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PAPERS OF THE MICHIGAN ACADEMY OF SCIENCE ARTS AND LETTERS

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MICHIGAN MOUNDS, WITH SPECIAL REFERENCE TO TWO IN MISSAUKEE COUNTY

EMERSON F. GREENMAN

IN THE summer of 1925 the University of Michigan Museum conducted work upon two inclosures belonging to it on the Missaukee Preserve in Missaukee County, Michigan. During the course of the investigations, two burial mounds were excavated with results which indicate the presence in prehistoric times of two different cultures in the region. One of the mounds was on the crest of a ridge within 1,000 feet of the smaller inclosure, and the other was on lower land about one and one-half miles to the south. The mound near the inclosures was between 17 and 18 feet in diameter and 2 feet 2 inches in height at the center, measured from the bottom of the shallow trench which surrounded the mound, out of which the material for its erection was taken. This trench was from 5 to 8 inches below the level of the ground outside, and 4 to 6 feet in width. At a depth of 3 feet and 6 inches below the surface at the center was found a male human skeleton, lying southwest and northeast, head to the southwest, the legs tightly flexed so that the bones of the feet were resting alongside the pelvic bones. The left forearm lay across the abdomen, and the right at an angle of 45 degrees to the axis of the trunk. The bones were partially decayed, the ribs, vertebrae and right and left radii having disappeared altogether. The upper end of the shaft of the left femur had been broken during life and mended without being set, which made it about an inch shorter than the right femur.

No artifacts were found with the skeleton, but there were two stones lying in a position indicating that at the time of the burial they had been laid on the chest. In size they were 10 by 9 by 3 inches, and 12 by 5 by 3 inches. The different strata of the mound were disposed in the following order, from the surface downward: first, a layer of dark brown, loose soil, containing pebbles and roots, 1 foot and 10 inches thick at the center of the mound; next below, a layer of black sand and charcoal about 2 inches in thickness and coming to the surface at the perimeter of the mound; immediately below this, a layer of light gray sand, firmly packed and containing few pebbles, varying in thickness from 3 to 10 inches. The outer edges of this layer turned downward to a depth of 2 feet. At the center of the mound there was a cone-shaped deposit of medium-brown, loosely packed sand containing small stones, which extended down through all three of the different strata, at the bottom of which was found the skeleton, about 20 inches below the natural level of the ground. The layer of white sand and charcoal at the base-line of the mound may be the remains of a fire which formed part of the burial ceremony after the body had been placed in the hole and before the erection of the mound, or it may represent simply the original surface of the ground. The cone-shaped deposit of loosely packed sand, with the apex reaching to the skeleton and of the same general consistency as the bulk of the mound above the layer of charcoal, may be taken to indicate that a hole was dug, uncovering the burial, sometime after the erection of the mound. The purpose of this hole can only be conjectured. Some aboriginal vandal may have taken out such artifacts as had been placed with the burial and left the two stones on the chest of the skeleton in their place, or the first burial may have been removed and another substituted.

The second mound, about one and one-half miles to the south, was like the first, circular, with diameters of 21½ and 25 feet, at the center 41 inches above the bottom of the surrounding trench, which was from 4 to 10 inches below the natural level of the ground. Excavation of this mound uncovered a small pile of charred bone fragments 6 inches wide, 9½ inches long and 1½ inches thick, 27 inches below the surface at the center of the mound. About 3 inches above this pile of bone fragments was a layer of bark 15 inches long by 10 inches wide and one half of an inch thick, which encased a copper "axe," 6¼ inches in length. The bone fragments proved upon examination to be those of an adult human being whose remains had been almost cremated. There was only one fragment, a piece of the proximal epiphysis of the humerus, which rendered certain identification possible. One end of the bark layer containing the copper piece lay under a stone about 7 inches in diameter, and directly over the pile of cremated bones, which was 8 inches to one side of the bark, was a large rock 11 inches in diameter, the top of which was 4 inches beneath the surface of the mound. The bark in which the copper piece was encased was found to be of two kinds, oak and elm. In other parts of the mound were found what was apparently a piece of human rib about 2 inches long, a small round bone an inch long which had probably been worked, two small pieces of psilomelane, a copper-bearing mineral found in Michigan, and two small pieces of flint which show little evidence of having been worked. About 2½ feet from the pile of cremated bones, and at the same level, was found a piece of stone 3½ inches long, 1 inch wide and three eighths of an inch in thickness, which had been worked and smoothed into a shape resembling a small whetstone. Another layer of bark 4 or 5 feet in length at a distance of 3 feet from the bark containing the copper piece may originally have connected with it.

The different strata of the mound occurred in the following order: first, a layer of brown sand, containing pebbles and roots of plants on the surface, from 1½ to 2 feet in thickness, following the curve of the surface of the mound; next below, a layer of black sand and charcoal from 2 to 6 inches thick. The bark encasing the copper piece was in this layer; directly beneath the outer 6 feet of this layer was a stratum of ashes and sand from 4 to 6 inches thick, which descended in places to a depth of 2 feet. Underneath this layer of sand and ashes on the outer side, and of sand and charcoal near the center of the mound, were the fine gravel and sand which constituted the base of the mound, and in the top of which was found the pile of bone fragments, 3 inches below the sand and charcoal layer. The evidence of fire of considerable intensity seems to have been localized at two points on opposite sides of the place where the cremated bones were finally deposited, at distances of 7 and 8 feet therefrom, and from 2 to 4 feet below the surface of the mound at those points. In these buried fire-pits were found abundant charcoal remains and stones which had been stained and cracked by fire. The small piece of worked bone already mentioned was found in one of these fire-pits.

There is small doubt that the cremation of the body occurred on the site of this mound. A very intense fire of short duration, such as is necessary to cremation of a human body, would leave nothing but fine ashes with little charcoal. That the fire was very hot is indicated by the lack of charcoal remains in the layer of ashes occupying the entire base of the mound between the two fire-pits, in the center of which was found the pile of cremated bones accompanied by the copper "axe." This axe, which showed no mark of fire, was laid beside the cremated remains, encased in its layer of bark, after the cremation had taken place. The two fire-pits, on opposite sides of the mound 11 feet apart, may be interpreted as fire-places in a lodge, very likely made of bark and poles, which occupied the site before the erection of the mound, since they were below the natural level of the ground, and showed evidence, both by this depression and by the thickness of the layers of charcoal in them, of a considerable duration. The finding of the piece of worked bone in one of them strengthens this conclusion. Fire-pits have been found in similar positions on the base-line of mounds in the state of Ohio.[1]

The strata of the surrounding trenches of the two mounds were very different. In the trench of the first mound, in which the complete skeleton was found, was a lens of vegetable mould about 8 inches thick in the middle at the surface. A cross-section of the trench of the mound containing the cremated burial shows at the surface a layer of humus 2 inches thick, next below a layer of clear yellow sand from 1 to 2 inches thick, and then a compact layer of humus 1 inch thick. Under this second layer of humus was a lens of dark gray sand about 6 inches in thickness, beneath which were the undisturbed gravel and sand. It is of course impossible to arrive at any conclusions as to the date of erection of the two mounds on the basis of these strata, but they may indicate that the first mound was older than the second, since the deposit of vegetable mould in the bottom of the surrounding trench was thicker by 7 or 8 inches. Nothing was found in either mound to indicate European influence.

In the state of Ohio, years of excavation have revealed two radically different cultures. The Fort Ancient culture is characterized by a very limited use of copper, burial in more or less conical mounds, occasionally in dug graves with no mound, interment above or on the base-line, and inhumation with rare cremation. The Hopewell culture is characterized generally by very free use of copper, mounds usually low and irregularly shaped, and often covering remains of wooden structures, and cremation with rare inhumation.[2] Inhumation and cremation are thus in Ohio accompanied by other practices equally different, establishing two cultures with essentially different traits. When one applies this method of culture differentiation to the two mounds in Missaukee County, it seems reasonable to conclude that they represent the work of two different cultural stocks, but one must bear in mind, of course, that there is only one example of each type under consideration. The two mounds have certain points in common, such as general size and shape, vertical disposition of strata, and proximity to one another, but these features would not be sufficient to demonstrate their common origin. The most important difference between them is the fact that one contained an inhumation and the other a cremation. Along with these two types of burial were other differences. With the inhumation there were no accompanying artifacts, while a copper implement was found with the cremation; the site of the mound containing the cremation had evidently been a dwelling site before the erection of the mound, and if this is true, it probably determined the location of the mound; there was nothing to indicate that the site of the other mound had been previously occupied, and its location was possibly determined by a desire for good drainage and a sense of the picturesque, as it was on the top of a ridge from which there was a view of the surrounding country for 10 or 15 miles. The proximity of this mound to the two inclosures, which are probably the remains of village sites,[3] leads to the tentative conclusion that it was built by the occupants of these villages, which would be consistent with the lack of evidence that the mound site had previously been a dwelling site. No such inclosures have been located near the site of the mound containing the cremation, which was in a narrow valley between two low ridges.

Not enough work has been done on Michigan archaeology to enable us to establish precisely the limits of the different archaeological groups of the state, but examination of the records in the Museum of Anthropology and of the accounts of excavations in the last forty or fifty years by Gillman, Hubbard and Harlan I. Smith[4] reveals several different types of culture based upon methods of burial. Skeletons are found in a sitting position, in a flexed position, and fully extended, lying on the back. Verbal reports have been given to members of the Museum staff of skeletons in mounds sitting facing each other, in a standing position, and lying on the back in parallel rows in groups of three's, but verification of these reports has not yet been made. There are authentic accounts of cremation for other parts of the Lower Peninsula than in Missaukee County, and it has been found accompanied by copper implements in mounds near Grand Rapids,[5] in the Ayers Mound in the city of Saginaw,[6] in a mound in Fort Wayne,[7] and in the Grattan group of mounds near Grand Rapids.[8] In addition there are reports of copper implements in mounds unaccompanied by a burial of any kind, but it is probable that in many cases ashes from cremation have been overlooked by inexperienced excavators. On the other hand copper implements have been discovered with complete skeletons and cremation has been found without accompanying artifacts of any kind.[9] A type of burial fairly frequent in Michigan is characterized by the placing of earthen pots, inverted or upright, over the heads of skeletons, or near the hands.[10] And finally, skulls with trephinations both before and after death have been found.[11] Just how far these various practices designate definite cultural groups and to what extent they correlate with the known practices of the historical Indians of this region, is yet to be determined. The differentiation of culture-groups based upon archaeological evidence alone is beset with peril unless the data are complete and voluminous. In the words of Cyrus Thomas, "It is often the case that different modes of construction and burial dependent upon station, condition in life, calling, achievements, etc., are found in the mounds apparently constructed by people of a single tribe or even a single village."[12]

Evidence is accumulating that certain traits of the prehistoric culture of Ohio extended into the Lower Peninsula of Michigan. The copper implement found with the cremation in Missaukee County resembles in detail implements of the same material found with cremated burials in the Edwin Harness Mound in Ohio,[13] and the inside of the sheath of bark in which it lay was lined with what are probably the remains of a textile fabric of some kind in which the implement was wrapped. Around the flaring end of the implement are the remains of a cord or string of finely woven material which has been completely replaced by copper salts. The copper axes in the Edwin Harness Mound were encased in bark and a woven fabric which was preserved in the same manner. The same is true for copper axes from mounds near Davenport, Iowa.[14] It is probable that when more information regarding the mounds of Indiana, Illinois and Iowa is available, the area represented by these three states and Ohio and Michigan will prove to have been occupied in prehistoric times by people with approximately the same technical culture, a culture which probably had its highest and most complete expression in the general area now comprising the state of Ohio. A list of articles found in the mounds of the Lower Peninsula of Michigan indicating a relationship to the prehistoric cultures of Ohio include mica plates, from the Grattan mounds near Grand Rapids, red ochre, a sea-shell from the Gulf of Mexico (*Busycon perversum* L.), the association of copper implements with cremated remains, copper ear-plugs, "vaults" of logs containing inhumed burials in mounds in Van Buren County, and several pieces of pottery in the Kent Scientific Museum in Grand Rapids which resemble a certain type of Ohio pottery and are not as yet found elsewhere in Michigan. So far as we can rely upon the records of excavations in Michigan in the last fifty years, supplemented by an examination of the articles of copper now in public and private collections throughout the state, there is good reason to believe that the use of copper had attained in Michigan about the same stage of development as that characterized by the Hope well culture of Ohio, in which copper was freely used both for utility and ornament.[15] Both implements and ornaments of copper are found in Michigan mounds and on the surface of the ground; ornaments of that material, however, are limited for the most part to mounds, as far as the records indicate.

Within historic times Michigan was occupied by various branches of the Algonquin family, Potawatomi, Sauk, Ottawa, Chippewa, Miami and others, and was subject to frequent invasion by members of the Iroquois family, but attempts to show that they erected the burial mounds of the region[16] have been unsuccessful. There are several accounts of Indian "funerals" in Michigan, by eye-witnesses, and burials both above the ground in log "pens" and beneath the surface are described,[17] but no mention is made of the erection of mounds. It is stated in the *Handbook of the American Indian*[18] that the Potawatomi built small mounds over their graves, but the evidence that they did so was not based upon actual observation. It is also stated here that the Potawatomi practiced cremation, which was limited exclusively to the Rabbit gens, but that their method of burial was chiefly that of inhumation. According to Pere Sebastian Rasles,[19] a certain division of the Ottawa tribe cremated their dead, while others interred their remains, but according to Bushnell,[20] his account may not be true.

European objects of brass, iron and steel have been found in Michigan burial mounds[21] and it is reported that some of the Jesuit silver, consisting of bracelets and other ornaments, now in the possession of the Museum of Anthropology, was taken from mounds near Cross Village, Michigan, but they are probably intrusive burials and should be so regarded until there is proof to the contrary. All the available evidence points to the conclusion that either the historic tribes of Michigan had discarded the practice of erecting mounds of earth by the time that white people reached this region, or that the mounds are the sole remaining evidence of the occupation of the peninsula by a people who became extinct, or migrated to other regions, before the advent of the Algonquin tribes found in possession of the state by the Europeans.

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[1] Wm. C. Mills, "The Feurt Mounds and Village Site," *Ohio Archaeological and Historical Society Publications*, 26: 321.

[2] H. C. Shetrone, "The Culture Problem in Ohio Archaeology," *American Anthropologist*, 22: 144.

[3] W. B. Hinsdale, *Primitive Man in Michigan, Michigan Handbook Series*, No. 1, p. 44.

[4] Harlan I. Smith, "Archaeology of the Saginaw Valley," *American Antiquarian and Oriental Journal*, XVI: 106.

[5] Bela Hubbard, *Memorials of a Half Century*, p. 207.

[6] Harlan I. Smith, p. 9 of his Field Notes, now in the Museum of Anthropology, University of Michigan.

[7] Henry Gillman, "*Investigation of the Burial Mound at Fort Wayne, on the Detroit River, Michigan*," Proceedings of the American Association, 1876, p. 315.

[8] W. L. Coffinberry, Coffinberry manuscript, in the Museum of Anthropology, University of Michigan, and Kent Scientific Museum, Grand Rapids, Michigan.

[9] *Michigan Pioneer and Historical Collections*, 3: 297.

[10] Bela Hubbard., *op. cit*., p. 222.

[11] W. B. Hinsdale, *op. cit*., p. 85.

[12] Cyrus Thomas, "Report on the Mound Explorations," *Annual Report of the Bureau of Ethnology*, 1890-91, p. 553.

[13] Wm. C. Mills, "Exploration of the Edwin Harness Mound," *Ohio Archaeological and Historical Publications*, 16: 156-158.

[14] R. J. Farquharson, "Recent Explorations of Mounds near Davenport, Iowa," *Proceedings of the American Association*, 1875, p. 304.

[15] H. C. Shetrone, *op. cit*., p. 156.

[16] Cyrus Thomas, *op. cit*., p. 659.

[17] *Michigan Pioneer and Historical Collections*, 27:330; 21:297; 18: 571, 574; *History of Livingston County*, 1880, Everts and Abbot Publishers, Philadelphia, p. 238.

[18] P. 291.

[19] *Jesuit Relations*, Editor Reuben Gold Thwaites, LXVII: 154-159.

[20] David I. Bushnell, Jr., "Native Cemeteries and forms of Burial East of the Mississippi," *Bureau of American Ethnology*, Bulletin 71, p. 38.

[21] John T. Blois, *Gazetteer of Michigan*, p. 167.

INDIAN MODES AND PATHS OF TRAVEL IN MICHIGAN: WATERWAYS

WILBERT B. HINSDALE

THERE was more long-distance travel upon the water than overland, except during the months when the lakes and streams were obstructed by ice. The streams brought the primitive hunters into immediate contact with a large quantity of their food-supplies, such as wild rice, fish, and water birds like wild geese, ducks, swans and the waders. The best fur-bearing animals, as beavers, minks, otters, fishers, muskrats and several others, whose skins and flesh were desired, were never found far from the water. In the summer time, deer fed along the banks in search of succulent herbage and protected themselves from flies and mosquitoes by wading to a considerable depth into the water. When hotly pursued, deer would swim into the lakes to escape from their enemies, wolves, dogs and hunters. The Indians made many of their captures of deer by overtaking them with canoes. A great many ancient camp-sites are in the vicinity of navigable streams and lakes. The canoe was an easier and, generally, more rapid means of travel than following the trail upon foot, especially when the family and household belongings were to be moved. One must bear in mind that the streams had a more constant volume before the surface run-off was facilitated by cutting away the forests, draining the marshes and swamps, and clearing out the thickets. With considerable degree of accuracy, we can make out what were the habits of primitive people from the physical surroundings in which they lived. Replace the forests, inundate the old swamps, let the streams meander as they did before the iron ax and spade came into the land, restore the animal and bird life, replenish the waters with their original numbers of fish, and the problem of how the Indians lived is easy. They themselves were a part of the wild life, an ingredient in the zoological complex, or what naturalists call the fauna. In the treatises upon the mammalia of the state, however, the Indians are generally left out, but meadow mice and bears are subjects for extended elucidation.

The Indian's bark canoes and dugouts were narrow and light. Creeks and brooks that are now quite insignificant, enabled the boatmen to ascend, in high water, for miles into places that we should deem utterly inaccessible by boat. For example, Mill Creek, that joins the Huron River at Dexter, was for miles a navigable stream for an Indian. The streams never got so low in summer as they do now and probably not often so torrential either, because the flow of water was more or less retarded by vegetation. Portages were numerous, and some of them very important to the subsistence of the population. The name 'Portage,' given to many of the lakes as well as to several streams, indicates the actual fact that they were in the line of water travel upon which there were carrying places or portages. When the "head of navigation" was reached, it was not much of a burden for the dusky travelers to carry their light canoes upon their shoulders and their scant luggage overland for a few miles to another branch of a river, flowing the other way from the one ascended, but leading in the general direction of the course pursued.

Maumee-Wabash-Little St. Joseph route. — In order to give more completeness to the account of the Indians' transportation routes of this territory, we include a small part of northwestern Ohio and northern Indiana. In ascending the Maumee from the head of Lake Erie to the St. Marys near Fort Wayne, the portage of seven miles to the Wabash is reached.[1] This, in historic and prehistoric times, was an important line of Indian travel. The French used it in going to and from their posts in Indiana. Considerable heavy freight was transported. Teams would meet the boats for the purpose of hauling goods and passengers across. Pontiac's allies and Tecumseh's warriors from the southwest came over these streams. For unnumbered years before that, it was the main line of Indian travel between the lower lakes and the Ohio River and mid-Mississippi regions. By taking the Little St. Joseph at the Fort Wayne junction, canoes could enter southern Michigan. In Hillsdale County portages of only a few miles enabled canoes to slip into the St. Joseph of Lake Michigan or into the headwaters of the Kalamazoo and of the Raisin.

Huron-Grand route. — The Huron River trans-peninsula waterway was very important to both Indians and pioneers. From the Huron, by a good-sized stream not more than forty rods long, the outlet of Big Portage Lake which is upon the line between Washtenaw and Livingston counties, the Portage Lakes are entered. Boats ascended Portage River from Little Portage Lake to the vicinity of Stockbridge in southeastern Ingham County. From this point the carry-over was but three miles to the Orchard, or what was formerly called Otter Creek, the north branch of the Grand.[2]

Mr. H. F. Wing, of Grass Lake, tells the writer that forty years ago he actually paddled across the divide between Portage River and Otter Creek, through the low lands and swamps, without having to get out of his canoe. The Indians, during high water, certainly could also do the same, and the only obstruction from Lake Erie to Lake Michigan would have been rapids and fallen timber.

The following is summarized from Samuel R. Brown in the *Western Gazetteer*, 1817 (pp. 74-75): There are upwards of twenty portages near the Michigan frontier only two of which have heretofore been used by whites. An important one of these was between the St. Marys branch of the Maumee at Fort Wayne, Ind., and the Little River branch of the Wabash and is nine miles long. It was by this route that the French, while in possession of Canada, passed to their forts upon the Wabash and on to the Ohio. Boats not infrequently passed from Lake Michigan into the Illinois and in some instances it was not necessary to have their lading taken out. In the winter of 1792-3 two boats (*pirogues*) were detached from Detroit, which passed without interruption from the Huron River, which enters Lake Erie, into the Grand River, which falls into Lake Michigan, by means of the rise at the heads of the two streams.

The Grand, the largest river of the state, afforded communication, by its tributaries, in many directions. One could go directly to its mouth at Grand Haven. At Ada, in Kent County, he could divert to the Thornapple and reach the center of Eaton County. By a short portage near the present site of Charlotte, Battle Creek is entered. Descending this stream in western Calhoun County, where the city of Battle Creek now stands, its confluence with the Kalamazoo opened up a water-route east or west. By leaving the main Huron-Grand channel at Big Portage Lake, in Livingston County, and going up Pinkney Creek as far as conditions of canoeing would permit, it is a carry-over of but a few miles to Cedar Lake in Marion Township, Livingston County, the head of Cedar River.[3] Cedar River unites with the Grand at Lansing in Ingham County. The Maple and Looking Glass rivers, branches of the Grand, as important channels of communication, will be traced in connection with Saginaw River tributaries.

Raisin-Kalamazoo-St. Joseph-Grand routes. — The Raisin has several branches. By the Saline River, which enters the Raisin at the old Macon Reservation in Monroe County, the salt springs of Washtenaw County, where the present village of Saline stands, were reached. At dark's Lake, southeastern Jackson County, which drains into the Raisin, the land obstruction was not more than three or four miles to the south branch of the Grand. In going directly up the Raisin into eastern Hillsdale County, portages less than a township wide would reach the Kalamazoo entering Lake Michigan at Saugatuck, Allegan County, the St. Joseph entering the same lake at St. Joseph, Berrien County, or the Little St. Joseph connecting at Fort Wayne, Indiana, with the Wabash and Maumee for "points east or west."

"From the southernmost portion of the great bend of the St. Joseph it is only a short four miles across to the headwaters of the Kankakee which, with the Illinois, empties into the Mississippi. In the old days this little neck of land was a famous crossing place, or portage, for the Indians of the south and west on their journeys to the northern wilderness. Once over the divide, by turning to the right they could follow up the St. Joseph to the fine hunting grounds beyond or a short paddle would bring them to Fort St. Joseph, a small French trading post or garrison."[4]

One must not forget the pristine situation of the landscape. Before the forest and brush cover were removed, the depth of water in the channels was more regular and never got so low as it does since the clearing was done and since the swamps were drained and the ditches dug. For example, what the older maps designated as the St. Joseph of the Maumee, a rather crooked stream, is now for miles a straight drain called the Maumee Ditch. The steam-shovel and the woodsman's axe have markedly accelerated the run-off of the surface water which at one time was sufficient to buoy up an Indian's dugout. In many parts of the state, the water table has been lowered as much as five feet and is going down all the time.

In pioneer times, steamboats were operated upon the St. Joseph as far as Three Rivers in St. Joseph County.[5] Navigation companies once promoted steam navigation upon the Kalamazoo. Flat boats came to within two miles of Ypsilanti upon the Huron. Steamers plied regularly upon the Grand up to the Rapids and above the Rapids pioneers did much freighting up to the Maple. Boats carrying two hundred barrels of flour descended the Shiawassee from Owosso to the Saginaw.[6] In early times there were all kinds of canal schemes to connect the natural waterways at the portages so that commerce could reach the inland counties, which led to extensive "wild-cat" speculation.

Grand-Saginaw route. — Canoes could ascend the Grand to Lyons, Ionia County, take the Maple and approach within the breadth of a half-township the Shiawassee in the center of the county of the same name, and descend to Saginaw Bay, going the entire length of the Saginaw River which is really only a continuation of the Shiawassee. The Looking Glass, which enters the Grand at Lowell, Ionia County, practically parallels the Maple to southern Shiawassee County and to Conway Township in northwestern Livingston.[7]

Saginaw-Tittabawassee-Chippewa-Muskegon route. — Suppose one were at the mouth of the Saginaw below

Bay City and wished to reach Lake Michigan at the mouth of the Muskegon. He could have done so, a hundred years ago, by boat, with only five or six miles of land obstruction in eastern Mecosta County. *Directions:* Ascend the Saginaw to the Tittabawassee, go up that stream to Midland, divert to the Chippewa River, on to Chippewa Lake in Chippewa Township, Mecosta County. Walk three miles, the guide carrying canoe, to Pogie Lake, same township. The outlet of that lake is a branch of the Little Muskegon. Go with the current. Look out for rapids. Or, if one would wish to arrive at the place where Ludington now stands, by going down the Little Muskegon to its junction with the main stream, he would turn up and ascend as far as the middle of the western side of Mecosta County. Two or three miles' portage to the west would bring him to the Pere Marquette River at the mouth of which is Ludington. Again, less than ten miles separates the head of the Chippewa from the Muskegon, main branch, in Osceola County. For boundary between Montcalm and Gratiot counties, take the Pine from the Tittabawassee. There was, at an early day, a line of flat freight boats projected to ply between Alma, in north-central Gratiot County, upon the Pine, and Saginaw.[8] The Cass River passes through what was a thickly populated Indian district lying east from the Saginaw. Down this stream, according to archaeological evidence, the Indians brought hundreds of chert nodules from which they made arrow points, knives and other edged tools. The Flint River nearly parallels the Cass into the "Thumb" and was used extensively in Indian commerce.

Au Sable-Manistee-Muskegon routes. — Ascend the Au Sable River to the boundary between Crawford and Otsego counties. Carry-over six miles to the swift Manistee and go merrily on to Lake Michigan. Wishing to reach Muskegon Lake and Lake Michigan into which it discharges, follow the south branch of the Au Sable, in Crawford County, to near Higgins and Houghton lakes in Roscommon County. Houghton Lake, the largest inland lake of Michigan, drains into the main stream of the Muskegon.

There were many other minor water circuits that facilitated random travel by the Indians. The Clinton-Huron circuit passed through Macomb, Oakland, Livingston, Washtenaw, Wayne and the northeast corner of Monroe counties. There was a Cheboygan, Mullets Lake, Burts Lake, Crooked Lake connection from Cheboygan to Little Traverse Bay.

Keweenaw-Peninsula cut-off. — A boat of almost any size could, by the Portage Lake inlet from the head of Keweenaw Bay, go to within three miles of Lake Superior. A light canoe made this passage with but a mile of portage, thereby saving eighty miles of travel that would be required by going around the point. The ship canal has now eliminated the obstruction and large steamers cross the peninsula.

Menominee-Sturgeon rivers route between Green and Keweenaw bays. — Foster and Whitney describe in detail the route which they took in the fall of 1848 coming from L'Anse to Green Bay. They remark that the streams they traversed, beside those of this route, had been Indian canoe-ways long years before voyagers came. The crossing from the Sturgeon, flowing into Keweenaw Bay, to the Michigamming, a branch of the Menominee, is in Township 48 W., R. 32 W., southwestern Baraga County. This trip required eleven portages around rapids varying from a half-mile to several miles each.[9]

Mr. George H. Cannon says the Wisconsin, which empties into the Mississippi, the Menominee with its branches, emptying into Lake Michigan, the Ontonagon, the Sturgeon and some others flowing into Lake Superior were navigable by bateaux for considerable distances from their sources, while the Indian, with his light bark canoe, could, with ease, overcome hindrances to freight-carrying boats and by shouldering his own make a portage around rapids and other obstructions and set out on the waters beyond. By such means streams were followed to their sources, divides crossed and voyages continued.[10]

In this paper frequent references have been made to the uses the pioneer tradesmen made of the streams. If traders could navigate so far in their scows and bateaux, the narrow, shallow and light craft of the Indians could, and did, go many miles farther.

The following by Dwight Goss is pertinent: "In autumn an entire family, and sometimes two or three families together, would leave the villages and wander up the smaller streams into the forests of the interior for their winter's hunt, and they would generally camp in or near a bunch of maple trees in order that they might make maple sugar in the spring. Indian villages and camping places were almost invariably upon banks of rivers and small streams."[11]

The white mechanic has not invented or perfected an appliance that more nearly fits a need than the bark canoe fitted the needs of the Indian. It could float on very shallow water. It was so light that when a portage or obstacle was reached, it could be lifted out like a basket. Accidents often occurred, for the bark canoe was easily punctured by sharp rocks, submerged roots and other parts of trees. When it was damaged bark, pitch and wattap were at hand for repairs.[12]

The canoe obeyed the propelling and guiding hand more sensitively than a power boat responds to its rudder. Without seeming effort, as a duck directs its course through the water by its perfectly adjusted foot, the Indian men and women directed their canoes by the blades of their paddles.[13] Foster and Whitney remark: "Communication throughout the northwest between distant points is effected almost entirely with the canoe. It serves the same purpose as the ship on the ocean or the camel on the desert."[14]

While it is out of the geographical limits of Michigan, it is interesting to trace the route of Marquette and Joliet from Lake Michigan to the Mississippi by the way of Green Bay, Fox and Wisconsin rivers. The portage from the one of these rivers to the other Marquette calls "2700 paces." Thwaites says, in his life of Father Marquette,[15] "With high water in the Wisconsin, this plain has frequently been flooded, so that continuous canoe passages from the Great Lakes to the Mississippi has been possible." Ordinarily, the portage was a mile and a half. To go still farther afield, for the sake of emphasizing the importance of water communication employed by the Indians, it was possible, and also practicable, for oar-propelled boats to go from the head of Niagara Falls to the mouth of the Mississippi by several routes, and, conditions being favorable, to do so, in some cases, without unloading.

The longest would have been the Huron-Grand route from the head of Lake Erie, to Lake Michigan, skirting that lake along the shore to Green Bay and following Marquette's route to the Mississippi. Then there was the Raisin-St. Joseph route across Michigan to nearer the head of Lake Michigan. From this lake, taking the channel now followed by the Chicago drainage canal to the Illinois river, the way was clear to the Mississippi and, at high water, continuous without unloading boats. La Salle followed this route upon one of his return trips from central Illinois, reaching Lake Erie by the Huron River. The Kankakee River, from near Chicago, afforded good facilities for leaving Lake Michigan. There is an old portage from the Sandusky River to the head of the Scioto. Probably the most important route was the Maumee-Wabash. The shortest route, which was used in both prehistoric and historic times, and which was controlled by the Iroquois, was to leave Lake Erie, where Cleveland is now situated, ascend the Cuyahoga to near the present site of Akron, follow the Portage Path seven miles to the Tuscarawas, down that stream to the Muskingum, which enters the Ohio River at Marietta, which in prehistoric time was a seat of wonderful industry, as evidenced by the extensive earthworks that existed there.

The intention is to follow this chapter by another upon "Trails."[16]

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[1] Map in Cadwallader Colden's *History of the Five Nations*, 1755.

[2] H. C. Carey and I. Lee, *Geographical, Statistical and Historical Map of Michigan Territory*, Philadelphia, 1823.

[3] Mrs. Franc. L. Adams, *Pioneer History of Ingham County*, p. 483. "Cedar River can be ascended for 25 or 30 miles by boats." — p. 125.

[4] Clyde Ford, *The White Captive, A Tale of the Pontiac War*, pp. 1-2.

[5] Fuller's *Economic and Social Beginnings of Michigan*, pp. 292-293.

[6] *Michigan Pioneer Collections*, 2: 486.

[7] "It (the Grand) is navigable 240 miles for bateaux, and receives in its course as its principal tributaries the Rouge, Flat, Maple, Looking-Glass and Red Cedar Rivers on the North, and the Thornapple on the South. It is navigable for steamboats 40 miles to the Grand Rapids, below which it has not less than four feet of water. At the Rapids a canal is constructing; and after it is completed steamboats may go up to the Village of Lyons, at the mouth of the Maple, a distance of 50 miles from the Rapids, without difficulty." — Mrs. Franc. L. Adams, *op. cit*., p. 126.

[8] *History of Gratiot county*, 1913, p. 44.

[9] *Report of the Geology and Topography of a Portion of the Lake Superior District, State of Michigan*, Part 1, 1850.

[10] *Michigan Pioneer Collections*, 30: 46.

[11] "The Indians of the Grand River Valley," *Michigan Pioneer Collections*, 30: 172.

[12] Footnote, p. 29, of Foster and Whitney's *Report of the Geology and Topography of a Portion of Lake Superior District*, 1850.

[13] T. L. McKenney, *Tour of the Great Lakes*.

[14] P. 23.

[15] P. 186.

[16] Since the foregoing was written the attention of the writer has been called to Franquelin's map of the eastern part of what is now the United States, made in Paris, 1688, upon which is distinctly marked a portage between the Saginaw and the Maple rivers, the Maple being the north branch of the Grand.

A POSSIBLE OCCURRENCE OF THE RICHMOND FORMATION IN THE VICINITY OF CLAYTON, IDAHO

CHARLES W. COOK AND GEORGE M. EHLERS

CLAYTON is situated near the center of Custer County, Idaho, approximately fifty miles northwest of Mackay, the terminus of the Blackfoot division of the Oregon Short Line Railroad. The main stratigraphic features of the area have been described by Umpleby[1] as follows: "The oldest rocks exposed in northwestern Custer County are schists, slates and quartzites of Algonkian age. Unconformably on these rocks in the eastern and locally in the northwestern part of the area lies a great series, at least 9,000 feet thick, of Paleozoic quartzites, slates and dolomitic limestones. These were not further subdivided, although there is some reason for thinking that they range in age from Cambrian to Devonian inclusive." He further states that fossils were not found. The finding of fossils in the Clayton area is thought, therefore, to be of sufficient significance to warrant recording the fact.

Fossils were found at two places in the canyon of Squaw Creek, a tributary of the Salmon River, entering this river from the north at a point about four miles west of Clay ton. The fossils suggesting the possible occurrence of the Richmond formation in the area were obtained from a dark gray, finely-crystalline dolomite exposed near the Redbird mine on the east side of Squaw Creek five miles above its mouth. Similar material was found at the Saturday mine on the west side of the canyon near the mouth of Squaw Creek.

All the fossils examined belong to a single species of compound coral. The specimens of the coral are composed of cylindrical corallites, usually separated from one another by interspaces of about 1 mm. to 5 mm.; some corallites are in contact and a few others are distant from one another as much as 10 mm. The average diameter of the corallites is about 3.5 mm. The diameter of the smallest one observed is 2.5 mm. and of the largest 4.5 mm. Where they appear at the surface of the weathered dolomite, the corallites are more or less silicified and show very imperfectly the septal arrangement. In a few better preserved corallites, sixteen septa reaching nearly to the center of the corallite were counted; alternating with these are shorter, almost rudimentary septa. The exterior of the corallites is marked by indistinct annular lines of growth and faint longitudinal lines corresponding with the septa within. Below the weathered surface of the rock, the corallites show no internal structure, owing to the fact that they have been removed by solution and the resulting cavities filled with crystalline, yellowish-stained calcite and a small amount of quartz. Such structure as is preserved in the corals suggests very much that of the late Richmond species, *Columnaria* (*Palaeophyllum*) *stokesi* (Edwards and Haime). Better preserved specimens of this coral may show structures proving this tentative identification of the coral to be incorrect.

Although the evidence is not conclusive, the corals are strongly suggestive of the late Richmond age of the beds in which they occur. On lithological grounds, Umpleby correlates the Clayton section[2] with the section near Gilmore,[3] Lemhi County, and assigns the 200-300 feet of massive blue dolomite above the massive quartzite to the Ordovician. In the Gilmore area, he found two groups of fossils concerning which Kirk[4] says they "seem to indicate unquestionably the Richmond age of the beds." In the Mackay area, Umpleby[5] also obtained a few fossils from the dolomitic beds above the massive quartzite, which he quotes Kirk[6] as saying "are certainly Richmond in age" and "should be correlated with the Fish Haven dolomite of Richardson."

It may be of interest to point out that Ulrich[7] in his paleogeographic map of Richmond time has extended the sea into and beyond the area in which the fossils under discussion were found. If this extension of the sea is based upon fossils from this area, the writers are unaware of the fact and believe that the occurrences just described afford evidence in substantiation of this portion of his map.

No attempt has been made to establish a stratigraphic section for the area in which the fossil corals were found as a considerable amount of faulting has taken place there. Hence, in the absence of more fossil evidence, more detailed knowledge of this faulting than is at hand at present, is necessary before the attempt should be made to establish a stratigraphic section on lithological grounds alone.

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[1]Umpleby, Joseph B., *U. S. G. S. Bull*, 539, 1913. 51

[2] *Ibid*., p. 20.

[3] *U. S. G. S. Bull*, 528, 1913.

[4] *Ibid*., p. 33.

[5] *U. S. G. S. Prof. Paper* 97, 1917.

[6] *Ibid*., p. 25.

[7] Ulrich, E. O., *Congrès Geologique International, Compte Rendu de la XII[e] Session*, p. 665, 1913.

THE GEOLOGY OF LA SAL MOUNTAINS OF UTAH

LAURENCE M. GOULD

CONTENTS

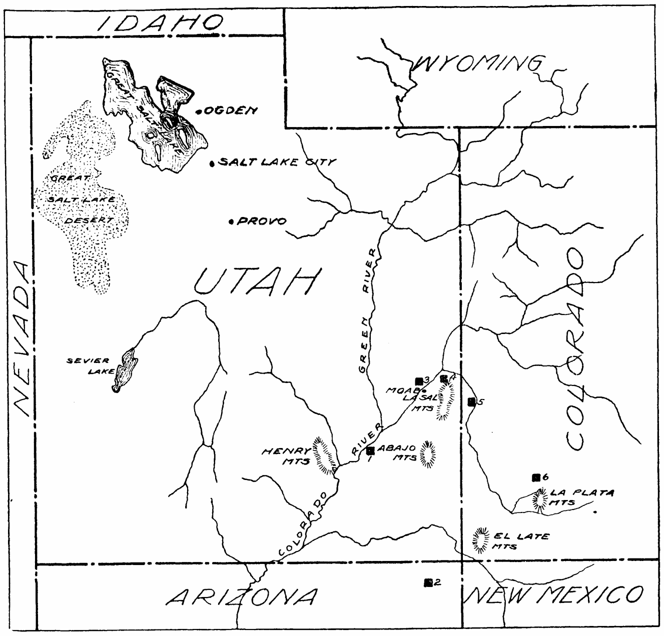
I. PHYSIOGRAPHY

LA SAL MOUNTAINS lie within the great Colorado plateau country so notable for its cliffs and canyon walls which exhibit with unparalleled perfection great cross-sections of the earth's history. The mountain group is nearly bisected by the meridian of 109 degrees and 15 minutes west longitude and lies between 38 degrees and 20 minutes and 38 degrees and 35 minutes north latitude (Map 1). The Colorado-Utah boundary line is distant only seven miles to the east.

One's first impression of this plateau country is deceptive. It seems to be a relatively flat surface possessing no marked features of relief; one needs to travel but a short distance across it, however, to be undeceived. It is found to be dissected by a veritable maze of canyons, most of which are steep-walled and present few favorable crossings. Permanent streams are found in only a few of them. The deceptive character of the topography is due primarily to the fact that there are practically no features, aside from the mountains themselves, which have been caused by uplifts of any consequence. The immense incisive work of running water over a once relatively flat surface has been the major factor in the development of this peculiarly deceptive relief. The almost total absence of depositional features further accentuates the results of the stream action.

Influence of Structure on the Erosional Processes

In the erosional processes which have been operative, whether due to wind or water, the rock structures have controlled to a marked degree. Indeed one might almost say that the present physiographic development is a direct reflection of the structural features of the plateau province. Longitudinal fractures along the nearly flat-lying anticlines facilitated the establishment of streams until these structures have become valleys separated by mesa-like lands which represent the synclinal areas. Joints and faults in the Navajo sandstone, which covers so much of the surface west of the mountains, have controlled the weathering and erosional processes with the production of rounded and elongated dome-like forms almost equally spaced. Northwest of the mountains, where the Wingate is the cover rock, fractures and joints have caused the formation of great mesas, which with the passage of time have been subdivided into smaller mesas and these in some places into buttes often capped only by small pinnacles (Pl. I, Fig. 1) of what formerly was an extensive overlying rock.



MAP 1. Index map to show location of La Sal Mountains and other laccolithic mountains of neighboring regions and of the areas from which the columnar sections of Figure 1 are copied or derived

Work of Running Water and Wind

Because of the immense amount of denudation which this region has undergone since Tertiary time, it is not possible to estimate the rate of the various agents operative in this semi-arid climate, or to evaluate with any degree of accuracy their relative importance. It is obvious, however, that running water has played the major role. The sparseness of the vegetation has been an important factor in the operation of this process as well as in the work of the wind. The run-off is extremely rapid and correspondingly effective in its erosional effects. In but a few minutes what seems to be a small rain may fill perfectly dry washes with raging torrents which transport enormous amounts of detrital matter. In an almost equally brief time enough water and debris may be added to the Colorado itself from side canyons to change it from a rather shallow stream, sluggish in places with noticeable sand bars, into a muddy turbulent river carrying an immense load. In the various weathering and erosional processes which are contributory factors to the efficiency of this sort of denudation, wind, temperature changes and frost, in the order named, are the most important. The wind is effective in two ways. In the first place it is an important agent of transportation in bringing much sand and other detritus to the streams or canyons where it may be further worked over and carried away. Again, in the formation of many of the land forms which now stand out in relief, wind action is seen to have been a dominant factor. Mention has already been made of the buttes and mesas in the Castle Valley region, which show in part the effects of wind, but a much more interesting group of such erosion remnants are the so-called "windows." These lie on the west side of Colorado River about twelve miles northwest of Moab. Here is a veritable museum illustrating the varied and fantastic forms that may result from wind-weathering and erosion. Joints together with cross-bedding have so controlled the denudational processes that massive castellated forms, chimneys, caves, bridges and arches of great variety have been developed (Pl. I, Fig. 2). This group of features presents such unusual scenic effects that from this standpoint alone they are deserving of wider recognition, and it is of interest to note that a movement is now on foot to have this unique region set aside as a national monument.

As one proceeds towards the mountains from the west, he is impressed with the changing profiles presented by the various physiographic forms. Whether the route is through Castle Valley (Pl. I, Fig. 1) or makes its way up over the sand flats (Pl. II, Fig. 2) from Moab, the sharp clean-cut erosion forms of semi-arid climates dominate the early part of the trip. As one ascends the first mesas west of the mountains, these give way to softened slopes and to land surfaces partly covered with vegetation, and finally as one climbs the last shelf adjacent to the foot of the mountains he finds himself on rounded forms such as characterize humid climates.

Vegetation is much thicker and the lower slopes of the mountains are densely forested with aspen and spruce. As one finally stands on the mountain tops the contrasted aspect presented by the plateau country on the Colorado side of the mountains as compared with that on the Utah or western side is very striking. To the west, except for the forested slopes of the mountains themselves and the vegetation-covered mesas that stretch a few miles out into the plateau lands, the landscape is largely one of bare rock surfaces. Even from so great a distance all manner of erosional forms typical of semi-arid climates are easily recognized. The buttes and mesas of the Castle Valley region and the rounded dome-like forms of the Navajo sandstone can be clearly identified. On the east or Colorado side of the mountains the bright-colored canyon walls of bare rock surfaces stand out in sharp contrast against the green of the more or less vegetation-covered lands. Sharp or clean-cut profiles like those of the western side are here much less pronounced. It is evident that on this side of the mountains more humid climatic conditions obtain.

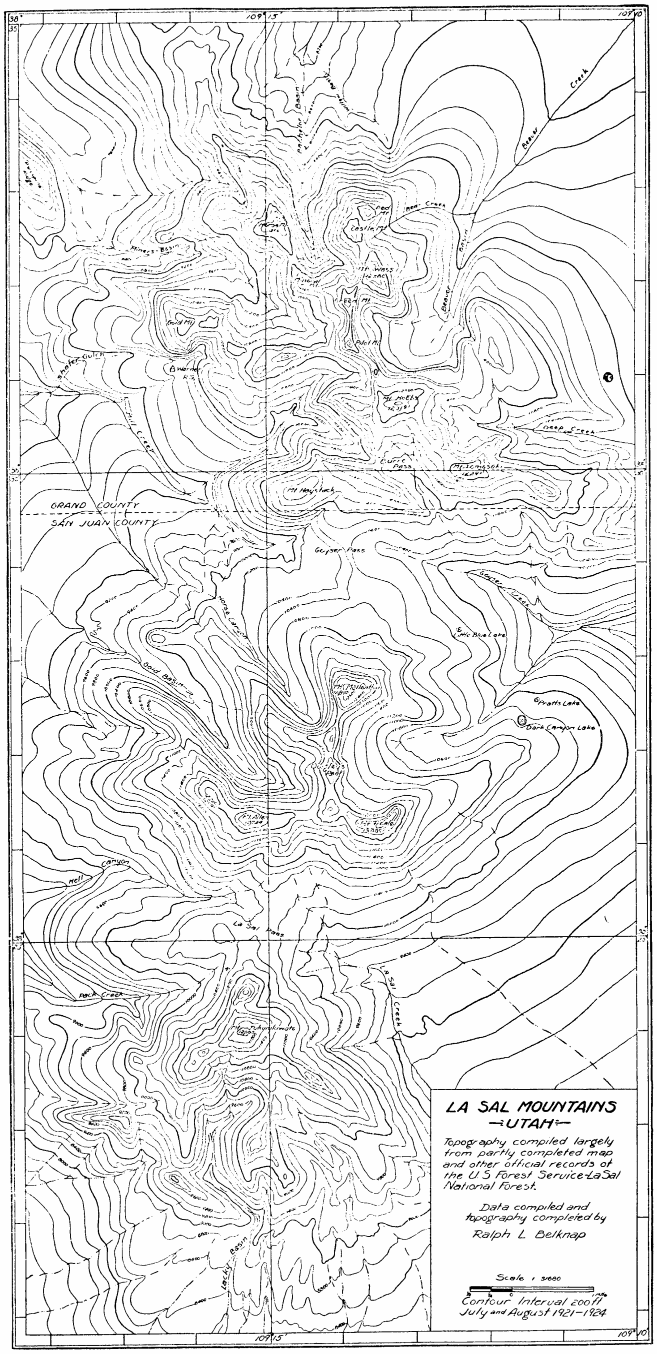
PHYSIOGRAPHIC DEVELOPMENT OF LA SAL MOUNTAINS

The Distribution of the Peaks and the Relief

La Sal Mountains as a whole consist of some twenty major peaks divided into three groups (see Map 2). These groups indicate areas of igneous activity and are separated by sedimentary saddles. Geyser Pass divides the north and central groups and La Sal Pass the central and southern groups. These passes are about a mile and a half wide. Most of the peaks are in the north group, which is greater in extent than the other two groups combined; only one major peak is found in the south and only three in the central groups. The central group, however, is considerably higher than either of the end groups and the three peaks here are the highest mountains in the whole region. The upper slopes of the mountains for 2,000 to 3,000 feet are quite precipitous. On the eastern side the lower slopes flatten out gradually and continue into Colorado at the level of the Dakota sandstone. Westward toward the Colorado River the descent from the mountains is more precipitous. The upturned sediments about the igneous cores flatten out very near the mountains proper, but the farther one goes westward from the mountains the greater is the depth to which erosion has proceeded. As a result, one descends by a series of stratigraphic steps, often with enormous treads, from the Mancos shales of Cretaceous age adjacent to the mountains, to the Carboniferous exposed in Moab Valley near the Colorado River. The summits of the peaks range in height from 11,000 to 13,000 feet. At Moab the Colorado River reaches a level of 4,000 feet. Of this difference in elevation between the mountain tops and the Colorado, fully half is due to the mountain uplift.

Weathering and Erosional Processes

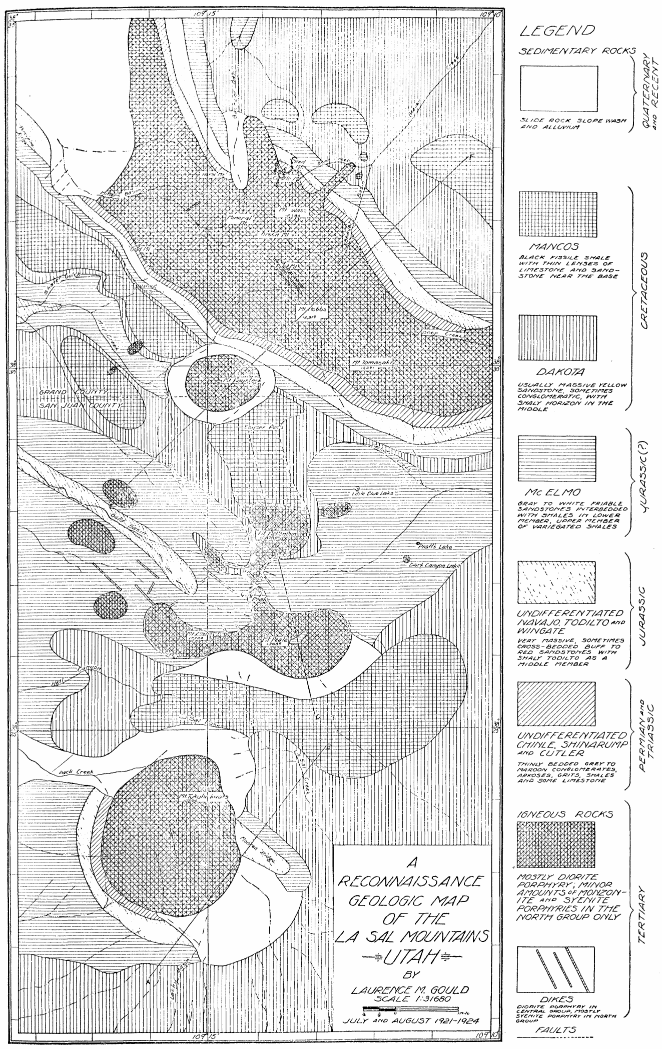
The mountains, including the sedimentary saddles or passes, are so much higher than the surrounding country that the drainage system as a whole is practically radial (see Map 2). The principal streams which drain into the Dolores River are: Beaver Creek, which heads in Beaver Basin of the north group; Rock Creek, which is formed by the junction of Geyser Creek and Deep Creek; and La Sal Creek (Tukuhnikivats Creek of the Hay den Survey map), which heads in La Sal Pass and the south group. The streams which flow directly into the Colorado River are Mill Creek which drains the greater part of the western slopes of the mountains and enters the Colorado by way of Spanish Valley and Castle Creek, which heads in the north group and enters the Colorado through Castle Valley. Though many of the mountain streams are not permanent, those whose courses extend across the surrounding mesas have in many cases cut deep canyons; of these the Mill Creek Canyon (Pl. VI) is the most pronounced.



MAP 2. Topographic map of La Sal Mountains

So far as the surface expression of the north and south groups of the mountains is concerned, the structure has had a profound effect. The shaly or thinly bedded strata adjacent to the igneous centers have eroded more rapidly than either the massive sandstones farther removed or the hard porphyry cores themselves. Hence these two groups present the aspects of gigantic necks surrounded by loosely fitting collars. In some places the mountain streams parallel the neck until an opening across the massive collar is reached. Structural conditions such as those described are lacking in the central group, so that here the higher precipitous mountain slopes merge with the lower slopes with no great breaks and the drainage is quite regularly radial.

Above the vegetation-covered slopes of the mountains the rocks have been so split and broken up by very intensive frost action that even the peaks and most of the slopes are covered with loose angular blocks sometimes of enormous size.



MAP 3. Geologic map of La Sal Mountains

Glaciation in the Mountains

The effects of the Pleistocene glaciation are still strongly marked in parts of the mountains. This statement applies to the erosional rather than to the depositional features, for the glaciers were very short and except in the central group did not leave deposits which are still very prominent. The heads of the major valleys in the mountains are referred to as 'basins.' The term in this sense usually means a feature much broader than the typical V-shaped valley head formed solely by the erosional work of running water. Most of these so-called basins are cirques. In the north group Miners' Basin, Bachelor Basin, Beaver Basin (Pl. II, Fig. 1) and Deep Creek Basin (Pl. III, Fig. 1) there occur prominent cirques. The glaciers did not extend far enough from any of these cirques to form recognizable U-shaped valleys. In most of them, however, low rounded deposits of morainal character are still preserved. In the central group the glaciers were developed on a larger scale. The head of Horse Canyon, Gold Basin, and the head of Dark Canyon are all well-developed cirques. In Dark Canyon and Gold Basin (Pl. III, Fig. 2), the glaciers have extended far enough from the cirques to form U-shaped valleys, which are still easily identified. Dark Canyon seems to have possessed the largest glacier in the whole mountain area. It not only scoured out the most extensive U-shaped valley, but left morainal deposits of sufficient magnitude to dam up the valley and to form morainal lakes. Dark Canyon Lake is the largest of these. About three fourths of a mile below it lies Pratt's Lake (Pl. IV, Fig. 1), which shows with particular clearness its morainal dam. Little Blue Lake northeast of Mt. Mellenthin is also a morainal dam lake. These three lakes are the only ones that merit the dignity of being so called, but there are numerous other basins, some of which are filled with swamps which owe their existence to glacial deposition.

There is some question whether or not the south group was glaciated. It is much lower than either of the other two groups and hence may have escaped such action, but Lackey Basin and the basin to the upper right of Pack Creek may be in part the results of glacial erosion.

Rock Glaciers

So-called rock glaciers are found in nearly all the cirques and along some of the valleys. These present a different profile and relief from ordinary talus slides. Rude concentric ridges characterize the lower lobe-shaped fronts which rise rather steeply from the valley floor upon which they appear to be advancing. Capps,[1] who studied similar phenomena in Alaska, believed that such masses were in actual motion because of the formation of interstitial ice. Howe,[2] after studying the same phenomena in the San Juan Mountains, reached the conclusions that the rock glaciers were not in motion and that their present position is due to landslides rather than to any glacier-like motion induced by the formation of ice in the crevices between the rock fragments. The latter theory seems more probable to the author than that of Capps. The best developed rock glacier in all La Sal Mountains is not found in or at the base of a cirque, but at the bottom of a steep valley side (Pl. IV, Fig. 2). The valley side from which the material of this rock glacier came is still so steep that it is difficult to see how it could have reached its present position in any other way than by landslides, as suggested by Howe.

II. THE SEDIMENTARY ROCKS

No beds older than Permian or possibly Permo-Pennsylvanian are exposed in the immediate vicinity of the mountain uplift. If, however, we consider Spanish or Moab Valley, as it is variously called, as a part of La Sal Mountain province or region, then there is exposed a sedimentary series extending from the Hermosa of Upper Pennsylvanian to the Mancos of Cretaceous. About a mile of strata is included in this series.

GENERALIZED SECTION OF THE ROCKS IMMEDIATELY TO THE WEST AND NORTHWEST OF LA SAL MOUNTAINS

The thicknesses were measured by aneroid

Series	Formation	Thickness (in feet)	Lithological Character
Cretaceous	Mancos	0 to 600	Black fissile shale with thin lenses of limestone and sandstone near base
	Dakota Sandstone	200	Light yellow, sometimes conglomeratic sandstone; sometimes two sandstone members with thin shale between
Jurassic?	McElmo	1000	Grey to white friable sandstones interbedded with shales in lower part; an upper division of variegated shales
Jurassic	La Plata Group Navajo Sandstone	800	Two massive members of brick-red to white, sometimes cross-bedded sandstone, separated by a thin zone of red shales, occasionally with some limestone; a prominent cliff-maker
	Todilto	0 to 200	Deep red thinly bedded sandstones and shales
Triassic?	Wingate	100 to 200	Massive somewhat cross-bedded deep red sandstone; vertical joints produce a columnar effect; a prominent cliff-maker
Triassic	Chinle		Thinly bedded red to red-blue sandstones and shales
	Shinarump Conglomerate	200	Very thinly bedded greyish-maroon calcareous conglomerates and sandstones
Permian	Cutler	800+	Purple, red, pink and sometimes white conglomerates, sandstones, shales, grits, arkose and earthy limestones

The Pennsylvanian has but a limited exposure, being found only in the bottom of Moab Valley. And here only a small part of the entire formation comes to the surface. As one studies the successively younger formations to the Navajo, he finds that all have an ever increasing area of outcrop. The Navajo sandstone of the Jurassic has the greatest areal distribution and constitutes the chief surface rock in the region between the Colorado River and La Sal Mountains. On the western side of the mountains, formations younger than the Navajo are restricted to the mesas which extend out five to seven miles from the base of the mountains. The youngest rock, the Mancos shale, is preserved only in small patches on the tops of the high mesas and on the saddles between the three groups. East of the mountains erosion has not proceeded as far as on the western side and the Navajo is nowhere exposed, except along canyon walls and where it is upturned about the mountains. The McElmo and, to a much greater extent, the Dakota, cover the surface on this side of the mountains.

The Pennsylvanian and Permo-Pennsylvanian

In the upper (northwestern) end of Moab Valley a thickness of at least 500 feet of grits, sandstones, shales and limestones is exposed along the valley. This series is predominantly sandstone and arenaceous shale, though some of the limestone strata attain a thickness of as much as 40 feet. The limestones are hard blue and blue-grey, especially in the lower part of the exposure. Reddish limestones are found higher up. Not only the limestones of the lower zone, but the sandstones and shales as well, are generally grey. In contrast to this the upper beds are dominantly red. Cross[3] called this series Hermosa. Its division into a lighter-colored zone below and a dominantly red one above is, however, suggestive of a possible separation of the two parts. Recognizing this fact Prommel[4] calls attention to the striking exactitude with which the description of the Rico from the type locality by Cross and Ransome[5] fits the upper portion of this Moab Valley series. He therefore recognizes the upper red portion as the Rico of Permo-Pennsylvanian age and the lower grey members as the Hermosa of upper Pennsylvanian.

The Permian

Because of its predominantly red color and sandy character the Rico is difficult to distinguish from the overlying Permian beds. Lithologically it resembles more closely the Permian above than the Hermosa below. These next younger beds, of Permian age, are the Cutler of the San Juan Mountains or the Moenkopi of the Navajo country. The formation is here mainly a series of thinly bedded maroon, "liver-colored," sometimes purple, conglomerates, sandstones, grits, arkoses, shales and minor amounts of limestone. Though the dominant color of the formation is red, there are lighter-colored horizons, especially in the lower portion. These are grey, greenish or pink grits, arkoses and thin sandstones. Occasional blue-grey or reddish earthy limestones occur with these lighter-colored rocks. The grits are generally friable; some effervesce when treated with dilute hydrochloric acid, which indicates a calcareous cement. Not infrequently the grits and conglomerate beds are three or four feet thick. In one locality a grey grit reached a thickness of from 10 to 12 feet. The upper portions of the formation are generally very thinly bedded and easily eroded. Where properly exposed, they produce a sort of bad land topography (Pl. V, Fig. 2).

The Cutler is locally gypsiferous. On either side of Moab to the east of the Colorado, low rounded hills of gypsum and gypsiferous earth are found along the base of the cliffs that form the valley walls. The upper central part of Castle Valley is covered with a light grey to very white porous gypsum. Together with the steep red-maroon valley walls on either side, this occurrence furnishes a notable display of rock color contrasts. The thickness of the gypsiferous part of the formation could not be determined. It is apparently very lenticular, but attains great thicknesses at various places.

The base of the Cutler does not outcrop in Castle Valley nor in the adjacent Colorado Canyon. Its maximum exposure does not here exceed 800 feet. In his Cutler-Moenkopi series, Prommel[6] places 1,300 to 1,400 feet of strata.

The Cutler is separated from the overlying beds by a great unconformity. Less than a mile down the Colorado Canyon from the place where Castle Valley enters, the angular character of this break is clearly shown on either side of the river (Pl. V, Fig. 1). In Moab valley this unconformity is apparent on account of a rapid thickening of the beds toward the northwest.

Although the formations here described as Cutler show many features similar to the Moenkopi of the Navajo country, at no place within the entire area studied is there any equivalent of the De Chelly sandstone. Descriptions of the same series of rocks from Paradox Valley[7] and other localities but a few miles east of the mountains fit the exposures in the immediate vicinity of the mountain uplift so well that it seems desirable to retain the term Cutler for the whole series. To be sure the gypsiferous phase of Moab and Castle valleys has no well-defined equivalents in the San Juan Mountains, nor even in the areas nearer the mountains mentioned above, and it might be well to emphasize the fact that the occurrences of gypsum here described as a part of the Cutler must not be confused with the occurrences of gypsum, gypsiferous shales, and the like, in the bottom of Paradox Valley and in similar localities of western Colorado. Coffin[8] points out that the gypsiferous series in the region of Gypsum Valley are separated from the Cutler by a well-recognized uncomformity. But he further states that considerable quantities of gypsum are found in the red shales of the Cutler itself, though at no place, to judge from the descriptions of the sections cited, on a scale comparable to the occurrences in the Moab and Castle valleys. Beds of recognized Permian age carrying gypsum have been described from many widely separated localities in the western states. It is so often not a persistent member that its absence or presence in adjoining areas, such as La Sal Mountain region and the neighboring parts of Colorado, can hardly be considered significant enough to prevent the correlation of otherwise similar beds.

The Triassic Formations

Overlying the Cutler is a series of very thinly bedded maroon or greyish-maroon, partly calcareous conglomerates. The presence of light-colored pebbles accounts for the greyish cast of the rock. These beds are the "saurian conglomerate" of Colorado. In his reconnaissance trip through this region Cross[9] noted the occurrence of fragments of bones and teeth of crocodilian or dinosaurian animals in this member. Some two hundred feet above this conglomerate in Castle Valley comes the massive Vermilion Cliff or Wingate sandstone. The rocks in between evidently do not all belong to the conglomerate series at the base. Indeed the upper portion consists of thinly bedded sandstones and arenaceous shales, in their lithological character, resembling much more closely the massive sandstone above than the conglomerate below. Further, this member thickens perceptibly toward the south. These two series of rocks are believed to be the equivalents of the Shinarump conglomerate and the Chinle of southeastern Utah.

The Dolores of the San Juan Mountains and western Colorado seems to be equivalent to this entire series of conglomerates, sandstones and shales, together with the massive rock at the top which is variously known as the Wingate or the Vermilion Cliff sandstone. Gregory[10] includes the Wingate and Todilto together with the Navajo as the equivalents of the La Plata group of the San Juan Mountains, and places the Shinarump conglomerate and the Chinle formations as the approximate equivalents of the Dolores. Cross[11] in his paper on the Red Beds suggests that the Dolores of Colorado includes diminished equivalents of the Shinarump group and Vermilion Cliff sandstone of the plateau province. This view, with some exceptions or qualifications in the case of the Shinarump, was further substantiated by him on his reconnaissance[12] through the then Grand River region of Utah just west of La Sal Mountains. Furthermore the Dolores of western Colorado, only a few miles to the east of La Sals, as described by Coffin,[13] clearly includes the massive member (Vermilion Cliff or Wingate), at the top, together with the formations below, which have been called in this paper the Shinarump conglomerate and the Chinle. Coffin, therefore, considers this massive member as the top of the Triassic. Gregory[14] places the Jurassic-Triassic contact, with a question mark, between the Chinle and the Wingate. Mehl's[15] paleontological studies in the vicinity of Ft. Wingate, New Mexico, would, apparently, place this massive sandstone member in the Triassic, thus raising the Jurassic-Triassic contact to the top of the Wingate; in other words the top of Coffin's Dolores as described from areas in Colorado a few miles to the east of La Sal Mountains.

Regardless, however, of the more exact delimitation of the ages and correlation of these various formations, the more detailed and definitive nomenclature of apparently equivalent strata in southeastern Utah seems more applicable and more desirable than the retention of the name Dolores for so great a thickness of beds that lend themselves rather easily to further subdivision.

In Plate V, Figure 2, the lower bench represents the probable lower level of the Shinarump conglomerate. Below lies the Cutler and above, the Chinle, capped by the Wingate. A comparison of this plate with Plate VII, Fig. 1, of *Professional Paper 132*, which illustrates Castle Butte near the mouth of Red Canyon in the San Juan Canyon region, suggests similarities or relationships between the formations indicated too evident to need comment.

The Wingate is a massive somewhat cross-bedded, red-brown rather than vermilion sandstone. In Castle Valley and the general region to the northwest of La Sals it is peculiarly important as a capping for buttes and mesas along which it characteristically outcrops in sharp cliffs. Remarkably well developed vertical joints give the cliffs a columnar effect and frequently cause them to weather into spines or castle rocks (Pl. I, Fig. 1, and Pl. V, Fig. 2).

The Jurassic Formations

Above the Wingate is a series of thinly bedded sandstones and arenaceous shales so like the massive cross-bedded rock below that it might almost be regarded as a shaly phase of the Wingate itself. This member is, however, persistent, sometimes attaining a thickness of nearly two hundred feet. It may, therefore, be considered a separate formation from the Wingate below, and on account of its position between the easily recognized Wingate below and the equally evident Navajo above may safely be designated as the Todilto, which occupies the same stratigraphic position in southeastern Utah.

Of all the formations that have affected the topographic expression of the plateau country to the west and to the south of La Sal Mountains none has played so important a role as the Navajo sandstone (the La Plata of the San Juan Mountain region). Most of the fantastic forms that give so much charm to this region are carved from the massive Navajo (Pl. I, Fig. 2).

In many of the places studied, if the major part of the formation is still preserved, it is recognizable in its tripartite divisions, a lower and an upper massive series separated by a thin zone essentially of red shales with now and then some limestone. The lower part consists of massive brick-red to buff sandstones which in places attain a thickness of four hundred feet. Bedding planes are notably absent. Not infrequently thicknesses of one hundred feet or more in which no indications of bedding planes may be found are exposed along the canyon walls. Particularly good exposures of this member are found along the canyon walls of Mill Creek. These walls are so blackened in places that they seem to have been painted. This effect is produced by a thin rind of desert varnish.

The upper member of the Navajo is a fine even-grained massive sandstone, frequently strongly cross-bedded. It is yellow-brown to orange for the greater part, becoming pink and lighter toward the top. In places the top portion of fifty to one hundred feet is practically white. It is this member of the Navajo that is locally so characteristically weathered into caves, alcoves, arches and numerous other fantastic forms. Small pockets also are common and frequently give to the rock a roughened or pitted surface.

Its massive character makes the Navajo everywhere a cliff-maker, but not with the sort of expression displayed by the Wingate. The Navajo is, generally friable, so that particularly where there is no overlying formation its steep walls terminate in rounded forms rather than in sharply angular forms exhibited by the Wingate.

On the so-called sand-flat between the Colorado and the mesas at the foot of the mountains, the Navajo is the chief surface rock (Pl. II, Fig. 2). Its occasional complex cross-bedding, together with its massive character and easy erodibility, have here produced a maze of erosion forms of unusual beauty. In many parts of the region excessive weathering and erosion along the joints have produced the elongated dome-like forms that from a distance so largely dominate the landscape. After the torrential desert rains, these rocks glisten in the sun; they are difficult to cross, hence the local name of "slick rock." These rounded forms are easily recognized from the peaks of La Sals. Because of their frequent and regular occurrence Peale,[16] who saw them from the mountains, thought they might be "sheep backs" of glacial erosion. Closer observation by Dr. Peale would no doubt have demonstrated their real origin.

The Jurassic (?) and Cretaceous Formations

The formations above the Navajo, i.e. the McElmo, the Dakota and the Mancos, constitute the fairly gentle vegetation-covered slopes from the mesa rims on the west to the foot of the mountains. Furthermore all three formations are generally easily eroded, so that their intimate relationships are rather obscure. Neither the McElmo-Dakota nor the Dakota-Mancos contacts were definitely located. On the basis of observations with an aneroid the thickness of the McElmo was estimated to be about 1,000 feet, the Dakota 200 feet, and the Mancos shale from 0 to 600 feet.

In a general way the McElmo may be divided into two parts, a lower which consists of sandstones separated by arenaceous shales, and an upper which is predominantly shales. A dense fine-grained reddish sandstone showing vertical jointing similar to the Wingate constitutes part of the mesa rim rock (Pl. VI). Though this member is quite unlike the recognized McElmo sandstone ledges above, it is believed to be here the basal member. In places the Navajo is directly overlaid by a shaly zone containing limestones and chert. But the dense red rim rock seems not to be separated from the Navajo by a well-defined shaly zone.

The other sandstone members of the McElmo are light grey to white. They are loosely cemented, calcareous material often constituting the binding material, and are therefore easily eroded. Occasionally a thin indurated surface gives the rock a pinkish or even darker tinge and makes it also much more resistive to erosion. This lower sandstone part of the McElmo is also characterized by beds of hard blue limestone and chert. On Wilson Mesa the early settlers burned this blue limestone to make lime. Fragments of chert are scattered over the surface in many places, but no beds greater than a few inches in thickness were found. Prospectors bring reports of a great bed of "chalcedony quartz" almost a hundred feet thick near the south group of La Sals. There was no opportunity to verify this story.

Pieces of silicified wood are not uncommon on the lower parts of the mesas, and fossil bones, which are probably saurian, were noted below Boren Mesa.

The upper part of the McElmo is one of the most vivid and individual horizons about the mountains. A great series of so-called "variegated shales" forms this portion of the formation. Green, blue, red, lavender and purple (with the lavender and purple predominating), together with grey, constitute the base from which the curiously mottled colors of these beds are produced. Varying grades of purity from very arenaceous shales to those which become plastic and slump when wet are represented in these shales. Exposures from slumping along the green vegetation-covered slopes present color displays that are fairly dazzling. When hammered these shales break into small angular fragments, but do not show any tendency toward fissility.

In contrast to the reddish rocks below, which dominate the landscape to the west of the mesas, the Dakota sandstone is light yellow to buff. The yellowish color is due to limonite which is sometimes so distributed in small patches that the freshly fractured surface presents a "freckled" aspect. Generally the Dakota is friable, but in places is indurated and takes on a pinkish coloration.

The lower part of the formation is conglomerate. The small gravel-sized pebbles of quartz, quartzite and chert, which constitute the conglomerate, are not distributed as definite beds but occur as lenses, which suggests a fluviatile origin.

East of the mountains from Geyser Pass the Dakota is easily recognized in its triple division, a lower and an upper massive zone separated by a shaly zone. The shale is carbonaceous and occasionally carries low-grade coal. There is such an occurrence east of Geyser Pass, which in the earlier prospecting days in the mountains was mined by the prospectors for use in their forges.

In places the Dakota is not easily recognizable, for at times it shows a surprisingly rapid transition from the characteristic occurrence noted above to more thinly bedded strata.

It is because of the extreme facility with which the formations above and below are eroded, and not because of inherent qualities of resistance to erosion, that the Dakota is often a singularly conspicuous formation near the mountains. It stretches away from the eastern foot of the mountains to constitute the main cover rock for much of the eastern edge of Utah and of western Colorado. When upturned about the eruptive centers of La Sals, it frequently forms particularly striking hogbacks (Pl. VIII, Fig. 1).

A few feet above easily recognized Dakota beds below Bald Mesa there was found an exposure of slate-colored to black shale. Thin lenses of blue limestone and some sandstone were found at this horizon. Numerous fossils were collected of which the following species have been identified: *Gryphaea newberryi; Inoceramus dimidius; Baculies gracilis; Scaphites warreni*. This is apparently the Mancos shale. Exposures higher up along the mesa show it to be predominantly a drab to black fissile papery shale. It erodes easily and when wet becomes very plastic. Its surface expression is, therefore, frequently a badland sort of topography.

Nowhere about the mountains does the Mancos exist in its full development. It is preserved in small patches northeast of Beaver Basin, on both La Sal and Geyser passes, and caps Boren and Bald Mesas. It attains its greatest thickness at the last named locality.

Pleistocene, Quaternary and Recent Deposits

As a result of the glaciation of the higher mountain valleys during the Pleistocene age some glacial deposits were formed. Most of the glaciers were short, so that the only deposits now recognizable are a few short moraines. Such deposits are found in the various basins of the north and central groups. The best preserved forms are those in the vicinity of Dark Canyon Lake and Pratt's Lake (Pl. IV, Fig. 1), which lie along the flat eastern slopes of the central group.

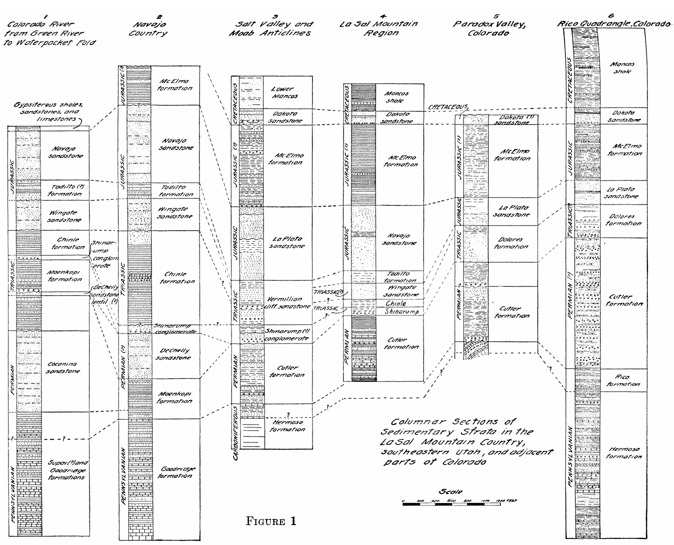
In many places the lower slopes of the steeper mountains are covered by great accumulations of slide rock, sometimes in quantities so great that they completely obscure the structural relationships with the surrounding regions.

Varying amounts of slope wash and alluvium are found about all three groups. The heads of the valleys, or the basins so called, are frequently filled with immense thicknesses of such materials. The deposits consist of both fine and coarse clastic materials showing little or no tendency toward assortment. The contained pebbles are subangular, which indicates transportation over but short distances. The upper parts of Castle Valley and Miners' Basin are covered with at least 200 feet, and perhaps much more, of such detritus. Recent gullying in other basins of the north group, but particularly in those about the south group, namely Pack Creek, Pole Canyon, and Lackey Basin, demonstrates the existence of equally great thicknesses of alluvium and slope wash in these basins.

Projecting out into Castle Valley toward the northwest as a spur from the lowest exposed igneous part of the north group is a conglomerate ridge which divides the upper part of the valley into two parts. It consists largely of subangular pebbles of porphyry so loosely cemented together that the rock crumbles easily under a blow from the hammer.

Figure 1 illustrates the relationship which the sediments of La Sal Mountain region bear to those of adjacent parts of Utah and neighboring portions of Colorado and Arizona. The geographic locations of the columnar sections shown in this figure are indicated on the map (Map 1). The sections are compiled from the following sources:

1. *Rock Formations in the Colorado Plateau of Southeastern Utah, and Northern Arizona*, by C. R. Longwell, H. D. Miser, R. C. Moore, Kirk Bryan and Sidney Paige. *U. S. Geological Survey, Professional Paper*, No. 132 A, 1923, Plate II, Section 11.
2. *The Geology of the Navajo Country*, by H. E. Gregory. *U. S. Geological Survey*, *Professional Paper*, No. 93, 1917.
3. *Geology and Structure of Portions of Grand and San Juan Counties*, Utah, by H. W. C. Prommel. *Bulletin of the American Association of Petroleum Geologists*. Vol. VII, No. 4, July-August, 1923, Plate III. It will be noted that the names of the formations for this section follow the older nomenclature of the plateau country. In the text, however, Prommel correlates the Permian, Triassic and Jurassic formations with those of southeastern Utah and adopts almost entirely the nomenclature of the Navajo country.
4. Generalized section of the rocks exposed in Castle Valley and along the canyon of the Colorado, north and west of La Sal Mountains, as studied by the author.
5. *Radium, Uranium and Vanadium Deposits of Southwestern Colorado*, by R. C. Coffin. *Bulletin 16, Colorado Geological Survey*, 1921, Plate LV, page 31.
6. *The Rico Quadrangle, Colorado*, by Whitman Cross and F. L. Ransome. *U. S. Geological Survey Atlas*, Folio 130. Generalized Section of Strata in the Rico Quadrangle, by Whitman Cross and Arthur C. Spencer.



[Fig. 1. Columnar sections of sedimentary strata in La Sal Mountain country, southeastern Utah and adjacent parts of Colorado]

III. The Igneous Rocks

EVIDENCE of igneous activity in the mountains is preserved principally as the cores of the three separate groups and as the igneous butte, Little Round Mountains, which lies out in Castle Valley about five miles northwest of the northern group. The latter occurrence is about two miles beyond the border of the area covered by the geological map (Map 3). In addition to these major igneous features a few radial dikes are found in connection with the central group; two small flows or former sheets are known, one as a cap for the lower end of the ridge north of Gold Basin and the other a mile west by northwest of Mt. Haystack. This last occurrence is cut into two parts by the canyon of Mill Creek. Dikes on either end of this bisected mass probably represent the conduits from which the magma came. Finally there is in the north group a number of strongly alkalic dikes which indicate a period of activity subsequent to that of the main intrusion. These dikes are injected into a more alkalic phase of the main intrusive than is elsewhere found. In some places they cut into the surrounding upturned sediments.

All the rocks have a porphyritic texture and in those from the main intrusive mass they are universally characterized by recognizable phenocrysts of feldspar. All the rocks belong to the hypabyssal members of those igneous rocks which are distinguished by the kind of feldspar that predominates. Their relationships to their plutonic and extrusive equivalents may be indicated thus:

PLUTONIC	HYPABYSSAL	EXTRUSIVE
syenite	syenite porphyry	trachyte
monzonite	monzonite porphyry	latite
diorite	diorite porphyry	andesite

Iddings[17] delimits the three plutonic groups on the basis of the predominating feldspar as follows: 1. Syenites, in which alkali feldspars exceed lime-soda feldspars by more than 5 to 3; 2. Monzonites, in which the alkali feldspars and the lime-soda feldspars vary within the proportions 5 to 3 and 3 to 5; 3. Diorites, in which the lime-soda feldspars exceed the alkali feldspars by more than 5 to 3.

In the determinations of the names to be applied to the rocks of La Sal Mountains, these proportions of the feldspars have been followed as carefully as possible. In fifty thin sections examined, representatives from all three of the hypabyssal groups were recognized. Most of the rocks of the major intrusion are characterized by phenocrysts of plagioclase and very few or none of orthoclase. They are very evidently diorite porphyries. The monzonite and diorite facies are localized, as will appear later.

Occurrence of the Various Types

The southern and central groups, including the radial dikes, Little Round Mountain, the dikes and flow west of Mt. Haystack and most of the north group of the mountains are composed of diorite porphyries.

Only in the northern group is there much evidence of magmatic differentiation. Mineral Mountain represents an area constituted of a particularly clear type of syenite porphyry. As one proceeds from this apparent center of the alkalic phase of the intrusion, there is a gradual decrease in the alkalic feldspars. Green Mountain is very clearly a monzonite porphyry. Sections examined from other adjacent localities demonstrate that parts, at least, of Mts. Waas, Castle and Hobbs are also of monzonite porphyry. The megascopic recognition of most of the monzonite porphyries was of course not possible and the number of slides studied was insufficient to enable one to delimit more exactly this phase of the intrusion.

The small igneous cap on the lower end of the ridge north of Gold Basin is a syenite porphyry differing essentially from that of Mineral Mountain only in texture.

Reference has been made to the fact that associated with the more alkalic phase, just noted, are a number of dikes. These dikes are found principally in two areas; one in Beaver Basin where there are three dikes which have an average strike of N. 40° W.; the other in Bachelor Basin, chiefly in association with Castle Mountain. The dikes in the latter locality have an average strike of N. 15° E. All these dikes are short and most of them were but a few feet in thickness. They represent various facies of syenite porphyries, differing in all cases from the more widely distributed Mineral Mountain and Gold Basin occurrences.

A very different type of rock is that represented by great slides about one half-mile west of the former town of Basin, in Miners' Basin. Though a definite outcrop could not be found, this rock is so different in appearance from the adjacent diorite porphyry that it is believed to be a dike rock. It is a rhyolite porphyry.

THE PETROGRAPHY OF THE INTRUSIONS

Diorite Porphyry

Megascopic appearance. — At first glance the diorite porphyry is seen to be a dense light-grey to white rock with black specks irregularly scattered through it. Closer examination shows that the black specks are phenocrysts of hornblende (many of them acicular in development) which, together with numerous light-colored tabular phenocrysts of feldspar, are imbedded in a light-grey aphanitic ground-mass. Light green phenocrysts of pyroxene are found, but are everywhere much less numerous than the hornblende. Phenocrysts of quartz are only occasionally found. Hornblendic inclusions sometimes measuring as much as four or five inches in length were noted from a few localities. In some places these grade into the surrounding mass. Careful examination shows that these inclusions consist of the same kind of materials as the main porphyry mass, but are developed on a different scale. Emery[18] describes hornblendic inclusions from the diorite porphyries of Carrizo Mountain which appear to be identical with these noted in La Sal Mountains.

Microscopic description. — Many broad tabular idiomorphic phenocrysts of plagioclase, usually with Albite twinning and often with Carlsbad twins as well, dominate the microscopic appearance of the rock. Most of the plagioclase is oligoclase, andesine, or gradations between the two; more alkalic or more calcic varieties being rare. Zonary banding is common; in one specimen fourteen distinct bands could be noted.

Orthoclase phenocrysts are sparingly distributed or even entirely lacking in the diorite porphyries and when present are always found in smaller crystals than the plagioclases. Most of it shows an elongated rather than a broadly tabular development. Carlsbad twins are common.

Hornblende of the common green pleochroic variety is the characteristic ferro-magnesian mineral. In a few slides there is a little brown hornblende, and in others some bluish-green varieties are noted. Idiomorphic outlines and acicular crystals, many of them with imperfect terminal faces, are common (Pl. VII, Fig. 1). Twinning is frequently noted in the elongated forms. In some places the hornblende is in intimate association with magnetite; in others it encloses magnetite crystals, and again it may be almost completely filled with tiny grains of magnetite, or surrounded by black magnetite borders.

Pyroxene is present in many of the specimens, though usually in amounts subordinate to the amphibole. It commonly shows an idiomorphic development and is frequently twinned. It is usually a pale green to colorless augite (Pl. VII, Fig. 2), though a few varieties from diposide to aegerine were found. Of these aegerine augite is next in importance to the augite.

In four or five slides small amounts of brown strongly pleochroic biotite were found. Even in the same rocks, however, the amphibole was far in excess of the mica.

Although quartz is a characteristic associate of the feldspar in the ground-mass, it is not common as a phenocryst. In only two or three specimens was it present in sufficient amounts to enable one to designate the rock a quartz-diorite-porphyry.

The most characteristic of the accessory minerals is magnetite, which in many specimens is present in two generations. Though not present in amounts so large, titanite is almost as widespread as magnetite. It is developed in long slender crystals which frequently show twinning. Apatite occurs in all the rocks, usually as tiny needles. Zircon, always as tiny grains, is very sparingly distributed in them.

The ground-mass is microcrystalline and consists almost entirely of allotriomorphic quartz and feldspar, usually orthoclase. Considerable variations in the texture of the ground-mass were noted, some specimens approaching on the one hand a coarsely micro-granular texture akin to their plutonic relatives, while others have a very finely holocrystalline ground-mass typically andesitic or trachytic. Fluxion structure was rarely found in the microscopic sections.

In some specimens the rocks were so badly altered that in thin section they presented a dusty or dirty appearance, often making their exact identification questionable. The feldspars were commonly found altering to sericite and to a lesser extent to calcite. Secondary calcite was widely developed in some specimens. In at least two slides the ferro-magnesian minerals were entirely lacking, but epidote was present in considerable quantities. It is sometimes the colorless variety, but more often the greenish pistacite with brilliantly speckled interference colors. In a few slides leucoxene was found. Small amounts of a fibrous material which may be the fibrous amphibole, uralite, were found in two or three slides.

Monzonite Porphyry

Megascopic appearance. — To the naked eye the monzonite facies present no essential differences from the diorite porphyries. In some places, as on Green Mountain, phenocrysts of orthoclase can be distinguished. Though hornblende is present, pyroxene is usually the dominant ferro-magnesian constituent.

Microscopic description. — Phenocrysts of orthoclase and plagioclase in relatively even amounts characterize these rocks. Both occur in well-developed tabular crystals with idiomorphic outlines. Carlsbad twinning is common in both and of course in the plagioclase, which is most often oligoclase and albite-oligoclase, albite twinning is common. In a few specimens perthite is almost well enough developed to be called a phenocryst. It is commonly found, however, only in the ground-mass.

Both pyroxene and hornblende of the green pleochroic variety are found. The pyroxene is commonly aegerine augite and is often twinned. The same accessory minerals that characterized the diorite porphyries occur also in these rocks.

Considerable variation is exhibited in the ground-mass of the specimens referred to this type of rock. Some are micro-granular and consist of about equal amounts of quartz and feldspar. Others, as those from Green Mountain and near by in Bachelor Basin, consist mostly of quartz, sometimes quite coarsely crystalline. In another specimen from Mt. Waas, identified as a monzonite porphyry, the ground-mass is of microperthite.

Syenite Porphyry

Megascopic appearance. — Some of the syenite porphyries closely resemble the types just discussed, while others, as that from Mineral Mountain, have a decidedly individual appearance. This rock has the general greyish-white color of the other types, but is seen to consist of numerous light-grey to white phenocrysts of feldspar crowded into a slightly darker ground-mass.

The tabular feldspars are evidently orthoclase and are especially prominent both on account of their light color and their size; a number of them have dimensions as great as 11 by 17 millimeters. A dark greenish pyroxene is also a noticeable phenocryst.

Toward Bachelor Basin or toward the northwest the large prominent orthoclase phenocrysts disappear and the rock more closely resembles the monzonite and diorite porphyries.

The Gold Basin occurrence of syenite porphyry shows a rock quite different from that of Mineral Mountain. In this rock pink phenocrysts of orthoclase, sometimes as large as those in the Mineral Mountain occurrence, are scatteringly distributed in a rather dark-grey ground-mass. Upon careful examination the ground-mass is seen to consist of lath-shaped crystals showing a decided fluxion structure.

Microscopic description. — The large phenocrysts in the Mineral Mountain specimens are found to be entirely orthoclase.

Most of the ferro-magnesian minerals are pyroxene, of which aegerine augite is the most important. Small amounts of a greenish-blue hornblende, which may be the soda-amphibole, catophorite, are also found. Magnetite and titanite in slender-twinned crystals are common. Apatite is present as small needles and as crystals almost big enough to be phenocrysts. The ground-mass, which is cryptoperthite, shows a subparallel arrangement.

In some of the more even-textured varieties a little way from the top of Mineral Mountain the rock is found to consist almost entirely of perthite and cryptoperthite. In other specimens the ground-mass is micro-granular and the phenocrysts are entirely of orthoclase. In one specimen enough hypidiomorphic quartz was found to enable one to designate the rock a quartz-syenite porphyry.

In the Gold Basin type the phenocrysts are found to be entirely orthoclase, frequently with Carlsbad twins. Both the phenocrysts and the cryptoperthitic ground-mass show a sub-parallel to parallel arrangement. In addition to small phenocrysts of aegerine augite, needles which are probably aegerine are scattered through the ground-mass. Magnetite, ilmenite and a hexagonal section with platy to fibrous structure, which may be zeolite altered from sodalite, are also found.

These syenite porphyries do not represent well-defined or unquestioned types. They show the most pronounced affinities for pulaskite or nordmarkite, and on account of their porphyritic texture may be designated pulaskite or nordmarkite porphyries.

Syenite Porphyry Dikes

Of the three dikes in Beaver Basin the two outer ones are quite similar both megascopically and in thin section. They consist of a greenish-grey ground in which are imbedded rhombic to elongated tabular phenocrysts of orthoclase, commonly measuring from 5 to 7 millimeters. Microscopically these rocks are found to consist principally of alkali feldspars (almost entirely orthoclase) as phenocrysts, set in a microperthitic ground-mass. Small amounts of greatly altered hornblende with a bluish-green color may be arfvedsonite. One slide contained phenocrysts of melanite garnet. Tiny needles of aegerine are crowded into the ground-mass which also contains small amounts of magnetite and titanite. Because of their aplitic (syenitic) character these dikes may be designated as syenite-aplite porphyries.

The third Beaver Basin dike, which lies between the two just described, is a light greenish-grey fairly aphanitic rock; no notable phenocrysts are visible. In thin section it is found to consist of phenocrysts of orthoclase (often apparent only in outline, the interior being filled with tiny needles of plagioclase feldspar), smaller phenocrysts of plagioclase and corroded quartz with inclusions, all set in an allotriomorphic ground-mass of quartz and feldspar. Both orthoclase and plagioclase feldspars are found in the ground-mass. Needles of aegerine are scattered through it. This rock might be classed either as a quartz-tinguaite porphyry, or as a grorudite porphyry.

Another unusual rock consisting of a bluish ground scatteringly speckled with small white feldspars was collected from the same locality as the dikes described above. This rock departs so widely from the country rock of the region that it seems likely that it is also a dike rock. I believe it is the same rock that Prindle[19] described as aegerine-granite porphyry, for in thin section it is found to have a fairly even subgranular texture and to consist almost entirely of quartz and feldspar, chiefly orthoclase. Much secondary calcite makes the further identification of the mineral constituents questionable. A few small phenocrysts of pyroxene and some epidote are sparingly distributed through the rock and tiny needles, which are probably aegerine, are found in small amounts in the ground-mass. Magnetite occurs in very small amounts.

The principal dike in Bachelor Basin is a strikingly "dappled grey" rock which cuts from the northern slope of Castle Mountain across the gully into the upturned sediments that constitute Red Mountain. The spectacular appearance of this dike is due to the presence of large zonally banded phenocrysts of orthoclase, which commonly attain a length as great as one and three-fourths inches. These, together with small phenocrysts of pyroxene, are set in a greenish-grey aphanitic ground-mass. In appearance this rock suggests an orbicular diorite. On either side of this dike are a number of smaller tabular outcrops which differ mainly in the orthoclase phenocrysts, which lose their zonary banding and take on an elongated tabular shape. In thin section most of the pyroxene is seen to be aegerine, though a few zonally banded phenocrysts were found which showed gradations from augite to aegerine. Phenocrysts of noselite are found also in considerable number. Frequently this sodalite is found altered to zeolite. Magnetite was noted only in very small amounts. The ground-mass is found to be microperthite clouded by tiny needles of aegerine. Fluxion structure with eddies about the phenocrysts is characteristic of this ground-mass. Secondary calcite and sericite often give the rock a cloudy aspect. The most nearly applicable name for this rock seems to be noselite-tinguaite porphyry.

Cutting clear through Castle Mountain is a narrow dike which megascopically resembles very closely the grorudite porphyry of Beaver Basin. Microscopically it is found to contain more aegerine, less plagioclase in proportion to the orthoclase, and less quartz as phenocrysts, but much more in the ground-mass. This rock shows about equal affinities for the porphyritic facies of grorudite, tinguaite and sölvsbergite.

Near the northwest end of Castle Mountain is a dike with a blue-grey ground-mass in which are embedded light-colored phenocrysts of orthoclase which commonly show a rhombic outline. These characteristic phenocrysts of orthoclase stand out against their blue ground suggesting grains of wheat, hence the local name coined by prospectors, "wheat grain porphyry."

Under the microscope the phenocrysts are found to be in part perthite, as well as orthoclase. A few oligoclase andesine phenocrysts were also noted. Pyroxene is rare, but epidote is developed in considerable quantities. Magnetite, apatite and ilmenite are common and a small amount of zeolite indicates that sodalite is also present. The ground-mass of this rock is of fine cryptoperthite. Though it suggests in its megascopic appearance a rhombenporphyry, a more accurate name for it seems to be laurvikite porphyry.

The huge slides in the western part of Miners' Basin, referred to above as rhyolite porphyry, show a light-grey to white rock, when not weathered. The weathered surface is grey to yellowish. Perfectly developed prismatic crystals of orthoclase are seen throughout the rock and may be collected in great numbers from the ground, where they have fallen as they weathered out of the parent rock. Quartz in rounded or corroded grains is also a very evident phenocryst. In thin section a few phenocrysts of albite and a little magnetite are also found. The ground-mass is very finely micro-granular.

From the south side of Castle Mountain the writer collected some specimens of a very fine grained slatycolored rock which seems to be a dike. No individual grains could be detected with the naked eye and even in thin section the rock was found to be so fine-textured as to defy classification. Much grey calcite obscures the major part of the rock, which seems to consist of about equal amounts of allotriomorphic quartz and a turbid feldspar.

A similar rock but lighter in color and even more finely grained was collected from Mt. Tukunikivats. In thin section it appears to be the same sort of rock as the one from Castle Mountain. It seems inadvisable to attempt to classify these rocks without a chemical analysis.

PLACE OF LA SAL MOUNTAIN INTRUSIVES IN THE QUANTITATIVE CLASSIFICATION

From Prindle's collection a rock collected two miles west of Mt. Peale was analyzed by Hillebrand[20] and placed by Prindle as akerose. The writer has examined a number of thin sections from this same general region and all appear to be fairly typical of the diorite porphyry, which constitutes the major part of the intrusive mass. The following analysis from Hillebrand probably represents, therefore, the general composition of the main igneous masses:

SiO_2	61.21
Al_2O_3	17.10
Fe_2O_3	2.72
FeO	1.88
MgO	1.47
CaO	4.83
Na_2O	5.66
K_2O	3.00
H_2O at 105	.34
H_2O above 105	.68
TiO_2	.51
ZrO_2	.02
CO_2	none
P_2O_5	.24
SO_3	none
Cl	.04
MnO	.15
BaO	.13
SrO	.07
Li_2O	trace?
Total	100.05

RELATION OF THE SIERRA LA SAL INTRUSIVES TO THOSE OF OTHER LACCOLITHIC AREAS

The nomenclature of petrography has changed so greatly in recent years that the names used here look little like those employed by earlier investigators to describe the same rocks. This statement is generally true for the other laccolithic areas of this region. Gilbert[21] identified his Henry Mountain rocks as "porphyritic trachyte." La Sal Mountain intrusives[22] were also first referred to as "porphyritic trachytes." Emery[23] has pointed out that the rocks of the Carrizo Mountain intrusion were called "trachyte" by Holmes and his contemporaries, and that the same rocks were later designated "hornblende porphyrite" by Cross. He further points out that the "hornblende porphyrite" of Cross is the "diorite porphyry" of American petrographers of today.

In his reconnaissance visits to El Abajo (The Blue), El Late (The Ute), and La Plata Mountains, the writer made collections in addition to field-studies. A comparison of these specimens with the diorite porphyries of La Sal Mountains demonstrates some differences in structure and mineral composition, but when the points of similarity are considered the differences become insignificant. These petrological studies have simply reaffirmed the evidence of the remarkable consanguinity of the laccolithic magmas of this part of the United States, a fact pointed out by the earliest investigators and continually substantiated by succeeding investigations.

IV. STRUCTURAL GEOLOGY

Structural Features of the Plateau Country

INSTEAD of being flat-lying, as is one's first impression, the sediments of the plateau country about the mountains are found to be gently folded. Particularly noteworthy are the anticlines which now exist principally as anticlinal valleys. The limbs of these structures are generally low and flat-lying, but they are much more perfectly developed than the intermediate synclines. Longitudinal or strike faults are characteristic of the anticlines and in some cases, as in the upper end of Spanish or Moab Valley, block-faulting has also occurred. All these structures have a general northwest to southeast trend.

On the Utah side of La Sal Mountains, Castle Valley, with its continuation of Salt Valley, and Spanish or Moab Valley are the principal anticlinal structures. Across the Colorado line, Sinbad, Paradox and Gypsum valleys may be continuations of similar Utah structures. The Castle and Spanish valley anticlines are of further interest because of the manner in which their alignment coincides with the axes of the doming of the north and south groups of the mountains. As may be noted from the geological map (Map 3), the axis of intrusion of the northern group is decidedly in a northwest to southeast direction, in direct alignment with Castle Valley. From the mountains of the north group it is seen that the limbs of Castle Valley flatten out as the axis approaches the Colorado River, only to reappear on the western side as Salt Valley anticline. The limbs of Castle Valley have a dip of from 4 to 5 degrees, but when the structure reappears on the farther side of Colorado River the dip is practically doubled, with the result that the anticlinal character of Salt Valley is much more pronounced than that of Castle Valley. Its limbs project high above the surrounding plateau country, so that it may easily be seen for many miles from almost any direction.

An interesting detail in the structure of Castle Valley is Porcupine Ridge which lies along the south rim adjacent to the mountain group. This ridge seems to be a portion of the valley wall which has faulted or slid downward.

As one looks eastward from the tops of the mountains of the north group into Colorado, the anticlinal Paradox Valley is a very prominent feature. It seems to be a continuation of the Castle Valley and the north group anticlinal structure. No opportunity was afforded to follow the axis of the Utah structure into Colorado, but from the mountains excellent views of all these structures may be obtained and the relationship suggested above seems a very reasonable one. Though the relationship is not clear as was the case with the north group, the doming of the south group is seen to be in alignment with the axis of Spanish Valley. The probable continuation of this structure into Colorado is not so clear as in the case of the northern group.

All these anticlinal valleys are traversed by conspicuous faults. Prommel,[24] who has studied these structures farther away from the mountains and also the anticlines down the Colorado from Spanish Valley, notes that the vertical displacement of the faults increases toward the mountains and that the structures down the river, which are entirely outside the area of possible effect from the mountain uplift, are practically unaffected by faulting. This suggests that the faulting is intimately associated with the mountain uplift. The vertical displacement along these strike-faults varies from almost nothing to 3,500 feet. A great fault with strike parallel to the axes of the anticlinal valleys passes south of the mountains in the vicinity of the property of the Big Indian Copper Company. Another similar break of undetermined displacement was noted north of the north group.

As regards minor structures the sediments of the plateau country are in many cases conspicuously jointed. As already pointed out, these structures have had a very marked effect on the weathering and erosional processes. The Wingate (Pl. V, Fig. 2) and the Navajo exhibit especially well developed vertical joints. These two formations constitute the principal cover rocks north and west of the mountains, so that weathering and erosion have caused the joint systems to become more noticeable than in other formations.

Structure of the Mountains

Though La Sal Mountains have always been considered laccolithic in origin, they exhibit many structures which depart widely from those which true laccoliths should have. The north group, except for Mt. Haystack, and the south group, may be considered as true laccolites. It is within the central group that the different structural conditions are developed.

In neither the northern nor the southern group is the floor of the igneous core of the mountains exposed. The horizon of intrusion is inferred to be immediately below that represented by the stratification contacts found around both these groups. The ridge southeast of Beaver Basin, Red Mountain, Burro Pass and the ridge just back of the Warner Ranger station all show actual contacts. The contact rock is found to be a series of grey to maroon arkoses, grits, conglomerates, sandstones, shales and some limestones. Lithologically the beds seem to be equivalent to the Cutler as studied in Castle Valley and elsewhere about the mountains. Furthermore, Little Round Mountain is probably the product of the same period of igneous activity as that which caused the formations of the mountains proper, and though its floor is not exposed, beds of undoubted Permian age are exposed at a distance from it and are seen to dip away as though it had been involved in its formation. In the discussion of the sedimentary rocks associated with the mountain region, it was pointed out that the Cutler beds resemble the Rico lithologically to so marked a degree that it is often difficult to delimit the two formations. And though no beds of known Rico age were found about any of the contact zones, it is not advisable to assume definitely that the Rico has not been involved in the formation of the mountains. On the basis of the thickness of the exposed shaly contact zone it is believed that the igneous mass is either intraformational, i.e. in the lower part of the Cutler, or interformational, i.e. between the Cutler and the Rico. Overlying this shaly horizon of intrusion come the thinly bedded rocks of the Shinarump and the Chinle, above which are the massive competent Wingate and Navajo sandstones.

Grits, conglomerates, sandstones and shales similar to those exposed about the north group are found at the contact zones southwest of Mt. Tukunikivats of the south group, from which it is inferred that the horizon of intrusion is here the same as in the north group.

In both the end groups with the upturned sediments about them, the shaly zone in contact with the igneous core has eroded much more rapidly than the competent Wingate and Navajo sandstones farther removed. Pronounced hogbacks have therefore been developed in many places (Pl. VIII, Fig. 2).

In all the contact areas about both the north and the south groups the upturned sediments were found to be dipping steeply. In no place was a dip of less than 45 degrees noted and along the western side of the north group the sediments are in some places practically vertical (Pl. VIII, Fig. 1). The intrusion into this group was essentially unsymmetrical with the steeper side along the western flank. In the south group the intrusion seems to have been more nearly symmetrical and in no case were the sediments found to be dipping so steeply as along the western flank of the north group. The change in dip from the steeply dipping conditions about the mountains to the nearly flat-lying position of the strata in the adjacent plateau country is very abrupt, especially along the western side of the north group. Immediately north of the north group just above the village of Castleton, the dip of the sediments, instead of flattening out into the characteristic mesa-like structures found elsewhere, reverses, with the formation of a rather sharp syncline.

Though the contacts around the north group are characteristically stratification contacts, it will be noted that along the northern border of the intrusion the rising magma broke across the strata in several places instead of doming them upward. This part of the mountain mass is also intersected by a number of short dikes, one of which at least, as already noted, not only cuts the porphyry mass but extends outward into the upturned sediments that constitute Red Mountain.

Mention has already been made of Little Round Mountain and though it does not come within the area covered by the map, it is no doubt an intimate associate of the mountain group proper, and at greater depth might show a more intimate relationship with the igneous core of the north group than now appears to be the case. So far as they can be observed, the structural features associated with this igneous butte are identical with those that characterize the north group proper.

As already noted, Mt. Haystack, though apparently a part of the north group, is yet quite different structurally from the remainder of the intrusion. An immense amount of slide rock has covered the contacts on every side except for a few feet of McElmo and Dakota beds which are exposed along the south side. These are not sufficient to give a definite clue as to the exact structure of the mountain. It appears to have been an intrusion which was so rapid that it cut across the sedimentary rocks instead of doming them up, except for small portions of the upper formations, i.e., the McElmo and the Dakota, which were locally so sharply upturned by the intrusion that the only outcrops visible have a vertical dip. Mt. Haystack seems therefore to be essentially a stock (Fig. 2).

In the south group what appears to be a finger from the main intrusive mass underlies Moore's Ridge (Fig. 3). The anticlinal character of this ridge is very evident, with the rocks dipping away on either side. The crest of the ridge is covered with the Navajo sandstone which is separated into great blocks and which seem to have resulted from tensional stresses brought about by the force of the up welling magma below.

It is in the central group that the conditions of intrusion seem to have been particularly complex. Wherever they are exposed about this group the sediments are found to dip toward the igneous core at an angle of about 5 degrees. When these dipping beds are followed toward the intrusive center, it is found that the exposed porphyry masses are above the level of most of these dipping sediments, that is, the exposed igneous masses do not seem to have caused the slight doming of these sediments. The suggestion at once arises that the exposed portion of the intrusion represents but a part of the main intrusive mass and that at greater depth below the gently domed strata exists another horizon of intrusion. A study of individual mountains substantiates this view; a particularly interesting example is Mt. Mellenthin.[25] From the Horse Canyon side the entire floor of this mountain is clearly exposed and the horizon of intrusion is seen to be at the base of the Mancos shale, just above the Dakota Sandstone. Considerable quantities of the Mancos shale are included in the porphyry mass at different levels. The feeders which supplied the magma to form this mountain are represented by a number of dikes which are clearly exposed along the east wall of Horse Canyon. These dikes cut upward from some unexposed source through the McElmo and the Dakota into the Mancos where the magma spread laterally. The thickest portion of the possible buried mass beneath the mountains of this group appears to be south of Mellenthin in the direction of Mt. Peale, for it will be noted from the structure section (Fig. 4) that the floor of Mt. Mellenthin is dipping upward in the direction of Mt. Peale. The latter mountain is the highest in the entire La Sal area and unlike any other peak it is capped by flat-lying sediments. These sediments are somewhat metamorphosed and discolored, but are believed to be from the lower portion of the McElmo. They do not, apparently, represent part of a fold that once covered the mountain, but they seem rather to have been broken off and carried upward by the immense force of a rising magma from below. A small exposure of practically flat-lying sediments is found on the southwest flank of this mountain. This may be the formation from which the strata on the top of Mt. Peale were broken off. Furthermore stratification contacts are notably lacking about Mt. Peale. In only one place and there for but a few feet were any sediments dipping away from the igneous mass with such contacts. Rather the beds involved in the intrusion are but slightly tipped up, the magma for the most part having broken across them.

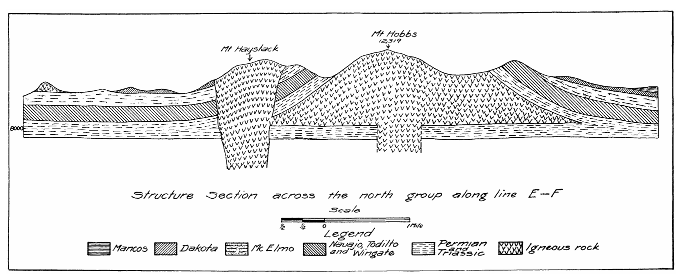


FIG. 2. Structure section across the north group along the line E-F of the geologic map

The third principal peak of the central group, Mt. Allen, presents still more complex structural conditions than either of the other two. On the south and west sides the McElmo beds are slightly upturned about the porphyry core, but not to such an extent as to form stratification contacts. On the south side, where erosion has cut deeply into the mountain, a wedge-shaped dike cuts upward into the sediments and sends out small lateral sheets into the shaly beds of the McElmo. On the Gold Basin side of the mountain this sort of structural feature is more pronounced. Toward the head of this basin, where one may see a considerable vertical section through the structure, sheets are seen to spread out into the McElmo beds from Mt. Allen and from dikes which cut upward through the masses of sediments and interstratified sheets. Though the McElmo beds seem to be the principal ones in immediate contact with the porphyry mass of Mt. Allen and the strata into which the rising magma mainly intruded itself as sheets, beds much lower stratigraphically seem to have been disturbed in the formation of this mountain, that is, it does not seem to be the product of a magma which rose through one or through a number of conduits and which upon reaching the McElmo in part insinuated itself into this formation and in part domed it up. On the western flank of Mt. Allen considerable portions of a maroon conglomerate with boulders as much as eight inches in diameter were found. I know of no formation in this general region from which such a rock might have come except the Cutler. It seems, therefore, that Mt. Allen is the result of an intrusion of stock-like character, which probably does not possess associated magma sheets except within the McElmo. Its rise through the beds above the Cutler, until it reached the McElmo, was so rapid as to cut completely across them except for the small area noted on the west flank.

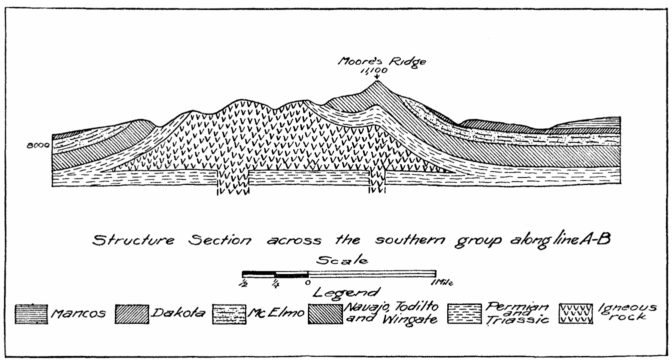


FIG. 3. Structure section across the south group along the line A-B of the geologic map

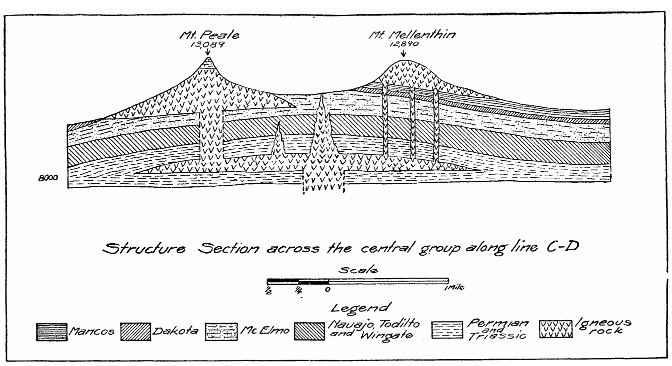


FIG. 4. Structure section across the central group along the line C-D of the geologic map

The isolated patches of igneous rock which lie to the west and northwest are probably parts of the same intrusion as that which constitutes Mt. Allen. Further erosion will very likely reveal a more intimate relationship at greater depth.

It has been pointed out that the porphyry mass capping the lower end of the ridge north of Gold Basin is a flow. Its floor is plainly seen to be the McElmo beds which are entirely undisturbed about it. A pronounced fluxion structure also characterizes this rock.

The small igneous mass at the upper end of this ridge was probably formed contemporaneously with Mt. Mellenthin, for it is in the same horizon. The formation of Horse Canyon has separated it from the major part of the intrusion. The ridge that extends northeast of Mt. Mellenthin is seen to be composed principally of igneous rock. This mass seems, however, to have no intimate relationship with Mt. Mellenthin, for it has disturbed the McElmo beds about it; that is, its horizon of intrusion is below the base of Mt. Mellenthin.

The dikes which are associated with this group of the mountains are in part radial, as is seen, from visible igneous masses (see Map 3). In part they seem to be roof dikes to some un-exposed mass below. Particularly interesting in this connection is the dike which strikes northwest-southeast along the upper north side of Gold Basin. It appears to be a wedge-shaped dike thinning rapidly toward the top. Its exposure does not at any place studied exceed thirty feet in width. Some years ago a mining company drove a tunnel into and near the bottom of the north wall of Gold Basin approximately at right angles to the probable continuation of this dike. In the summer of 1921 it was still possible to go into this tunnel, which penetrates nearly a hundred feet into the porphyry mass with the end of the tunnel still in the igneous rock. This igneous body appears to be the lower portion of the narrow dike outcrop several hundred feet higher up the side of the basin.

From a general view of the structure of this entire group it seems that, just as was the case in the end groups, there was an intrusion in or below the Cutler beds, but for reasons which will be given later the intrusion did not here greatly dome up the overlying strata. Instead, the magma broke through the roof of this lower horizon so as to well upward through the smaller fissures and form dikes. Through others it formed conduits or feeders, intruding itself at different horizons according to local conditions of structure, viscosity of the magma, or as the rate of intrusion may have controlled. Mt. Allen seems to have been a breaking upward from a small portion of the lower intrusion itself. In the case of Mt. Peale the magma welled upward until it reached the lower part of the McElmo, where it spread out and continued to rise with such great force as to break off and carry upward the flat-lying sediments now found upon its top. In the formation of Mt. Mellenthin the rising magma did not spread laterally until it had reached the Mancos shale. The three main mountain masses of this group illustrate gradational phases between true laccoliths and stock-like structures. Mt. Allen suggests a stock; Mt. Peale represents a more intermediate stage, an imperfect sort of laccolith, while Mt. Mellenthin appears to be a true laccolith. As already noted the porphyry of this mountain is intruded into the Mancos shale. To judge from the attitude of a few outcrops of this shale to the north of the mountain, it seems to have covered the igneous core and formerly it may also have had small intruded sheets of porphyry, which have since been eroded.

V. The Origin of La Sal Mountains

REVIEW OF THEORIES ON THE ORIGIN OF LACCOLITHS

POWELL[26] seems to have been the first investigator to make any suggestion concerning the possible origin of the laccolithic mountains of the southwestern part of the United States. He thought the Henry Mountains, which he named, were formed by quantities of molten matter pouring out through fissures and spreading over the country before it had been eroded to its present depth. Later investigators of the Hay den Survey pointed out the error of Powell's suggestion and demonstrated the intrusive character of these mountains. Peale[27] in 1877 assembled the information available concerning these so-called "eruptive" mountains of the southwest. He concluded that they were all the result of igneous material which came up through fissures in the sedimentary rocks, in some places only slightly tipping up the ends of the strata, and which upon reaching the Cretaceous shales generally spread out in them.

It was Gilbert[28] however who first gave a statement of the more exact character and probable cause of this type of mountain. His idea is so concisely stated that it merits quoting in his own words. After pointing out that it is usual for igneous rock to ascend to the surface of the earth and there issue forth to form mountains or hills, he adds: "The lava of the Henry Mountains behaved differently. Instead of rising through all the beds of the earth's crust, it stopped at a lower horizon, insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds. In this chamber it congealed, forming a massive body of trap. For this body the name *laccolite* (from two Greek words meaning cistern and stone) will be used."

In 1893 Cross[29] published a very comprehensive account of the geology of the laccolithic areas of the southwestern part of the United States, in which he suggested a new force operative in the formation of this type of mountain. Gilbert ascribed the entire doming of the strata to the hydrostatic force of the rising magma, but Cross believes that orogenic stresses are necessary, in a few cases at least, to account for the doming of the sediments over some of the laccoliths which he describes. He does not appear ready, however, to go so far as Steinmann[30] in the matter of the relationship between folding and igneous intrusion. The latter, in discussing the relationship between the Andes and their igneous core, expressed the belief that the space for the intrusive mass was formed by the folding itself. Hobbs[31] would carry over to laccolithic mountains the ideas expressed by Steinmann with reference to Andean structure; that is, he ascribes to regional compressional stresses the entire cause of the doming of the strata over laccolithic mountains. He believes further that the laccolithic magmas themselves are not the products of intrusion in the ordinary sense, but rather that they have resulted from the fusion of shales upon the pressure being relieved by the doming of the competent structures above. McCarthy[32] has recently given an excellent review of the various notions concerning laccoliths and has further pointed out the importance of such factors as the rate of intrusion, and the viscosity of the magma, as well as of orogenic stresses in the effects that all these may have had upon the structures resulting from intrusions. His conclusions are based further upon experimental data which in part seem to have excellent representatives in some La Sal Mountain structures, as will be pointed out later.

APPLICATION OF THESE THEORIES TO LA SAL MOUNTAINS

The structural conditions of the central group of La Sal Mountains are so different from those of the end groups that one is forced at the outset to the conclusion that greatly differing conditions of formation obtained in the various groups. In other words, no one of these theories, without some modifications, explains all La Sal Mountain structures.

The Central Group

It has been pointed out that the north and south groups show a definite alignment with anticlinal structures of the plateau region. Here the relationship of orogenic stresses to the formation of the mountains is evidently a very intimate one. In the central group there is no evidence that such stresses played any part. The plateau areas adjacent to this group are flat-lying or even slightly synclinal, since they represent the region between the well-developed Castle Valley and Spanish Valley anticlines. The structures of this group seem to be explained by Gilbert's theory in which the hydrostatic force of the ascending magma was the sole cause of the rupturing and upturning of the sediments. McCarthy's experiments, as described in the paper referred to, suggest that the rate of intrusions has a great effect upon the character of structures. Other things being equal, if the intrusion be sufficiently slow the round-arch type of laccolith represented by the Henry Mountain is formed. At the other extreme with too rapid rate of intrusion stocks result. In the central group of La Sal Mountains, except for the postulated lower horizon of intrusion which, if present, is a thickened sheet or a greatly thinned laccolith, the structures indicate that the rate of intrusion was too rapid to allow a complete doming of the overlying strata with the development of stratification contacts, after the fashion of the Henry Mountains. Mt. Mellenthin may be an exception to this statement, for though the strata above its horizon of intrusion are almost entirely eroded, the remnants suggest that it represents the Henry Mountain type of structure. As regards the other mountain masses of this group, the ascending magma rose with such force that it cut across the sediments in some places, insinuated itself between the strata in others, and in still others tipped up the surrounding sediments, but rarely with the formation of stratification contacts. These mountains really represent intermediate stages between true laccoliths and stocks.

The North and South Groups

So far as the end groups of the mountains are concerned, Gilbert's theory of the doming of the strata as due solely to the force of an ascending magma, is clearly inadequate. It is hardly conceivable that the intrusion of so great a mass as that represented by either of these end groups could take place uninfluenced by outside factors, especially with the formation of sediments so steeply upturned about the igneous cores, without the formation of numerous radial dikes. When one considers the great differences between the structures of the central group as compared with the north and south groups, it is at once apparent that the anticlinal structures of the plateau country associated with these two groups truly indicate that orogenic stresses have played a very important part in the doming of the strata over the igneous cores. It is, therefore, apparent that the structural features of the end groups accommodate themselves more nearly to the theory of the fusion of shales or to the idea that orogenic stresses even to the point of folding accompanied or preceded the intrusion of the magma. It should not be inferred from this statement that the writer believes that folding must proceed to such a point as completely to form reservoirs in order that such structures as those represented by the end groups of La Sals may form. Indeed the hydrostatic force of a rising magma may have been the major force, with the orogenic stresses in the nature of incipient folding simply acting as a rudder.

Quite like the other laccolithic mountains of the southwestern United States, extensive contact metamorphic effects are notably lacking in all three groups of La Sal Mountains. There have been bleaching and discoloration of the red rocks of the contact zones in the north and south groups and in a few places, notably Red Mountain of the north group, some shales have been changed to slate and small amounts of iron ores have been developed. But these contact effects are much less pronounced than one might expect to be produced by the intrusion of so great a mass as that represented by the north group especially. It has been customary for investigators to explain this general absence of great contact metamorphic effects about laccoliths on the basis of the temperature of the intruding magma; the supposition has been that magmas might be intruded at so low temperatures and with so small an amount of mineralizers that no appreciable contact metamorphic effects were produced. Hobbs takes a different view and attaches great importance to the absence of such effects in support of his theory of the fusion of shales.

The inference from this theory is that the temperature of a magma formed in such a manner would so closely approximate that of the country rock that the tendency for contact metamorphic effects would be reduced to a minimum.

Cross[33] has shown that the geologic horizons occupied by laccoliths range in age from the Cambrian to post-Laramie. So far as they are expressed by the structure, the conditions of cooling in the highest were identical with those in the lowest. The conclusion is inevitable, therefore, that several thousand feet of sediments must have covered the highest of these laccoliths at the time of their formation. In view of the depth below the surface necessited by so great a load, the temperatures at the horizons of intrusion of the various laccoliths may well have been so high that magmas could easily have been intruded at temperatures approximating those of the country rock. Furthermore, if the igneous masses which now constitute the cores of laccoliths were formed by the fusion of adjacent bodies of shales, some evidences of such fusion ought to be preserved. Gradational phases between the shales and their igneous equivalents should be found especially about the contacts and in connection with the masses of shales included in the porphyry bodies. Cross[34] notes that the statements of Peale and Holmes that the magmas "absorbed" sedimentary masses are not supported by definite evidence of fusion. Neither in such masses of shales as those found included in the porphyry body of Mt. Mellenthin, nor about any of the contacts in La Sal Mountains is there any evidence of such fusion. The contacts between the two kinds of rock are sharp and furnish easy planes of parting. El Abajo and El Late Mountains are intruded into Cretaceous shales. None of the contacts studied about either of these groups showed any evidence of assimilation of the shales by the igneous mass. In La Plata Mountains brief studies were made of Mt. Hesperus and Banded Mountain with their remarkable banding due to the interbedded shales and sheets of porphyry. Though some slight metamorphic effects are noticeable, the lines of demarcation between the shales and the igneous rock are generally well defined and give no suggestion of an intimate genetic relationship.

CONCLUSIONS

In trying to arrive at a proper conclusion with reference to the origin of La Sal Mountains, I have dealt with the various groups as though they might not be intimately associated. Such is not the case. Indeed the igneous cores of the three groups, at the horizon of intrusion of the north and south groups, may be connected beneath the sedimentary saddles. There is no evidence that the entire mountain uplift is not the result of a single or of a number of closely spaced periods of igneous activity. Viewed as a whole then, La Sal Mountains seem to be unusually well developed examples illustrating the profound effects that orogenic stresses may have upon the structures produced by laccolithic intrusions. The differences in the structure of the end groups as compared with the central group may be entirely accounted for by the fact that in the central group the intrusion was uninfluenced by folding stresses, hence the complex structures and semi-stock-like character of parts of this group. In the end groups horizontal compression to the extent of folding affected the intrusions in such a manner as to allow the doming of the surrounding strata without the development of widespread tensional effects.

THE AGE OF LA SAL MOUNTAINS

The youngest rocks exposed anywhere near the mountains are the Mancos shales of Cretaceous age. These have been involved in the mountain uplift. Therefore beyond the statement that the intrusion was at least post-Cretaceous, nothing definite can be said about the age in which the Sierra La Sal were formed. Cross[35] has pointed out that the West Elk Mountains in Colorado are certainly Tertiary in age and that everything suggests that the other groups, including La Sal Mountains, are of the same age.

The field-work upon which this report is based was conducted during the summers of 1921 and 1924, which were spent in La Sal Mountains and in neighboring regions. This extensive work was made possible only because of the very generous financial assistance of Mr. R. C. Allen of Cleveland, in whose honor Mt. Allen is named.

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PLATE I

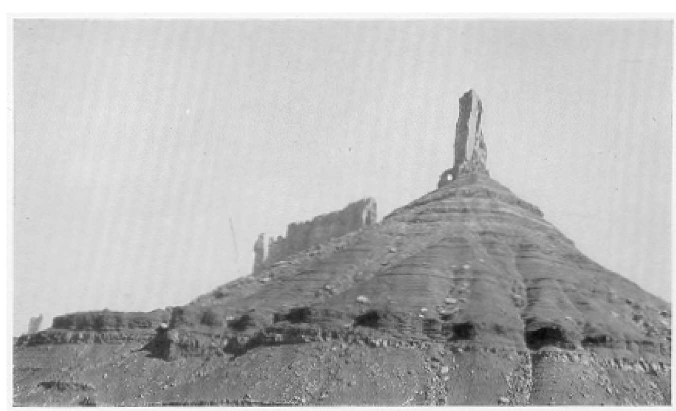


FIG. 1. Castle Butte in Castle Valley

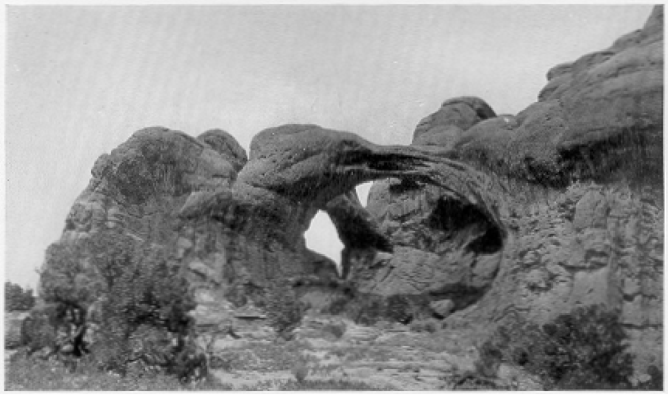


FIG. 2. Arches in the Upper Navajo Sandstone

PLATE II

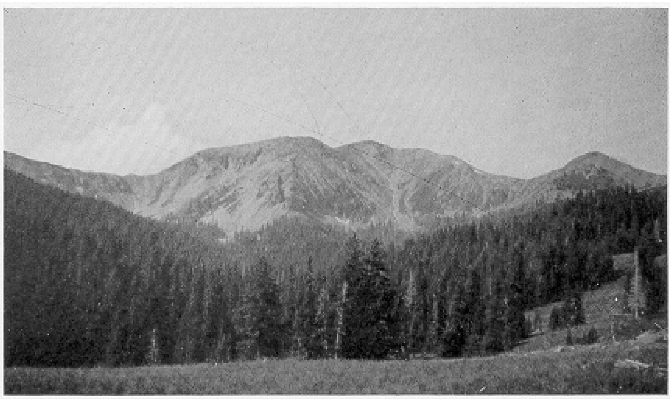


FIG. 1. Mt. Hobbs at the Head of Beaver Basin, showing Schrund Line

FIG. 2. Typical Forms of the Navajo on the "Sand Flats," Where It Is the Cover Rock

PLATE III

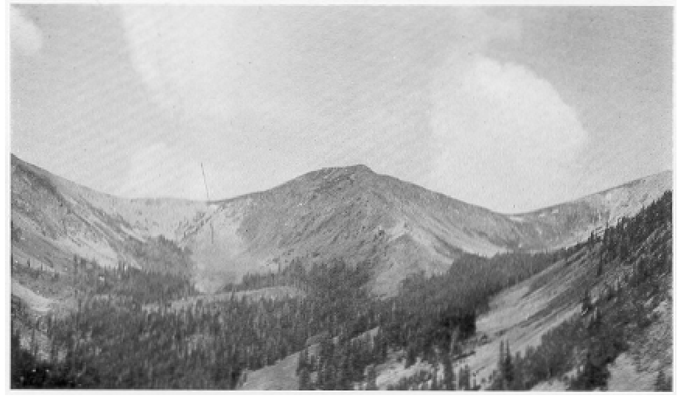


FIG. 1. Cirques at the Head of Deep Creek Basin

FIG. 2. Gold Basin showing U-shaped Valley and Cirque

PLATE IV

FIG. 1. Pratt's Lake in Dark Canyon, a Morainal-dam Lake

FIG. 2. Rock Glacier in Lower Part of Deep Creek Basin

PLATE V

FIG. 1. Unconformity between Permian and Triassic exposed in Colorado Canyon

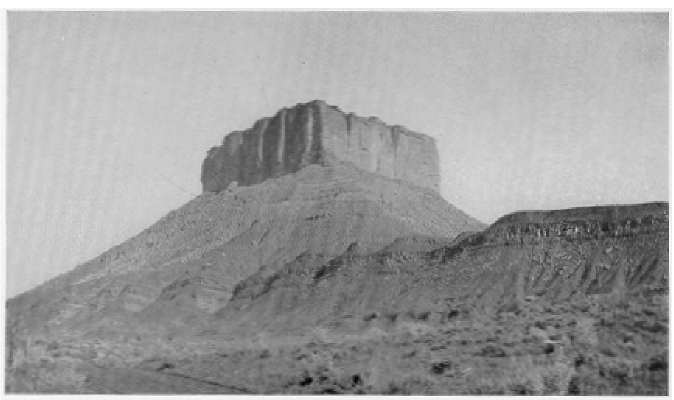
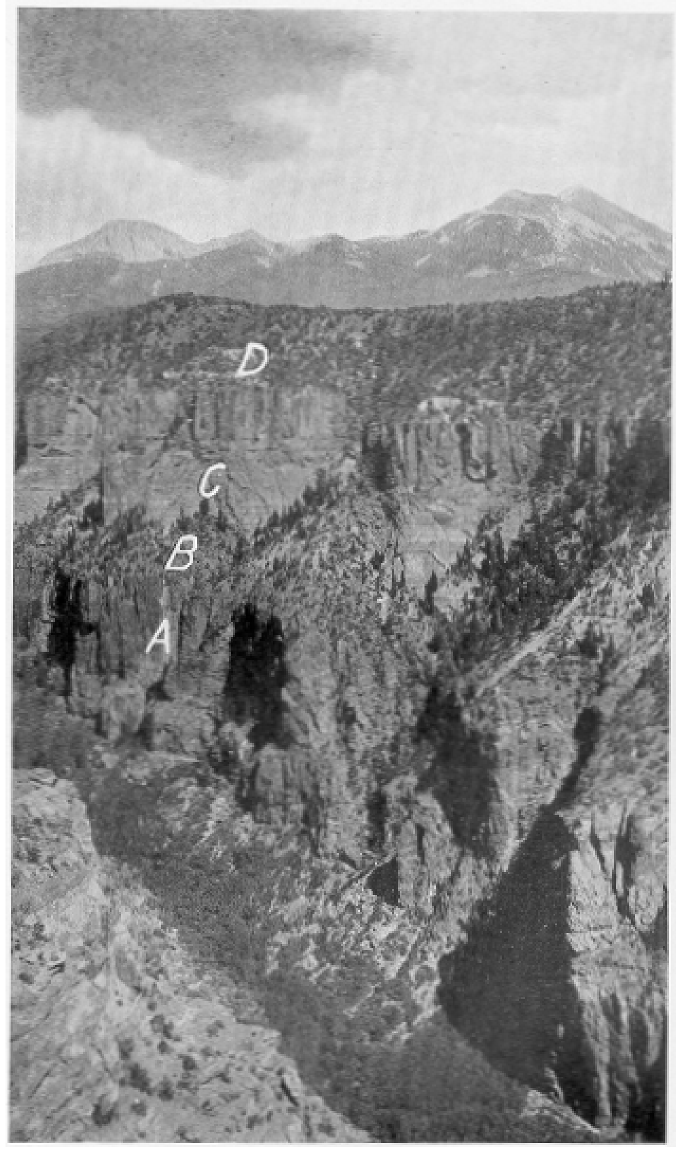


FIG. 2. Mesa in Lower End of Castle Valley
The lowest rock exposed is Cutler and the cap rock is the Wingate

PLATE VI



The Canyon of Mill Creek near the Central Group
A is the Lower Navajo; *B*, the Middle Navajo; *C*, the Upper Navajo; *D*, the McElmo

PLATE VII

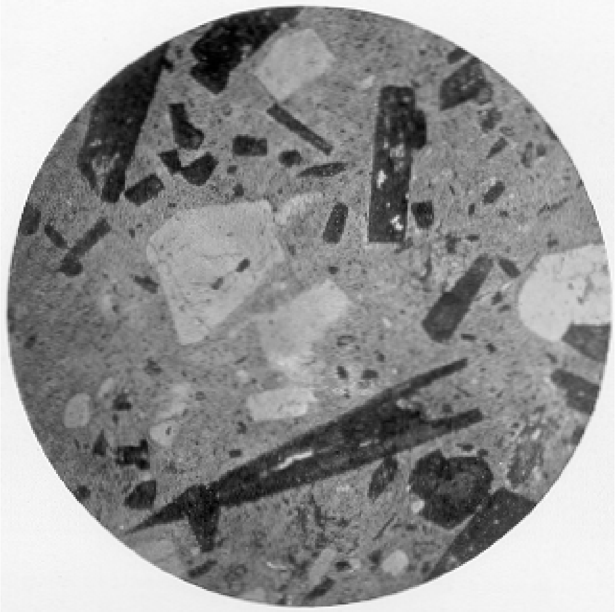


FIG. 1. Photomicrograph of Diorite Porphyry showing Acicular Development of the Hornblende

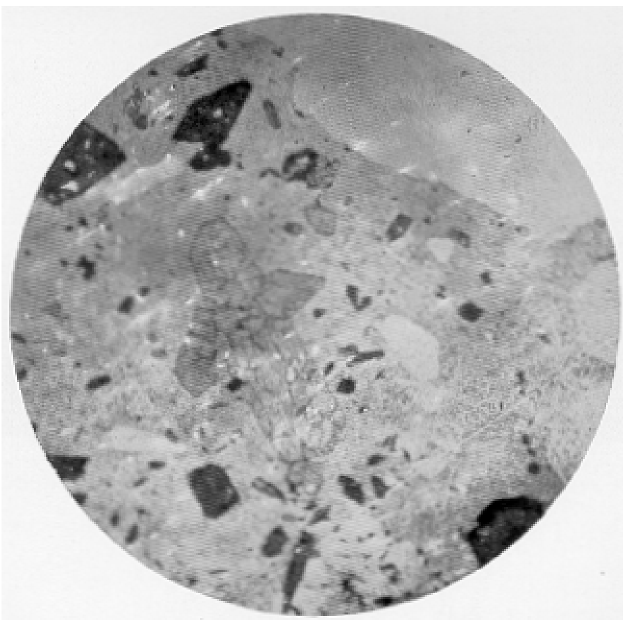


FIG. 2. Photomicrograph of Diorite Porphyry showing Characteristically Twinned Crystal of Augite

PLATE VIII

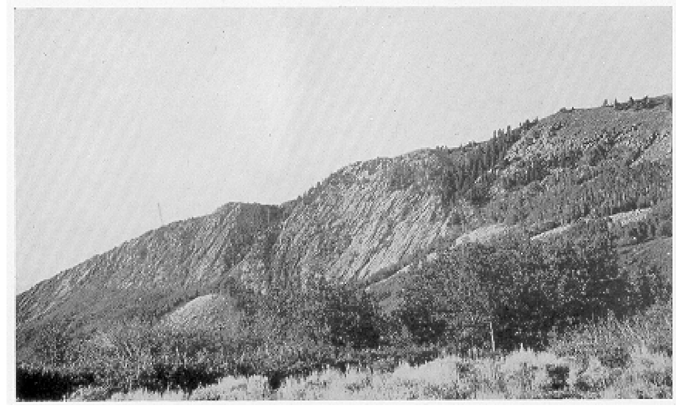


FIG. 1. Hogback of Dakota Sandstone along the Western Side of the North Group

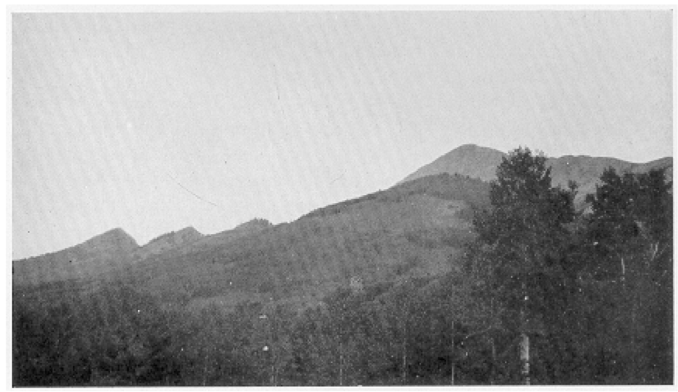


FIG. 2. Hogback of Massive Triassic Sandstone along the Southern Side of the North Group

ICE-PUSH ON LAKE SHORES

IRVING D. SCOTT

FOR some time the writer has had the conviction that ice action on the shores of the smaller inland lakes was quite prevalent and, therefore, deserving of greater consideration in the texts on geology than is generally the case. This conviction has been amply confirmed by a study of several years' duration of a large number of the inland lakes of Michigan, few of which worthy of the name lake are without evidence of ice-push on their shores.

PROCESSES

Two theories have been advanced for the shove of ice on the shores of lakes, namely expansion and ice-jam. Both theories appear to be well established by observation, but that of expansion, which appeared first, seems to have received almost exclusive recognition. If, then, two processes are active in forming similar features, the question arises, aside from the mechanics of the processes, as to their relative importance. The writer's observations have some bearing in this connection as well as on the mechanics of the processes and, therefore, some discussion of the action of ice and its results on shores is attempted in this article.

The expansion theory accounts for the shove of the ice on shores by the contraction and expansion of ice due to variations in air temperatures. Recent papers on this subject have been written by Buckley (1, pp. 141-162), Gilbert (2, pp. 225-234), and Hobbs (3, pp. 157-160), and of these Buckley's is the most comprehensive.

This theory is based on the fact that ice under normal pressures acts as do other solids under varying temperatures below the freezing point, expanding with a rise in temperature and contracting when the temperature falls. The linear coefficient of expansion as given by Landolt-Bornstein-Roth varies from .0000237 to .000054 per degree centigrade with an average value of .0000417. In using the average value, the linear expansion of an ice sheet one mile in diameter is .12 feet for each degree Fahrenheit rise in temperature. The expansion attendant on water changing into ice has little or no effect on the shores, but the resultant ice-sheet forms a complete cover over the lake and increases in thickness by addition to the lower surface. A subsequent lowering of temperature of the air is transmitted to the ice from the upper surface downward, giving temperatures in the ice ranging from approximately that of the air at the upper surface to 32° F. at the lower surface where the ice is in contact with the water (1, p. 151). Thus, a differential horizontal contraction is set up which is greatest at the upper surface and decreases downward to zero at the bottom of the ice. This tends to deform the ice-sheet concave upwards (4, pp. 29-49). This deformation is opposed by gravity and the buoyancy of the water, and horizontal stresses result which are tensile at the upper surface and compressive at the lower, with an intermediate zone of no lateral stress. When the tensile strength of the ice is exceeded, a V-crack is formed and extends downward to the zone of no lateral stress, which itself is simultaneously lowered until the stresses are relieved. If sufficient tensile stress is developed, the zone of no lateral stress and the crack as well extend to the lower surface of the ice. In this way cracks develop in sufficient number to reduce the stresses below the tensile strength of the ice and the ice surface remains nearly flat, except locally on either side of the cracks where it may curve upward.

It has been noted (5, Append. 7, p. 23) that at times lanes of water are opened along such cracks with a drop in temperature at night, but are closed during the warmer temperatures of the day. Since the temperature of the lower surface of the ice remains constant at the freezing point, there should be no variation in volume in this zone and, consequently, no spreading of the cracks nor pulling away from the shores. In explanation it may be suggested that the apparent contraction of the lower layer is due to the appreciable compressibility of the ice, which, according to Ludlow (6, p. 923), is one twelfth of its volume under pressures varying from 21 to 64 tons per square foot (temperature probably 32° F.). Also there is the possiblity of melting due to the lowering of the melting point by compression on the lower layers previous to the relief of the tension in the upper layers by fracture. In either case no values can be given for the compression, so that the importance of these factors cannot be stated.

Where the V-cracks extend through the ice the water rises about nine tenths of the total thickness of the ice and freezes, forming wedges of ice with points down. As the temperature lowers, old and new cracks are opened and healed, and the ice cover remains constant in linear extent but increases in average density. When the temperature reaches its lowest point, the surface of the lake is completely covered with ice of maximum average density.

With a rise in temperature, expansion of the upper layers takes place and with it a tendency to deform the ice-sheet convex upward. This tendency is intensified by the presence of the wedges mentioned in the preceding paragraph. Stresses are, therefore, set up which are the opposite of those active during contraction, namely, horizontal compression in the upper layers and tension in the lower. When the stresses exceed the tensile strength of the lower layers, inverted V-cracks are formed from below, which are probably healed in most cases. In this way a permanent expansion results which is equal in amount to the total thickness of the ice wedges formed at the upper surface, as shown in Figure 5. The process may be repeated a number of times during a winter and the amount of expansion is proportional to the total rise in temperature below the freezing point, provided the temperatures are promptly transmitted to the ice.

If sufficient expansion takes place, either the rigidity of the ice is overcome or the edge of the ice expands on the shore. In either case the stresses are relieved suddenly (1, p. 151). In case the rigidity of the ice is overcome it usually buckles or arches, although troughs have been noted (5, p. 23). The prevalence of anticlinal structures is due to the tendency of the ice-sheet to assume a convex upward surface during expansion, the presence of wedges in the cracks placed head up, and the upward warped edges of the cracks. The troughs, which occur infrequently, are caused by one wall of the cracks slipping under the other (7) and resemble thrusts rather than synclinal structures as suggested by Meigs. On the other hand when the ice expands on the shore, it pushes before and carries with it earthy material which, upon the melting of the ice, is left at the most advanced position of the ice edge.

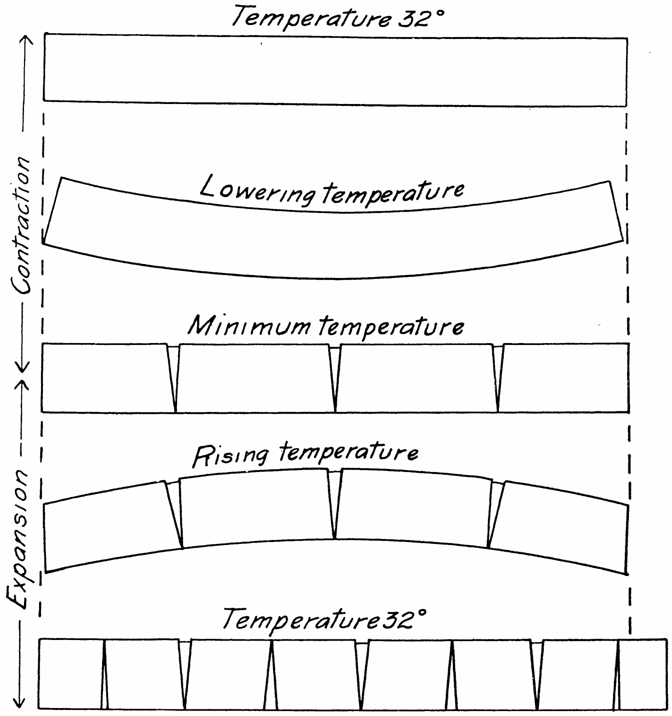


FIG. 5. Drawing (after Barnes) showing the linear expansion of an ice-sheet due to lowering temperature followed by a rising temperature

The conditions under which this expansion on the shores takes place have been stated by Hobbs (3, pp. 157-160) and may be grouped under two headings, climatic and mechanical. The climatic elements are a winter season during which a complete cover of ice of considerable thickness is formed, large and relatively rapid alternations of temperature below the freezing point, and an absence or light accumulation of snow on the ice. The seasonal variation in temperature is quite generally fulfilled in north temperate latitudes above 42° or 43°. For large and relatively rapid temperature changes during the winter, there are cyclonic and diurnal variations as possibilities. Buckley's studies have shown, however, that the cyclonic variations are particularly effective and that the diurnal changes have little or no effect (1, pp. 141-162). Further, of the cyclonic changes it is those attendant on a low pressure closely following a cold spell that are effective. An analysis of the temperature record taken at Madison, Wis., for the months of December, January and February, 1898-99, given by Buckley (1, p. 143), shows a total range of more than 1200° F., excluding temperatures above 32°. Inasmuch as the daily range represents both a rise and fall of temperature of like amount on the average, it is indicative of the amount of expansion that might be expected if all the energy were expended in this way. The 1200° should produce a total expansion of about 144 feet, or 72 feet on each shore of a lake one mile in diameter where the ice is free to move. This amount is far in excess of the facts. Evidence to this effect is supplied by the position of the ramparts with reference to the shores. The writer's observations show that in most cases permanent ramparts are found in close proximity to high water shore-line of the lake. Thus, it seems evident that only the larger rises in temperature are effective. Here again we may suggest that the compressibility of the ice and melting due to compression may be the factors that render the diurnal changes in temperature ineffective.

A snow covering more or less effectively blankets the ice and prevents or retards the transmission of air temperatures to it. The occurrence of a snow covering depends on the amount and kind (wet or dry) of snow and also on the wind velocities during and subsequent to the precipitation.

From the mechanical side it is necessary that the ice be of sufficient strength to act as a strut against the stresses imposed upon it. As stated by Hobbs (3), the factors are the flatness of the surface, the homogeneity of the ice, and the thickness of the ice in relation to its length.

As to flatness of surface, lake ice free from snow tends to deform with changes in temperature, as has been shown above. This is effective during expansion when the ice-sheet tends to become convex upward and makes the ice less able to transmit the horizontal stresses, necessitating thicker ice than would otherwise be the case. The homogeneity of the ice is greatly interrupted by the numerous healed cracks which are sometimes crushed by subsequent expansion, according to Tyrrell (8).

The thickness of the ice in relation to its length is important, since the competency of a strut varies inversely as its length. Not only are there lakes of various sizes (length of strut) in a given locality, but also there are important variations in the thickness of the ice formed during different winters. We may have, then, lakes so small that the expansion results in a shove on the shores, since the thickness of the ice is always great enough to cause it to serve as a strut. In such cases the amount of expansion is often small and the results insignificant. On the other hand there are lakes so large that the ice is never thick enough to serve as a strut, but buckles into pressure ridges which usually occur in the same locations each year. An intermediate class are those upon which the ice attains sufficient thickness only during winters when meteorological conditions are especially favorable. Upon such lakes expansion is most important.

However, the size of the lake (length of strut) seems to be the most important of the mechanical factors and there is a limit in size of lake upon which a competent ice layer is formed under given climatic conditions. This limit, as stated by Hobbs (3), is not much over one and one-half miles and is certainly under four miles for climates such as southern Michigan. The writer's observations indicate that expansion seldom, if ever, occurs in an ice-sheet of more than two miles in extent. In considering the size of lake the smallest diameter must be taken. Thus, on long, narrow lakes the ice is incompetent for the long diameter and buckles in lines which run across the lake between salient points, while along the shorter diameter the ice pushes on the shores. The expansion in this case is radial from the center of each block and not necessarily normal to the shores. Likewise the ice may expand in a more or less enclosed indentation, but not on the main lake.

The essentials of this theory are: Ice contracts with lowering temperatures and the contraction is accommodated by tension cracks in the upper part of the ice and not by pulling away from the shores; these cracks are healed by freezing and the ice completely covers the lake; the average density of the ice increases as the temperature is lowered; with rising temperatures the ice expands; the result of the expansion is either a buckling of the ice or a shoreward extension of its edge, which remains until the ice melts.

The necessary conditions are: A lake not too large to form a competent ice layer; a winter season of sufficiently low temperature to form a competent ice layer; large and relatively rapid cyclonic changes in temperature during the winter and the absence of a snow blanket, in order that the temperatures may be communicated to the ice. All these factors vary, therefore expansion takes place only under a favorable combination of the climatic factors on the smaller lakes.

Another method of ice-shove was advocated by Tyrrell (8), as a result of his observations on Canadian lakes which lie well to the north of those studied by the writers cited. This we may call the ice-jam method. It has also been advocated independently by Taylor (9, pp. 337-338) to account for ramparts found on the shores of glacial Lake Maumee, although not worked out as to detail. The essentials of Tyrrell's theory follow.

Ice on lakes in regions of heavy snowfall increases primarily from the top rather than from below. The snow forms an insulating covering which prevents the air temperatures from being rapidly transmitted to the ice and changes in volume do not occur. At times, however, the snowfall is light and the temperatures are transmitted to the ice. With a drop in temperature cracks and open lanes of water are formed and these are promptly frozen over. But with subsequent rise in temperature the ice does not expand farther than to close up these lanes by crushing the new ice and “the shores remain undisturbed all winter.” According to Tyrrell, the horizontal expansion which is not relieved by crushing in the healed cracks and lanes is expended in a vertical direction and has very little effect in increasing the thickness of the ice.

Other ways in which this expansion may be accommodated without shove on the shore have been discussed above, but another factor is present in this case which may have some importance. The load of snow which ice may carry without downward deformation is limited, especially if it falls soon after the ice is formed. Tyrrell states that one inch of ice will carry only five eighths of an inch of snow, and a three-inch ice sheet but two and one-half inches of snow. If the superjacent snow is proportionally greater than the amounts stated, the ice will sag and water will rise through the openings and wet the snow, thus increasing the load. It is possible, then, that the expansion may result merely in a greater downward deformation of the ice sheet, or that the ice formed from the freezing of this slush is weaker than normal ice and will crush under the compression to which it is subjected.

In the spring the ice melts first near the shores because of the relatively rapid heating of the earthy material of the shore and the shallow bottom. An open lane of water is formed which is further widened by a rise in lake level from the water added by the melting snow of the surrounding slopes. If strong winds develop before the ice becomes rotten, the ice is blown about from side to side by the varying winds and pushes on the shores "with almost irresistible force." The direction of the shove is related to that of the winds and may vary along any shore even during a jam, if the winds shift considerably. The force of the push depends on the firmness and momentum of the ice, the latter being determined by the velocity and duration of the wind, the weight of the ice and to some extent the distance through which the ice is free to move.

Since strong surface winds in latitudes where climate suitable for ice action prevails are largely controlled by cyclonic disturbances, all shores of a lake may be affected by ice-jams, but not to the same degree. Strong winds occur in the cyclonic or low pressure areas whose centers move eastward over North America, passing in the vicinity of the Great Lakes for the most part. The passage of one of these storms is accompanied by a shifting of the winds and an increase in velocity, which usually reaches its maximum when the air is moving directly to the low from the high adjacent on the west, winds with westerly component. The shifting of the winds is through the southerly half of the circle if the center of the low passes to the north and through the north when the path lies south of a locality. There is, then, at first a crowding of the ice to the northwest or southwest parts of the lake, depending on whether the center of the storm passes to the south or north. This crowding is of moderate intensity because of the generally low velocities of the easterly winds, but serves to open a wide lane of water on the east side. This wide lane of water, together with the increased velocity as the wind shifts to the west, tends to give increased push on the northeast or southeast shores. In southern Michigan most of the storm-centers pass to the north, giving the strongest push on the northeast shore. Occasionally a storm-center passes directly over this region, which intensifies the push on the east shores. Farther north this condition should be reversed and the southeast shores should be most affected. Weather conditions, however, are extremely variable and it should be evident that all shores of a lake may be affected by jams, but not to the same degree.

Ice-jams are not effective on small lakes because of the inferior amount of ice, but should increase in power with the size of the lake within limits, the upper limit depending more or less upon whether the lake completely freezes. This does not preclude the possibility of ice-jams on lakes, such as the Great Lakes, which do not completely freeze ordinarily, but their effects are removed subsequently by the powerful wave action. Another factor that may or may not increase the effectiveness of jams is the piling up of the ice at its margin as a result of the buffeting to and fro. This increases the depth to which the ice extends and, therefore, the amount of material available for transport, but also tends to prevent the jam from reaching the beach. Thus, there are two ways in which ice shoves on the shores of lakes. Each is dependent on a favorable combination of weather conditions and, therefore, may or may not be active during any winter. Of the two the ice-jam has a much wider application both as to size of lake and climatic variation and may cooperate with expansion on some lakes during the same winter. As to the force exerted in each case, the writer has nothing to offer except that both are effective from a physiographic standpoint.

EFFECTS

It is obvious that, whatever the cause of the ice-push, the effects produced are in part dependent on shore conditions, and in this are included the material at hand and the topography of the shore. The work of physiographic importance is the shoreward transportation of earthy material which may be frozen in the ice or pushed in front of the ice edge. The amount transferred depends on the area swept by the ice, the number of times the ice has advanced and the amount of available material. The first and second of these conditions need no discussion. Under available material must be considered the consolidation, and the size and quantity of particles. In general, lack of consolidation is necessary but some consolidated rocks, as the term is generally used, where closely fractured, e.g. thinly bedded limestones, are moved by the ice as at Indian Lake near Manistique, Michigan.

Coarse material is readily transported while fine material, such as sand, allows the ice to pass over it with little or no disturbance. Usually, however, materials of all sizes are mixed and much fine material, which would otherwise not be moved, is carried along with the coarse. Exceptions are to be noted in the case of fine material which is bound by vegetation. Excellent examples of this were noted by the writer on the shores of Torchlight and Crystal lakes in Antrim and Benzie counties, Michigan. At the north end of Torchlight Lake a sand rampart was noted which ran parallel to the shore just in front of a row of poplars. This rampart plays out at each end of the row of trees. Inasmuch as it showed little effect of subsequent wave-erosion, its absence, where it was not bound by the roots of the trees, signifies that none was formed there. On Crystal Lake a small, but well-defined, rampart was noted where a strong growth of dune grass served as binder for the sand (see Fig. 6).

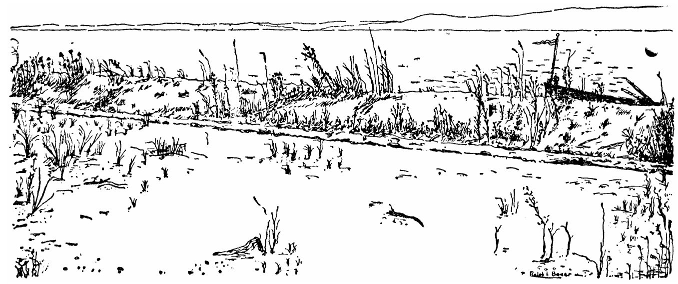


FIG. 6. Small ice rampart of sand, Crystal Lake
(Drawn from photograph)

The permanence of ramparts depends largely on the size of the constituent material and its position with reference to the shore. Sand, when bound by vegetation, is frequently pushed into ramparts only to be destroyed by waves during the following season, while coarse material may successfully withstand the beating of the waves for a long period. Obviously ramparts formed beyond the reach of the waves will develop faster and persist longer than those within the range of wave action.

The quantity of available material refers to the amount of coarse material. This material will sooner or later be exhausted unless the lake level is lowered, in which case fresh areas are brought into the zone of ice action.

The topography of the shores is of great importance. The amount of forward movement possible varies inversely as the steepness of the shores. At the foot of steep cliffs the movement is least, but some is always possible even in expansion because this process works during periods of low water. In such cases the material is eventually forced into the bank, giving a paved or mosaic effect, or is left at the foot of the cliff where wave action removes the finer material arid leaves a line of boulders as shown in Plate IX, Figure 1. Low cliffs are sometimes overridden by the ice and the brow is pushed over into a rampart that is well beyond the reach of the waves. On sloping shores more ice movement is possible and ramparts are developed, provided material is available. The proviso is necessary because many flat shores are developed by wave and current action and the material is fine.

Ice ramparts have been described and classified by Braun (10) and Buckley (1). According to the latter, they are as follows: ridges formed on shelving shores, those formed on a low cliff, and folds formed on low marshy shores. The first two may be considered as relatively permanent, but the third type disappears when the frozen vegetal mat thaws. Of the permanent ramparts those formed on shelving shores are much more common and may be considered typical.

Such ridges stand above the surrounding land both fore and back and are somewhat irregular in continuity, height and slope. They increase in size with each advance of the ice until the available material is exhausted, at which time they have reached a maximum development, or until the rigidity of the rampart exceeds that of the ice. When the latter condition prevails, the expanding ice will buckle and ice-jams will shear over the top of the rampart. Since some movement is possible, each advance leaves a deposit in front of that left by the preceding advance, forming a terrace composed of a series of typical ridges, known as an ice-push terrace. According to Fenneman (11, p. 34), a gradually lowering lake level is necessary for the formation of these terraces by expanding ice. One other topographic form which results from ice-shove has been described by Fenneman (11, p. 33) as follows: "Ridges are frequently met with which in position and horizontal form would be called spits, but whose composition is of bowlders and thoroughly unassorted material. Such ridges may generally be accounted for by the agency of ice, pushing up the materials of a shoal bottom which a subsidence of the water level has brought within the reach of the ice. Similar forms were observed by the writer on one lake and will be discussed later."

Thus far the writer has attempted to state somewhat fully the principles involved in the two theories of ice-shove and to discuss the effects. No attempt has been made to differentiate between the effects of the two processes and purposely so. All the topographic forms, with the possible exception of boulder spits, which result from ice action, may be accounted for by either method of shove, and the writer knows of no distinctive characteristics. Of these the boulder-lined strand at the foot of cliffs is readily accounted for, since such places mark the limit of forward-moving ice of either process. The fact that the ice is often piled up at its forward edge during a jam makes the depth to which the ice will scour the bottom greater than where expansion takes place and the available material is thereby greater, giving stronger effects.

Ramparts due to expansion have been observed in the process of formation, but the same cannot be said for ice-jams. Tyrrell (8) has found well-developed ramparts back from the shore and also large boulders in the process of shoreward movement on lakes much too large for expansion, and states positively as a result of observation that expansion does not take place. In addition the paths of the boulders in some cases abruptly change direction, a fact readily explained by a shifting of the wind during a jam or successive jams, but offering difficulties when the attempt is made to account for them by expansion. On first thought it would seem that the ice edge of jams would be irregular and that the resulting rampart would show less regular delineation than those of the expansion type, thereby giving a means of differentiation. The writer, however, was unable to find any such criteria and wishes to call attention to Plate IX, Figure 2, a view of an ice-jam on Crystal Lake, Benzie Co., Michigan, which shows a remarkable (to the writer at least) regularity of the edge. Other photographs of this same jam and of jams on other lakes, not here reproduced, show less regular ice edges, but sufficiently so to form ramparts when it is considered that the rampart is an indication of the average position of the ice front of numerous jams, and that a strong rampart may offer considerable resistance to the movement of the ice.

As regards ice-push terraces, it is readily seen that successive advances of the ice may form a succession of the ridges, provided the available material be sufficient. If they are formed by expansion, it is generally necessary to assume with Fenneman a gradual depression of the water level of the lake, which would bring the material of new areas of the bottom of the lake into the zone of ice action and also progressively decrease the outer limit of ice movement for each advance. Such a terrace might be formed if the expansion during successive seasons were progressively smaller, but would be destroyed on being overridden by a subsequent large expansion. In case it is formed by ice-jams, no lowering of water level is necessary. The available material is greater to start with — see discussion of boulder-lined strand above — and may be added to by the along-shore movement of coarse material by floating blocks of ice driven by waves and currents. Successive jams force the material into a series of ridges, and subsequent jams of great force will pass over the terrace by shearing rather than scour. Such an ice-push terrace is shown in Plate X, Figure 1, a view of Poplar Point on Lake Athabaska, Canada. This lake is one of large dimensions in a region of heavy snowfall where expansion does not take place, according to Tyrrell's observations.

The sufficiency of simple ice expansion, that is normal to the shore, for the formation of boulder spits is doubtful, but may be a contributing factor where a normal spit continues along the main shore-line of the lake. Under such circumstances the ice may push against the spit, but suitable material is unlikely inasmuch as it is largely current-born, that is, sand. Only two of these forms were seen by the writer, both on Long Lake, Alpena Co., Michigan. One, shown in Plate X, Figure 2, has characteristics resembling a cuspate foreland, except that the material is angular and much too large to have been moved by waves and currents on this lake. It extends abruptly out into the lake and is clearly formed by deposition. Obviously expansion normal to the shore cannot have formed this feature. The suggested explanation is that this point on the shore is the location of one end of a pressure ridge which extends across the lake. The expansion is then towards the pressure ridge and, therefore, towards the sides of the cuspate foreland. This resembles the holm of Gustafsson (12, pp. 145-178).

Another similar form, which occurs on Long Lake also, is shown in Plate XI, Figure 1. The main body of the lake is to the left in the picture and it will be noted that the surface material of the spit is coarse, the shape serpentine, presenting a convex curvature to the lake near its attachment to the shore. Much of the material below water is sand, the slopes are characteristic of normal spits and its position is across the mouth of an indentation, although the form leaves the shore at an abrupt angle. This spit, then, has characteristics which indicate both ice and current action. It is possible to explain this form in the same manner as that discussed in the preceding paragraph, but there is also the possibility of ice-jams having been effective. Both methods of ice-shove are active on this lake, according to the testimony of the inhabitants of the region. The jams are especially severe on the northeast shore, sometimes reaching a height of ten feet. Ramparts are found at favorable locations on all shores, but are higher and more continuous on the northeastern shore. This may be due in part to more favorable shore conditions, but other evidence indicates that jams are especially effective on this shore. In Plate XI, Figure 2, is reproduced a photograph of one of a number of boulders which have been pushed shoreward by the ice on this lake.

Such boulders were found in three localities, all on the northeastern shore, and the direction of their paths, which were very clear, was found to deviate but slightly from N. 50 E., irrespective of the direction of the shore-line. Near the north end this varies considerably from the normal to the shore-line, which would be the direction of ice expansion, and it is evident that all were moved by an ice-jam, and perhaps by the same jam, although the lake is well within the limits for expansion.

The following statement of conclusions may be made: (1) Since many of the largest ramparts noted on Michigan lakes were found on lakes which are too large for expansion to be effective, e. g., Indian Lake, Schoolcraft Co., Pine Lake, near Charlevoix (Nipissing shore), Higgins and Houghton lakes, Roscommon Co., and Hubbard Lake in Alcona Co., ice-jams push on the shores of inland lakes in climates such as that of Michigan and, therefore, both ice-jams and expansion are effective; (2) Similar topographic forms result from the work of either process; (3) Both methods may be effective on the same lake, provided it does not exceed two miles in shortest dimension; (4) The ice-jam, on account of its greater range as to climate and size of lake, is of wider occurrence; (5) In climates similar to that of Michigan the ice-jam appears to be the more effective; (6) In the cases of some of the lakes the evidence points clearly to a stronger push on the northeastern shore, indicating cyclonic control of ice-jams.

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PLATE IX

FIG. 1. Raised Boulder Strand, Torchlight Lake

(Photograph by Donald Gibbs)

FIG. 2. Ice-Jam, Crystal Lake

PLATE X

(Courtesy of the Department of Mines, Geological Survey)

FIG. 1. Ice-Push Terrace, Athabasca

FIG. 2. Ice-formed Cuspate Foreland, Alpena County

PLATE XI

FIG. 1. Ice-formed Spit, Long Lake, Alpena County

FIG. 2. Boulder pushed on Shore by an Ice-Jam, Long Lake, Alpena County
This boulder will travel up the beach in stages and eventually become part of the rampart

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THE CREELSBORO NATURAL BRIDGE

IRVING D. SCOTT AND RALPH L. BELKNAP

IN CONNECTION with the work of the University of Michigan Summer Camp for Geologists and Geographers, there has been brought to the attention of the authors an unusual case of stream-diversion which resulted in the formation of a natural bridge. This bridge, known as the Creelsboro Bridge, is located in a narrow ridge which separates the Cumberland River from one of its tributaries, Miller Creek, or, as more commonly called, Jim's Creek. The bridge itself is about four miles down-stream from the town of Creelsboro, which in turn is located in southwestern Russel County, Kentucky.

The geologists who have worked in this area, as well as those who have made a special study of natural bridges, have made but few references to the Creelsboro Bridge. In the literature on this subject only two references to this bridge have been found. Cleland (1), without citing any literature, has referred to it as an example of the type of bridge formed by lateral planation of a stream and its tributary working from opposite sides of a narrow ridge. Miller (2) has accepted this explanation of its origin and adds further that "the rock formation pierced in the forming of the bridge or tunnel is Richmond limestone of Cincinnatian age." Inasmuch as this statement of the origin has been questioned, the authors, in the summer of 1925, availed themselves of the opportunity of making a more careful and detailed investigation of this bridge than had previously been made. The data and information, and the conclusions reached as a result of this study, are believed to be of such importance as to warrant their presentation.

The introduction to this discussion may well include a definition and brief classification of natural bridges. Since this has been so well presented by Cleland, attention is again called to the first reference of this paper.

Natural bridges are defined as arches spanning valleys of erosion. Since in the case of the Creelsboro Bridge it is a ridge between two valleys that is pierced, it might at first seem somewhat inconsistent with this definition to apply the term bridge to this particular arch. Since, however, the arch spans the present channel of Jim's Creek, the term bridge can quite properly be applied.

Natural bridges have been classified as follows by Cleland according to their manner of formation:

A. Bridges formed by deposition;
B. Bridges formed by gravity;
C. Bridges initiated by wave action;
D. Bridges initiated by solution;
E. Bridges initiated by stream-erosion.

It will be noticed that unless consideration is given to the possibility of wind action in the formation of bridges this classification is quite complete.

It is also evident, after a brief study of the bridges that have been described, that the last two causes are by far the most important in accounting for the formation of existing natural bridges.

Cleland has made three subclasses of the bridges initiated by solution. In the first group are included those which are explained so commonly as being due to the combined action of subterranean and subaerial erosion. This is the most frequently used explanation of natural bridges. In classifying bridges, however, it is found that there are only a surprisingly small number that can be included in this group. It is, then, the most common explanation, but the bridges to which it can be applied are actually of rare occurrence.

The second group of bridges due to solution includes those which are formed primarily by seepage. The Virginia Natural Bridge and the North Adams Marble Bridge are both well-known examples of this type. In this case the water seeps from the bed of a stream down a joint plane to a bedding plane, then along the bedding plane to the surface — usually in the face of, or beneath, a water-fall, or in a rapids.

In the third group of bridges due to solution are included those which owe their origin to the partial caving in of a superficial tunnel. Inasmuch as there is no indication of this action at Creelsboro, it will not be discussed in this paper.

In general it can be said that bridges formed by solution occur very frequently, but are usually quite small. They are found in a region which has a well-developed joint-system and well-defined bedding planes.

Of the bridges initiated by stream-erosion, seven different subclasses are given. Of these the only type considered in this paper is the one resulting in the perforation of the neck of an incised meander. This is the type illustrated by the great sandstone bridges of San Juan County, Utah, a type perhaps relatively less important quantitatively, but including some of the largest bridges yet described.

Bridges formed by this process possess several important characteristics. First of all the bridge is located in the narrowest part of the meander where the two meanders were formerly back to back. There is also a large amount of undercutting near the base, resulting in the formation of overhanging cliffs. Usually the two sides of the bridge, the ends of the piers or abutments, are buttressed or planed off so that they point in toward the center of the opening; if not, the line through the center of the bridge or tunnel perpendicular to the span is nearly perpendicular to each of the streams forming it.

A modification of this method of forming the opening would be the perforation of a ridge between a tributary and main stream, by erosion where two meanders were back to back. This modification referred to as lateral planation is given by Cleland and Miller in accounting for the Creelsboro bridge.

Facing the bridge from the Cumberland side as shown in Figure 7, one is reminded of a massive skew bridge with the ends of the abutments parallel to the Cumberland and its axis almost coincident with the abandoned channel of Miller Creek below the bridge. The opening of the bridge varies in height from 15 feet on the north side to 40 feet on the south side. It has a span of 75 feet while the dimension that should be its width, the length of the tunnel, is about 100 feet, somewhat greater than the span. The floor, while quite uneven, is about 20 feet higher than the level of the Cumberland River on the river side and rises to an elevation of over 40 feet above river level on the opposite side. In fact the bottom of Jim's Creek is about 30 feet above the normal summer level of the Cumberland. The two pictures, Figures 7 and 8, may give a more definite impression of the appearance of the bridge, particularly the condition of the faces of the cliffs. It will also be noticed from these pictures that the thickness of the rock above the opening is greater than the height of the opening. It varies greatly, but is not less than fifty feet at any point. In addition it is also observed in Figure 7 that the lowest part of the ridge is not over the bridge, but to the right, that is, on the up-stream side. This of course marks, as well, the narrowest part of the ridge separating the two streams. It is, then, the place where the bridge would normally be located if it had been formed by lateral planation alone.

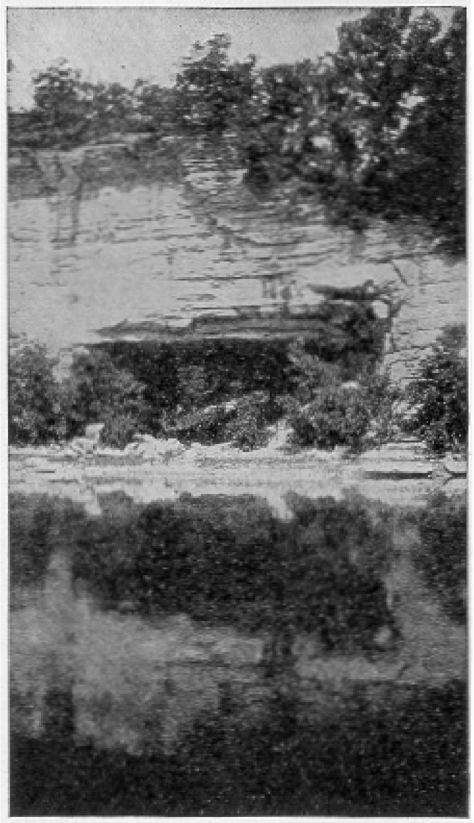


FIG. 7. Creelsboro bridge from river side

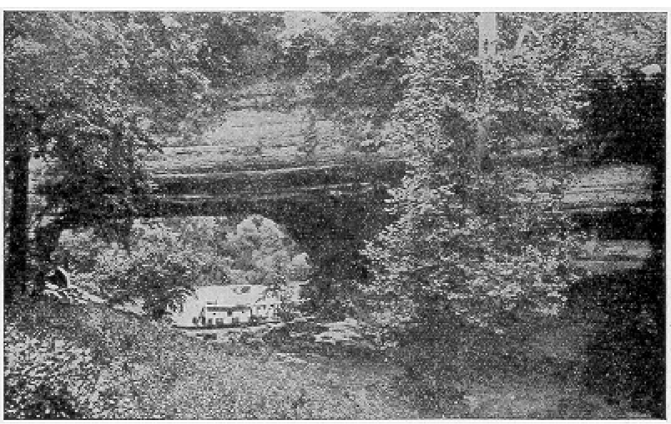


FIG. 8. Bridge from Jim's Creek side

The beds pierced in the formation of the bridge are rather heavy, massive, siliceous gray limestone shaly in places, usually quite fossiliferous, showing no effect of solution, and characterized by the absence of, rather than the presence of, joints.

These beds are the ones referred to by Miller as being of Richmond age. Although the authors were not interested in the stratigraphic section of the bridge, an important fact in this connection has been brought to their attention. Believing some information concerning the possible origin of the bridges could be obtained from descriptions of the physical and chemical characteristics of the Richmond limestone, they studied several references.

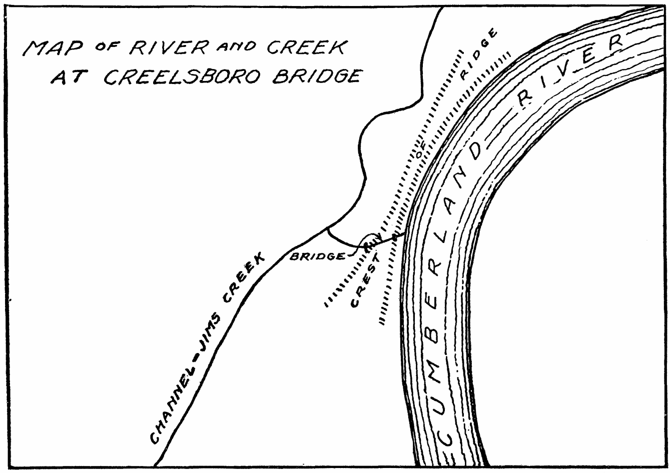
The results of this study were of no importance except to call attention to some work done by Professor G. M. Ehlers and Mr. C. F. Deiss, of the University of Michigan, who had been studying the fossils collected particularly from the beds exposed in the bridge-section. As a result of their study, as yet unpublished, it was found that the bridge was in a lower geological horizon than the one in which it had previously been supposed to be located, that is, the fossils collected from the bridge-section were those of Maysville, rather than of Richmond, age. The Richmond formation would then be represented, if at all, by some of the beds near the upper part of the arch over the opening.

In general the surfaces exposed, while showing no indications of solution, are quite smooth. This is particularly true on the creek side of the arch where the surface conditions lead one to conclude that weathering and erosion are taking place very slowly, somewhat in contrast with the conditions on the opposite face.

Although there are indications of lateral planation by the Cumberland on the river side of the bridge, a more important effect is that due to weathering. The cliff on this side is faced with small but innumerable blocks of rock, which have been loosened by the action of weathering. Here, even though the Cumberland is cutting into the cliff, weathering is going on even a little faster, so that the cliff, rather than overhanging, is sloping in toward the crest at such a rate as to enable one to climb up at least twenty-five feet above the floor of the bridge, where further progress is blocked more by the loose material lining the face of the cliff, than by the verticality of the wall. Above this zone, however, the face of the cliff does become vertical with an occasional narrow overhanging ledge at the top.

Map 4 shows a part of a traverse which was run from the bridge down the old channel of Jim's Creek to the river, back up the river to a point above the bridge where the ridge was crossed and the traverse closed by running down the creek bed to the starting point. One of the significant things noticed in the diagram is that the bridge is located not at the narrowest point in the ridge, the logical location if lateral planation is the cause of the bridge, but some distance down-stream from this point.

From the data presented so far the authors have concluded that the opening is actually too much of a tunnel as it has been called by Miller, that is, too long and narrow to be formed by lateral planation. This conclusion is supported by the following facts: First, the axis through this tunnel is not perpendicular to the axes of the streams forming it, but is more nearly parallel to the channel of Miller Creek on the down-stream side and makes an obtuse angle with the Cumberland on the up-stream side. Secondly, indications of lateral planation are not found on the Miller Creek side of the bridge. Although lateral planation is active on the Cumberland side, it has been so slow that practically no undercutting has resulted, weathering having kept pace with it. Last and most important of all is the fact that the bridge is located down-stream from the narrowest and lowest point in the ridge. Since, then, lateral planation does not appear to have been the cause of the formation of the bridge, some other explanation must be found.



MAP 4

Since the bridge is located in a ridge made up almost entirely of limestone, solution would be the next explanation to suggest itself. Because of the entire absence of any indication of solution in the bridge-section, the rocks being quite insoluble, and because of the almost complete absence of joints, it has previously been thought that solution was not responsible for the formation of the bridge.

A careful investigation of the rocks in the vicinity of the ridge resulted in the discovery on the Cumberland side of the bridge of two particularly interesting beds that had not been noticed in the bridge-section, the beds being slightly lower than the level of the floor. These beds were not more than a foot thick, of a blue limestone only slightly siliceous, showing a considerable amount of solution on the under side, particularly along a few of the innumerable incipient joints. A photograph, Figure 9, shows the condition of the under surface of one of these layers.

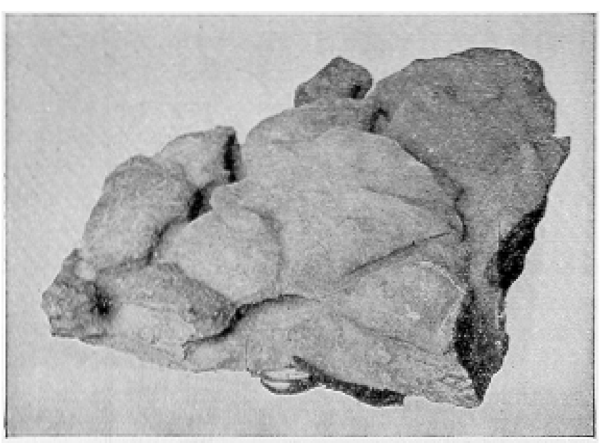


FIG. 9. Solution channels along the under surface of a bed of the soluble blue limestone

The discovery of these beds in their present condition points, it is believed, to the proper explanation of the formation of this bridge. The conclusions drawn in this regard will now be presented.

The fact should be emphasized that the present condition of the bridge is not due to one factor or process alone. It is difficult even to select the predominate process that is responsible for its formation and development. Not to make a definite attempt to do this, it is believed that the following explanation not only accounts for the formation of the bridge but indicates in the proper time-order the processes that have been chiefly responsible for it.

The bridge was initiated by solution. Water seeping downward from the bed of Jim's Creek, which is thirty feet above the normal level of the Cumberland, came to the bedding planes between the soluble blue limestone and the underlying beds, where it moved laterally, probably along the incipient joints, until it came to the surface on the Cumberland side of the ridge. It has been suggested that at this initial stage the water seeped down from the bed of the creek along a joint plane, and that the location of the plane at this point thus accounts for the location of the bridge.

The opening or channel thus initiated by solution was gradually enlarged by this process primarily along the upper surface until it allowed a more rapid movement of the water. It was then enlarged by stream-erosion, corrosion and corrasion. This would represent a second stage in its development.

At the present time the opening is being enlarged by weathering and by stream-erosion, the latter being particularly effective when the flood waters of the Cumberland rush through into the almost abandoned channel of the creek. While this action is enlarging the bridge-opening, weathering, assisted by the lateral planation of the Cumberland, is wearing away the Cumberland face of the cliff, thus decreasing the width of the bridge.

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EVIDENCE OF RECURRENT DEPRESSION AND RESILIENCE IN THE REGION OF THE GREAT LAKES

FRANK BURSLEY TAYLOR

ON THE basis of present knowledge one seems fully justified in saying that nothing within the realm of Pleistocene geology is more clearly established than the depression of the land during the growth of the Wisconsin ice-sheet in the region of the Great Lakes, with its subsequent resilience during and after the glacial retreat. It seems impossible to assign this movement of the land to any other cause than the weight of the ice, and this is the generally accepted explanation. This is assumed to be true, and it is the object of this paper to point out certain suggestive facts, and also some interesting conclusions and corollaries that follow.

It is admitted that there is not much direct evidence of recurrent depression and resilience, but this lack is largely made up by the clearness and power of certain lines of indirect evidence. In the case of the Wisconsin ice-sheet, by far the greater part of the facts upon which we rely for our understanding of the cause of the tilting movement of the land relates to the movement of resilience. The phenomena of progressing depression under the growing ice-weight were not openly recorded, and are now hard to find and interpret. But evidence which proves the differential uplifting of the land during and after the retreat of the last ice-sheet is recorded in great profusion in the uplifted and tilted shore-lines of the temporary glacial lakes which formed in front of the ice. From the first relatively small glacial Lake Maumee in the Erie basin, the waters fell to successively lower levels as the receding ice uncovered new and lower outlets farther north. At the same time, the uplifting and tilting of the land in the north raised some of these new outlets to such altitudes that the overflow returned to previously abandoned outlets at the south. Thus, the location of outlets was changed both by the retreat of the ice-sheet and by the tilting of the land, and the interplay of these changes concurrently with the lowering of lake levels and the tilting of the abandoned beaches has built up a record which shows a remarkably close relation between resilience of the land and the retreat of the ice-sheet. A considerable part of this complex history is recorded in the story of Niagara Falls and its gorge.[1]

The story revealed by these complex changes leaves no possible doubt, as it seems to the writer, that the uprising of the land in the north is really a movement of elastic resilience following the removal of the ice-weight. If this be true — if the movement of resilience was not due to any other cause — then we are bound to believe that the depression of the land was brought about and produced by the weight of the growing ice-sheet.

There is a vast store of evidence proving the existence of other drift-sheets older than the Wisconsin. These were obviously made by ice-sheets of corresponding ages, and the evidence shows that they grew to be as extensive as the Wisconsin ice-sheet, some of them perhaps slightly more extensive. If depression and resilience of the land were an inseparable physical accompaniment of the Wisconsin ice-sheet, how can we doubt that they occurred also in connection with the Illinoian, the Kan-san and the pre-Kansan or Jerseyan ice-sheets? Indeed, we should need special evidence to prove that it failed to occur in connection with any ice-sheet of continental extent that ever existed on the earth. In the writer's opinion, we are forced to believe that this phenomenon was associated with every one of the great ice-sheets.

We have before our minds, then, an imaginary picture of four successive ice-sheets, each one producing a slow depression of the land in the Great Lakes region as the glacier grew, followed each time by a slow resilience during and after the glacial retreat. Perhaps there is yet some uncertainty as to the exact physical process by which the earth's crust yields and becomes depressed under the ice-weight, but it appears to be simple elastic yielding in a rigid body. If this be true, then the movement of resilience is in all probability simply the elastic rebound or recovery following the removal of the ice-weight. If the elastic distortion under the ice-weight is substantially perfect, with no loss from movements which pass beyond the capacity of the crust for elastic yielding, then resilience may be equally perfect.

This would mean that whatever the altitude and attitude of the surface of the Great Lakes region may have been before the beginning of the growth of a given ice-sheet, complete resilience, such that all of the elastic stress produced by the ice-weight had disappeared, would bring the surface of the Great Lakes region back to exactly the same altitude and attitude that it had before the ice-sheet began to grow. It is perhaps hard to think of elastic movements in the earth's crust as being so perfect, but if they are slow enough and do not anywhere exceed the elastic limit so as to produce faults or plastic changes of form that become set and lose their tendency to return to their original form, they may show remarkable perfection in recovery; that is, in the resilience of the region previously depressed.

Since the time when the Wisconsin ice-sheet and the accompanying lake waters uncovered the Niagara region, the cataract has cut out of the solid rocky strata the gorge or canyon in which the river now flows from the Horseshoe Falls to the escarpment south of Lewiston, New York, a distance of about seven miles. The factors which determined the course of overflow from the upper lakes, and caused the Niagara River to be placed where it is, instead of flowing southward through Chicago to the Mississippi, or eastward at some point in Canada, are the main topographic features of the region — the lake basins and the barriers between them and around them — and the relation of these to the level of the waters in the lakes.

If the Illinoian ice-sheet produced a great depression of the lake region substantially equal in amount and distribution to that produced by the Wisconsin ice-sheet, and if a similar near-perfect resilience followed during and after its retreat., it is not inconceivable that in the restored drainage the overflow of the lakes may have followed almost the same path as that of the present Niagara River. If this river carried the whole discharge of the upper lakes, as the writer believes it did, it had the same volume as the present river, and the geological conditions being the same, it would have formed a vertical cataract at the escarpment and begun the making of a gorge the same as did the present river. But the history is not by any means so simple as this statement might seem to imply.

THE EVIDENCE: SUCCESSIVE NIAGARA GORGES

When the present river had made about half of its gorge from Lewiston up, it came to a place where it encountered only loose, soft sediments, a great cavity in the rock filled only with clay, sand and boulders, all the rocky strata having been removed at an earlier time. The modern river cleared out the loose detritus very quickly, and the place is now known as the Whirlpool.[2]

When the modern river had cleared the Whirlpool basin, it met solid rock walls all around, except on the northwest side. Here the wall is composed of the same loose material extending far below the water-level. In short, the Whirlpool basin is the southeast end of a great buried gorge which extends two miles northwest to the escarpment south of St. Davids, and is known as the St. Davids gorge. Until the modern river opened it, this ancient gorge was wholly buried under glacial deposits of Wisconsin age, and could have been found only by borings and by the break in the rock ledges south of St. Davids.

The top width in rock of the ancient gorge is about the same as the modern full-volume gorge from Wintergreen Flat to Niagara University, and at the American Falls. It might be expected from the long period of weathering to which it was probably exposed before it was filled that it would be considerably wider, but the difference is small. Although glacial striae were found in Bowman's ravine on the west wall ninety feet below the top, glacial abrasion seems scarcely perceptible in amount. As revealed at the Whirlpool and near St. Davids, all the characteristics of the ancient gorge indicate that it was made by a vertical cataract of great volume.[3]

It is believed, therefore, that the buried St. Davids gorge was made by the cataract of an earlier great river, in reality by an Illinoian Niagara which did its work probably after the recession of the Illinoian ice-sheet and late in the Illinoian resilience. This gorge was later overridden and filled with detritus by the advancing Wisconsin ice-sheet. The fact that there are only two miles of the St. Davids gorge as against seven miles of the Wisconsin or modern gorge may possibly be due to a different distribution of outlets in the north during the earlier part of the Illinoian resilience. In the present resilience, the outlet of Lake Algonquin was on a sill of gneiss at Kirkfield, Ontario. This resisted erosion strongly. But suppose that the Illinoian analogue of this outlet had been at some point on the deep drift barrier north of Lake Ontario. As resilience progressed the outlet would be cut down, and the shift of outlet to the south, analogous to the modern shift from Kirkfield to Port Huron, might not have occurred. Then there would have been no Illinoian gorge section corresponding to our present Lower Great gorge. It would then be only late in the Illinoian resilience, when all northern outlets had been uplifted, that the four lakes would send their whole discharge to the Niagara escarpment to make a gorge. Then, too, there is only a drift barrier between Lake St. Clair and Lake Erie, so that the latter may have begun flowing north to Lake Huron as soon as an eastward outlet was opened from that lake. Slight differences in drift distribution in the Illinoian resilience may have made large differences in the Niagara and Great Lakes history.

Farther west, as shown in Figure 10, there is another significant break in the escarpment. This lies about four miles southwest of the City of St. Catherines. It is evidently an old gorge of some kind, but the features are very different from those seen at the St. Davids gorge. It is not buried, except perhaps a little at its south end. It is much wider and its slopes are more gentle and much more modified by weathering and erosion. Its portals, where it opens out toward Lake Ontario, are more subdued and rounded off. In some places very little bed rock is exposed. It extends south into the plain two or three miles, and directly south in front of it is a prominent drift hill over 200 feet high called Font hill. The St. Davids gorge lay athwart the main glacial movement, and consequently was not much affected by it, but this older gorge is nearly in line with the glacial trend. It is fully a mile wide on its floor and two miles or more at its top. It seems certain that the ice current entered it pretty strongly, and where it reached the head of the gorge, the ice took an upward course and built the high deposit of Font hill.[4]

This depression was recognized as an ancient river valley long ago, but it was probably first pictured by the late Dr. J. W. Spencer as the course of a preglacial outlet of Lake Erie, and named by him the Erigan Canyon. Spencer's views of its relation to the lake history were entirely different from those here outlined, for he did not accept the idea of the continental glacier; he was a follower of Lyell, Selwyn and Sir Wm. Dawson.

When we recall how greatly the Kansan drift-sheet, where it is typically exposed in the west, has suffered by leaching and by subaerial erosion, and how the first trenching streams have widened their valleys until scarcely any of the original flat surface is left, we ought to be prepared to expect a great gorge made during and after the retreat of the Kansan ice-sheet to show just such extreme weathering and modification as this one does. The Erigan Canyon has only the very small Twelve-Mile Creek flowing in it now; yet in this peculiar terrane, with the heavy bed of the hard Lockport dolomite above and deep soft shales below, we seem bound to recognize that this canyon was made by a great river, and if so, it must have had a vertical cataract, like the present falls of Niagara. Except as an outlet of Lake Erie, there is no chance in this locality for a great river from the south.

FIG. 10. Sketch map of part of the Niagara Peninsula between Lakes Erie and Ontario, showing the location of the Niagara escarpment and the three gorges described in the text

If the overflow of the upper lakes during and after the retreat of the Kansan ice-sheet passed south to Lake Erie, and thence north to Lake Ontario, as does the present Niagara River, then, in the opinion of the writer, there is much reason to believe that Spencer's Erigan Canyon is the much-weathered survivor of the gorge of a Kansan Niagara. Of a possible pre-Kansan or Jerseyan Niagara gorge we know nothing, and there seems to be no place for it, unless it entered from the west through the Dundas Valley. No reason has been given for regarding the Erigan Canyon as preglacial rather than early interglacial.

Our conclusion, therefore, is that on theoretical grounds depression and resilience of the land in the Great Lakes region have occurred in connection with at least the last three of the Pleistocene ice-sheets, and probably with the first one also, and that, at least for a part of the time, the full drainage of the upper lakes was each time restored to the Niagara district, after having been temporarily taken away. Hence, looking backward in time, we have (3) the gorge of the Wisconsin Niagara (now in the making); (2) the gorge of the Illinoian Niagara (the buried St. Davids gorge, and (1) the gorge of the Kansan Niagara (Spencer's Erigan Canyon). Back of this there is still the possibility of an earlier gorge of a pre-Kansan or Jerseyan Niagara, but of this nothing is now known.

If this interpretation of the features described is in the line of truth, it seems to throw a new light on the capacity of the earth's crust to yield by elastic distortion to a slowly accumulating weight, and on its ability to return by elastic resilience or rebound to the exact shape and position which it had before. The amount of depression north of Lake Superior and Georgian Bay was certainly not less than 1,000 feet, and the depression affected a very wide area. Within the depths reached by slow distortion under growing ice-weight, the behavior of the earth's crust certainly bespeaks the solid, more-rigid-than-steel condition set forth by the writer in recent papers on continental crust-sheet movements, and it also agrees with the " elastico-static" condition recently described by T. C. Chamberlin (*Journal of Geology*, Jan.-Feb., 1926).

From their specific gravities we know that 3,000 feet of glacier ice is equal in weight to about 1,000 feet of average crust rock. Ice-sheets come and go in a way that rock sheets do not, and they act more to protect and preserve the rock surface beneath them than to destroy it. This is why they reveal so clearly the elastic capacity of the earth's crust. Rock sheets are eroded and carried away in a manner that gives no indication of the resilience effects which they produce. The behavior of the earth's crust under the loading and unloading of ice-sheets shows what great distortions must affect much of the crust all the time. With increasing depth, resistance to distortion increases and finally, combined with rigidity, becomes adequate to support large features of topographic relief, even mountain ranges and continents.

FORT WAYNE, INDIANA

[1] The lake history as thus far worked out, is presented in considerable detail in *Monograph No. 53, U. S. Geological Survey*, by Frank Leverett and Frank B. Taylor, 1915. The history of Niagara Falls and its relation to the Great Lakes history are discussed in the *Niagara Folio, U. S. Geological Survey*, Folio No. 190, by E. M. Kindle and Frank B. Taylor, 1913. The relation of a part of the Niagara gorge to the Great Lakes history is also discussed m another paper in this volume entitled "The Present and Recent Rate of Land Tilting in the Region of the Great Lakes."

[2] The characteristics of this part of the gorge are given in some detail in the *Niagara Folio*, page 17, columns 1 and 2, including especially Figure 7, and on the large scale gorge map. The general relations of the features of this area are shown on the accompanying sketch map, Figure 10.

[3] Space forbids a more detailed description of the features around the Whirlpool or an adequate discussion of their significance. The key to the history of the Whirlpool area is revealed in the origin and history of the Eddy basin. This is a very short but wide and deep-gorge section next above the Whirlpool, from which it is separated by a well-defined reef and rapids. (See *Niagara Folio*, Figure 14, page 21. The history of its development is shown more fully in Figure 7, page 17.) The features show conclusively that the Eddy basin was made by the modern cataract with full volume plunging from a solid ledge, thus disproving the suggestion of Pohlman, Grabau and others that the St. Davids gorge, the Eddy basin and the gorge of the whirlpool rapids are simply the weathered ravine of a small preglacial river uncovered,

scoured out and now occupied by the Niagara River. The more recent idea that the St. Davids gorge may have been made by a small cataract carrying only the discharge of Lake Erie (15 per cent of the full volume), and later enlarged by weathering, is hardly more satisfactory, for, so far as now visible, the amount of cliff recession caused by weathering is no greater in the ancient gorge than in the modern gorge below the Whirlpool. Besides, the hard stratum of the Albion sandstone, here just above the water, is widely and deeply penetrated; whereas, in the gorge of the whirlpool rapids the cut through this stratum is notably narrow and shallow, and this section of the gorge is known for a certainty to have been made by the small-volume Erie cataract.

[4] *Evolution of the Falls of Niagara*, by J. W. Spencer, Canadian Department of Mines, Geological Survey Branch, Ottawa, 1907. Chapter XXXVII, maps on pages 415 and 121.

THE PRESENT AND RECENT RATE OF LAND-TILTING IN THE REGION OF THE GREAT LAKES

FRANK BURSLEY TAYLOR

CORRELATIVE CHAPTERS IN NIAGARA AND GREAT LAKES HISTORY

IT IS interesting to know that the Niagara and Great Lakes histories are really parts of one story, and that while the Upper Great Gorge (the newest section) was being made at Niagara, a corresponding chapter in the history of the upper lakes was being enacted, and that this chapter, like that in the gorge history, extends down to the present time. When the retreating ice-sheet opened the outlet at North Bay, Ontario, the whole discharge of the upper three lakes went eastward through the Mattawa and Ottawa valleys, leaving Niagara with only the overflow from Lake Erie, amounting to about 15 per cent of the present full volume. This condition lasted for several thousand years, and it was during this time that the so-called gorge of the Whirlpool Rapids was made at Niagara, and also the Nipissing beach in the northern part of the upper lakes. These two features are exact correlatives in time, and we may know from this that both of the processes which they represent stopped at the same time and began some new activity. As a matter of fact, the small-volume fall stopped making the gorge of the Whirlpool Rapids, and the great fall began making the Upper Great Gorge, while at the same time the waves of the upper lakes stopped making the Nipissing beach and began making the post-Nipissing beaches at lower levels.

In the upper lake region, the differential uplift of the land was either going on continuously during the time of the Nipissing Great Lakes, or else was renewed after a time of rest, so that finally it raised the North Bay outlet to the same altitude as that at Port Huron. In this transitional phase both outlets were for a time active at once, the discharge being divided between them. But soon North Bay was raised enough to shut off all overflow at that place and that outlet went dry, the whole discharge thereafter going past Port Huron to Niagara. This, of course, stopped the making of the Gorge of the Whirlpool Rapids, brought full 100 per cent volume back to Niagara, and started the making of the Upper Great Gorge. Since that time, which was probably between 2,700 and 3,000 years ago, the great cataract has gone on steadily in the work of gorge-making down to the present day, and has made a little more than two miles of wide deep gorge.

The time factor derived from the study of the Upper Great Gorge tells us that the North Bay outlet was closed by uplift 2,700 to 3,000 years ago. If, now, we go to North Bay we see something that is almost startling, for we find that since that time North Bay has been uplifted about 102 feet. These facts furnish part of the data for determining the rate of tilting in this period before the beginning of gage readings. But before one undertakes to calculate the rate, it is necessary to consider certain other factors. In working out the history of the Great Lakes (Monograph 53, U. S. Geological Survey, 1915, Chapter XXII, "The Nipissing Great Lakes")? it was found that the differential uplift which caused the tilting of the land did not affect the whole area of the upper lakes. For example, if one were to start on the Nipissing beach at North Bay, Ontario, and follow it toward the south-southwest, one would find the beach descending very evenly at the rate of about 0.43 feet per mile. But as the south end of Lake Huron was approached, it would be seen that within the space of a few miles the beach ceased to descend and became perfectly horizontal, continuing in this attitude to its southern limit at Port Huron. (See Fig. 11.)

HINGE-LINES AND AREAS OF HORIZONTALITY

The line of maximum rise for the Nipissing beach runs about N. 22° E., and the isobases or lines of equal elevation run at right angles to this or about N. 68° W. The isobase of zero marks the northern limit of horizontality and is parallel to the other isobases. This line passes through Grand Bend, Ontario, about two miles north of Richmondville on the east shore of the thumb of Michigan and about the same distance north of Standish on the west side of Saginaw Bay. It divides the beach-plane as a whole into two parts; north of the line is the area of tilting, south of it the area of horizontality. On account of this relation, the isobase of zero is conveniently called the *hinge-line*. In the field it is commonly easy to limit it to a belt four or five miles wide by direct observation, but by plotting many observations to the north and the south and drawing an eye-line mean through the plotted points, it may be located theoretically within a mile or less.

Using the general chart of the Northern and Northwestern Lakes (U. S. Lake Survey) as a base, and drawing the line of maximum rise from Port Huron in a direction N. 22° E., one finds that this line intersects the Nipissing hinge-line at a point about thirty-five miles north of Port Huron and meets the isobase of the northern outlet at a point about forty-seven miles west-northwest of North Bay. The distance between the hinge-line and the isobase of North Bay is about 238 miles. The tilting of the land in the post-Nipissing stage of the lakes has amounted, therefore, to 102 feet in 238 miles. This gives a rate of northward rise of nearly 0.43 feet or slightly less than six inches per mile.

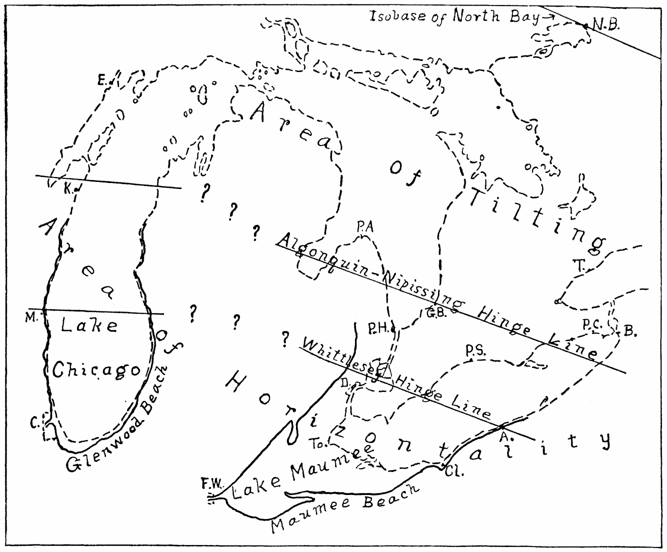

FIG. 11. Sketch map of region of Lakes Michigan, Huron and Erie and of glacial lakes Maumee and Chicago, showing earliest known position of hinge-line (Whittlesey) and the latest position (Algonquin-Nipissing), with area of tilting to the north and area of horizontality to the south. (Compare with Figure 12.) A. = Ashtabula; B. = Buffalo; C. = Chicago; CL = Cleveland; D. = Detroit; F.W. = Fort Wayne; G.B. = Grand Bend; K. = Kewaunee; M. = Milwaukee; N.B. = North Bay; P.A. = Port Austin; P.C. = Port Colbourne; P.H. - Port Huron; P.S. = Port Stanley; T. = Toronto; To. = Toledo.

If we assume that the tilting of the land went on evenly during the post-Nipissing period in the area here considered, these facts furnish the means of calculating the rate of uplift during that period, nearly all of which antedates the gage readings, but which extends down to the beginning of the present or gage-measured period in which the fluctuations of water-level in the Great Lakes have been accurately recorded on gages set by the Government for that purpose. The uplift has affected the area as though it were a great sheet of rigid inflexible material lifted up at its northern edge. (See Fig. 12.)

If we follow the method employed by Mr. Gilbert, and calculate the rate of uplift since the closing of the North Bay outlet, we find that on the assumption that the period endured 3,000 years the rate of uplift was 1.38 feet per 100 miles per century, while if the period was 2,700 years, the rate was 1.58 feet per 100 miles per century, the mean being 1.48 feet. At this point a question of great interest naturally presents itself, namely: Has the tilting of the land continued in the same direction and at the same rate down into and through the present or gage-measured period? So far as I can see, there is every reason to believe that the tilting movement has so continued with all the attendant conditions unchanged. Let us see what light recent investigations throw on this question.

STUDIES OF LAND-TILTING IN THE LAST FIFTY YEARS

The first careful study of the records of the water gages on the Great Lakes was made by Mr. G. K. Gilbert about thirty years ago. His results are embodied in a paper entitled "Recent Earth Movement in the Great Lakes Region."[1] Mr. Gilbert used measurements covering a period of about twenty years, from 1875 to 1895. In the Michigan-Huron area he used gage readings at two pairs of stations, Milwaukee and Escanaba, and Milwaukee and Port Austin; in Lake Erie, Cleveland and Port Colbourne; in Lake Ontario, Charlotte and Sacketts Harbor. Mr. Gilbert used the whole distance between Milwaukee and Escanaba in estimating the rate of uplift and obtained a rate of 0.43 feet per 100 miles per century, and he treated the other pairs of stations by the same method, obtaining as a mean rate 0.41 feet per 100 miles per century.

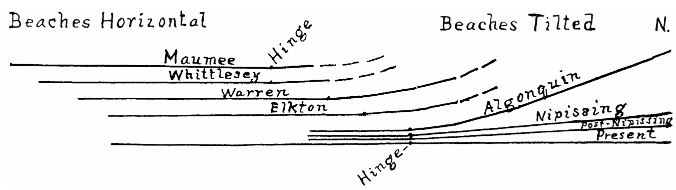

FIG. 12. Diagram showing the shifting position of the hinge-line with recession of the ice-sheet and the fall of lake level. Shows tilted attitude of shore-lines to the north and horizontal attitude to the south of each position of the hinge-line. (Not drawn to scale)

There is no question of the correctness of Mr. Gilbert's results on the data which he used, but he was somewhat unfortunate in preparing his paper a little too soon. Fieldwork in the study of the Great Lakes history was going on at that time, but had not yet proceeded far enough to show the existence of *hinge-lines* or isobases of zero separating areas of tilting on the north from areas of horizontality on the south. Except in the case of the oldest or Maumee beach in the Huron or Erie basin and the Glenwood beach in the Lake Michigan area, hinge-lines were found for all the ancient beaches, but the Algonquin and the Nipissing and post-Nipissing beaches converge to the same line. This hinge-line, spoken of above as passing through Grand Bend, Ontario, also crosses Lake Michigan at a point considerably farther north. The data for determining its place in this basin are relatively poor, yet as nearly as could be determined, it passes about five miles north of Arcadia on the east side and two or three miles north of Algoma on the west. The line, therefore, runs more nearly east and west,—about five degrees north of west.

On the supposition that the earth movement recorded in the gages really affected only that part of the area which lay north of the hinge-line, it is evident that Mr. Gilbert did not obtain a true result when he distributed the tilting over the whole distance from Milwaukee to Escanaba. He obtained a rate of 0.43 feet per 100 miles per century, but if the tilting was confined to the 84 miles, which is the distance from the hinge-line to Escanaba, the rate figured by the same method would be about 0.98 feet per 100 miles per century (see Fig. 13). It is believed that this correction of Mr. Gilbert's result gives it full value from the present understanding of the lake history. The remaining pairs of stations used by Mr. Gilbert do not appear to be so easily adjusted to the limits set by the hinge-line. This is true especially of Port Austin and Port Colbourne.

The oldest hinge-line thus far found is one which is recorded in the Whittlesey beach. It passes through about the middle of Lake St. Clair and through Ashtabula, Ohio (see Fig. 11). Neither the Algonquin beach nor the Nipissing extends to the Lake Erie basin, so that the place of their hinge-line in that basin cannot be determined by observation, but only by inference and general relations. If it is parallel with the Whittlesey hinge-line, as it appears to be in the basin of Lake Huron, then it would lie about four miles north of Dunkirk, New York. This leaves both Port Colbourne and Port Austin about twenty-two or twenty-three miles north of the hinge-line. But the conditions are very different at Port Colbourne, for the outlet of Lake Erie is at its extreme northeast end, and every inch of uplift at Buffalo raises the water-level over the whole of the lake. If the hinge-line is rightly placed, Buffalo is about thirty miles north of it, and almost the whole of the lake is south of it and hence in the area of horizontality. Theoretically, all parts of the shore south of the hinge-line should be flooded the same amount by every inch of uplift at Buffalo. Port Stanley or Erie should show no less flooding than Cleveland, and Toledo and Sandusky no more.[2] In Lake Ontario, Charlotte and Sacketts Harbor are both in the area of tilting far to the north of the hinge-line, and Mr. Gilbert's result is not affected by the present revision.

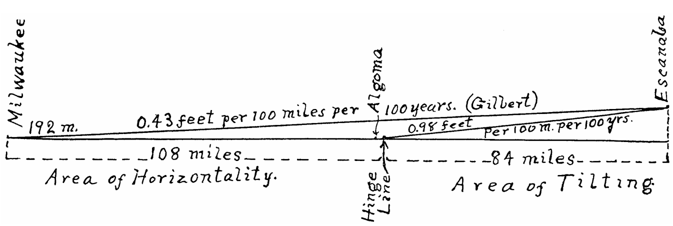

FIG. 13. Diagram showing how Gilbert's estimate of rate of tilting between Milwaukee and Escanaba is modified by taking account of the hinge and the area of horizontality

For about six years the water-level in Lakes Michigan and Huron has been steadily falling and has now reached a stage considerably lower than ever known before, about 577.5 feet above sea-level in December, 1925. The Government made the Livingston channel in Detroit River, and enlarged it later, without putting in any contraction or controlling works above to counteract the strong tendency of the deepened channel to lower the water in the lakes to the north. It looks, therefore, as though the Government had adopted the policy of lowering permanently the water-level in the Michigan-Huron basin, in spite of the great injury that this change is doing to all the people living on its shores. To make the lowering still more effective, building contractors of Detroit have been allowed to take immense quantities of gravel from the great spit at Point Edward opposite Port Huron, although the resistance of this spit was known to account for a foot or more in the height of the water-level in the lakes above. There has been talk of building a dam at Buffalo to raise and control the water-level in Lake Erie. There is great need of some kind of control, but the level of Lake Erie cannot be raised more than a foot or so without doing even greater injury to property interests on all its shores than is being done on the shores of Lakes Michigan and Huron.

This situation has aroused the keen interest of a number of engineers, and among other things, is causing them to see the great importance of the tilting of the land in the Great Lakes region when planning permanent works for improvement or control which look forward over periods of 50 or 100 or several hundred years. In November last, Mr. John R. Freeman, consulting engineer, of Providence, Rhode Island, called my attention to a paper entitled "Tilt of the Earth in the Great Lakes Region,"[3] by Mr. Sherman Moore, assistant engineer, U. S. Lake Survey, Detroit. Mr. Moore's paper is of great interest and importance, for he takes up the study of the gage records where Mr. Gilbert left off thirty years ago. It is very gratifying to see how closely Mr. Moore's results accord with Mr. Gilbert's. In his studies Mr. Moore had all the data that were available to his predecessor and a great deal more besides. Mr. Gilbert was limited to a twenty-year period ending with 1895. Mr. Moore, having brought his studies up to 1925, has thirty years of new and mostly better material in addition to all that Mr. Gilbert had. The fact that Mr. Moore's results are so nearly in accord with Mr. Gilbert's has a powerful cumulative effect toward the truth, so that it is no longer possible for anyone to deny that uplifting and tilting of the lands in the northern part of the Great Lakes region is still going on; indeed, it seems certain that it is affecting a much wider region toward the north, southeast and northwest.

The mean rate of uplift found by Mr. Gilbert from his four pairs of stations was 0.41 feet per 100 miles per century. Mr. Moore's mean found in the same way from nineteen pairs is 0.43 feet per 100 miles per century. In weighing the value of this close accordance it is necessary, however, to take cognizance of the fact that in one very important and rather unfortunate respect Mr. Moore followed the exact method employed by Mr. Gilbert. As pointed out above, Mr. Gilbert wrote his paper before the "hinge-line" and "the area of horizontality" had been fully established. But these modifying conditions have been quite fully described and discussed since that time (Monograph 53). Yet Mr. Moore follows Mr. Gilbert and ignores the influence of these modifying circumstances. Both of the engineers mentioned, while readily admitting that hinge-lines and areas of horizontality may have had much importance before the time of gage readings (i.e., before 1875), are inclined to maintain quite strongly that within the gage-measured period (since about 1875, when gage records in sufficient numbers became available) hinge-lines and areas of horizontality do not enter in, and if there is any such thing as a hinge-line or its equivalent in a broad belt of transition from a tilted attitude to horizontality, it must lie some distance south of the Great Lakes region. Let us examine briefly into the bearing of the geological records of land-tilting upon that of the gage-measured period, into which it merges by imperceptible degrees.

RELATION OF EARLIER TO PRESENT TILTING

Figure 11 shows the region of Lakes Michigan-Huron and Erie, with the area of the ancient beaches south and west of Lake Erie. Crossing the middle of Lake St. Clair, and extending about S. 68° E. through Ashtabula, Ohio, is the Whittlesey hinge-line, the oldest thus far found. At relatively short intervals northward there is a hinge-line for each of the principal beaches, the Warren, Elkton and Algonquin-Nipissing. The last two, with all of the post-Nipissing beaches, converge at one line, the latest line known, and which, as defined above, passes through Grand Bend, Ontario, and crosses the southern part of Lake Huron and Saginaw Bay. The same line less clearly defined crosses the northern part of Lake Michigan. The line shown crossing near Milwaukee is presumably the same as the Whittlesey, but Lake Whittlesey did not extend to that basin. South of the Algonquin-Nipissing hinge-line the Algonquin and all later beaches are now horizontal. South of the Whittlesey hinge-line all the ancient beaches are now horizontal. The highest and oldest beach is the Maumee. In the Lake Michigan basin the highest and oldest is the Glenwood beach of glacial lake Chicago, probably a close correlative in time of the Maumee.

The time indicated by the Niagara gorge (approximately say 25,000 years), plus that shown by a few of the recessional moraines, shows that the Maumee and Glenwood beaches have been lying just where they now are for not less than 30,000 or 35,000 years, perhaps longer, and the highly significant fact to be noted is that they are still horizontal, not tilted or warped in a measurable degree. It is reasonable to assume that this attitude of horizontality affects not alone these two beaches, but the whole area between them, and a wide area also to the south and east and west. In New England, certain geologists claim to find a belt of upward bulging of the land outside the glacial boundary, with later depression coincident with resilience farther north. This idea does not seem to apply in the Great Lakes area. It would seem gratuitous to suppose that the Maumee and Glenwood beaches have been raised and lowered or tilted or warped up and back again by a measurable amount to be finally brought back to sensibly perfect horizontality, as though no such movements had taken place.

If the engineers continue to maintain their contention that in the gage-measured period, comprising the last fifty years, there has been no hinge-line nor any area of horizontality within the present lake region, but that the hinge-line or its equivalent, if it existed, lies well to the south beyond the boundaries of the lakes, they will have to prove their case in the face of the facts shown by the Maumee and Glenwood beaches, for it is certain that if there has been any tilting or warping of the land on which these beaches lie within the last 30,000 or 35,000 years, it must have been recorded in these beaches by effects of tilting or warping. It is hardly conceivable that tilting should have suddenly begun to affect the region south of the Algonquin-Nipissing hinge-line in 1875, when it has produced no measurable effect of that kind in so long a previous period, especially when the forces which cause tilting are supposed to be on the wane.

We seem bound to believe, therefore, that discrepancies in the gage readings which seem to indicate land-tilting now going on within the area of horizontality (to the south of the Algonquin-Nipissing hinge-line) are, in all probability, due to defective setting or action or interpretation of the gages. It is absolutely clear that the geological conditions attending land-tilting before the establishment of gage readings come right down to 1875, the beginning of Mr. Gilbert's period of gage readings. That these conditions should have changed so suddenly as to begin an upsetting of the area of horizontality just at that time seems incredible.

It is worthy of note that in the Lake Superior region Mr. Moore finds a tilt rate of 0.94 feet per 100 miles per century, and in Lake Ontario 1.44 feet, and that in both of these areas all the stations used are well to the north of the hinge-line. Is it not somewhat significant that these two rates are so nearly in accord with the rate found above for the tilting in the post-Nipissing prehistoric period, with its mean rate of 1.48 feet per 100 miles per century, as indicated by the rate of recession in the Upper Great Gorge at Niagara? From his other stations in the basins of Lakes Michigan-Huron and Erie, Mr. Moore gets rates very closely in accord with those of Mr. Gilbert, but in both cases the influence of the hinge-line and the area of horizontality were not considered at all. Mr. Gilbert's rate between Milwaukee and Escanaba, if concentrated in the space north of the hinge-line, gives a rate of 0.98 feet, which is in fairly close accord with Mr. Moore's rates in Lakes Superior and Ontario.

Thus, we seem to find that the rate of land-tilting in the last 2,700 or 3,000 years in the Lake Huron area is in fairly close accord with the rates found from gage readings in the last fifty years *in the area north of the hinge-line*, but that this statement does not apply to the area south of the hinge-line.

Certain features in the Niagara gorge which cannot be dwelt upon here indicate that the falls began making the gorge at the escarpment near Lewiston something like 20,000 or 30,000 years ago, possibly slightly less than the mean of 25,000 years. But some other time values are more accurately determined. For example, the isobase of North Bay, the outlet of the Nipissing Great Lakes, passes about through Mazokama, a few miles east of Nipigon on the north shore of Lake Superior, where Lawson[4] records a strong terrace at 98 feet above the lake or 698 feet above sea-level. At Peninsula Harbor, thirteen miles north of the North Bay isobase (the farthest point north of this line on Lake Superior) the Nipissing beach is a plain of heavy bars 110 to 115 feet (aneroid) above the lake.[5] The stage of the Great Lakes history known as the Nipissing Great Lakes was a stage of long duration, believed to have lasted 6,000 or 7,000 years. Being on or near the isobase of the outlet at North Bay, the lake stood at or near the level of the Nipissing beach at Mazokama and Peninsula Harbor for this whole period. This explains the extraordinary strength of this beach on the north coast of Lake Superior. The beach in that region began to be abandoned about 2,700 to 3,000 years ago, when the outlet at North Bay was abandoned. South of the isobase of North Bay, the Nipissing beach of this later time (marking the two-outlet transitional phase) is prominent at many places, at Copper Harbor, Marquette, Sault Ste. Marie, Mackinac Island, St. Ignace, Rogers, Alpena, Midland, Owen Sound, Petoskey, Charlevoix, Escanaba, etc. The time factor supplied by Niagara could be followed if space permitted through the earlier stages of the postglacial lake history with equally interesting results.

It is to be earnestly hoped that the engineers will continue their study of this important subject, and that the United States and Canadian governments will give the necessary support. The most urgent need just now is the establishment of two new gage stations, on the most northerly shores, at the mouth of French River on Georgian Bay and at Peninsula Harbor on Lake Superior. The great locks at Sault Ste. Marie are nearly one hundred and fifty miles north of the Algonquin-Nipissing hinge-line, and at the rate of tilting found, the water has fallen away from the locks something more than a foot in the last fifty years, and at the same rate it will fall away more than two feet in the next one hundred years. The governments and the many interests concerned can ill afford to overlook or neglect so important a factor of change.

FORT WAYNE, INDIANA

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[1] *Eighteenth Annual Report U. S. Geological Survey*, 1896-1897, pp. 596-647.

[2] If one supposes the present rate of uplift in the area of tilting to be about 1.5 feet per 100 miles per century, and if one supposes Buffalo to lie about 30 miles north-northeast from the present hinge-line produced from Lake Huron, it is interesting to note the probable effect of continuing uplift on the future status of the lakes. Under these conditions Buffalo is probably being uplifted about 0.5 feet per century. Until the present excessively low stage, Lake Erie was normally about 8 feet lower than Lakes Huron and Michigan, and Lake Michigan lacked only about 8 feet of overflowing at Chicago. With no interference by man at Buffalo or Chicago or anywhere else, the natural course of change would raise Lake Erie to the level of Lake Huron in something like 1,600 years, and in twice that time overflow would begin at Chicago. Then in 1,200 or 1,500 years more the whole discharge would go out past Chicago. The uplift of 0.5 feet per century at Buffalo is extremely slow, but it has gradually flooded all the shores of Lake Erie. Active cutting of the drift banks on the north or Canadian shore is going on nearly all the way from Long Point to the mouth of Detroit River, and has been in progress for a very long time. The heavy cutting at Huron, Ohio, and other points on the south shore is probably intensified by this slow flooding.

[3] *Military Engineer*, May, 1922, pp. 153-155, 181, 183.

[4] "Sketch of the Coastal Topography of the North Side of Lake Superior, with Special Reference to the Abandoned Strands of Lake Warren," by Andrew C. Lawson, *20th Annual Report, Geological and Natural History Survey of Minnesota*, 1893. Also, "The Nipissing Beach on the North Superior Shore," by F. B. Taylor, American Geologist, Vol. XV, May, 1895, pages 304-314. Discusses bearing of Lawson's observations on distribution of Nipissing Beach.

[5] "Notes on the Abandoned Beaches of the North Coast of Lake Superior," by Frank B. Taylor, *American Geologist*, Vol. XX, August, 1897, page 125.

GEOLOGY OF ROSCOMMON COUNTY, MICHIGAN

WALTER A. VER WIEBE

THE geology of Roscommon County was studied during the last half of June and during July of 1924 as a part of the investigations conducted by the Land Economic Survey of the state of Michigan.

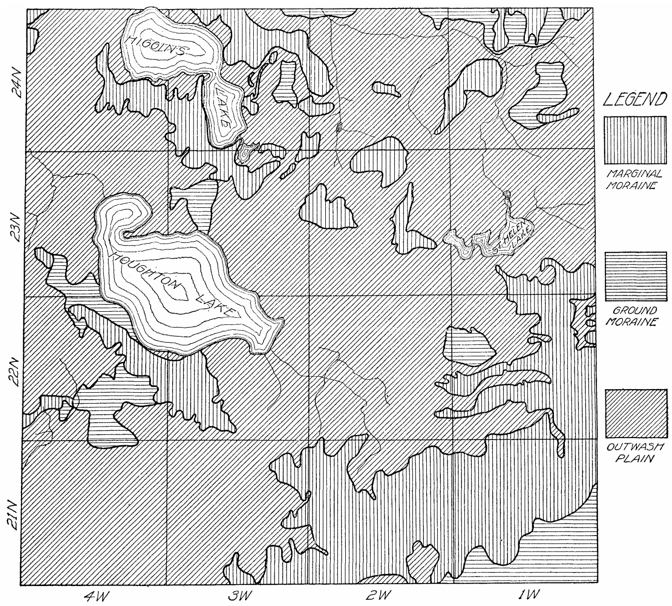
The geological formations exposed at the surface in Roscommon County all belong to the Pleistocene system and more specifically to the Wisconsin series of glacial deposits. In Roscommon County only three of these glacial types of deposits are present, marginal moraines, ground moraines and outwash plains. See Map 5.

MORAINES

MARGINAL MORAINES

The marginal moraines consist of the following: West Branch moraine, Houghton moraine, South Higgins moraine, North Higgins moraine, and seven small morainic fragments. These will be described in the order of their importance.

West branch moraine. — The West Branch moraine was described in considerable detail by Frank Leverett.[1] It is one of the large moraines formed by the Saginaw lobe of the ice-sheet and only a small part occurs in this county. It was named after the town of West Branch in Ogemaw County, where it is well displayed and can be conveniently studied. It crosses Roscommon County in the southeast portion, extending from Section 33, T. 21 N., R. 3 W., to Section 36, T. 21 N., R. 2 W., along the south line of the county and leaving the county on the eastern side between Sections 25, T. 23 N., R. 1 W. and 12, T. 21 N., R.1 W. The northwestern edge of this moraine, which was the side away from the ice, is very much indented and very irregular. In several places tongues nearly five miles long and less than a mile wide reach out toward the west.



MAP 5. Geologic map of Roscommon County, Michigan

On the tongue extending out to Section 24, T. 22 N., R. 2 W., there are no boulders toward the tip, but quite a few pebbles and much sand. In a cut along the section line between Sections 24 and 19, T. 22 N., R. 2 W., the sand appears to be stratified. On the tongue farther south numerous erratics were observed near the tip in Section 25, T. 22 N., R. 2 W. Both of these tongues are remarkable for their length and narrow width. In other respects, however, they show the characteristics of the main part of the West Branch moraine.

In a general way the outwash side of the moraine may be described as having the 'knob-and-basin' type of topography, whereas the inner side has a 'sag-and-swell' type. This distinction is well brought out on the township road through the middle of Nestor Township, that is, between T. 21 N., R. 1 W., and T. 21 N., R. 2 W.

Houghton moraine. — The Houghton moraine extends across the southern side of Houghton Lake from Section 4, T. 22 N., R. 4 W., to Section 33, T. 22 N., R. 3 W., in a northwest to southeast direction. This moraine was formed by the melting of a transverse lobe of ice lying to the northeast and roughly upon the present site of Houghton Lake. The surface of this moraine is moderately irregular, but it lacks the pronounced accentuation described as occurring on the West Branch moraine.

To the southeast in Section 29, T. 22 N., R. 4 W., lie a number of small morainic knobs. They are about fifty feet high and make a striking contrast with the outwash gravels all about them. A number of gravel pits have been opened in them in which the sand and gravel are distinctly stratified. Because of this fact, these hills may be more properly classed as kames than as simple moraines.

South Higgins moraine. — The South Higgins moraine lies just south of Higgins Lake and extends from Section 10, T. 24 N., R. 4 W., on the northwest to Section 2, T. 23 N., R. 3 W., on the southeast. It resembles the Houghton moraine in being relatively long and narrow. The surface, however, is more sharply irregular than in the latter and its borders are more sharply defined. The northern edge, especially, stands in strong contrast with that moraine because of the well-marked change in angle of slope and its irregular horizontal outline as shown on the map.

North Higgins moraine. — On the north and northeast side of Higgins Lake is another moraine which is very similar to that south of the lake. It also is rather narrow and long. It is characterized by a great abundance of gravel. Pockets of gravel are found chiefly on the northern flank, though some are present on the southern flank. Erratics are fairly numerous and rather evenly distributed. Along M-14 state highway this moraine is seventy-five feet high above the outwash plain and reaches somewhat greater elevations farther west.

Morainic fragments. — Small fragmentary morainic areas are found between the north and south Higgins moraines on the east side of the lake, a fact which conveys the impression that they were once connected.

All these fragments compare favorably in relief with the larger moraines described. They strongly suggest vigorous stream work practically contemporaneous with their formation such as to produce small hillocks separated from the main mass of ice deposits by deep trenches. Some of these old river channels were filled up by outwash gravels and later abandoned, but others were continuously the site of stream action and are today occupied by streams. The most prominent example of this is the stream known as the 'Cut' which flows east out of Marl Lake, turns sharply south in Section 36, T. 24 N., R. 3 W., and then flows southwest between the main mass of the South Higgins moraine and another isolated morainic fragment. Subsequent additional masses of outwash material brought down from the northeast at a later stage in the ice retreat almost succeeded in choking up this stream, so that it is now very sluggish and winding.

An interesting fragment in Sections 15 and 22 of T. 24. N., R. 3 W., has the flat surface and gently sloping expression of an old beach. It is twelve feet higher then the present lake level and was no doubt worked upon by the lake waters when they stood at a higher level. A fragment in Sections 14, 15, 22 and 27 of the same township very markedly suggests similar wave-erosion by its elongated, attenuated outline and even crest-line, as well as general and uniform slope toward the present lake. In appearance it resembles a 'spit.' The material is unassorted, however, and too coarse for a normal spit. It might possibly be an ice rampart formed at the higher level of lake water.

Connecting moraines. — There are three fairly large fragments of morainic material in T. 23 N., R. 2 W., which appear to form a connecting link between the Higgins moraines and the West Branch moraine. The reason for the fragmentary nature of this transverse moraine is twofold. For one thing, the deposition of this transverse (or interlobate) ice-mass was weaker than that of the two main lobes on each side of it because of the shorter time that the ice halted on the retreat. Secondly, it was ideally situated to suffer violent contemporaneous erosion. Strong erosion was accomplished by the great quantities of water which resulted from the melting of the ice as the transverse ice front retreated to subsequent positions farther northeast. These waters were augmented by accretions coming from the melting ice fronts of both main lobes on the sides, since the waters from these also had to pass through the constricted central discharge zone between the Saginaw and Michigan lobes. It is not surprising, therefore, to find the transverse moraines reduced to mere patches and elongated ridges. It is also to be noted that the original relief of these moraines was considerably reduced by subsequent deposition in the drainage channels. If this outwash material could be removed, it would probably be found that some of the moraines are buried under only a slight thickness of sand and gravel.

General character of Roscommon moraines. — In general it may be stated that the moraines of Roscommon County are remarkable for the great amount of sand they contain. In some places the sand is the only constituent and it becomes difficult to decide whether one is dealing with a moraine or a sand dune.

GROUND MORAINES

Loxley ground moraine. — The largest area of ground moraine in Roscommon County is located near the settlement called Loxley in T. 22 N., R. 4 W. The structure of this deposit is shown in a ditch along the east side of the section line between Sections 27 and 28 in front of the house of H. J. Sundberg. This six-foot section reveals the following sequence:

10 in. clay
7 in. fine sand
12 in. clay
4 ft. sand
3 ft. clay

Houghton ground moraine. — On the southwest side of Houghton Lake is another which covers approximately five square miles and connects the Michelson moraine with the Houghton moraine, besides enveloping the northwestern end of the latter. This is perhaps the most typical ground moraine area in the county. It is gently rolling and is composed of clayey material with numerous erratic boulders scattered about evenly, though sparingly, over the whole area.

Markey ground moraine. — North of Houghton Lake in the southwestern part of T. 23 N., R. 3 W. (Markey Township), is a small area which resembles a till plain in many respects. It is very flat, and gives the impression of having been formed on the bottom of a standing body of water. Pebbles are almost wholly absent and erratics entirely wanting. These details lend strength to the supposition that it is a lake deposit. In the absence of complete evidence, however, it was considered a till plain.

Nester ground moraine. — The Nester ground moraine is located in the southeastern part of Nester Township (T. 21 N., R. 1 W.) in the extreme southeastern part of the state. It is the largest till plain area in the county and forms part of a much larger one in adjacent Gladwin and Ogemaw counties. It has considerable relief in places and in this respect is fully equal to some of the morainic patches in the county. In distinction to these, however, it everywhere presents smooth surfaces and gently rounded slopes. Furthermore, the material is more clearly allied to that of a ground moraine than that of a marginal moraine.

OUTWASH PLAINS

Outwash material covers over three fourths of the area which is not under water at the present time. The most typical outwash apron in the county occurs northwest and in front of the West Branch moraine. It shows a low concave slope from the moraine outward. The material shows a definite assortment according to distance from the source. Near the moraine the material is very coarse, consisting almost entirely of cobbles and large pebbles. At a greater distance from the moraine coarse gravel and pebbles predominate, and at a still greater interval only sand and small pebbles are seen. The third phase usually sets in within a mile of the moraine and from there outward one can expect only sand and pebbles.

Two outwash levels. — In several parts of the county there appear two distinct levels of accumulation. One such area is in Sections 1, 2 and 3 of T. 21 N., R. 3 W. Here the upper terrace lies about fifteen feet above the lower outwash plain. Another place where the two levels appear is in Sections 23 and 26 of T. 22 N., R. 2 W. Whether these two levels represent a lowering of the base level of the streams carrying the outwash or whether the ice formed a temporary dam for the upper terrace will make an interesting problem for future investigations.

An interesting feature of the outwash deposits is the long narrow tongues of such material which appear to extend far back into the moraines. These are especially evident in the lower southwestern part of Richfield Township (22 N., R. 1 W.). Such tongues of outwash are perhaps more properly to be called 'valley trains.' They show a well-defined gradation of material from head to mouth. Near the head cobbles are quite the rule. Another feature is the gradual curve of the slope of the upper surface.

THE LAKES OF ROSCOMMON COUNTY

Houghton Lake. — The largest lake in the county and the largest in the state is Houghton Lake. It covers an area of over thirty square miles, being nearly ten miles long and over four miles wide at its widest point. An outstanding characteristic is the fact that it is very shallow, being scarcely more than fifteen feet deep in its deepest portions and shallower over most of its extent. There are much mud and vegetation over its basin, which accounts for the excellent fishing that annually attracts tourists from all over the state. As regards the cause of the original basin of this lake, it is probable that a number of factors have been operative. Among these the most important is probably the favorable position between two transverse moraines which served to deflect the drainage from the melting ice lying to the northeast. Most probably it is an example of a 'pit lake,' such as have been abundantly described from other areas.

Higgins Lake. — Higgins Lake has an area of fifteen and one-half square miles. It differs greatly from Houghton Lake in many respects. For one thing it is much deeper. According to most reliable information it has a depth exceeding one hundred feet in many places. Furthermore, the bottom is sandy and gravelly instead of muddy as is Houghton Lake. At the southern end waves have cut into the moraine producing a 'cut-and-built' terrace of considerable width. The line marking the 'drop-off' is very distinct because of the clearness of the water and is marked by a change in color from emerald or grey to a deep azure-blue. Evidences of a former higher level of the water are present at a number of places. For example, in Section 15, T. 24 N., R. 3 E., is a beautiful wave-cut cliff. Farther east is another long ridge extending from Section 22 into 14, T. 24 N., R. 3 W., which appears to have been cut by waves. Evidences of a terrace made at the higher level are to be found in Section 32, T. 24 N., R. 3 W., and to some extent in the section north of this one. For further details regarding the shores of this lake the reader is referred to the excellent treatise on lakes by Irving D. Scott entitled Inland Lakes of Michigan, published by the Michigan Geological Survey.

Origin of Higgins Lake. — As regards the origin of Higgins Lake, it may be stated that it appears to be a 'pit' lake. It is possible, however, to assume here also that it owes its existence partly to its protected position between two prominent moraines that offered transverse obstacles to drainage from the retreating ice-sheet.

Clear Lake. — Clear Lake lies at a point scarcely more than a mile south of Twin Lake. It is a horseshoe-shaped body of water occupying a deep irregular depression in the West Branch moraine. As the name implies it is a very clear body of water because it is deep and free from sediment, being fed entirely by seepage waters. The basin of this lake was originally a hole in the West Branch moraine due to irregular deposition of material. It therefore belongs to the class of lakes called 'morainic.'

UNIVERSITY OF MICHIGAN

[1] Leverett and Taylor, *The Pleistocene of Indiana and Michigan, U. S. G. S., Monograph LIII*, Washington, 1915, pp. 232 ff.

SURFACE GEOLOGY OF MENOMINEE COUNTY, MICHIGAN

WALTER A. VER WIEBE

THE rock formations of Menominee County reveal a very interesting geological history for that part of the state. In fact it would be a difficult problem to find an area of the same size anywhere in Michigan which shows a similar variety of geological phenomena. Not only that, but in addition, some of these phenomena are so well displayed and in such profusion that the county may well be considered a typical region for their careful study. These statements apply particularly to the eskers and drumlins.

ICE DEPOSITS

Marginal moraines. — In Menominee County there are two large marginal moraine areas. One of these extends from T. 34 N., R. 29 and 28 W., in a northerly direction to T. 38 N., R. 28 W. This area is marked by the usual rugged, abrupt topography of marginal moraines. The relief amounts to 150 feet in places not more than one-half mile apart. One such spot lies about two miles west of Blom on the north line of Section 33, T. 38 N., R. 28 W. Another is on the north line of Section 25, T. 35 N., R. 29 W.

Eastern marginal moraine. — The eastern marginal moraine extends from the north line of T. 34 N. in a southwesterly direction nearly to the Menominee River just west of the city of Menominee. It is narrow and not any too well defined. There are spots, however, where all the characteristics of a marginal moraine are well displayed and there is no doubt that the margin of an ice lobe halted here for a time on the last Wisconsin retreat.

In Menominee Township the moraine becomes very much attenuated, partly on account of its original narrowness, and partly because the waves of Lake Algonquin have cut cliffs back into it and destroyed portions of it. The highest level of this lake is indicated by a line of wave-cut cliffs and narrow, cut terraces.

Ground moraine. — The ground moraine in Menominee County occupies a strip running through the central part of the county from north to south. It takes in a larger portion of the county than any other type of glacial deposit. In the three northern tiers of townships it extends across the whole width of the county.

It is fairly typical in its surface expression, being gently undulating, in general, except where it is interrupted by drumlins or eskers. It is made up of red boulder clay with occasional erratics. This boulder clay is not always a stiff, sticky clay, but commonly contains a sufficient amount of sand and silt to produce a loamy soil.

DRUMLINS

Distribution. — Among the features that modify the level character of the till plain the drumlins are most prominent. They are present in nearly every township and are so abundant that hardly any square mile is without at least a portion of a drumlin. Over six hundred drumlins were counted in twenty-five townships.

Forms. — Most of the drumlins are elongated hills with very smooth slopes. They are elongated in the direction of major ice movement, which is fairly constant over most of the area, as shown by glacial striae at many places. This direction is S. 40° W., but a slight departure is noted in the western part of the county. See Plate XII, Figure 1.

Most of the drumlins are about three quarters of a mile long. A few are over one and one-half miles long. Most of them show the characteristic tapering off of the profile in the direction away from the ice and the blunt end on the stoss side.

Some of the modifications of drumlin form are rather interesting. For example, double or triple drumlins occur in which two or three parallel ridges are superimposed upon one broad drumloidal arch.

Structure. — Ordinarily the material of the drumlin is unassorted and unstratified. Occasionally, however, a cross-section will show some sections set off from the rest by rude bedding planes, parallel to the surface contour of the drumlin. A good example to show this concentric bedding is one which crosses the center line of Section 23, T. 37 N., R. 26 W., in the east half of the section. In this particular drumlin there are sand zones along the bedding planes. A prominent one is located about four feet below the surface of the drumlin and parallels the contour or profile for a distance of twenty feet. There is a similar one about two feet lower.

Formation. — Many suggestions have been made by geologists to explain the form and other features of the drumlin. None of these fits all cases and it is entirely probable that they may originate in various ways. Indeed, the drumlins of Menominee County furnish evidence in support of at least two explanations.

Chamberlin has suggested that their formation may be in some way related to longitudinal crevassing. Alden[1] found that "the ice of the drumlin-forming segments of the Green Bay Glacier was moving and spreading under conditions which developed stresses along transverse lines; and these stresses, though perhaps not causing the actual opening of longitudinal crevasses, facilitated the spreading of the basal ice about obstructing piles of drift and their formation into drumlins rather than their obliteration by erosion. This condition may also have induced localized deposition in piles or ridges which later were shaped and perhaps added to by the plastering on of drift."

Fairchild[2] believes that "drumlins are shaped by the sliding movement of the lowest ice, that in contact with the land surface. As the ice-sheet thinned by ablation there came a time when the drift-loaded ice in contact with the ground was subjected to less vertical pressure and to relatively greater horizontal pressure by the deep ice in the rear, and was pushed forward bodily."

The last explanation seems to agree most closely with the conditions observed in Menominee County, for there is much evidence that the ice mass had thinned considerably at the time the drumlins were formed. The writer's studies on the piedmont glaciers of Alaska lead him to believe that the ice never gets very thin even at the margin. It is conceivable, however, that a large mass might become detached and stranded in the retreat of the main glacier. This relatively stagnant glacier could then be thrust forward bodily by a renewed advance of the main glacier from the rear. It is not difficult to see that such a movement would tend to smooth out small accumulations of boulder till under the stagnant mass and shape them into elongated hills. It also explains how additional layers might come to be plastered on, for melting, with the formation of a layer of till followed by a forward thrust of the ice with its smoothing effect, and renewed melting with the formation of another layer of till and this followed by still another forward thrust, would produce just such a rude stratification or bedding as has been described.

Double and triple drumlins and especially flutings on the till plain, which are common in parts of Menominee County, strongly suggest the erosional effects of ice as the process by which they are produced. If thick masses of ice can produce *roches moutonnées*, there is no reason why lesser ice masses cannot gouge out softer boulder clay and produce elongated grooves such as constitute the troughs between drumlins.

Some unusual drumlins. — On the main road running north from Spalding to Faunus on the south line of Section 33, T. 39 N., R. 26 W., there is a peculiar drumlin. It has the topographic form of a drumlin, being smooth on the surface, oval and elongated in the usual direction. A cross-section revealed by a road-cut and increased by a gravel pit shows a remarkable duality of structure. On the northwest side it consists of alternating layers of gravel, sand and clay. On the southeast side it consists of unstratified boulder clay with erratics. The north half thus has all the characteristics of an esker, while the south half has the characteristics of a typical drumlin.

The explanation that suggests itself is that an esker stream has cut away a portion of a preexisting drumlin and deposited, in place of the clay, some sand and gravel. Subsequently the whole deposit was overridden by the ice and smoothed off into the drumlin form.

Dissected drumlins. — Two cases of notable interest came under the observation of the writer in the form of drumlins dissected by an esker stream. One of these is a drumlin which crosses the section line between Sections 10 and 11 of T. 38 N., R. 26 W. An esker which winds along from the northeast for several miles intersects the drumlin in Section 11, T. 38 N., R. 26 W., a short distance north of M-15 and ends somewhat abruptly. At this point there is a trench across the drumlin which cuts through it nearly to the level of the till plain. On the other side of the drumlin in Section 10, T. 38 N., R. 26 W., the esker ridge begins anew and winds south across M-15 and on into Sections 14 and 15 for a distance of nearly a mile.

It appears as though there had been contemporaneous erosion of the drumlin at the time the esker was being formed. Also it is probable that the esker stream began as an eroding stream at the level of the top of the drumlin and did not begin to deposit material until erosion had cut down to the level of the till plain.

An interesting example of the same phenomenon may be seen in the SE. quarter of Section 12, T. 36 N., R. 26 W. Here a drumlin has been cut through nearly to the till plain level. The cut is about 15 feet deep and 25 to 40 feet wide. On the northwest side a somewhat poorly defined esker ridge may be discerned trending NNW. On the southeast side there is quite an amount of stratified sand and gravel, as though a stream had built an alluvial fan out from the point where the esker stream finished cutting through the drumlin, carrying the clay away but leaving the coarser material behind.

THE ESKERS

Perhaps the most interesting feature of the surface geology of Menominee County is the wide distribution of eskers and the unique nature of some of them.

Distribution. — The eskers occur on the till plain, one or more being present in twenty-seven of the twenty-nine townships of the county. The greatest number in any one township is twenty-one (T. 33 N., R. 27 W.) and the next is twenty (T. 36 N., R. 27 W.). They are distributed fairly evenly otherwise.

Forms. — There seem to be two types of eskers in Menominee County which can be distinguished by the forms. One of these is the usual and typical hogback form in which there is a sharp ridge that is nearly as high as it is wide at the base. The other form is flatter and more nearly the shape of a drumlin. Both are characterized by an interrupted profile, and the esker may stop abruptly and then begin again along the same trend farther on. The horizontal profile or ground plan also is quite irregular. Some of them change their direction very suddenly or sharply, turning off nearly at a right angle in extreme cases. Frequently they bifurcate or branch in several directions. See Plate XII, Figure 2.

Trend. — The eskers all show very nearly the same general trend, which conforms in a remarkably close manner to that of the drumlins. In a general way, all the long eskers run from northeast to southwest, and the average would not be far from S. 30° W. Most of the shorter ones also take this direction, but in their case the exceptions are more numerous. Many of these run nearly south and some of them even southeast.

Formation. — It is generally believed that eskers have been built by streams which flowed under the ice, within the ice, or upon the ice. In Menominee County eskers formed by each of the three kinds of streams appear to be present. The low flat drumloidal ridge produced by a stream flowing under the ice is illustrated at a number of places. On the south line of Section 10, T. 33 N., R, 27 W., such an esker crosses the section line road. It is about 20 feet high and 160 feet wide. The pebbles in it are well stratified and assorted and most of them average about two inches in diameter. Such eskers are ten to twenty times as wide as they are high and consist predominantly of small gravel and sand.

The opposite type, which, it is presumed, was fashioned by a stream on the ice, is illustrated by an esker three quarters of a mile east of Bagley. In this, the central portion, which consists of very coarse cobbles and boulders, was presumably made by a swiftly flowing stream capable of carrying off all the finer materials. This settled down to the ground with the gradual melting of the ice. The lateral sections, however, consisting of much finer materials were probably the top set beds of the stream which slumped into that position when the ice melted.

The characteristics of this type of esker are, therefore, coarseness of material and greater disturbance of stratification. The relation of width to height in this type is approximately three to one.

A stream flowing within the ice would leave a record of deposition in all essential respects similar to the surface stream. It is logical to assume that the water flowing through such a tunnel would have great force and therefore clean out all finer particles, as silt and sand and even large pebbles. This results in an accumulation of very coarse cobbles and boulders. Most of the eskers of Menominee County are of this last type.

Boulder eskers. — This type may include the peculiar boulder eskers of which a few are found in Menominee County. A boulder esker is one in which occur large erratics or slabs of sedimentary rocks, which in themselves are too large to be moved by a stream. In other respects they have all the characteristics of eskers, such as the serpentine ridge, the assortment, and the like.

The most interesting boulder esker seen is one which crosses M-90 in the NW. quarter of Section 28, T. 39 N., R. 24 W. (one and one-half miles southeast of Shaffer). It is about three quarters of a mile long but twice interrupted, and consists mostly of large, flat slabs of Trenton limestone. Some of these measure over three feet in largest diameter and are arranged with their flat sides parallel to the stratification planes.

Relation of eskers to drumlins. — One of the interesting phenomena that may be seen in Menominee County is an esker crossing a drumlin. In view of the great number of each of these types of glacial deposits, it seems odd that only a few cases of such a superposition appear. Of the two hundred or more eskers in the county only four were observed to rise as high as the crest of a drumlin.

In the SW. corner of Section 17, T. 38 N., R. 25 W., lies one of the most perfectly symmetrical drumlins in Menominee County. It is located on the Sugarbush farm which is well known in that part of Michigan. This drumlin reaches over into Section 19, T. 38 N., R. 25 W. Near its southern end an esker (which starts in Section 16, T. 38 N., R. 25 W.) crosses this drumlin. The esker is rather flat and low on the drumlin, but takes on the steep-sided ridge form west of the drumlin.

KAMES

For the most part the kames are found in a broad zone which trends from northeast to southwest beginning near Perronville in Section 2, T. 39 N., R. 25 W., and extends to Section 29, T. 33 N., R. 27 W. This zone is from six miles wide (near the two ends) to about ten miles wide in the latitude of Daggett. Most of the kames are small in area and not very high.

Formation. — Some kames are made by subglacial streams at the point where they issue because of loss of pressure and velocity. Other kames are made by ice surface streams depositing gravel and washing out boulders into a funnel-shaped basin in the ice. This funnel-shaped deposit later becomes inverted by the melting of its supporting walls. Some kames are formed at points where an esker stream tunnel is enlarged into a cavern.

It is probable that all these types of kames are represented in Menominee County, though it is not an easy matter to pick them out. The first type, which may be called an 'ice-front' kame, may be expected anywhere, i.e. in front of a marginal moraine and anywhere behind it on the till plain. The second type, which we may call a 'kettle' kame or 'moulin' kame, should be most common on a marginal moraine, for where the ice front stands during a prolonged period of time and melting or ablation is pronounced, there the conditions for surface streams to collect material into holes or moulins would seem most favorable. It is likely that the kames on the eastern marginal moraine of Menominee County in Sections 28 and 32 of T. 34 N., R. 26 W., and Section 1, T. 33 N., R. 26 W., are of this type.

The third type, or 'ice-cavern' kame, might logically be expected to show a rather close relation to eskers. There are several kames in Menominee County which appear at nodes or branching points of eskers. The best example of this kind is near the center of Section 11, T. 38 N., R. 26 W. An esker which begins in Section 1, T. 38 N., R. 26 W., and trends southwest, has several branches, and turns in its course where a hill of irregular outline rises to about twice the height of the esker. The hill covers an area of perhaps an acre and has the hummocky appearance of a kame.

Another interesting kame is to be seen on the south line of Section 29, T. 38 N., R. 26 W. A cut 20 by 140 feet made for road-building purposes reveals a central mass which has the character of a kame and an envelope of boulder till. The central core consists of well-stratified and assorted sand and gravel lenses, but the periphery is made up of only clay and boulders. It appears as though a kame had been formed in the normal way and had later been overridden by the ice and fashioned into a short drumlin.

OUTWASH

The outwash features of Menominee County are of three kinds, viz., kame terraces, outwash and subglacial wash. All of it is more or less perfectly assorted by water action, but it differs in respect to position or mode of formation, so that the threefold division is necessary. The kame terrace will be described first.

Kame terrace. — The name kame terrace was first suggested by Salisbury.[3] He describes it as a deposit made by a stream flowing between an ice mass on one side and a rock mass on the other, and which, on the melting of the ice mass, leaves a terrace of somewhat irregular slope.

Such deposits are fairly numerous in Menominee County. One of the most typical may be seen along the quarter line in Section 25, T. 38 N., R. 26 W., near the west side of the section. A drumlin crosses the road at the extreme west side of the section and on its side an esker is perched. Beyond this to the east is a nearly flat terrace about 75 feet wide. It is composed of small pebbles and sand and at the edge slopes off somewhat irregularly toward the lower land to the east.

One of the best examples in the whole county was observed south of a drumlin one quarter of a mile east of Faithorn in Section 15, T. 38 N., R. 28 W. This kame terrace is 600 feet wide between the drumlin and the railroad.

Outwash. — In Menominee County there are two types of outwash plains which are distinguished by their position with reference to other deposits and also by their size. One type is found in front of the marginal moraine. The other type appears in small patches on the till plain behind the moraine.

The frontal outwash apron associated with the western marginal moraine in Menominee County occupies disconnected patches along the Menominee River. It may be studied in its most typical development in the area north of Shaky Lake. Here it consists of sand and small pebbles assorted and stratified. It is quite thick and shows several levels. In other words, after its original formation, sections of it were removed by streams, so that now terraces are to be seen instead of a simple plain.

The other type of outwash which occurs on the till plain consists of the same material, i.e. sand and gravel. In this case, however, the material is rather fine-grained, the pebbles are quite small as a rule and sand is more common as an admixture. The areas where such outwash is to be seen are quite small in extent and rarely cover more than a square mile. One of the largest areas and also one of the most typical may be seen along M-15 in Sections 4, 5, 9, 10 of T. 38 N., R. 25 W. Small patches occur here and there in a six-mile zone (approximately) extending toward the southwest through Carney, Bagley, Daggett to Koss.

Subglacial wash. — In addition to normal outwash material and kame terraces, there is another type of deposit which has certain features that set it off from these and make it appear that other conditions are responsible for their deposition than were operative in the case of normal outwash.

This type of deposit is characterized by stream-laid material somewhat irregularly stratified and assorted, but it contains a good deal of coarse material and it lacks the surface regularity of outwash. Instead it is marked by rather broad domes of slightly hummocky aspect or low, flat knolls. Typical areas show no high knolls such as might be called kames nor any ridges that might be interpreted as esker fragments.

In studying these deposits at numerous scattered places in Menominee County one gets the impression that they were formed essentially like outwash plains by waters that result from the melting of the ice, but that these waters flowed *under* the ice instead of in front of it. Hence the name 'subglacial wash' is suggested for such a deposit. It is not difficult to visualize a relatively stagnant mass of ice of large size (such as the front portion of the Malaspina Glacier) left behind in the general retreat of the main glacier. By ablation this mass would in time resemble a limestone region with sink holes, underground channels and caverns. The sink holes of such a honey-combed ice mass are marked by a kame when the ice finally disappears completely. Similarly the underground passages occupied by a stream during the incumbency of the ice are marked by an esker after the ice has melted away. Some of the large caverns and especially those that are low but extensive on the ground level are marked by subglacial wash. For here the streams deposit under pressure and also leave numerous small blocks of ice buried with the rock debris. These two features will produce a hummocky and low, knolly surface when the ice has finally melted. The frequent appearance of large boulders and blocks of limestone is easily explained by assuming that the material was incorporated in the roof of the cavern.

In Menominee County areas where such subglacial wash can be seen are scattered in a broad zone which trends from northeast to southwest and roughly coincides with the zones in which outwash, kame terraces, kames and eskers are most numerous. Perhaps the most instructive area of subglacial wash is the one in the NE. corner of T. 33 N., R. 27 W. It covers a large part of Sections 1, 2, 3, 9, 10, 11, 12, 14, 15, 16.

Record of Lake Algonquin. — In Menominee County the existence of Lake Algonquin is clearly indicated by beach lines and similar evidence in a broad zone bordering the present shore of Lake Huron.

The highest shore-line of Lake Algonquin enters Menominee County in Section 1, T. 37 N., R. 25 W., and winds in and out among the drumlins and other ice-deposits along a line trending southwest. It enters R. 26 W. in T. 36 N. in Section 36, and R. 27 W. in T. 33 N. in Section 25. It reaches the Menominee River in Section 32, T. 32 N., R, 27 W.

In this distance the elevation of the shore-line drops from 655 feet above sea-level at the north end to 620 feet at the south end. It is marked in part by beach ridges, or constructional features, and in part by wave-cut cliffs or destructional features.

Warping of the shore-line. — The highest Algonquin water plane rises from 39 feet (620 A. T.) near Menominee City to 69 feet (650 A. T.) west of Cedar River. It thus shows a rise of 30 feet in about 20 miles or 1½ feet per mile. When compared, the elevations show a drop from east to west also of 20 feet from Fish Creek to Menominee City and of 21 feet from Washington Island to a point 7 miles west of Cedar River. The distance from east to west is 24 miles to the northwest corner of Washington Island and 30 miles to Rock Island. Thus the drop from east to west amounts to about 10 inches per mile in this latitude. The line of equal deformation or isobase would thus run very nearly N. 15° W., which is the angle found by Goldthwait in Door Peninsula.

PLATE XII

FIG. 1. Drumlin One Mile West of Bark River

FIG. 2. Esker One Mile South of Detgen Farm

LAKE NIPISSING

In Menominee County the Nipissing beach is prominently developed and may be seen at many points. The state highway M-91 enters Menominee County in Section 4, T. 36 N., R. 24 W. For two or three miles southward this highway is built on the Nipissing beach. Numerous cuts along the roadside show stratified sand, gravel, and in places, shingle. Occasionally large slabs of limestone appear intermingled with the gravel and sand. In Section 9 fine stretches of shingle are developed in which 95 per cent of the material is Trenton limestone. Along this stretch of M-91 the elevation of the beach, as determined by hand level, is 27 feet above lake level (608 A. T.).

In Menominee County the shore-line features of Lake Nipissing show a drop in elevation of about 6 feet in 30 miles or 1 foot in 5 miles. This agrees very closely with the figures established by Goldthwait and Hobbs on the basis of careful measurements made in the vicinity of Green Bay.

UNIVERSITY OF MICHIGAN

[1] Alden, Wm. C., *The Quaternary Geology of Southeastern Wisconsin. U. S. G. S., Prof. Paper*, 106, 1918, p. 255.

[2] Fairchild, H. L., *Drumlins of Central-Western New York, New York Stale Museum Bull*, 408, 1907, pp. 429 and 430.

[3] Salisbury, R. D., *Ann. Rep., N. J. Geol. Sur*., 1891, p, 156, and *Glacial Geology* of N. J., 1902, pp. 121-124.

THE STRATIGRAPHY OF ALPENA COUNTY, MICHIGAN

WALTER A. VER WIEBE

THE observations upon which the data set forth in the following pages are based, were made in the northeastern part of Alpena County. The field-work was done in the month of August, 1924, and June, 1925, for the Land Economic Survey of Michigan . All the consolidated rocks exposed in the county belong to the Devonian system, and the formations in order of their relative age are the Bell shale, the Traverse group (consisting of the Long Lake series, the Alpena limestone and the Thunder Bay series) and the Antrim shale. See Map 6.

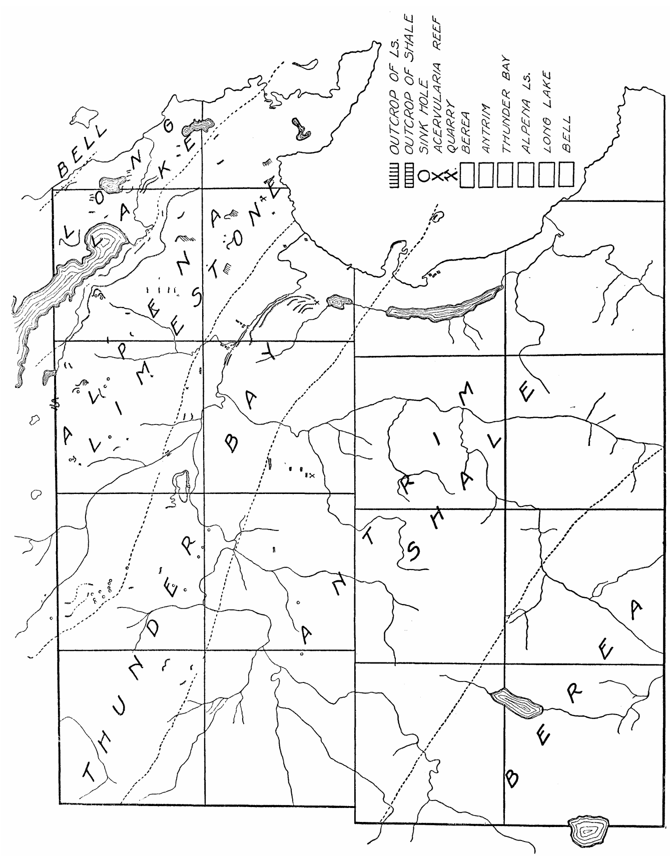
Bell shale. — The Bell shale was first described in detail by Rominger on page 49 of Volume III of the publications of the Geological Survey of Michigan (1873-76). At the time of the writer's visit in 1925 the Bell shale was to be seen at only one place in the county. This exposure is in the quarry of the Great Lakes Stone and Lime Co. at Rockport. It may be seen at the north side of the quarry and also at the east end. The first exposure shows a thickness of 12 feet of a soft, blackish or blue, rather massive clay shale. In the greater part of this mass fossils are quite scarce, but in the uppermost eight inches, which is a calcareous mudstone, fossils are very numerous indeed. At the east end of the quarry only a few feet of the shale are exposed under the limestone.

Long Lake or Lower Traverse series. — Grabau, in the annual report for 1901 of the state geologist, divides the Traverse series into three divisions and calls the upper one the Thunder Bay series, the middle one the Alpena limestone, and the lower one the Long Lake series. In this paper Grabau's terminology will be followed, but with considerable modifications as to the rocks to be included under each name. The Long Lake series, according to Grabau, includes, for example, all the rocks below the 25-foot limestone at the top of the Churchill well (297 feet of section). In this discussion the Long Lake series includes only the basal part of the Traverse (members 7 to 14 in Churchill well), having a thickness of 196 feet. It is felt that such a subdivision agrees more closely with mapable units. Later investigations based on the fossils it contains may make some other grouping more desirable. This series crops out in a zone about three and one-half miles wide, which cuts across the northeast corner of Alpena County from southeast to northwest. In general the outcrops show a thickness of about 80 feet of alternating limestones and shales which form the upper member of the series, below which there are about 70 feet of argillaceous shale (the middle member) and 40 feet of limestone (Rockport limestone) as a basal member.

Upper member of Long Lake series. — The topmost layers of the formation are exposed in Sections 19, T. 32 N., R. 9 E., 24, T. 32 N., R. 8 E., and 30, T. 32 N., R. 9 E. This is Grabau's locality Nos. 29 and 30, described on page 187 of the report for 1901 mentioned above. The writer measured the following section along the section line between 19 and 30 in 1925:

1. Limestone, thin-bedded, in irregular layers, argillaceous and blue	4 ft.	
2. Covered	2 ft.	
3. Limestone, argillaceous, similar to No. 1	3 ft.	
4. Covered	6 ft.	
5. Limestone, argillaceous mudstone		4 in.
6. Shale, clay blue and massive	6 ft.	
Total	21 ft.	4 in.

In the top layer fossils are very numerous. Farther down they also occur, but more sparsely. Very good outcrops of the harder layers in the upper part of the Long Lake series may be seen along the main road to Rockport, especially on the center line of Sections 11 and 12 of T. 32 N., R. 8 E.



MAP 6. Areal geology and outcrops in Alpena County, Michigan

Middle member of Long Lake series. — The middle member of the Long Lake series is composed almost entirely of soft shales. For that reason outcrops are very rare. The old quarry of the Alpena Portland Cement Co. in the SE. quarter of Section 18, T. 32 N., R. 9 E., was apparently located in this part of the stratigraphic section. It is now abandoned, but was visited by Grabau, who lists fossils from that locality (which he calls locality No. 31). R. A. Smith, the state geologist, has informed the writer that drill holes to test the extent of the Rockport limestone in Section 6, T. 32 N., R. 9 E., encountered as much as 70 feet of shale above the basal limestone of the Long Lake series.

Rockport limestone or basal member. — On page 175 of publication 21 of the *Michigan Geological and Biological Survey* (*Mineral Resources of Mich. for 1915*) Smith first differentiated the Rockport limestone as a stratigraphic unit. He describes it as a limestone consisting of "essentially stromatopora, coral, etc., with a matrix of dark or black crystalline and very bituminous limestone. The stone contains from about 94% to about 98% calcium carbonate."

At the time of the writer's visit in 1925 the quarry opened by the Great Lakes Stone and Lime Co. in this basal part of the Long Lake series was in full operation and exposures permitted thorough study of the characteristics of this member. The following section was measured here:

1. Limestone, buff, lithographic, weathers out in rectangular blocks, and with a characteristic yellow color. Fossils are scarce, but stylolites are common	10 ft.	
2. Limestone, blue, with many large masses of *Acervularia* and *Stromatopora*, as well as innumerable small individual corals. Many black seams and masses of bituminous matter	12 ft.	
3. Shale, bituminous, tough	1 ft.	
4. Limestone, forming the lower quarry rock, irregularly bedded, streaky, white, blue, and grey limestone, many bituminous partings. Fossils are numerous, particularly *Acervularia*, *Stromatopora*, and individual corals like *Zaphrentis*, *Cyathophyllum*, etc.	17 ft.	
5. Mudstone, calcareous shale filled with fossils		8 in.
6. Bell shale, soft, blackish blue, argillaceous	12 ft.	

It will be seen from this section that the Rockport consists of about 40 feet of limestone, most of which is very bituminous. Another feature is the strikingly different lithology of the upper ten feet, which is buff-colored and very fine-grained and breaks with a blocky cleavage. This part of the Long Lake series corresponds to member No. 14 of the Churchill well record.

The Alpena limestone. — The Alpena limestone was set off from the Traverse as a separate division by Grabau.[1] He assigns a thickness of 25 to 35 feet to it and calls it the "Traverse middle limestone." The thickness is based on the Churchill well, a record of which is given on page 169 of the article.

There can be no question of the possibility of separating the middle portion of the Traverse series from the rest as a distinct lithologic unit. It is sharply bounded above by a most pronounced change in the character of the material, which was laid down in the Devonian seas. There is a change from markedly calcareous shale to a crystalline, hard limestone which seems to be traceable over a large area.

When it comes to a determination of the base of this middle limestone, however, there appears to be no good reason why it should be placed at a depth of 25 or 35 feet, for the same type of rock that characterizes the top of the division continues on down at least 80 feet, as is clearly shown in the quarry of the Michigan Alkali Co. near Alpena. A drill-core taken in the northern part of the same section as that in which the quarry is located shows a thickness of 125 feet of essentially the same kind of rock.[2] If we compare the Churchill well with this record, we find a striking correspondence. Numbers 2 to 6 inclusive are listed as limestone with only two thin shale breaks recorded. The first real shale interval of importance is No. 7, which has a thickness of 20 feet. Below this the shales almost equal the limestone in thickness. It would seem, therefore, more logical to draw the line marking the base of the Alpena division at the base of No. 6 in the Churchill well. This would give a thickness of 126 feet for the whole division. Careful correlation of the various layers of the Alpena division in the outcrops northwest of Alpena indicates a similar thickness. Therefore, in this report a thickness of 126 feet will be used as the type thickness of the formation.

Outcrops of Alpena limestone. — A section was made along the Long Lake road by Grabau, the nature of which is discussed in the annual report of the state geologist of Michigan for 1901. He believes that the basal part of the formation (using 35 feet as the thickness) crops out at station No. 19 or locality No. 5, which is a point a few rods north of the northwest corner of Section 35, T. 32 N., R. 8 E. As nearly as the writer can determine, the layers which crop out here lie about 75 feet below the top of the formation, indicating clearly that the thickness assumed by Grabau was one which could not be used in the field. A short distance north of this locality the black zone (lower one) in the formation crops out. This lower black zone appears to come about 35 to 40 feet above the base of the formation. By following the outcrops which are almost continuous from here north, we find evidence of successive limestone layers coming up from below to the surface as far as and beyond the forks in the road (Grabau's locality No. 8, station No. 22).

The lowest layer of the Alpena limestone division has an elevation of about 660 feet, being found about 8 feet above Long Lake where it is first met. This layer, or the ones immediately above it, can be traced toward the northwest so as to allow a correlation with the section at Killian's, where it appears at an elevation of 670 feet above sea-level. It reappears again on the section line between Sections 5 and 8 of T. 32 N., R. 8 E., at an elevation of 675 ft. It continues across Section 6, T. 32 N., R. 8 E., as far as the small lake on the township line in the SE. quarter of Section 1, T. 32 N., R. 7 E. Beyond this point it is difficult to follow because of the steep cliffs and the forest cover. However, the black limestone zone, which lies about 40 feet above it, becomes very prominent here and by means of the latter it is possible to fix the position of the base of the Alpena limestone with satisfactory accuracy.

An important key section may be seen on the Prezinski farm in Section 2, T. 32 N., R. 7 E. The rock succession above a small lake which enters Alpena County from Presque Isle County in this region is as follows:

1.	Limestone, thin, shaly, buff, crinoidal; makes a good terrace south and southeast of the farm buildings.	1′	1′
2.	Covered	21′	22′
3.	Limestone, hard, dense, black, crinoidal, *Favosites*, *Stromatopora*, *Orthoceras*, etc. Elevation about 752 A. T.	3′	25′
4.	Covered	9′	34′
5.	Limestone, massive, hard, buff, crinoidal; just below the level of the buildings at edge of farmyard	3′	37′
6.	Covered	14′	51′
7.	Limestone, dark, massive, with numerous corals; makes a prominent terrace	1½′	52½′
8.	Covered	5′	57½′
9.	Limestone, dark, shaly, bituminous	1′	58½′
10.	Covered	4′	62½′
11.	Limestone, very hard, black, crinoidal. Elev. 710 ft. A. T.	1½′	64′
12.	Covered	24′	88′
13.	Limestone, dull grey, argillaceous, with innumerable *Atrypa reticularis*	1′	89′
14.	Covered to level of small lake. Elev. 680 ft. A. T.	6′	95′

Layer 11 in the foregoing section is a very prominent terrace-making rock and can be traced to the southeast through the woods as far as the Donakowski farm, where it forms the topmost terrace under the buildings and the barnyard. It can be traced farther to the southeast through Sections 7 and 8 of T. 32 N., R. 8 E., and appears to be equivalent to a part of the prominent black zone in the Killian section. By means of this layer, therefore, the sections southwest of Long Lake can be correlated. If the correlation is correct, it develops that the base of the Alpena limestone lies below the level of the little lake in Section 2, T. 32 N., R. 7 E. Accordingly the line between the Alpena and lower Traverse passes through Section 35, T. 33 N., R. 7 E., about a half-mile south of Long Lake.

Thunder Bay or upper Traverse rocks. — The uppermost division of the Traverse group has been named the Thunder Bay series. It has received the least attention on the part of geologists of any of the divisions of the old Hamilton group of Rominger. For that reason the writer spent considerable time and effort in tracing the various members of this division. He was able to find outcrops which show nearly every individual portion of the division at one place or another. Also by careful comparisons he was able to trace certain members along from one outcrop to another, so that a complete section of the whole division might be built up. This section is as follows:

1. Limestone, blue to pale buff, crinoidal; weathers rusty-yellow or brown, many corals	5′	5′
2. Limestone, argillaceous, with thin beds of calcareous shale, very fossiliferous	7′	12′
3. Covered interval	?	
4. Limestone, dull grey, crystalline; weathers out in flat pieces with a rusty color	1½′	13½′
5. Covered	1′	14½′
6. Limestone, dense, hard, bluish-grey; weathers out nearly white, microcrystalline	2′	16½′
7. Covered	1′	17½′
8. Limestone, dark grey to blackish-brown, semi-crystalline; crinoids, corals	6½′	24′
9. Limestone, similar to No. 8	1′	25′
10. Limestone, hard, brittle, dense, grey	1′ 2″	26′ 2″
11. Limestone, blue; made up almost entirely of silicified corals	1′	27′ 2″
12. Limestone, similar to No. 10	10″	28′
13. Shale, calcareous, with bituminous streaks	1′ 3″	29′ 3″
14. Limestone, blue, thin-bedded, many fossils	2′	31′ 3″
15. Shale, calcareous, blue and black	9″	32′
16. Limestone, very massive; weathers out in peculiar nodular masses when fresh, and in red or yellow, porous, crumbly masses when weathered for a long time	2′	34′
17. Limestone, dark brownish-buff, shaly on top	1′	35′
18. Covered	2′	37′
19. Limestone, yellow to buff	2′	39′
20. Limestone, shaly, crinoidal, rusty outcrop	1′	40′
21. Limestone, hard, buff, microcrystalline	1′	41′
22. Limestone, similar, but top is coarsely crinoidal	2′	43′
23. Shale, calcareous, blue; weathers rapidly with rusty discoloration, very fossiliferous, in SE quarter of Section 20, T. 31 N., R. 8 E.	19′	62′
24. Silo Terrace. Limestone, grey, encrinal, semi-crystalline; weathers buff, yellow and red; fossils	8′	70′
25. Shale, blue, calcareous, very fossiliferous	3′	73′
26. Alternating layers of argillaceous limestone and calcareous shale, less fossiliferous	10′	83′
27. Covered	11′	94′
28. Shale, blue, calcareous; disintegrates readily into blue clay	10′	104′
29. Limestone, blue, argillaceous, shaly,	2′ 4″	106′ 4″
30. Shale, blue, clay shale; weathers rapidly, fossils	3′ 6″	109′10″
31. Limestone, blue, argillaceous, shaly	10′	119′10″
32. Same as No. 31	2′ 2″	122′
33. Covered	?	122′ ?

Nos. 1 and 2 of the foregoing geologic section are typically exposed at Partridge Point. The black shale was not found directly above the limestone here, but it was found in two wells drilled by the Alpena Business Men's Association in Section 22, T. 30 N., R. 8 E., at such a depth as to indicate that the limestones found on the point are practically the top of the formation. The very top layers are exposed only at one locality. North of the quarter line in Section 17, T. 31 N., R. 7 E., large pieces of crinoidal limestone similar to those at Partridge Point may be seen in an abandoned field. South of the quarter line on the land of Mr. Patterson are very good outcrops of the black (Antrim) shale. This is probably the only place in the county where the exact contact between the upper Traverse and the Antrim shale is to be seen.

The covered interval (No. 3) probably does not exist at all. In fact, it is more than probable that Nos. 1 and 2 in the section find their counterpart in Nos. 4 to 8 inclusive of the section. In that case we have instead of a covered interval, a duplication of 12 feet. If this duplication is allowed for, the whole section would total 110 feet as a minimum and 140 feet as a maximum. Nos. 4 to 24 are the composite section made for the Potter farm (Section 20, T. 31 N., R. 8 E.). The rocks exposed on Orchard Hill are in all probability the equivalent of Nos. 22, 23, and 24. The limestone which crops out on Stony Point is about the same horizon as Nos. 21 and 22 in the composite section.

No. 24 is an excellent key horizon. It makes a prominent terrace on the Potter farm and because of the fact that a high, hollow-tile silo, which can be seen for miles, stands directly on it, the writer has called it the Silo Terrace. It crops out practically uninterruptedly from the Thunder Bay River in the SE. quarter of Section 20, T. 31 N., R. 8 E., in a northwest direction to Section 12, T. 31 N., R. 7 E., and therefore makes a convenient datum plane for the rest of the geologic section above and below. Nos. 16 to 20 also make well-defined terraces, but they must be used with caution as any one of the four benches may make the terrace. The peculiar nature of No. 16 will serve to identify the horizon of the terrace.

No. 23 is the zone that offers the happy hunting-grounds for the collector of fossils. It is doubtful whether there is a more prolific source of fossils than this zone as exposed in the SE. quarter of Section 20, T. 31 N., R. 8 E., and the adjacent part of Section 21, T. 31 N., R. 8 E. These are Hindshaw's localities Nos. 7 and 9.

Nos. 25 and 26 are exposed on the north side of Thunder Bay River west of the upper dam in Sections 1 and 12 of T. 31 N., R. 7 E. No. 28 is exposed at several places. The full ten feet show up where the line between Sections 17 and 18, T. 31 N., R. 8 E., crosses Thunder Bay River in the south bank. A portion of this clay shale also shows in the south bank below the lower dam and again in the south bank below the upper dam.

Nos. 29, 30 and 31 may be studied at the Fletcher (lower) dam. They are Nos. 8, 9 and 10 of that section. The equivalents of the same layers probably occur also below the upper dam. There they would correspond to Nos. 3 and 4 of the geologic section for that particular section. No. 32 is exposed along the township road between Sections 1, T. 31 N., R. 7 E., and 6, T. 31 N., R. 8 E. This correlation is not as precise as might be wished, but close enough for all practical purposes.

The final covered interval at the base is entirely conjectural. Inasmuch as there is a slight gap between the lowest outcrops of the lower Traverse and the upper beds of the Alpena limestone, it is likely that 10 to 15 feet of calcareous shale are present in this part of the stratigraphic section. It is not certain, however, that there is any interval and on the other hand it may be as great as 30 feet in thickness.

Antrim shale. — Outcrops of the Antrim shale are not numerous in Alpena County because the shale is so easily destroyed by weathering agents, and also because of the thin sheet of glacial drift which obscures so large a part of the consolidated rocks of this region. The best place to study the formation is in the quarry of the Huron Portland Cement Co., which is located in Section 30, T. 31 N., R. 7 E., in the northeast quarter of the section.

The concretions found in the shale are of two kinds. The large ones consist chiefly of calcium carbonate with some clay and iron carbonate as impurities. They are very numerous in certain zones. In size they range from eight inches in diameter to over three feet. During past years of quarrying thousands of these 'hardheads,' as the drillers call them, have been uncovered. They now lie in the bottom of the quarry in long rows where they were left because they form an objectionable impurity in the shale. Consequently they offer a unique opportunity for study and it is hoped that someone who is interested in their mode of formation will take advantage of this opportunity before they are covered up. The writer was impressed by the fact that many of them have a bituminous calcite (called anthracolite) as a central core. Even more suggestive is the fact that this calcite shows by its strong elongation of one axis of growth (the 'c' axis?) that this mineral has grown from the center outward. A core of this type will, therefore, show crystal growth radiating in all directions from the center outward. Other concretions that were examined show only a cavity in the center, sometimes of large size. In still others this cavity was filled in geode form with secondary calcite, siderite or magnesite or rarely with quartz. In some concretions the shale shows a tendency to arch up and down, that is, around the concretion as if the latter had grown after the shale was laid down.

The second kind of concretion which is abundant in this shale is a form of iron sulphide, probably pyrite. It also occurs at all levels, though it is frequently found in definite rows at certain levels in the section. Masses of this mineral are not so uniformly round or oblately spherical as masses of the other material. Besides being irregular in shape they are also much smaller. Concretions of the size of a large walnut are most common and many are of the size of a large apple.

Fossils are rare in this shale. The writer found one piece of a kind of Calamite stem and a few fragments of a Devonian fish. The latter was found in the center of a single concretion which had been broken open and the fossil was, therefore, broken into many fragments. It may lend itself, however, to identification and may prove to be a new genus. No systematic search for microscopic fossils was made.

Outcrops of the Antrim shale. — Outcrops of the Antrim shale occur at three other localities in the county. One of these is in Section 17, T. 31 N., R. 7 E., another in Section 15, T. 31 N., R. 6 E., and the third in Section 22, T. 30 N., R. 8 E. The first one of these is probably the most interesting as it marks the precise boundary line between the Antrim and the Traverse formations.

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[1] Grabau, Amad. *W., Stratigraphy of the Traverse Group of Michigan. Geol. Survey of Mich., Ann. Rept*., 1901, pp. 164-210.

[2] Smith, R. A., *Limestones of Michigan. Mich. Geol. and Biol. Survey,* Publ. 21*, Geol. Series 17*, 1915, p. 181.