal, and to the foliation if megascopically evident, were collected in the field. An attempt to group these according to megascopic physical characteristics was made. Unfortunately, each specimen was so different from the others that grouping for descriptive purposes was impossible. Therefore, only a general definition of structures and textures is given.

Flow Rock: The "red rock" of the Porcupine Mountains, while exhibiting wide ranges in physical characteristics, is striking in its chemical and mineralogical uniformity (table 2). The color of freshly broken surfaces, depending upon the locality in which they are observed, ranges through various shades of pink, purple-pink, yellow, orange, red, and red-brown.

Weathered zones are shades of pink or yellow, and may extend so deeply into the rock that fresh samples cannot be obtained. This deep penetration of weathering processes may be due, not only to the original high porosity and permeability of certain portions of the "red rock" mass, but also to the great length of time during which weathering was able to progress.

In addition, fractures related to original flow and to shrinkage upon consolidation, and comminuted zones related to later deformational forces, present avenues of access to weathering agencies even in those portions of the "red rock" which are hard and dense. Such open fractures are universally covered with drusy quartz.

The rock possesses a clayey odor even on fresh surfaces, indicating considerable kaolinization by infinitely penetrating solutions.

In general, the rock exposed in the northern and northwestern parts of the area is dense and compact. It is aphanitic and looks like dull red jasper, or is aphanitic-spherulitic, in which case the accretion of more highly quartziferous material in the spherules imparts to the rock a spotted appearance and a somewhat more vitreous luster. In either case, the rock breaks with conchoidal fracture.

Vesicles are uncommon in the "red rock" but miarolitic cavities are prevalent. Large cavities, distorted and drawn out into the plane of foliation are occasionally developed in the rock exposed on the upper part of the Carp River near locality 74 (pl. 15, in pocket). These cavities range up to 12 inches in length and are partially or wholly filled with euhedral quartz (pl. 3, A). Similar rock is exposed at the top of the cliff on the west side of Government Peak near locality 1, but here the cavities are subspherical and average 5 millimeters in diameter.

A well developed, finely laminar, eutaxitic structure is common in the rock of the northern part of the area. The separate bands constitute layers of varying composition. The dark bands are composed of magnetite, glass, and partially crystallized feldspathic material and light ones are composed of quartz and quartz-feldspar intergrowth. The distance between successive dark or light bands is usually a millimeter or two (pl. 3, D), but occasionally, as at localities 3 and 58, single layers, generally those of the quartziferous material, may be 25 millimeters wide (pl. 3, E).

Weathering is relatively easier along those planes in which magnetite and feldspathic material is predominant due to chemical instability of these minerals in the presence of oxidizing and hydrolizing solutions. Therefore, the deeply weathered, foliate phases of the rock possess the appearance of old lumber, the light bands protruding while the dark bands are recessed.

The texture of the "red rock" in the southern part of the area is generally granitic or aphanitic-porphyritic. The phenocrysts of the porphyritic varieties are euhedral or subhedral quartz averaging 1 millimeter in diameter, or potash feldspar averaging 1.5 millimeters in diameter.

The feldspar phenocrysts are zoned. This zoning is made evident by differential alteration or by differential inclusion of foreign material, probably hematite or other ferrite, or by both, resulting in abrupt changes in color oriented concentrically with respect to the center of the phenocryst. This coloration, various shades of red, is usually more intense in the outer zones of the crystals. Carlsbad twins can occasionally be identified by the darker shade of one twin.

Other megascopic structures are cracks which formed during the final consolidation of the rock. As the more completely crystallized portions of the rock were carried forward by still fluid portions, tension fractures developed. These were, in some cases, completely filled by the remaining liquid which, as the end product of crystallization, was considerably more acidic (quartziferous) than the earlier crystallized portions and hence a lighter color.

In other instances, the cracks were left open or were only partially filled. Many of these open fractures persist in the rock at the present time.

Pyroclastic Rock: Pyroclastic "red rock" was seen at many localities. The best outcrops are near locality 11 on the upper Carp River, and at locality 22. The rock exposed at locality 22 is composed of angular blocks of typically foliate "red rock" cemented by a hard, dense, aphanitic material of the same composition. Foliation in the cementing material conforms to the outlines of the included fragments, wrapping around them in smoothly curving layers and breaking up into disorganized eddy-like bands on the lee sides of the larger fragments.

The included angular blocks, usually flat sided, are rhombohedral or rectangular. They range from 1 millimeter to more than 40 centimeters in diameter (pl. 3, C; pl. 11, C).

The agglomerated zone at locality 22, although not exposed in its entirety, has a minimum thickness of 3 meters. This type of brecciated material is typical of the tops of these flows in which a crust of solidified lava was formed and subsequently fractured and enveloped by the remaining fluid lava. The writer believes that rending of the crust may have been accomplished by bulging and bursting due to an increase in hydrostatic pressure in the fluid lava; by collapse due to a decrease in hydrostatic pressure and consequent failure of support, or by an extension of the crust beyond its elastic limit through differential translocation during continued flow by magma below. Normally, several of these processes act in conjunction.

The pyroclastic rock on the upper Carp River near locality 11 is composed in part of included angular blocks as described on page 26. The fragments here, however, are much smaller, usually averaging about 1 centimeter in diameter. In addition, a very small portion of the rock is composed of compressed and indurated volcanic dust, and of fragments less than 4 millimeters in length. This is interbedded with the fine breccia.

The tuffaceous material shows an indistinct bedding (pl. 3, B). The bedding is sinuous and discontinuous and consists of fine dark bands weaving around small, light colored, ellipsoidal clots. Induration, accompanied by alteration, has obscured the original character, so an accurate description of structures is impossible. However, the small clots are similar in many respects to structures described in many papers on pyroclastic rocks as mud balls or as muddy rain drops. An abundance of cryptoclastic devitrified glass shards is also indicative of its exogenetic origin.

Petrography

Thin sections were made from hand specimens. They were oriented, in cases of megascopically foliate rocks, normal to the plane of foliation and were ground to 30

Explanation of Plate 3

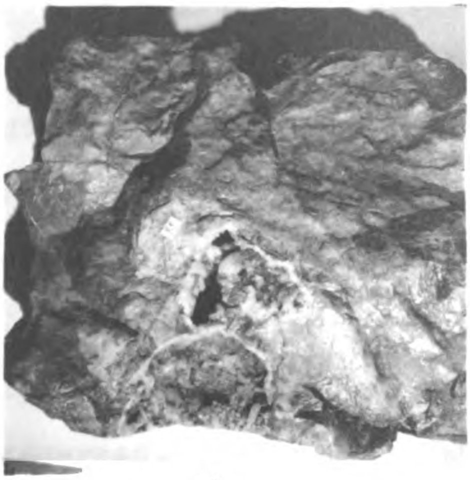
A. Specimen collected near locality 74 on the Upper Carp River. Miarolitic cavities are well developed, one to the left of the large cavity at the bottom being completely filled. Faintly visible is flow banding trending from lower right to upper left. x 0.35.

B. Specimen from the upper Carp River near locality 11 showing displacement of a thin pyroclastic zone by a small fault trending from the bottom to the top of the photograph and dipping to the right. x 0.40.

C. Volcanic agglomerate from locality 22 north of Mirror Lake showing subangular fragments cemented by a foliated matrix. x 0.75.

D. Specimen from locality 34. Two faces polished at right angles show the complex form that flow banding may assume. Note the occasional large magnetite phenocrysts within the quartziferous (light colored) layers. x 0.75.

E. Specimen from locality 3 illustrating the pronounced planarity that most of the "red rock" exhibits, and also showing the extremely variable thickness of flow layers noted in some specimens. Note the penetration of weathering agencies (light streaks) along the dark magnetitiferous layers and also the large number of spherulites (dark clots). x 0.75.

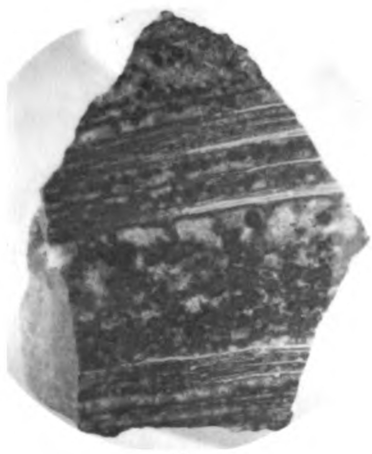


A

B

C

D



E

microns thickness. When discovered that in some cases the direction of flow could be determined, other sections were cut normal to the foliation but parallel to the direction of flow, in order more clearly to observe the structures developed as a result of movement.

The microscopic petrography of the "red rock" is not difficult in so far as the number of minerals present is concerned. It is extremely difficult, however, in that the minerals are exceptionally small and are not only incompletely crystallized in some cases, but are to a great extent altered to, and masked by, secondary minerals.

The minerals were identified by physical and optical characteristics using a standard Leitz petrographic microscope and heterochromatic light. As criteria for microscopic identification of minerals can be found in such works as Rogers and Kerr (1942) and Wahlstrom (1947), only in those cases where abnormal or variable features are observed, is reference made to them.

The "red rock", although of manifold megascopic character, shows a relatively large but limited number of crystalline types. To obviate the description of each thin section, an attempt was made to group the specimens according to microscopic characters. It was found that each thin section would conform to one of eight types. These types are described in detail.

An ocular micrometer, calibrated to several lens systems, was used to measure mineral diameters. The diameters of minerals in thin section, are not true size. Where, in a broken rock, full sized minerals may be exposed on the surface (if fracturing occurs between minerals rather than through them), the minerals are transected in a thin section. They are, consequently, somewhat smaller. Krumbein (1935, pp. 494-496), using averages of many observations, indicated that the full size minerals are approximately $4/\pi$ larger than those exposed in thin section. Later, Chayes (1950, p. 159) brought out the fact that this ratio holds regardless of the mineral shapes. Therefore, to obtain true sizes for the described minerals, the measurements given must be multiplied by approximately 1.25, except in cases of sections cut parallel to a lineation of minerals or of minerals less than the thickness of the sections (30 microns).

"Red Rock", Type 1: Good examples of specimens of type 1 are exposed at localities 3, 34, and 56. These represent a phase of the "red rock" in which eutaxitic structure is well developed (pl. 4, E).

The purple bands, which range from 50 to 500 microns in width, resolve themselves into aggregates of closely disposed, strictly parallel, and relatively continuous layers of magnetite grains. The grains of magnetite are equidimentional and average 3 microns in diameter, or are elongated crystallites and small asymmetrically developed crystals with columnar appearance. (See pl. 9, A for the various types of crystalline development of magnetite).

These crystallites and assymmetrically developed crystals may be as long as 40 microns. Long axes of the crystals, and the long directions of margarites and elongated cumulites into which the small grains are often gathered, are oriented normal or subnormal to the trend of the layers.

Magnetite as phenocrysts, ranging up to 500 microns in diameter is distributed throughout the rock irrespectful of foliation, and situated as likely in the light colored bands as in the magnetiferous ones. Most magnetite phenocrysts are euhedral and equidementional but a few are skeleton crystals with one, and sometimes two faces incompletely developed.

Directly on either side of any dark band and constituting interstitial material between magnetite grains within the dark band, is a zone of partially crystalline and incompletely individualized substance which appears to be an aggregate of devitrified ferritic glass and quartz-feldspar mixture pl. (4, C). Originating at the edges of, and extending away from the dark bands for a distance of approximately 350 microns, this material is arranged in groups of fibrous tufts. Each radiating tuft subtends two to five degrees and each group of tufts approximately forty degrees in the plane of the section. The fibres are submicroscopic in width near their origin but individuals, or small groups of individuals, can be seen due to differences in composition and consequent differences in color.

The tufts are slightly flamboyant and grade from dark brown isotropic material near their bases to more or less anisotropic material near their termini. They distort or even split the arms of the anomalous pseudo-uniaxial cross which is present when radial aggregates of acicular crystals or partially crystalline material is viewed under crossed nicols. The tufts are mutually interfering and margarites of magnetite grains are often insinuated between them (pl. 9, B).

In those portions of the tufts where the optical characteristics are not obscured by ferritic material (pl. 4, B), their relief is low and their indices are split by Canada Balsam. It is believed, therefore, that the composition of the feldspar constituting these clear areas is oligoclase, with a composition somewhere between $Ab_{80}An_{20}$ and $Ab_{90}An_{10}$. If this mineral is oligoclase, it is normal and expected that the composition will become more sodic with continued crystallization, and it is likely that the unidentifiable feldspar near the origins of the radiating fibrous tufts is the more calcic.

At an indefinite and gradational boundary at the terminal ends of the planiolitically arranged radial tufts, oligoclase gives way to small but identifiable orthoclase crystals which, in turn, give way to large orthoclase euhedrons. These large crystals project from the spherules in a manner well described by Iddings (1899, p. 412),

"The spherulites bordering more crystalline areas in lithoidal rhyolite have sometimes continued their crystallization a short distance into these areas, when they exhibit distinct prismatic rays that project beyond the apparent periphery of the spherule and resemble the teeth of a cogwheel."

The only well developed terminal crystal faces are 001, parallel to the basal cleavage. The large orthoclase crystals range from 15 x 50 microns to approximately 150 x 600 microns. Commonly, several will develop parallel and adjacent to each other with their prismatic faces close or even touching. Carlsbad twinning is common, one twin usually more highly altered and ferritic than the other.

Interestingly, sanidine, which might have been expected in a rock such as this, is entirely lacking.

Filling the interstices between orthoclase crystals, and occupying the remaining space in the area between adjacent dark bands, is anhedral to euhedral quartz. The grains are quite uniform in size, averaging 170 to 200 microns in diameter. Contacts between them are usually sutured, but occasional well developed pyramids or even bipyramids can be found.

Strained quartz is present within unstrained quartz. Occasional wavy extinction in one crystal, and occasional extinction progressing from one to another of elongated individuals arranged in fascicular groups, indicates crystallization while there was still a tendency for flow within the mass.

A peculiar micrographic quartz-feldspar intergrowth is present in small areas of the specimen from locality 3. This intergrowth is an intertongueing of thin projections of quartz and orthoclase in the manner of a rabbeted joint. Each projection is about 5 microns in length (pl. 9, C).

Many large orthoclase crystals have been broken off and included in the quartz. These fragments are often oriented with their long axes inclined toward the plane of flow as illustrated in plate 9, D.

The specimen from locality 56 has many microspherulites . These microspherulites, less than 80 microns in diameter, originate at any point in the rock and radiate outward from a group of magnetite granules.

In the specimens from localities 3 and 34, large spherules up to 5 millimeters in diameter occur everywhere in the rock (pl. 4, A, D). When in the dark bands, these large spherules radiate from a core of magnetite grains but do not affect the disposition of the layers of magnetite grains, radiating through and including them without distortion (pl. 8, A).

The spherules are compound, that is, made up of several concentric layers of tufts of radiating fibres, and are often separated to some extent by zones of magnetite or quartz granules. Occasionally these zones are entirely devoid of mineral matter. Bifurcation of the pseudo-uniaxial cross under crossed nicols is common in the compound spherules and double, or even triple splitting is not infrequent. Margarites and micro-phenocrysts of magnetite occur along the sides of the tufts of fibres, separating them into distinct units (pl. 8, A).

Other spherulites, entoölitic, and cored by aggregates of small quartz grains, or even enclaves of quartz grains without surrounding fibres, occur between or near the layers of magnetite and impart a mottled appearance to the dark bands. These spherulites average about 500 microns in diameter (pl. 8, B). The mineral coring these spherulites may be the high temperature quartz, tridymite, since identical textures described by Whitman Cross (1892, p. 441) contained this mineral.

Other minerals occur in minor amount. Very small, but perfectly developed zircon is seen occasionally in the dark bands. Occasional biotite flakes, not larger than 30 microns, are found in the planiolitic zones. A dark red, transparent mineral with parallel extinction, and sometimes as large as 70 microns, is found in quartz. This mineral, although not positively identifiable, is probably sphene (titanite). Viridite, as aggregates of cryptocrystalline green scales, is present near several large magnetite phenocrysts. This unidentifiable mineral may be either an alteration product, or microlites of a ferromagnesian mineral.

Hematite and leucoxene are alteration products of magnetite, the presence of leucoxene indicating that the magnetite is titaniferous. In addition, feldspars have altered to kaolin, and small scaly masses of yellow calcite have been secondarily introduced. The above named alteration products, together with the secondary calcite and microcryptocrystalline opacite grains, so thoroughly permeate the rock that it has a dirty, dusty-brown appearance, and the optical characteristics of minerals are obscured to the point that smaller individuals can rarely be identified.

Layers of opacite grains occupy cleavage planes in orthoclase and fill curved fractures in quartz. Small magnetite granules occupy interstices between quartz crystals, and occasionally occur as long strings lying in, or nearly in, the plane of foliation.

Elongated fluid inclusions are found in quartz and orthoclase. The clear, colorless liquid of the inclusions infrequently contains small immoveable gas bubbles. The inclusions are oriented in strings or layers in the plane of foliation and transect quartz boundaries, although those in orthoclase do not transect boundaries. Orthoclase may, thus, have a reticulate appearance, due to planes of opacite grains in the cleavage surfaces and to fluid inclusions in the plane of foliation (pl. 10, A). Quartz may be filled with opacite grains and then be included in a larger mass of clear quartz (pl. 10, B).

"Red Rock", Type 2: Specimens from localities 14 and 39 are representative of type 2. Megascopically, type 2 is dense, white, and homogeneous, with scattered, black, pepper-like spots. The thin sections appear brown under the microscope due to the universal distribution of small fluid inclusions and grains of dark minerals.

Magnetite, in the section from locality 14, is represented only as crystallites of margaritic, spiculitic, and skeleton crystal form. These are evenly disseminated throughout the rock. The section from locality has evenly distributed magnetite granules 2 to 5 microns in diameter, and scattered euhedrons and skeleton crystals of magnetite approximately 50 x 170 microns. The larger crystals range from perfectly developed, although asymmetrically formed crystals, to loose spongy aggregates of granules which tend to conform in shape to typical magnetite crystal outlines.

The groundmass consists of a finely crystallized aggregate of quartz and orthoclase averaging 30 microns in diameter, associated with tufts of radial fibres of hemi-crystalline material. The tufts are probably devitrified glass and partially crystalline acidic plagioclase, and are about the same size as the quartz and orthoclase.

Quartz, with occasional crystals which show the typical wedge-shaped twinning of tridymite, forms enclaves in the rock about 1 millimeter in diameter. The individual grains are sutured and range in size from 100 to 200 microns.

The specimen from locality 89 has, in addition to the above structures, orthoclase phenocrysts up to 150 x 500 microns. Extinction on 010 faces at 5 or 6 degrees implies that the orthoclase is very low in soda content.

A curious and unusual primary constituent in the specimen is calcite. It is perfectly clear, colorless, fractured, and is associated with quartz in enclaves. Boundaries between calcite and quartz are sutured, and calcite occasionally occurs in small grains completely surrounded by clear quartz. The calcite exhibits variable relief according to the orientation of the section, has indices both higher and lower than quartz, and is highly twinned, the 8 or 9 color bands produced by refraction being visible on the inclined twinning surfaces. These are the only primary constituents; biotite, zircon, apatite, and other minerals are absent in specimens of type 2.

Spherulization is absent but the groundmass has areas of more, and less, coarsely crystalline substance, the finer grained and more felt-like material forming an indistinct and partially developed layering in the plane of flow. However, megascopic eutaxitic structure is not present.

Magnetite, of three distinct generations (pl. 4, F), has been partially altered to hematite and leucoxene, and feldspars have been altered to scaly and fibrous secondary micas. Large quantities of secondary yellow calcite replaces feldspars and devitrified glass, destroying the mineralogical identity of large portions of the sections.

Elongate fluid-filled inclusions 1 to 60 microns in length (pl. 10, C), and large quantities of small opaque grains, cinder-like, and averaging 1 micron in diameter but ranging from 500 millimicrons to 9 microns, are oriented in discontinuous crenulate layers in the plane of flow. They may transect mineral grain boundaries or may stop abruptly.

"<u>Red Rock</u>", <u>Type 3</u>: Rock of type 3 is similar in many respects to type 1. It lacks, however, planar flow structure (pl. 5, F). Rather, it has ellipsoidal spherulites oriented in rude planes and often connected end to end. An individual spherule may be extended in this manner to 20 times its width.

Entoölitic spherules are well developed in specimens from localities 110 and turning point 8 on the traverse of the upper Carp River (pl. 16, in pocket). Individual spherules may be 3 millimeters in short dimention and, in the case of connected strings of spherules, as much as 60 millimeters in length.

The centers of the spherules are usually aggregates of anhedral quartz surrounded by older euhedral quartz and sometimes bounded by layers of magnetite granules (pl. 5, C). In addition to quartz, small tridymite crystals are occasionally identified in this zone in the specimen from locality 1. Quartz individuals range from 250 microns to 4 millimeters in size.

Extending entoölitically into the spherules from the periphery are small quartz grains or euhedral orthoclase crystals or both (pl. 5, E). Occasionally there will be an alternation of layers; a layer of orthoclase, one of quartz granules, another of orthoclase, and culminating at a center composed again of quartz. The crystals in these peripheral zones average approximately 155 microns in diameter.

Bounding the spherules, in some cases, are dark brown bands of altered devitrified glass and magnetite grains. The bands, conforming to the outlines of the spherules, are contorted and discontinuous (pl. 5, E). In other cases, tufts of fibrous feldspar-devitrified glass mixture is interposed between the margins of the spherules and the dark magnititiferous bands. In these, the layers of magnetite occupy a position between opposing sets of tufts radiating from adjacent spherules.

The situation in the interspherulitic areas is often confused. Innumerable microspherulites are sometimes present. They are either composed of radiating fibres, in which case good pseudo-uniaxial crosses are developed under crossed nicols, or are composed of an interesting, apparently homogeneous, brown substance which will neither become bright nor go extinct upon rotation under crossed nicols. Although unidentifiable, it is inferred that the material is brown glass, devitrified only to the point where it is not isotropic and yet not anisotropic.

Magnetite is present as phenocrysts 500 millimicrons in diameter and as granules 5 microns in size. The phenocrysts are evenly distributed throughout the rock and the granules are linear crystallites of various types in the felty and semi-amorphous groundmass. The crystallites are often insinuated between crystal interfaces of other minerals. This is well exemplified in the specimen from locality 1.

The specimen from turning point 8 has small quantities of primary calcite associated with quartz. It is, as described before, small, clear, colorless, fractured grains, with sutured contacts.

Orthoclase euhedrons in all specimens go extinct on 010 faces at positive 5 degrees. Small tabular orthoclase euhedrons 10 to 15 microns in diameter occur in the specimen from locality 79. These are included in areas of quartz; the quartz individuals range from 60 to 150 microns in diameter. The small orthoclase crystals are arranged in lines, the lines bifurcating and sometimes branching in one plane and at a high angle from a central axial line of crystals. This arrangement is best described as dendritic (pl. 5, A). What the paragenesis of such quartz-feldspar intergrowths might be is not known to the writer. It can only be hypothesized that the crystallization of the minerals was contemporaneous and that the intimate presence of quartz affected in some manner the habital preference of the orthoclase. The peculiar dendritic structure of the orthoclase is well described by J. P. Iddings (1899, p. 415) who says,

"These crystals branch out in two different

> ways. In some cases they appear to split, the parts being slightly inclined to one another at first, and becoming more divergent farther on. ... In other cases the branching of the long, twinned prisms is seen to obey a crystallographic law. Short prisms project from opposite sides of the Manebach twin at an angle corresponding to that between the vertical axis and clino axis, about 64°."

The quartz crystals which bear the dendritic orthoclase are oriented with their elongated c axes parallel to the trend of the orthoclase dendrites. Clear quartz tends to become euhedral, and perfect hexagonal prisms with simple pyramidal terminations extend into partially filled miarolitic cavities.

Planes of oriented fluid inclusions, filamental magnetite crystallites (pl. 5, D), and linear aggregates of opacite grains are present in the feldspar and quartz. These are oriented in the same direction as the quartz-feldspar intergrowths, the elongation of spherulites, and the layers of magnetite grains. Also included in the quartz are zircon euhedrons up to 100 microns in length.

Again hematite, leucoxene, and various other alteration products cloud the rock. Secondary calcite is abundant in the felty fibrous areas and interstitially between quartz grains in the centers of spherules. Its color is yellow and its form is radiating "books" of scales, no "book" more than 20 microns in length.

"<u>Red Rock</u>", <u>Type 4</u>: Examples of type 4 crop out at localities 39, 60, and 62. A specimen from locality 73 was obtained from a sandstone conglomerate overlying the "red rock". Whether the conglomerate is in the Ashbed group or in the "Great conglomerate" is not known.

Specimens of type 4 appear mottled megascopically (pl. 6, A, B). Microscopically, the light colored spots are aggregates of quartz crystals and the dark areas are masses of radially fibrated felty material and minute quartz granules. Actually, the basis of the rock is quartz, the dark material scattered through it in jagged patches. This imparts to the rock a brecciated or stippled aspect.

Although alike texturally, the degree of crystallization of the several samples is different. The average diameter of quartz grains in light colored areas of the rock from locality 62 is 40 microns, and those in specimens from localities 39 and 73 average 80 microns. Quartz in the specimen from locality 60 is intermediate between these in size. Other minerals vary proportionally. Quartz in the light colored areas may, however, be as large as 200 microns. It is generally sutured and includes strings and layers of submicroscopic opaque grains and small fluid inclusions oriented in the plane of flow.

The dark areas of less well crystallized specimens are composed entirely of fibrous and tufted devitrified glass-feldspar mixture in random orientation, and magnetite granules. The magnetite averages 2 microns, and the fibrous tufts 40 microns, in diameter. In the more completely crystallized specimens, equant anhedral quartz grains are associated with the fibrous tufts, both averaging 40 microns in diameter. Small unidentifiable feldspar crystals were noted. The feldspars are somewhat larger in specimens from localities 59 and 73 than in the specimen from locality 60, but they vary little from an average diameter of approximately 10 microns. Since there are no enclaves of single minerals, the dark areas are homogeneous throughout.

Spherulites of fibrous material and small orthoclase crystals become better developed with increasing crystallinity of the rocks. In the samples from localities 59 and 73, spherulites become compound, concentric layers of feldspar-devitrified glass mixture alternating with quartz (pl. 6, C). Many of these compound spherules have diameters greater than 4 millimeters. Elongated crystallites of magnetite granules radiate from the centers of the spherules, but elsewhere in the dark areas, are heterogeneously oriented.

Subspherical aggregates of magnetite grains and skeleton crystals of magnetite, both as large as 600 microns, are evenly distributed as phenocrystoid masses throughout the rock. Small, perfect, euhedral zircons are associated with the magnetite phenocrysts (pl. 6, D). Sphene, in very small subhedral grains, is also present, not only in association with magnetite, but as inclusions in quartz.

An unusual structure present in the sample from locality 59 is a fracture, evidently formed during consolidation of the rock, and filled with a more finely crystalline material of the same composition and texture. The hand specimen exhibits portions of this crack which were never filled. It may be assumed that at this stage the magma was too viscous to enter the crack (pl. 6, C).

Other than the above, type 4 specimens are similar to other "red rock". Planes of fluid inclusions with small gas bubbles, and planes of magnetite, are present in quartz and feldspar. Secondary calcite and dusty hematite, leucoxene, and kaolin minerals cover all portions of the rock. Also, unidentifiable viriditic material associated with magnetite, and appearing in interstitial spaces between quartz and orthoclase, is present in small quantities.

"<u>Red Rock</u>", <u>Type 5</u>: Type 5 rocks are aphanitic-porphyritic to aplitic-porphyritic in texture. A specimen from locality 103 consists principally of sutured quartz individuals about 100 microns in diameter, orthoclase phenocrysts, and magnetite grains. A specimen from locality 116, occuring as an included pebble in a conglomerate lens in the Ashbed group, has a basis not so completely quartziferous, but composed of microscopic unoriented orthoclase laths.

Magnetite phenocrysts in this specimen reach dimentions greater than 1 millimeter and are often nearly destroyed by the growth of a light green, scaly, unidentifiable secondary mineral. Magnetite phenocrysts in the specimen from locality 103 are smaller, averaging about 20 microns in diameter. These are usually euhedrons or semi-euhedral skeleton crystals, many of which have columnar outlines, or are aggregates of small grains. Both specimens are filled with globulites, longulites, and trichites of magnetite, occuring anywhere in the rock, and assuming random orientation except in a few partial spherulites in the specimen from locality 11b. In these, they are arranged radially with respect to a central point.

Orthoclase was the only feldspar identified. It is located in the areas of partial spherulitic growth and is associated there with fibrous devitrified glass-feldspar material. It is developed as laths in those portions of the groundmass which are completely crystalline, it is found as intergrowths with quartz, and it occurs as phenocrysts.

In the areas of partial spherulitic growth, the orthoclase crystals are elongated, twinned according to the Carlsbad law, and average about 10 x 40 microns. As laths in the groundmass, it is gradational in size, but a tendency to group into three sizes is apparent. These are approximately 10 x 40 microns, 30 x 120 microns, and 180 x 550 microns. Carlsbad twinning is common in the laths and is almost universal in the phenocrysts. The phenocrysts, highly altered to kaolin, and filled with layers of magnetite, ferritic grains, and fluid inclusions, range up to 1 x 3 millimeters in size. Clinodomes and various oblique faces are present on some crystals.

Micrographic intergrowth of quartz and feldspar is common, but the orthoclase, rather than crystallizing in dendritic forms as Manebach twins as described earlier, exists as separate, more or less equant, euhedral, and untwinned crystals arranged in lines parallel to a microscopically well defined, but megascopically unobservable, foliation.

Quartz is often twinned in the section from locality 116. The twinning is especially noticeable in quartz occurring in a primary fracture which was filled by more acidic later magma (pl. 6, E). The c axes of the twins are parallel, and the twins, if oriented parallel to the proper prism face, will become extinct as a unit. Usually, however, extinction is progressive, and looks much like the albite twinning of plagioclases. Associated with quartz is subhedral zircon up to 300 microns in length.

"Red Rock", Type 6: Rocks of this type vary in megascopic appearance in that some, like the specimen from locality 74, are uniformly dark brown and appear completely aphanitic, while others, including a sample of the supposedly intrusive rock from the hill upon which stands the Bergland fire tower (46° 40' N., 89° 38' W.), possesses numerous small light colored spots and feldspar phenocrysts. This rock appears in the literature as the "Chippewa" felsite.

Microscopically, the basis of all specimens of this type is a micrographic intergrowth of quartz and orthoclase. The quartz individuals average 210 microns in diameter, have sutured contacts, and are equantly subpolygonal to subcircular in outline. Upon insertion of the upper nicol, the specimen assumes the appearance of a "buttermilk sky" (the intergrowth), superimposed upon a larger "patchwork quilt" (the sutured equant quartz crystals) (pl. 7, A, B).

The intergrown subhedral to euhedral feldspar is high potassium orthoclase. The crystals are slightly elongate and average 7 microns in diameter. Most are thinner than the section and, therefore, go extinct with the enveloping quartz. These are oriented, long axes parallel, in lines and in bifurcating and branching linear groups like similar structures described in specimens of type 3. The linear groups transect boundaries of the quartz grains without changing direction.

Light colored areas in the specimens from the Bergland Fire Tower hill are merely zones of relatively clear quartz which have no intergrown orthoclase. These areas average 350 microns in diameter and usually contain several quartz individuals. Occasionally, however, a single crystal, as large as 600 microns, will constitute a light area. A progressive tendency to euhedrality is apparent in quartz crystals in a traverse of the section from an area of intergrowth to an area of pure quartz.

Bounding and projecting into the quartz enclaves are elongated euhedrons of orthoclase approximately 10 x 60 microns in size. These are apparently untwinned, although the presence of ferritic material might obscure such structures. Also in the quartz are curved and intersecting perlite-like cracks filled with magnetite granules.

The rock from locality 74 also has areas of quartz more or less free of orthoclase, although they are not megascopically apparent. This is due to the continued presence of intergrown orthoclase. It is, however, in lesser amount and more widely dispersed than elsewhere. The feldspar crystals, averaging approximately 8 x 25 microns in these areas, are unoriented and larger than those in the rest of the rock. The quartz here, as in similar areas of other specimens, tends to become euhedral and to possess curved cracks filled with magnetite granules.

Euhedrons of zircon up to 100 microns in length, and grains of sphene less than 15 microns in length, are present in small quantities as inclusions in the quartz of all specimens. Biotite in very small and thin flakes is also present, but usually occurs associated with, or relatively near, groups of magnetite grains or hematitic zones.

Magnetite in all specimens varies from 1 to 100 microns in diameter, but a large percentage of the grains fall into one of three distinct sizes, 2 microns, 10 microns, and 50 microns. It is much altered to hematite; leucoxene is rare.

The only real difference between the other specimens of type 6 and the specimens from Bergland Fire Tower hill is the development in the latter of orthoclase phenocrysts.

These are elongate, up to 1.1 millimeters in length, and, if those exposed in the thin sections are representative, untwinned.

Kaolinization is far advanced and ferritic material, mostly hematite secondary after magnetite, has so thoroughly clouded the rock that mineralogical identification is often impossible. The feldspars, especially phenocrysts in the specimen from the fire tower hill, are masked with these alteration products, staining them dark brown and rendering them incapable of reacting anisotropically under crossed nicols.

"Red Rock", Type 7: Only one thin section of this type of rock was made. The specimen came from locality 73 and occured, as did one of the specimens described in type 3, as an included pebble in a sandstone conglomerate.

This thin section is similar in microscopic characteristics to those of type 6, but is approximately twice as coarsely crystalline, with quartz crystals averaging 450 microns in diameter as opposed to a diameter of 210 microns in type 6 specimens. The size ratio of other minerals is similar.

Orthoclase is again intergrown with quartz. The separate euhedrons average 15 x 25 microns and are thinner than the section, going extinct with the quartz in which they are included. Only an occasional crystal shows specific mineralogical characteristics, and optical measurements of these were the basis upon which they were identified.

As described before, clear areas are produced by the failure of intergrown orthoclase to completely fill the quartz. The clear areas thus left usually have polygonal outlines, not in the shape of quartz crystals, but square or rhomboid. The cause for this habit of parallelogrammetricity of clear areas is unknown to the writer. Slightly larger orthoclase crystals project into these clear quartz enclaves, which, in this specimen, average 250 microns in diameter and are usually a single individual.

Orthoclase phenocrysts are considerably altered, untwinned, and similar in every respect to those of type 6 except they are larger, averaging 2 x 3 millimeters.

Magnetite aggregates as large as 1.5 millimeters, and made up of loosely grouped, 6 micron grains, are scattered through the rock (pl. 6, F). Some of these aggregates have been oxidized to hematite, the hematite spreading through the rock and enlarging the area covered by ferritic material to 3 or 4 times its original size. Magnetite euhedrons averaging 300 microns in diameter are also abundant.

Other primary minerals are biotite, calcite, and euhedral zircon. The biotite occupies cracks in quartz, and calcite is found as clear, fractured grains, sutured to quartz and surrounded by it (pl. 7, C).

Secondary calcite is abundant. It replaces both feldspar and quartz and, further, tends toward selective replacement of individual quartz crystals, assuming the original sutured quartz boundaries, rarely transecting them. The replacement progresses by precipitation of small calcite crystals which eventually coalesce by continued growth. All calcite crystals replacing one quartz individual will assume the same orientation and, when the quartz is completely replaced, will go extinct as a unit as the quartz originally did. A "ghost" of the original micrographic intergrowth texture is preserved. Thus, one not acquainted with the specimen, and viewing it for the first time, not knowing otherwise, would be inclined to believe it a primary mineral.

"Red Rock", Type 8: Specimens classified in type 8 are the pyroclastics. Since such fragmental rocks occur under a variety of environments, both endogenetic and exogenetic, they can be expected to possess wide ranges in physical and mineralogical characteristics. They are extremely difficult to describe sufficiently accurately that one not having seen the specimen can picture its appearance. In cases like this, one photograph is, indeed, worth ten thousand words. The specimen to be described is from locality 22, the only outcrop of pyroclastic rocks of which a satisfactory photograph is available (pl. 11, C).

This rock is type 3. Two large included fragments, approximately 30 millimeters in diameter, have all the characters described in the section on type 3 rocks. In addition to large fragments are small angular pieces, variable in composition, and evidently the result of brecciation or exfoliation of larger fragments. These range in size from 50 microns to about 5 millimeters. Although not shown in the section, a full range of fragment sizes, from very small ones to blocks several decimeters in diameter, is probably present.

The fragments have come from previously consolidated and differentiated material and therefore include those which have discontinuous, closely spaced strings of magnetite granules, and those which are composed of brown, semi-anisotropic, felty material filled with microcrypto-crystalline ferritic grains. Broken pieces of zircon crystals up to 50 microns in diameter, and angular rock fragments which include numerous sutured quartz grains with strings of fluid inclusions, are also present. Pieces of rock with well developed and relatively coarse foliation like those of type 1, and fragments of spherulites with attached dark bands, mineralogically and texturally identical with portions of the foliation of type 1 rock, are abundant (pl. 7, D). This is to be expected since specimens of types 1 and 3 are separable only in degree of planarity of foliation; the degree of crystallization, and the number and behavior of minerals in the two types is identical.

The presence of numerous fragments of perfectly clear, colorless, vitreous glass filled with magnetite granules and with elongated fluid inclusions, a few of which have very small gas bubbles, is unusual.

The fragmental material has been inundated and cemented by still fluid portions of the same magma. Differentiation between the inclusions and the cementing material is difficult due to continued fracturing through both the cementing material and the fragments, both of which were later cemented. As this cycle progressed, the remaining magma became more acidic, until the latest fractures were filled with quartz.

The cementing magma conforms to type 3 rock. Micrographic intergrowth of orthoclase and quartz is common; quartz is sutured; euhedral zircon up to 110 microns in length is present in small quantities. Strained quartz is evident everywhere, and large areas of partially crystalline devitrified glass-feldspar mixture occurring as fractured fragments, the fractures filled with quartz, are scattered through the rock. These fractured spherulitic growths are, in this specimen, nearly isotropic and range from dark brown to black. In most places these spherulites are surrounded by sinuous and discontinuous bands of magnetite grains, typical of type 3.

Fascicular aggregates of a brown material become extinct progressively and at a slight positive angle. A faint granular texture in these aggregates at, or just below, the limit of resolution of the eye-microscope combination, is inferred to be minute orthoclase crystals a few millimicrons in diameter and arranged in parallel orientation. This mineral could, by the single criterium of slight positive extinction, be inferred to be plagioclase.

However, after consideration of the facts that plagioclase was found exclusively in fibrous radiating tufts, that the texture in question is, like the usual quartz-orthoclase intergrowths, in lines of granules --although smaller than usual, and that the background material appears to be homogeneous like quartz, its identification as orthoclase is felt to be correct.

The banding in the cementing material conforms to, and wraps around, the included fragments. The fragments have been attacked, corroded, and embayed by the cementing material, and as a result their crystallinity has been considerably reduced for distances as great as 3 millimeters into their interiors. In many places, the outer edges of the fragments have become colorless to brown glass, filled with magnetite granules (pl. 7, E).

Secondary calcite as yellow, radiating packets of scales, has replaced large quantities of glass, feldspar, and quartz.

Basic Rock within the "Red Rock" Area: Although not properly a part of this paper, several basic rocks associated with the "red rock" are described.

Two dike-like bodies of dark rock are found within the "red rock" at localities 13 and 15 on the upper Carp River. The specimen from locality 13 exhibits a faint megascopic lineation which is reproduced microscopically by sub-parallel orientation of elongated plagioclase laths. These range in composition from $Ab_{72}An_{28}$ to $Ab_{70}An_{24}$. They are often bent into simple or sigmoid curves, and are approximately 25 x 125 microns in size. Between these laths are 10 to 40 micron grains, globulites, and spiculites of magnetite. Being interstitial to the feldspar, they are also in linear orientation.

Unoriented plagioclase phenocrysts averaging 1 x 2 millimeters are scattered through the rock. Their composition is approximately $Ab_{46}An_{54}$ and twinning in them is uncommon or is obscured by ferritic material and fluid inclusions.

The specimen from locality 15 is exceedingly fine grained, but has occasional phenocrysts of feldspar. This rock fractures conchoidally to knife-like edges. The groundmass consists of plagioclase laths of composition $Ab_{76}An_{24}$ and averaging 13 x 80 microns, although they may range from 1/4 to 4 times this large. Associated with the groundmass feldspar is euhedral, equant to prismatic magnetite crystals 3 to 15 microns in diameter. There are also patches of magnetite and quartz, the quartz strained and going extinct in an extremely wavy and discontinuous manner.

Feldspar phenocrysts, averaging $Ab_{66}An_{34}$, and zoned, are scattered through the rock. They are never more than 1 millimeter in diameter and are highly twinned according to the Carlsbad and albite laws.

Evenly dispersed through the rock are dark patches, up to 6 millimeters in diameter, and consisting of concentrations of magnetite and pennine. Pennine, an alteration product of basic silicates, is a member of the chlorite group. The iron for this mineral was probably derived from magnetite. The dark mineral concentrations, although containing many small crystallites, tend to have rectangular outlines, and the tendency for magnetite granules in them to gather into linear strings oriented parallel to the long axes of the dark concentrations is evident (pl. 7, F).

Other secondary products are kaolin and small quantities of epidote from feldspar phenocrysts, and hematite from magnetite. The hematite is in dust-like particles and clouds all minerals. A small amount of secondary calcite is also present.

Basic Rock Superincumbent upon the "Red Rock": Basic flows overlying the "red rock" are usually quite vesicular near their tops and their bottoms, although the vesicles are generally small. They are elongated and oriented in the direction of flow. They are filled with secondary epidote, quartz, and microlites of calcite and epidote. The microlites are intergrown with the quartz.

In a specimen from an outcrop 40 meters downstream (north) from locality 11, the intervesicular material is small plagioclase laths oriented in the direction of flow and ranging in albite milecule from 70 to 80 percent. Unoriented plagioclase phenocrysts which are, curiously, unzoned, range in albite molecule from 60 to 70 percent. Cleavage planes in these are often filled with biotite.

Ferritic material, mostly hematite surrounding magnetite grains, is abundant to the point of making large sections of the rock completely black. These large opaque sections are more or less spheroidal and are evenly distributed throughout the specimen.

Another specimen, from a locality approximately 100 meters downstream from locality 11, is highly vesicular, even scoriaceous. The vesicles, arranged in rude lines, average approximately 60 microns in diameter. The original vesicular structure has been preserved but most intervesicular areas have become opaque with secondary hematite. Epidotization of the groundmass is nearly complete, and quartz and calcite constitute the rest of the secondary mineralization. No original feldspars are left, nor are pseudomorphic outlines of them retained.

A specimen from locality 18 is also highly vesicular, the vesicles 500 microns to 10 millimeters in diameter. The specimen comes from the extreme bottom of a flow, and the vesicles, which are elongated and crushed, decrease progressively in size and number toward the center, and disappear entirely within 4 meters.

The poorly oriented feldspars of the groundmass are approximately $Ab_{70}An_{30}$. Opaque ferritic areas are present in the groundmass of this specimen, but the vesicles are filled with beautiful, clear, subhedral quartz which often surrounds and suspends the broken walls of the vesicles. Small quantities of secondary epidote are also found associated with the quartz within the vesicles (pl. 8, C).

Basic Rock within Sandstone: Near the Nonesuch road, and approximately 645 meters south of the point where the road crosses Union River, is a basic dike intruding a sandstone. The sandstone strikes 30° and dips 40° north.

The basic rock is aplitic and nearly black. Although it is not entirely exposed, it is thought to be a dike rather than a flow, because it is much more basic than the flows and lacks vesicles. It trends 100° and dips 40° north.

Plagioclase laths in "log jam" orientation and averaging 200 x 550 microns are the basis of the rock. Their composition ranges from $Ab_{50}An_{50}$ to $Ab_{60}An_{40}$. Fluid inclusions lying in cleavage planes were noted. Interstitial between the plagioclase laths is pigeonite, but unusual pigeonite in having an extremely small axial angle.

Magnetite euhedrons and skeleton crystals, many with prismatic outline and averaging 100 microns in diameter, are scattered through the rock. A few, however, are as large as 600 microns and a few are as small as 40 microns. Biotite, in small thin flakes, is also present.

A secondary mineral, pennine, is relatively abundant. It replaces both pyroxene and feldspar, and crystallizes as fibrous, "Berlin blue", aggregates which show the negative axial figure under crossed nicols (pl. 8, D, E). It is a member of the chlorite group, occuring in metamorphic and altered rocks.

Explanation of Plate 4

A. Specimen from locality 3 illustrating dark and light layers, euhedral orthoclase crystals, and magnetite phenocrysts in the quartziferous layers. It also shows spherulites with bifurcating negative axial crosses. Nicols crossed. x 14.

B. Specimen from locality 5 showing ferritic material which tends to be most dense near the dark bands. Plain light. x 16.

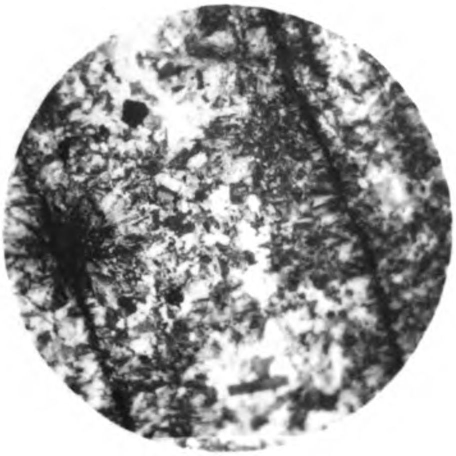
C. Specimen from locality 54 showing twinning in orthoclase, multiple layers of magnetite granules composing one dark band, and orientation of elongated crystals normal to the trend of flow bands. Nicols crossed. x 14.

D. Specimen from locality 54. Same field as C. Note spherule in the quartziferous band. Plain light. x 16.

E. Specimen from locality 56 showing contorted foliation, multiple dark layers separated by partially crystalline material, and penetration of weathering along the dark layers. Nicols crossed. x 14.

F. Specimen from locality 89 showing 3 distinct generations of magnetite crystals. Plain light. x 16.

PLATE 4



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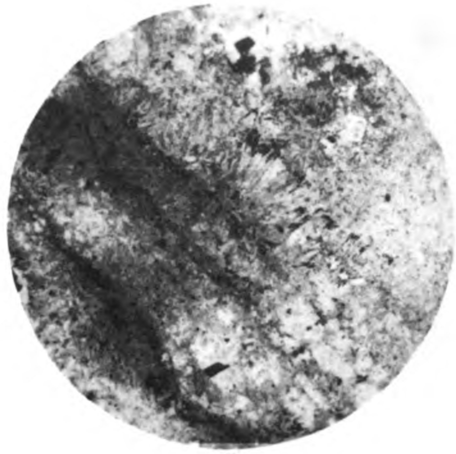
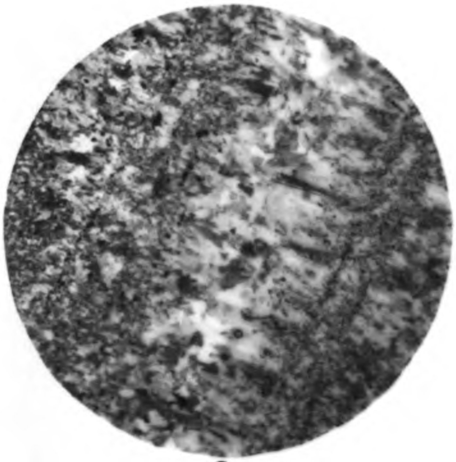
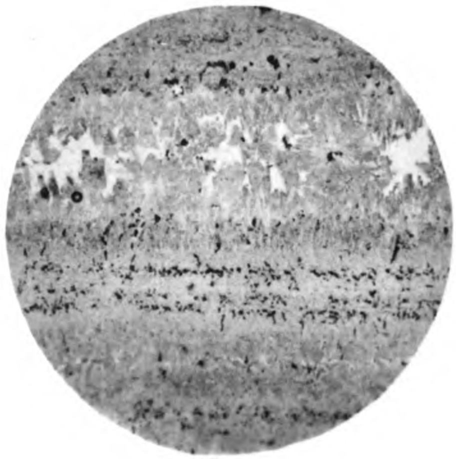


B



C



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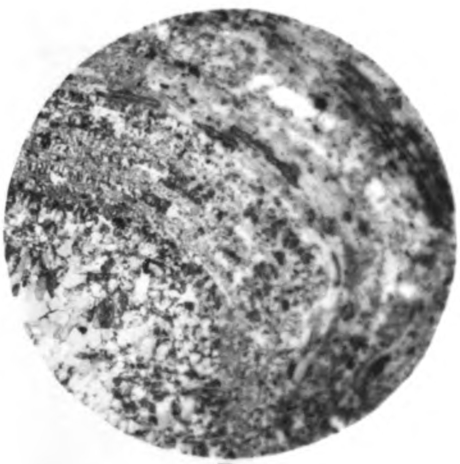
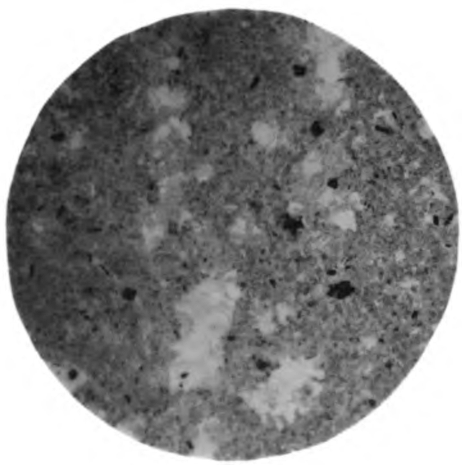


E



F

Explanation of Plate 5

A. Specimen from locality 79. Intergrown quartz and orthoclase with "buttermilk sky" aspect. Plain light. x 55.

B. Specimen from locality 79 showing spherulitic groundmass and euhedral orthoclase in quartz enclaves. Crossed nicols. x 14.

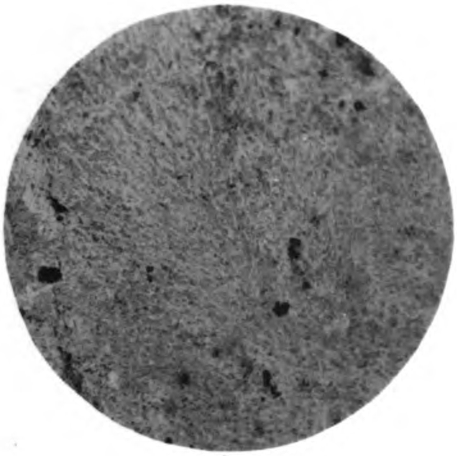
C. Specimen from locality 110 illustrating sinuous flow banding and quartz clots. Plain light. x 16.

D. Specimen from locality 79. Elongated magnetite crystallites. Plain light. x 280.

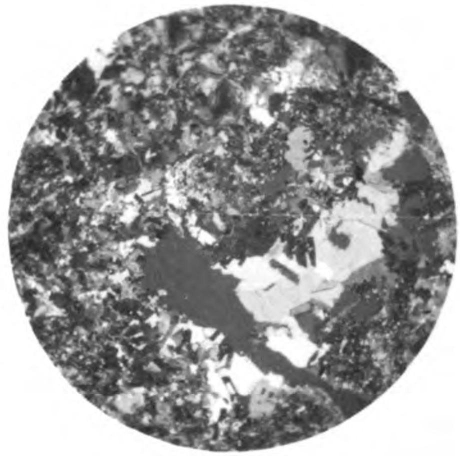
E. Specimen from locality 8 on the upper Carp River traverse (pl. 16, in pocket). Quartziferous spherulites connected end to end and surrounded by radiolitic felty material. Crossed nicols. x 14.

F. Specimen from locality 1 showing torturous flow banding. Dark bands are layers of magnetite grains. Plain light. x 16.

PLATE 5



A



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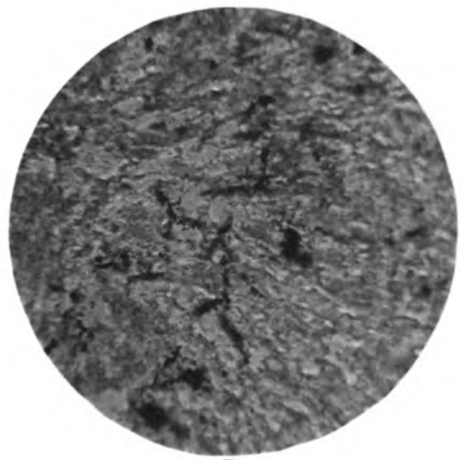
C



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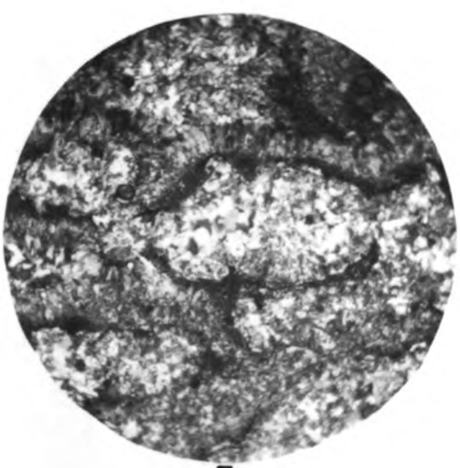

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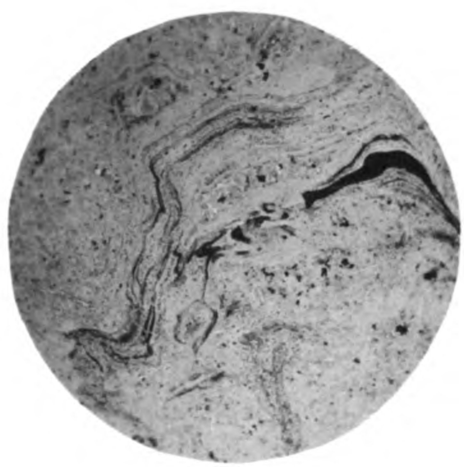


F

Explanation of Plate 6

A. Specimen from locality 62 showing patchy appearance. The light areas are quartz and the daek areas are microcryst lline feldspar. Plain light. x 10.

B. Specimen from locality 62. Same field as A. Nicols crossed. x 14.

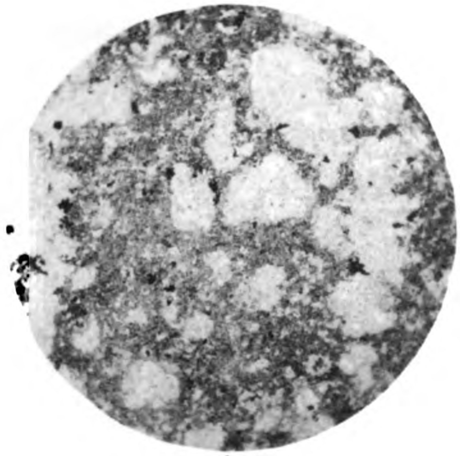
C. Specimen from locality 39 showing compound spherule and a primary fracture (right side of photograph) filled with a more acidic later magma and broken rock fragments. Plain light. x 16.

D. Specimen from locality 73 showing euhedral zircon in magnetite phenocrysts. Note the small elongate magnetite crystallites. Plain light. x 55.

E. Specimen from locality 116. This is a primary fracture filled with a magma of quartz and zircon. Note small twinned quartz near the bottom. The twinning is parallel to the c axis. Crossed nicols. x 50.

F. Specimen from locality 73. This is typical of large spongy aggregates of magnetite granules in phenocrystoid masses. Note the "buttermilk sky" quartz-feldspar intergrowth. Plain light. x 55.

PLATE 6



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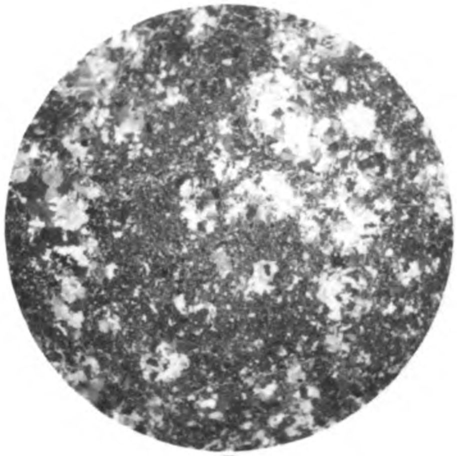

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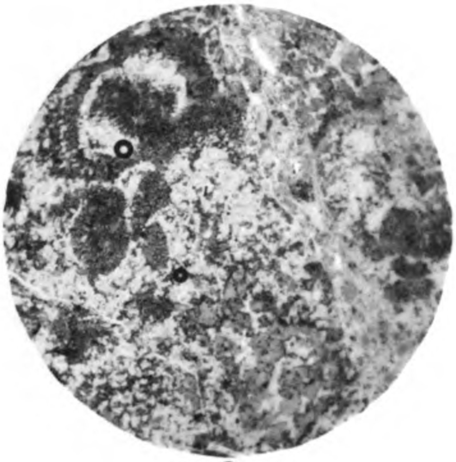
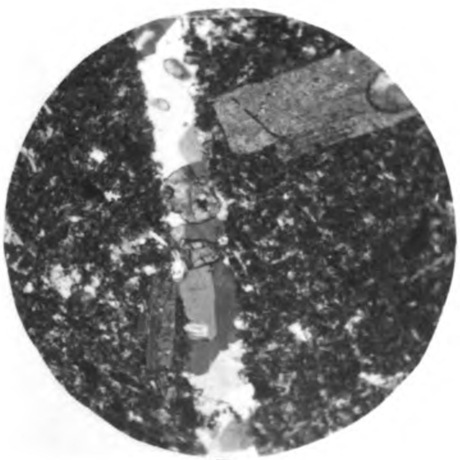
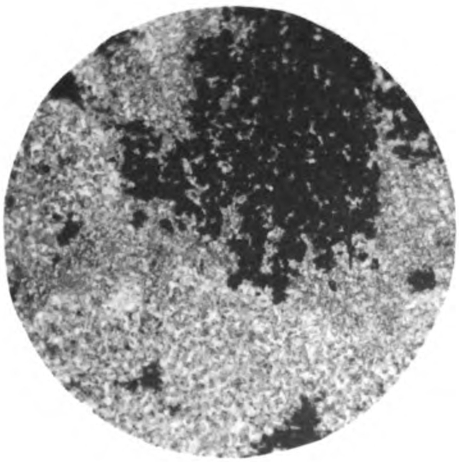


C

D



E



F

Explanation of Plate 7

A. Specimen from Bergland Fire Tower hill showing euhedral zircon in quartz enclaves. Plain light. x 55.

B. Same field as A showing the "patchwork quilt" with superimposed "buttermilk sky". Crossed nicols. x 50.

C. Specimen from locality 73 showing primary calcite (high relief) in quartz. Note spongy magnetite aggregates. Plain light. x 55.

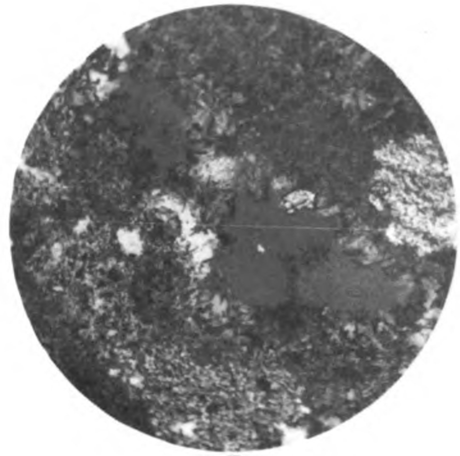
D. Specimen from locality 22 showing the microbrecciation of the "red rock" in pyroclastic zones. Plain light. x 16.

E. Specimen from locality 22. This is the contact between enveloping magma (upper right) and an included fragment. The outside of the fragment has become glassy. Note how the fragment has become dark brown with oxidized ferritic material. Plain light. x 55.

F. Specimen from the basic dike-like body at locality 15. The rock is aphanitic and contains straight sided aggregates of dark minerals (bottom). Plain light. x 16.

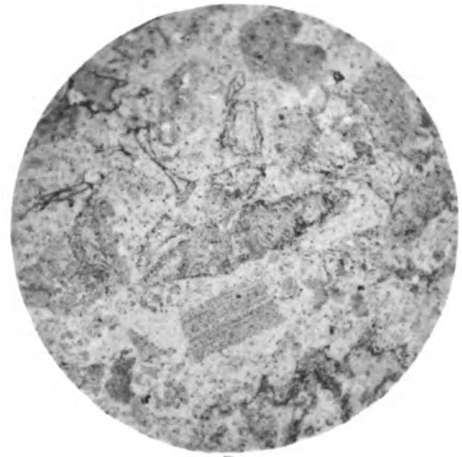
PLATE 7

A

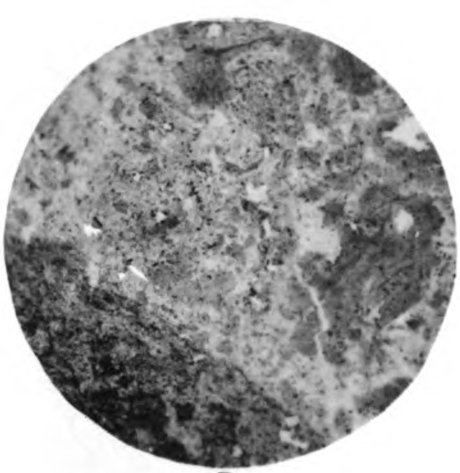


B

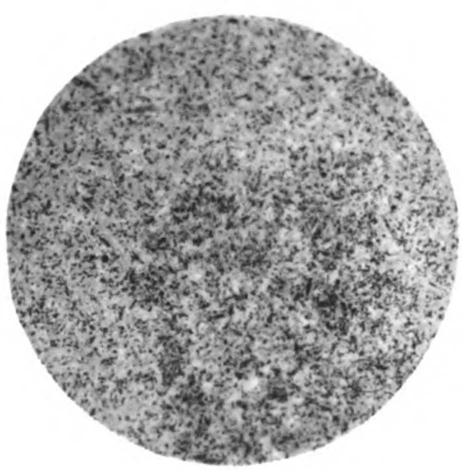
C



D



E



F

Explanation of Plate 8

A. Stylized camera lucida drawing of a spherule, cored in magnetite, and penetrating layers of magnetite without distortion to the layers or to the spherule. Note bifurcation of the negative axial cross and the several layers of fibres, bounded by magnetite granules or by open spaces (right).

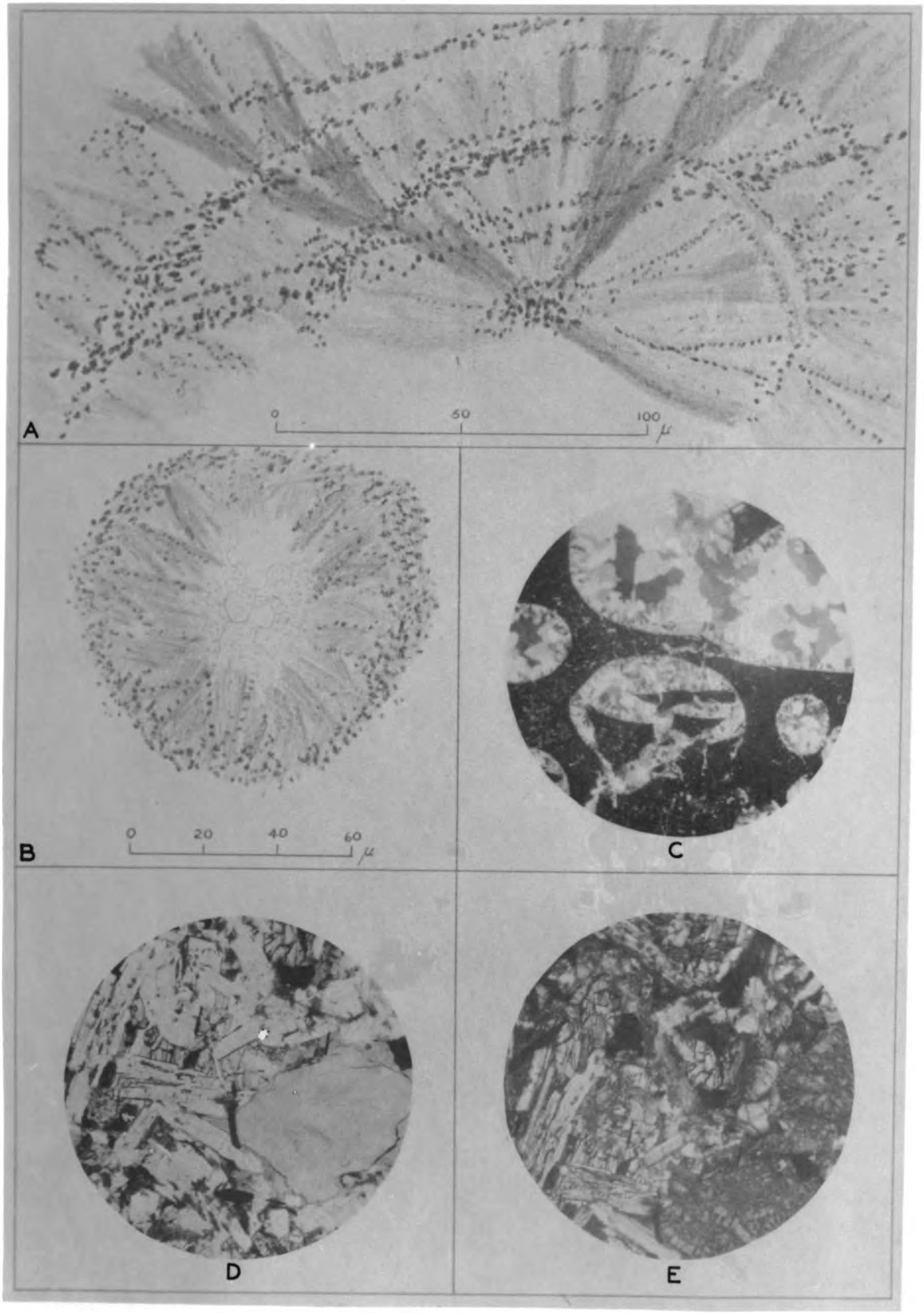
B. Stylized camera lucida drawing of an entoölitic spherule. Bounded by magnetite, it is cored by quartz.

C. Specimen from locality 18. This is a basic flow directly overlying the "red rock". Note the broken vesicle walls, surrounded and suspended by secondary quartz. Crissed nicols. x 14.

D. Specimen from basic dike along Nonesuch road showing plagioclase laths and secondary pennine. Plain light. x 55.

E. Same field as D. Crossed nicols. x 50.

PLATE 8



Explanation of Plate 9

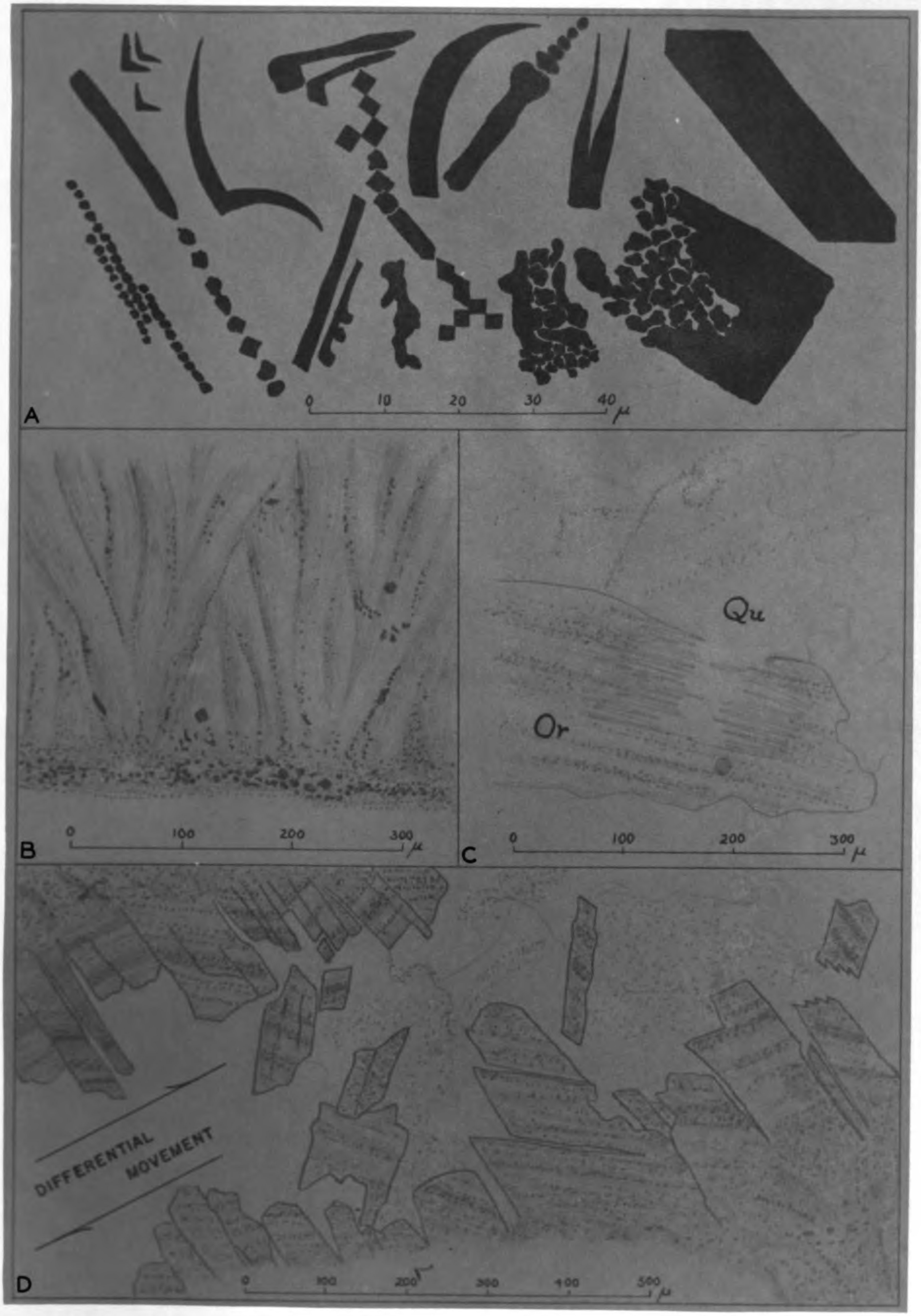
A. Diagram illustrating various forms that incipient magnetite crystals may assume in the "red rock".

B. Stylized camera lucida drawing of the planiolitically arranged radial tufts. They originate at a layer of magnetite granules and radiate subnormal to it. Note the strings of magnetite granules between adjacent tufts, separating them.

C. Camera lucida drawing of a peculiar intertongueing intergrowth of quartz and orthoclase.

D. Stylized camera lucida drawing of a quartziferous layer in the "red rock" showing how orthoclase crystals are broken off by differential movement.

PLATE 9


A
0 10 20 30 40 μ
B
0 100 200 300 μ
C
Qu
Or
0 100 200 300 μ
D
DIFFERENTIAL MOVEMENT
0 100 200 300 400 500 μ

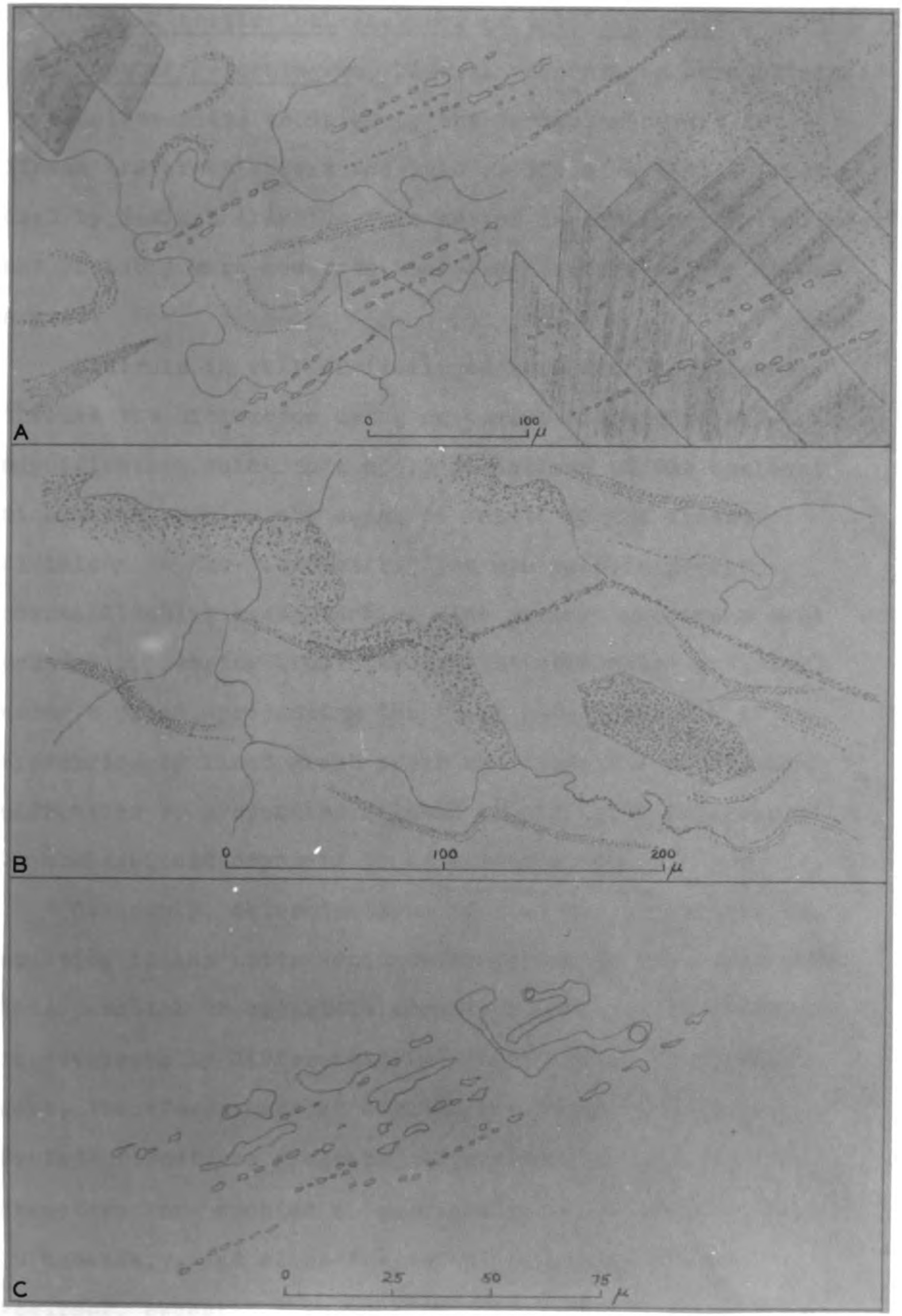
Explanation of Plate 10

A. Diagram illustrating the attitude of fluid inclusions, strings and layers of magnetite, and ferritic material in quartz and orthoclase. Note especially that ferritic material occupies cleavage planes in orthoclase and that magnetite and fluid inclusions lie in the plane of flow. Note also that fluid inclusions transect quartz boundaries but do not transect orthoclase boundaries.

B. Diagram illustrating the attitude of layers and areas of magnetite in quartz.

C. Enlarged camera lucida drawing of one series of fluid inclusions. Note the occasional gas bubble.

PLATE 10



Mineralogical Analyses of the "Red Rock"

Mineral Percentages: Mineral percentages were obtained by counting units occupied by the various minerals in linear traverses across the thin sections, a method first used by Rosiwal (1898). This method is considerably easier and probably more accurate than areal estimation by use of a grid.

Minerals in well crystallized specimens were counted through the microscope using an ocular micrometer and a magnification which made short dimentions of the smallest minerals approximately equal in length to the finest divisions on the micrometer. The minerals in poorly crystallized or exceptionally fine grained specimens were counted by passing light through the microscope and, by using a prism, projecting the image onto a table. If appropriately lined graph paper was used, the added magnification by projection allowed linear units intercepted by the smallest crystals to be easily counted.

Obviously, determinations of mineral percentages by counting linear units would be erroneous if traverses were made parallel to eutaxitic structure, since such structure is developed by differentiation of minerals. Traverses were, therefore, made at high angles to any linear or foliate structures present. Approximately 1,000 crystal diameters were counted on each slide. This is more than is necessary, and since the method is not of extreme accuracy, especially in rock as fine grained as the "red rock", decimal percentages were rounded off to the nearest percent, except in those slides where it was felt that greater accuracy was obtained (table 2).

Mineral Determinations: Since plagioclases occur in small amount, and only as microcryptocrystalline aggregates with other minerals, they could not be counted. Likewise, ferritic dust, biotite, and sphene were not counted. Ferritic dust, although in large volume, is submicroscopic, and biotite and sphene occur only in traces, their combined volumes not significant to proper classification of the rock.

Specimens with quartz-orthoclase intergrowths presented an unusual problem. The distances across orthoclase crystals averaged approximately 3 microns, and interfeldspar areas of quartz, approximately 2 microns. In view of the fact that counting through this material in each traverse of the sections would involve an unnecessary amount of work, an average composition for this material was obtained. Traverses of 3 millimeters were made across this material on each of ten slides. Thus, approximately 1,000 crystal units per slide were counted. In every case, the ratio of quartz to orthoclase was 43 to 57. From these measurements it was assumed that similar areas in other thin sections would have similar composition.

Unidentifiable groundmass feldspar was counted as such, and assumed to be 100 percent feldspar. This assumption may not be valid since such areas may include considerable quantities of glass. Clouding by ferritic material, however, makes identification of the minerals impossible, and since the groundmass appears anisotropic, the assumption that it is feldspar is probably not far from the truth.

Spherulitic growths contain a variety of mineral matter in such small particles that differentiation cannot be made. Iddings (1899, pp. 412-416) considers spherules from Yellowstone Park to be composed entirely of orthoclase. The writer, unable to determine the minerals, with the exception of a highly uncertain identification of oligoclase in one thin section, was faced with the necessity of assuming a composition not based on experimental data.

Interestingly, and possibly significantly, if the material in spherulitic growths is assumed to contain quartz and orthoclase in the same proportion as was determined for the micrographic intergrowths, the quartz-feldspar ratio of a large percentage of the specimens will be nearly the same (table 2).

Classification: Unfortunately, the determination of mineral percentages was so uncertain that synthetic chemical analyses derived from mineralogical determinations for purposes of comparison with analyses of acid extrusive rocks from other areas, was impossible. However, they were sufficiently accurate that classification could be made. A classification by Johannsen (1932, pp. 141-161) was used since it is based upon the percentage by volume of minerals present. It has the additional advantage

TABLE SHOWING MINERAL PERCENTAGES IN VARIOUS "RED ROCK" SPECIMENS

Locality	Type	Percent Quartz	Percent Orthoclase	Percent Spherulitic Material	Percent Unidentifiable Groundmass Feldspar	Percent Magnetite	Percent Secondary Calcite	Percent Zircon	Total Quartz Percent	Total Feldspar Percent
3	1	30	4	21 Quartz 9.0 Feldspar 11.0	38	7		0.1	39	53
34	1	19	22	57 Quartz 24.5 Feldspar 32.5		2			43.5	54.5
56	1	18	21	59 Quartz 26.5 Feldspar 32.5		2			44.5	53.5
14	2	38			25	2	35		38	25
89	2	34	8		44	3	11		34	52
1	3	44	2	52 Quartz 22.5 Feldspar 29.5		2			66.5	31.5
08 on river traverse	3	38	51	8 Quartz 3.5 Feldspar 4.5		3			41.5	55.5
79	3	35	43	19 Quartz 8.2 Feldspar 10.8		2	1.		43.2	53.8
110	3	31		47 Quartz 20.0 Feldspar 27.0		16	6		51	27
39	4	42			56	2		0.1	42	56
60	4	42			55	3			42	55
62	4	38			52	7	3		38	52
73	4	36	3	57 Quartz 24.5 Feldspar 32.5		4		0.1	60.5	35.5
103	5	- - - - - - u n i d e n t i f i a b l e - - - -				5.5		0.1		
116	5	16	16		61.5	6.5			16	77.5
△74 on river traverse	6	41.4	55.1			3.5			41.4	55.1
98	6	41.8	56.1			2.0		0.1	41.8	56.1
22	8	- - - - - - u n i d e n t i f i a b l e -								

Ferritic dust, sphene, leucoxene, biotite, and other accessory minerals are not included as they occur only in traces.

Spherulitic material is assumed to contain the same quartz-feldspar ratio as the more highly crystalline intergrowths of quartz and feldspar, 43 parts quartz to 57 parts feldspar.

Groundmass feldspar is assumed to be one hundred percent feldspar.

Magnetite is almost entirely primary but some secondary hematite may have been counted as magnetite.

that rocks can be identified by number as well as by name and, thus, do not suffer from the frailities of language.

According to this classification, the "red rock" is 115E. The first number indicates that there are less than 5 percent dark minerals; the second number indicates that the plagioclase is more acidic than $Ab_{90}An_{10}$; the third number indicates that the orthoclase is in larger quantity than quartz and that there is less than 5 percent plagioclase; E denotes that the rock is extrusive.

By name, this rock is kalitordrillite, a rock similar to the extrusive alaskites of the Tordrille Mountains, Alaska, but containing less plagioclase.

Discussion

Origin: The possibility that the "red rock" is clastic or metamorphic must be considered. The evidence presented in the descriptions is overwhelmingly against the "red rock" being clastic and no more need be added here. However, structures and textures similar to those in the "red rock" are sometimes developed in metamorphic rocks, especially those which have been derived from clastics by granitization due to lit-par-lit injection or allied process.

Therefore, a comparison and contrast between the structures and textures of the "red rock" and those of metamorphics might be made as follows:

(1) Several generations of mineral growth are evident in the "red rock". Magnetite, for instance, is

often present in three, or even four, distinct sizes, while metamorphic minerals tend to be of one generation and of one size only.

(2) A normal progressive crystallization, typical of igneous rocks, has taken place in the "red rock", older, basic, minerals included in younger, more acidic, ones. In metamorphic rocks, crystallization of all minerals is often contemporary, and produces a crystalloblastic texture, all minerals included in the others. Other metamorphic rocks, especially contact metamorphics, show a reverse order of crystallization, acidic minerals forming first, followed by basic minerals.

(3) Zoned feldspars, indicating progressive crystallization and progressive change in composition, are present in every specimen of the "red rock" studied. In most types of metamorphic rocks, feldspars are unzoned, due to simultaneous development of all minerals.

(4) Sharp boundaried phenocrysts of quartz and orthoclase, as found in the "red rock", are seldom developed in metamorphic rocks. Phenocrysts in metamorphics are usually high temperature anhydrous minerals more or less the same size, and in the case of porphyroblasts, are often abraded and rounded.

(5) Crystallitic growths such as globulites, margarites, trichites, cumulites, and skeleton crystals, abundant in the "red rock", are rare in metamorphic rocks.

(6) Spherulitic and radiolitic textures are almost universal in the "red rock" but are rare in metamorphics.

(7) Eutaxitic structure is present in the "red rock". The foliation is relatively continuous, with minerals crystallizing subnormal to them in most cases. In metamorphic rocks, true eutaxitic structure is absent. In these, only a lineation or foliation of minerals is developed and, depending upon the type of metamorphism, is either strictly normal to compression or strictly parallel to planes of weakness in the original clastic rock (H. H. Read, 1939, pp. 772, 773).

(8) Although some crystals in the "red rock" are strained, they are surrounded by later crystals which are not. Crystals in metamorphic rocks are generally strained or deformed.

(9) Typical metamorphic minerals, such as staurolite, garnet, sericite, actinolite, cyanite, and tourmaline, are universally absent in the "red rock".

(10) Tridymite, glass, and other primary igneous minerals and mineraloids, common in flow rocks, and found in the "red rock", are rarely, if ever, developed in metamorphic rocks.

Manner of Emplacement: The evidence indicating an igneous origin for the "red rock" likewise indicates that it is extrusive, although textures and structures in a few specimens might suggest an intrusive manner of emplacement. Most "red rock" specimens can be recognized as extrusive rather than intrusive from the following comparisons and contrasts:

(1) Tuff, agglomerate, volcanic dust, and other pyroclastic materials are found at the tops of some "red rock" flows or interbedded with them. Pyroclastic materials of this type are absent in intrusive rocks.

(2) Eutaxitic flow structure is well developed in most of the "red rock". Such structure is, according to Balk (1937, p. 91), weakly developed in laccolithic and other near-surface intrusions; nor is eutaxitic structure, with minerals oriented subnormal to the foliation, developed in dikes or sills. Such rock bodies possess only a foliation or lineation of oriented minerals.

(3) Eutaxitic structure, as finely banded as that in the "red rock", is rare in intrusives.

(4) Glassy textures, including spherulitic and crystallitic forms and glass, abundant in the "red rock", are seldom developed in intrusive rocks, and if present, occur only at chilled contacts.

(5) Although foliation of the "red rock" is usually well developed at, and subparallel to, contacts with adjacent rocks, these contact zones are not gneissic, or obviously chilled, as is often the case in intrusive rocks.

(6) Although miarolitization is not by any means prevalent in the "red rock", it is, nevertheless, much more common than in intrusives.

(7) Voids in the "red rock" are often large, elon-

gate, and sinuous. Voids in intrusive rocks, if present at all, tend toward sphericity and small size because of greater pressure and less movement.

(8) The "red rock" lacks pegmatitic zones --with the exception of miarolitic cavities; intrusive bodies often have them.

(9) The "red rock" is aphanitic; intrusive rocks are usually phaneritic.

(10) The "red rock" has abundant phenocrysts in a microcrystalline to microcryptocrystalline groundmass. Intrusives seldom crystallize as a fine grained groundmass with phenocrysts.

(11) Phenocrysts, although common in the "red rock", are larger and more abundant in intrusive, especially hypabyssal, rocks.

(12) Tridymite, high temperature SiO_2, observed in the "red rock", is seldom if ever developed in intrusives.

(13) The length-width ratio of metamorphic minerals is usually greater than that of the minerals in the "red rock".

(14) Tension fractures, formed in the "red rock" during consolidation and immediately filled with the same magma, are not developed in intrusives. Pressure at greater depths prevents fissures from forming.

<u>Mineral Paragenesis</u>: Interpretation of the mineral paragenesis of the "red rock", based upon inferences derived from observation of mineral associations and textures, and upon results of previous investigations of extrusive

rocks, especially those of Yellowstone Park, is as follows:

(1) The magma rises in its conduit while scattered phenocrysts of feldspar and small crystals zircon are forming. Possibly some small grains of magnetite are also forming. These grains may group into bundles because of viscosity differences or because of turbulent flow of the magma past obstructions in the conduit walls. Probably a linear or planar fluid compositional heterogeneity is present. This may have been developed by near-surface stoping of a previously consolidated heterogeneous rock and flow of the differentially viscous material in the conduit.

(2) Near the surface, the magma picks up large quantities of ground water, possibly initiating a new generation of crystallization of magnetite or feldspar or both. The water is heterogeneously dispersed within the magma, taking a position within the more viscous, basic, portions of the magma, adjacent to the magnetite.

(3) Extravasation of the magma takes place, resulting in a change of physical environment (a temperature or pressure change, or both). Another generation of magnetite begins.

(4) The magma becomes greatly extended through an, "...evenly distributed, very penetrative, differential, viscous flow" (E. B. Mayo, 1944, p. 606). Segregation of magnetite crystals into layers, along with the small zircon phenocrysts, is accomplished. These are separated

by layers of still fluid, and more acidic material. At this time tridymite, which forms between 1470° C. and 870° C., begins to crystallize along with the magnetite in the dark layers.

(5) Partially crystalline material forms as fibrous tufts nearly normal to the layers of magnetite grains. It originates at the magnetite layers and extends away from them in either direction. Some tufts originate at groups of magnetite granules while others originate at tridymite crystals. Some margarites of magnetite and small flakes of biotite develop interstitially in the tufts of radiating spherulitic material. The rate of movement of the magma becomes very slow during this period.

(6) Large crystals of euhedral feldspars form at the termini of the spherulitic growths. As consolidation of the magma progresses, the remaining fluid becomes more acidic. Therefore, these euhedral feldspar crystals are orthoclase, and extremely high potassium orthoclase at that. Layers and strings of fluid inclusions occur in great number in the orthoclase. They are oriented, not parallel to the cleavage, but to the layers of magnetite grains (the foliation).

(7) Quartz, along with small quantities of sphene and biotite, are the last minerals to crystallize. The quartz fills the space between opposing sets of orthoclase crystals and occupies interstices between them. Evidence that the magma is still moving at this time is shown by orthoclase

crystals broken off at their bases and inclined toward the planes of differential movement. Those in less rapidly moving layers are inclined toward the direction of greater movement, while those in more rapidly moving layers are swept away from the direction of greatest movement (pl. 9, D). The first formed quartz, which encloses abundant lines of fluid inclusions oriented in the plane of flow, is strained. This indicates that some movement of the lava is still taking place. The last formed quartz, completing the consolidation of the rock, is usually unstrained, and fluid inclusions, although fewer in number than in earlier formed minerals, show little tendency to orient. This indicates the lava has ceased to move. At the completion of consolidation, the feldspar phenocrysts are well zoned, with nearly pure $KAlSi_3O_8$ in the outer zone and more sodic toward the center.

(8) Subsequent to consolidation, alteration and devitrification of glass takes place. Secondary hematite, leucoxene, and kaolin, in dust-like particles, cover and obscure all minerals. Secondary calcite has also, in many specimens obscured the original minerals.

Evidence Indicating a "Wet" Magma: That a large quantity of water was present in the "red rock" as assumed in number 2 (p. 84), is indicated by the following observations:

(1) Decrease in the quantity of water and other liquids in a magma increases the vapor pressure. When

sufficient quantities of liquids have been removed by crystallization, vapor should form. Yet, quartz and orthoclase, the last two minerals to crystallize, and after most of the liquids have been removed by crystallization, contain abundant fluid inclusions. On the other hand, the fluid inclusions rarely contain gas bubbles.

(2) With decrease in liquids and formation of vapor, vesicles should develop, but vesiculation in the "red rock" is very low.

(3) Formation of vapor because of inadequacy of liquids results in explosive eruptions with consequent formation of large quantities of pumice, scoria, ash, and other exogenetic pyroclastic material. The "red rock" has little of this material.

(4) Large quantities of water result in the ability of a magma to remain fluid to much lower temperatures. Formation of large quantities of quartz and small quantities of tridymite are indicative of low temperatures of consolidation in the "red rock".

(5) Likewise, development of orthoclase, rather than its high temperature dimorph, sanidine, indicates a low consolidation temperature.

(6) The presence of large quantities of water results in the magma maintaining low viscosity at low temperatures. This is shown by the extreme thinness of the eutaxitic structure.

(7) Since minerals in the "red rock" have little

tendency to orient with their long axes in the plane of flow, the magma must have flowed rapidly --notwithstanding its extremely acidic and, therefore, supposedly viscous nature, and come to rest before much crystallization took place.

(8) As will be brought out in the section on structure, the flows are relatively thin, also indicative of the extreme fluidity of the flows.

(9) The minerals formed are dependent upon the presence of water.

(10) As indicated by Iddings (1899, p. 424), localization of water causes formation of spherules in areas where crystallization would not otherwise take place. Spherules are prominent in the "red rock", while glass is not.

The assumption that the water was derived from near-surface sources was based, in part, upon the fact that magmas can hold only a small quantity of water in solution (S. J. Shand, 1949, p. 38). Since it is evident that much larger quantities of water were available than can be dissolved in a magma, water must have been present in an undissolved state, and its only source could be ground water. In addition, water originally in the magma would be homogeneously dispersed. This does not seem to be the case. As Iddings says (1899, p. 425),

> "The heterogeneity of the acid lavas, so far as is known, is confined to the distribution of vapors, presumably of water, and suggests

> that the water thus irregularly disseminated has not existed within the magma long enough to become uniformly diffused. It must therefore be looked upon as water absorbed near the earths surface."

Classification: As indicated on pages 77 and 79, the "red rock" is a kalitordrillite, or 1159, by Johannsen's classification (1932, pp. 141-161). It is a rock high in quartz and orthoclase, and has less than 5 percent each of dark minerals and acid plagioclase.

STRUCTURE

Primary Structures

Flowage Folds: The "red rock" is highly flow folded in many places. It is thought that these structures develop because of viscosity differences in adjacent portions of a flow (E. B. Knopf, and Earl Ingerson, 1938, p. 132) and that less plastic portions were dragged foreward by more fluid adjacent portions (pl. 11, A). In the "red rock", folds as large as 3 meters from trough to apex, were seen. Mayo (1944, p. 606) describes flowage folds similar to those in the "red rock", in a rhyolite near Big Pine, California. Sandberg (1938, pp. 814, 818) describes similar structures in acidic Keweenawan flows along the coast of Minnesota; these flows are possibly correlative with the "red rock".

The direction in which the flow moved cannot be determined, as fluid portions may occur above, as well as below, more viscous portions. They are adiagnostic, like current ripple marks.

The eutaxitic structure usually retains its co-planarity (pl. 11, B) even when involved in flow folding.

Bedding: Bedding is not clearly evident in the field, but at a few localities, as at the southern side of Government Peak, one is required to ascend a series of step-like rises over several flows to attain the top.

(The word "trap", a Scandinavian word meaning "step", was first used by them in its geological sense to denote the step-like topography resulting from the differential weathering of superincumbent lava flows.) However, the contacts between the flows are not exposed. They are, evidently, highly weathered, recessed, and, therefore, covered with talus. At a few localities the brecciated upper portions of flows are exposed (pl. 11, C), although the actual contacts are not.

Bedding is well shown on aerial photographs. Not all contacts show on the photographs, but positively identifiable ones are plotted on plate 10 (in pocket). Interestingly, the "Chippewa" felsite at the Bergland Fire Tower hill is also bedded, although many geologists believe it a sill.

The flows are thin. A thick flow would probably have a thickness of 250 feet, while average flows are probably less than 50 feet.

Secondary Structures

Fractures: Fractures in the "red rock" include both joints and faults (pl. 11, D). Plate 12 shows the face poles of 95 fractures, and plate 13 is its contoured equivalent. The number of points is too small to be statistically accurate, and the contoured diagram, therefore, is merely an indication, and not a true picture of the stresses which have acted on the "red rock". However, it is felt

Explanation of Plate 11

A. Contorted flow banding by flow folding in the "red rock" exposed in an outcrop at locality 2. 1 inch equals 1 foot.

B. Extremely coarse foliation of "red rock" at locality 60. Note the resistance of more quartziferous layers to weathering. 1 inch equals 1 foot.

C. Coarse volcanic agglomerate at locality 22. Note diversely oriented foliate blocks. 1 inch equals 1.1 feet.

D. Near locality 116 on the upper Carp River. Intersection of the bedding of basic flows with a major set of joints controls the course of the stream. The bedding dips gently to the left and the joints dip steeply to the right.

PLATE 11

A

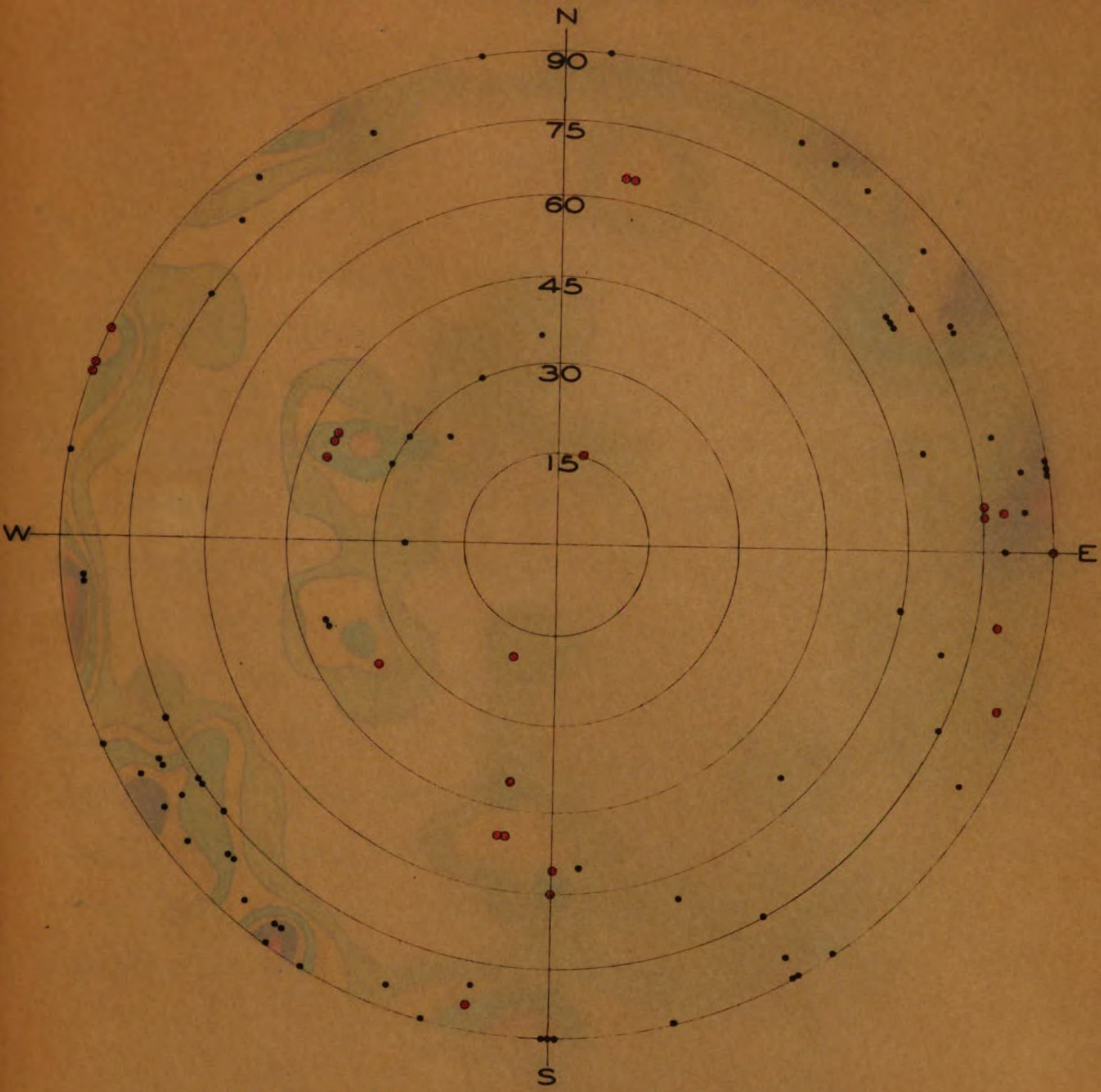
B

C

D

PLATE 12

FACE POLES OF 95 FRACTURES IN THE "RED ROCK"



LAMBERT'S EQUAL AREA PROJECTION, POLAR CASE
PLOTTED ON LOWER HEMISPHERE

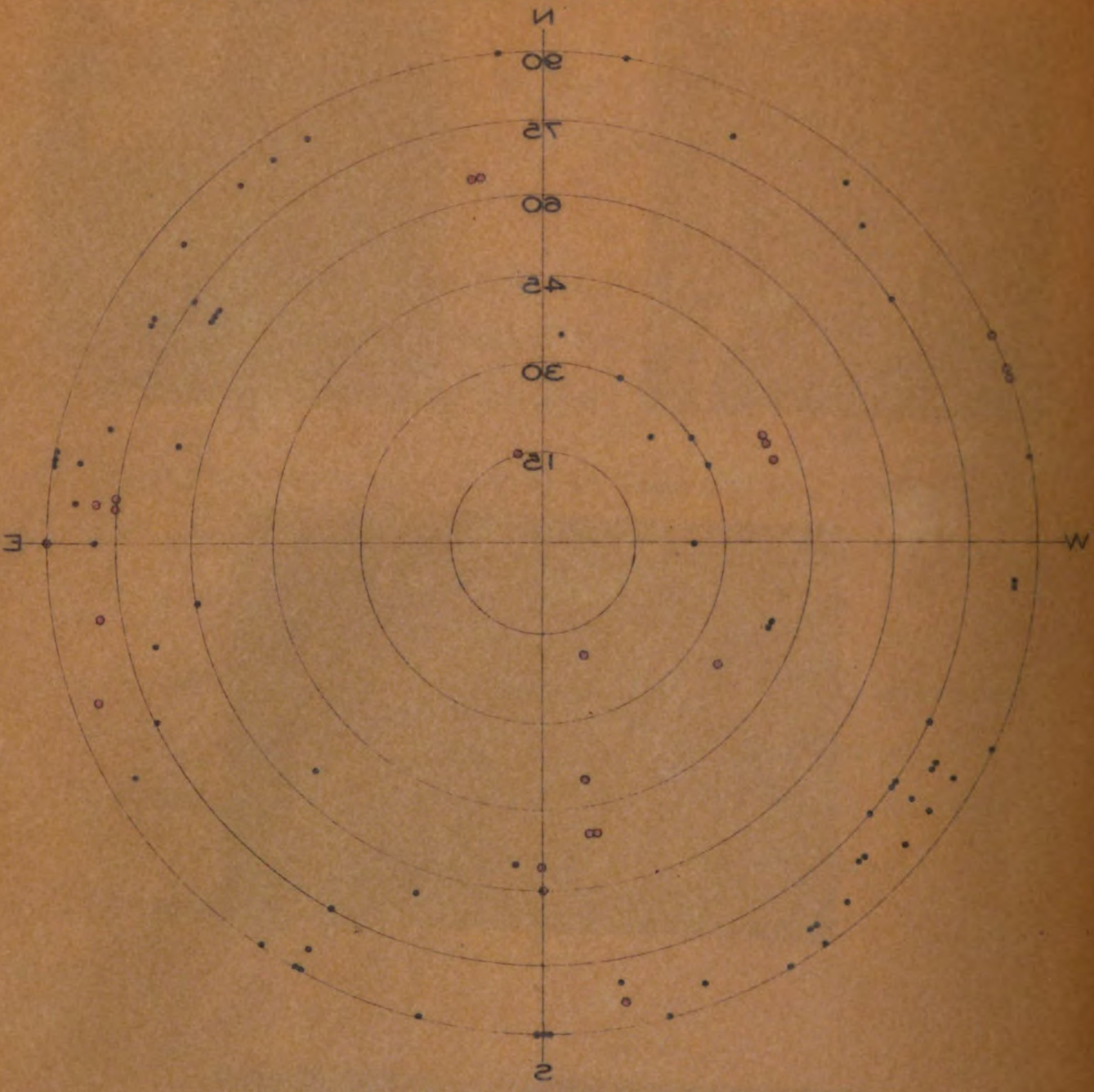
BEARINGS ARE MAGNETIC

• JOINTS AND UNRECOGNIZED FAULTS
• KNOWN FAULTS

R.E.T. '50

PLATE 12

FACE POLES OF 95 FRACTURES IN THE "RED ROCK"



LAMBERT'S EQUAL AREA PROJECTION, POLAR CASE
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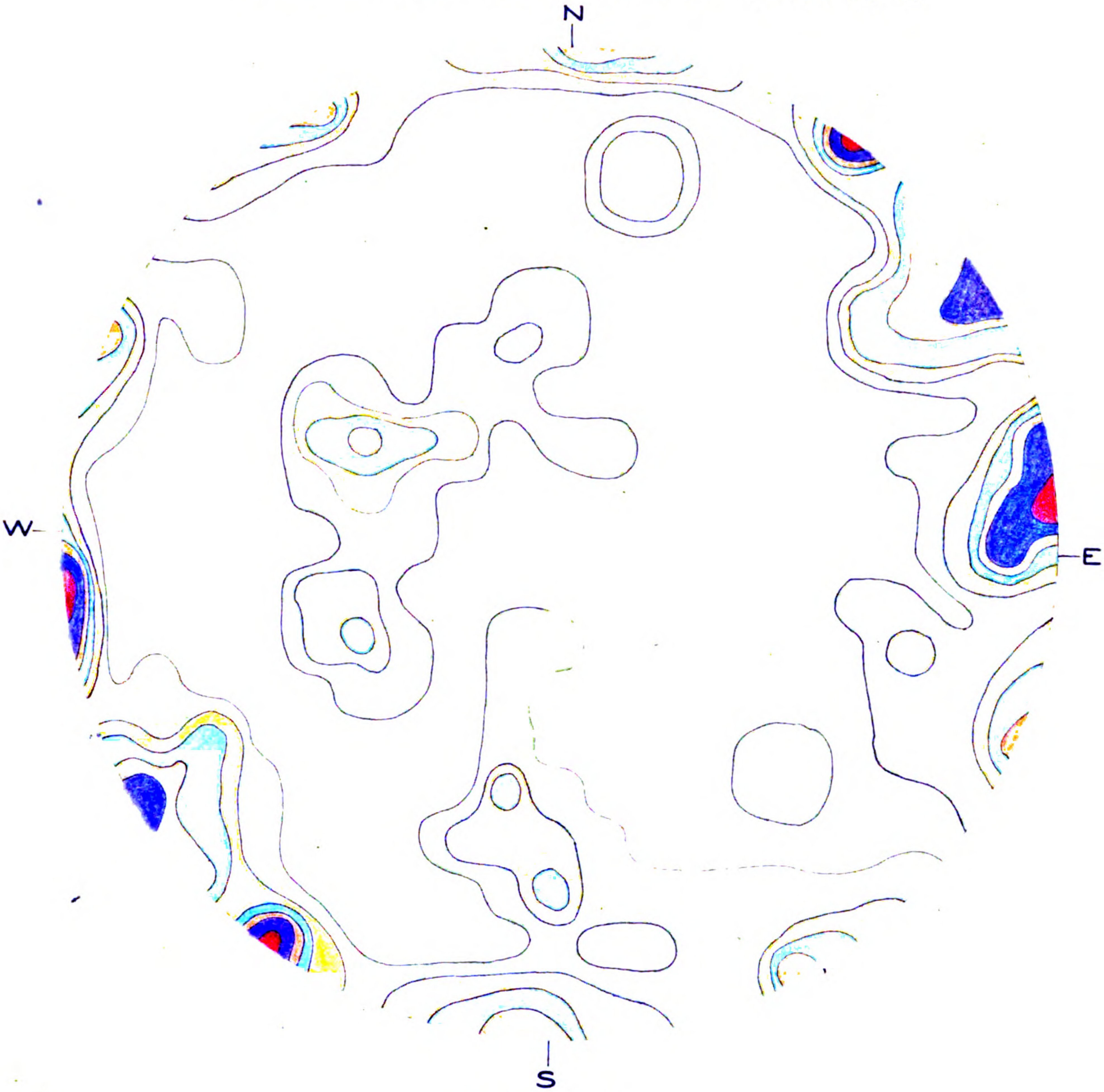
○ KNOWN FAULTS

R.E.T. '50

PLATE 13

CONTOURED DIAGRAM EQUIVALENT TO PLATE 12



CONTOURS

1 %
2 %
3 %
4 %
5,6 %
7,8 %

RET '50

that the addition of more readings would only confirm what is indicated on the contoured diagram.

The first faulting was shallow and steep angle strike faults. The major movement along these faults was vertical, but a small amount of lateral movement accompanied the vertical; the south blocks moved east. The shallow faults dip either north, or south, and probably represent shear surfaces developed as a result of subhorizontal north-south compression. These faults are inferred to be correlative in age with the main Porcupine Mountain fault -- which probably dips northward, and with the great Keweenaw fault to the south near Bergland.

Dip faults, usually vertical, developed later. These are not parallel, as are the strike faults. This may be because they trend near the strike of a set of major joints and, in some cases, developed alont the joints rather than at an angle to them. The west blocks, in general, moved down with respect to the east blocks.

Discussion

Bedding: Structural observations lending more evidence to the extrusive character of the "red rock" are the following:

(1) The "red rock" is bedded in the form of a series of lava flows.

(2) Flowage folds, present in the "red rock", do not generally occur in intrusives.

(3) The overlying sediments and traps are not metamorphosed at their bases.

(4) The "red rock" apparently maintains one horizon, remaining just below the mixed basic extrusives and sedimentaries of the Ashbed group.

(5) The overlying sediments and traps contain fragments of the "red rock".

(6) No overlying rocks were seen as xenoliths in the "red rock".

(7) No apophyses or stringers of the "red rock", so far as is known, project into the overlying rocks.

Since the "Chippewa" felsite is mineralogically and texturally like the "red rock", and since they are both bedded (extrusive) and apparently occupy the same horizon, the "red rock" of the Porcupine Mountains is inferred to be the same formation as the "Chippewa" felsite. If this is so, the "red rock" has a maximum thickness of approximately 2,000 feet, the approximate maximum thickness of the "Chippewa" felsite as determined by diamond drill holes.

Attitude: It is thought that subhorizontal, north-south, compressive forces were responsible for the development of a large fold in the Porcupine Mountains, the fold subsequently denuded, exposing the "red rock" ("Chippewa" felsite). This fold trends approximately east and west. During this compression, the southern limb of the fold was thrust above the adjacent rocks to the south. The upthrown beds were bent down in the vicinity of the fault (A. C. Lane, 1911, p. 682).

Later, north-south faulting, the west blocks downthrown, displaced the east-west faults. This later faulting may have been due to the development of tension fractures in a north-south direction during the first (east-west) faulting, and normal faults were the result of relaxation of compression.

Other forces have acted on the "red rock". Evidence from foliation readings indicates numerous small folds, trending both east-west and north-south, superimposed on the larger anticline. This minor folding may be a northward extension of the situation described by Allen and Barrett (1914, p. 60) in the region of Lake Gogebic.

CONCLUSIONS

On the basis of the evidence acquired in the prosecution of this investigation, it is felt that the following major conclusions are justified:

(1) The "red rock" is igneous.

(2) The "red rock" was emplaced as lava flows.

(3) The direction from which the lavas came is indeterminable.

(4) The magma was an extremely "wet" magma, and the flows were, consequently, very thin, averaging less than 50 feet in thickness.

(5) The "red rock" is a leucocratic rock, a kalitordrillite (115E) by Johannsen's classification (1932, pp. 141-161).

(6) The "red rock" is the "Chippewa" felsite brought to the surface by denudation of a large anticline which is thrust to the south over younger rocks. It is the basal member of the Ashbed group in this region.

(7) Its total thickness is less than 2,000 feet.

(8) The folding was probably correlative in time with development of the great Keweenaw fault.

BIBLIOGRAPHY

Houghton, Douglas, Third annual report of the Geological Survey of Michigan: Mich. Joint Docs., pp. 487-490, 1841.

Jackson, C. T., Report on the geological and mineralogical survey of the mineral lands of the United States in the State of Michigan: 31st Cong., 1st Sess., Mich. Joint Docs., pp. 371-502, maps, 1849.

Jackson, C. T., idem., pp. 649-696, by J. D. Whitney.

Whitney, J. D., Field notes for 1847: 31st Cong., 1st Sess., Mich. Joint Docs., pp. 713-738, 1849.

Foster, J. W., and Whitney, J. D., Report on the geology and topography of a portion of the Lake Superior land district in the State of Michigan, pt. 1, Copper lands: 31st Cong., 1st Sess., H. Ex. Doc. 69, 224 pp., maps, 1850.

Whitney, J. D., idem.

Hubbard, Bela, Geological report of field work in the Lake Superior Land District: 31st Cong., 2nd Sess., Mich. Joint Docs., pp. 833-842, 882-932, 1850.

MacFarlane, Thomas, Report on the geology of Lake Superior: Canada Geol. Survey Rept. Progress for 1863-1866, pp. 115-143, 1866.

Irving, R. D., The copper-bearing rocks of Lake Superior:

U. S. Geol. Survey Mon. 5, 464 pp., maps, 1883.

Irving, R. D., and Chamberlain, T. C., Observations on the junction between the Eastern sandstone and Keweenaw series on Keweenaw Point, Lake Superior: U. S. Geol. Survey Bull. 23, 124 pp., 1885.

Cross, C. W., Constitution and origin of spherulites in acid eruptive rocks: Phil. Soc. Wash. Bull. 11, pp. 411-443, 1892.

Van Hise, C. R., A central Wisconsin base-level: Science, New Ser., Vol. 4, pp. 57-59, 1896.

Rosiwal, August, Ueber Geometrische Gesteinanalysen, Verhandle. K. K. Geol. Reichsanstalt, Wien, 1898.

Iddings, J. P., Geology of the Yellowstone National Park: U. S. Geol. Survey Mon. 32, pt. 2, ch. 10, The rhyolites, pp. 356-432, 1899.

Wright, F. E., Report of the progress made by the Porcupine Mountain party during the summer of 1903: Mich. Geol. Survey Ann. Rept., 1903, pp. 35-44, 1905.

Gordon, W. C., assisted by Lane, A. C., A geological section from Bessemer down Black River: Mich. Geol. Survey Ann. Rept., 1906, pp. 405-507, maps, 1906.

Ruthven, A. G., An ecological survey in the Porcupine Mountains and Isle Royale, Michigan: Mich. Geol. Survey

Ann. Rept., 1905, pp. 17-55, 1906.

Wright, F. E., and Lane, A. C., Preliminary geologic map of the Porcupine Mountains: Mich. Geol. Survey Ann. Rept., 1908, pl. 1, 1909.

Lane, A. C., The Keweenawan series of Michigan: Mich. Geol. Survey Ann. Rept., 1909, 2 vols., 983 pp., 1911.

Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, 641 pp., maps, 1911.

Allen, R. C., and Barrett, L. P., Contributions to the pre-Cambrian geology of northern Michigan and Wisconsin: Mich. Geol. Survey Publ. 18, Geol. Ser. 15, pp. 13-164, maps, 1914.

Hotchkiss, W. O., The Lake Superior geosyncline: Geol. Soc. America Bull., Vol 34, No. 4, pp. 669-678, 1923.

Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U. S. Geol. Survey Prof. Paper 144, 238 pp., 1929.

Johannsen, Albert, A descriptive petrography of the igneous rocks, Vol. 1, 318 pp., University of Chicago Press, Chicago, Illinois, 1932.

Krumbein, W. C., Thin-section mechanical analyses of indurated sediments: Jour. Geol., Vol. 43, No. 5, pp. 482-496, 1935.

Michigan Geological Survey, Centennial map: Mich. Geol.

Survey Ann. Rept., 1936, 1936.

Balk, Robert, Structural behavior of igneous rocks; Geol. Soc. America Mem. 5, 177 pp., 1937.

Knopf, E. B., and Ingerson, Earl, Structural petrology; Geol. Soc. America Mem. 6, 270 pp., 1938.

Sandberg, A. E., Section across Keweenawan lavas at Duluth, Minnesota; Geol. Soc. America Bull., Vol. 49, No. 5, pp. 795-830, 1938.

Read, H. H., Metamorphism and igneous action; Nature, Vol. 144, pp. 729-731, 772-774, 1939.

Rogers, A. F., and Kerr, P. F., Optical mineralogy, 2nd ed., 390 pp., McGraw-Hill Book Co., Inc., New York, 1942.

Mayo, E. B., Rhyolite near Big Pine, California; Geol Soc. America Bull., Vol. 55, No. 5, pp. 599-619, 1944.

Wahlstrom, E. E., Igneous minerals and rocks, 367 pp., John Wiley & Sons, Inc., New York, 1947.

Shand, S. J., Eruptive rocks, 3rd ed., 488 pp., John Wiley & Sons, Inc., New York, 1949.

Chayes, F., On the bias of grain-size measurements made in thin section; Jour. Geol, Vol. 58, No. 2, pp. 156-160, 1950.

El Khalidi, H. H., A field and petrographic study of the sandstones and conglomerates of the Porcupine Mountains, Ontonagon County, Michigan, Unpublished Master's Thesis, Michigan State College of Agriculture and Applied Science, East Lansing, Michigan, 110 ms. pp., 1950.

Eichmeier, A. H., U. S. Weather Bureau, East Lansing Station, personal communication.

Kelly, W. A., Department of Geology and Geography, Michigan State College of Agriculture and Applied Science, personal communication.

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