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# PAPERS OF THE MICHIGAN ACADEMY OF SCIENCE ARTS AND LETTERS

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VOLUME XVII

"Pusilla res mundus est nisi in illo
quod quaërat omnis mundus habeat."
—SENECA, *Naturales Quaestiones*

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# SOME CHARACTERS OF THE SKULL AND SKELETON OF THE FOSSIL HARE, *PALAEOLAGUS HAYDENI*


LEE R. DICE


THE fossil hare, *Palaeolagus haydeni* Leidy, is still incompletely known, in spite of the fact that many fragments of its skull and skeleton have been collected from the White River beds of the Great Plains. These beds are considered to be Oligocene in age.

Associated with *Palaeolagus haydeni* in the White River beds are the remains of a very large hare of a distinct species, *Palaeolagus turgidus*. These two species of *Palaeolagus* are paleontologically the oldest known members of their order, the Lagomorpha. The fact that at its first known appearance in geological time the order is represented by two species, differing from each other in numerous characters, indicates that the Lagomorpha had a long previous period of evolution in Eocene time and perhaps earlier.

The Museum of Paleontology of the University of Michigan has two almost perfectly preserved skulls of the fossil hare *Palaeolagus haydeni*. Accompanying one of them are the complete mandible and most of the bones of the skeleton. A third specimen has the skull incompletely preserved, but several bones of the skeleton are in excellent condition. All these specimens were collected by expeditions of the University of Michigan from beds of White River age, four miles south of Douglas, Wyoming. They probably are from the Oreodon Zone. For permission to study this material I am indebted to Dr. E. C. Case, director of the Museum of Paleontology.

Skull 8942 (Pl. XXV) represents a very old individual with the molars much worn; the internal reëntrant angles have completely disappeared. The size of the skull is very small for a rabbit (see Tables I-II), being smaller than that of the sage rabbit *Sylvilagus* (*Brachylagus*) *idahoensis*, which is probably the smallest living member of the Leporidae. The fossil skull also is considerably more flattened dorso-ventrally than is the skull of any living kind of rabbit or hare. Further, it is much less arched than the skull of any other genus of the Leporidae. The angle between the planes of the basioccipital and the palate is only 16.5 degrees.

TABLE I

MEASUREMENTS OF *PALAEOLAGUS HAYDENI*, SKULL 8942

| | Mm. |
|---|---|
| Condylo-premaxillary length | 44.6 |
| Breadth across zygomatic processes of maxillae | 24.6 |
| Breadth across mastoid processes | 22.9 |
| Breadth of brain case | 19.4 |
| Depth of brain case | 15.9 |
| Interorbital constriction | 6.5 |
| Breadth of rostrum, just anterior to $P^2$ | 12.4 |
| Depth of rostrum, just anterior to $P^2$ | 9.7 |
| Breadth of both nasals | 8.9 |
| Depth of malar | 4.0 |
| Length of incisive foramen | 11.8 |
| Width of both incisive foramina | 3.5 |
| Length of bony palate | 7.7 |
| Condyle to incisive foramen | 30.9 |
| Palatine breadth, posterior to $M^3$ | 4.3 |
| Length of auditory bulla | 10.4 |
| Diastema, upper jaw, on alveoli | 10.0 |
| Upper molar series, length on alveoli | 11.9 |

A supraorbital process is present in *Palaeolagus haydeni*, but it is only slightly developed, consisting of a short tapering process, directed backward and outward. This process is somewhat imperfect in all the specimens, but it probably resembled that of *Romerolagus*, a member of the same subfamily, Palaeolaginae, living today on an isolated mountain mass in Mexico.

The bony palate in the fossil species is long as compared with those of modern hares and rabbits (Pl. XXVI, Fig. 1). It extends from about opposite the anterior edge of $P^2$ to opposite $M^2$. In modern *Lepus* the palate is shortened from both ends, extending in some species only from behind $P^2$ to behind $P^4$. The part of the palate formed by the palatines has been especially reduced in the modem Leporidae, and, whereas in the fossil specimen the palatines form more than half the median length of the bony palate, in all modern hares and rabbits, so far as known, the palatines form less than half, and in some species they constitute only the narrow posterior edge of the palate.

Among modern leporids the genus *Romerolagus* is most like *Palaeolagus haydeni* in the structure of the palate. In *Pronolagus*, also, a relatively large proportion of the bony palate is formed by the palatines. Some individuals of the domestic rabbit (*Oryctolagus*) have the palatines forming nearly half of the bony palate, but in most individuals of this genus the palatines cover a much smaller area.

TABLE II

MEASUREMENTS OF *PALAEOLAGUS HAYDENI*, 14317

| | Mm. |
|---|---|
| Mandible | |
| Length of mandible, posterior angle to end of incisor | 39.9 |
| Posterior coronoid process to end of incisor | 38.8 |
| Diastema, on alveoli | 7.8 |
| Skull | |
| Breadth of nasals | 9.0 |
| Length of zygoma | 21.4 |
| Interorbital constriction | 8.4 |
| Skeleton | |
| Length of tibio-fibula | 56.3 |
| Length of ulna (probably incomplete) | (40.0) |
| Length of radius | 33.6 |

The palate is proportionately longer in the young of *Lepus* and *Sylvilagus* than in the adults, and in the young the palatines form a larger proportion of the palate. In this character the young resemble the primitive form.

The incisive foramina in the fossil skull extend forward between the posterior pair of upper incisors, differing in this respect from modern rabbits and hares, in which the foramina do not extend so far forward. In one of the figures (Fig. 2) of *Palaeolagus haydeni* given by Troxell[1] a similar condition is shown, whereas in another figure given by him (Fig. 3) the foramina do not reach the incisors.

The width of the combined incisive foramina in the fossil is actually and proportionally much less than in any modern leporid. In this character *Palaeolagus haydeni* is most nearly like the Sumatran genus *Nesolagus* and the Indian form *Caprolagus hispidus*.

The posterior palatine foramina in the fossil are of about the average size for the family. In the related genus, *Romerolagus*, these foramina are relatively very large, but in *Pronolagus* they are very small.[2]

The posterior nares are narrow in the fossil, being smaller than in any wild member of the family which I have seen. But in the domestic rabbit the air passages are as constricted as in the fossil. On account of the small size of its air passages, *Palaeolagus haydeni* could have had only weak endurance in running.

The right mandible of specimen 14317 (PI. XXVI, Fig. 2) is apparently perfect, and for the first time there is opportunity to determine the correct shape of the whole lower jaw. The posterior angle is long and pointed, and the specimen figured by Troxell[3] is thus shown to have been defective in this part. The posterior part of the mandible, though well provided with space for the attachment of the masseter muscles, is not nearly so well developed as in the hares of the subfamily Leporinae. The lower border of the mandible has no important downward development in the hinder third, as is true of *Lepus*, *Sylvilagus*, and their relatives.

The mandible of *Romerolagus* is closely similar to that of the fossil, differing chiefly in being somewhat larger and in having the vertical ramus higher in proportion to the length of the mandible. On the other hand, the mandible of *Alilepus annectens*, which I have also placed in the subfamily Palaeolaginae,[4] is much more like those of the Leporinae in type, as shown by the figure of the incomplete jaw published by Schlosser.[5] The posterior part of the mandible of this genus has a pronounced enlargement, such as is found in the genus *Lepus*. The genus *Alilepus* occurs in beds presumably of Pliocene or Late Miocene age in China and from its antiquity would be expected to be nearer to *Palaeolagus* in the character of the mandible than the published figure indicates it to be. *Alilepus* is considerably larger than either *Palaeolagus haydeni* or *Romerolagus diazi*, being closer in size to *Pronolagus*, a south African living genus belonging to the same subfamily.

FIG. 10. Right scapula

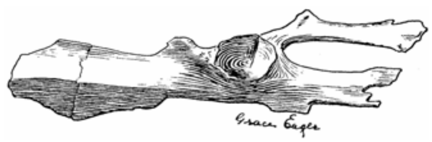

FIG. 11. Right innominate

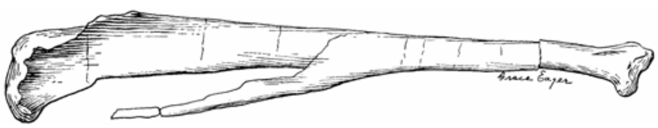

FIG. 12. Right tibio-fibula

*Palaeolagus haydeni*, Museum of Paleontology, University of Michigan, No. 14317. X 1½

The scapula is shorter and broader proportionately in the fossil than in any other known leporid (Fig. 10). Lying in the matrix posterior to the lower end of the scapula is a thin piece of bone, probably the metacromion, which is generally much elongated in the Leporidae. By the breaking away of the lower part of the spine of the scapula this piece of bone has lost its connection with the rest of the scapula. Compared with modern leporids, this metacromion is remarkably long for the size of the scapula.

The iliac wing of the innominate bone of the fossil (Fig. 11) has a prominent keel on its exterior surface; this is distinctly more pronounced than in *Lepus* or *Sylvilagus*.

The ulna and the radius in both specimens 14317 and 14318 are fully separate, with no indication of fusion. The two bones are about equal in size. In modern *Lepus* the ulna is more slender than the radius and the two bones tend to fuse together.

The trochanters of the femur of the fossil are relatively undeveloped. The present specimen agrees closely with the figure given by Cope.[6] Compared with the femur of the California brush rabbit, *Sylvilagus* (*Microlagus*) *bachmani*, which is one of the smallest living rabbits, the first trochanter is very weakly developed, and the third trochanter and the minor trochanter are of only moderate size. The small size of these muscle attachments indicates that the animal must have had rather feeble jumping ability.

The tibia and fibula are fused at their lower ends, as in all modern rabbits (Fig. 12). The combined bone is relatively short for a rabbit, measuring only 56.3 mm. in total length in specimen 14317 and 53.4 mm. in 14318.

## SUMMARY

Many of the characters of *Palaeolagus haydeni* are those to be expected in a primitive type of rabbit. Among simple characters exhibited by this fossil form may be mentioned small size, skull short in proportion to its length, skull relatively low and flat, plane of the occiput forming only a slight angle with the plane of the palate, supraorbital processes small and of a simple type; air passages small, palate long, enamel folding on the teeth simple, muscle attachments on the mandible and on the femur weakly developed. Notwithstanding its large number of simple characters *Palaeolagus haydeni* is characteristically a leporid, with the characteristic rabbit type of skull and skeleton and with the usual rabbit type of teeth, though with some minor differences in enamel pattern.

UNIVERSITY OF MICHIGAN

[1] Troxell, E. L., *Am. Journ. Sci*., 1 (1921) : 340-348.

[2] Lyon, M. W., Jr., *Smithsonian Misc. Publ*. 45 (1904) : 342.

[3] *Loc. cit*., fig. 1.

[4] Dice, L. R., *Journ. Mammal*, 10 (1929) : 340.

[5] Schlosser, Max, *Palaeont. Sinica*, Ser. C, Vol. 1, Fasc. 1 (1924), pl. 3, fig. 27.

[6] Cope, E. D., *Vertebrata of the Tertiary Formations of the West*, Book I, Rep. U. S. Geol Surv. Terr., Vol. 3 (1885), pl. 66, fig. 21.

PLATE XXV

FIG. 1. Dorsal side of skull

FIG. 2. Left side of skull

*Palaeolagus haydeni*, Museum of Paleontology, University of Michigan No. 8942. X 2

PLATE XXVI

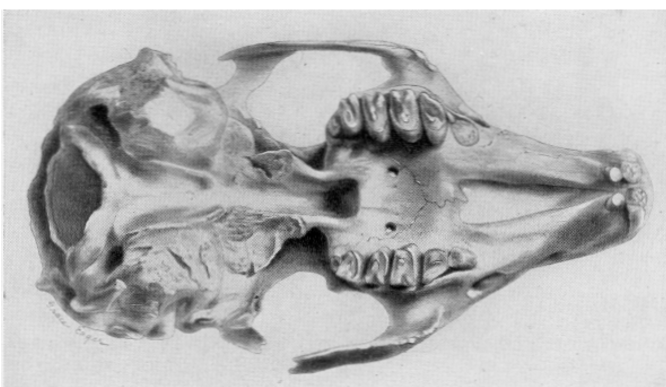

FIG. 1. Lower view of skull

FIG. 2. Right side of skull and mandible

*Palaeolagus haydeni*, Museum of Paleontology, University of Michigan, Nos. 8942, 14317. X 2

# STRATIGRAPHY OF THE SOUTHERN WASATCH MOUNTAINS, UTAH

ARMAND J. EARDLEY

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## INTRODUCTION

THE southern Wasatch Mountains are situated in the central part of the State of Utah about sixty miles south of Salt Lake City. They lie on the boundary of three physiographic and structural provinces, namely, the Basin and Range, the Middle Rocky Mountains, and the Colorado Plateaus (Map 31); owing to this strategic position they are of much geologic interest. The present paper treats of their stratigraphy. Only a broad outline of the rock sequence can be presented because of insufficient knowledge of detail. Much paleontologic and stratigraphic work still remains to be done.

## THE STRATIGRAPHIC COLUMN

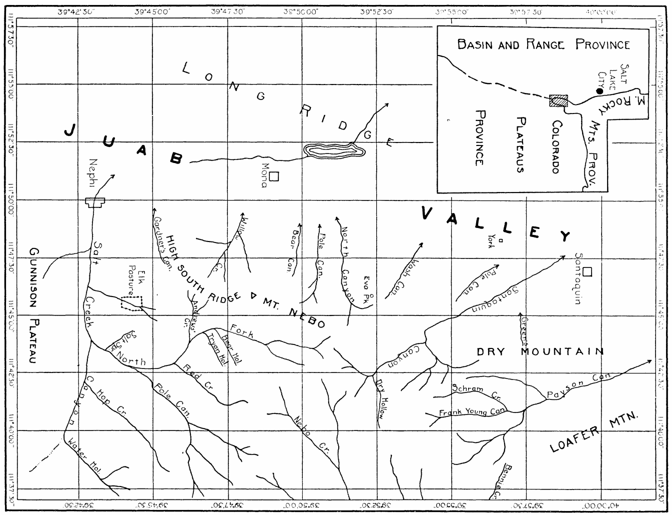
The rocks of the southern Wasatch Mountains range in age from Archean to Recent, and are representative of all the eras and most of the periods of geologic time. Many unconformities and hiatuses, however, attest the fact that the record of past time in this region is only partly complete.

Three unconformities of the first rank exist, namely, the Archean and Algonkian, the Algonkian and Cambrian, and the post-Cretaceous or Laramide. There appears to be no reflection of the Appalachian revolution in the strata of this region.

The Archean, Algonkian, and Cambrian rocks are quite similar to rocks of the same age in surrounding regions;

but the rest of the Paleozoic strata does not bear lithologic similarities of correlation value. The Triassic series is probably closely related to rocks of the same age farther north, but the Jurassic rocks compare more closely to the Colorado Plateau lithologic types. Rocks of Cretaceous age do not outcrop in the area of the southern Wasatch Mountains, but are present in neighboring regions as part of the general Mesozoic sequence. The Tertiary Period is represented by rocks of Lower Eocene and Pliocene (?) age. Quaternary rocks cover large areas, and may contain a record of the entire period.

A summarized description of the strata of the southern Wasatch mountains is given in tabular form for convenient reference.




MAP 31. The southern Wasatch Mountains, with inset showing location of the area in the State of Utah

STRATIGRAPHIC COLUMN OF THE SOUTHERN WASATCH MOUNTAINS, UTAH

| System | Series | Formation | Thickness (feet) | Character |
|---|---|---|---|---|
| Quaternary | Recent and Pleistocene | Alluvium | 0–3,000 | Alluvial fans and valley fill |
| | | *Unconformity* | | |
| | Pleistocene | Salt Creek fanglomerate | 100 ± | Partly cemented, red fanglomerate |
| | | *Unconformity* | | |
| Tertiary | Pliocene ? | Volcanic rocks | 0–800 | Volcanic breccia, bedded pyroclastic rocks, sills, and dikes |
| | | *Unconformity* | | |
| | Lower Eocene | Wasatch conglomerate | 0–1,200 | Coarse red conglomerate containing a fresh-water ooidal limestone |
| | | *Unconformity* | | |
| Jurassic | Upper Jurassic | Jurassic shales | 3,000–9,000 | Gray-drab shale with thin interbedded limestones. Develops red patches upon weathering |
| | | *Unconformity* | | |
| Triassic ? | Upper Triassic or Lower Jurassic | Ankareh formation | 1,400 | Deep red, arkosic sandstone |
| | | *Disconformity* | | |
| Triassic | Lower Triassic | Thaynes formation | 500–1,000 | Buff, fine-grained sandstones, and arkoses |
| | Lower Triassic ? | Woodside formation | 200–500 | Limestones and red shales |
| | | (?) | | |
| Pennsylvanian | Post-Pottsville<br>Pottsville | Intercalated series | 10,000 ± | Great interbedded series of sandstones and limestones. Most sandstones are buff-colored, and many limestones are siliceous |
| | | *Unconformity* | | |
| Mississippian | Brazer ?<br>Madison | Brazer (?) and Madison | 1,600 | Dark, usually massive, marine limestones and dolomites. Black shale horizon at top |
| Cambrian ? | Cambrian or post-Cambrian — pre-Mississippian | Cambrian and undifferentiated limestones and dolomites | 2,300 ± | Rather massive, marine limestones and dolomites |
| Cambrian | Upper (?) Cambrian | | | |
| | Lower Middle Cambrian | Ophir Shale | 200–300 | Olive-drab, micaceous shales, quartzites |
| | Lower (?) Cambrian | Tintic quartzite | 900 | Pure silica, pink and gray quartzites |
| | | *Unconformity* | | |
| Algonkian | | Algonkian formation | 500–1,000 | Dark red quartzites and shales. Shales also maroon and yellow |
| | | *Unconformity* | | |
| Archean | | Archean basal complex | ? | Schists, gneisses, granites, and pegmatites |

## ARCHEAN

The lower 2,000 feet of the pre-Cambrian series, the Archean, is composed of granite, gneiss, schist, and pegmatite.

### SCHISTS AND GNEISSES

About one third of this Archean basal complex is made up of highly contorted schists and gneisses. The gneisses are much like the schists in mineral composition and may be distinguished from them only by the coarser banding. The schists are well foliated and may be divided into two varieties, mica and hornblende.

Thin sections of the Dry Mountain schists and gneisses correspond closely to those described from Ogden and Farmington canyons, by Zirkel.[1]

The approximate strike of the foliation is N. 4° W.

### PEGMATITE

The pegmatite consists of great dikes intruded into the schists and gneisses. It composes about one half of the basal complex and is usually very coarse and consists chiefly of microcline and quartz. This pegmatitic quartz has contributed largely to the conglomerates of the overlying Algonkian and Cambrian quartzites.

### GRANITE

The granite is massive and rather fine grained. Hand specimens are pink, and in places have distinct porphyritic tendencies and even pegmatitic facies. Phenocrysts of pink feldspar in the porphyritic granite range in size from 0.5 to 1.5 cm.

In thin sections the following, minerals were found: quartz, 15 to 50 per cent; plagioclase (albite to oligoclase), 40 to 70 per cent; microcline; biotite much altered to chlorite; and accessories (apatite, magnetite, and certain small isotropic grains which may be garnet). No granulation or crushing was observed in thin sections of the various rocks.

In outcrop the granite shows two joint systems, both slightly inclined to the vertical and at right angles to each other.

### INTRUSIVE RELATIONS

The schists and gneisses are the oldest of the three rock types, being intruded by both the pegmatite and the granite. No intrusive contacts were found between the pegmatites and the granite, and hence their relative age is not known.

### REFERENCE

Loughlin's reconnaissance description of this basal complex characterizes it as "granite-gneiss with schist inclusions."[2] His mineral description is at variance with that given here in only one particular. He determines the plagioclase as sodic andesine, whereas the writer has found it to be gradational between albite and oligoclase.

## ALGONKIAN

Loughlin[3] reports 800 to 1,000 feet, by aneroid measurement, of Cambrian quartzite and shale resting " unconformably upon the pre-Cambrian granite" and "gneiss complex." No Algonkian rocks were described; on the ground of this report the statement has often been made that in the Cottonwood district there are over 10,000 feet of Algonkian quartzite, but just fifty miles to the south in the Santaquin region similar rocks are entirely absent. More detailed work has shown that "Loughlin's Cambrian" is composed of Algonkian and Cambrian rocks, which are separated by a pronounced unconformity.

*Character of sediments*. — The Algonkian rocks of Dry Mountain are shales and quartzites. The quartzites are generally dark red, with fine and coarse variations. Most of them are hard and firmly cemented, but occasional sandy beds are encountered. Quartz-pebble conglomerates are frequent within the formation. The pebbles, which are rounded and about one inch in diameter, are composed of white quartz, and are set in a dark red, quartzitic matrix. Fractures break cleanly through the pebbles as if the rock were homogeneous.

The shales are generally dark red also, but occasionally green and bright yellow beds appear. They weather rapidly into transient talus slopes of small angular fragments.

*Thickness*. — The Algonkian has a thickness of from 500 to 1,000 feet. It is thickest at the abrupt fault termination near Santaquin Canyon, and thinnest about four miles to the north, where it is also terminated by a fault.

*Correlation*. — No fossils were found except questionable worm borings, which Loughlin mentions.[4] Therefore, correlation of the Algonkian of the Santaquin district with other formations must be based entirely on diastrophism and lithology. This Dry Mountain Algonkian correlates roughly in lithology and exactly in position with the Algonkian in the Cottonwood district and in the American Fork district. In these three localities the Algonkian is composed, in part, of dark red quartzite, is overlain unconformably by characteristic pink Cambrian quartzite, and rests unconformably on a crystalline basal complex, except in the Cottonwood district, where a granite intrusion has destroyed the lower contact.

*Archean and Algonkian contact*. — The contact of the dark Algonkian quartzites and shales upon the granite is well displayed above the Black Balsam claim on the ridge forming the south side of Green's Canyon. It is sedimentary, with large and small, angular and round, quartz phenoclasts embedded in a light green, and in places dark red, coarse matrix of quartz sand. This basal conglomerate is not more than fifteen feet thick, and is immediately overlain by the dark quartzite. There were no signs of contact metamorphism in any place along the granite contact, thus indicating the granite to be Archean in age.

## CAMBRIAN

The Cambrian in the southern Wasatch Mountains consists of three parts: a lower quartzite, a middle shale, and an upper limestone. In this respect it is similar to the Cambrian of the northern and central Wasatch Mountains, of the Oquirrh Mountains, and of the East Tintic Mountains. On the evidence at hand the two lower formations are correlated with the "Tintic quartzite" and the "Ophir shale." The Tintic quartzite in the East Tintic Range was described and named by Loughlin.[5] The name "Ophir Shale" was proposed by B. S. Butler, of the United States Geological Survey, in 1920, with whom Loughlin was associated in the preparation of *Prof. Paper 111, Ore Deposits of Utah*. Loughlin's reconnaissance report of the southern Wasatch Mountains points out the various exposures of the Cambrian. A reference to his map accompanying the report will show these areas; a description of their extent will not be repeated here.

### TINTIC QUARTZITE

*Character of sediments*. — Megascopically the quartzite is of two colors, light gray and light pink. Both varieties are hard and dense, with a decided conchoidal fracture which cuts through the individual quartz grains. In the light gray quartzite rounded quartz grains one-half to three-fourth mm. in diameter are firmly cemented by secondary silica, which fills almost the entire interstitial space. The quartz grains are quite fresh. In the pink variety they are smaller, being only one-tenth to three-tenth mm. in diameter, and are rounded or angular. There is considerable interstitial sericite, but little secondary silica. The cleanness of the silica sand, the roundness of the larger grains, and the angularity of some of the smaller ones suggest that the quartzite consists of ancient beach sands.

The Tintic quartzite is easily recognizable in boulders, and forms a large part of the Wasatch conglomerate and Recent deposits.

*Thickness*. — The Tintic quartzite has been measured in Green's Canyon on the west slope of Dry Mountain, and presents a thickness of 900 feet. Elsewhere its base is not exposed, and therefore other measurements could not be made.

*Correlation*. — No fossils are known from the Tintic quartzite. In this section the Ophir shale in which fossils have been found is of upper Lower Cambrian or lower Middle Cambrian age. Therefore, the Tintic quartzite which underlies the Ophir shale must have been formed during some part of Lower Cambrian time.

*Algonkian and Cambrian contact*. — The Tintic quartzite rests unconformably on the Algonkian. This unconformity is seen at the bottom of the ore shoot on the loading platform of the Union Chief Mine. A conglomerate there exposed contains white quartz pebbles ranging in size from one-half inch to two inches, the majority being about one inch in diameter. The angularity of the contact near the mine is about 15 degrees. The unconformity may best be seen from the top of the ridge between the lower part of Santaquin Canyon and Pole Canyon, Section 30, T. 10 S., R. 2 E. Here the line of the unconformity is about level with the eye, and the truncation of a large series of the Algonkian quartzites and shales by the overlying Cambrian quartzite at an angle of about 25° is visible with textbook clearness. When Dry Mountain is viewed from below, the angularity of this unconformity is greatly decreased by acute perspective, and is not discernible unless its exact position is known.

An extremely coarse phase of the basal conglomerate of the Cambrian is encountered about 1,000 feet north of the mouth of North Canyon, where a prospect hole at an elevation of 6,450 feet follows in along a fault which dips 55° to the west. Just above the prospect hole a basal conglomerate is encountered which is of exceedingly variable composition. The matrix shades between light graywacke and a dark quartzite. The phenoclasts range from small, rounded quartz pebbles to large, angular quartz fragments, and even large, angular blocks of gneiss and schist. The total thickness of this conglomerate is fifty feet or more. Above it lies the typical lighter Cambrian quartzite, in which an igneous sill is found.

## OPHIR SHALE

*Character of sediments*. — The shale is generally thin-bedded, and of an olive-drab color. It has a very characteristic, micaceous sheen on the parting surfaces. In thin beds it is a true shale, but in beds over one-half inch thick it occurs in the form of a well-cemented sandstone. A thin section of such sandstone shows it to be an aggregate of small, angular, and poorly rounded quartz grains one-tenth to three-tenth mm. in diameter, with a few microcline and plagioclase grains irregularly distributed, and with muscovite shreds along the bedding planes. Muscovite flakes produce the characteristic sheen of the shale. Other light lemon-green grains of the same size as the quartz grains occur prominently and are alteration products of a mineral of rather high relief. They are usually dark between crossed nicols. Neither the alteration product nor the original grains could be determined. A small amount of secondary silica as a cement was observed around the quartz grains, but not enough to make the rock a quartzite.

*Thickness*. — A good section of the Ophir shale, which is available for study in North Canyon, shows that the contact of the shale with both the underlying quartzite and the overlying limestone is one of gradation between shale and quartzite at the bottom and shale and limestone at the top. The upper and lower limits must, therefore, be arbitrarily established and under this condition the thickness measures approximately 300 feet. On the west face of Dry Mountain it was estimated to be 250 feet.

*Fossils and correlation*. — In the summer of 1928 fragmental trilobites were found at the Union Chief mine in a rather soft, gray clay-shale, distinctly different from the typical Ophir shale in lithology, but occurring in its upper horizons or in the lower horizons of the limestone into which the shale is transitional. Professor B. F. Howell of Princeton University has kindly identified the following fossils from this formation: *Bathyuriscus sp.; Olenopsis sp.; Ptychoparia sp*. Two brachiopods from the typical Ophir shale found in Long Range west of York were also identified by him. They are *Obolus sp*. and *Micromitra sp.*

The fauna, especially the trilobites, is similar to that found in the Gordon Shale of Montana and the Ross Lake member of the Ptarmigan formation of British Columbia. This fauna represents either uppermost Lower Cambrian or lowermost Middle Cambrian time, according to Professor Howell.[6]

The Ophir shale has also many tubular structures which, instead of piercing through the layers as worm borings do, repose on them. No detail is preserved, and the meaning of these marks is obscure. Other markings very closely resemble traces of seaweeds. Peculiar mottled surfaces of unknown origin are common.

## CAMBRIAN AND UNDIFFERENTIATED LIMESTONES AND DOLOMITES

Above the Ophir shale a thick series of dark, and generally massive, limestone and dolomite beds occur, the lower 2,300 feet of which, so far, have yielded no fossils. Their age is consequently indeterminate and, therefore, the term "undifferentiated" is used in naming them. Certain lithologic peculiarities, such as "ribbon banding" and "oölitic texture," are found in limestones of tentative Cambrian age farther north in the Wasatch Mountains and to the west in the Tintic Mountains. These two characters, which are found in the strata immediately above the Ophir shale also, occur in limestones of the same horizons in the southern Wasatch Mountains and serve as the only basis of correlation. It is, therefore, probable that the lowest 300 feet of the limestones in North Canyon is Cambrian in age.

The rest of the overlying limestones and dolomites may be Cambrian, Ordovician, Silurian, and Devonian, or they may represent all or only part of any one of these. There are no pronounced unconformities within the group. The conclusion may thus be drawn that throughout pre-Carboniferous Paleozoic time the region of the southern Wasatch Mountains was subject to a series of very gentle, alternating emergences and submergences, producing, in the absence of fossils, almost undetectable disconformities. The region was one of almost exclusive carbonate deposition, which fact indicates that throughout this long span of time no emergence was vigorous enough to cause the deposition of clastic sediments.

The thickness of this Cambrian and undifferentiated series, as measured between the Ophir shale and an arbitrarily established upper boundary where the Carboniferous sediments are thought to begin, is about 2,300 feet.

SECTION OF CAMBRIAN AND UNDIFFERENTIATED BEDS IN NORTH CANYON, T. 11 S., R. 1 E., UTAH

| Description of beds | Thickness in feet |
|---|---|
| Limestone, brecciated | 220 |
| Limestone series, noted for sharp jointing. Bedding 6 to 12 inches | 200 |
| Dolomite, fine-grained, light gray, fairly massive. Weathers to sandy appearance | 100 |
| Dolomite, fine-grained, light gray. Ribbon structure somewhat smaller than lower ribbon horizons | 100 |
| Limestone, dark. Bedding 6 to 18 inches. Beginning of great cliff-making horizon | 350 |
| Dolomite, dark, wormy | 250 |
| Dolomite, white | 6 |
| Limestone, dark. Bedding thin | 100 |
| Dolomite, dark, wormy | 35 |
| Limestone, massive, dark | 100 |
| Limestone, ribbon. Bedding 1 inch | 25 |
| Limestone, massive, dark | 225 |
| Dolomite. Weathers to sandy appearance | 3 |
| Limestone, massive, dark | 225 |
| Dolomite, dark, small irregular white markings, somewhat wormy. Strike N. 60° E., dip 39° SE. | 15 |
| Limestone, ribbon. Bedding 3 to 6 inches | 280 |
| Limestone, oölitic. Oölites 2 to 3 mm. in diameter | 10 |
| Limestone, characteristic ribbon. Bedding ½ inch to 3 inches, chiefly 1 inch, with irregular gray-buff stringers | 50 |
| | 2294 ± |

## CARBONIFEROUS

Though there is probably a full sequence of Carboniferous formations in the southern Wasatch Mountains, the compilation of a complete section has not been found possible because of insufficient paleontologic and stratigraphic study. However, Dr. Girty of the United States Geological Survey, who identified the Carboniferous fossils collected by the author, feels certain that the Madison formation, the Pottsville and post-Pottsville horizons, and probably the Brazer formation, are represented in the rocks of the area.

### MISSISSIPPIAN

The Mississippian series includes the Madison limestone below, and probably the Brazer formation above. They are both composed almost entirely of limestone and dolomite, except where, toward the top of the Brazer, a considerable amount of black shale appears. The best sections of the Mississippian series are exposed in Santaquin Canyon and North Canyon, but the inability of the writer to find fossils or unconformities in these sections makes the determination of boundaries impossible for the time being. For this reason the Mississippian series has been mapped as one unit.

In the North Canyon and Santaquin Canyon sections the establishment of a lower limit of the Mississippian is purely arbitrary. The series of non-fossiliferous limestones above the Cambrian merges into the Madison without any observed erosional break. Usually the first appearance of small crinoid stems has been taken to represent the boundary. In North Canyon a windblown, pure silica, quartzitic sandstone is encountered, together with the first observed crinoid stems. Because of the exceptional occurrence of a sandstone in all the limestone series from Cambrian to Pennsylvanian, it is thought that this sandstone may have some diastrophic import; it has, therefore, been arbitrarily selected, without any fossil evidence, as the lower limit of the Mississippian and as a mappable horizon. It is hoped that some paleontologist will become interested in making a more thorough study of this part of the stratigraphy which is so well exposed in North Canyon.

SECTION OF MISSISSIPPIAN BEDS IN NORTH CANYON, T. 11 S., R. 1 E., UTAH

| Description of beds | Thickness in feet |
|---|---|
| Shale, dark, thin-bedded, with thin limestone lenses. Highly distorted. In Wash Canyon two or three heavy quartzite beds occur | 200–300 |
| Limestone, massive, blue. Bedding 1 inch to 4 inches | 300–400 |
| Limestone, massive, finely speckled. Cup corals ¾ inch in diameter | 200 |
| Limestone, dark, massive, dense. Regular beds of chert 1 inch thick at bottom. Chert beds pass upward into chert lentils, which are larger and more irregular toward top | 350 |
| Limestone, massive, dark, crinoidal. Small white blotches and markings | 15 |
| Shale, black, carbonaceous, calcareous. Dark argillaceous limestone beds intercalated | 30 |
| Limestone, dark, fine-grained, conchoidal fracture. Bedding 2 to 6 inches. Small crinoids and cup corals | 240 |
| Dolomite, dark, finely crystalline | 50 |
| Limestone, gray, massive, small crinoid horizons | 120 |
| Quartzite, wind-blown, sandy lenses, pure silica sand | 6 |
| Dolomite, gray, with very small crinoid stems and brachiopods. Possibly not Mississippian | 30 |
| | 1600 + |

*Madison formation*. — Loughlin[7] collected fossils from two horizons, one 400 feet above the other, on Dry Mountain and in Santaquin Canyon. These were declared by Dr. G. H. Girty of the United States Geological Survey to be of Madison age. The upper fossiliferous horizon is a cherty limestone which, because of its singular occurrence, is easily recognizable elsewhere and therefore serves as a convenient stratigraphic marker in other localities.

Collections of Madison fossils were also found, by the writer, in the mouth of Santaquin Canyon, but, because of the complexly faulted rocks in which they occur, their position in the Madison was not determined.

The cherty horizon is thought to mark approximately the top of the Madison formation, because of the occurrence of a fossiliferous horizon 400 feet above the chert, the fossils of which Girty has tentatively assigned to the Upper Mississippian. A sharp boundary, however, cannot be located in this 400-foot zone because of the lack of any unconformity to mark a definite break.

*Brazer (?) formation*. — A series of limestones, with 200 to 300 feet of shale at the top, is included between the known Mississippian and the great Intercalated series of the Pennsylvanian. Loughlin reports a collection of fossils from a horizon 400 feet above the cherty limestones of the Madison, and assigns them tentatively to the Upper Mississippian.

From the low Glenola Valley Hills southwest of Santaquin a single fossil was found by the writer, which Dr. Girty identifies as *Productus brazerianus*. He feels rather confident that it belongs to the Brazer formation which overlies the Madison formation. It is, then, rather definitely known that a post-Madison Mississippian series of limestones is present, and with the occurrence of this Brazer type of fossil, the series is tentatively called "the Brazer formation." It may well be that the Brazer fossil horizon is represented by a hiatus in Santaquin Canyon and North Canyon, and that, therefore, the rocks found in the Glenola Valley Hills must be supplied in the section through North Canyon to make the sequence at all complete. The limestone in the Glenola Valley Hills has facies resembling dense, gray, fresh-water types. Limestones of fresh-water origin are, however, probably not present in the Carboniferous of this region, but a rock of such striking character would have been noticed in the sections through the main ridge of the southern Wasatch, if it did occur. The absence of this limestone, then, strengthens the suspicion that a post-Brazer erosion epoch in Upper Mississippian or early Pennsylvanian time has been responsible for its removal.

The black shales such as are found in North Canyon and Bear Canyon are not present in Santaquin Canyon or in Dry Mountain. Also, the Mississippian series is conspicuously thinner through Dry Mountain than in North Canyon. These additional facts necessitate the conclusion that post-Mississippian emergence and erosion removed a large amount of rock in increasing proportion to the north, especially in the vicinity of Dry Mountain.

This erosion surface, although not accurately located, was buried by a new lithologic unit of Pottsville age, and is thought to mark the boundary between the Mississippian and the Pennsylvanian.

### PENNSYLVANIAN

*Intercalated series*. — The sedimentary rocks above the Upper Mississippian have a distinctive lithology and have been called by Loughlin[8] the "Intercalated series," a name which is here retained. They are 10,000 feet thick, and consist chiefly of a series of interbedded sandstones and limestones. Very little shale is present. Some of the sandstones are pronouncedly quartzitic, and some of the limestones very siliceous. The Intercalated series forms the whole of Mount Nebo and the high South Ridge. It underlies the Wasatch conglomerate to the east of the Wasatch Mountains from Mount Nebo to Loafer Mountain, and also forms most of the hills south of Santaquin.

Fossils collected at various horizons in the Intercalated series in Santaquin Canyon were identified by Dr. Girty. The lower 7,000 feet contains rather nondescript fossils which he refers to the Pottsville or Lower Pennsylvanian.

Above these lower horizons of the Pennsylvanian a group of faunas occurs which Girty believes are post-Pottsville. In the section in Santaquin Canyon, where a complete sequence is thought to be present, post-Pottsville fossils were found about 9,000 feet above the base of the Intercalated series and 2,000 feet above the last-mentioned Pottsville horizon.

A fauna from the High South Ridge of Mount Nebo is probably also post-Pottsville in age, especially if the evidence from the Gold Hill region applies to the southern Wasatch Mountains. In the Gold Hill region *Fusulina* does not occur in any of the Pottsville faunas and, therefore, the occurrence of this fossil is thought to indicate the presence of some post-Pottsville horizon.

Other post-Pottsville faunas were found on the south slope of Loafer Mountain above the mouth of Schram Creek and on the east slope of Dry Mountain above Maple Dell.

In Gardner's Canyon *Fusulina* are abundant in the limestones which overlie the Jurassic shales.

At the head of Santaquin Canyon in Dry Hollow, above the post-Pottsville horizons, a fauna is encountered which, according to Girty's incomplete fossil evidence from Gold Hill and the Oquirrh Mountains, is correlated with the Pottsville horizon of the Gold Hill section. This confirms the writer's suspicion that a repetition of the strata, probably by faulting, has occurred here.

As already mentioned, Dr. Girty finds that the Carboniferous faunas of the southern Wasatch Mountains are represented in the Gold Hill and Oquirrh Mountain sections. It would, therefore, appear that the Carboniferous strata of the southern Wasatch Mountains bear close relationship to the rocks of equivalent age to the west and northwest. To the north, in the central and northern Wasatch Mountains, Carboniferous rocks of entirely different lithologic aspects occur. It is concluded, then, that the Carboniferous rocks of the southern Wasatch Mountains are to be correlated with those of Gold Hill and the Oquirrh Mountains, rather than with those to the north in the Wasatch Mountains.

## RELATION OF PENNSYLVANIAN TO TRIASSIC

The transition from the Carboniferous to the Triassic may be seen in the North Fork of Salt Creek Canyon at Camp Dadandson. From a distance red strata appear sparingly interbedded with the upper members of the Intercalated series, but become more and more numerous, until they finally form the entire rock series. Since no decided lithologic change or any evidence of an angular unconformity was noted, the contact between the Intercalated series and the Woodside of the Triassic is purely an arbitrary one, and leaves several hundred feet of strata, in which a few red beds occur, assigned to the Intercalated series.

No definite break between the Carboniferous and Triassic has been found to the north, either at Park City[9] or in southeastern Idaho,[10] although in the Wasatch front east of Salt Lake City Schneider[11] recognizes "evidence of a disconformity." The nature of this disconformity is not stated, probably because of the brevity of the paper.

Because of lack of fossils, especially in the red beds, it is not known whether rocks of Permian age are present. From physical evidence it would appear that possibly a complete transition is present; but from the previously noted difficulty in finding fossils or erosional breaks, it must be concluded that that part of the geologic history represented in the transition from Pennsylvanian to Triassic time remains an unsolved problem in the southern Wasatch Mountains.

## TRIASSIC

### OCCURRENCE

The Triassic series of rocks follows down the eastern flanks of the Wasatch Mountains from the Park City district to the Nebo district. At Thistle Junction the Triassic beds, which dip steeply to the east, begin to swing westward. They soon disappear under the Tertiary cover in the neighborhood of Bennie Creek, only to reappear again in the North Fork of Salt Creek Canyon, where erosion has cut through the flat-lying Tertiary rocks into the upturned Mesozoic strata beneath. Here the beds strike northeast and dip from vertical to 45° northwest. The area mapped does not include the Thistle Junction exposure, but only the ones in Salt Creek Canyon.

### WOODSIDE (?) FORMATION

*Character of sediments*. — The base of the Triassic rocks in the North Fork of Salt Creek Canyon consists of dull red sandstones and shales interbedded with thin, light gray and buff-colored shales and sandstones. Limestone beds 2 to 4 feet in thickness, apparently of marine origin, are also present. The bottom of Bear Hollow marks the lower limit of this formation. It may also be seen as a red band around the steep slope of the high south ridge of Mount Nebo, some 500 feet above the junction with the more gentle relief of the north slopes of Salt Creek Canyon.

*Thickness*. — This group of beds is only 150 to 200 feet thick. The lower limit is purely arbitrary, as previously explained under the caption "Relation of Pennsylvanian to Triassic," and could without difficulty be shifted to lower horizons, which would thus increase the thickness.

*Correlation*. — This series of red beds with intercalated marine limestones passes conformably into a light gray and buff-colored series called "the Thaynes formation." The Thaynes bears fossils corresponding to those identified from the Thaynes of the Park City district, which is Triassic in age. Conformably underlying the Thaynes in the Park City district is a homogeneous dark red shale 1,100 feet thick. So far as known, this bears no fossils, and is called Triassic only on the ground that it resembles certain beds in the known Triassic Thaynes. This dark red shale group has been called by Boutwell[12] "the Woodside Shale." Although the thickness of the red beds at the base of the Triassic in Salt Creek Canyon is only a sixth of that in Park City, the two occupy similar stratigraphic positions and are of the same color. On these grounds they will be tentatively correlated as the same formation. Schneider mentions the Woodside on the Wasatch front east of Salt Lake City as more sandy and more calcareous than in the Park City district, but not so deep red.[13] The thickness is not given, but the writer's own examination of the ground would estimate it as only a few hundred feet. Thus the Woodside east of Salt Lake City corresponds more closely to the Woodside of Salt Creek than does the Park City. It may be that this Wood-side formation in Salt Creek is considerably reduced in thickness by being involved in the Nebo overthrust, of which not all details have yet been fully worked out.

At the head of Santaquin Canyon, a short distance up Dry Hollow, a red sandstone begins with typical Ankareh color and laminations, but apparently in stratigraphic position with the Woodside. Major faulting has probably occurred in this vicinity, as previously mentioned, and the significance of this red sandstone at the top of the Intercalated series in Santaquin Canyon is, therefore, not known.

### THAYNES FORMATION

*Occurrence*. — The Thaynes formation occurs stratigraphically above the Woodside (?) formation, but in outcrop below it because of the overturned structure. It crosses the North Fork of Salt Creek Canyon between Bear Hollow and Cow Hollow, but is poorly exposed. It transects the upper part of Andrew's Canyon, where it is most accessible, and a few fossils may be found in the float and weathered outcrop. It comprises roughly the lower 500 feet of the high South Ridge below the Woodside, and here finally wedges out toward the west owing to implication in the Nebo overthrust.

*Character of sediments*. — The Thaynes formation consists of a series of fine buff and gray sandstones, with some distinctly limy beds intercalated. The sandstones are both thinly and thickly bedded, and some have a good development of laminations. Thin sections show the sandstone to be composed chiefly of an aggregate of quartz and muscovite grains, with maximum diameter of one-twentieth mm. The quartz grains form the greater part of the rock. The rock effervesces freely when tested with hydrochloric acid.

*Thickness*. — Because of varying dips and acute truncation by the Nebo overthrust, the thickness can be only estimated. It ranges from 500 to approximately 1,000 feet.

*Fossils and correlation*. — The following fossils found in this formation were identified by Dr. Girty: *Aviculipecten sp.; Pseudomonotis ? sp.; Bakewellia ? sp.; Myacites inconspicuus ?*. These fossils, though few, correlate with those of the Thaynes[14] of the Park City district. In lithology the two formations are somewhat alike.

Therefore, in view of the stratigraphic position, the lithological similarity, and the fossil evidence, this group of fine, buff sandstones of Salt Creek and Mount Nebo is called "the Thaynes formation."

Boutwell, in his first studies of the Park City district, found the fossil content of the Thaynes to agree with that of the "Permo-Carboniferous beds" of the Fortieth Parallel Survey, but his later work states it to be faunally related to Peale's "Mekoceras beds"[15] of southeastern Idaho, which had been referred by C. A. White[16] to the Triassic, although the Park City district does not contain ammonites. Further studies of the cephalopod genera by Hyatt and Smith[17] showed that the fauna of Idaho is intimately related to the Lower Triassic faunas of India and eastern Siberia, and that it contains species which may even be identical with those from Asia. The Thaynes is, therefore, assigned to the Lower Triassic. No ammonites were revealed in the Salt Creek Triassic, but it is held to be of the same age as the Park City Triassic, whose tripartite lithologic and stratigraphic division it so closely resembles.

Professor A. A. L. Mathews[18] has published an article on a new ammonite fauna of the Thaynes formation which he found east of Salt Lake City. In this paper he splits the previously recognized Thaynes into two groups, and names the lower one "the Pinecrest formation," from Pinecrest Ridge in Emigration Canyon, the upper group retaining the name "Thaynes formation." Later he applies the name "Emigration" to the upper formation instead of "Thaynes," but still uses "Thaynes" as a group name which includes both the Pinecrest and Emigration formations.[19] The Pinecrest formation is reported as lower than Boutwell's Park City Thaynes, and is not represented there in the type locality. In personal conversation Professor Mathews has stated that he believes that the Thaynes as represented in Salt Creek Canyon is equivalent to the upper division or Emigration formation and does not include his Pinecrest formation.

## ANKAREH FORMATION

*Occurrence*. — The Ankareh in Salt Creek Canyon emerges from under the Tertiary cover just below Tryan Hollow, dipping 40° to 60° NW., and strikes southwest diagonally across the North Fork to Andrew's Canyon, where it crosses at the head of the road and swings into Mahogany Knoll. Continuing west, it thins rapidly until at the knoll formed of Wasatch conglomerate, about one mile west of the elk pasture, it is entirely lacking. From there west to the Wasatch front the Intercalated series is in contact with the Jurassic shales, with only occasional irregular red rocks observable. The entire Triassic system of some 2,500 feet in thickness has disappeared here at the base of the high, overturned South Ridge of Mount Nebo, which is within four miles. The Nebo overthrust is undoubtedly the cause.

In the Ankareh formation in Andrew's Canyon is an old quarry from which the red sandstone has been extracted for use as a building stone by the early settlers. It breaks evenly along the bedding and at right angles across the bedding, so that it is easily worked.

*Character of sediments*. — In the Park City district, where the type section of the Ankareh occurs, the major part of the formation consists of red shales, but these grade through considerable thicknesses into sandy facies. A number of well-marked, coarse, gray sandstone beds are also present, together with intercalated blue-gray limestones. In Salt Creek Canyon a solid red massive sandstone is the dominant rock type. Purple, light pink, and creamy shades lend variation, however, to the dominant red. A fifty-foot shale member is also noted near the lower part of the formation, which varies in color from red to light green. Limestone float suggests the presence of limestone layers, as in the Park City district, but none were found in place.

A microscopic examination of a laminated specimen of red Ankareh sandstone, taken from the quarry at the head of the road in Andrew's Canyon, shows that the quartz grains range from one-tenth to one-fifth mm. in size, are mostly angular, and comprise about 50 per cent of the slide. Andesine-plagioclase grains are plentiful and little weathered. The second most abundant constituent is an alteration product consisting of sericite and probably calcite. The sericite may have come from a more sodic feldspar. The calcite is probably secondary. The rock effervesces freely when tested with hydrochloric acid. Some muscovite shreds and a zircon grain were observed. Silica in small amounts around the quartz grains is common, but the chief cement is dark brown hematite. It is interstitial, but bunchy and not consistently distributed between all the grains or in coatings around the sand particles. A thin section of the Ankareh sandstone east of Salt Lake City showed the hematite to be concentric around each sand grain, however. If the single slide studied is at all characteristic of the formation as a whole in Salt Creek, the rock is undoubtedly an arkose. Although the writer is not aware that any rocks of this nature, either in Park City or east of Salt Lake City, have been recognized, this occurrence is not unusual, because the Triassic sandstones of the Colorado Plateau are in places quite arkosic.

*Thickness*. — The upper beds of the Ankareh in the North Fork of Salt Creek Canyon are thought to be absent because of concealment by the Nebo overthrust. The section as exposed in Salt Creek Canyon measures 1,500 feet in thickness; but the total thickness is probably greater.

*Correlation*. — No fossils were found in any part of this red series of the Triassic. The writer's acquaintance with the litho-logic characteristics of the Ankareh formation east of Salt Lake City makes him feel positive that these upper red beds in Salt Creek Canyon are also Ankareh. The conspicuous red Ankareh can be traced almost continuously down the east flank of the Wasatch Range from the type locality at Park City to the Nebo district. This fact, together with the similarity in stratigraphic position and lithology, is the basis for correlation with the

Ankareh of the Park City district and the Ankareh of the Wasatch front east of Salt Lake City.

## JURASSIC

*Occurrence*. — Strata of Jurassic age are found on both sides of Salt Creek Canyon, down the west side of the Gunnison Plateau as far as the town of Fayette, and in southern Sanpete Valley south of Mayfield. Their total thickness is very great, but because of the extreme contortion and incomplete exposures of the beds the exact thickness cannot be stated. It probably is represented by a figure between 4,000 and 11,000 feet.

*Character of sediments*. — A gray-drab shale is without doubt the thickest formation in the Jurassic series. It may be readily recognized by the subdued, bad-land terrane into which it erodes and by the red or pink patches of coloring scattered promiscuously over the surface (see Pl. XXVII).

An unusual rock type in the Jurassic series is a travertine, probably of spring origin. If it were not shattered so extensively by joints it would probably make a good interior-decoration stone. Because of its vivid, wavy, red and white banding it is called commercially "jazz marble." Specimens are shown in Plate XXVIII, Figure 2.

*Thickness*. — The Jurassic section is represented in the table at the top of the opposite page.

*Fossils and correlation*. — In the lowest observed member of the Jurassic series, the oölitic limestone, the following fossils were found by the writer and identified by J. B. Reeside, Jr.: *Pentacrinus asteriscus* Meek and Hayden and *Ostrea strigilecula ?* White.

In the thick shale formation the following fossils were identified, again by Dr. Reeside: *Camptonectes stygius* White, *Camptonectes sp*., *Pentacrinus asteriscus* Meek and Hayden, *Ostrea strigilecula ?* White.

These fossils are upper Jurassic, according to Dr. Reeside, and possibly equivalent to the Sundance formation of Wyoming. The Jurassic shales as found in Salt Creek Canyon have been noted by Gilluly and Reeside[20] along the west front of the Wasatch Plateau and correlated with the Carmel formation of the San Rafael Swell and the Henry Mountains.

SECTION OF JURASSIC BEDS IN SALT CREEK CANYON, UTAH

| Description of bed | Thickness in feet |
|---|---|
| Shale, drab, calcareous, arenaceous, generally thin-bedded. Occasional thin, lenticular limestone and sandstone beds intercalated. Patches of red coloring frequent, but do not follow any one bed. Highly contorted. Weathers into soft landscape. Salt and gypsum lenses | 3,000–10,000 |
| Travertine, wavy alternating bands of white and red calcium carbonate. Red bands highly impregnated with hematite. White bands are columnar aggregates of calcite crystals. Some silica replacement | 100 + |
| Sandstone, red to drab, thin-bedded, in part laminated | 10 |
| Gypsum, stubby lens in North Fork of Salt Creek, coarsely crystalline (crystals 1/16 inch to 2 inches in length). Considerable earthy material admixed | 250–300 |
| Travertine, same as travertine above | 400 ± |
| Shale, same as shale above | 400 |
| Limestone, rather massive, creamy brown. May be somewhat siliceous | 30 |
| Limestone, drab with pink tint, oölitic, fossiliferous (Pl. XXVIII, Fig. 1) | 20 |
| PLANE OF OVERTHRUST | 4,210–11,260 |

Lithologically, these shales have no counterpart either north in the Wasatch Mountains or southwest in the Colorado Plateau. They do, however, bear a closer resemblance to the Entrada and Curtis formations of the Swell than to the Twin Creek limestones of the central Wasatch. For correlation of Triassic and Jurassic sections in the Wasatch Mountains see Figure 13, page 332.

*Triassic and Jurassic contact*. — The Ankareh sandstone is separated from the Jurassic oolitic limestone by an unconformable contact which may be interpreted as either an erosional unconformity or an overthrust fault. This question will be discussed in detail in a future paper on the structure of the southern Wasatch Mountains, and therefore will not be introduced here. The conclusion reached, however, is that the contact is an overthrust fault in which neither Upper Triassic beds nor the lower beds of the Jurassic series are represented, owing to concealment by the thrusting.

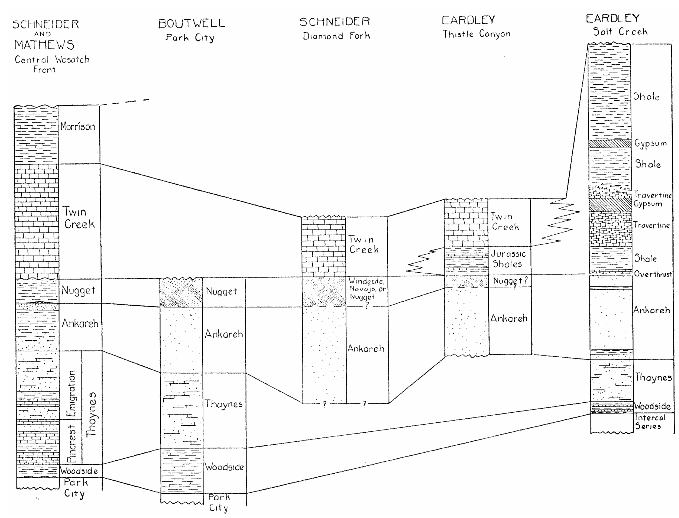



FIG. 13. Triassic-Jurassic columnar sections of Wasatch Mountains. 1 inch = 1,000 feet

*Gypsum*. — The Wheeler Survey recognized the Salt Creek shales as Jurassic,[21] and in the report stated that "The Jurassic rocks are everywhere found to be gypsiferous, and in some places good workable beds of gypsum are seen. One of these beds occurs at Salt Creek near Nephi.[22]

In 1904 a report of the gypsum deposits of the United States was published by the United States Geological Survey, in which the Nephi deposits were described by J. M. Boutwell.[23] His visit was made in the wintertime when snow concealed the outcrops, but nevertheless, his conclusions as to origin agree with those of the writer. He says:[24]

> Although the study of the region was too hasty to obtain sufficient data for a complete explanation of the deposit, general observations, together with facts brought out by analyses, afford accordant evidence for an opinion. The bedded structure of the gypsum, the agreement of this bedding with that of the country rock, the interbedding of wall rock and gypsum, and the occurrence in the same series in this neighborhood of rock salt, common salt and gypsum of various degrees of impurity tend to indicate a sedimentary origin. The presence of about 17 per cent calcium carbonate, one-half of one per cent of magnesium carbonate, and minor amounts of potassium and sodium salts afford additional basis for the belief that this gypsum is the product of deposition from surface water bodies, such as inland lakes, lagoons, and bayous.

This gypsum deposit has since been mined out, and proves to be a bunchy-thick lens without much continuation between the bedding planes. Gypsum is now being mined about two miles to the north on the spur between Red Canyon and Quaking Asp Canyon. This deposit likewise cannot be traced for any distance along the bedding. Another outcrop in Gardner's Canyon is also terminated rather abruptly at both ends of the outcrop. Other gypsum showings have been discovered and claimed farther up Salt Creek Canyon, all of which are only of short surface extent. Boutwell's reasons for determining the genesis of the gypsum are sufficient. The only addition to be made here is one explaining the thick lenticular nature of the deposits. The shales show intense compressional distortion. It is thought likely that under such conditions thin gypsum beds have yielded to variations of pressure by flowage, thickening where relief occurred, and thinning where pressure concentrated. The pressure and subsequent folding of the Jurassic shales came from the competent Paleozoic rocks in the Nebo overthrust.

*Salt*. — Two rock-salt pits and a salt spring are located in the North Fork of Salt Creek Canyon. One salt pit is found just to the north of the mouth of Red Creek. Another is located on the west side of North Fork about half a mile up from the main Salt Creek Canyon. Impure rock salt has been mined for cattle. In both places a red earthy material is associated with the salt. This may be due to the fact that the surface outcrop is badly weathered and that quarrying has not proceeded far enough to expose the true nature of the salt, or, on the other hand, to the secondary deposition of salt at the surface by evaporation of salt water issuing through seeps or springs. The fact that the salt is associated with detrital material of the travertine country rock in one pit and with volcanic-ash country rock in the other seems to justify the conclusion that the salt is secondary. If this idea of origin is true, then there would be no hope of finding more solid and massive beds of salt with greater development of the pits. It is inferred that the salt comes from the Jurassic shales, where it existed as interbedded deposits, perhaps associated with the gypsum. The salt spring about one-half mile up the gulch opposite Red Creek flows from the Jurassic shales just above the point where the gypsum deposit dies out. In Sanpete Valley great beds of salt are interbedded in Jurassic sediments. From these known sources and from the irregular occurrences of salt near the surface in younger deposits it is concluded that all the salt in Salt Creek comes from the Jurassic shales.

The salt water emerges saturated and, upon slight evaporation, deposits crusts of salt along either side of its course. The salt brine is piped to an evaporation plant where a very high grade of salt is obtained. It was reported over 99 per cent NaCl. It settles as flakes on the bottom of large evaporation pans, and is claimed by the management of the plant to be of particular commercial value in the curing of meats, the making of cheese arid butter, etc.

## TERTIARY

### WASATCH CONGLOMERATE

*Occurrence*. — The Wasatch conglomerate is confined chiefly to the east slopes of the high, sharp, single ridge of the southern Wasatch Mountains. It also occurs east and west of York in T. 10 S., R. 1 E. It is separated from the underlying rocks of Paleozoic and Mesozoic age by a pronounced unconformity. In Salt Creek Canyon the pre-Tertiary beds have been overturned, truncated, and covered by this Wasatch conglomerate.

It has a maximum thickness of about 1,200 feet, measured in the area between Red Creek and Bear Hollow, but has suffered erosion intermittently from Eocene time to the present, so that it was once much thicker.

*Character of sediments*. — Loughlin's description of this conglomerate holds for most places, though in one or two localities varying types are found. He says:[25]

> The conglomerate consists of pebbles, and in places even small boulders, mainly of quartzite, limestone and black chert in a soft red sandy matrix. The quartzite pebbles include both Cambrian and upper Mississippian (Intercalated series) types, the Cambrian greatly predominating. The limestone pebbles include the shaly Cambrian types, dolomitic types of lower Mississippian and probably earlier age, and the coarse grained gray limestone of upper Mississippian age. This variety of pebbles proves that almost the entire Paleozoic section was exposed to erosion while the conglomerate was forming. There is no evidence, however, that the pre-Cambrian rocks were exposed to erosion at this time. Owing to the tendency of the red matrix to rapid weathering, many outcrops of the conglomerate are reduced to an aggregate of loose pebbles and boulders in a soft red soil.

Dark purple quartzite boulders are quite numerous, and these come from the Algonkian which, as previously explained, Loughlin has grouped with the Cambrian. Therefore, the Algonkian rocks were also exposed to erosion during the deposition of the conglomerate.

About one mile up the North Fork of Salt Creek the conglomerate does not have the characteristic red appearance, but is more yellow and gray, and is not composed of rounded pebbles and boulders, but of very angular phenoclasts. It resembles a skree or fanglomerate more than a basal conglomerate in this particular place. The difference in color is partly due to the difference in kind of phenoclasts, chiefly sandstones and limestones of the Intercalated series. Very little Cambrian material is here present.

In Payson Canyon, west of Maple Dell, is a small ridge, the lower half of which is Tertiary conglomerate. Here large fossiliferous limestone blocks, some over six feet long, are firmly embedded. They come from the Intercalated series.

The dip of the conglomerate immediately east of the southern Wasatch Mountains is mainly initial, and has been changed but little by deformation since deposition, although in two localities dips up to 40° have been recorded. This conclusion is verified by the horizontal position of a bed of limestone occurring within the conglomerate in the immediate vicinity of the high dips.

*Source of sediments*. — The contact of the Wasatch conglomerate with the underlying rocks is sedimentary. Therefore, in solving the problem of the source of the material it is safe to assume present relationships as existent at the time of deposition. The conglomerate becomes finer to the east, eventually changing to shales and limestones, thus indicating a western origin of the sediments. They begin on the east slopes of the southern Wasatch Mountains in alluvial-fan structure. This, then, must have been the western margin of the basin into which they were deposited. The present high ridge of the southern Wasatch Mountains was much higher than it is now, and also the Basin and Range country to the west stood 5,000 or 6,000 feet higher before the block-faulting began. The high ridge and the area to the west is therefore postulated to have supplied the material which composes the Wasatch conglomerate.[26]

*Age*. — Within the Wasatch conglomerate is a fresh-water limestone bed of interesting character which the writer has described in a separate publication.[27] It has yielded gastropod fossils determined as lower Eocene in age, probably equivalent to the Knight formation of southwestern Wyoming. The paper on this limestone formation discusses the questions of age and name and therefore repetition is not necessary here.

## QUATERNARY (*Pleistocene ?*)

### SALT CREEK FANGLOMERATE

*Occurrence*. — A thin formation overlying the volcanic, water-laid deposits and the Jurassic shales in Salt Creek Canyon will here be called "the Salt Creek fanglomerate." From the main highway it may be seen as a red capping on the west side of the mouth of Foots Canyon and over the castellated volcanic ash at the junction of the North Fork and the main canyon. Without close inspection this latter occurrence might be mistaken for Wasatch conglomerate. The beds show a low dip away from the high South Ridge. This is most probably initial, since no deformation has disturbed the beds since deposition.

*Character of sediments*. — The Salt Creek formation is composed of a mixture of large and small angular rock fragments, rudely sorted, with a matrix of red earthy material. Cementation is usually poor. Stratification is rough and channeled. In most places the formation is a fanglomerate. At the head of Foots Canyon, above the elk pasture, it contains no Cambrian quartzite or older Paleozoic limestones. It is composed entirely of material from the Intercalated series, the Triassic sandstones, and the Jurassic shales and limestones. In this particular location, then, it is demonstrated to be alluvial-fan material coming from the high South Ridge of Mount Nebo immediately to the north.

*Age*. — The Salt Creek fanglomerate overlies the volcanic deposits unconformably. The former is, therefore, decidedly younger than the latter, which in turn is younger than the Eocene Wasatch conglomerate. No fossils have been found in either the fanglomerate or the volcanic deposits by which a definite age of one or both could be determined, although separation from Eocene deposits by two unconformities suggests late Tertiary or Pleistocene age for the fanglomerate.

The physiographic setting, however, lends some aid to the solution of the problem. The fanglomerate rests on an old, mature, valley floor which has since been incised to a depth of about two hundred feet where the fanglomerate occurs. The rejuvenation is due to block-faulting of Basin and Range age which has lowered the base of deposition of Salt Creek. If this old valley upon which the fanglomerate lies can be shown to be of prefaulting age, then the fanglomerate must also be of prefaulting age and, therefore, probably Pliocene. But there exists certain evidence which suggests that the older valley was eroded during an interim of faulting, in which case the fanglomerate would correspond in age to an epoch of time in the Pleistocene. The problem is not yet solved and must await further physiographic study.

### RECENT ALLUVIUM

Fault scarps and subaërial deposition have given rise to topographic forms typical of the Great Basin. All along the west front of Mount Nebo, from York to Nephi, large and symmetrical alluvial fans coalesce, forming a piedmont slope. The piedmont grades out into the flat bottom of Juab Valley, where the finer sediments have been deposited. Another well-developed piedmont is found between the upper part of Salt Creek Canyon and the north end of the Gunnison Plateau. The piedmont on the west front of Dry Mountain, east of Santaquin, reflects the influence of Lake Bonneville. Deltaic deposits, reworked to some extent by alongshore currents, here supplant the fans of Juab Valley.

G. K. Gilbert mapped Lake Bonneville at its uppermost level, the Bonneville level, as extending past York into Juab Valley. This conclusion is warranted by the presence of a few small terraces on the west side of the valley at the base of the east slope of Long Ridge. But the body of water was small and probably short-lived, because of its almost complete isolation from the main body of water by a shallow pass at York. The piedmont along the west front of Nebo shows no effects of the presence of a lake, and it marks a striking change from the deltaic and terraced piedmonts northward along the Wasatch.

Some small, low bars southwest of Santaquin indicate that the currents which carried the sand and gravel came from the northeast.

The terraces and bars date from the Bonneville level of old Lake Bonneville. This is the oldest of the recorded stages of the lake.

Alluvial fans are building at the present time, but, like the valley-floor deposits, are older at the greater depths, so that those deposits immediately overlying the lowest areas of the hard rock floor of the down-faulted block date back to the initiation of the Basin and Range faulting of this section.

## Igneous Rocks

### EXTRUSIVE ROCKS

Extrusive rocks in the form of volcanic breccia and water-laid volcanic ejectamenta cover considerable portions of the district.

#### *Volcanic breccia*

*Occurrence*. — The largest area of volcanic breccia occurs in Payson Canyon flanking the east slope of Dry Mountain, where it covers roughly four square miles and has a maximum thickness of about eight hundred feet. This deposit is not shown on the geologic map of the state of Utah. On the west side of Dry Mountain, at the mouth of Santaquin Canyon and in the hills both east and west of York, are large amounts of felsite-porphyry boulders of all sizes. Loughlin views these aggregates of loose cobbles as the result of rapid weathering of the soft-tuff matrix of a volcanic breccia. It must not be erroneously inferred, however, that the presence of these volcanic cobbles indicates the occurrence of the original breccia beneath. In most places boulders of Cambrian and Algonkian quartzite are mixed with the volcanic boulders. This condition could not arise if the latter represent a reduction of the breccia to an aggregate of loose cobbles. Volcanic boulders, which are seen in road cuts and washes, form part of the alluvium. They may be residual to this alluvium. Over other small areas the surface is a mass of volcanic cobbles to the exclusion of everything else. In such places it is quite likely that the original breccia has existed or still exists beneath. Most of the boulders are rounded, but the exact significance of this observation is not known. The rounding may be due to exfoliation, or to stream wear, so that boulders of a residual deposit may be rounded as well as those found in the alluvium.

In Pole Canyon, south of Santaquin Canyon, a small patch of volcanic breccia, which is the same as the Payson Canyon breccia, was mapped. This small remnant is probably the last of a once much more extensive deposit; the boulders and fragments which now strew certain parts of the low hills around confirm this assumption.

In the upper basin of North Canyon another small patch of breccia is still intact, and indicates the former existence of the deposit, at least for this distance south of Payson Canyon.

*Petrographic description*. — Loughlin briefly describes the type of volcanic rock found around York[28] and finds two varieties, namely, "augite andesite" and " hornblende-augite andesite." Thin sections from all the eruptive volcanic rocks of the area studied by the writer agree with Loughlin's determination. It should be pointed out, in addition, that these rocks are porphyritic, the phenocrysts being largely labradorite.

*Age*. — The volcanic breccia is later than the Wasatch conglomerate because it rests unconformably upon it. Its relation to the Basin and Range faulting is very difficult to determine directly, but by correlation with a deposit of clastic volcanic rock of known age it is thought to predate the faulting. This evidence will be given later.

### VOLCANIC CONGLOMERATE

*Occurrence*. — In the Salt Creek Canyon area another deposit of volcanic material exists, which in surface extent is about as large as that of the Payson Canyon breccia. In the fork of Salt Creek that drains the eastern slopes of Mount Nebo this deposit extends from Red Creek to the main Salt Creek Canyon.

*Character of sediments*. — Unlike the andesite breccia of Pay-son Canyon, the volcanic deposit here consists of andesite pebbles and boulders of all sizes from one-half inch up to two feet in diameter, embedded in a roughly stratified, water-laid matrix of volcanic ash. In Pole Canyon this deposit of igneous material consists of two parts: an upper, dark horizon, with stratification, channeling, and thick lenses, all extremely coarse, and a lighter and lower division, in which poor but better sorting is evident (see Pl. XXIX).

The Wheeler Survey observed this volcanic material along the road in Salt Creek Canyon, and drew on their maps a considerable area of "extrusive igneous rock." This same area has been transcribed upon the geologic map of the State of Utah which accompanies *Professional Paper 111*. The deposit is, in reality, only about one tenth as large as there mapped and, strikingly, is roughly limited to the present main drainage channels of Salt Creek. From the nature of this volcanic material and its position in reference to the Wasatch conglomerate and the present drainage lines, it is interpreted as being valley fill in old channels in the Wasatch conglomerate. The old drainage lines followed somewhat the same courses as now. The streams in these courses suddenly became torrential and overloaded with loose volcanic material. Deposition with rough stratification accompanied this overloading, and as a result the old stream channels were filled in (see Pl. XXX).

Dutton[29] describes similar clastic volcanic rocks in the High Plateaus of Utah and arrives at the same conclusions as the writer regarding their origin. He says: "The process which formed the conglomerates consisted in the transportation of fragmental matter from high-standing ancient volcanic piles to low-lying plains and valleys around their bases or along their flanks."

The present drainage system east of Mount Nebo has been reestablished in essentially the same lines as those followed prior to the fill of the old drainage system. As a result, only patches of the water-laid, igneous material flanking the old channel walls are now left.

*Origin*. — The volcanic breccia in Payson Canyon to the north and a similar deposit in Thistle Creek Canyon to the northeast are the possible source areas of the volcanic conglomerate. Thin sections show all three to be composed of the same type of rock, and hence the probability of the derivation of the clastic volcanic rocks from the volcanic breccias. The dip of the cross-bedding and the gradation to finer material down the present channels corresponds in direction to that shown by the position of the probable source rock, the volcanic breccia, and therefore the conclusion is drawn that the volcanic conglomerate came from the north and northeast.

*Age*. — The water-laid deposit is younger than the Wasatch conglomerate and in this respect correlates with the breccia. If the clastic deposit and the breccia were both derived from the same episode of volcanism they must be of approximately the same age.

If a great mud flow by which the elastics were deposited accompanied the eruption of the breccia, the two would be contemporaneous. Such a phenomenon may have occurred to form certain phases of the Salt Creek Canyon volcanic deposit, since parts of the darker division of the clastic rocks are so heterogeneous and unstratified and so many of the boulders angular that a viscous mud flow is a possible interpretation. For the most part, however, the stratification, sorting, and rounding demonstrate the deposits to be water-laid. This fact may lead to the assumption that the elastics are younger than the breccia by being an erosional derivative of it. Torrential rains, however, may have accompanied the eruptions which extruded the ash and fragmental material, depositing great quantities in the lower courses of the stream channels, thus effecting a simultaneous accumulation of the two volcanic-rock bodies.

The block-fault bounding the northeast end of the Gunnison Plateau has caused the partial burial of the clastic volcanic deposits in Salt Creek by large alluvial fans, and the block-faulting appears, therefore, to have postdated the deposition of the volcanic sediments. The writer is of this opinion, but he believes, however, that only a short period of time elapsed between the volcanism and the faulting, for reasons based upon physiographic evidence which will be presented in-a future paper on the physiography of the region.

## INTRUSIVE ROCKS

*Dikes*. — Loughlin has described in much detail two lamprophyre dikes in the area, one on the west face of Dry Mountain on the Black Balsam claim in Green's Canyon, and the other at the mouth of Bear Canyon, on the west slope of Mount Nebo.[30] To these intrusions may be added several other dikes and sills, all of definite affinity. A group of small dikes occurring at the Nebo Highland Mine on the north side of Eva Peak, at the Eva Mine on the south side of the same peak, and in Bear Canyon about three hundred yards up from the mouth are all hydro-thermally altered to such an extent that the exact nature of the original rock is undeterminable. They seem to bear closer similarity to the lamprophyre dikes than to any of the other types to be mentioned.

In the North Fork of Salt Creek Canyon, about two miles up from its junction with the main canyon, a wall of dull red to purple felsite extends across the canyon. It is about thirty feet wide, and on the east side stands fifty feet high. It is interpreted as a dike cutting the water-laid volcanic material described in the preceding pages. Thin sections show the rock to be a porphyritic andesite, and, as such, it corresponds with the effusive types into which it is intruded.

*Sills*. — Two sills were located, one intruded into the Cambrian quartzite in North Canyon, and one into the same formation in Loafer Mountain on the east slope of Payson Canyon just south of Rock Canyon.

The North Canyon sill is by far the largest post-Archean intrusive body exposed at the surface on the area mapped. It extends from the south slope of North Canyon north to Dry Canyon, but breaks in two places, cutting the bedding in very irregular fashion and terminating against brecciated limestone. Metamorphism is very slight. Sintering effects are all that are noticed in the quartzite; they extend only half an inch from the contact. The sill closely resembles the Salt

Creek Canyon dike in color, mineral composition, and texture.

At the first bridge in North Canyon, where the sill disappears, dipping to the east, xenoliths of quartzite up to four feet long are observed embedded in the sill rock. The cross-cutting intrusion and the xenoliths prove it to be an intrusion into the Cambrian quartzite, and not an interbedded lava flow. The truncation on a spur of the Wasatch fault proves it to be preblock-faulting in age.

The intrusion at the Wilson prospect in Payson Canyon is thought to be a sill. It parallels the Cambrian quartzite strata, but is of such short linear extent that the sill structure may be doubted. It is about one hundred feet thick; there is, however, only a very restricted zone of metamorphism along the dike walls. Copper showings were encountered at the surface, but nothing has since been struck in the prospect tunnel. Megascopically, it is also dark, dull red in color, somewhat like the North Canyon sill. Microscopically, it consists of a glassy ground-mass with prismoidal phenocrysts entirely replaced by calcite. The rock as a whole has suffered a great deal of hydrothermal alteration.

### RELATION AND AGE OF EXTRUSIVE AND INTRUSIVE ROCKS

In conclusion, it may be said that the volcanic breccia, the water-laid volcanic ejectamenta, the dikes, and the sills all show petrographic relationships, and all apparently belong to the same eruptive epoch. This vulcanism occurred in post-Eocene time and shortly prior to the Basin and Range faulting.


## ACKNOWLEDGMENT

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UNIVERSITY OF MICHIGAN


[1] Zirkel, Ferdinand, *U. S. Geol. Expl. 40th Par*., 6 : 22, 25, 26. 1870.

[2] Loughlin, G. F., *Ore Deposits of Utah, U. S. Geol. Surv., Prof. Paper 111*, pp. 1-324. 1920.

[3] *Op. cit*., p. 324.

[4] *Ibid*.

[5] Lindgren, Waldemar, and Loughlin, G. F., *Geology and Ore Deposits of the Tintic Mining District, Utah, U. S. Geol. Surv., Prof. Paper 107*, p. 23. 1919.

[6] Howell, B. F., personal communication.

[7] Loughlin, as cited in note 2, p. 325.

[8] Loughlin, as cited in note 2, p. 325.

[9] Boutwell, J. M., *Geology and Ore Deposits of the Park City Mining District, Utah, U. S. Geol Surv., Prof. Paper 77*, p. 46, Pl. V. 1912.

[10] Mansfield, G. R., *Geography, Geology, and Mineral Resources of Part of Southeastern Idaho, U. S. Geol. Surv., Prof. Paper 152*, p. 85. 1927.

[11] Schneider, Hyrum, "A Discussion of Certain Geologic Features of the Wasatch Mountains," *Journ. Geol*., Vol. 33 (1925), No. 1.

[12] Boutwell, as cited in note 9, p. 52.

[13] Schneider, as cited in note 11, p. 38.

[14] Boutwell, as cited in note 9, p. 55.

[15] Peale, A. C., "Report of the Green River Division," *U. S. Geol. and Geog. Surv. Terr.,* Eleventh Ann. Rep., pp. 621-629. 1879.

[16] White, C. A., "Triassic Fossils of Southeastern Idaho. Contributions to Invertebrate Paleontology," No. 5, *U. S. Geol. and Geog. Surv. Terr*., Twelfth Ann. Rep., pp. 105-118. 1880.

[17] Hyatt, Alpheus, and Smith, J. P., *The Triassic Cephalopod Genera of America, U. S. Geol. Surv., Prof. Paper 40*, pp. 17-19. 1905.

[18] Mathews, Asa A. L., "The Lower Triassic Cephalopod Fauna of the Fort Douglas Area, Utah," *Walker Museum Memoirs*, Vol. 1, No. 1. 1929.

[19] Mathews, Asa A. L., "Mesozoic Stratigraphy of the Central Wasatch Mountains," *Oberlin College Lab. Bull*, New Ser., No. 1, p. 4. 1931.

[20] Gilluly, James, and Reeside, J. B., Jr., *Sedimentary Rocks of the San Rafael Swell and Some Adjacent Areas in Eastern Utah, U. S. Geol. Surv., Prof. Paper 150-D*, p. 73. 1928.

[21] *U. S. Geog. and Geol Surv. W. 100th Mer*., atlas sheets 50 and 59.

[22] Howell, E. E., *U. S. Geog. and Geol Surv. W. 100th Mer*., 3: 264.

[23] Boutwell, J. M., *Gypsum Deposits of the United States, U. S. Geol. Surv., Bull 223*, pp. 102-109. 1904.

[24] Boutwell, *op. cit*., p. 109.

[25] Loughlin, as cited in note 2, p. 326.

[26] Eardley, A. J., "A Limestone Chiefly of Algal Origin in the Wasatch Conglomerate, Southern Wasatch Mountains, Utah," *Pap. Mich. Acad. Sci., Arts and Letters*, 16 (1931) : 406, Fig. 14.

[27] *Op. cit*., pp. 399-414.

[28] Loughlin, as cited in note 2, pp. 326-327.

[29] Dutton, C. E., "Geology of the High Plateaus of Utah*," U. S. Geog. and Geol Surv., Rocky Mt. Region*, pp. 69-81. 1880.

[30] Loughlin, G. F., *Two Lamprophyre Dikes near Santaquin and Mount Nebo, Utah, U. S. Geol Surv., Prof. Paper 120-E*, pp. 101-109. 1918.

PLATE XXVII

Overturned fold in Jurassic shale; north side of Salt Creek Canyon

PLATE XXVIII

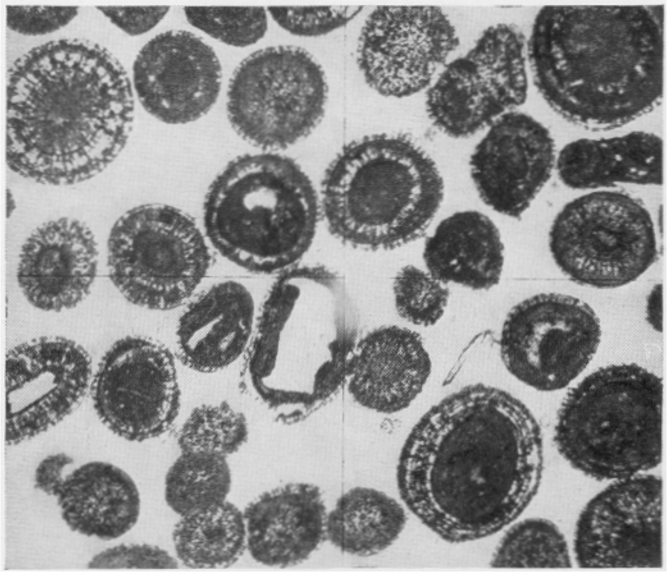


FIG. 1. Photomicrograph of Jurassic oolitic limestone. X 30

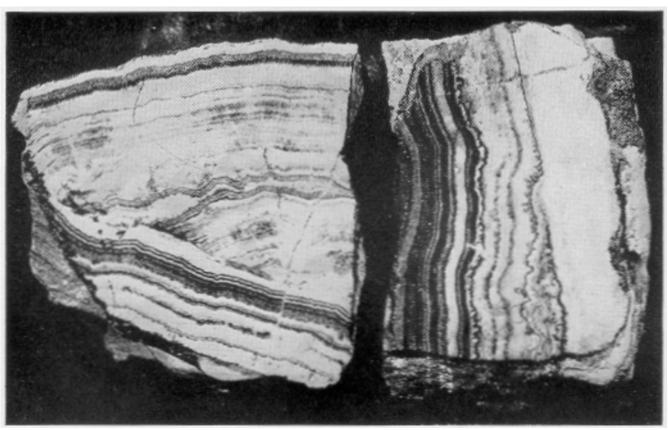
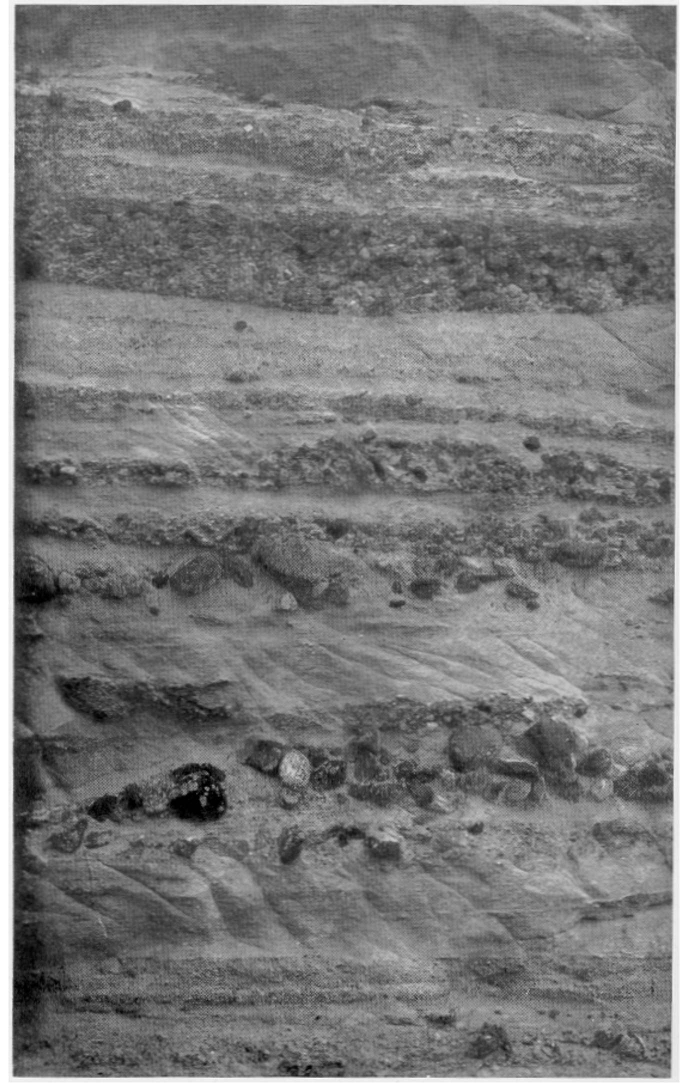


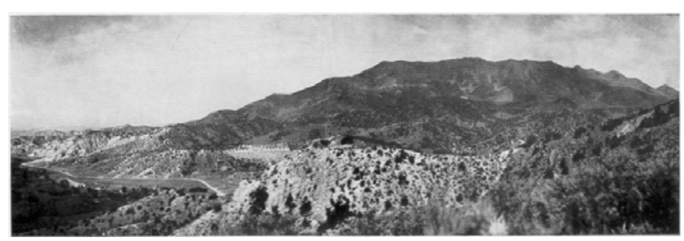
FIG. 2. Polished specimens of Jurassic travertine. X ½

PLATE XXIX



A twelve-foot section of volcanic conglomerate in Salt Creek Canyon

PLATE XXX



View down Salt Creek Canyon, with high South Ridge and Mount Nebo on the right. White formation in foreground is remnant of volcanic conglomerate which formerly filled old drainage channels now reëxcavated. It rests in contact with Wasatch conglomerate

# A STUDY OF THE INSOLUBLE RESIDUES OF THE LOWER TRAVERSE, BELL, AND UPPER DUNDEE FORMATIONS OF MICHIGAN

GERALD E. EDDY

## INTRODUCTION

THE correlation of the Lower Traverse, Bell, and Upper Dundee formations of Michigan is one of the difficult problems encountered in the study of the subsurface geology of the state. This is especially true of the Dundee formation. Geologists are of different opinions about the age relationships of the quarry sections and the samples collected from wells drilled in the drift-covered part of the state. In this paper the writer will attempt to show that there are definite characteristics by which the several formations may be recognized. Most of the five hundred samples prepared and examined were furnished through the courtesy of the Michigan Geological Survey. Additional samples were obtained from quarry sections, but there, are only a few localities in the state where good exposures of these formations occur.

Certain characteristics have been found which indicate that correlations may be made over wide areas with a reasonable degree of accuracy. Not enough work has been done at present to enable one to distinguish the lower Traverse and Dundee formations from either older or younger beds; hence no attempt is made to discuss these relationships. It is highly probable that similar results might be obtained from studies of the older and younger strata in the Michigan Basin.

## PREVIOUS STUDIES

The study of insoluble residues from calcareous well cuttings is not new. Methods for the examination of limestone samples have been used as far back as 1920. In that year Trager[1] proposed a method by which the sand, shale, and limestone fractions of a residue may be separated and analyzed. The samples were first treated with hydrochloric acid and then centrifuged to separate the sand and shale portions. Lamar[2] carried out experiments in which he examined residues from the Chester Series of Illinois. He obtained the residues by treating the cuttings with hydrochloric acid. The size of the particles, the textural features of the limestone, the heavy minerals, and the microfossils were all considered in his paper. Claypool and Howard[3] have prepared residues from limestones by dissolving them in hydrochloric acid: the heavy minerals were separated by means of a centrifuge. The work upon which this paper is principally based was carried on in 1931 by H. S. McQueen[4] under the direction of the Missouri Bureau of Geology and Mines. His method involves the treating of the samples with dilute commercial hydrochloric acid and the examination of the residues thus prepared by means of a binocular microscope.

So far as the writer is aware, there has been no attempt to correlate Michigan limestones by any of these methods. All the correlations to date have been made from logs compiled by drillers, by the geologists of the oil companies operating in the state, and by R. B. Newcombe and O. F. Poindexter, under the direction of the Michigan Geological Survey, and have been based primarily upon their lithologic characteristics. Fossils found in the samples are practically valueless, owing to the fact that most of them have been destroyed by the drilling operations. Microfossils are significant, and considerable work has been done on them.

## PURPOSE OF THE STUDY

The purpose of this investigation was to study the residues prepared and to see whether there were any definite characteristics by which the lower Traverse, Bell, and upper Dundee formations could be correlated. The method was the same as that used by McQueen,[5] described in his paper on the Cambrian and Ordovician rocks of the Ozark region.

The topic was suggested by R. A. Smith, state geologist of Michigan, as possessing potentialities as a new method of correlating Michigan strata. The suggestion was made after he had been convinced by H. A. Buehler, state geologist of Missouri, of its great value in naming formations very difficult to recognize by means of their paleontologic or lithologic content.

## METHOD OF PROCEDURE

The reaction of hydrochloric acid on magnesium and calcium carbonates is a familiar one and has long been known, but its application to the study of limestones and dolomites is comparatively recent.

The samples prepared were taken from limestone quarries or were obtained from the state survey files. Any weight from 2 to 30 grams may be used, depending upon the amount available. Samples of about 10 to 15 grams were found to be the most convenient. The cuttings were ground to pass a ten-mesh screen and placed in a 250 or 500 c. c. beaker. They were then covered with 50 c. c. of commercial hydrochloric acid diluted to half strength with distilled water. In some of the more violently effervescing limestones the acid must be added very slowly in order to decrease the strong immediate reaction. It was discovered good practice to add water to the sample first and then the acid to make up the 50 per cent solution. In the case of the more slowly effervescing limestones, shales, and dolomites, heating on a sand bath was necessary in order to be sure of complete digestion of the carbonates. Care must be taken not to leave the samples in the sand bath too long, because the mixture may become thick and gelatinous, producing small crystals of gypsum. Gypsum is formed by the reaction between the sulphuric acid in commercial hydrochloric acid and the limestone or dolomite. After all reaction has ceased, the residues are washed by decanting off the clay and silt fractions. These fractions were not saved for examination, owing to their fine subdivision, which renders them too small for study. They also tend to obscure the nature of the larger, recognizable fragments. After washing, the samples were placed on a sand bath or in an oven and thoroughly dried. They were then put in glass vials for future study. It was found necessary to treat some samples with the acid a second time in order to have complete digestion and to remove the siliceous film on the grains of the siliceous carbonate rocks.

The equipment required varies, depending upon the number of samples to be run. The writer has been able to run as many as seventy-five samples in five hours, but this number could be greatly increased with more efficient equipment. It was found most convenient to run the samples in groups of twenty or twenty-five. In actual field work samples may be prepared with a simple field kit, and the examinations can be made with the ordinary hand lens.

The residues were examined with a binocular microscope. Low to medium magnification was used in order to obtain a fairly large field and still have a magnification high enough to enable one to recognize the different types of residues. Small, black cardboard trays were used to hold the specimens for examination. They measured about two by three inches by one-half inch deep. One corner was cut off to facilitate the pouring back of the samples into their vials.

About sixty photographs were taken of definite horizons. Those of the finer residues have a magnification of twelve diameters; those of the larger ones, of about eight diameters. Comparison of photographs was found to be much more reliable for correlation purposes than examination with the microscope, since the student has nothing to carry over from one slide to the next.

## CHARACTERISTICS OF THE RESIDUES

The characteristics of the residues of the lower Traverse, Bell, and upper Dundee formations are quite variable, but they show enough contrast to be of value in indicating formational units as well as the larger stratigraphic divisions.

Shales are the predominant insoluble constituents of all the residues. They range from very fine, thin-bedded, micaceous shales to massive, coarse-bedded ones, which are shown in the residues as well-rounded particles or angular fragments.

Next in importance to the shales is the sand content. The grains vary from the very fine, angular, and poorly rounded type to the large and well-rounded. Some sands are frosted and others are not grains at all, but are well-developed crystals of quartz.

Other insoluble materials found in the residues are chert and secondary quartz in the form of irregular masses, and the very small fragments making up the siliceous shales. Other minerals that occur are pyrite, hematite, limonite, and magnetite. The writer did not examine these minerals in detail, since the study of the mass characteristics of the residues was the object of the investigation.

Another, and perhaps the outstanding, feature of the residues, was the occurrence of what McQueen[6] calls "dolocasts." He proposes this name because they are the impressions of the dolomite crystals in the insoluble chert, shale, or pyrite. To like structures found in the Michigan limestones the name "cast" is applied, because these features occur in residues not only from dolomite, but from limestones as well. These casts are formed by the deposition of silica and other insoluble materials in the interstices between the crystals of dolomite and calcite. The casts are of two types. To the first type, in which the intervening walls are thick and the openings caused by the dissolving out of the calcite are relatively small, the name "spongy" is given. In the second type the openings are large and the intervening walls are relatively thin. These are called "lacy." The occurrence of these casts seems to be more or less limited to zones close to unconformities, which the writer thinks indicates a tendency toward their development where there are extensive circulation of ground water and deposition of silica and pyrite.

## FORMATIONS STUDIED

The formations studied in this paper are of Middle Devonian age, ranging from the upper Dundee, through the Bell Shale, to the top of the Long Lake Series at the base of the Traverse formation. The investigation did not extend farther up into the Traverse because the object was to distinguish between formations and not between the groups of series within a formation. The Bell Shale at the base of the Traverse presents an interesting problem because of its great difference in thickness and its total absence in some parts of the state. Figure 14 shows the Middle Devonian unconformity of western Michigan.[7] The study of the Dundee formation is also very interesting because of the occurrence of oil in it. The prominent erosion surface at its top and the irregular deposition in parts of the state make a study of this nature of considerable importance in the field of economic geology. A summary of the characteristics of the residues follows.

### *Long Lake Series*

The Long Lake Series is a gray or dark gray, thin-bedded shaly limestone, locally fossiliferous, cherty, or bituminous. The bituminous property is distinctly observed in the preparation of the samples; the acid takes on an oily appearance, and the mixture gives off a strong odor of crude petroleum. Near the base of the formation are beds of chert and dolomite, which have been the source of well-developed casts.

The residues from wells in Muskegon, Newaygo, Midland, Crawford, Cass, Missaukee, and Livingston counties reveal a definite development of casts in the brown and gray shale members in the lower part of the series. In Plates XXXII, Figure 1, is illustrated the type of casts found in well No. 631 in Oceana County in a bed about one hundred feet above the top of the Bell-Traverse contact. The residue here is a light brown shale, and the shape of the openings in the shale indicates that the dissolved mineral was probably dolomite. In Plate XXXI, Figures 1-2, there are shown casts in a gray shale. The openings are not so large or so well developed as those in the brown shale beds. These casts come from a bed fifty feet above the top of the Bell-Traverse contact, and are from well No. 1133 in Missaukee County. In Plate XXXII, Figures 1-2, there are shown residues from beds one hundred and fifty feet above the Bell-Traverse contact, respectively. Figure 1 is from well No. 1020 in Livingston County; Figure 2, from well No. 1177 in Wexford County. Another important difference in the residues from these two zones is the shape of the shale fragments. The fragments from the bed one hundred feet above the contact are very angular, whereas those from the bed fifty feet above the contact are rounded. This seems to indicate that the particles have been transported, and also that it is possible that they have been eroded from the Bell surface.

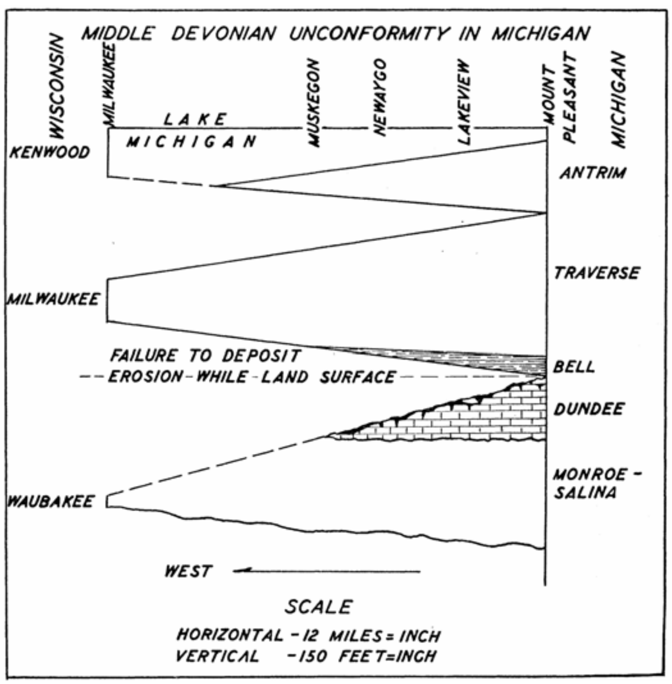



FIG. 14. Diagrammatic sketch of the Middle Devonian unconformity in western Michigan (after R. B. Newcombe)

The casts in the brown shale are the best developed of the types found, and the presence of this type, together with casts in gray shale and chert, seems to point quite definitely to the beds in which they occur as belonging to the Lower Long Lake Series. The only places where these casts do not occur are in two wells in Newaygo County. Here the residues consist of irregular, secondary quartz fragments showing iron staining, which gives a brown color to the residue as a whole.

### *Bell Shale*

The Bell (Marcellus) Shale, which is blue or black to dark gray, is locally fossiliferous. In some parts of the state it is missing; in others its maximum thickness is eighty feet.

The insoluble residues consist principally of a massive shale. "Massive," in this sense, means a shale coarse-bedded and also lacking casts. The fragments are light to dark gray. They are either well rounded or sharply angular. Though some have the same shape as those found in the bed fifty feet above the Bell in the Traverse, they differ in that they are massive (see Pl. XXXIV, Fig. 1). There are some very fine, well-developed casts in a brown shale, but it is probable that they originated in the Long Lake Series and have become mixed with the Bell cuttings as a result of caving or slumping in the hole. They are almost identical with those already described. Care must be taken not to misinterpret these apparent results. It was concluded that they fall in the Long Lake Series because of their striking similarity and also because they occurred in only two of the twelve wells sampled. There are a few casts in a brown shale that are not like the ones mentioned. They are coarser and possess what might be called a drusy structure. They also resemble very fine solution channels.

The residues of samples from the eastern part of the state are fairly consistent, but those from wells in the western part show a great variation which seems to indicate different conditions of erosion or non-deposition of the Bell Shale. They vary from gray, massive, black, well-rounded or angular gray shales to very fine angular silt (see Pl. XXXIII, Figs. 1-2).

### *Dundee limestone*

The Dundee formation is gray and buff crystalline limestone, locally cherty, fossiliferous, and bituminous. Sulphate waters and highly mineralized brines occur in the lower beds; oil is found in commercial quantities in the upper beds. The thickness ranges from sixty-five (?) to two hundred and fifty feet.

Samples of the formation were taken from nineteen wells and two quarries. It was found that the residues from the Dundee are the most variable of those studied. The first ones examined were of rock specimens from the Rogers City quarry in Alpena County and from the Calcite quarry in Presque Isle County in the northeastern part of the state and from the Sibley quarry in Wayne County in the southeastern part. These localities were selected with the idea of correlating the horizons from these areas with the beds in the Mount Pleasant field and also with the "Dundee" in the Muskegon field in the western part of the state. There are but few complete sections of the Dundee available in the oil fields because the drilling usually has ceased as soon as oil is struck in its upper beds. Only six of the nineteen wells sampled penetrated through the Dundee into the Detroit River group.

The residues from the rock quarries in Alpena and Presque Isle counties were found to be quite different from those of the Sibley quarry in Wayne County. Sands are the predominant constituents in the residues from both areas, but they differ in size and shape. The residues from the northern area show an angular to subangular type of grain which is, in general, larger than the angular grain of the southeastern area. The residues from several beds of the Sibley quarry have a well-rounded type. Many of the grains are also frosted (see Pl. XXXV, Fig. 2). This rounding of grains may be due to a greater amount of transportation or to the action of solutions. J. J. Galloway[8] says that the rounding may be done by solutions in a manner similar to the process of exfoliation. The size of the largest grain that may be formed in this way is given as 0.1 millimeter, so that it seems more likely that the grains in the Sibley section are caused by abrasion and not by solution. There are, in addition to the rounded grains, very fine angular grains in several beds. These are very small, and hence their angularity does not mean that they have been subjected to less mechanical transportation and abrasion than the rounded type. It is much more probable that it is due to the fact that their size is below the theoretical limit for mechanical abrasion. That is, they are so small and their mass is so slight that the water film between the particles is sufficient to hold them apart (see PI. XXXIV, Fig. 2).

At a level about twenty-five feet below the top of the section are two chert beds about six feet apart. These cherts are massive, with but a poor development of casts. Residues from them are illustrated in Plate XXXV, Figure 1.

The top seven feet of the section presents a good development of casts in a very thin bedded brown shale. They are of the lacy type, with thin walls between the openings.

The predominant constituent from well No. 130 in Macomb County is a rounded type of sand grain. In addition to these grains there are a few beds containing grains of the very fine angular variety of quartz (see Pl. XXXVII, Fig. 1); one bed about fifty feet from the top of the formation containing abundant pyrite masses; and one bed of slightly castic chert at about the same horizon. There was also one horizon in which casts occurred. They are in brown shale and are very fine and poorly developed. They are similar to those in the upper seven feet of the section at Sibley quarry.

The predominant constituent of the residue from well No. 130 in Lenawee County is pyrite. This mineral is principally of the crystalline variety. In addition to it there are several samples with the typical rounded grains of sand, as described above. The massive chert beds of the same age as those noted at Sibley quarry were also found. There were several fragments of black shale, but it is most probable that they are cavings from the overlying Bell Shale.

Rounded grains of quartz are the most characteristic features in the residues from well No. 1020 in Livingston County. They vary from white through brown to a deep reddish brown. This coloring is due to limonitic staining, which gives a brownish color or cast to the residue as a whole.

In the last six paragraphs there is given a summary of the characteristics of the residues from wells in the southeastern part of the state. It will be noted that large, rounded sand grains occurred in every section sampled. The writer, however, did not find grains of this type in any other section studied with the possible exception of a few in the hand specimens from the Rogers City quarry in Alpena County.

In the northeastern part of the state samples were obtained from four wells and from the Calcite quarry in Presque Isle County and from the Rogers City quarry in Alpena County. The wells are in Presque Isle, Alpena, Crawford, and Ogemaw counties. For an exact location of the wells sampled see Map 32.

The samples from the quarries were given to the writer by G. M. Ehlers and were obtained from the collection of the University of Michigan Museum. Though their geographical location is known, their stratigraphic position was not definitely established. As already stated, the sand grains are angular and differ from the residues from the southeast part of the state only in their size. The grains in the northern area are much larger and seem to indicate less abrasion, and hence a smaller distance from the source to the point of deposition. There is one sample that has a non-castic chert residue, and two contain abundant pyrite and hematite which have no counterpart at Sibley quarry.

The residues from well No. 830 in Alpena County show an angular quartz grain, a few beds of siliceous shale, and a mixed residue of pyrite, brown and black shale about one hundred feet from the base of the formation. There are a few good casts from a bed about forty-five feet from the top of the formation.

In cuttings from Campbell No. 1 well in Alpena County the residues from the top seventy-five feet consist of an impure cherty quartz, all the fragments of which are very angular or are irregular, crystalline masses. An increase in amount up to 40 per cent was noted. The cherty quartz also changes to an impure chert. The lower sixty feet has a residue of angular, crystalline quartz and cherty quartz.

In well No. 1143 in Ogemaw County the top seventy-five feet has a residue consisting of a light gray, thin-bedded shale. The particles of shale are massive and well rounded. Below this there is a bed of irregular, smoky quartz and chert, which is a decided change from the overlying beds. These are followed by forty feet of brown to gray shale, containing casts in the brown shale and considerable amounts of pyrite and hematite. Below these beds are ten feet of gray shale and very fine sand grains cemented together to form features resembling casts. The fine sands persist downward for an additional ten feet; this in turn gives way to a few feet of impure chert, which is slightly castic. This is followed by massive shale containing abundant hematite, especially in the last twenty feet of the section.


MAP 32. Location of wells and quarries from which samples were secured

The residues from Grayling No. 1 well in Crawford County are principally fine-bedded, siliceous gray shales and a few rounded, frosted quartz grains. Crystalline pyrite is quite common, and there are also a few particles of blue, irregular, massive quartz.

All these samples are from the northeastern part of the state. To summarize, the outstanding characteristics of the residues from this area are the angular, large sand grains and a greater abundance of either crystalline or massive pyrite (see Pl. XXXVI, Fig. 1). In one well the percentage of pyrite in some of the cuttings runs as high as sixty. The residue from the Grayling well differs from those of all the rest in that the principal constituent is siliceous shale, thin-bedded and entirely lacking in casts.

Cuttings from wells in Newaygo, Oceana, and Muskegon counties were studied and the following points noted:

The residues from this area were the most variable of those examined. There seemed to be a greater difference over a much smaller area than from any wells in other sections of the state. In other areas the residues seem to show a distinct similarity, as the descriptions given above indicate.

In well No. 631 in Oceana County the residues consist of fine, poorly rounded to angular quartz grains. In well No. 346 in Muskegon County the residue is a light gray shale whose fragments are well rounded. This feature was found elsewhere only in wells in the central part of the state. The residue from well No. 788 in Newaygo County is a brown sand. The grains are chiefly rounded and frosted, with a few grading over into the angular type. All are iron-stained and are very similar to the ones from well No. 654 in Newaygo County. In addition to these features there were also found clear, crystalline quartz and a few fragments of magnetite partly altered to limonite. In well No. 696 in Newaygo County the residue consists of gray shaly fragments, some angular quartz, and a few grains of the rounded type.

Residues from four wells in the central part of the state were prepared and examined. They differed widely from any other Dundee samples, with the exception of that from well No. 346 in Muskegon County. A description of the residues is given in the succeeding paragraphs.

In No. 73 in Midland County the residue consists chiefly of a gray to brown shale, the fragments of which are fairly well rounded. This feature is shown in Plate XXXVI, Figure 2. There are also some thin-walled casts in chert and a fairly abundant occurrence of pyrite. In well No. 982 in Mecosta County the residue is also chiefly a shale. The particles are clearly rounded. The color of the shale varies from gray through brown to black. The next most common feature was the great abundance of pyrite. This mineral occurs in all but twenty of the one hundred and twenty feet in the section and is of both the massive and the crystalline varieties. Limonite also occurs in beds near the base of the section. The residues from well No. 1149 in Isabella County are much the same as those from well No. 982 in Mecosta County, with gray, brown, and black shales predominating. One horizon contained rounded quartz grains like those found at Sibley quarry. This is shown in Plate XXXVII, Figure 2. Near the base of the section the residues grade into much darker shales, some of which are almost coal-black (see Pl. XXXVIII, Fig. 1). In well No. 8 in the Saginaw field the residues of the entire Dundee section consist of shale fragments, all of which are distinctly rounded (see Pl. XXXVIII, Fig. 2). There were a few casts in pyrite and chert, but they occur in quantities so small that they are not significant. A few beds of brown shale occur in which there are what appear to be casts, but it is more probable they are the result of solution by ground water.

## SUMMARY AND CONCLUSIONS

The depositional features of the Michigan Basin are found to be much different from those in any other part of the country. Sediments have been laid down in fluctuating basins and between the structural ridges, which have acted as natural barriers to the migration of the several types of fauna. The seas that entered the Michigan Basin have come from several different directions and the barriers have kept them from intermingling.[9] G. M. Ehlers[10] is of the opinion that the Dundee section of the Calcite quarry is of a different age from that of the Sibley quarry. He bases his opinion on the difference in the faunal life. Some species that occur in the northern section of the state are not represented in the southeastern part, and vice versa. R. A. Smith[11] is of a similar opinion. In the study of the residues no features were found which the writer could be sure occurred in both areas. It was ascertained, however, that the residues were consistent over small areas. This fact seems to bear out the idea of R. B. Newcombe[12] that at the end of Dundee time there was a long period of erosion or non-deposition of marine sediments. This is also shown by the fact that the Dundee varies as much as two hundred feet in thickness over comparatively short distances.

The residues from the Dundee formation in the Mount Pleasant field are much different from any that occur elsewhere in the state. They do not conform to typical Dundee "purity," owing to the fact that the principal constituent is shale, gray to brown. It was first thought that they were cavings from the overlying Bell Shale because the fragments were all well rounded. They occur much too consistently for this to be true. The presence of this shale would seem to indicate that the Dundee in this locality is a shaly facies, having been laid down in close proximity to some land mass.

In the western part of the state the residues are not at all consistent. The area studied includes Oceana, Newaygo, and Muskegon counties. Even in so small an area the residues from the different wells do not correspond as closely as those from samples from other parts of the state. This is probably due to erosion or non-deposition of the Dundee beds. Newcombe[13] says that there is an east-west area across Oceana, Newaygo, and Muskegon counties with smaller basins paralleling it on either side. This structural feature no doubt accounts for the lack of similarity in the residues. With one exception those from all the wells are characteristically "Dundee" in that they consist of sand grains. They are usually brown, owing to limonite staining.

The Bell formation has a residue consisting entirely of shale fragments. They may be either distinctly rounded or subangular. This feature is most prominent in wells from the central and the eastern parts of the state. The residues from wells in the Muskegon area do not seem to be so consistent. This is not surprising, since the Bell Shale was laid down in a sea progressively overlapping to the west.[14] The Bell has never been found in wells in the southwestern part of the state. The oscillatory nature of the sea bottom caused the alternating beds of shale, limestone, and calcareous shale.[15]

The residues of the Long Lake Series appear to be the most consistent of those examined. Two horizons were found which have the same characteristic type of residue. It was in the Long Lake Series that the good casts were discovered. There were two zones in which they were especially common. These zones are fifty and one hundred feet above the top of the Bell Shale. The casts from the two zones differ in the shape of the shale fragments in which the residues occurred. Those from the lower horizon are in pieces of rounded shale; those from the upper beds, in fragments of angular shale.

It is not true that all residues from the same horizon have the same characteristics. There are small differences, the addition of new material or the loss of others. They are of minor importance, since the main and characteristic features are the significant things by which the zones may be recognized.

Erosion surfaces may be located by this method. A good circulation of ground water is conducive to the formation of good casts by furnishing abundant insoluble material.

It is very probable that further work would shed much more light on the problem, and this paper is written with the purpose in mind of stimulating further investigation in the study of insoluble residues.

## ACKNOWLEDGMENTS

The writer is greatly indebted to the following persons for helpful suggestions and invaluable aid in the preparation of the paper: To Dr. C. W. Cook, under whose direction the investigation was carried on; to R. A. Smith and R. B. Newcombe of the Michigan Department of Conservation, who have made the work possible; to Drs, G. M. Ehlers and E. C. Case of the University of Michigan; to L. W. Price of the Michigan Department of Conservation, who prepared all the well samples examined by the author; and to H. S. McQueen of the Missouri Bureau of Geology and Mines.

UNIVERSITY OF MICHIGAN

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[1] Trager, Earl A., "A Laboratory Method for the Examination of Well Cuttings," *Econ. Geol*., 15 (1920) : 170-176.

[2] Lamar, J. E., "Sedimentary Analysis of the Limestones of the Chester Series," *Econ. Geol*., 21 (1926) : 578-585.

[3] Claypool, C. B., and Howard, W. V., "Method of Examining Calcareous Well Cuttings," *Bull Am. Assn. Petrol Geol.*, 12 (1928) : 1147-1152.

[4] See McQueen, H. S., "Insoluble Residues as a Guide in Stratigraphic Studies," Appendix I of *Biennial Report of the State Geologist*, 1931, pp. 102-110. Missouri Bureau of Geology and Mines.

[5] *Op. cit*., pp. 1-9.

[6] *Op. cit*., pp. 111-131.

[7] Newcombe, R. B., "Middle Devonian Unconformity in Michigan," *Bull. Geol Soc. Am*., 41 (1930) : 734.

[8] Galloway, J. J., "The Rounding of Sand Grains by Solution," *Am. Journ. Sci.*, Fourth Ser., 47 (1919) : 270-280.

[9] Newcombe, R. B., "Depositional and Structural Features of the Michigan Synclinal Basin," pp. 94-97 of unpublished manuscript. June, 1931.

[10] Oral communication.

[11] Oral communication.

[12] *Op. cit*., pp. 161-164.

[13] *Op. cit*., p. 163.

[14] Newcombe, as cited in note 7, pp. 725-738.

[15] Newcombe, as cited in note 9, p. 258.

PLATE XXXI

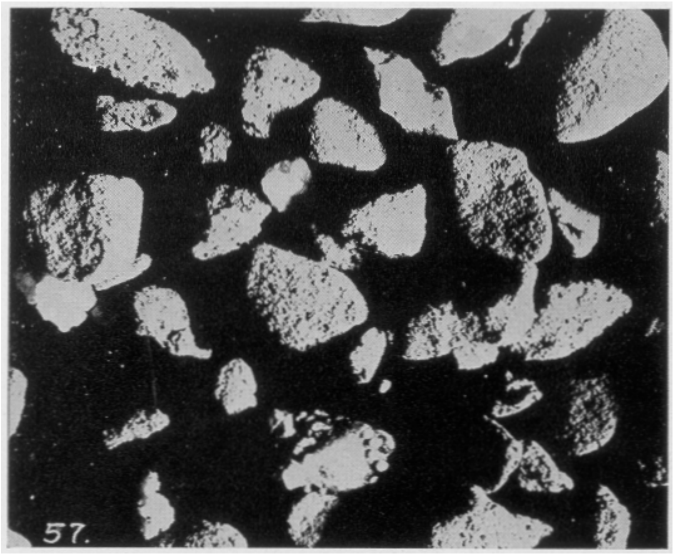



FIG. 1. X 8

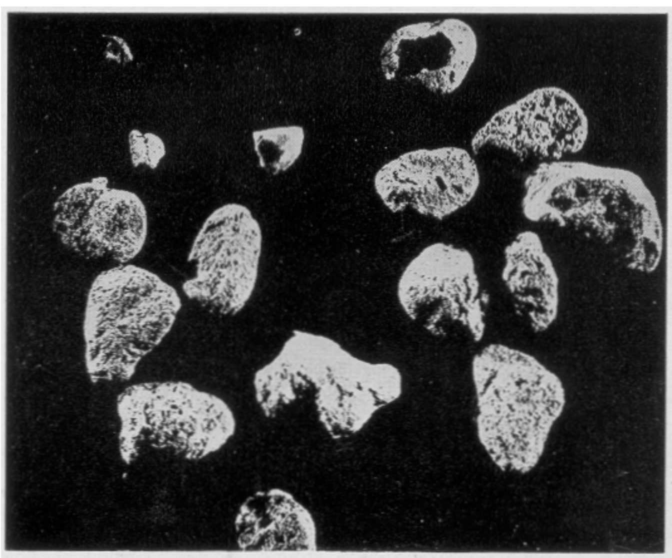
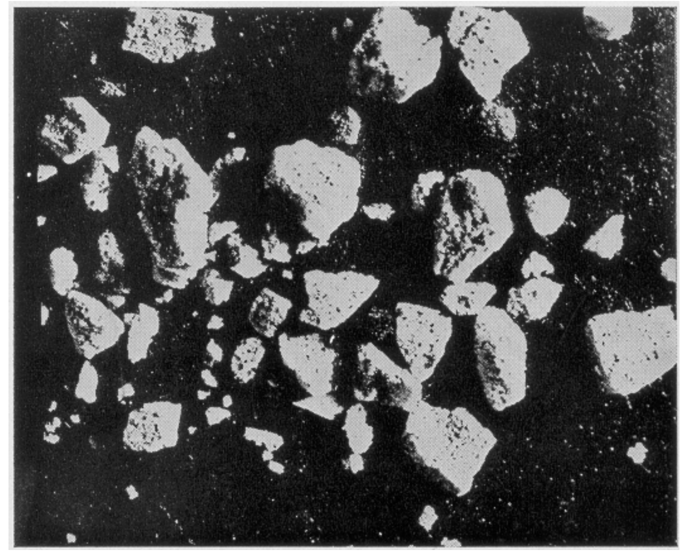


FIG. 2. X 8

RESIDUES OF THE LONG LAKE SERIES

Samples are from, beds fifty feet above the top of the Bell Shale

PLATE XXXII



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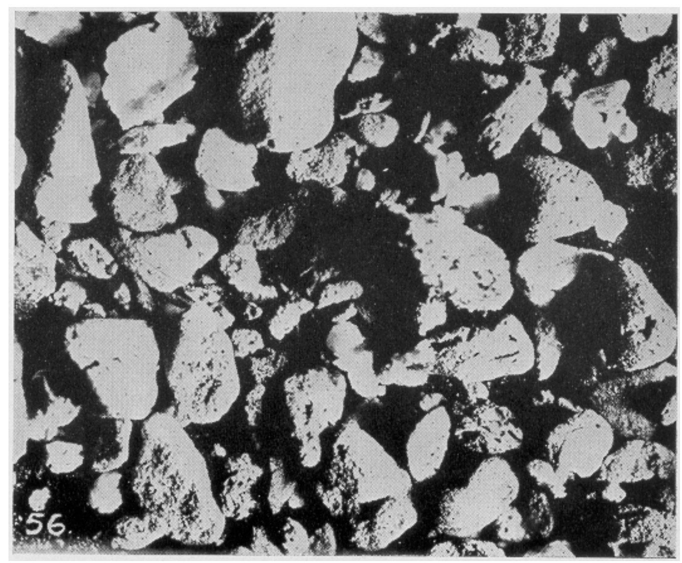
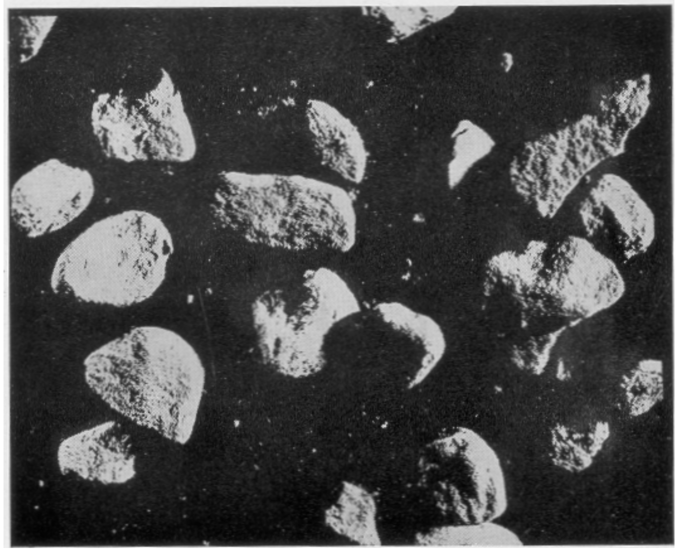



FIG. 2. X 8

RESIDUES OF THE LONG LAKE SERIES

Samples are from beds one hundred and fifty feet above the top of the Bell Shale

PLATE XXXIII



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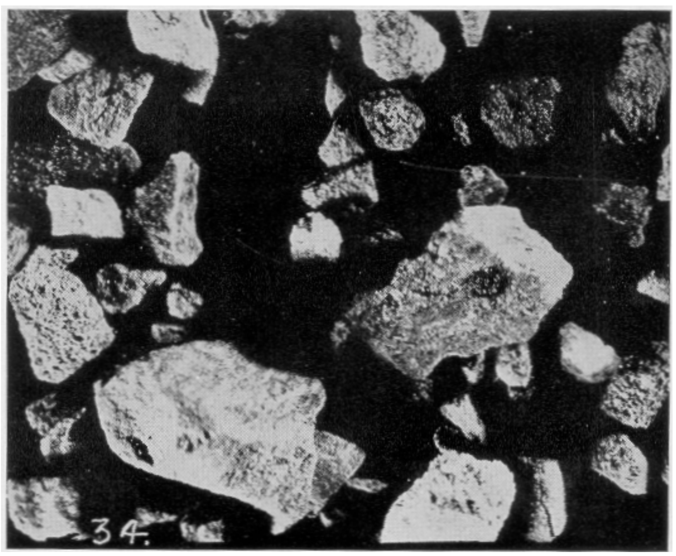



FIG. 2. X 8

RESIDUES OF THE BELL SHALE

PLATE XXXIV

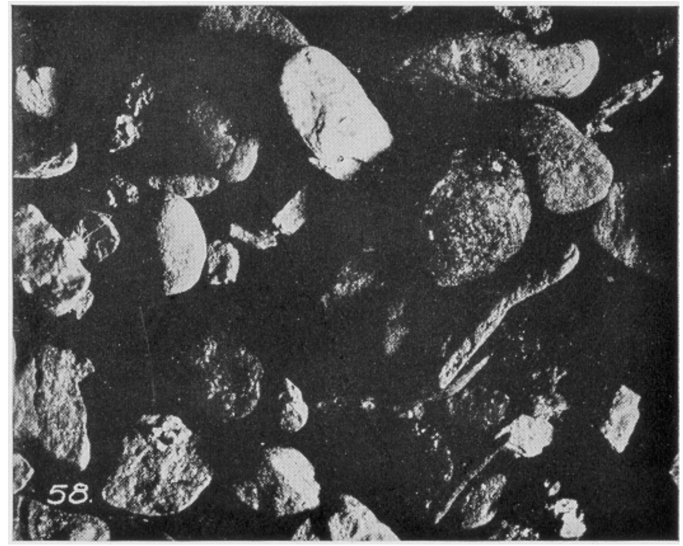



FIG. 1. X 8

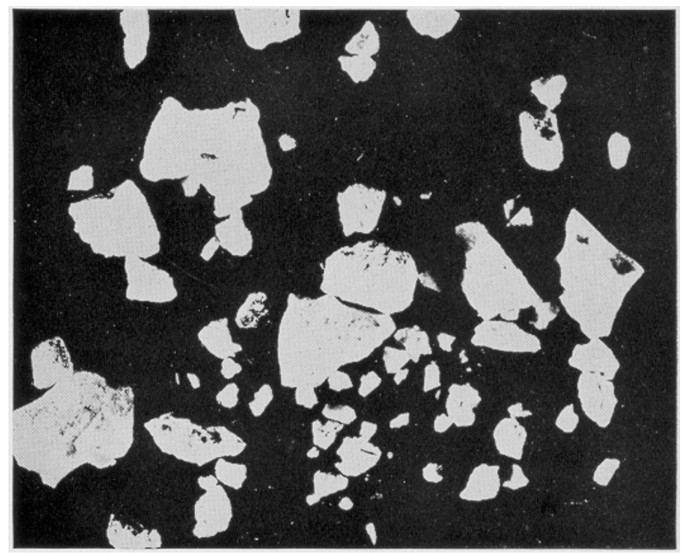


FIG. 2. X 8

CHARACTERISTIC RESIDUES OF THE DUNDEE FORMATION

Samples are from a bed fifty feet below the top

PLATE XXXV

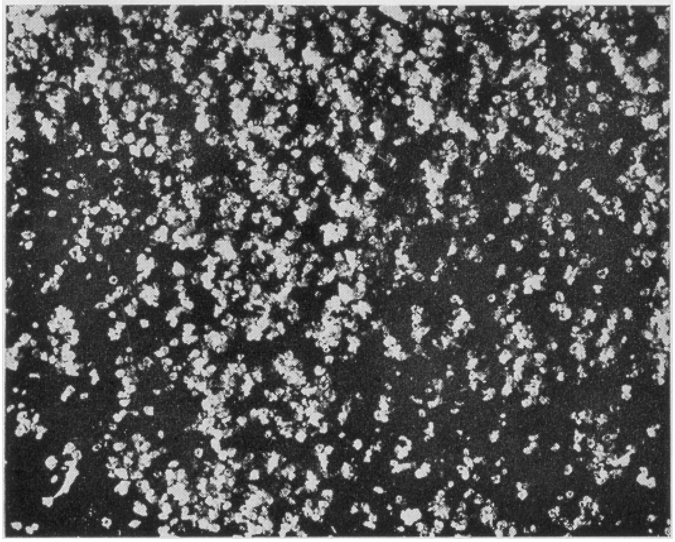


FIG. 1.  X 12

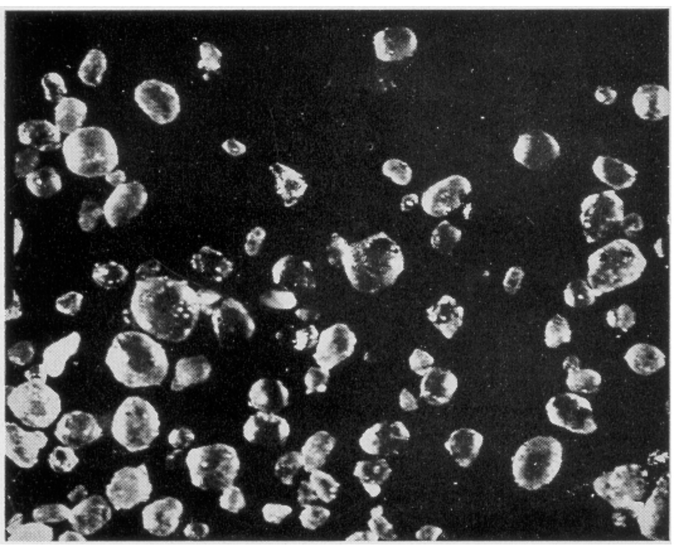


FIG. 2.  X 12

CHARACTERISTIC RESIDUES OF THE DUNDEE FORMATION

Samples are from a bed fifty feet below the top

PLATE XXXVI

FIG. 1.  X 8

FIG. 2.  X 8

CHARACTERISTIC RESIDUES OF THE DUNDEE FORMATION

Samples are from beds fifty feet below the Bell Shale

PLATE XXXVII

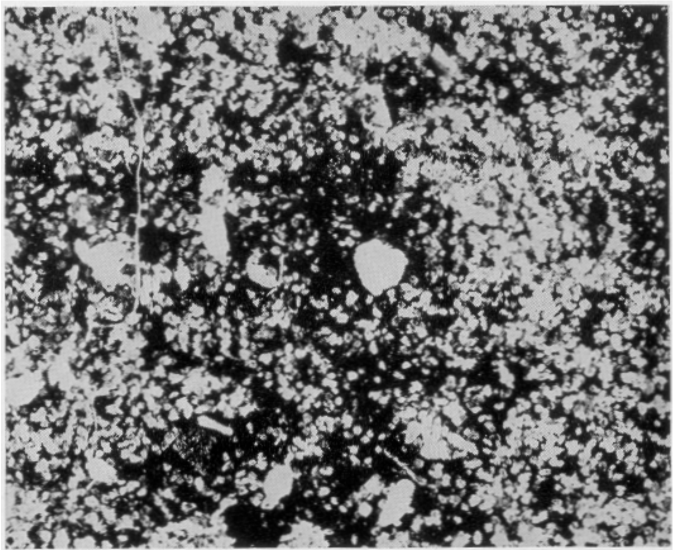


FIG. 1. X 12

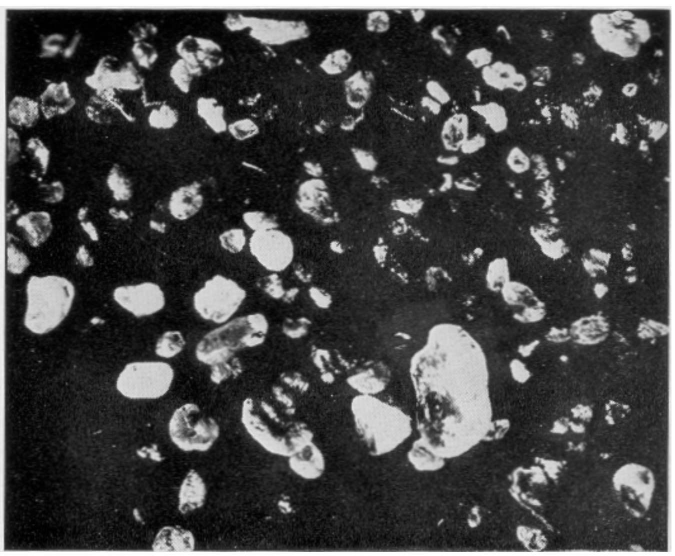


FIG. 2. X 12

CHARACTERISTIC RESIDUES OF THE DUNDEE FORMATION

Samples are from a bed one hundred feet below the top

PLATE XXXVIII

FIG. 1. X 8

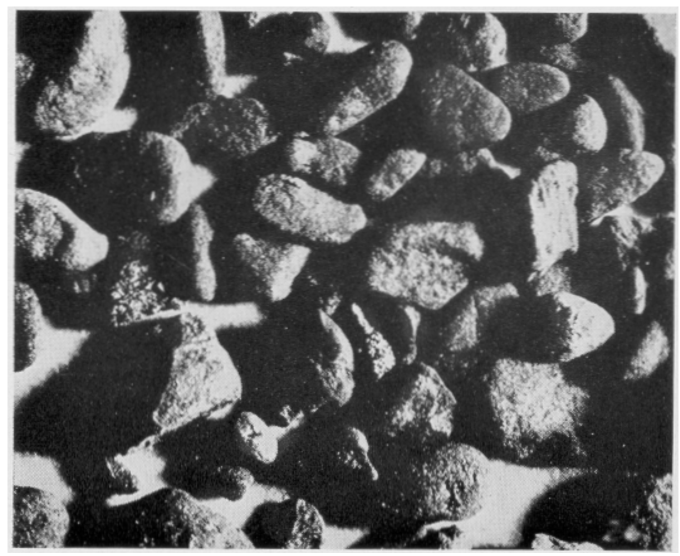


FIG. 2. X 8

CHARACTERISTIC RESIDUES OF THE DUNDEE FORMATION

Samples are from a bed one hundred feet below the top

# GREENLAND, THE ADVANCES OF A DECADE (1921-1931)

WILLIAM H. HOBBS

## INTRODUCTION

THIS is notably an era of polar exploration, and nowhere is inquiry proceeding more rapidly than on the land-mass of Greenland, which convention seems to have designated an island, though it is very largely submerged beneath one of the two continental glaciers which still exist. Greenland's history is so largely concerned with this glacier that I prefer to regard it as a continent. Up to the year 1921 no authoritative work treating of Greenland had been published since H. Rink's *Grönland* (1852-57) and his *Danish Greenland, Its People and Products* (1877), the latter printed in the English language. In 1921 occurred the two-hundredth anniversary of the landing of the first missionary, Hans Egede, on the west coast, with which event the modern history of Greenland begins. As part of the notable celebration of this anniversary, in which the Danish sovereign paid a ceremonial visit to his great northern colony, there was published in the Danish language a great work of compilation in two massive volumes entitled *Grönland*.[1] In 1928 there appeared in English a magistral work in three volumes with the same title (*Greenland*),[2] and with three of its four editors the same as those of the Danish work, namely: Vice-Admiral Arndrup and Drs. L. Bobé and Ad. S. Jensen, but under the chairmanship of Dr. M. Vahl, professor of geography at the University of Copenhagen.

The Danish language work had, however, a wholly different plan, since it treated each of the twelve districts of Greenland separately, whereas in the later work printed in English separate authoritative articles in Volume I discussed the entire country with respect to: early explorations, scientific investigations, cartography, geographical situation, surrounding waters, geology, climate, flora, vegetation, fauna, inland-ice, and physiography.

The appearance of these comprehensive surveys of Greenland makes the date of the issue of the earlier work a convenient point from which to take up later work in many lines, and I shall therefore here discuss the developments since 1921. Both before and since that date much of what has been learned of Greenland is to be found in that magnificent publication, *Meddelelser om Grönland* ("Contributions on Greenland"), issued by the Commission for the Direction of the Geological and Geographical Investigations on Greenland, a commission which dates from 1877 and which has already issued more than eighty volumes. The earlier volumes were printed in the Danish language, sometimes with brief French abstracts appended, but beginning with the eleventh volume (1887) an ever-increasing number of the monographs have appeared in the better-known European languages, German, English, or French. Few countries can boast a more magnificent series of scientific publications devoted to a single subject, and this is true both as to subject-matter and to dress, thanks to the generous grants made from the Carlsberg and Rask-Oersted Foundations.

## SURVEYS

Until within the last decade surveys of Greenland have been carried out largely by traverses of coasts and navigable fjords, checked by a considerable number of astronomical observations, but all before the use of radio time signals. These surveys have in general been much more complete for the far more accessible west coast to the southward, of Upernivik (in latitude 72° 45' N.).

In 1927 the Danish Government began work on a new map of Greenland. A base line 600 meters long was laid out on the island of Disko on the west coast, and between 1928 and 1930 a primary triangulation was partly completed for the coastal area between Jakobshavn on the south and Upernivik Island just north of Umanak. This survey, begun by the General Staff of the Danish Army, is now being prosecuted by the newly organized Institut Géodesique, in which the Topographical Division of the Army General Staff has been combined with the Geodetic Service under the Ministry of War (N. E. Nörlund, 1930). Some preliminary flying by naval seaplane has been carried out for aërial map work.

In addition, a precise determination of the position of Kornok, near Godthaab in southwest Greenland, was made in 1927 — a station which had been used for the same purpose before the advent of radio time signals and which is now to be made permanent. The latitude of this station has now been determined as 64° 32' 6". 28 ± 0'' . 10, and the difference of time Greenwich-Kornok as $3^h\ 24^m\ 23^s . 405 \pm 0^s . 008$.

## MAPS

Up to the date of the Two Hundredth Anniversary in 1921 the latest official map of Greenland bore the date of 1906-8 and was printed on a scale of about 1: 2,000,000. In connection with the work *Grönland*, published to commemorate the anniversary, there was issued an atlas which included separate physical and geological maps of Greenland on a scale of 1:10,000,000, and, in addition, district maps on a scale of 1:1,000,000, of each of the eleven administrative districts: Egedesminde and Christianshaab; Jakobshavn, Ritenbenk and Godhavn; Umanak; Upernivik; Thule; Holstensborg; Sukkertoppen; Godthaab; Frederikshaab; Julianehavn; and Angmagssalik. In addition, the atlas included plans of the settlements (colonies) and historical maps of the house ruins of each of the principal settlements of the tenth century.

In 1926 the Danish Government issued a new and much improved general map of that part of Greenland which is south of 75° north latitude, or south of Melville Bay on the northwest coast, on a scale of 1:2,000,000, with an inset map of the entire country on a scale of 1: 6,900,000. This is the best general map of Greenland available today and, like all official maps of Greenland, it is obtainable from the publisher, C. A. Reitzel, 7 Lövstrade, Copenhagen. Of special use to English-speaking readers is the map with English place names, prepared by Professor M. Vahl and issued in 1929 in connection with the three-volume work Greenland, but obtainable separately. This map is on a scale of 1: 4,000,000.

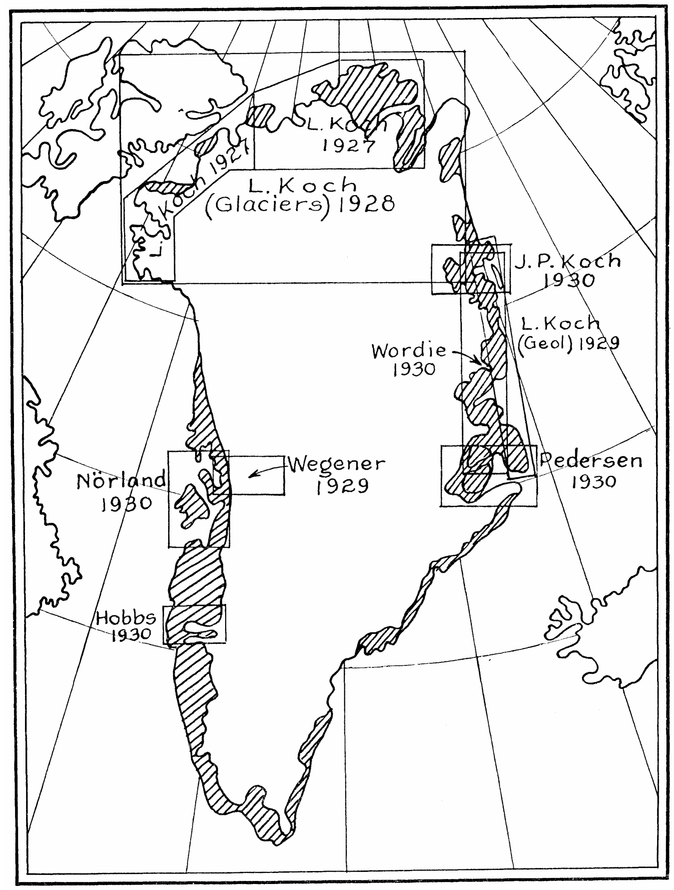
The American Geographical Society, which has devoted so much attention to the polar regions, brought out in 1930 a Physical Map of the Arctic on a scale of 1: 20,000,000 (Joerg, 1930*a*). In the same year the Scientific Cabinet of the Prince of Monaco issued three of a total of four sheets of a general bathymetric map of the northern oceans, on which north Greenland is represented on a large scale, copied from existing maps. Also in 1930 a geological map of the Arctic regions was published by Otto Holtedahl (Holtedahl, 1930).

Special areas of Greenland have been studied and maps have been published since 1921; those of Danish origin generally in the *Meddelelser*, the others scattered. These areas are roughly indicated on Map 33. The area of the north Greenland coast land, from Melville Bay on the west to Cape Bismarck on the east, has been mapped by Dr. Lauge Koch, in part while cartographer and geologist of the First Thule Expedition under Dr. Knud Rasmussen, and in part on his own expedition (L. Koch, 1927, 1928a).[3] The east coast south of Cape Bismarck as far as Scoresby Sound he has mapped and studied geologically on later expeditions and has issued a colored geological map (L. Koch, 19296).

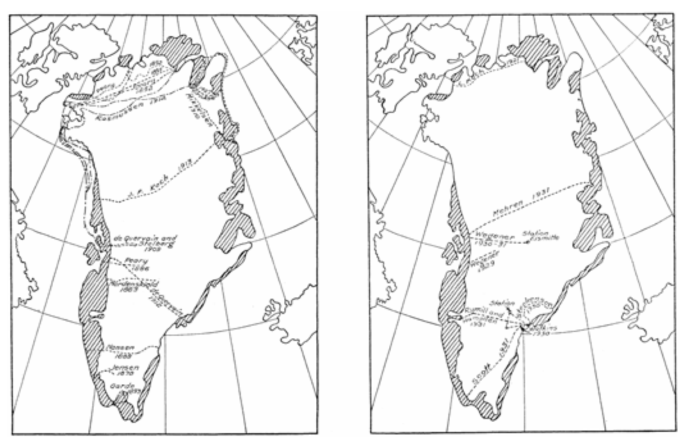
The Cambridge University Expeditions of 1926 and 1929, commanded by J. M. Wordie, have mapped parts of this long shore line and prepared detailed maps of the neighborhood of Petermann Peak and the Nordenskjöld Glacier (Wordie, 1930*a*, 1930*b*). The difficult ascent of Petermann Peak was accomplished and the altitude of the summit fixed as 9,650 feet, more than 1,200 feet higher than Nathorst's determination.

About Scoresby Sound itself some important surveys have been made by Alwin Pedersen, who has published a small map of the district (Pedersen, 1930). Pushing his way past a blockade of icebergs frozen into the remote Northwest fjord, he discovered an ice-free area with an abundance of game animals. In 1931 Louise A. Boyd in the Veslekari carried out a photographic survey of both Franz Joseph and King Oscar fjords on the east coast and published a map (Boyd, 1932).

On the west coast the University of Michigan Expeditions, of which Dr. Ralph L. Belknap has been cartographer, have prepared maps of the hinterland of the Holstensborg district about Mount Evans (Hobbs, 1927, 1930, 19316). Dr. Alfred Wegener, who has since perished on the Greenland ice-cap, published a sketch map of the coast district north of Umanak, including his sled trips on the ice-cap in the summer of 1929 (Wegener, 1930a, 19306). Preliminary reports on his main expedition of 1930-31, which was exceptionally fruitful of results, have now appeared (Else Wegener, 1932, and Berlin Geog. Soc., 1932).




MAP 33. Sketch map showing the areas covered by special maps of Greenland published since 1921



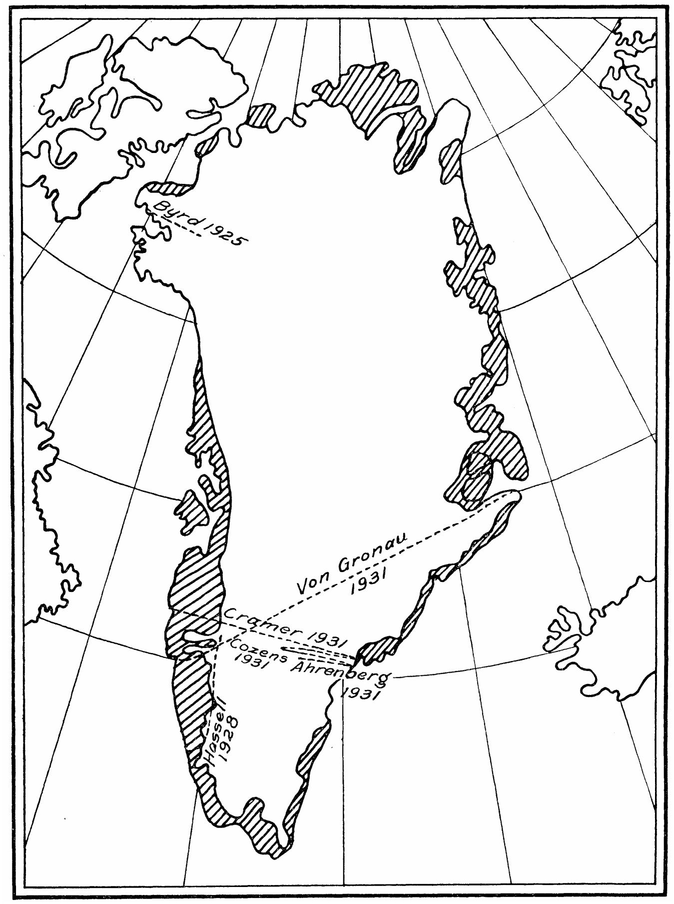
MAP 34. Sledge routes of explorers: at left, before 1921; at right, 1921-31

The east Greenland coast of the Angmagssalik district from the Sermalikfjord to Kangerdlugsuatsiak has been surveyed from the air by the British Arctic Air Route Expedition of 1930-31, under command of H. G. Watkins (Brit. Exped., 1930), who has since perished in

Greenland. Mount Forel is estimated to be 11,200 feet high. A party under Stephenson of the British Expedition attempted in May, 1931, to climb this mountain and succeeded in reaching an altitude of 10,880 feet. The summit they estimated to be at 11,500 feet. In the same district this party climbed a nunatak to the summit at 10,500 feet latitude.

New transection reconnaissances of the inland-ice, either complete or partial, have been carried out during the decade just past, as follows (Map 34): (*a*) in 1929 by Dr. Alfred Wegener, from the Kamarujuk Glacier on the west coast near latitude 71° eastward for a distance of 130 miles and also from Quervainshavn near latitude 69° northeastward a distance of 93 miles; (*b*) in 1930 by Wegener's party several times from Kamarujuk Glacier to Eismitte, the camp established on the medial line of the ice-cap 250 miles away (Wegener, 1930*a*, 1930*b*); and in 1931, after Wegener's death, several times by members of his expedition (New York *Times*); (*c*) in 1930 and 1931 several times by Watkins' parties, from the British Air Route Expedition base near Angmagssalik to their central ice station on the crest of the ice-cap, and, once, southward from the station down slope a distance not definitely stated (Brit. Exped., 1930; *The Polar Record*, No. 2, 1931); (*d*) in June and July, 1931, by three members of the British Air Route Expedition under James M. Scott, from Angmagssalik on the east coast southwestward behind the coastal mountains to the latitude of Umivik Bay, and thence direct to Ivigtut on the south coast; and (*e*) in the summer of 1931 by Rymill and Hampden, from Angmagssalik westward past Mount Evans to Holstensborg. The Norwegians Mehren and Höygaard in the summer of 1831 crossed from Umanak on the west coast to the east coast at Gael Hamke Bay (Höygaard, A., and Mehren, M., 1931). On his main expedition of 1930-31 Wegener carried a series of precise levels from the Kamarujuk Glacier on the west coast in lat. 71° 10' N. over the inland-ice to the central station of Eismitte (Else Wegener, 1932, and Berlin Geog. Soc. 1932).

Reconnaissance by airplane over the Greenland ice-cap was first attempted by Lieutenant Commander, now Rear Admiral, Richard E. Byrd, when in 1925 with the late Floyd Bennett he flew over the ice-cap in the Loening amphibian NA 1 from Igloohouny in the Cape York district, an estimated distance of about 40 miles in a direction south of east, where from an air elevation of 11,000 feet, with excellent visibility, he viewed the ice-cap for a distance of a hundred miles (Byrd, 1925). His claim that the ice surface rose to the level of his plane (11,000 feet) seems unlikely in view of the known altitudes reached by sledging parties in that district[4] (Map 35).




MAP 35. Flights over the ice-cap of Greenland

The next flight over the ice-cap was made by Bert H. J. Hassell and Parker Cramer on August 19, 1928, when they flew in a Stinson monoplane partly over and partly off the ice-cap from east of Fiskensesset on the southwest coast near latitude 62° northward and across the broad Knud Rasmussen ice-arm until forced down on the ice about 40 miles southeast of Mount Evans (Hobbs, 1930).

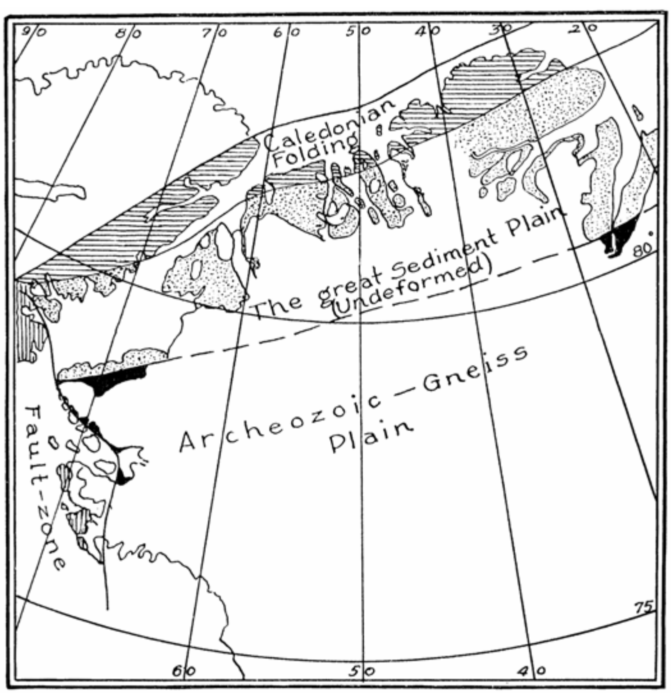
On February 25, 1931, Cozens and Scott of the British Expedition flew in a Moth plane from the Angmagssalik base on the east coast due westward to near the medial line of the ice-cap in an unsuccessful attempt to find the central station of the Expedition. In May of the same year Captain Albin Ahrenberg of Stockholm flew from the same base westward an estimated 130 miles in an attempt to rescue Courtauld, but found Watkins' sledge party returning with the rescued man.

The first crossing of the ice-cap by plane was accomplished by the late Parker Cramer on August 5, 1931, when he flew a Bellanca plane, provided with pontoons and propelled by a Packard-Diesel engine, from Holstensborg on the west coast and landed at Angmagssalik. The next crossing was by Wolfgang von Gronau in a southwesterly direction from Scoresby Sound to Sukkertoppen on August 15 of the same year.

## GEOLOGY

In connection with the memorial volumes of 1921 there was published a geological map of Greenland on a scale of 1:10,000,000 (Plate II of Atlas), which indicated that the greater part of the continent is a complex of crystalline rocks of pre-Cambrian age — gneisses, schists, and intrusive igneous rocks of both acid and basic types — a part of the Canadian shield. This relates wholly to the ribbons of coast land, since all else is buried under the ice-cap. On the west coast between latitudes 69° and 73° and on the east coast between latitudes 68° and 75° this map shows sheets of basalt; and on the north coast throughout and on the east coast generally within the area to the northward of Scoresby Sound sedimentary rocks of unknown age are represented. At the extreme south of Greenland occurs a most interesting series of highly alkaline igneous rocks, described among others by Ussing (Böggild, 1928), and having closest affinities with the alkaline igneous rocks of southern Norway. This was the status in 1921.

Since the centenary an immense amount of geological work has been done in Greenland, quite largely by that indefatigable explorer-geologist, Dr. Lauge Koch, who has with keen insight gone to the heart of the major geological problems. His work has dealt mainly with the sediments of the difficultly accessible north and east coasts.




MAP 36. Zones of the north coast of Greenland (after Lauge Koch)

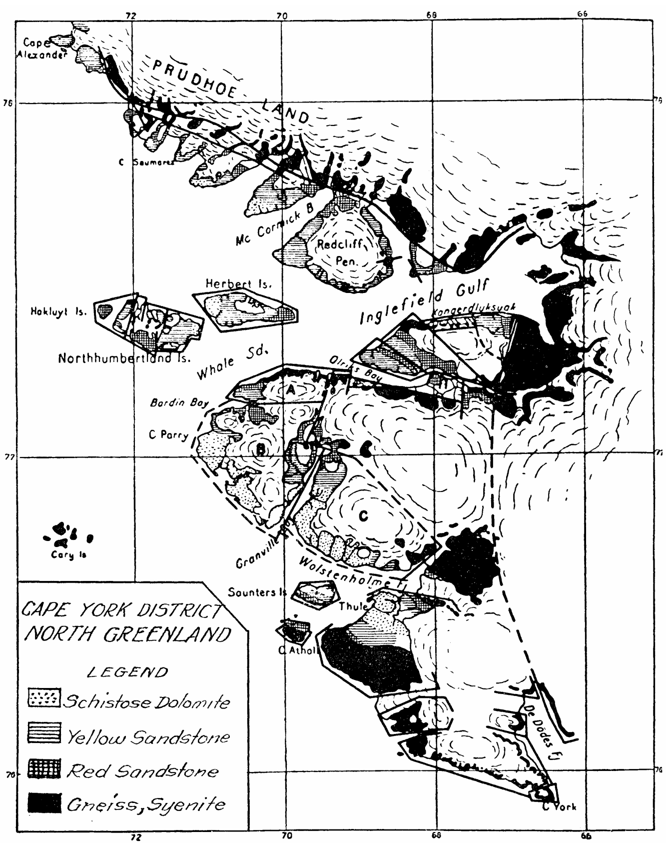
In 1916, while cartographer and geologist of the Second Thule Expedition, Koch had discovered Paleozoic fossils in the sedimentary rocks of southern Washington Land, and on his own later expeditions to north Greenland he devoted much of his attention to collecting fossils and working out the stratigraphy and structure of this coastal region.

Koch found that the basement of pre-Cambrian crystalline rocks ended rather sharply on a northern boundary extending from Etah on the west near latitude 78° to near the head of Denmark Harbor on the east near latitude 80° 30'. To the northward of this boundary is a low plateau of Algonkian and Paleozoic sediments which includes Cambrian, Ordovician, Silurian, and Carboniferous rocks. The strata have not been disturbed from their original positions and are unaffected by faults. The extensive fossil collections have been described by Troedsson (Troedsson, 1926).

On the northern border of the plateau of sediments with relatively rugged topography there occur folded and metamorphosed beds which are ascribed to the period of Caledonian folding (Map 36). The distribution of the geological formations is set forth in Map 37. The Caledonian arc of the north coast shows affinities with the Caledonian arc (Map 39) of the northwest coast of Scandinavia (L. Koch, 1923*a*, 1923*b*, 1925*b*). Along the west of these zones in the Cape York region is found a zone of complex faulting (Map 38) quite in contrast with the undisturbed character of the two northern zones which it borders (L. Koch, 1926*a*). In later expeditions Koch has studied the belt of sediments of the east coast (L. Koch, 1923*b*, 1929*b*, 1929*c*, 1930) and found there a somewhat similar much-folded arc of Paleozoic sediments which strikes roughly with the east coast, as the northern arc does with the north coast. These two Greenland mountain arcs are apparently joined in a vertex near the northeast angle of Greenland (Map 39).

Wordie, in command of the Cambridge University Greenland Expeditions of 1926 and 1929, found the overthrust folds of the eastern arc pushed westward over the pre-Cambrian rocks of the main basement series (Wordie, 1927, p. 252). Backlund has studied the structures of the folded arc within the area north of Franz Joseph Fjord and supplied colored sections with the surfaces of over-thrust indicated (Backlund, 1930, p. 225, Pls. II-III). The fauna collected from the east Greenland sediments has been studied by Paulsen (Paulsen, 1927) and the fossil plants by Harris (Harris, 1926). Koch has drawn attention to the fact that the Greenland basalts strikingly resemble those of Iceland and the Faroes, and that their position corresponds to a continuation of the submarine basalt band which joins the Faroes to Iceland (Koch, 19236, p. 56). This correlation is even better displayed on the new geological map of the Arctic (Holtedahl, 1930).

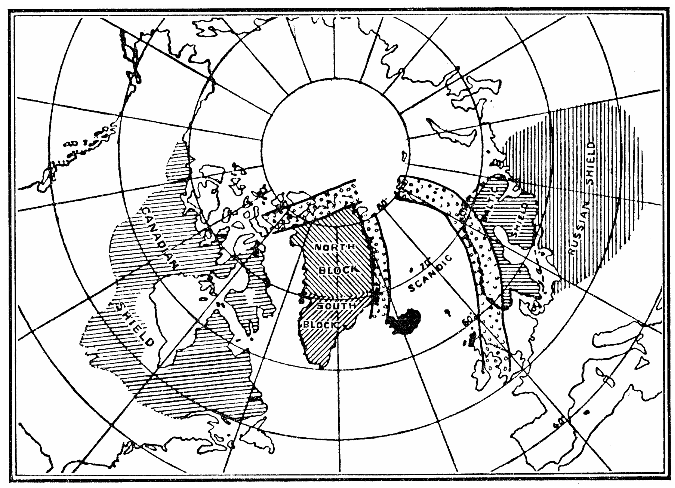

MAP 37. Geological map of north Greenland. Scale approximately 1:9,700,000 (after Lauge Koch)




MAP 38. The faulted Cape York district of northwest Greenland (after Lauge Koch)

Dr. A. C. Seward has made an exhaustive study of the fossil plants of the Cretaceous beds of the Nugssuak district of west Greenland (Seward, 1927).

H. K. E. Krueger, who has since perished in the Arctic, studied an area of the west coast about Disko and Umanak bays, and, confirming earlier studies by Steenstrup and others on other parts of the coast, showed that the fjords quite generally take their courses parallel to existing faults (Krueger, 1928). With associates of the recent Hessian Greenland Expeditions Krueger has made petrographical studies, with accompanying rock analyses of peridotite and basalts of the Cretaceous-Tertiary formation (Krueger, 1927; Drescher and Krueger, 1927). Ball, as the result of a reconnaissance along the southwest coast, has drawn the conclusion that, with the exceptions of the valuable cryolite deposits at Ivigtut and the coal deposits on both east and west coasts farther north, Greenland is not likely to yield valuable mineral deposits.




MAP 39. Shields and arcs (geosynclines) about the north Atlantic Ocean (after Lauge Koch)

## PHYSIOGRAPHY

Ever since the transaction expeditions of J. P. Koch and Alfred de Quervain in 1913, it has been known that a sag occurs in the domed surface of the ice-cap over Greenland near the latitude of Disko Bay (Map 42). Lauge Koch, by making north-south profiles of the land areas of the eastern and western coastal districts, has been able to show (L. Koch, 1923*b*) that a similar sag occurs in the glaciated surface of the rock basement near the same latitude, or about the line connecting the Disko Bay district of the west coast with the Scoresby Sound district of the east coast (Map 40). It is along this transverse zone that the Tertiary basaltic lava flows are found. To the southward and to the northward of this transectional zone the ice-cap appears to have separate domes which merge over the depression (Koch, 1923*b*, 1924).

The physiography of Greenland has been discussed in separate coastal sections: that of north Greenland by Koch (Lauge Koch, 1928*a*); that of the east coast by

Storgaard (Storgaard, 1928); and that of west Greenland by Birket-Smith (Birket-Smith, 1928).

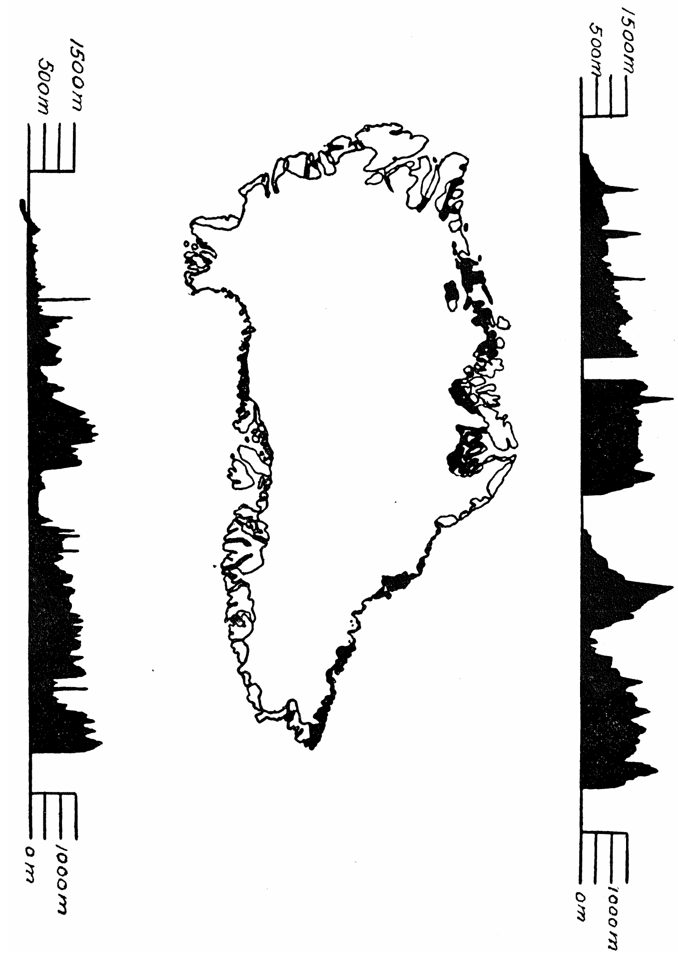
The geological units in north Greenland already described (p. 374) have largely determined the physiographic development there. The outer zone of Caledonian folding is characterized by Alpine topography, best illustrated by the northern half of Peary Land, whereas the undisturbed sedimentary strata at its back present only a monotonous plateau.

In east Greenland there are within the ice-free land zone large plateau areas over basalt flows and smaller plateau areas above the unfolded sediments, as on the north coast. The remaining portion of the district is distinctly mountainous, even Alpine, and all, with the exception of the tops of some of the highest peaks, has been sculptured under a former extension of the inland-ice from the interior. It thus presents the convexly rounded forms (*roches moutonnées, Rundhocker*) and in addition, where outlets from the interior and detached mountain glaciers have operated since the retirement of the main ice-front, comb ridges, horns, U-shaped valleys, fjords, and even cirques, have formed (Storgaard, 1928). Wordie has prepared maps and beautiful photographs which display this topography in the Franz Joseph Fjord region (Wordie, 1930*a*). Alwin Pedersen also has supplied other examples from the south, particularly of Scoresby Sound (Pedersen, 1930). Watkins has shown (Brit. Exped., 1931) not only the Alpine characters, but the very strong relief of the coast land all about the Sermilikfjord of the Angmagssalik district, and near the route of his sledge party under Scott while traveling from Angmagssalik to Ivigtut in June and July, 1931.

Lauge Koch and Backlund have both supplied evidence from proved faults that at least many of the great fjords of the east coast have been given their directions by displacements or by earth fractures. Such a view, suggested by any careful inspection of the map of Greenland, has been often expressed by early investigators, but usually without proof. The fault directions chiefly noted by Koch are E.-W. and N.-S., those by Backlund E.-W., ENE.-WSW., and ESE.-WNW. (Backlund, 1930).

The west coast land over the main crystalline areas in the southwest presents to the sea a high plateau once covered by an advance of the inland-ice and strongly glaciated, later to be deeply dissected by the outlet glaciers and by detached areas of mountain glaciers; so that U-shaped valleys, comb ridges, and many deep cirques are prominent features of the landscape. A large and general subsidence of the coast-land has sufficed to submerge in many places the floors of the cirques. A subsequent uplift has produced strongly developed coastal terraces running up several hundred feet and always best preserved at the heads of the fjords (Hobbs, 1927).

The pattern of the fjords is one mainly determined by the fracture system within the rocks, of which a relatively small number of directions exercise control. This has been shown by Steenstrup, by the writer (Hobbs, 1927), by Krueger (Krueger, 1928), and by R. L. Belknap in a monograph on the physiography of the Holstensborg district of Greenland to be published in the *Reports of the Greenland Expeditions of the University of Michigan*.




MAP 40. Profiles along the east and west coasts of Greenland, which display a sag of the rock basement (after Lauge Koch)

As on the east coast, so here in the west the plateau is everywhere glaciated, though an excessively rapid frost weathering has effaced the polish and scorings from all but the better protected places in the bottoms of the fjord valleys. On the tops of the plateau remnants of glacial boulders are perched in great numbers as mute witnesses to the former expansion of the inland-ice, and the U-sectioned fjords show the work of the outlet tongues after the main ice-front had retired.

From the sea in the southwest Greenland country the coast rises in a great staircase, the steps of which are orographic blocks, each with much the same leveled and glaciated upper surface. The lowest of these steps is composed from a swarm of low islets and reefs which form a *skaërgaard* or "skerry fence," at the back of which rises an assemblage of larger islands which push up a few hundred feet from the sea. Then on precipitous slopes rises the third step several times as high as the second. Within the Holstensborg district the height of this coastal plateau fifty miles back from the sea averages about 1,700 feet, but it in turn abruptly gives place to a hinterland of low rounded hills, first described by Nordenskjöld,[5] which the writer found to be explained by a second advance of the inland-ice. The average altitude of the hilly hinterland is from one half to two thirds of that of the dissected plateau at its front (Hobbs, 1927).

Peculiar to this hinterland are certain scars of cirques found in connection with isolated areas of mountain glaciers left behind by the continental glacier in its earlier retreat, with their cirque scars largely eroded away during the readvance of the ice.

The basalt flows of the Disko and Umanak bays afford flat plateau surfaces quite different from the deeply dissected plateaus of the basement of crystalline rocks.

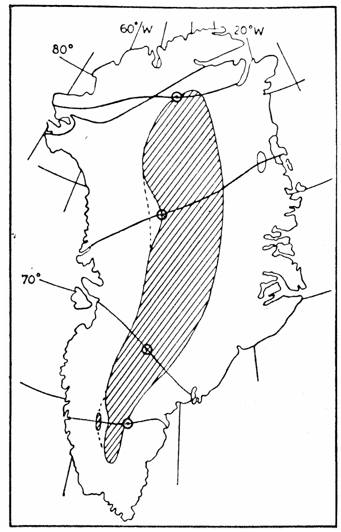
## GLACIOLOGY

The glaciology of Greenland may be conveniently discussed for: (*a*) the main body or carapace of ice; (*b*) the marginal glaciers which serve as outlets to the parent glacier; and (*c*) detached areas of true ice-cap and mountain glaciers.

Though the transection of Greenland in its widest section was accomplished by J. P. Koch and A. Wegener in 1913 and a valuable narrative with much scientific data was brought out in 1919,[6] the technical report was delayed for seventeen years and first appeared in 1930 (Koch and Wegener, 1930).

FIG. 15. Profile of the Greenland ice-cap along the route of J. P. Koch in 1913. Vertical scale fifty times the horizontal (after J. P. Koch and A. Wegener)

One of the most important results is concerned with the profile of the ice-cap along the route of the expedition. This section as corrected by Koch with fifty-fold exaggeration of the vertical scale is reproduced in Figure 15. The track of the journey appears on Map 41. The crest of the dome on this section is well to the west of the medial line of the continent, whereas the divide on Nansen's section lay well to the east and that on De Quervain's section near the medial line (Map 41). The divide on Koch's section is at an altitude of 10,463 feet, much the highest point thus far discovered upon the ice. The Swiss Expedition's section, made in the same year under the late Alfred de Quervain, was from near Jakobshavn (Quervainshavn) on the west coast to Angmagssalik on the east coast, and the final report, mainly in the German language, appeared in 1920.[7] In the French language this important report has now been issued in the *Meddelelser* (De Quervain and Mercanton, 1925). At Wegener's central station of Eismitte eastward from Umanak the altitude was found to be 9,840 feet (Berlin Geog. Soc., 1932). Since the crest reached by De Quervain was at an elevation of 8,197 feet and that of Nansen farther to the south at 8,932 feet, it is clear that a depression of the ice surface must occur in the neighborhood of De Quervain's section.



MAP 41. Transection routes of explorers, and cold central area of Greenland. From top to bottom, routes of Rasmussen, J. P. Koch, De Quervain, and Nansen, respectively. Divides are shown by small circles (after J. P. Koch and A. Wegener)

Two profiles across the marginal portion of the inland-ice have been made by Wegener in his preliminary Greenland Expedition of 1929 (Wegener, 1930*a*), which indicate that north of De Quervain's route near the west coast the slopes rise rapidly. Wegener's longer section was directed to the east, the other to the northeast (Fig. 16).

In June and July, 1931, J. M. Scott, with two companions of the British Arctic Air Route Expedition, crossed the inland-ice from the base near Angmagssalik south-westward inside the mountain belt to the latitude of Umivik Bay and thence direct to Ivigtut. After they had crossed Nansen's route a crest of the ice was passed, which from uncorrected observations was "well over 9,000 feet," thus confirming the view already arrived at that a southern dome of the ice surface is in this general region. Cramer in his flight over the ice-cap on August 5, 1931, from Holstensborg to Angmagssalik to clear the ice easily flew at an altitude of 9,600 feet. Koch's revised contour map of Greenland is reproduced in Map 42 (Lauge Koch, 1930).

That the inland-ice formerly extended over most of the now ice-free land on its borders has been made clear (Hobbs, 1927; L. Koch; 1928*b*). With the exception of the tops of some of the highest peaks, which appear to have protruded through the larger glacier as nunataks, the only considerable area of Greenland not covered was the northern half of Peary Land (L. Koch, 1923*b*), where a marginal moraine has been found (Map 43) south of the high Alpine region (L. Koch, 1928*b*).

As regards recent changes in position of the ice-front, Lauge Koch has found that in north Greenland the coast once stood 210 meters (689 feet) higher than now, and that since the culmination of the subsidence none of the glaciers near the 210-meter level have advanced (L. Koch, 1928*b*). Within the Cape York district most of the glacier fronts appear to be stationary.

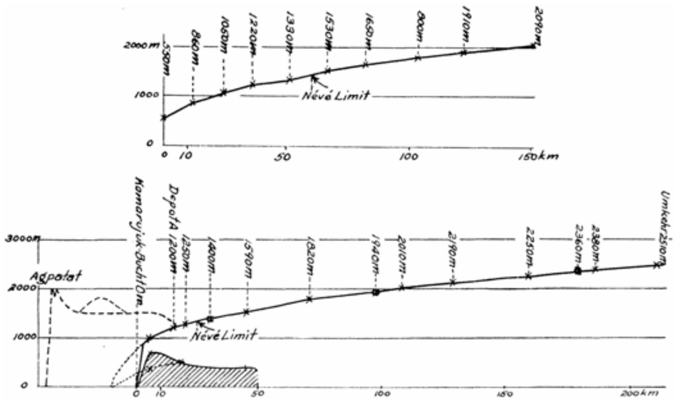
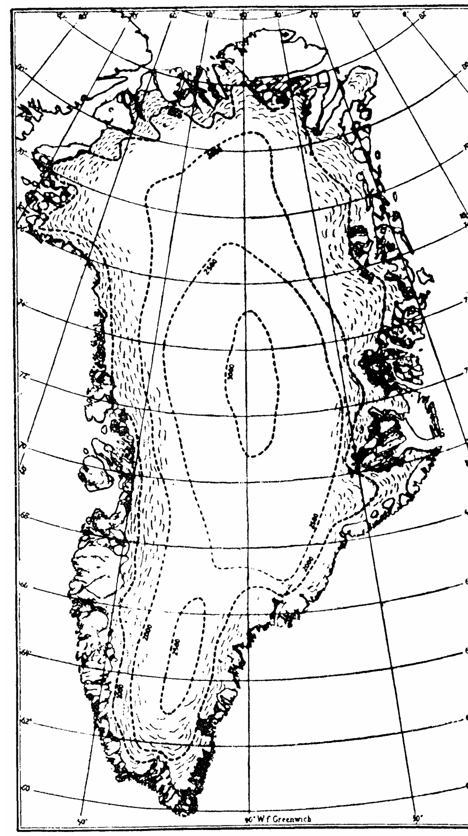


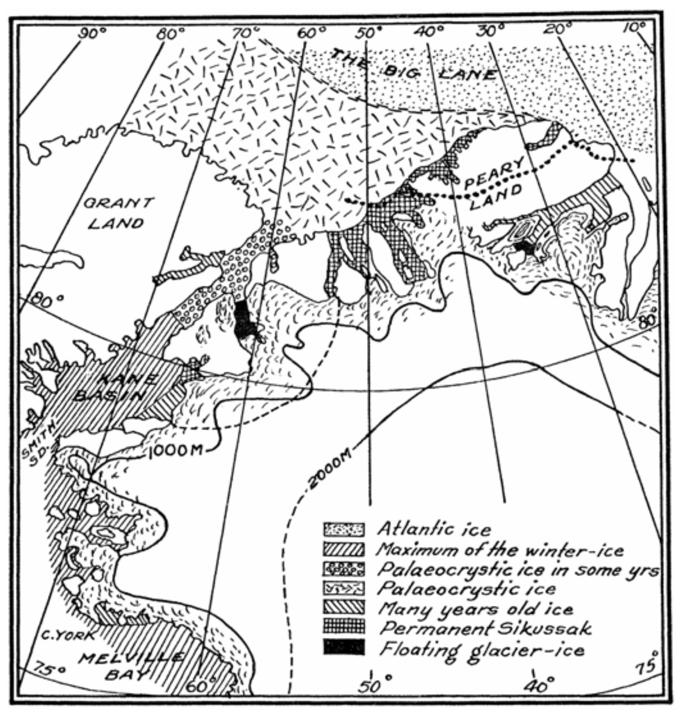

FIG. 16. Two profiles across the marginal zone of the inland-ice of the Greenland west coast, in the Umanak-Disko Bay region, with part profile of the rock basement (after A. Wegener)

On the west coast Wegener has made important measurements in the Disko-Umanak district and found that, with the exception of the Great and Small Karajak glaciers near latitude 71°, whose fronts are practically where they were forty years ago, the glacier fronts have retired by distances which vary from about one-half kilometer in the case of the Sermilik glacier since 1891, to three and eight-tenths kilometers in the case of the Kome outlet since 1893 (Wegener, 1930*a*). William S. Carlson, in charge of the Northern Party of the Fourth Greenland Expedition of the University of Michigan, has in the summer of 1931 remeasured the front of the north arm of the Cornell Glacier near latitude 74°, which was measured by Tarr's party thirty-four years before, and found a maximum retirement of about 2,500 feet, with an average of about 1,500 feet. The Upernivik glacier he found to have retired since 1886 (Ryder) a maximum of 5,000 feet, with average 3,500 feet. Giesecke's glacier within the same period retired a maximum distance of 3,200 feet, with average of about 2,000 feet. He has photographed the fronts of all glacier outlets of the west coast from the latitude of Upernivik to the Devil's Thumb (latitude 72° 30' to 74° 45').

The rate of the flow of the ice within glacier outlets of Greenland has been measured in the past with results surprisingly large, in one instance 75 feet per day. Few have attempted the far more difficult task of measuring the rate in the inland-ice itself. De Quervain, however, by use of bamboo poles set at the corners of a network of nearly equilateral triangles which extended two kilometers in from the ice edge, discovered that within this distance the rate varied but little, the range being from one to two feet per day (De Quervain and Mercanton, 1925). The ablation indicated for a period of thirty-nine days during the summer of 1912 amounted in some instances to as much as 1.2 meters. Carlson measured the movement in the Upernivik glacier over a period of fifteen days, with maximum movement 67 feet per day, and the average movement at different points of the front varying from 2 to 59 feet.



MAP 42. Revised contour sketch map of the Greenland ice-cap (after Lauge Koch, 1930)



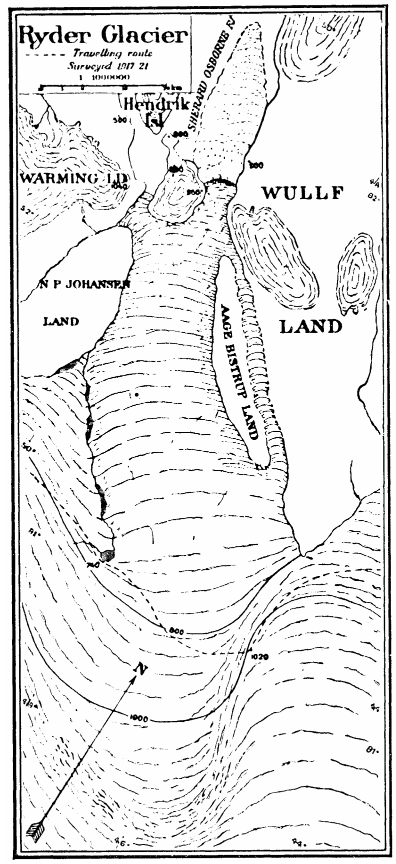

MAP 43. Form of ice-cap in north Greenland and conditions surrounding it (after Lauge Koch)

There has been much speculation about the level of the rock basement beneath the Greenland inland-ice, but until 1929, when echo soundings were made in connection with the Preliminary German Expedition of Dr. Wegener, nothing was known. Dr. Sorge applied the seismic method perfected by H. Mothes[8] in measurement of the thickness of Alpine glaciers (Wegener, 1930*a*; Sorge, 1930). Wegener's measurements were made along his main sledge route eastward from the Kamarujuk glacier near latitude 71°; and the derived profile extended to a point nearly fifty kilometers from the ice edge, where the thickness was found to be 1,200 meters (Fig. 16, p. 384). Though the ice surface rose steeply along this section, the rock bed was depressed into the form of a saucer. These soundings were extended on the main expedition of 1931-32 (Else Wegener, 1932, and Berlin Geog. Soc., 1932). Like the earlier data these seem to indicate considerable irregularity of the rock floor, though the saucer form seems to continue to the end of the profile at Eismitte. At this place, which is at an altitude of about 3,000 meters, the rock floor was found to be between 300 and 500 meters above the sea. The soundings further indicated the depth of *névé* upon the glacier surface, this contact being relatively definite in the outer portions, but much less so below the interior station.

The interior of the "Great Ice" of Greenland offers little save monotony of aspect once the marginal zone has been left behind — a vast plain with grades so slight that a theodolite is necessary to make them known; but as one approaches the margin from the interior the grades increase at an accelerated rate. Lauge Koch has sketched the contours of 2,000 and 1,000 meters on this surface in north Greenland; the former, far back from the margin and with strong embayments above each of the principal outlets into the fjords (L. Koch, 1928*b*). Peary described these amphitheaters as "basins of exudation" and von Drygalski mapped one main outlet above the Umanak fjord. Lauge Koch has mapped the amphitheaters at the heads of the Petermann and Ryder glaciers of north Greenland (Map 44). These are a universal feature wherever the inland-ice exudes through outlets of the rock basement. De Quervain prepared a map of the inland-ice margin on Petersens Bay on the Sermilik fjord near Angmagssalik (De Quervain and Mercanton, 1925), where the amphitheaters are directly at the shore (Map 45).

In northwest Greenland on Melville Bay from the Devil's Thumb to Cape York the inland-ice in similar manner comes close to the sea over a stretch of 250 miles of coast, though divided by projecting rock into seventy separate passages within which the glaciers are given names.

On the northeast coast between latitudes 78° and 79° two large outlets discharge so much ice that it accumulates in the Jökelbugten behind a line of rocky islets which hem in the bay. This ice was described by J. P. Koch and A. Wegener[9] as the "floating inland-ice of Glacier Bay," and it supplies the nearest parallel in the Arctic today with the shelf-ice of the Antarctic. L. Koch has now described this floating ice under the name "confluent ice" (Map 46).

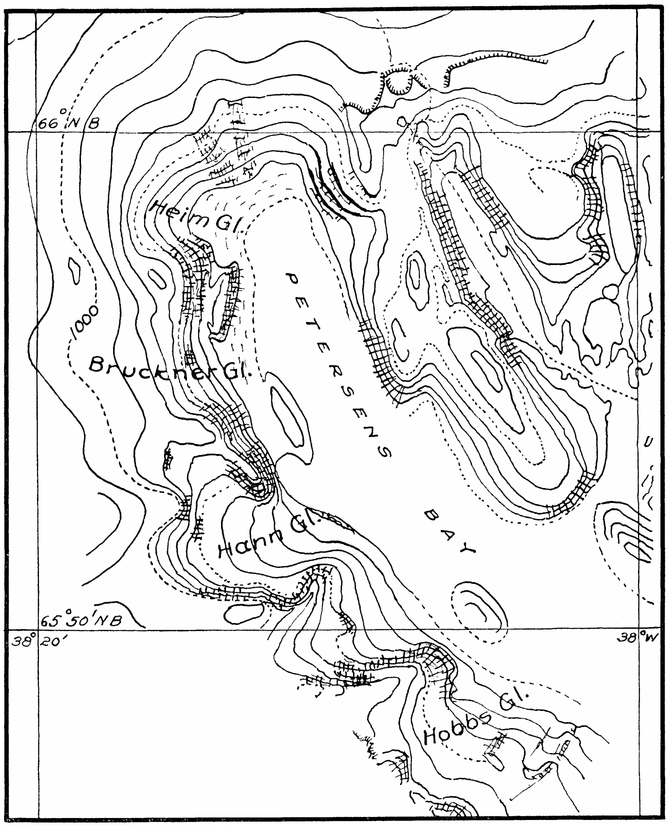



MAP 44. Ryder Glacier of north Greenland, with its floating tongue (after Lauge Koch)

Some of the glacier outlets of the north coast end in tongues which float upon the fjords, separated near their fronts from the fjord walls by the sea ice (Lauge Koch, 19286, p. 346). Examples are the Petermann and Ryder glaciers (Map 44, p. 388). The essential difference between these floating tongues and those of the Antarctic Koch illustrates by Figure 17. Ice tongues of the

Antarctic type, which push out beyond the coast line, have Greenland representatives in Petermann and Sherard Osborne fjords, and beginnings of such tongues are at the fronts of the Jungenen and Academy glaciers. Since in northern Greenland icebergs cannot issue from the fjords, a gradual transition sometimes occurs from the crevassed glacier front to closely packed groups of bergs.

A district where outlet glaciers end upon the land is the area north of the head of Independence Bay. This is the most northern and most inaccessible group of glaciers that is known, and one that occupies a controversial area which has been mapped most recently by Lauge Koch. This group is shown in Map 47.




MAP 45. Petersens Bay and the edge of the inland-ice (after De Quervain and Mercanton)

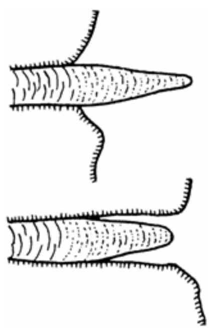
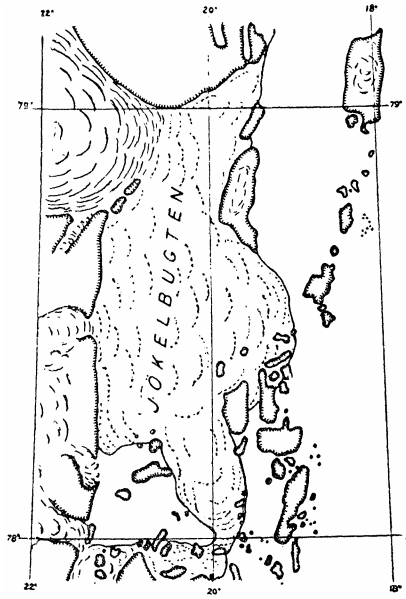
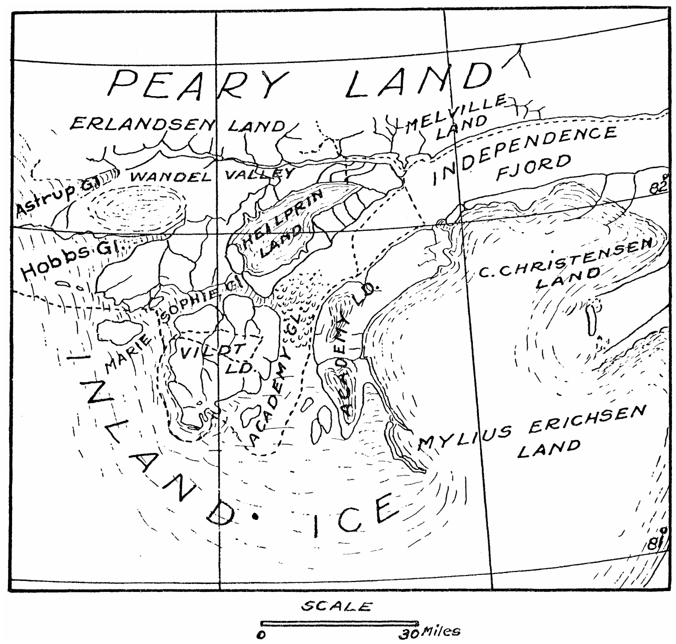


FIG. 17. Ice tongues afloat: above, Antarctic type; below, Greenland type (after Lauge Koch)

Either wholly or partly detached from the inland-ice are what Lauge Koch has described by Priestley's term, "highland ice" — local ice-caps. Such glaciers, just separating from inland-ice, are found well developed in the Cape York district (Map 48). Similar small ice-caps appear upon Map 47, and they are found in many other places outside the inland-ice where the land rises sufficiently for them to survive in the existing climate. To indicate how the waning of the glacier remnants of a small ice-cap persists on the basalt plateau of Disko Island, there are found on the west side of this plateau outlets from this ice-cap which have discharged over the steep sides of the plateau, but are now detached (Koch, 1928*b*, pp. 339-340) and melt chiefly at their upper ends, as do the much larger detached slabs of ice in the Antarctic of South Victoria Land.[10]




MAP 46. The confluent ice of Jökelbugten northeast Greenland (after Lauge Koche)

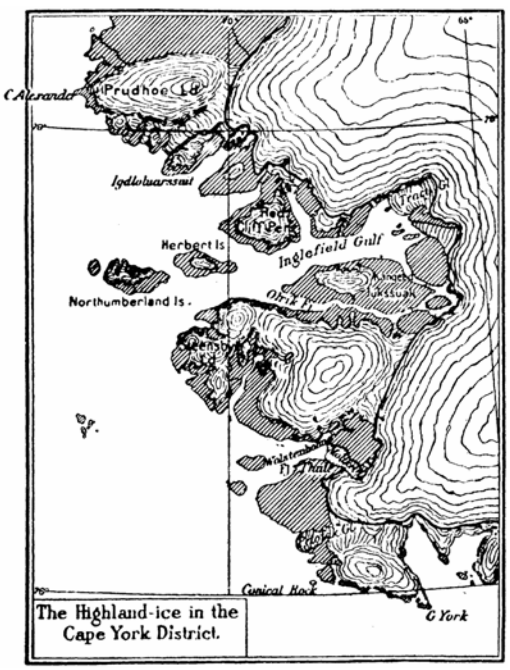



MAP 47. Group of glacier outlets near the head of Independence Bay, Peary Land (after Lauge Koch, 1927)

True mountain glaciers are found well developed within certain of the coastal Alpine districts of Greenland on both the east and west coasts. Here, in consequence, we find locally a development of cirques, comb ridges, U-shaped valleys, and other related forms.

## METEOROLOGY

By reason of its auto-circulation the ice-cap of Greenland assumes very special importance in the earth's general atmospheric circulation, and hence in meteorology and especially in aërometeorology. Two great polar explorers, Nansen and Peary, the former at the time of his transection of the ice-cap in 1888, and the latter through his many Greenland sledge journeys which began in 1886, reached independently the conclusion that the surface air currents blow outward from the interior at all times. The necessary deductions to be made from these observations and others which confirm them were expressed by the writer in 1911, 1912, 1915, and 1926 (Hobbs, 1926), and the circulation over continental glaciers was described under the name "glacial anticyclone" —Greenland anticyclone and Antarctic anticyclone — which are fixed in position as the northern and southern wind poles of the earth. Summarized, these circulations are represented in Figure 18 and their part in the general circulation in Figure 19.




MAP 48. Glaciers of the Cape York district (after Lauge Koch)

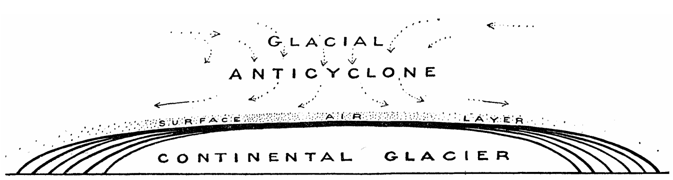



FIG. 18. Mechanism of the fixed Greenland anticyclone (after Hobbs)

Every new expedition has added its testimony to the correctness of the theory of centrifugal distribution of the surface air currents, with deviation clockwise in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere. So constant and reliable is this circulation that each party that has crossed the ice-cap has battled against head winds and fierce blizzards in advancing to the divide of the section, and has then sailed out on the other side in long *étapes*.

One of the latest examples is supplied by Dr. Wegener on his two sled journeys of the Preliminary German Expedition to Greenland in 1929. From examination of the diagrams of Figure 20 it will be noted that wind was constantly from near the east or southeast (down slope with clockwise deviation), except when the wind force fell to near a dead calm (Wegener, 1930*a*).

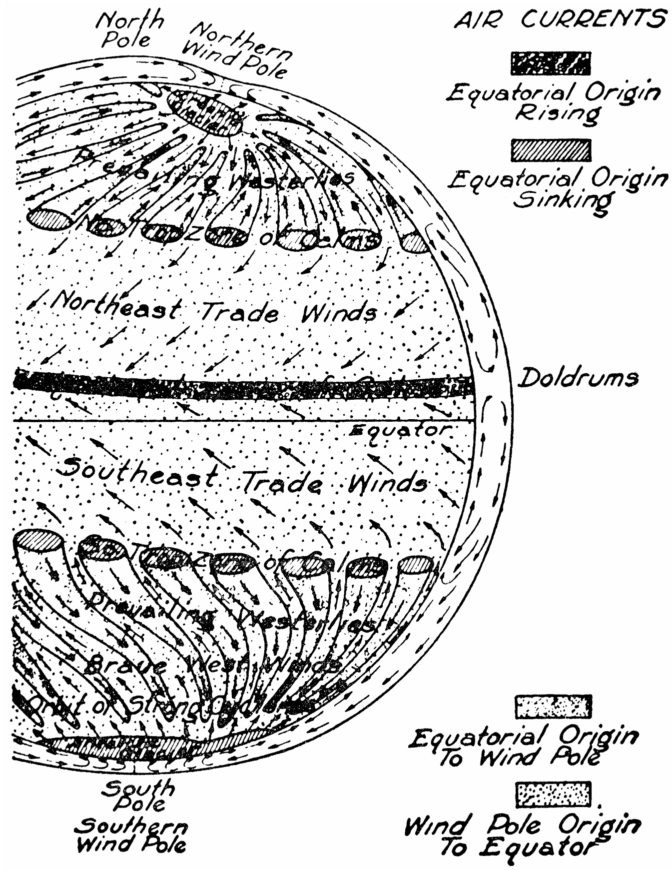



FIG. 19. The earth's general circulation, with conventionalized representation of the complex system of opposing currents in middle latitudes (after Hobbs)

The Meteorological Institute of Copenhagen maintains in Greenland meteorological stations at six coast settlements well distributed on the west, south, and east coasts, but all south of latitude 71°. At each of these stations the usual meteorological elements are regularly observed and recorded, and at each station a powerful radio sender of long wave length puts certain fundamental data regularly on the air for the use of various meteorological and forecasting services. These stations are at Godhavn, Godthaab, Ivigtut, Julianehaab, Angmagssalik, and Scoresby Sound. In addition, the Norwegians maintain a station at Mygbukta on the east coast, near latitude 73°, where there is a short-wave radio station. The location of these stations is indicated on Map 49.

In addition to the stations provided with radio, meteorological observations are regularly made at a number of other stations, such as Nanortolik, Igaliko, Sagdlit, Kornok, Holstensborg, Karsut, and Upernivik, by an observer who is usually an intelligent Greenlander. These observations are published annually at Copenhagen in the *Meteorologisk Aarbog* of the Meteorological Institute. The Danish service has not as yet employed aërological methods, and since the Greenland stations are generally within the mouths of steep-walled fjords their wind and temperature data have little value.

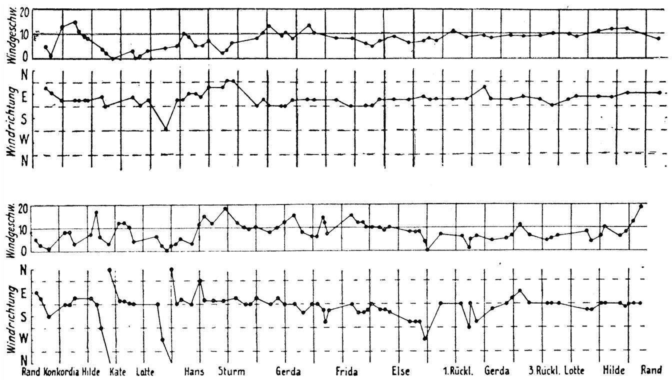
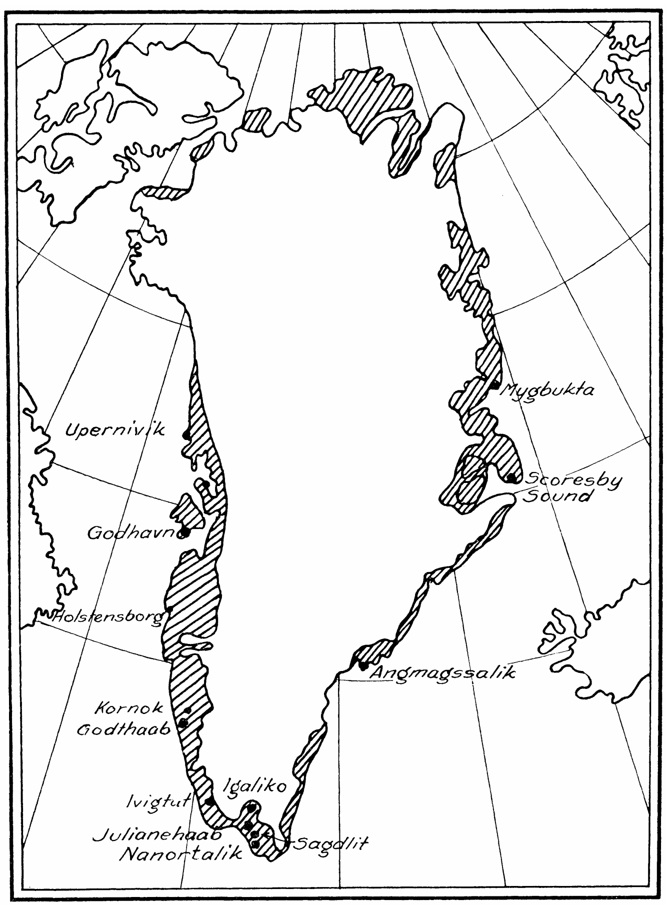



FIG. 20. Diagrams showing the direction and velocity of the wind on the journeys over the ice-cap toward the interior of Greenland in the summer of 1929. Above, hand-sled expedition in direction northeastward from Jakobshavn; below, dog-sled expedition directly eastward from the Kamarujuk Glacier (after A. Wegener)




MAP 49. Meteorological stations of Greenland

Upper-air methods were first introduced in Greenland on the Danish Northeast Greenland Expedition of 1907-8 by Alfred Wegener, the meteorologist of the expedition, who made use of kites and captive balloons; and though the ascents did not go higher than 2,000 to 3,000 meters, the results were of the greatest value in showing that above the local winds of the fjords the winds blowing off the ice dominated up to the highest levels reached. Until that time all studies of winds over any considerable period had been made on the west coast, and since these always came from easterly quadrants it had been assumed that they had blown *across* the ice-cap.

The Swiss Expeditions of 1909 and 1912-13 made special use of pilot balloons, which were sent up from several stations of southwest Greenland, including Godhavn (85 ascensions), Jakobshavn (6), Quervainshavn (7), and Holstensborg (22). These balloons were followed to an average altitude of 6,000 meters with several which reached exceptional heights.

In the summer of 1926 the First University of Michigan Greenland Expedition established a base at Camp Michigan near the head of the Maligiakfjord about forty miles east of the coast settlement of Holstensborg. Here during the months of July August, and September some 90 pilot balloon ascensions were carried out by Mr. S. P. Fergusson, the aërologist of the expedition (Hobbs, 1931*b*, pp. 49-67). The location proved to be less satisfactory than had been hoped, and the Second Expedition of 1927 established a new base with an aërological station on Mount Evans, near the head of the Söndre Strömfjord, one hundred and twenty miles from the sea and only twenty-five miles distant from the margin of the inland-ice. This station, with its clear skies, proved admirably suited for aërological work. It was maintained in continuous operation for two years, during which time 776 pilot balloon ascents were carried out by Clarence R. Kallquist, William S. Carlson, and Leonard R. Schneider, the successive aërologists in charge (Hobbs, 1931*b*, pp. 71-239). The results showed that all strong surface winds blew off the ice, and that these extended up to a level which varied with the season, being highest during the winter when the strophs were stronger. At levels varying generally from 2,000, meters as a minimum to 6,000 or even 8,000 meters or more, the outflowing air was replaced above by inblowing currents. The averages for two successive years are given in Figure 21. Pilot balloons sent up in the summer of 1927 at the Norwegian station of Mygbukta on the east coast were in part simultaneous with those sent up at Mount Evans. These ascensions, 35 in number, if we ignore the local currents below the level of 1,000 meters, indicated reversed directions, as was to be expected from the mechanism of the glacial anticyclone. The surface winds blow off the ice here from the northwesterly quadrant (Hobbs, 1931*b*, pp. 32-37).

The report of Koch and Wegener on the scientific results of the Danish Expedition of 1912-13 affords most important data for the study of the conditions over the interior of the ice-cap. Comparisons of the daily air temperature measurements made during the transections of Greenland by Nansen, De Quervain, and Koch show that in each case the sled parties passed suddenly from areas of moderate summer air temperatures on the flanks of the ice-dome into a central area of intense cold (Figure 22). The boundaries of this central area of cold and calm, as determined from the three transections, are given in Map 41, p. 383, and Koch and Wegener's representation of the glacial anticyclone appears in Figure 23.

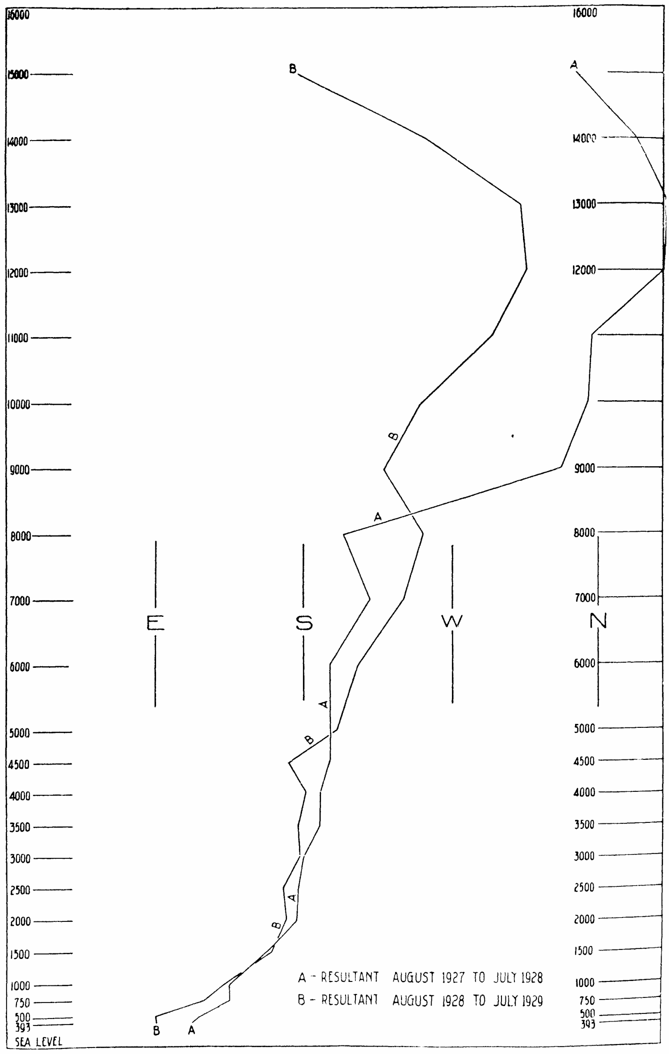



FIG. 21. Average wind directions over Mount Evans, Greenland, for successive years (after Hobbs)

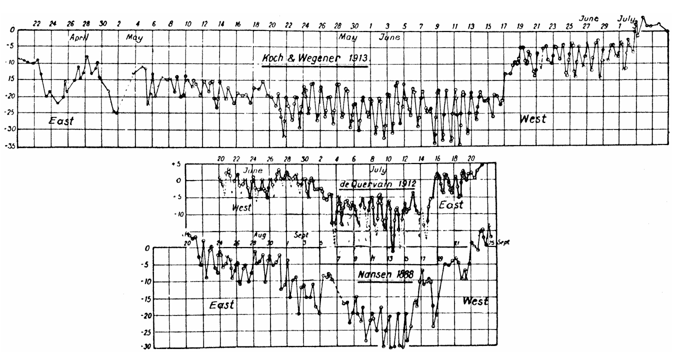



FIG. 22. Daily air temperatures measured on transections of the Greenland ice-cap, by Koch and Wegener, De Quervain and Nansen (after J. P. Koch and A. Wegener, 1930)

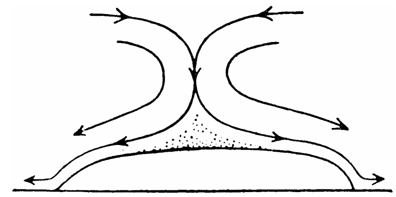
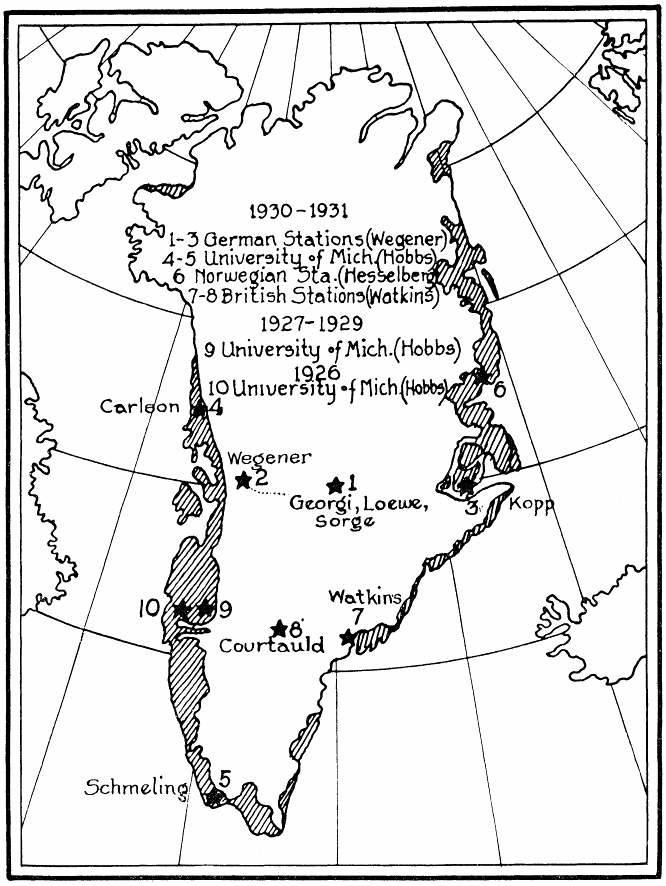


FIG. 23. Mechanism of the glacial anticyclone (after J. P. Koch and A. Wegener, 1930)

In 1930-31, for the first time, something approaching coordination in upper-air studies from definite stations of Greenland was attempted for the period of a year (Map 50). Following upon his preliminary expedition of 1929, Dr. Alfred Wegener went to Greenland in 1930 in command of one of the largest and, for scientific purposes, best organized expeditions which have ever gone to the polar regions. His plans contemplated setting up three stations near the latitude of 71°, one on the ice-cap itself though near to its western margin, one on the east coast near but not on the ice-cap, and one near the medial line of the ice-cap between the other two. This extremely difficult program was carried out. The eastern station had to be managed as a separate expedition under Dr. Kopp. The central station was reached from the west coast, and the arduous and hazardous problem of providing its supplies of equipment, food, and fuel was solved by dog-sled caravans, and for a part of the distance by motor sleds from the west coast. This central station was in charge of Dr. Johannes Georgi, veteran aërologist of the Deutsche Seewarte at Hamburg. Despite the many hardships and disasters, which included the loss of the heroic leader, the central station was maintained for a full year, with scientific results which have now been published in narrative and in summarized technical reports (pp. 410-411).

Farther south and in about the latitude of Mount Evans were the two stations of the British Arctic Air Route Expedition under command of H. G. Watkins. These stations have had meteorological but, unfortunately, not aërological equipment. Under conditions similar to those encountered by Dr. Georgi and his two companions at the German central station of Eismitte, Augustine Courtauld of the British Expedition spent nearly seven winter months entirely alone at their central ice-cap station northwest of Angmagssalik.

The University of Michigan maintained in 1930-31 two aërological stations on the west coast, the northern one at Camp Scott on a small island two miles distant from the ice margin and to the eastward of Upernivik near latitude 72° 45' (Hobbs, 1931*c*). This station, in charge of William S. Carlson, assisted by Max Demorest, was maintained for eight months (Aug. 28, 1930, to April 27, 1931), during which time 238 pilot balloon ascensions were carried out. At the south station in the mining settlement of Ivigtut, Evans S. Schmeling carried out 177 pilot balloon ascensions and 94 cloud-altitude observations (Sept. 1, 1930, to Sept. 1, 1931).




MAP 50. Positions of aërological or meteorological stations actually set up in Greenland in 1930-31

In the Second International Polar Year, 1932-33, it is expected that several aërological stations will be maintained in Greenland and in positions not before occupied, notably at Angmagssalik on the east coast and Cape York in the northwest.

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[1] *Grönland i Tohundredaaret for Hans Egedes Landing, udgivet af Kommissionen for Ledelsen af de Geologiske og Geografiske Undersögelser i Grönland, under Redaktion af G. C. Amdrup, Louis Bobé, Ad. S. Jensen, Pl. P. Steensby.*† Vol. 1, 567 pages; Vol. 2, 795 pages. Illustrated. C. A. Reitzel, Copenhagen, 1921.

[2] *Greenland*, published by the Commission for the Direction of the Geological and Geographical Investigations in Greenland. Editors, M. Vahl, Ph.D. (chief editor), G. C. Amdrup (Vice-Admiral), L. Bobé, Ph.D., Ad. S. Jensen, Ph.D. Vol. 1 (*The Discovery of Greenland, Exploration, and Nature of the Country*), 575 pages; Vol. 2 (*The Past and Present Population of Greenland*), 415 pages; Vol. 3 (*The Colonization of Greenland and Its History until 1929*), 468 pages. Illustrated. C. A. Reitzel, Copenhagen. 1928 and 1929.

[3] In 1931 there was issued a portfolio of maps of north Greenland, on a scale of 1: 300,000 of the area which was surveyed by Lauge Koch in the years 1917-23. This portfolio, published by the Geodetic Institute of Denmark, includes eighteen plates executed in nine colors and giving altitudes, and a supplement. Each of the maps covers an area of about 20,000 square kilometers. The individual maps are designated Beaumont Island, Lockwood Island, Cape Morris Jesup, Cape Bridgman, Hall Land, Black Horn Cliff, Wulff Land, Adams Biering Land, Navy Cliff, Denmark Fjord, Cape Constitution, Petermann Glacier, Etah, Cape Agassiz, Cape Parry, Inglefield Gulf, Cape Atholl, and Cape York. These maps are sold by Levin & Munksgaard, Copenhagen.

[4] The highest point of the ice-cap surface yet reached is at an altitude of 10,463 feet, on the divide passed by J. P. Koch in 1913 (Koch, J. P., and Wegener, A., 1930).

[5] Nordenskjöld, Otto, "Einige Züge der physischen Geographic und der Entwickelungsgeschichte Süd-Grönlands," *Geog. Zeitschr.*, 20 (1914) : 425-441; 505-524; 628-641, pls. 9-10.

[6] Koch, J. P., *Durch die weisse Wüste, Die dänische Forschungsreise quer durch Nordgrönland 1912-13*. Deutsche Ausgabe besorgt von Prof. Dr. Alfred Wegener, 248 pages, 158 text figs., 2 maps. Springer, Berlin, 1919.

[7] De Quervain, A., and Mercanton, P. L., *Ergebnisse der schweizerischen Grönland Expedition*, Denkschr. d. schweiz. Naturf. Gesell., 53 (1920) : xx and 492, Pls. 10.

[8] Mothes, H., "Seismische Dickenmessungen von Gletschereis," *Zeitschr. f. Geophysik*, 3, Heft 4, pp. 121-134.

[9] Koch, J. P., and Wegener, A., "Die glaciologischen Beobachtungen der Dänemark-Expedition," *Med. om Grönl.*, 46 (1912) : 7-16.

[10] Taylor, Griffith, *Brit. Ant. Exped. 1910-13, The Physiography of the McMurdo Sound and Granite Harbour Region*, 1922; map on page 101.

## BIBLIOGRAPHY ON GREENLAND, 1921-31

General Geography, Surveys and Cartography, Geology, Physiography, Glaciology, Aërometeorology


ARNOLD, CHESTER A. 1932. Microfossils from Greenland Coal. Pap. Mich. Acad. Sci., Arts and Letters, 15 : 51-61, 4 pls., 1 text map.

BACKLUND, HELGE G. 1930. Contributions to the Geology of Northeast Greenland. Med. om Grönl., 74 : 209-295; 2 pls., 10 figs.

—— 1931. Über die Lagerungsbedingungen eines Torffundes in N.O. Grönland, *ibid*., 87: 1-25, 3 figs.

BALL, SYDNEY H. 1923. The Mineral Resources of Greenland. Med. om Grönl., 63 : 1-60, 23 figs.

BANGSTED, HELGE. 1928. A Winter Sledging Expedition on the Inland-Ice of Greenland. Sci. Monthly, 26 : 253-256, 1 text map.

BARTLETT, CAPT. ROBT. A., AND BIRD, JUNIUS. 1931. The Bartlett East Greenland Expedition. Geog. Rev., 21 : 398-414, 21 text figs.

BAUR, FRANZ. 1929. Das Klima der bisher erforschten Teile der Arktis. Arktis, 2 : 77-89, 110-120, 2 pls., 7 figs.

Berlin Geographical Society. 1932. Deutsche Grönlandexpedition Alfred Wegener: Gedächtnisfeier fur Alfred Wegener. Zeitschr. d. Gesell. f. Erdkunde zu Berlin, 1932, pp. 83-145. (English review in Geog. Rev., 22 [1932] : 681-683.)

BIRKET-SMITH, K. 1928. Physiography of West Greenland. Greenland, 1 : 423-490, illustrated.

Bobé, Louis. 1928. Early Explorations in Greenland. Greenland, 1 : 1-35.

Böggilt, O. B. 1927. The Meteoric Iron from Savik near Cape York, North Greenland. Med. om Grönl., 74 : 9-30, 6 pls., 5 figs.

—— 1928. The Geology of Greenland. Greenland, 1 : 231-255, illustrated.

BOYD, LOUISE A. 1932. Fiords of East Greenland, a Photographic Reconnaissance throughout the Franz Joseph and King Oscar Fiords. Geog. Rev., 22 : 529-561, 37 figs., 1 map.

(British Exped.) 1931. T he British Arctic Air Route Expedition. Geog. Journ., 76 : 67-68, 426-427; 77 : 551-554, 4 pls.

BROOKS, CHARLES F. 1923. The Ice-Sheet of Central Greenland, A Review of the Work of the Swiss Greenland Expedition. Geog. Rev., 13 : 445-453, 2 figs.

BYRD, RICHARD E., JR. 1925. Flying over the Arctic. Nat. Geog. Mag., 48: 519-532, illustrated.

CALLISEN, KAREN. 1929. Petrographische Untersuchung einiger Gesteine von Nordgrönland. Med. om Grönl., 71 : 217-256, pl. 1, map 1, figs. 1-2.

DEBENHAM, FRANK (Editor). 1931. Greenland. Polar Record, No. 2 : 44-53.

DE QUERVAIN, A., ET MERCANTON, P. L. 1925. Resultats scientifiques de F expedition suisse au Greenland 1912-13. Med. om Grönl., 69 : 55-297, pls., figs.

DRESCHER, F. K., UND KRUEGER, H. K. E. 1927. Der Peridotit von Kaersut (Grönland) und sein Ganggefolge als Beispiel einer Sekretions-differentiation. Neues Jahrb. f. Mineral. Beilage Band 57, Abt. A, pp. 569-616, pls. 7-8, text figs. 1-6.

FOERSTE, AUG. F. 1929. The Ordovician and Silurian of American Arctic and Subarctic Regions. Denison Univ., Bull. Journ. Sci. Lab., 24 : 27-79, pls. 1-2.

FREBOLD, HANS. 1931*a*. Unterer mariner Zechstein in Ostgrönland und das Alter der Depot Island Formation. Med. om Grönl., 84 : 1-38, 2 pls.

—— 1931*b*. Das marine Oberkarbon Ostgrönlands, leitende Fauna, Altersstellung, Paleogeographie. *Ibid*., 84 : 1-88, 7 pls.

—— 1931*c*. Fauna, stratigraphische und paleogeographische Verhältnisse des Ostgrönländischen Zechsteins. *Ibid*., 84 : 1-55, 5 pls.

FRODE, F. 1925. Some Observations Made in North Greenland 1923. Med. om Grönl., 59 : 41-54, pl. 1, 12 figs.

FUCHS, V. E., AND WHITTARD, V. F. 1930. The East Greenland Pack-Ice and the Significance of Its Derived Shells. G eog. Journ., 76 : 419-425, 4 figs.

Geodetic Institut (Denmark). 1928. Bulletin of the Seismological Station, Scoresby Sound, No. 1, pp. 1-21.

Geodetic Institut (Denmark). 1930. The Seismological Stations Köbenhavn and Scoresby Sound, pp. 1-32, pls. 1-9, 20 figs.

Geol. and Geog. Comm. Greenland. 1906-8. Kort over Grönland, Udgivet af Kommissionen for Ledelsen af de Geologiske og Geografiske Undersögelser i Grönland. Scale 1 : 2,000,000.

Geol. and Geog. Comm. Greenland. 1921. Grönland, i tohundredaaret for Hans Egedes Landing, issued by the Commission for the Direction of the Geological and Geographical Investigation in Greenland, under editorial supervision of G. C. Amdrup, Louis Bobé, Ad. S. Jensen and H. P. Steensby. Atlas to volumes 1 and 2 of Grönland. C. A. Reitzel Bookstore, Copenhagen. General and geological maps of Greenland on a scale of about 1 : 10,000,000; 4 historical sectional maps, 13 district and settlement maps on a scale of 1 :1,000,000. The best sectional maps extant. Sold separately, but out of print.

Geol. and Geog. Comm. Greenland. 1926. Kort over Grönland Syd for 75° N. Br., udgivet af Kommissionen for Ledelsen af de Geologiske og Geografiske Undersögelser i Grönland. Map of Greenland south of 75° N. lat., issued by the Commission of the Direction of the Geological and Geographical Investigation in Greenland. Scale 1 : 2,000,000. Inset map of all Greenland on a scale of 1 : 6,900,000. Copenhagen.

GEORGI, J. 1928. Aerologie der hohen Breiten und Grosse Zirkulation. Arktis, 1: 83-96,

HALLE, T. G. 1931. Younger Paleozoic Plants from East Greenland Collected by the Danish Expeditions 1929 and 1930. Med. om Grönl., 85 : 1-26, 6 pls.

HANSEN, H. 1922. *See* Mikkejsen, Ejnar.

HARRIS, T. M. 1926. The Rhaetic Flora of Scoresby Sound, East Greenland. Med. om Grönl., 68: 43-147, 13 pls., 34 figs.

HARRIS, T. M. 1931. The Fossil Flora of Scoresby Sound, East Greenland. Med. om Grönl., 85 : 104, 18 pls.

HARSHBERGER, JOHN W. 1924. The Gardens of the Faroes, Iceland and Greenland. Geog. Rev., 14 : 404-415.

HEINZ, ANATOL. 1930. Oberdevonische Fischreste aus Ost-Grönland, Norges Svalbard-og Ishavs-Undersögelser, Oslo, No. 30 : 31-46, pls.

HOBBS, W. H. 1926. The Glacial Anticyclones, the Poles of the Atmospheric Circulation, with an Introduction by Hugh Robert Mill. 198 pages, 1 colored pl., 3 pls., 53 text figs. University of Michigan.

—— 1927*a*. The First Greenland Expedition of the University of Michigan-Geog. Rev., 17 : 1-35, 33 text figs.

—— 1927*b*. The Second Greenland Expedition of the University of Michigan. Nature (Dec. 24, 1927), pp. 920-922.

—— 1928. The Aërological Weather Station on Mount Evans in Southwestern Greenland. Pet. Mitt., Ergänzungsheft 201, pp. 34-36, pls. 3-4.

—— 1929*a*. The Greenland Flying Route to Europe. Bull. Am. Meteorol. Soc., 10 : 34-36.

—— 1929b. The Northern Flying Route to Europe. Aero Digest, Sept., pp. 66-67, 290, 292, figs. 1-5.

—— 1930. Exploring about the North Pole of the Winds. 376 pages, illustrated, maps. Putnam's Sons, New York.

—— 1931*a*. Loess, Pebble Bands, and Boulders from Glacial Outwash of the Greenland Continental Glacier. Journ. Geol., 39 : 381-385, text figs. 1-3.

—— 1931*b*. Director, Reports of the Greenland Expeditions of the University of Michigan (1926-31), Part I, Aërology, Expeditions of 1926 and 1927-29, S. P. Fergusson, Editor. 259 pages, 23 pls., 30 text figs. University of Michigan Press.

—— 1931*c*. Investigations in Aërological and Other Research in Greenland. Carnegie Institution Year Book, No. 30 (1930-31): 429.

HÖYGAARD, ARNE, UND MEHREN, MARTIN. 1931. "Ajungilak," eller Grönland på Tvers. Oslo, 151 pages, illustrated.

HOLTEDAHL, OTTO. 1930. Geologische Karte der Arktis mit angrenzenden Gebieten. Arktis, 3: 49-60, pl. 4, 4 figs. Colored geological map of the Arctic, including Greenland.

HOVEY, EDMUND OTIS. 1924. Geology of Northwest Greenland and Its Relation to the Flora, Fauna and People of the Region. Am. Journ. Sci., 8: 189-200.

HOVGAARD, WILLIAM. 1925. The Norsemen in Greenland. Recent Discoveries at Herjolfsnes. Geog. Rev., 15 : 605-616, 5 figs.

HUTCHINSON, ISOBEL W. 1930. Flowers and Farming in Greenland. Scot. Geog. Mag., 46 : 214-230, 6 figs.

JENSEN, A. S. 1928. The Fauna of Greenland. Greenland, 1 : 319-355.

JOERG, W. L. G. 1930*a*. Physical Map of the Arctic. Scale 1 : 20,000,000. Am. Geog. Soc., Spec. Publ. No. 11, 50 pages, 8 text maps. Issued in cover, with a Bathymetric Map of the Antarctic on the same scale and accompanied by a brief history of polar exploration since the introduction of flying.

—— 1930*b*. Second revised edition, pp. 1-95, 9 text figs.

KAYSER, O. 1928. The Inland Ice. Greenland, 1 : 357-422, 21 figs.

KIMBALL, H. H. 1931. Solar Radiation Intensities within the Arctic Circle. Month. Weather Rev., 59 : 154-157. Mount Evans, Greenland, observations on page 156.

KLUTE, FRITZ. 1925. See Krueger, H. K. E.

KNUDSON, MARTIN. 1923. Dr. Thorild Wulff's Hydrographical Investigations in the Waters West of Greenland. Med. om Grönl., 64: 89-100, 1 pl., 1 text map.

KOCH, J. P. 1919. Durch die weisse Wüste, Die dänische Forschungsreise quer durch Nordgrönland 1912-13. Deutsche Ausgabe besorgt von Prof. Dr. Alfred Wegener. 248 pages, 158 text figs., 2 maps. Springer, Berlin.

—— UND WEGENER, A. 1930. Wissenschaftliche Ergebnisse der dänischen Expedition nach Dronning Louises-land und quer über das Inlandeis von Nordgrönland 1912-13 unter Leitung von Hauptmann J. P. Koch. Med. om Grönl., 75 (two parts) : 676, 1 portrait, 4 pls., 3 stereoscopic views, 149 and 240 text figs.

KOCH, LAUGE. 1922. Note to Maps of Melville Bay from Wilcox Point to Cape York and of North Greenland from 81°-83° 55' N., 38°-56° W. Med. om Grönl., 64: 79-88, 2 maps on a scale of 1: 500,000.

—— 1923*a*. Preliminary Report on the Geology of Peary Land, Arctic Greenland. Am. Journ. Sci., Fifth Ser., 5 : 189-199, 2 maps.

—— 1923*b*. Some New Features in the Physiography and Geology of Greenland. Journ. Geol., 31 : 42-65, 8 text figs.

—— 1924. On the Physiography of the Interior of Greenland. Geog. Rev., 14: 175-176.

—— 1925*a*. The Question of Peary Channel. Geog. Rev., 15 : 643-649, sketch maps.

—— 1925*b*. The Geology of North Greenland, Am. Journ. Sci., Fifth Ser., 9 : 271-285, figs. 1-5 (maps).

—— 1926*a*. A New Fault Zone in Northwest Greenland. *Ibid*., 12 : 301-310, figs. 1-2 (maps).

KOCH, LAUGE. 1926*b*. Ice Cap and Sea Ice in North Greenland. Geog. Rev., 16 : 98-107, 2 figs.

—— 1927. Report on the Danish Bicentenary Jubilee Expedition North of Greenland 1920-23. Med. om Grönl., 70 : 1-232, 13 pls., 106 text figs.

—— 1928*a*. Physiography of North Greenland. Greenland, 1 : 491-518, 13 figs.

—— 1928*b*. Contributions to the Glaciology of North Greenland. Med. om Grönl., 65 : 181-464, 6 pls., 140 text figs.

—— 1928*c*. Two Recent Journeys on the Coast of Eastern Greenland. Geog. Journ., 71 : 1-15, 1 map, 16 illustrations.

—— 1929*a*. The Geology of the South Coast of Washington Land. Med. om Grönl., 73 : 1-39, pl. 3, 15 text figs.

—— 1929*b*. The Geology of East Greenland. *Ibid*., 73 : 1-204, 6 pls., 53 text figs.

—— 1929*c*. Stratigraphy of Greenland. *Ibid*., 73 : 205-320, 1 pl., 8 text figs.

—— 1930*a*. Preliminary Report on the Danish Expedition to East Greenland in 1929. *Ibid*., 74 : 175-205, 3 pls., 30 figs.

—— 1930*b*. Remarks on the Map of Dusén Fiord. *Ibid*., pp. 383-394, 1 fig.

KOELZ, WALTER N. 1926. A Naturalist with MacMillan in the Arctic. Nat. Geog. Mag., 49 : 299-318, illustrated.

KRABBE, TH. N. 1930. Greenland, Its Nature, Inhabitants and History (4$^{to}$). 129 pages, 170 pls., 50 portraits, 1 map. Levin & Munksgaard, Copenhagen, and Humphrey Milford, Oxford University Press.

KRUEGER, H. K. E. 1927. Über eine sogenannte Basaltbreccie in der Kreide-Tertiar-Formation von Westgrönland. Notizbl. d. Vereins f. Erdkunde und d. hess. geolog. Landesanst. z. Darmstadt f. d. Jahr. 1927, 5 Folge, 10 Heft, pp. 270-281, figs. 1-3.

—— 1927. *See* Drescher, F. K.

—— 1928. Zur Geologic von Westgrönland, besonders der Umgebung der Diskobucht und des Umanak-fjordes. Med. om Grönl., 74 : 97-136, 1 map, 10 text figs.

—— 1929. Neuere geologische Forschungen in der Arktis. Notizbl. d. Vereins f. Erdkunde und d. hess. geolog. Landesanst. z. Darmstadt f. d. Jahr. 1927, 5 Folge, 10 Heft, pp. 282-291.

—— 1929. Recent Geological Research in the Arctic. Am, Journ. Sci., Fifth Ser., 17 : 50-62.

—— 1929*b*. Gesteinskörper und Inlandeis Grönlands in ihrer gegenseitigen Beziehung und Auswirkung. Zeitschr. f. Gletscherk., 17: 1-32, 1 map, 15 figs.

——— und Klute, Fritz. 1925. Die hessische Grönlandexpedition 1925. Pet. Mitt. (1926), pp. 105-111, pl. 8.

Kulling, Oskar. 1930. Stratigraphic Studies of the Geology of Northeast Greenland. Med. om. Grönl., 74 : 317-346.

Laub, Vilhelm. 1922. *See* Mikkelsen, Ejnar.

Longstaff, T. G. 1929. The Oxford University Expedition to Greenland, 1928. Geog. Journ., 74 : 61-69, 5 half-tone illustrations, 2 maps in text.

Martens, James H. C. 1929. The Mineral Composition of some Sands from Quebec, Labrador, and Greenland; Results of the Rawson-MacMillan Sub-Arctic Expedition of 1926, Publ. 260 (Geol. Ser., Vol. 5, No. 2), pp. 15-30, pls. 7-9. Field Mus. Nat. Hist.

Mecking, Ludwig. 1928. The Geography of the Polar Regions. Am. Geog. Soc., Spec. Publ. 8 (Greenland), pp. 233-279, figs. 73-92.

Meinardus, W. 1926. Die hypsographischen Kurven Grönlands und der Antarktis und die Normalform der Inlandeisoberfläche. Pet. Mitt., 72: 97-105.

Mercanton, P. L. 1925. *See* De Quervain, A.

Mikkelsen, Ejnar. 1922. Alabama-Expeditionen til Grönlands Nordöstkyst 1909-12 under Ledelse af Ejnar Mikkelsen ("Alabama Expedition to the Greenland Northeast Coast under Leadership of Ejnar Mikkelsen"), with articles by Vilhelm Laub und H. Hansen (meteorology). Text in English, Med. om Grönl., 52 : 1-295, 8 pls., 95 figs.

—— 1927. The Colonization of Eastern Greenland, Eskimo Settlement on Scoresby Sound. Geog. Rev., 17: 207-225, 18 figs.

Nielsen, J. N. 1928. The Waters round Greenland. Greenland, 1 : 185-230, 12 figs.

Nissen, N. W. 1924. Die südwestgrönländische Landschaft und das Siedlungsgebiet der Normannen, Abh. aus dem Gebiet der Auslandskunde. 112 pages, maps. University of Hamburg.

Nörlund, N. E. 1930. Rapport sur les travaux géodésiques executés de 1927 à 1930 (presenté à la quatrième assemblée générale de l'Union Géodesique et Géophysique Internationale tenue à Stockholm en août, 1930), pp. 1-21, pls. 1-13. (Iceland and Greenland.) Imp. Bianco Luno, Copenhagen.

Ödum, Hilmar. 1927. Geologiske lagttagelser i Landet Öst for Igaliko Fjord. Med. om Grönl., 74: 45-54, pl. 7, 7 figs.

Orvin, Anders K. 1930. Ekspedisjonen til Östgrönland med "Veslekari" sommeren 1929. Norsk Geog. Tideskrift, 3 : 89-146. Review in English by E. Antevs, Geog. Rev., 21 (1931) : 498-499.

—— 1930. Beiträge zur Kenntnis des Oberdevons Ost-Grönlands. Norges Svalbard- og Ishavs-Undersögelser, No. 30, pp. 1-28, 5 figs.

Parkinson, M. M. L., and Whittard, W. F. 1931. The Geological Work of the Cambridge Expedition to East Greenland in 1929. Quart. Journ. Geol. Soc. London, 87: 650-674, pls. 53-60, 2 figs.

Paulsen, Chr. 1927. The Cambrian, Ozarkian and Canadian Faunas of Northwest Greenland. Med. om Grönl., 70:233-343, pls. 14-21, 10 text figs.

—— 1930. Contributions to the Stratigraphy of the Cambro-Ordovician of East Greenland. *Ibid*., 74 : 299-316, figs. 15-21b.

Pedersen, Alwin. 1930. Der Scoresby Sund. 157 pages. Map with original data and 56 half-tone illustrations. August Scherl, Berlin.

Petersen, H. 1928. The Climate of Greenland. Greenland, 1 : 257-276, 6 figs.

Prince de Monaco Cabinet Scientifique de S. A. S. le Prince de Monaco, Carte générale bathymétrique des oceans. Feuille. 1er Nov., 1930.

Rasmussen, Knud. 1921. Greenland by the Polar Sea, The Story of the Thule Expedition from Melville Bay to Cape Morris Jesup, with Preface by Admiral Sir Lewis Beaumont. Transl. from Danish by Astra and Rowland Kenney. 327 pages, 8 color plates, many illustrations and maps. London.

—— 1925. The Danish Ethnographic and Geographic Expedition to Arctic America, Preliminary Report of the Fifth Thule Expedition. Geog. Rev., 15 : 521-562, 1 map, 24 figs.

—— 1927. Report on the Second Thule Expedition for the Exploration of Greenland and from Melville Bay to De Long Fjord 1916-1918. Med. om Grönl., 65 : 1-180, illustrations, 1 map.

Reisinger, Erich, og Steinböck, Otto. 1927. Forelöbig Meddelelser om vor Zoologiske Reise i Grönland 1926. Med. om Grönl., 74 : 35-42.

Rosenkrantz, Alfred. 1930. Summary of Investigations of Younger Paleozoic and Mesozoic Strata along the East Coast of Greenland in 1929. Med. om Grönl., 74 : 349-364, figs. 22-25.

Schneider, Leonard R. 1930. Greenland West Coast Foehns of January, 1929. Month. Weather Rev., 58 : 135-138, 7 figs.

—— 1931. Observing the Weather at Mount Evans, Greenland. *Ibid*., 59: 118-120.

Schultz-Lorentzen. 1927. Dictionary of the West Greenland Eskimo Language. Med. om Grönl., 69 : 1-303.

Seidenfaden, Gunnar. 1931*a*. Moving Soil and Vegetation in East Greenland. Med. om Grönl., 87:1-21.

—— 1931*b*. Notes on a Map of East Greenland from 73° 00' to 74° 50' N. Lat. *Ibid*., 1-29, 1 map, 2 pls. 3 figs.

Seward, A. C. 1922. A Summer in Greenland. 100 pages, illustrated. Camb. Univ. Press.

—— 1927. The Cretaceous Plant-bearing Rocks of Western Greenland. Phil. Trans. Roy. Soc. London, 215, 13 : 57-176, pls. 4-12, 2 maps, 35 figs., bibliography.

Sorge, Ernst. 1930. Die ersten Dickenmessungen des grönländischen Inlandeises, Zeitschr. f. Geophysik, 6 : 22-31, text figs. 1-4.

Spath, L. F. 1927. Eotriassic Ammonites from East Greenland. Geol. Mag., 64: 474-475.

—— 1930. The Eotriassic Invertebrate Fauna of East Greenland. Med. Om Grönl., 83: 88, 12 pls.

STEFANSSON, V. 1922. Some Erroneous Ideas of Arctic Geography. Geog. Rev., 12 : 264-277.

STEINBÖCK, OTTO. 1927. *See* Reisinger, Erich.

STEWART, DUNCAN, JR. 1930. Analyses and Derivations of Two Beach Sands from the Holsteinsborg District of Greenland. Am. Mineral., 15:74-77, pl. 1.

STORGAARD, E. 1928. Physiography of East Greenland. Greenland, 1 : 519-575, 31 figs.

TRAP, F. H. 1828. The Cartography of Greenland. Greenland, 1 :137-179, 23 figs.

TROEDSSON, G. 1926. On the Middle and Upper Ordovician Faunas of Northern Greenland. I. Cephalopods. Med. om Grönl., 71: 1-157, 56 pls., 17 figs.

VAHL, M. 1928. The Geographical Situation of Greenland. Greenland, 1:181-184, 7 figs.

—— 1929. Map of Greenland on Equivalent Azimuthal Projection with Place Names in English. Scale 1: 4,000,000. Reitzel, Copenhagen.

WAGER, L. R. 1932. Preliminary Account of the Geological Work (of Brit. Exped., 1930-1931). Geog. Journ., 79 : 483-488.

WANDEL, C. F. 1828. Scientific Investigations in Greenland. Greenland, 1: 37-136.

WATKINS, H. G. 1932. The British Arctic Air Route Expedition. Geog. Journ., 69 : 353-367, 8 pls., 1 fig., 2 maps.

—— 1932*b*. *Ibid*., 79: 353-367, 466-501; 80: 1-30.

WEGENER, A. 1930*a*. Deutsche Inlandeis Expedition nach Grönland, Sommer, 1929. Vorläufige Berichte über die Ergebnisse. Zeitschr. d. Gesell. f. Erdkunde zu Berlin, Nr. 3-4, pp. 81-124, 1 text map, 5 text figs., pls. iii-vi.

—— 1930*b*. Mit Motorboat und Schlitten in Grönland. 192 pages, illustrated. Velhagen und Klasing, Leipzig.

WEGENER, ELSE (editor, assisted by Dr. Fritz Loewe). 1932. Alfred Wegeners letzte Grönlandfahrt: Die Ergebnisse der deutschen Grönland-expedition 1930-1931, geschildert von seinen Reisegefährten und nach Tagebüchern des Forschers. Leipzig, 304 pp., 3 pls., 11 maps, 122 text figs. (English review in Geog. Rev., 22 [1932]: 681-683.)

(Wegener Exped.) 1930. Deutsche Inlandeis-Expedition nach Grönland Sommer 1929. Vorläufige Berichte über die Ergebnisse. Zeitschr. d. Gesell. f. Erdkunde zu Berlin, 1930, pp. 81-124, pls. 3-6, figs. 22-27.

—— 1919-1930. *See* Koch, J. P.

WEGENER, KURT, AND OTHERS. 1932. Deutsche Grönland-Expedition Alfred Wegener. Zeitschr. d. Gesell. f. Erdkunde zu Berlin, pp. 83-145.

WHITTARD, W. F. 1930. *See* Fuchs, V. E.

—— 1930. *See* Wordie, J. M.

—— AND PARKINSON, M. M. L. 1931. The Geological Work of the Cambridge Expedition to East Greenland in 1929. Quart. Journ. Geol. Soc. London, 87: 650-674, pls. 53-60, figs. 1-2.

WORDIE, J. M. 1927. The Cambridge Expedition to East Greenland in 1926. Geog. Journ., 70: 225-265, 1 map, 12 half-tone illustrations, 5 text figs.

—— 1930*a*. Cambridge East Greenland Expedition, 1929 : Ascent, of Petermann Peak. With Appendices by R. C. Wakefield, W. F. Whittard, and G. Manley. Geog. Journ., 75 : 481-504, 1 map, 8 half-tone illustrations, 1 text fig.

—— AND WHITTARD, W. F. 1930*b*. A Contribution to the Geology of the Country between Petermann Peak and Kjerulf Fjord, East Greenland. Geol. Mag., 67: 145-158, pls. 8-10, 5 text figs.

# GEOLOGIC STRUCTURE OF A SMALL AREA WEST OF MILL SPRINGS, KENTUCKY*

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## INTRODUCTION

THIS paper describes the geological structure of the rocks in a small area in Wayne, Pulaski, and Russell counties a few miles west of Mill Springs, Wayne County, Kentucky. The area, which is shown in the north-central part of the Monticello topographic sheet of the United States Geological Survey, is rectangular. Its length in a north-south direction is about 6 miles and its width about 3½ miles (see Map 51).

The study of the structural geology of the area was suggested to the writers by Professor G. M. Ehlers of the Department of Geology of the University of Michigan, to whom they are greatly indebted for aid in planning the field work and in preparing the manuscript of this paper. They are also under obligation to Mr. Robert Hefferan, a student at the University of Michigan, for assistance in the field.

## PHYSIOGRAPHY OF AREA

The area is in the Highland Rim section of the Interior Low Plateaus. The major topographic features are the result of erosion and deposition by the Cumberland River during past and present geologic times. Three distinct topographic levels have resulted from the work of this river. The lowest is represented by a river flat, the "river bottom" of the local residents, the average elevation of which is about 640 feet above sea level. In summer the Cumberland River is usually about 50 feet lower than the river flat; in the winter season it often covers the flat. A higher topographic level, the Highland Rim Plateau, has an elevation of from 900 to 950 feet. This level was produced by planation of the river during late Tertiary or early Pleistocene time. The surface of the plateau is modified by sink holes, which are very numerous in the southeastern part of the area, and by stream erosion, which has been especially active north of the river. The highest topographic level is the

Cumberland Plateau, the average elevation of which is about 1,300 feet in adjacent areas.

A small outlier of this plateau, the summit of which has been lowered by erosion to an elevation of 1,100 feet, is close to the eastern boundary of the area about 1¾ miles northeast of Rankin (see Map 51).

## STRATIGRAPHY OF AREA

The area is on the southeast limb of a saddle connecting the Jessamine and Nashville domes of the Cincinnati Geanticline. Owing to its position on the southeast side of the saddle, the regional dip is to the southeast. Except where local reversals of dip occur, successively younger beds are encountered as one proceeds southeastward across the area.

Rocks of Mississippian age compose most of the stratigraphic section, but older beds of Ordovician and Silurian age outcrop at Shinbone Cliff and at many places in the tributary streams on the north side of the Cumberland River.

### *Description of formations*

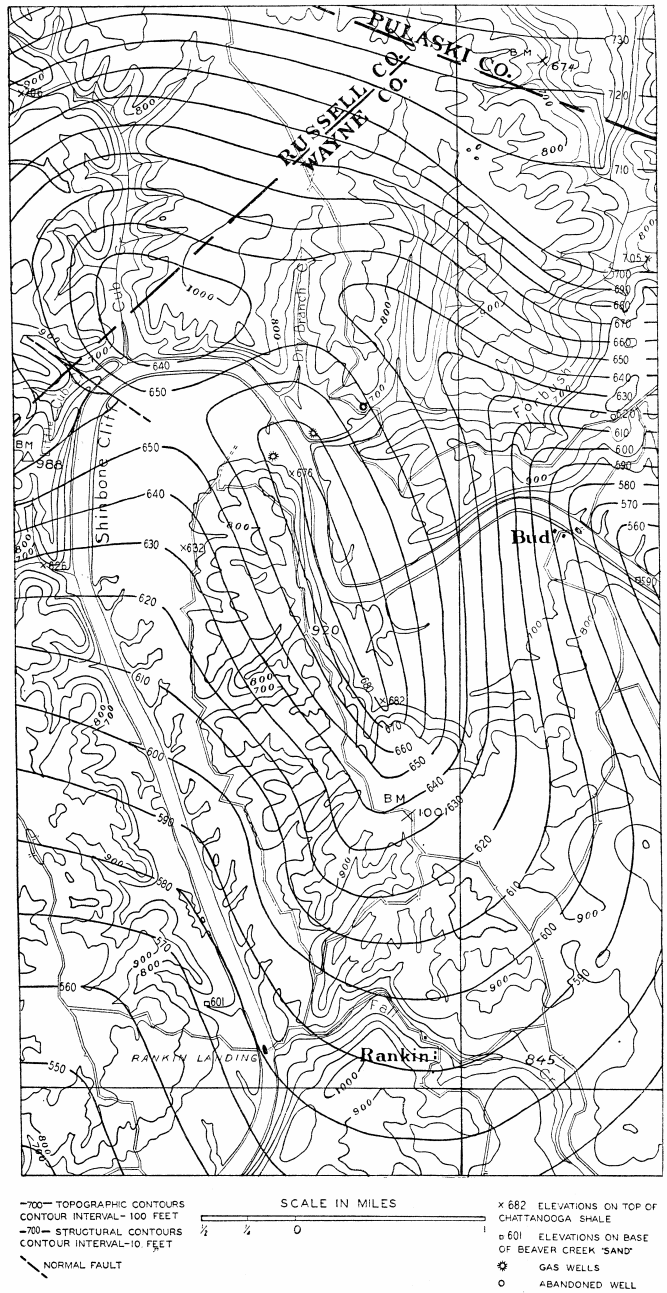
*Richmond formation*. — The Richmond formation, which is included in the Ordovician system by most geologists and in the Silurian system by a few, is the oldest formation exposed. It outcrops at Shinbone Cliff, in Little Cub Creek, and in Forbush Creek. The lower half consists of a thin and even-bedded, ripple-marked and sun-cracked, greenish gray limestone; the upper part, of uneven and thicker-bedded buff-gray limestone, which has a nodular appearance on weathered surfaces. According to Donald C. MacLachlan,[1] 46 feet of Richmond is exposed at Shinbone Cliff.

*Brassfield formation*. — The Brassfield formation of lower Silurian age rests disconformably upon the Richmond. It is a massive buff to reddish gray magnesian-limestone, containing fluted cystid columnals. At Shinbone CM it is approximately 10 feet thick. Good exposures occur along Forbush Creek and some of its tributaries.

*Crab Orchard formation*. — The Crab Orchard formation of middle Silurian age rests disconformably on the Brassfield. It consists of interbedded greenish shale and greenish gray to buff limestone. Dr. Foerste[2] noted the occurrence of 17 feet at Shinbone Cliff. A small exposure is also in the bank of Cub Creek about 200 feet upstream from the Wayne-Russell county line.

During pre-Mississippian time the Richmond, Brassfield, and Crab Orchard formations were subjected to erosion. The Brassfield and Crab Orchard were entirely removed from some parts of the area, so that the Mississippian beds were deposited unconformably on the Richmond.

*Chattanooga formation*. — The Chattanooga shale is the oldest Mississippian deposit in the area. It is a well-jointed, black, fissile, bituminous shale containing linguloid brachiopods and conodonts (see Pl. XXXIX, Fig. 1). A brown sandstone, 1 to 2 inches in thickness, commonly lies at the base of the formation. At a few places this sandstone has a thickness of 3 feet. At some localities the upper beds of the formation contain nodules of marcasite. A small number of cherts occur near the base along Little Cub Creek. The formation ranges in thickness from 33 to 38 feet.




MAP 51. Topography and geologic structure of top of Chattanooga shale

*New Providence formation*. — The New Providence formation, which rests disconformably on the Chattanooga shale, is composed of three distinct parts. The lower part consists of a greenish gray to bluish gray shale, which weathers to a greenish gray clay (see Pl. XXXIX, Fig. 2). The basal beds of the shale contain phosphate nodules, which in some places are very numerous. The middle part of the formation is a hard, siliceous, encrinal limestone, containing irregularly shaped masses of chert arranged parallel to the bedding. This limestone, known locally as the "Beaver Creek sand," is an oil- and gas-producing stratum in the Monticello-Steubenville pool a few miles southeast of the area. The upper part of the New Providence, which is lithologically similar to the lower, differs from it in being more calcareous. The thickness of the lower New Providence ranges from 23 to 50 feet; of the middle, from 3 to 7 feet; and of the upper, from 35 to 50 feet.

Overlying the New Providence in the order named are the Fort Payne, Warsaw, St. Louis, Ste. Genevieve, and Gasper formations of Mississippian age. The Pennsylvanian is represented by the Lee sandstone, which caps the tops of several outliers of the Cumberland Plateau a short distance southeast of the area. River gravels, thought to belong to the Irvine formation of late Pliocene or early Pleistocene age, occur in patches on the Highland Rim Plateau. The alluvium of the river flat may be in part of later Pleistocene as well as post-Pleistocene age.

## FIELD METHODS USED IN DETERMINING STRUCTURE OF AREA

The top of the Chattanooga shale was selected as a key horizon for mapping the structure of the area. This selection was made because the shale was very little eroded prior to the deposition of the overlying New Providence shale and is lithologically distinct from overlying and underlying strata.

The elevations of the top of the Chattanooga shale and their locations were determined by the use of a telescopic alidade and plane-table.

The approximate elevation of the top of the Chattanooga shale was obtained at many places by first determining the elevation of the base of this shale or of the base of the Beaver Creek limestone. When the elevation of the base of the Chattanooga shale was used, the thickness of the shale, which ranges from 33 to 38 feet, was added to it. When the elevation of the base of the Beaver Creek limestone was used, the interval between this limestone and the top of the Chattanooga shale was subtracted from the elevation of the base of the Beaver Creek limestone in order to obtain the elevation of the top of the Chattanooga shale. Owing to a considerable range in the thickness of the interval between the Beaver Creek limestone and the Chattanooga shale, it was necessary to make frequent measurements of this interval.

## STRUCTURAL GEOLOGY OF THE AREA

The most prominent structural feature is an elongated dome located in the central part of the area (see Map 51). It has a narrow crest which extends N. 25° W. for a distance of about 1½ miles. The elevation of the highest point along the crest is about 685 feet. The closure of the dome is from 25 to 30 feet. The dome is slightly asymmetrical; the dip per mile on the east side is about 90 feet; on the west side, about 80 feet. The crest of the dome plunges to the southeast at a rate of about 80 feet per mile for the first quarter of a mile, decreasing gradually to 25 feet per mile near the southern boundary of the area. The southeast end is modified by a structural nose which curves to the southwest and disappears in the syncline on the west side of the dome. At its northwest end the dome dips northward at a rate of 50 feet per mile for a quarter of a mile and then flattens out abruptly into a structural saddle connecting the dome with a homocline occupying the northern quarter of the area. The elevation of the lowest point along the crest of this saddle is about 643 feet above sea level.

In 1927 MacLachlan[3] published a map on which he showed the dome as having a lower and flatter crest than the findings of the present writers would indicate; he also represented the elongation of the dome as extending in a north-south direction instead of in a northwest-southeast direction, as determined by the writers. The difference in the form and orientation of the dome as illustrated on MacLachlan's and the writers' maps is due to different methods of determining elevations of the top of the Chattanooga shale. MacLachlan obtained these elevations by reference to elevations given on the Monticello topographic sheet. Careful observations by the writers have demonstrated that numerous elevations on this sheet are incorrect; apparently many of the contours were plotted without an adequate number of readings. The fact that the present writers based their mapping on a larger number of more accurately determined elevations of the top of the Chattanooga shale is ample reason for believing that the morphology of the dome as shown on Map 51 is correct. In the northeastern part of the area the homocline is modified by a structural terrace, the southern margin of which is at an elevation of 700 feet. Below this margin of the terrace the inclination of the top of the Chattanooga shale is 105 feet per mile. This rather steeply inclined surface forms the northeast limb of a pitching syncline which lies to the east of the dome. North of the margin of the terrace the surface of the structure rises gradually at a rate of about 25 feet per mile to the northern boundary of the area, where the elevation is a little more than 730 feet, the highest structural elevation in it.

In the north-central and northwestern parts of the area the amount of inclination of the homocline is fairly uniform.

The syncline south of the terrace previously mentioned, and northeast of the dome, pitches S. 45° E. A similar pitch for this syncline is shown on the map published by MacLachlan.

A quaquaversal syncline having a slight east-west elongation occurs northwest of the dome. The elevation of the bottom is between 630 and 635 feet. The only closed contour within the syncline represents an elevation of 640 feet.

The writers' representation of this structure differs from that of MacLachlan, whose map shows the syncline as opening to the south, with the 640-foot contour not closed, but curving southward around the dome and partly around a faulted anticline to the southwest. A saddle to the south of the syncline is indicated on his map by a constriction of the 640-foot contour line opposite the southeastern extension of the fault. The absence of outcrops which might give information relative to the elevation of the top of the Chattanooga shale precludes the possibility of determining from direct observation the exact nature of the structure. A factor which has a bearing on the position and the height of the saddle south of the syncline is the orientation of the faulted anticline. The plane of the fault follows the crest of the anticline at Shinbone Cliff. It is possible, therefore, to obtain the direction of the trend of the anticline from the strike of the fault. MacLachlan[4] states that the strike of the fault is N. 22° W. If this were true, the anticline would pitch into a broad syncline west of the dome, and hence the saddle southeast of the anticline very probably would be low. The supposed lowness of the saddle, therefore, led MacLachlan to believe that the 640-foot contour was not closed. The writers plotted the fault and found its strike to be N. 55° W. The trend of the anticline, which coincides with this strike toward the northwest end of the dome, and the nearness of the dome very strongly indicate that the top of the saddle is higher than 640 feet. The height of the saddle leads the writers to close the 640-foot contour north of the saddle, thus accentuating the quaquaversal nature of the syncline to the north.

The fault at Shinbone Cliff is a normal one, with a displacement of 15½ feet measured on the base of the Brassfield. The dip of the fault plane, which is easily recognized by a thin band of gouge, is 89° to the northeast; the strike of the fault is N. 55° W.

A considerable drag of the Richmond, Brassfield, and Chattanooga strata occurs on the northeast or downthrown side of the fault. The 22-degree dip of the Brassfield strata near the fault decreases very rapidly toward the northeast and at a distance of about 150 feet from the fault is only 5 or 6 degrees.

On the southwest or upthrown side of the fault the beds are nearly horizontal for the first 5 feet beyond the fault; at a distance of 15 feet beyond the fault they dip 6° S. 75° W.

A few hundred yards southwest of the fault the dip of the strata changes to a northeast direction. This is well shown on the face of Shinbone Cliff and in Little Cub Creek. The Chattanooga shale does not have so great a dip as the underlying Brassfield and Richmond; it rests on the thin, even-bedded limestone of the lower part of the Richmond a few hundred yards southwest of the fault.

The reversal in dip noted above and the determination of certain elevations of the top of the Chattanooga shale indicate the presence of a nose at the western margin of the area to the southwest of the faulted anticline.

South of the saddle connecting the faulted anticline with the dome is a broad syncline, which flattens out to the south.

It is quite likely that the folding of the Chattanooga shale in the entire area took place during the interval between the cessation of deposition of this shale and the beginning of deposition of the New Providence sediments. This is indicated by the thinning of the lower part of the New Providence over the higher structural elevations of the top of the Chattanooga shale. The rather striking uniformity in thickness of the Chattanooga formation over the entire area suggests that there was very little erosion during the interval prior to the deposition of the New Providence.

## POSSIBILITIES FOR OIL AND GAS IN AREA

Three wells have been drilled near the north end of the dome. Two produced gas; the third was abandoned at shallow depth. A short distance north of Forbush Creek one of the gas wells, before it became flooded with water, supplied the farmhouse of Mr. W. L. Scott with gas fuel for three or four years. The second well, which is about a quarter of a mile southwest of the first well, was drilled to a depth of 1,100 feet, but was permitted to become flooded as the result of improper casing.

So far as can be learned, four gas "sands" were encountered in these wells. According to the driller of the second gas well, the sands consist of porous zones within limestones. They probably occur in the Lexington or so-called Trenton group.

It is very likely that producing gas and oil wells may be drilled on the dome and possibly on the structural terrace.

Unfortunately, the number of wells drilled is insufficient to indicate the structure of the producing sands. However, intelligent drilling, based on the structure of the Chattanooga shale, will eventually make it possible to determine the nature of the subsurface structure.

FLINT, MICHIGAN

* A contribution from the Geological and Geographical Field Station of the University of Michigan at Mill Springs, Kentucky.

[1] MacLachlan, D. C., "Geologic Structure of a Small Area in Wayne, Pulaski and Russell Counties, Kentucky," *Pap. Mich. Acad. Sci., Arts and Letters*, 8 (1927) : 300.

[2] Foerste, Aug. F., "The Cincinnati Anticline in Southern Kentucky," *The American Geologist*, 30 (1902) : 362; idem, "The Silurian, Devonian, and Irvine Formations of East-Central Kentucky," *Kentucky Geol. Surv.*, Bull. 7 (1906): 114-115.

[3] *Op. cit*., Figure 24.

[4] *Op. cit*., p. 306.

PLATE XXXIX

FIG. 1. Typical exposure of Chattanooga shale, about one hundred feet north of house of Mr. W. L. Scott, located one-quarter mile north of mouth of Forbush Creek

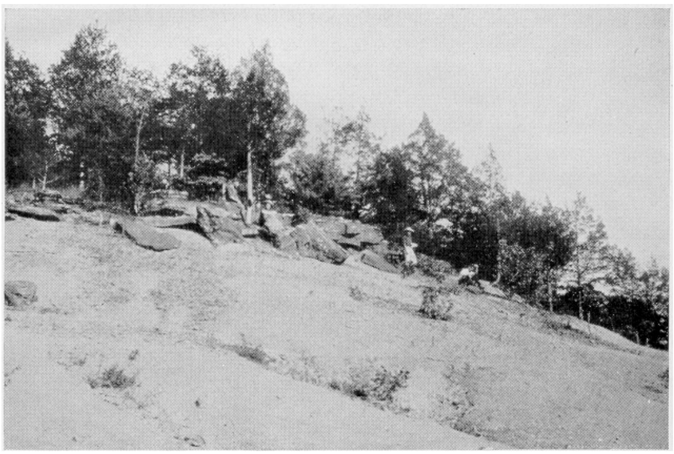


FIG. 2. Weathered shale of lower part of New Providence, shown on hillside about one-quarter mile east of mouth of Forbush Creek. Beaver Creek limestone is shown at top of shale; white irregular-shaped bands on surface of limestone represent chert

# A NOTE ON THE STRATIGRAPHY OF THE BRUNSWICK FORMATION (NEWARK) IN PENNSYLVANIA

DEAN B. McLAUGHLIN

THE difficulty of recognizing individual beds in the Newark Series is traditional. Such statements as "The absence of easily recognizable strata . . . unfortunately renders it difficult to determine the structure of the region"[1] are of frequent occurrence in the literature. Most investigators of the Newark rocks have cautiously qualified their determinations of thicknesses of the formations by stating that the probable existence of undiscovered faults and the uncertainty of the displacement of known ones render all computations of thickness unreliable.

The continuity of the large formations along the strike has been recognized for many years, but the extent of individual beds appears to have received scant attention. Statements by Lyman[2] appear to indicate, though not perfectly clearly, that he believed that relatively thin beds could be recognized at localities some miles apart along the strike, although we shall see in the discussion which follows that he did not successfully identify definite horizons at different localities. Stose[3] states that in the Gettysburg area "individual beds and aggregates of beds maintain the same character for many miles along their strike. . . ." A very definite statement is made also by Darton and Kummel[4] in regard to the Lockatong formation on the Hunterdon plateau of western New Jersey: "Hard dark-red flags are interbedded with the black argillite and some of the more prominent beds can be easily traced for several miles along the strike. This has been done in so many cases at different horizons as to render it almost certain that this belt is not traversed by oblique faults of any magnitude."

Most investigators of the Newark rocks of Pennsylvania have mentioned the occurrence of dark shales interbedded with the red shales of the Brunswick formation, but the tendency has been to pass them by as of no consequence, and to regard them as thin lenticular bodies of trivial extent. This appears to be the view taken in the most recent publication[5] dealing with the same area as that studied by the writer. The statements by Stose and by Darton and Kümmel just quoted are the only indications that continuity of thin strata for some miles has been recognized anywhere in the New York-Virginia area of the Triassic. Hawkins[6] refers to "beds of passage" (interbedded red and black shales) at the transition from the Lockatong formation to the overlying Brunswick, but does not indicate that they are anything other than thin lenses of very limited extent.

The present paper reports results of a preliminary study of the black shales in the portion, of the Brunswick formation below the Haycock diabase sheet in Bucks and Montgomery counties, Pennsylvania. Several good sections were studied, and their correlation was based almost entirely upon the tracing of the black shales along the strike from one section to another. In a few places, for distances not greater than six miles in any case, and less than four miles in all but one, the trend of definite topographic features has served to identify horizons in different sections.

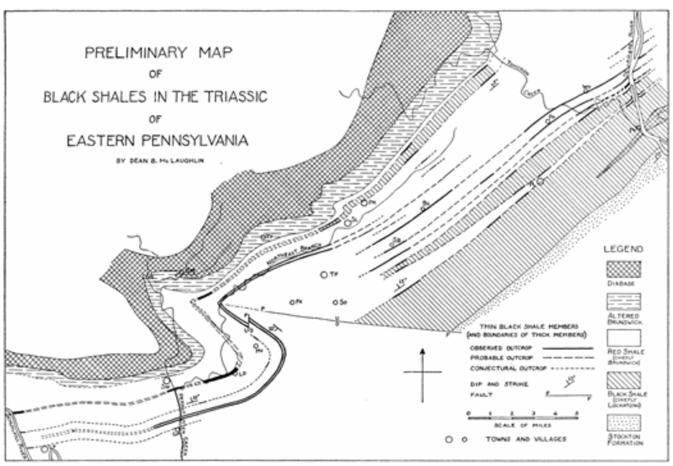
In general the black shales[7] occurring in the Brunswick formation are lithologically indistinguishable from those of the Lockatong formation which underlies it. They are chiefly thick-bedded, hard, dark gray or greenish gray to black argillites. The weathered rock is usually olive-green to greenish yellow. Contacts between the black shales and the inclosing red shale are not often sharp. Usually there is a foot or so of purplish or brownish shale marking the transition. In some localities the black shale contains beds of fine gray sandstone, and at others it is lighter in color and more fissile than the more common hard argillite. The black shales are more resistant to erosion than the inclosing red beds, and the course of a prominent black shale member is usually marked by a definite ridge.

The observed outcrops of black shale are indicated by heavy full lines and diagonally shaded areas in the accompanying map (Map 52). Dashed lines show the probable course of outcrop in regions not yet examined. The lines of short dashes indicate uncertain correlations or conjectural continuations of observed outcrops. In the descriptions which follow, two-letter symbols after the names of villages serve to identify those villages on the map.

The writer's results can be most conveniently treated under three headings: (1) the Upper Lockatong and Lower Brunswick, which have been studied chiefly in Bucks County; (2) the Graters members; and (3) the Sanatoga member.

## THE UPPER LOCKATONG AND LOWER BRUNSWICK

In a previous paper the writer[8] has mentioned alternation of red and black shales in the Delaware River section. At the time that paper was written the interpretation was still in doubt; repetition by faulting had not been ruled out. In 1931 it was found that new road cuts along the west bank of the river had laid bare the rocks in almost continuous exposure for more than a mile, and most of the crucial contacts were easily found, conclusively proving the alternation to be due to interbedding. Exposures on the east and west banks were found to match very satisfactorily. The following section was measured on the west side of the Delaware River. The base of the section is one and one-quarter miles north of Point Pleasant (Pf); the top is about one-half mile up the bed of a tributary stream which flows from Wormansville (*Wv*) northeastward to the Delaware River.




MAP 52. Preliminary map showing distribution of black shales in the Triassic of eastern Pennsylvania. Boundaries of diabase from *U. S. Geol. Surv., Bull. 828*, and Lyman's map. Boundaries of altered Brunswick, with small modifications by the author, and Stockton-Lockatong boundary from the same bulletin. Mapping of black shales entirely by the author.

Abbreviations: Bg, Blooming Glen; Fr, Franconia; Gf, Grater's Ford; Hv, Harleysville; Ld, Lederachsville; Lf, Linfield; Pk, Perkasie; Pl, Plumsteadville; Pp, Pipersville; Pt, Point Pleasant; Sd, Silverdale; Sl, Sellersville; Sm, Sumneytown; So, Soudreton; Sw, Schwenksville; Tf, Telford; Tp, Tylersport; Wv, Wormansville

SECTION ALONG WEST BANK OF DELAWARE RIVER NORTH OF POINT PLEASANT AND ALONG A TRIBUTARY STREAM

| | Feet |
|---|---|
| Red shale | undetermined |
| Dark gray argillite, with some fissile shale (*D*) | 72 |
| Red shale, partly covered | 400 ± |
| Dark gray argillite, partly covered (*C*) | 100 ± |
| Red shale, partly covered | 200 ± |
| Black argillite (few thin red beds) (*B*) | 190 |
| Red argillite, containing 30 feet of black | 85 |
| Black argillite, with few feet of red (*A*) | 540 |
| Alternate 20- to 30-foot strata of red and black argillite | 150 |
| Gray shale with some red, covered | undetermined |

With the exception of the contacts of shale (*C*), every contact of red and black shale in this section is excellently exposed. On the basis of this section alone the top of shale (*B*) should probably be regarded as the top of the Lockatong formation, since it is immediately overlain by a large thickness of red shale typical of the Brunswick, containing smaller thicknesses of black shale. As nearly as can be determined from measurements on Lyman's map,[9] that author placed his Gwynedd-Lansdale contact at precisely the same horizon. However, the rapid westward thinning of (*B*) and the accompanying thickening of the red shale between (*A*) and (*B*) incline the writer to place the Lockatong-Brunswick contact at the top of shale (*A*). It must be borne in mind, however, that any precise definition of the boundary is, in the nature of the case, rather arbitrary.

The section above is supplemented by one measured partly along Tohickon Creek and partly on the hills about three miles west of the Delaware River. The shale (*D*) was traced continuously along the strike between the two sections, leaving no doubt as to the correlations indicated by assignment of letters to the dark shale members.

SECTION ON AND NEAR TOHICKON CREEK EAST OF PIPERSVILLE

Base of section at Smith's Corner; top at road intersection three quarters of a mile southwest of Wormansville

| | Feet |
|---|---|
| Red shale, and upper beds of (*D*), unexposed | undetermined |
| Black argillite (*D*) | 45 |
| Red shale, partly covered | 350 |
| Dark gray argillite, with 30 feet of red (*C*) | 130 |
| Red shale | 180 |
| Red shale (?) exposures scarce | 150 |
| Red shale | 20 |
| Dark gray shale (part of *B*) | 20 |
| Covered region | 130 |
| Red shale (soil on hills, no exposures) | 50 |
| Gray shale (soil on hills, few exposures) (*A*) | > 400 |

The total thicknesses found for the strata between the top of (*A*) and the base of (*D*) in the two sections agree well, but there is a large discrepancy between the figures for the red shale between (*B*) and (*C*). Probably part of (*B*) in the Tohickon Creek section occurs in the region of scarce exposures, and the red shale above the observed part of (*B*) is an interbedded member. In both sections the strike is N. 50° E., dip 14° NW.

The member (*D*) was traced three miles southwest from Tohickon Creek. From that point the continuation of the strike, and also the topography, serve to connect it with a dark gray shale member of similar thickness which crosses the Doylestown-Quakertown highway one and one-half miles northeast of Blooming Glen (*Bg*). In the intervening stretch of four miles the positions of outcrop of (*C*) and (*A*) confirm this identification of (*D*).

In the vicinity of Silverdale (*Sd*) and Blooming Glen the composite section given below was obtained. Exposures are not numerous, and thicknesses are based chiefly upon dip and width of outcrop, the character of the rock being determined from fragments in the soil.

The pronounced thinning of shales (*A*) and (*B*), as compared with their thicknesses in the Delaware River section, and the accompanying thickening of the red shale separating them, are to be noted especially. A similar thinning of the main body of the Lockatong formation toward the west is well known.

COMPOSITE SECTION IN AREA ABOUT SILVERDALE AND BLOOMING GLEN

| | Feet |
|---|---|
| Red shale | undetermined |
| Greenish gray shale (*F*), unexposed | 15? |
| Red shale | 250 |
| Gray shale (*E*) | < 30 |
| Red shale | 400 |
| Gray shale (*D*) | 70 |
| Red shale | 520 |
| Gray shale (*C*) | 60 |
| Red shale | 350 |
| Gray shale (*B*) | 60 |
| Red shale | 500 |
| Gray shale (*A*) | 270 |
| Red shale | undetermined |

The dark shales discussed above have not yet been traced to their end against the Chalfont fault. The member (*F*), however, has been followed around the end of the fault and is found to be part of the black shales which the writer calls the Graters.

## THE GRATERS MEMBERS

The Graters is a group of three strata of black shale, separated by comparable thicknesses of red shale, occurring about 2,200 feet above the base of the Brunswick formation in the Silverdale section. Owing to the westward thinning and probable disappearance of the upper argillite member (*A*) of the Lockatong formation and the thinning of the main body, the Graters is about 4,000 feet above the top of the Lockatong black shale in the Perkiomen Creek section. The writer has applied the name "Graters" because of the excellent exposures in Landis Brook just west of Grater's Ford (*Gf*) on Perkiomen Creek.

The shale designated (*F*) in the Silverdale section is the lowest of the three members of the Graters and occupies a well-defined ridge just south of the Northeast Branch of Perkiomen Creek. Northeastward from the Doylestown-Quakertown highway the Graters apparently thins decidedly and may disappear completely. Southwest of the highway the member (*F*) probably thickens slowly for a few miles, then rapidly, for in a large quarry a mile north of Telford (*Tf*), thirty feet of black shale underlain by twenty feet of red shale are exposed. A fissile carbonaceous layer three feet thick occurs about fifteen feet above the base of the black shale. This same stratum has been identified in two more quarries within the next two and one-half miles southwest-ward along the ridge. The higher members are exposed at several places in the stream bed north of the ridge. Just west of the third quarry the ridge ends, and the intrenched meanders of the stream cross the strike of the hard rocks at several places in the next few miles. Three of these cuts across the Graters shales furnished the following composite section:

COMPOSITE SECTION OF GRATERS SHALES ON NORTHEAST BRANCH OF PERKIOMEN CREEK, ABOUT FOUR MILES WEST OF TELFORD

| | Feet |
|---|---|
| Red shale | > 150 |
| Greenish gray argillite, massive (*H*) | 50 |
| Red shale | 30 |
| Gray-green thick-bedded shale (*G*) | 70 |
| Red shale | 30 |
| Greenish gray shale (*F*) | 60 |
| Red shale | > 350 |

The exposures of the dark shales lead directly to the point where the Sumneytown road crosses the Northeast Branch, about three miles northwest of Harleysville (*Hv*), where a new deep road cut has exposed the rocks for a distance of over 200 yards. At the southeast end of the cut red shale is exposed, with strike N. 50° W., dip 15° SW., practically at right angles to the strike and dip of the shales in the stream east of there. Just northwest of this first exposure, for approximately 100 yards, the rock is badly shattered, and there are apparently at least three vertical faults causing alternation of red and gray shale along the strike. The rock in the northwest portion of the cut is red shale, and the strike changes quickly from N. 50° W, to N. 10° E., with gentle dip west, indicating a sharp fold. This locality is directly on the line of the Chalfont fault, which farther east has a displacement of over 10,000 feet. Probably the fault itself does not extend as far west as this locality. The faults in the cut are small and local, for the gray-green shale occurs southeast of this faulted exposure with a strike directly toward it. The outcrop of dark shale through the sharp anticline may be regarded as practically continuous.

About two miles southeast of the faulted exposure, at a place about a mile northwest of Harleysville, the Graters shales are offset to the north somewhat more than one-quarter mile by a fault whose strike is approximately north. If we regard the movement as entirely vertical with downthrow on the east, the total displacement of the fault is a little less than 400 feet.

Southeastward the dark shales can be traced through a syncline which pitches northwestward. The line of outcrop crosses the Sumneytown road two miles southeast of Harleysville, and the lower member is exposed in contact with the overlying red shale, in a large quarry a mile southwest of the road.

Southwest of the quarry the trace of the outcrop changes from southwest to west-southwest. The Graters members cross the Skippack road just north of Lucon and pass through the grounds of the Eastern State Penitentiary to the Perkiomen Creek, which they cross about one-half mile north of Grater's Ford (*Gf*). Exposures occur in tributary streams on both sides of the Perkiomen, along the road on the east side, and in a railroad cut on the west. The best exposures, however, occur along Landis Brook, just west of Grater's Ford, where the following section was obtained:

SECTION ALONG LANDIS BROOK

Base of section near road bridge at western edge of village of Grater's Ford

| | Feet |
|---|---|
| Red shale and fine sandstone | > 45 |
| Greenish gray shale | 6 |
| Red shale | 15 |
| Gray shale and fine gray sandstone (*H*) | 20 |
| Red shale, partly covered | 77 |
| Gray shale, partly covered (*G*) | 28 |
| Fine red sandstone, partly covered | 40 ± |
| Dark gray, thick-bedded argillite (*F*) | > 40 |
| Fine red sandstone and red shale, partly covered | 380 |
| Dark gray shale | 6 |
| Red shale | 165 |

So far as they are exposed, the rocks on the east and west banks of Perkiomen Creek furnished sections in good agreement with the table above.

The Graters members were not traced farther west, but evidence of their extent is furnished by the topography. Throughout the course described above, their outcrop is marked by a definite ridge. This ridge continues westward from the Landis Brook exposures, but comes to an end before reaching the Schuylkill River. In line with the course of the ridge a long covered stretch occurs in the section in the Philadelphia and Reading Railroad cuts on the east bank of the Schuylkill. It appears probable that the Graters shales underlie this covered interval.

## The Sanatoga Member

The highest black shale member studied by the writer is here designated the "Sanatoga" because of the excellent exposures in a large quarry and in the railroad cut at Sanatoga Station on the Schuylkill River. It forms a part of what Lyman[10] called the Perkasie shales. Wherry[11] has pointed out that the Perkasie should not be regarded as a definite formation, since a large part of it is merely red shale which has been altered by the diabase intrusion. The Sanatoga member, however, although slightly altered in places, does not owe its dark color nor most of its hardness to baking.

About two miles southeast of Haycock Mountain the baked shale is underlain by about 90 feet of red shale. This in turn is underlain by greenish gray shale, the conformable contact being exposed. The thickness of green shale below the red is about 350 feet. The red stratum separating the baked shale from the naturally green shale persists southwest ward along the strike. It is clearly evident on the Doylestown-Quakertown highway southeast of Rock Hill. What is believed to be the same stratum occurs in a ravine a mile west of Sellersville (*Sl*) and again on the Sumneytown road one and one-half miles southeast of Sumneytown (*Sm*). From there it is possible to trace the course of the dark shale by means of the topography, taking account of the known course of the underlying Graters members. A well-marked ridge leads southward to Lederachsville (*Ld*), where large areas of the fields contain weathered black and green fragments. In this region the red shale above the black is almost a mile wide, for the diabase has migrated upward in the series.

Excellent exposures of the thick black shale member occur at the road bridge over the Northeast Branch one and one-half miles west of Lederachsville. An equal distance farther west this member crosses the main stream of the Perkiomen just south of Schwenksville (*Sw*) and is well exposed on the west bank, where the measured thickness is about 200 feet.

From the Perkiomen westward the course of this shale is indicated by a prominent ridge which reaches the Schuylkill River at Sanatoga Station, where the thickness is about 160 feet, including some interbedded red shale.

The relative positions of the Graters and Sanatoga members are indicated by the following section along Perkiomen Creek:

SECTION ALONG PERKIOMEN CREEK

Base at tributary stream on east bank, one-half mile north of Grater's Ford; top at the southern limits of Schwenksville

| | Feet |
|---|---|
| Red shale | undetermined |
| Dark gray and green shale (Sanatoga) | 200 |
| Hard red argillite and red shale, partly covered | 1200 ± |
| Covered, probably all red shale | 180 |
| Red shale, mostly covered (includes *H*) | 630 |
| Gray shale (*G*), middle Graters member | 20 |

From the base to the top of the section the dip increases from 15 to 25 degrees. A corresponding uncertainty attaches to calculated thicknesses in the covered portions of the section.

It is of interest to compare the thicknesses along the Perkiomen with those along the Schuylkill River, given in the following section.

If the Graters members occur in the covered interval, then the thickness of red shale between the Graters and Sanatoga is only about 1,100 feet in the Schuylkill section as compared with about 2,000 feet along the Perkiomen. If we attempt to correlate the Graters with the shale here designated (*E ?*), we violate the topographic evidence. The conditions of deposition in the two sections were somewhat different, as shown by the greater amount of sandstone along the Schuylkill and the presence of thin beds of conglomerate. Only a few miles westward all the rocks of this section, except for the uppermost 600 feet or so, pass along the strike into conglomerate. A detailed study of this region of transition is contemplated.

SECTION ALONG PHILADELPHIA AND READING RAILROAD

East bank of Schuylkill River, from Linfield at base, past Sanatoga Station, and along a tributary stream to Pottstown highway

| | Feet |
|---|---|
| Red shale and sandstone, partly covered | 600 |
| Fine conglomerate and sandstone | 5 |
| Red shale and sandstone | 340 |
| Sanatoga black, green, and red shale | 160 |
| Red shale and fine red sandstone | 280 |
| Green shale and fine gray sandstone | 5 |
| Fine quartz conglomerate with few red shale pebbles | 1.5 |
| Red shale and fine red sandstone | 105 |
| Fine gray sandstone [12] | 18 |
| Fine gray and red sandstone, with diabase dike | 500 |
| Greenish gray sandstone | 25 |
| Red shale, partly covered | 150 |
| Covered, possibly containing Graters shales (*F*, *G*, *H*) | 330 |
| Red shale and sandstone, partly covered | 250 |
| Fine gray sandstone and gray shale (*E ?*) | 15 |
| Red shale and sandstone | 185 |

## Discussion

The courses of outcrop of the several dark shale members described above are shown in the accompanying map (Map 52). Owing to the difficulty of correctly representing the three members of the Graters, those shales are indicated by a double line. The Sanatoga can be readily identified as the broad belt of dark shales closely paralleling the altered shale just beneath the Haycock diabase sheet. The shales (*C*) and (*D*) pass very close to Pipersville (*Pp*) and Wormansville (*Wv*) respectively. A comparison and correlation of the four principal sections is given in Figure 24.

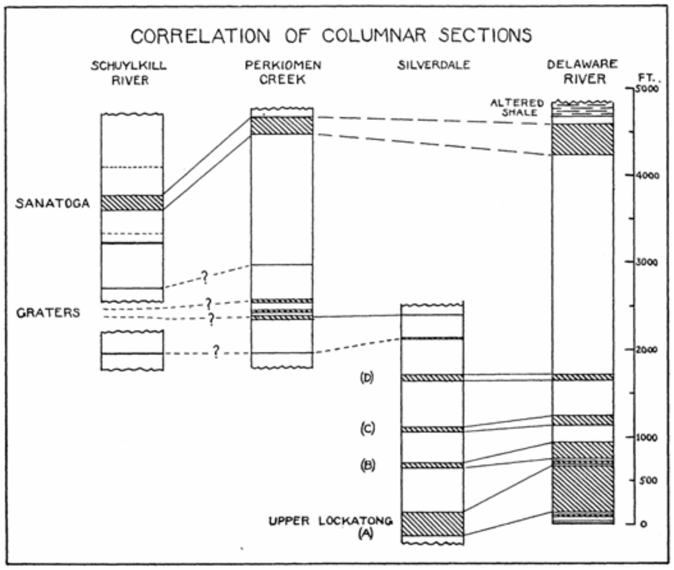



FIG. 24. Correlation of four sections of the Brunswick formation in eastern Pennsylvania. Explanation of figure: diagonal shading, black shale; clear, red shale; horizontal broken shading, altered shale; dotted lines, conglomerate. Correlation lines: full, certain correlation; long dash, probable correlation; short dash, conjectural correlation

The present study leads to some revision of the identification of horizons which would result from a use of Lyman's map.[13] Thus, according to that author, the member (*D*) would be 1,000 feet higher in the series near Silverdale than at the Delaware River. Again, the Graters near Sellersville would be regarded as about 1,500 feet lower stratigraphically than the same shale near Grater's Ford. Other similar discrepancies occur. It is thus evident that Lyman did not succeed in tracing thin members for long distances along the strike.

The writer's results also differ considerably from those of Wherry,[14] who has drawn the Lockatong-Brunswick contact cutting across some of the dark shale members at a considerable angle. He has also included in the Lockatong formation a large thickness of sediments which the writer would regard as lower Brunswick on the basis of the large ratio of red to black shale.

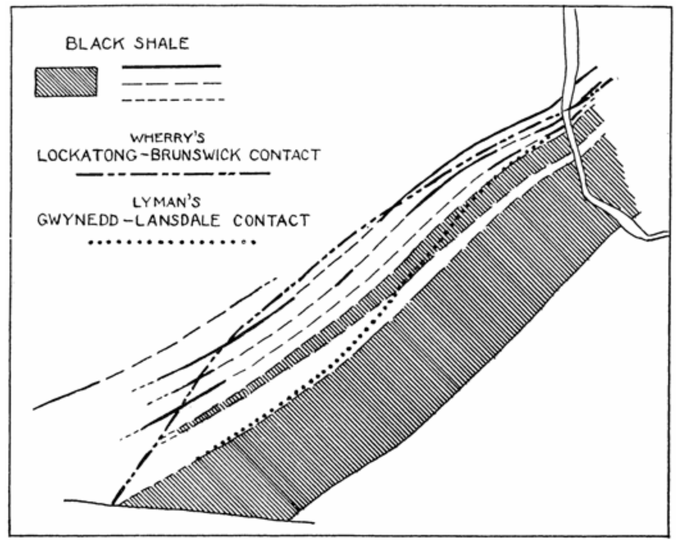



FIG. 25. Comparison of distribution of black shales with Lockatong-Brunswick boundary by Wherry and with Gwynedd-Lansdale boundary by Lyman

These discordances are shown in Figure 25, in which the distribution of black shales as observed by the writer is compared with the positions of the Gwynedd-Lansdale contact as mapped by Lyman and the Lockatong-Brunswick contact as mapped by Wherry.

It is evident that at any one time during the deposition of the lower Brunswick the conditions were far more uniform over considerable areas than has been previously supposed. The old concept of the merely local and lenticular character of the black shales in the Brunswick must be abandoned. The tracing of these dark shales furnishes a definite basis for identification of horizons at localities considerable distances apart.

It is also evident that small cross-faults may be detected by offsets of the dark shale belts, and if any important strike faults exist they will become evident from their effect in repeating such belts. The actual tracing of the black shales along the strike through regions of uniform dip and strike, as well as through the pitching folds in Montgomery County, should definitely dispose of the hypothesis that important repetition of beds by faulting has occurred — other than the repetition already recognized as due to the Hopewell and Chalfont-Flemington faults. It is inconceivable that important faults would continue so uniformly along the strike within the belts of outcrop of the red shales as to cause no offsets or cutting out of some of the black shale members. It can now be stated with considerable assurance that unrecognized strike faults are not likely to be responsible for more than a negligible percentage of the apparent thickness of the Newark Series in eastern Pennsylvania.

UNIVERSITY OF MICHIGAN

[1] Russell, I. C., *U. S. Geol Surv., Bull. 85*: 84. 1892.

[2] *Penna. Geol. Surv., Final Rep.*, 3, Part 2 : 2597 and 2605. 1895.

[3] *U. S. Geol. Surv.*, Folio 225 : 15. 1929.

[4] *Ibid*., Folio 167 : 7. 1909.

[5] *U. S. Geol Surv., Bull. 828*. 1931.

[6] *N. Y. Acad. Sci., Annals*, 23 (1914) : 160.

[7] The term "black shale" will here be used to cover all gray, green, or black shales occurring in the Brunswick and Lockatong formations.

[8] "The Thickness of the Newark Series in Pennsylvania and the Age of the Border Conglomerate," *Pap. Mich. Acad. Sci., Arts and Letters*, 16 (1931) : 424.

[9] *Penna. Geol. Surv., Final Rep*., Atlas, sheets 10 and 11. 1895.

[10] *Penna. Geol Surv., Final Rep*., 3, Part 2 : 2609. 1895.

[11] *Proc. Acad. Nat. Sci. Phila*., 64 (1912) ; 376.

[12] At the base of this member there is an apparent angular unconformity, the significance of which is not clear.

[13] *Op. cit*.

[14] *U. S. Geol Surv., Bull 828*. 1931.

# CORRELATION OF THE UPPER HURONIAN OF THE MARQUETTE AND CRYSTAL FALLS DISTRICTS

JUSTIN ZINN

## INTRODUCTION

AT THE present time the Upper Huronian of the Crystal Falls district is correlated with that of the Marquette district mainly on the basis of the continuity of the thick slate succession (the Michigamme slate) between these districts. In the geologic literature on these districts[1] no concise statements of the detailed succession of the sediments of the Upper Huronian have been given. The lower portion of the series in the Marquette district has been described and subdivided, but the upper part is grouped under the term "Michigamme slate"; in the Crystal Falls district the whole succession has been called the "Michigamme slate series." The data obtained by the field work of the Michigan Geological Survey in 1930 have made it possible to separate the Upper Huronian of the Marquette district into distinct lithologic units which may be correlated from place to place. These units are easily recognized, and appear to be in as well defined a succession as that of the Middle Huronian. It is of geologic importance to see whether the Upper Huronian has similar sequences in other districts. If definite lithologic successions do exist, then it should be possible to correlate the Upper Huronian in a detailed way from one iron-bearing district to another, as has been done in the past in regard to the Middle Huronian. Such a correlation would be of twofold value. In the first place, it would give considerable information on the sedimentary changes from place to place in Upper Huronian time, and result in a more unified sedimentary history. In the second place, it would be of economic value, for the Upper Huronian iron formation could be more easily traced.

It is the belief of the author that the Upper Huronian sediments do have a definite succession which can be correlated between some of the pre-Cambrian areas, especially those which occur in Michigan. In this paper the attempt will be made to correlate the Upper Huronian sediments of the Marquette district with those of the Crystal Falls district. Such a correlation, to be of any consequence, necessitates the division of the Michigamme slate series into several parts or horizons, some of which may be given the distinction of formations. A subdivision of the Upper Huronian is especially necessary in the Crystal Falls area, since at the present time it is all included in the literature as the Michigamme.

The observations upon which the discussions of this paper are based were made during several summers of field work, of which the last two provided the most data. The summer of

1930 was spent with the Michigan Geological Survey in the Marquette district, in a detailed study of the area between Mt. Humboldt and Lake Michigamme. During the field season of

1931 the author covered in detail several small areas in the vicinity of the village of Crystal Falls. Two summers previous to 1930 were also devoted to the study of the Crystal Falls district and adjacent areas. It was not until 1931 that a definite succession in the thick Upper Huronian sediments of the Crystal Falls district seemed apparent to the author, and this recognition was facilitated by the knowledge of the Upper Huronian succession of the Marquette district, obtained during the previous summer.

It may be said that the Crystal Falls area is the northwestern extension of the Menominee district of Michigan and Wisconsin. In this paper, however, the whole Menominee district will not be taken into consideration, but the discussion will be limited to the part which is in the vicinity of Crystal Falls village. This part is located in Iron County, Michigan, and continues westward toward the Iron River district and southward through the Alpha location to the Florence district in northern Wisconsin.

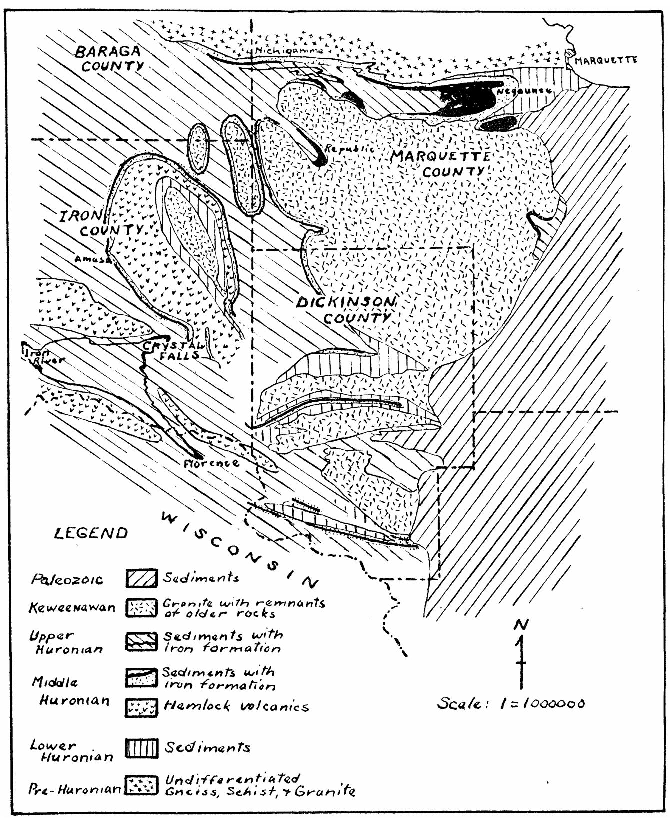
The western part of the Marquette district occurs about thirty-five miles northeast of Crystal Falls. It extends toward the east to Ishpeming and Negaunee in Marquette County. The area between these two districts is occupied by several anticlines or domes, which are commonly called "ovals." These ovals have granitic cores around the margins of which Huronian sediments occur. This intervening area is not well known geologically, since it has not been a large producer of iron ore and thus has not been extensively explored. It is not distinguished by a separate district name. The accompanying outline map (Map 53) shows the location of the areas which are concerned in this paper.

The attempted correlation of the Upper Huronian sediments in these two districts must be made in one step because of the meager amount of information obtainable on the area between them. The sedimentary succession in each area will be briefly described, after which certain points of similarity may be discussed. Elaborate descriptions of certain sections have been omitted, since they would make this paper unduly long.

## THE BASE OF THE UPPER HURONIAN

The base of the Upper Huronian in each district is marked by an unconformity of some magnitude, and persons not familiar with the field observations might think it an easy matter to locate such an unconformity readily. With the exception of the Marquette district, however, the location of this base has been a question about which there has been much difference of opinion. In many places the unconformity is not marked by a well-defined conglomerate, and beveling of beds is not easily proved where outcrops are not numerous. In other places it has not been clear where the base should occur because of incorrect correlations of the iron formations.

The base of the Upper Huronian has been well established in the Marquette district. The unconformity between the Middle and Upper Huronian of this district is distinctly marked in most places by the Goodrich conglomerate and quartzite. It is also marked by the beveling of the Negaunee iron formation. There is no sedimentary horizon of Middle Huronian age above the Negaunee in the Marquette district; thus the base of the Upper Huronian series may be found just above this iron formation in places where it is not missing.




MAP 53. Outline map showing the location of the Marquette and Crystal Falls districts and the general areal geology

The unconformity between the Middle and Upper Huronian is not easily distinguished in the Crystal Falls district. The competent quartzitic basal sediment of the Upper Huronian does not occur in this area, and the Negaunee iron formation is found only in the eastern part of the area. In the past, the base of the Upper Huronian has been placed at three different horizons, namely, at the top of the Hemlock volcanics, above the principal iron formation of the Crystal Falls district, and, later, upon the recognition of two different iron formations, above the lower and below the upper of the iron horizons. The last interpretation places one iron formation in the Middle Huronian and the other, which is the principal producer of the district, in the Upper Huronian. In *Monograph 52*[2] of the United States Geological Survey the unconformity between the Middle and Upper Huronian of the Crystal Falls district is put at the top of the Hemlock volcanic formation in all places on the southwest side of the Crystal Falls oval. Allen and Barrett[3] put the unconformity above the Vulcan iron formation and in this way classed all the iron formations of the district as Middle Huronian. Subsequent detailed magnetic field work has shown that there are really two different iron formations in this area. The lower iron formation, which occurs in a succession of sediments which are conformable above the Hemlock volcanics, has been correlated with the Negaunee formation of the Marquette district. The correlation is based upon lithologic similarity and the continuity of the magnetic line associated with the Negaunee formation from the west end of this district. A satisfactory discussion of it is given by Allen and Barrett.[4] The higher or later iron formation occurs in a series of sediments which are unconformable above the Hemlock volcanics. It extends from Crystal Falls westward and southward to Iron River and Florence. This higher formation is now considered to be of Upper Huronian age by most of the geologists who are familiar with the Crystal Falls district, and has been distinguished as such on the geologic map of Iron County which was published by the Department of Conservation of the State of Michigan in 1929. The discussion in this paper is on a basis conforming to the last interpretation. The base of the Upper Huronian in the Crystal Falls district occurs, therefore, somewhere between these two iron formations. It overlies the beveled Middle Huronian series, resting on the Hemlock volcanics in most places south and west of Crystal Falls. Around the large, oval to the northeast of this village, however, it rests on remnants of the Negaunee iron formation or on a Middle Huronian slate conformably overlying the Negaunee, both of which occur above the Hemlock volcanic greenstone in this part of the district. At no place in this area, however, are there outcrops that show the unconformity between the Middle and Upper Huronian, and the data given are based on observations in diamond drilling and in mine workings. The uncertainty about the base of the Upper Huronian in the Crystal Falls district is thus more apparent.

## THE MARQUETTE DISTRICT

The Upper Huronian sediments of the Marquette district are divided into the following formations:

| | |
|---|---|
| Upper Michigamme | graywacke, quartzite, slate |
| Bijiki | iron-bearing |
| Lower Michigamme slate | |
| Clarksburg | volcanic sediments |
| Greenwood | iron-bearing |
| Goodrich | conglomerate, quartzite, etc. |

Each of these formations will be described in sufficient detail for identification and for a later comparison with the succession in the Crystal Falls district. For a fuller description the reader may be referred to the report on the field work of the Michigan Geological Survey in 1930.[5]

### *The Goodrich Formation*

The Goodrich formation lies unconformably above the Middle Huronian sediments, beveling off in many places the Negaunee iron formation and perhaps even the Siamo slate. It consists of a basal conglomerate overlain by quartzite and quartz slate. The conglomerate ranges in thickness from a few feet to several hundred feet and is composed of pebbles of iron formation, quartzite, and granite, in a matrix of finer material of the same character. The Goodrich conglomerate shows the greatest development in the Marquette syncline from Mt. Humboldt eastward and is especially thick in places on the south side of the syncline. In the west end of the district the conglomerate is thin and, in some places, missing. The quartzite overlies the conglomerate and grades downward into it. Most of the quartzite is composed of rather pure quartz sand that forms thick, massive, light-colored beds. It, also, appears to be thicker in the southern and eastern parts of the district. It grades upward into quartz slate and, in places, into true slate. To show the variation of the Goodrich formation from place to place the section of this formation at Michigamme may be compared to that at Mt. Humboldt. At the latter locality there are about two hundred feet of basal conglomerate overlain by several hundred feet of quartzite, above which some slate occurs. At Michigamme the whole formation is only about two hundred feet thick, and is made up almost entirely of the quartzite. For correlation purposes important facts to keep in mind regarding the Goodrich formation are that it is variable in lithology within short distances, and that it seems to become uniformly thinner toward the west.

### *The Greenwood Formation*

At the top of the Goodrich formation occurs the Greenwood ferriferous horizon. This sediment is not a pure iron formation, but was deposited as an interlayered accumulation of clastic material and chemically deposited chert and siderite. The parts exposed in outcrops now consist of grunerite schist, with inter-layered chloritic material or quartz sand. The unmetamorphosed portions are probably a sideritic slate. The thickness of the Greenwood formation varies somewhat, being perhaps fifty feet at a minimum. Where metamorphosed, it is magnetic and creates a magnetic line that marks the top of the Goodrich formation. Where the Greenwood is overlain by the Clarksburg volcanics, the interlayered clastic zones seem to be mostly chloritic material, but where the Clarksburg is not present, as at Michigamme, the interlayered material is mostly clastic quartz. This iron horizon has not yet proved to be of economic importance.

### *The Clarksburg Formation*

The Clarksburg volcanic formation is limited to the south side of the Marquette syncline and extends from Ishpeming westward to a short distance east of Lake Michigamme. It consists mainly of agglomeratic and ash beds, having in most places interlayered normal sedimentary horizons. Very few lavas are to be found. The volcanic rock is rather basic, probably being the equivalent of gabbro in composition. The observation that the volcanics occur on only one side of the Marquette syncline indicates the local extent of the formation and suggests that this horizon may not exist at all in other districts.

### *The Lower Michigamme Slate*

The Michigamme slate series of the Marquette trough includes within it the Bijiki iron formation which divides it into two parts. The part below the iron formation will be considered first.

The lower slate lies conformably upon the Clarksburg volcanic sediments, and, in the places in which the Clarksburg is missing, conformably upon the Greenwood iron horizon. This condition suggests that the Clarksburg occupies the lower part of the time interval of the lower slate, and, further, that it grades laterally into this slate. The basal part of the slate is chloritic, but it grades upward through a gray variety into a black carbonaceous or graphitic slate which lies just below the Bijiki iron formation. The slate varies in thickness from three hundred to five hundred or more feet.

### *The Bijiki Iron Formation*

The Bijiki iron formation occurs near the base of the Michigamme slate series, and detailed field work has demonstrated it to be a continuous, well-defined horizon. It consists of ferruginous cherts, and, where metamorphosed, of grunerite schists. The original material was undoubtedly cherty siderite. The formation is from fifty to seventy-five feet thick in the Marquette district. The Bijiki, in general, contains very little clastic sediment, being nearly pure chert, interlayered with iron-bearing minerals. It does, however, contain some graphitic material, which may be seen in the gruneritic phases. It differs from the Greenwood formation in being associated with graphitic slates and in having very little clastic admixture. Several mines have been located in the Bijiki formation in the past, and the Imperial mine at Michigamme is still active. This formation is thus a productive horizon.

### *The Upper Michigamme Formation*

The part of the Michigamme series above the Bijiki iron formation is much thicker than that below, and is the highest horizon of the Upper Huronian that has been recognized. Immediately above the Bijiki this formation is a highly graphitic slate, but this slate passes upward very abruptly into a dark graywacke and quartzite. Some horizons of the coarser sediment are a dark felspathic quartzite, which in some sections approaches conglomerate in texture, whereas in other sections the sediment is a black, finer-grained graywacke. These gradations are lateral as well as vertical. In some places at or near the base of the coarser elastics lenses of conglomerate occur. They contain pebbles of chert, quartz, and graphitic slate in a matrix of quartz sand. The conglomeratic lenses and the quick transition to coarse clastic sediment above the Bijiki horizon suggest a temporary break in the sedimentation of the Upper Huronian series. Not much true slate is found in the Upper Michigamme formation in the Marquette district. The highest horizon of the formation seen was still coarsely clastic. The thickness of the graywacke series may be two thousand feet or more.

No specific figures can be given for the total thickness of the Upper Huronian of the Marquette district. Relative thicknesses may be shown, however, indicating what seems to be characteristic of the succession. The sediments up to the Greenwood formation range from about three hundred feet as a minimum to perhaps ten times this thickness as a maximum. The sediments above the Greenwood, with the exception of the Clarksburg, which is local, seem to be of a much more even thickness. The study of the sediments gives one the impression that the lower part of the Upper Huronian largely fills up irregularities which were present on the Middle-Upper Huronian erosion surface.

## THE CRYSTAL FALLS DISTRICT

For several reasons the Upper Huronian succession cannot be so easily studied in the Crystal Falls district as in the Marquette district. Magnetic lines are not so numerous or so strong, so that magnetic surveys do not give so much information. Outcrops are scarce in most places where the interpretation is questionable, and the different horizons are not so easily identified lithologically. For the present discussion the Upper Huronian sediments are included under the following subdivisions:

| | |
|---|---|
| Upper Michigamme formation. | graywacke and slate |
| Crystal Falls iron formation | |
| Footwall slates............... | graphitic and pyritic |
| Basal sediments.............. | conglomerate, graywacke, and slate |

In the past, these divisions have generally been grouped under the term "Michigamme slate," and the iron formation has generally been called the "Vulcan member." This formation in the Menominee range proper is now thought to be of Middle Huronian age and thus is to be correlated with the Negaunee formation, whereas there is little doubt that the iron formation of the Crystal Falls, Iron River, and Florence districts is Upper Huronian. For this reason the iron formation at Crystal Falls will be referred to in this paper as the "Crystal Falls formation," and not as the "Vulcan." It should be kept in mind that it is entirely distinct and stratigraphically higher than that which has been traced around the large granite oval to the northeast of Crystal Falls.

### *The Basal Sediments*

The location of the actual base of the Upper Huronian has not been determined at many points in the Crystal Falls district. For this reason the true stratigraphic positions of some of the outcropping sediments, near where the base should be, cannot be definitely given. The basal conglomerate has been exposed in mine workings at Amasa,[6] and test pits show the conglomerate at the Redrock mine location north of this village. At the latter place it is composed of fragments of iron formation and of greenstone. Near the Alpha location south of Crystal Falls numerous outcrops show the type of sediments below the graphitic slate footwall of the Crystal Falls iron formation. Immediately below the graphitic slate occurs a gray, fine-grained, and well-banded slate. A short distance above the Middle Huronian Hemlock greenstone there is a fine-grained, chloritic graywacke, which is thought to grade upward into the gray slate. Green chloritic and gray slates have been encountered just east of Crystal Falls below the graphitic slates, but the lowest sediments at this place have not been seen or explored. The thickness of the basal sediments varies decidedly within relatively short distances. Just east of Crystal Falls they seem to be many hundreds of feet thick, but west of this village at the Fortune Lake mine location it is reported that the Crystal Falls iron formation occurs immediately above the Hemlock greenstone, thus allowing only a very small thickness for both the graphitic footwall slates and the basal sediments. The abundance of chloritic graywacke and slate incorporated in the basal sediments which have been described suggests a considerable erosion of the underlying Hemlock greenstone. This deduction is supported by the fact that only remnants of the Middle Huronian sediments, which occur above this greenstone, still remain in the Crystal Falls district.

### *The Footwall Slates*

The footwall graphitic slates are found above the gray slates and immediately below the Crystal Falls iron formation. They are fissile black slates which contain much carbonaceous or graphitic material and generally also much pyrite. Some of them burn when ignited. This sediment ranges in thickness from ten to fifty or more feet. It grades downward into the underlying gray slate.

### *The Crystal Falls Iron Formation*

The Crystal Falls iron formation consists of rather thick horizons of cherty siderite, interlayered with thinner horizons of ferruginous or graphitic slate. The cherty siderite may be relatively pure or may contain some pyrite and graphite. There are two or perhaps more principal horizons of the cherty siderite. The whole iron formation is of considerable thickness if the interlayered slates be included. At Crystal Falls it outcrops over a width of about a quarter of a mile and is steeply dipping, but in the exposure in question there may be some duplication by folding. To the west and south it becomes thinner in most places. The iron formation, which lies conformably above, grades abruptly into the foot wall slates. It passes in the same manner into the hanging-wall sediments above it. It has been traced almost continuously to the Iron River district to the west and to the Florence district to the south. This continuity is sufficient to show that the Crystal Falls iron formation is a definite horizon and not a series of discontinuous lenses.

### *The Upper Michigamme Formation*

In most places the sediment immediately above the Crystal Falls iron formation is a graphitic slate very similar to the footwall slates. In some mine workings and drill holes it is difficult to tell which was the top and which the base of the iron formation, because the slates are so similar on each side and because the exploration is not carried far enough outside the iron formation to permit a study of the transitions. In the Crystal Falls district, however, the hanging-wall slate seems to be thin, giving place upward to a relatively coarse grained quartzose graywacke. This graywacke, which is dark gray to black with incorporated carbonaceous material, varies in composition from a normal sediment of the graywacke type to one which approaches a quartzite. It may be distinguished from the graywacke which forms part of the basal sediments by the large amount of quartz sand and lack of chloritic material. Higher horizons of this formation, so far as can be determined from outcrops, are either graywacke or coarse gray to black slate. The lower horizons of the graywacke are somewhat magnetic in places and the tracing of it by the dip-needle has helped in locating the iron formation below it. The base of the graywacke has horizons of chert breccia within it in at least one locality. There are some reasons for believing this breccia to be sedimentary rather than deformational. The horizons parallel the base of the formation and grade laterally into the quartzitic graywacke. No chert horizons were found in the graywacke series which could have been broken up by folding to produce the breccia. If this breccia is sedimentary, it indicates a slight erosional interval at the base of the Upper Michigamme sediments.

The graywacke slate series is the highest Upper Huronian formation to be recognized in the Crystal Falls district. Its thickness is not known, but may be several thousand feet. This formation, which has been called the "Paint slates" by Allen and Barrett,[7] is said by them to extend widely to the west and north of the Crystal Falls district.

## CORRELATION

With brief statements of the succession of sediments in the Crystal Falls and Marquette districts and short descriptions of these sediments given, it is now possible to point out evidences upon which correlations can be made. Definite horizons of the Upper Huronian have not yet seen continuously traced from one district to the other; consequently, the only means of correlation which can be used at the present time are by lithologic resemblance and similar stratigraphic successions. The correlation may best be started with the top of each succession and the consideration of the lower formations may be made in order.

The highest recognized formation of the Upper Huronian in each district under consideration is the thick, quartzitic graywacke slate. In the Marquette district this sediment is quartzitic enough in places to be called a quartzite; at one time it was mistaken for the Goodrich quartzite. It is felspathic, however, and contains enough carbonaceous material to give it a predominant dark color. In the Crystal Falls district the graywacke slate is not quite so quartzitic, and the coarsest horizons are more truly graywacke than quartzite. This formation of the latter district seems to contain more slate, at least in the higher horizons, than is found in the Marquette district. It also contains carbonaceous material in the base, and this gives it a dark gray to black color. In each district the base of the graywacke formation contains conglomerate lenses which, as suggested above, may indicate a temporary break in the Upper Huronian sequence. In both places this sediment directly overlies the principal Upper Huronian iron formation. The set-ups in the districts are so nearly alike that there should be no serious doubt in concluding that the Upper Michigamme formation of the Marquette district is the counterpart of the graywacke slate formation of the Crystal Falls district. The correlation seems more likely when one considers that there are no other formations of either district which are lithologically similar to the carbonaceous, quartzitic graywacke.

In the Crystal Falls district the Upper Michigamme formation contains more slate than in the Marquette district, but it is much thicker, occupying broader synclines, and it may be that most of the slate phases are in the higher horizons which are not present in the Marquette syncline. On the other hand, the formation may become coarser and more quartzitic toward the latter area. So far as known at present, there are no iron-bearing horizons in the Upper Michigamme formation, and the only marker horizon of it which is easily recognized in each district is its base. This sediment makes up more than half of the volume of the Upper Huronian sequence.

The Bijiki iron formation directly underlies the Upper Michigamme in the Marquette district and at Crystal Falls the Crystal Falls iron formation is present beneath it. This observation alone suggests that these two iron formations represent the same Upper Huronian iron-bearing horizon. Lithologically, the Bijiki and the Crystal Falls are almost identical. They have about the same chemical composition and both of them are associated with graphitic slates. Much of the Bijiki now exists as grunerite schist, whereas the Crystal Falls formation has no gruneritic phases; but this character is a secondary change due to metamorphism and does not depend upon the original composition. The Crystal Falls is several times as thick as the Bijiki, and it includes interlayered slate horizons whereas the Bijiki formation does not, but aside from these differences, there seems to be nothing of importance which would suggest that these iron-bearing horizons are not of the same age.

There are two horizons of ferruginous deposition in the Upper Huronian of the Marquette district, the Bijiki and the Greenwood formations, but, so far as known, the Crystal Falls district has only one in this division of the Huronian. The Greenwood iron formation is not of economic importance, but the possibility that it is of the same age as that at Crystal Falls should be considered. The Greenwood may be equivalent to the Crystal Falls, or it may be of the same age as the lowest part of this formation, or it may be at a lower horizon entirely, and not existent in the Crystal Falls district. There is little reason for believing that the Greenwood rather than the Bijiki is equivalent to the Crystal Falls iron formation, since the latter is so much more like that at Crystal Falls. It is possible, however, that the Greenwood is equivalent to the lower part of the Crystal Falls formation. If the Clarksburg volcanic sediments, which are known to be local, are disregarded, the only sediment occurring between the Bijiki and the Greenwood is the lower Michigamme slate, which on the average is not very thick. If the Greenwood formation is of the same age as the lower part of the Crystal Falls, then the Bijiki could be correlated with the upper part of the Crystal Falls, and the intervening slate would be represented in the Crystal Falls district by the interlayered slate horizons in the iron formation of this place. An observation which would support this hypothesis is that the combined thickness of the Greenwood and the Bijiki with the intervening slates does not greatly exceed the thickness of the Crystal Falls formation. The lower part of this sediment is associated with carbonaceous material as well as the top of it, however; whereas the Greenwood is stratigraphically lower than the graphitic horizon of the Upper Huronian in the Marquette district. If the carbonaceous deposition of each district was contemporaneous, then it would necessarily follow that the Greenwood horizon is lower stratigraphically than the Crystal Falls iron formation. At the present time it is not possible to correlate the Greenwood definitely with any horizon of the Crystal Falls district, and the question will be left open until further data on the extent of the Greenwood are obtained.

The higher formations of the Upper Huronian of these districts have now been tentatively correlated and attention may be turned to the basal members. There is little similarity between the basal sediments of the Crystal Falls and Marquette districts. Except for the fact that the higher formations have been correlated there would not be much reason for saying that these lower sediments are of the same age.

The basal conglomerate in each district is composed in part of fragments of the rock which underlies it at any one place. For instance, the Goodrich conglomerate of the Marquette district has a high percentage of iron-formation breccia at those places where it overlies the Negaunee iron formation, and a smaller amount of such material where this iron formation was removed by erosion before the deposition of the sediment began. In the Crystal Falls district the basal conglomerate and graywacke are composed mainly of greenstone debris where they overlie the Hemlock volcanic formation, and of iron-formation fragments where remnants of the Middle Huronian iron formation remain beneath. These observations show that much of the material forming the basal sediments was incorporated without being moved far from its source. The local character of these sediments was probably the result of deposition over a moderate topographic relief on the Middle-Upper Huronian erosion surface. An uneven surface of some magnitude is indicated by the amount of beveling which the Middle Huronian sediments experienced. At Mt. Humboldt the Negaunee iron formation is estimated to be about a thousand feet thick, although less than a mile west of this place it is entirely missing. At the Armenia mine location in the Crystal Falls district the Negaunee formation, with at least three hundred feet of Middle Huronian hanging-wall slates, occurs, but three miles to the west these sediments are missing, together with all the underlying slate and some of the Hemlock volcanics. There seems to be sufficient reason, therefore, for expecting the basal sediments of the Upper Huronian to have local facies. The difference in lithology, then, does not bar the correlation of these sediments from one district to the other. The Goodrich formation of the Marquette district is essentially quartzose because the underlying terrain, with the exception of the Negaunee iron formation, is quartzose and granitic. The basal sediments of the Upper Huronian of the Crystal Falls district are mainly chloritic slates and graywackes because they are underlain throughout this district by the thick Hemlock volcanic greenstone, except where remnants of some of the higher formations of the Middle Huronian remain beneath the Middle-Upper Huronian unconformity.

Since certain horizons of the Upper Huronian of the Crystal Falls district may be correlated with similar ones in the Marquette district, and since the underlying Middle Huronian sediments of these districts have been correlated, it appears probable that the basal sediments of the Upper Huronian, which have been discussed above, are of the same age. The foregoing discussion shows, however, the difficulty which would have been encountered had the attempt been made to start the correlation with the base. The accompanying chart shows the correlation which has been discussed.

## FUTURE CORRELATION

It should not be difficult to correlate the Upper Huronian sediments which might in the future be investigated in the area between the Marquette and Crystal Falls districts. Two horizons, the quartzose graywacke slate and the iron formation, should occur with the same characteristics which they have in these districts, and for this reason they should be readily identified. The basal sediments should be found with local facies, as they have been in the two districts described. In the areas where the Hemlock formation does not exist, the basal formation of the Upper Huronian may more closely resemble the Goodrich formation of the Marquette district.

| | Previous correlation * | | Correlation as discussed | |
|---|---|---|---|---|
| | Marquette district | Crystal Falls district | Marquette district | Crystal Falls district |
| Upper Huronian | Greenstone intrusives and extrusives | | Upper Michigamme formation | Upper Michigamme formation (Paint and Hanbury slates) |
| | Michigamme slate, partly replaced by Clarksburg volcanics | Michigamme slate | Bijiki iron formation | Crystal Falls iron formation |
| | | | Lower Michigamme formation | Footwall graphitic slates |
| | | | Clarksburg volcanic formation | |
| | Bijiki schist (iron-bearing) | | Greenwood formation (iron-bearing) | |
| | Goodrich quartzite | | Goodrich formation | Basal conglomerate graywacke and slate |
| Unconformity | | | | |
| Middle Huronian | | Paint slates? | | |
| | | Greenstone intrusives and extrusives | | |
| | | Hanbury slate | | Slate |
| | Negaunee iron formation | Vulcan iron formation | Negaunee iron formation | Negaunee iron formation "Vulcan" |
| | Siamo slate | Ajibik quartzite | Siamo slate | Slate |
| | Ajibik quartzite | Mansfield slate | Ajibik quartzite | Hemlock volcanics |
| | | Hemlock volcanics | | |

Chart showing previous correlation between the Marquette and Crystal Falls districts by Allen and Barrett, and the correlation suggested by later investigation
* Allen and Barrett, *op. cit.*, p. 30.

It is probable that the correlation of the Upper Huronian sediments may be extended to other iron-bearing districts of Michigan. The discussion of these has shown that the Upper Huronian does have some easily identified horizons which are extensive. The Upper Michigamme formation has certain characteristics which should facilitate its identification over a wide area where it may exist. It is noteworthy that this formation is more or less quartzose, and that it has much coarsely clastic material in it. This may imply a renewed erosion of the land areas which were supplying the material for this formation. The land areas may have been reëlevated, perhaps by the forces which later folded the whole Huronian sequence at the end of Huronian time. If these deductions are correct, then one should expect the Upper Michigamme formation to be a sandy clastic sediment in most places. The lower portion, at least, of this formation contains carbonaceous material, and for this reason the sediment is generally very dark colored. This characteristic distinguishes it from all stratigraphically lower quartzite formations of the Huronian.

The Upper Huronian iron formation in both the Crystal Falls and the Marquette districts is characterized by its close association with graphitic slates. There is in this instance the association of two unusual types of deposition. It may be conceded that the sedimentary deposition of cherty siderite is unusual and must be explained by special processes. Likewise, sedimentary deposition of carbonaceous material seems to be unusual in the pre-Cambrian, since up to the present time there has been found only one horizon in the Huronian of the Lake Superior region containing this material. It seems improbable that more than one sedimentary horizon will be found in the Huronian which has this association of iron formation and carbonaceous material. Since this peculiar sedimentation has been demonstrated to be Upper Huronian in these two districts, it may well be that any iron formation which in the future should be found associated with carbonaceous or graphitic slates is of Upper Huronian age. On this basis it should be possible to correlate the Upper Huronian as accurately as the underlying Huronian groups have been correlated in the past.

## CONCLUSIONS

Recent field work in the Marquette and Crystal Falls iron-bearing districts of Michigan has produced data which show a more or less definite succession of Upper Huronian sediments in each area. A comparison of their sedimentary sequence leads to the conviction that at least some horizons can be correlated from one district to the other. There seems to be sufficient ground for believing that the Upper Huronian iron formation of the Crystal Falls district is of the same age as the Bijiki formation of the Marquette district. The overlying quartzose graywacke slate which is found in each area is also thought to belong to one formation. There is some evidence for believing that there may be a sedimentary break at the base of this graywacke slate formation. Though the sediments underlying the iron formation in each district are quite dissimilar, reasons have been given for believing that they are contemporaneous. The conditions of sedimentation during the lowest part of the Upper Huronian deposition were such that local facies developed, with the result that the type of sediment found at any one place depends somewhat upon the character of the underlying rocks.

It is probable that field work in other iron districts of the Lake Superior region will give sufficient data on the Upper Huronian rocks encountered to show successions which may, in part at least, be correlated with the better-known sequences of the Marquette and Crystal Falls districts.

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[1] Clements, J. M., and Smyth, H. L., *The Crystal Falls Iron-Bearing District of Michigan, U. S. Geol. Surv., Mon. 36* (1899): 155-186; Van Hise, C. R., and Bayley, W. S., *The Marquette Iron-Bearing District of Michigan, U. S. Geol. Surv., Mon. 28* (1897): 408-486; Van Hise, C. R., and Leith, C. K., *The Geology of the Lake Superior Region, U. S. Geol. Surv., Mon. 52* (1911) : 265-268, 298-300.

[2] Van Hise and Leith, *op. cit*., p. 299.

[3] Allen, R. C., and Barrett, L. P., "Contributions to Pre-Cambrian Geology," *Mich. Geol and Biol. Surv*., Publ. 18 (1915): 26.

[4] *Op. cit.*, p. 25.

[5] Zinn, J., "Geology of the Portion of the Marquette Range between Humboldt and Lake Michigamme," *Mich. Geol. Surv*., 1931. Available, in mimeographed copies.

[6] Allen and Barrett, *op. cit*., p. 26.

[7] *Op. cit*., p. 131.