MAP OF SAINT CROIX INTERSTATE PARK
Showing location of giants' kettles

GIANTS' KETTLES ERODED BY MOULIN TORRENTS

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INTRODUCTION

The most interesting feature of the Interstate park of Minnesota and Wisconsin, at the Upper Dalles of the Saint Croix river, consists in many large and small water-worn rock potholes, which are also, in their large examples, often called "wells." The languages of Germany, Sweden, and Norway give the name "giants' kettles" to such cylindric or caldron-shaped holes of stream erosion, which are everywhere characteristic of waterfalls and rapids, especially in crystalline rocks. Their Spanish name, *remolino*, used in the Republic of Colombia, has been recently advocated by Mr Oscar H. Hershey for adoption by geologists;*

* Science, new series, vol. 10, p. 58, July 14, 1899, followed by remarks of criticism or approval by others on pages 88, 187, and 298 of the same volume.

but either the common English term, potholes, or the German and Scandinavian designation, apparently alluding to mythical giants, seems preferable.

These potholes, occurring most numerous near the steamboat landing of Taylors Falls, Minnesota, at the central part of the Upper Dalles, and within a distance of 50 rods northward, are unsurpassed by any other known locality in respect to their variety of forms and grouping, their great number, the extraordinary irregularity of contour of the much jointed diabase in which they are eroded, and the difficulty of explanation of the conditions of their origin.

In view of the late Glacial confluence of ice currents there, known by the occurrence of drift on all the country eastward derived from the northeast and largely from the basin of lake Superior, while all the region westward is enveloped by drift from the northwest, with gravel and large masses of limestone from Manitoba, it is evident that the surface of the ice-sheet at its time of departure sloped downward from each side toward this area. The superficial line of boundary between the northeastern and northwestern drift, mapped for the Saint Croix Dalles area by Doctor Charles P. Berkey,* passes from south to north in coincidence with this part of the Saint Croix river. Beneath the ice-sheet during its later accumulation here, after the Buchanan interglacial stage, a subglacial brook flowed in the summers along the course of the interglacial Saint Croix. It probably ceased while the ice of that time attained its greatest area, depositing the Illinoian and Iowan drift; but when the ice was finally melting away, remaining here with only a depth of a few hundred feet, the same subglacial stream course doubtless received torrents plunging vertically down through crevasses and moulins. Such glacial waterfalls and the subglacial streams flowing rapidly away to a more deeply channeled avenue of discharge southward along the valley seem to have been the chief agencies of erosion of the potholes in the Interstate park and its vicinity.

A consideration of the diverse classes of streams which are capable of eroding potholes shows two modes of their origin dependent on glaciation. The purpose of this paper is to describe these "giants' kettles" at the Dalles and elsewhere near Taylors Falls, Minnesota; to compare with these, for aid in their explanation, other examples of their kind in many localities of North America and Europe, which are unquestionably of subglacial origin; to inquire what conditions were necessary for this result, and in what parts of a stage of glaciation they were apt to occur;

*Am. Geologist, vol. 20, pp. 355-369, with maps and sections, December, 1897. Compare my paper, "Changes of currents of the ice of the last Glacial epoch in eastern Minnesota," Proc. Am. Assoc. Adv. Sci., vol. 32, for 1883, pp. 231-234, and Geology of Minn., Final Report, vol. 2, 1888, pp. 409-417.

and to ascertain the relations of the glacial torrents forming potholes with the larger glacial brooks and rivers that produced kames and eskers.

CLASSIFICATION OF ROCK POTHoles OR GIANTS' KETTLES

POTHoles OF SUBAERIAL WATERFALLS AND RAPIDS

In all parts of the world the falls of rivers in cascades or rapids over granitic or other hard and enduring rocks wear portions of their rock bed into beautifully smoothed and gracefully or often fantastically curved forms, among which are frequently found bowl-like or cylindrical holes. These range in dimensions from a diameter of a foot or less up to 10 or 15 feet or rarely more, with an equal or often greater depth.

In a few places such abundantly water-worn rocks, with potholes, are found where no stream now flows nor has existed since a lake hemmed in by the barrier of the departing ice-sheet had its outlet there, flowing over a col of the present watershed between independent hydrographic basins. This is one mode of stream action forming giants' kettles due to the Glacial period; but these kettles are not filled or covered by glacial drift.

Good examples of this class occur in New Hampshire at two localities where the watershed dividing the Merrimack and Connecticut River basins is crossed by railroads. The more northern and lower place, at Orange summit of the Northern railroad, had numerous potholes, some of which were partly and others entirely blasted away for the passage of the railroad. The most remarkable one, known as "The Well," was described by Jackson as 11 feet deep, 4½ feet in diameter at the top, and 2 feet at the bottom. It contained earth and round stones. Another locality of the same character is also reported by Jackson in Warwick, Massachusetts, "on the southern declivity of a bare ledge of gneiss forming the dividing ridge between the Ashuelot and Millers rivers."*

GIANTS' KETTLES OF MOULINS AND SUBGLACIAL STREAMS

The class of potholes more particularly considered in this paper depended directly on glacial action. They may be called, by way of distinction from those of subaerial streams, glacial potholes; or perhaps, by usage among geologists, the German and Scandinavian term, giants' kettles, may be restricted to this class of holes, bored in the bed-rock beneath glaciers or an ice-sheet by torrents of water falling through deep moulins. This name, moulin, coming from the French and meaning a

*C. T. Jackson: Final Report on the Geology of New Hampshire, 1844, pp. 113, 114, 282. Warren Upham, in Hitchcock's Geology of New Hampshire, vol. 3, 1878, pp. 64-66.

mill, is applied to a vertical tunnel, melted at first by the waters of the surface trickling into some very narrow crevasse that has just begun to open, until, after enlargement by this dissolving action, it receives sometimes a large stream, such as could not be waded, pouring with a thunderous roar down a cylindric shaft to the rock floor under the ice. But the streams that bored these potholes or giants' kettles were very small, and were only very scantily drift-laden, in comparison with the glacial rivers which formed the great esker ridges.

Rock exposures adjoining glacial potholes are often unmarked by other waterwearing; but in every present stream having falls and eroding potholes, larger spaces are irregularly worn and channeled. The rock kettles of moulin formation, found where no stream now exists nor can be supposed to have ever flowed except when the country was ice-enveloped, are the predominant or the only form of water erosion in their vicinity; but at the falls of ordinary streams, potholes are exceptional or a subordinate feature among more extensive grooving and other fantastically waterworn sculpture. It is evident, too, that glacial planation, ensuing after the moulin origin of the giants' kettles, although probably in many places effective to intensify this contrast, can not generally be its chief explanation, which is rather to be found in the protection afforded by the ice covering the rock contiguous to the base of the moulin. The rebounding water, indeed, welling up from one side of the rock kettle, may perhaps have usually flowed away, for its immediate exit, in an englacial tunnel, or at least with some drift between it and the rock. The conditions of erosion of the giants' kettles prevented or minimized contiguous waterwearing, which, on the other hand, is favored and predominant wherever potholes are made by sub-aerial streams.

Another way in which subglacial streams probably sometimes or often acted to erode potholes has been pointed out by Mr T. T. Bouvé* and Professor George H. Stone,† who well remark that the subglacial waters, after falling down the crevasses and moulin shafts, would flow rapidly away upon the surface of the bed-rock, and there might sweep past the mouths of potholes during the process of their erosion, supplying all the current needed for their further deepening by the whirl thus given to the water and stones at the bottom. For the largest and deepest of the giants' kettles, however, to be here noted as discovered in many localities of glaciated countries, I can not doubt that the pothole was cut down

* "Indian potholes, or giants' kettles of foreign writers," *Proc. Boston Society of Natural History*, vol. 24, pp. 219-226, April, 1889, with ensuing discussion by Warren Upham, pp. 226-228.

† "Glacial gravels of Maine and their associated deposits," *U. S. Geol. Survey, Monograph* 34, 1899, pp. 324-330.

exactly at the foot of a great and very deep moulin by its powerful descending torrent.

Potholes of subglacial erosion, whether bored just beneath a moulin or in or beside the pathway of a rapid stream flowing from it, may subsequently have become partly or wholly filled by till, the direct deposit of the ice-sheet, unmodified by water action, or such potholes may be completely concealed under a later general sheet of glacial drift. On the other hand, too, they may remain nearly or quite empty, having been so left, without drift accumulation, while the overlying ice disappeared.

LOCALITIES OF SUBGLACIAL POTHOLES

INTERSTATE PARK OF THE SAINT CROIX DALLES

The northern part of this park and the adjoining southern part of the town of Taylors Falls are mapped on plate 1. The potholes are mostly on the western or Minnesota side of the Saint Croix, occurring plentifully on certain areas between Trap Rock street (the road to the steamer landing) and the river. These areas of their abundant development are comprised within a length of 50 rods from north to south and about 12 to 15 rods from east to west. With other tracts where single examples or a few occur, as west of this street, again on the Wisconsin side of the river, and again on a low rock hill in the valley about a mile north of Taylors Falls, not less than a hundred potholes are known in this vicinity. Many of them, however, are small, as a foot or less in diameter and one to five feet deep. The greater number were originally left empty, or with only a partial filling of rounded grinding stones, silt, mud, or peat, differing much in their contents. Others, mostly of small size, were found completely filled, and some were covered and hidden by a hard deposit of glacial drift, almost typical till.

The chief area of large potholes, worthy to be called giants' kettles, reaches from the steamboat wharf about 15 rods east-northeastward to Angle rock and about 20 rods northward, comprising only an acre and a half, within which space are all the very large and deep potholes known in the entire district. Counting the small and large holes, I found 30 on that area, including several so remarkable for their great diameter or depth, unusual form, or contents that they deserve to be separately described. The rock, like that of all the places having potholes in and near the Interstate park, is the very hard diabase trap of Keweenawan age, which here forms extensive outcrops, everywhere much divided by vertical and oblique systems of joints. Under the glacial and river erosion there has resulted a very ruggedly broken surface of rock cliffs and dells. Little or no drift and only few boulders have been left on the rock

tracts. Some of the potholes are on the slopes and tops of low cliffs, 5 to 20 feet above adjoining hollows. The height above the almost still river in the adjoining Dalles varies from 25 to 50 or 60 feet, rising highest northward.

In general, the rock surface has angularly broken slopes and cliffs, more or less glaciated, but since so weathered that the glacial striæ are effaced. Occasionally a little place, 10, 20, or 50 feet in extent, is smoothly waterworn; but more commonly the surface adjoining the potholes on this area and wherever they occur in this neighborhood, excepting in and near the river channel at the Saint Croix rapids, is roughly fractured or has been abraded only by the ice-sheet. The rim of the potholes, of whatever size, is usually abrupt, not merging with waterworn curving outlines of the adjacent rock, as at subaerial rapids and falls of our present rivers.

The giants' kettle of greatest diameter, which may be named "the caldron," is situated about 30 feet northeast from the east end of the wharf and 25 feet above the river. It is nearly circular, 25 by 27 feet in transverse diameters. Its sides descend vertically 8 to 12 feet, below which depth this kettle is filled with many angular rock masses from 1 to 5 feet long. Some of these may have been dislodged by frost action from a much-jointed cliff which rises at the northeastern brink of the kettle to a height of 10 feet above other parts of its rim. More probably, however, as in the case of the only other pothole observed to be similarly almost filled by rock masses, they are attributable to falls through the moulin, having previously been contained in the lower part of the ice-sheet as englacial drift.

Near the northern end of this area and 6 feet northwest of a foot-bridge, the most northwestern of a series of bridges which span little gorges and lead to Angle rock, is the other pothole mentioned for its contents of rock blocks and boulders. Its diameter is about 12 or 15 feet, and its depth, to be proportionate, should reach far below the surface of the many angular trap fragments, up to 3 or 4 feet long, which fill it to within 4 feet below the rim. No high nor fractured rock surface adjoining this kettle could yield its contents, which must therefore have come from the ice-sheet. They are unworn examples of the rock masses which in other instances, being less plentifully supplied, were gyrated in the bottom of the pothole by the torrent, wearing it deeper and grinding themselves to powder, until new masses of rock, falling in, took their places as the work of kettle erosion continued. Two very large kettles thus appear to have been interrupted in their formation by the abundance of their supply of grinding stones.

Honorable George H. Hazzard, the Minnesota commissioner of the Interstate park, has partially cleared and sounded a very deep pothole situated 15 rods north-northeast of the wharf and about 5 rods east of the road (called Trap Rock street on the plat of Taylors Falls). The diameter of the mouth of this hole, not exactly circular, is 13 by 15 feet. Beneath several feet of water it was found filled to 15 feet below its mouth by peat and decaying leaves, branches, and trunks of small trees, but with no sand or gravel. By bailing out the water and excavating, the workmen went to the depth of 55 feet below the mouth, finding the diameter of the hole undiminished to that depth, its average being from 10 to 15 feet, with vertical cylindric form. A pole was then thrust 10 feet farther down, to a total depth of 65 feet, without reaching any grinding stones such as are almost invariably present at the bottom of these holes. The mouth being about 40 feet above the river, the bottom of this giants' kettle is thus ascertained to be more than 25 feet beneath the river level. The ratio of its diameter to its depth (so far as that has been probed) is as 1 to 5, showing thus a similarity with the deep cylindric giants' kettles near Christiania, Norway, but having a depth that exceeds them or any others known elsewhere.

It is exceeded, however, by its very close neighbor on the west, another pothole 25 feet distant, which has a diameter of 10 by 12 feet. This hole, filled by water to about 15 feet below its top, was sounded in the year 1878 by Dr Greeley Murdock, who since 1877 has been the principal resident physician of Taylors Falls. He found no bottom at the depth of 84 feet below the top of the rock at its mouth. It was an amusement of boys to thrust down tamarack poles 30 feet long into the water of this pothole, and it has now become partly filled with these poles and with driftwood, leaves, etcetera, that have been washed into it from a little marsh, a watercourse in times of river floods, adjoining it on the north and west. The mouth of this hole is mostly about 35 feet above the river, but its northeastern third falls off 8 or 10 feet—nearly to the marsh level. On the west the higher part of the mouth or rim is divided by only 5 or 6 feet of rock from a vertical descent of 12 feet of rock face or cliff bordering the marsh. It will be noticed that the ratio of the diameter to the known depth of this pothole is 1 to 7, but its entire depth has yet to be determined. It is known to extend about 50 feet beneath the surface of the river, which itself, near the angle of these Upper Dalles, is stated by Dr C. P. Berkey to be 160 feet deep.*

At a distance of about 40 to 70 feet northeast of "the caldron," the southern side of a rock knob is smoothly waterworn in two half cylin-

*Am. Geologist, vol. 20, p. 379, December, 1897.

dric, vertical, or in part slightly overhanging surfaces, as if halves of two very large potholes, each open toward the south, were joined, giving a combined diameter of 30 feet from west to east. The curved and cusped rock face, rising 15 to 20 feet, from about 30 to 45 or 50 feet above the river, has variegated colors in different parts—reddish and black (by iron and manganese stains), a dark dull green (the natural color of the rock), bright yellow (patches of lichens), and, in some spots and streaks, light gray or even white (lichens, and efflorescence of carbonate of lime from water leaching through thin drift and the rock crevices). On account of their smokelike and fiery coloring, these halves of giants' kettles are called "the Saint Croix Fireplace." For the explanation of their erosion I can only suggest that here, as in places of moulin torrent action in Massachusetts and New York, effective erosion nearly as in a pothole of the largest size took place on a mural surface, with only ice, as we must suppose, to form the other side of the moulin. It is quite sure that they were worn as half-potholes instead of having undergone demolition and removal of the wanting part. On a smaller scale such mural segments of cylindric water-wearing are seen in several other places within this little area.

Close south of one of the foot-bridges leading to Angle Rock the narrow gorge, 15 to 20 feet deep, which the bridge spans, is enlarged, nearly like a great pothole about 15 feet in diameter, by the same cylindric water-wearing. The open passage of the gorge leading to the north is only half as wide, with roughly fractured walls due to nearly vertical joint planes. This place has been named by visitors the "Devil's Kitchen."

Again, a curious freak of the water-wearing is displayed by the "Bake Oven," a pothole 6 by 7 feet in diameter and 10 to 15 feet deep from its unequal rim. It is filled lower by soil and earth, forming a floor, on the continuation of which, by crouching, one may pass out eastward through an opening, waterworn under a thick roof of rock, to a lower space ten or 15 feet away. Only six feet of rock on the north side of the "Bake Oven" separates it from the hole that was excavated and probed to a depth of 65 feet, as before described.

Among the smaller potholes of this most interesting area, near the wharf, is one which is named the "Hourglass Well," situated about 10 feet northwest of "the caldron." Its diameter is about three feet at the mouth, and somewhat increases to the depth of 3 or 4 feet; it is then constricted, within two feet lower, to a diameter of only 18 inches, but widens again below to nearly three feet, the bottom being about eight feet below the highest part of the mouth. The constriction may have been due to a harder band of the rock which comprises successive lava flows. It should be noted, however, that a similar form of a pothole at

Gurleyville, Connecticut, described by Professor B. F. Koons,* seems to have been caused by varying conditions of erosion, there referable to a moulin torrent, rather than by inequality of hardness of the rock.

In a few instances the rock wall of a pothole intersects one, two, or three smaller potholes, which were partly worn away and merged with the larger one. A good example of such a compound rock kettle is situated 5 to 10 feet south of the very deep kettle sounded by Dr Murdock, the central hole there being five feet in diameter, with truncated holes 1 to 1½ feet in diameter.

With the large giants' kettles, interspersed upon the same area, are a greater number of others that measure a few feet, or only 1 or 2 feet, or even less than 1 foot, in diameter. These small kettles are mostly cylindric, with depths ranging commonly from twice to five times their diameter; but many are partially filled with sand, gravel, and rounded stones. Rarely a pothole displays a somewhat spirally grooved form, sweeping around once, or nearly so, in the whole descent, due apparently to erosion by the falling stream and stones after the hole had attained almost its full depth.

Farther north several small tracts, varying from 20 to 50 or 75 feet in extent, at heights of 50 to 70 feet above the river, including the highest part of the rock surface between Trap Rock street and the river, have many small potholes, varying from 3 or 4 feet to less than 1 foot in diameter, occurring mostly in groups of five to ten near together, but occasionally isolated. About forty were counted by me, and doubtless others were overlooked. On larger tracts of the adjoining rock, including its northeastern slopes toward the river, potholes are rare or entirely absent.

The most northern group is on a rock outcrop about 6 rods south of the northern boundary of the park. Within a space of 15 by 20 feet on this ledge are ten small potholes, from 4 to 10 inches in diameter, some of them cylindric, but others shallow, like a bowl. Their edges, as is usual elsewhere, are mostly cut abruptly into the rock, with sharp transition, at right angles, from the general rock surface.

The other potholes of this vicinity may be more briefly described. They are very scantily represented east of the river. One on that side, having a diameter of 3 by 4 feet at its mouth, with increase to 4 by 5½ feet at the depth of 5 feet, below which it is filled with earth, is situated about 20 feet northeast from the top of the head of the "Sentinel" or "Old Man of the Dalles." It is only 8 feet back from the verge of the cliff, which falls about 65 feet to the river.

* Amer. Jour. Sci., third series, vol. 25, p. 471, June, 1883.

Within 5 to 10 rods west of Trap Rock street and at the height of about 100 feet above the river several potholes from 1 foot to 3 or 4 feet in diameter, originally filled with drift, have been recently excavated under Mr Hazzard's direction. From these and from other potholes on their chief area before described multitudes of very smoothly worn stones have been taken, varying in size from small cobbles to nearly spherical masses 2 feet or more in diameter, while others, waterworn on all sides, but remaining oblong, measure 3 to 4 feet in length.

On the higher rock outcrops west of the park limits no potholes have been found. My search on the extensive tract of rock at and near the school-house, 200 feet above the river, detected only one spot definitely waterworn. This is about 30 feet west-northwest of the United States Geological Survey bench-mark of leveling (890 feet above the sea). It is a rounded hollow, about a foot in diameter, smoothly eroded by water to a depth of 6 or 8 inches, where no stream can have flowed since the departure of the ice-sheet.

About a mile north of all these localities a hill of the same trap rock rises between the railway freight-house of Taylors Falls and the river, its top being about 50 feet above the end of the railway, or 110 feet, approximately, above the river in the Dalles. Much of the rock surface on this hill is waterworn, and it has numerous small potholes, scattered, probably not less than 20 in all, mostly from 6 to 12 inches in diameter and about one foot deep. Two others of similar size were also seen on the northeastern slope of this hill, some 25 feet below its top and close east of the Saint Croix valley road.

In many other localities which have undergone glaciation potholes are found where they must be referred to moulin torrents and subglacial streams. Short notes of these, so far as they have come to my knowledge by observations, reading, and correspondence, are here added, that they may be compared with the foregoing in the Interstate park, which seem to me also referable to this phase of torrent work during the Ice age.

MAINE

Professor George H. Stone describes potholes on the island of Georgetown, adjoining the east side of the mouth of the Kennebec river.* One is near the level of high tide, and two others are about 60 feet above the sea. These are 4 to 6 feet in diameter and 5 to 10 feet deep, and others of smaller size occur in the same vicinity. The topographic relations show that no stream can have existed there, excepting when confined in

* "The glacial gravels of Maine and their associated deposits," U. S. Geol. Survey, Monograph 34, 1899, pp. 324-330.

an ice channel or tunnel. As it is known that the land there at the time of final recession of the ice-sheet stood about 230 feet lower than now, the pothole erosion seems probably referable to some earlier part of the Glacial period, before the continental subsidence restored a warm climate on the boundary of the ice and caused it to be melted away.

Another pothole, measuring about two feet in both diameter and depth, attributed by Professor Stone to glacial origin, is in Paris, Maine, on the side of a cliff. He thinks that the cliff caused a crevasse, into which a stream fell from the melting ice surface.*

Mr Charles Fry, of Boston, informs me, by letter, of a few small glacial potholes, occurring near together, about a foot or slightly less in diameter and of nearly the same depth, observed by him on the southeastern ridge of Green mountain, on Mount Desert island, at a height between 500 and 550 feet above the sea.

NEW HAMPSHIRE

Professor C. H. Hitchcock notes a pothole, 4 feet deep, on the top of Swetts mountain; one of large size on the southwest slope of Carrs mountain; and another, about two feet in diameter and depth, in Dunbarton, 125 feet above an adjoining valley. Another, described from my observations, is near the top of Beech hill, in New Hampton, about 600 feet above contiguous lowlands and lakes. This, like the one in Dunbarton, is called an "Indian mortar." Its diameter is 15 inches and its depth about two feet. †

Each of these potholes was quite certainly of subglacial origin; and at least the two instances on or near the tops of a mountain and a high hill seem explainable only by a torrent impinging on the rock at the bottom of a moulin.

VERMONT

Doctor Edward Hitchcock reported potholes at numerous localities in Vermont, far above any present stream, and in several instances high on the slopes or ridges of mountains. They are of different sizes, up to a diameter of 20 feet and depth of at least 25 feet. ‡

MASSACHUSETTS

On the seashore in Cohasset, subglacial potholes have been described and figured by Mr T. T. Bouvé, showing vertical water-wearing to depths

* *Ibid.*, pp. 327, 328.

† *Geology of New Hampshire*, vol. 3, 1878, pp. 249, 250.

‡ *Geology of Vermont*, 1861, pp. 216, 217, 763, 930, 933.

of 5 and 10 feet.* Only one side of these holes is rock, with shallow rock basins at the bottom, the other side having been probably the ice-wall of the moulins through which the eroding torrents fell. Professor W. O. Crosby has also described this locality, referring the pothole erosion to the closing stage of the Glacial period.† At two other localities in Cohasset, Bouvé and Crosby report waterworn places on rock ledges where their origin must likewise be referred to a moulin or a subglacial stream.

Professor Crosby further supplies me the following notes, in a letter, concerning several localities of glacial potholes in Massachusetts.

At East Braintree a pothole, doubtless of subglacial formation, was discovered in excavating for a foundation, and later was destroyed by blasting. It was about 12 feet long, 3 to 6 feet wide, and 3 feet deep, shaped somewhat like a bathtub, but opening outward at one end, its smoothed sides there blending gradually with the irregular surface of the rock.

At Newton Upper Falls, on the abrupt southern slope of a high ledge of conglomerate, is a very distinct half of a pothole, some $2\frac{1}{2}$ to 3 feet in diameter and 6 or 8 feet deep, to speak from memory. The appearance suggests at first that the southern half may have been split off by the action of the ice and the edges subsequently rounded; or possibly the pothole was formed between the rock on one side and the ice on the other. At the bottom the waterworn surface curves and runs off horizontally along the face of the ledge for several feet, gradually fading out.

Several small and large glacial potholes, up to 8 or 10 feet in diameter, are worn in granite ledges close to the Fitchburg railroad between Roberts and Stony Brook stations. They are nearly filled with drift, and their depth therefore cannot be stated.

In the village of Clinton, a very perfect, but small, glacial pothole, about 1 foot in diameter and 2 feet deep, is eroded in a beautifully glaciated slate ledge.

During the work on the Wachusett reservoir, at a point about a mile southwest of Clinton, two potholes were temporarily exposed last summer on the lee slope of a prominent ledge of contorted phyllite, which rises above the surface of a widely extended glacial sand plain. They were 1 to 2 feet in diameter and of corresponding depths.

At West Berlin station are several small potholes, which Professor Crosby attributes to erosion by the outlet stream of the glacial lake

* "Indian potholes, or giants' kettles of foreign writers," *Proc. Boston Soc. Nat. Hist.*, vol. 24, 1889, pp. 219-226; with discussion by Warren Upham, pp. 226-228.

† "Geology of the Boston Basin" (*Occasional Papers of the Boston Soc. Nat. Hist.*, iv), vol. 1, 1893, pp. 148-159.

Nashua, formed in the basin of the Nashua river by the barrier of the departing ice-sheet.*

CONNECTICUT

At Gurleyville, on the east side of the Fenton river, a group of glacial potholes, at the height of 98 feet above the river and 42 feet above the highest terraces of valley drift in the vicinity, is described by Professor B. F. Koons, before cited. The one which remains entire, on being cleared from its contents of water and stones, was found to be $6\frac{1}{2}$ feet deep, with a shorter diameter at the surface of 3 feet and 9 inches and a longer diameter of 4 feet and 3 inches. The author notes its unusual form, somewhat like an hourglass, and its relationship to the group as follows:

"About 2 feet above the bottom the diameter is reduced to about 30 inches, and then widens again below this point, leaving a horizontal ring at the narrow place. What can have been the cause of the forming of the ring at this point is not entirely evident. If the rock were horizontal, it would seem that a hard layer in the rather uniform gneiss would account for it; but, since the rock dips at an angle of about 30 degrees and this projecting ring is horizontal and only a couple of inches thick, I find myself at a loss for an entirely satisfactory answer.

"This pothole is near the edge of the cliff, and the remnants of three others appear upon the face of it, and one of these three shows a diameter of 9 feet and a depth of 6. All are within a few feet of each other, a couple of them separated by a thin partition only." †

Professor James D. Dana mentioned the occurrence of potholes in the gneiss of islands off the Connecticut coast and others on Thimble island, in the bay of Stony creek.‡

NEW YORK

The earliest published information, so far as I have learned, of potholes in America attributable to moulin torrents was given by Doctor Ebenezer Emmons, in 1842, describing and picturing a very large pothole in Antwerp, Jefferson county, New York, and noting others near Hammond, in Saint Lawrence county. The Antwerp pothole is about three-fourths of a mile south of Oxbow village, and has a height of about 100 feet or more above the Oswegatchie river, which bends in its course at Oxbow, thus giving the name of that village. Only one side of this pothole remains. Very probably, as at other places already mentioned, only half of it was worn in the rock, the other half having been the ice of a moulin. The hole is from 24 to 30 feet deep, with a diameter of 12 feet

* "Geological History of the Nashua Valley during the Tertiary and Quaternary Periods," *Technology Quarterly*, vol. 12, December, 1899, p. 318.

† *Amer. Jour. Sci.*, third series, vol. 25, June, 1883, p. 471.

‡ *Manual of Geology*, fourth edition, 1895, p. 949.

in its upper part and 14 feet below. On a later page of the same report, in a discussion of the drift and striation of the northeastern part of this state, Emmons wrote of "the numerous potholes in ledges of rock now distant from any stream and far above all the creeks in the region."*

In southeastern New York potholes which may be of glacial origin have been described by Doctor N. L. Britton in the Bronx valley, 2 to 3 miles north of Williams Bridge, two having depths respectively of about 9 and 10 feet,† and others were noticed by Professor Oliver P. Hubbard in the Hudson valley, opposite to the town of Catskill.‡

PENNSYLVANIA

The most remarkable known of these giants' kettles, whether we consider their size or the manner of their occurrence and discovery, are two found in 1884 and 1885 in Lackawanna county, Pennsylvania, about three miles northwest of Archbald. As described by Mr C. A. Ashburner, the Archbald potholes are 1,000 feet apart and were both discovered in coal mining, their bottoms being in the coal bed. When the drift filling the one first discovered was cleared out, it was found to be 38 feet deep, with a diameter of about 15 feet at the bottom, increasing to a maximum of 42 feet and a minimum of 24 feet across its top. The second pothole, of similar basal diameter in the coal bed, had not been cleared of its drift contents, but it is known, from the leveling and test-pits or borings of the mining company, to have a depth of about 50 feet in the rock, with a covering of 15 feet of drift above.§

IDAHO

A very interesting series of glacial gravel deposits in north central Idaho, resting along a part of its course on a rock bed that is much waterworn and marked by potholes, is described by Professor George H. Stone. It is a short distance south of Elk City, on head streams of the south fork of the Clearwater river. The area was covered during a part of the Glacial period by a piedmont ice-sheet or broad glacier, deploying westward from the Bitter Root mountain range, nearly as the present Malaspina ice-sheet of Alaska is spread out between Mount Saint Elias and the sea. These gravel deposits belong in the same class with the prolonged series of esker or osar ridges and gravel plains which are so grandly developed in Maine and in Sweden, and of which occasional examples occur also, although of less extent, in nearly all broadly gla-

* *Geology of New York*, part ii, survey of the second geological district, 1842, pp. 410, 411, 424.

† *Trans. N. Y. Acad. Sci.*, vol. 1, 1882, pp. 181-183; *Amer. Jour. Sci.*, third series, vol. 25, p. 158, February, 1883.

‡ *Trans. N. Y. Acad. Sci.*, vol. 9, 1890, p. 3.

§ *Geol. Survey of Pa., Annual Report for 1885*, pp. 615-625, with a map, sections, and two plates (views from photographs of the first pothole when cleared out for use as an air shaft).

ciated districts. Beneath the ice-walled esker river the bed rock was worn and sculptured with hollows and giants' kettles. Of the locality where this has been made known by gold mining, Professor Stone writes as follows:

. . . "On the hills between Red Horse and American rivers the placer miners have washed away the overlying gravel. The rock beneath the gravel is very much smoothed and polished, but is very uneven, containing many rounded depressions, bowls, and potholes up to five feet in depth. Evidently here was a broad river that flowed up and over hills and valleys. That it disregarded the surface forms of the land proves that it was enclosed between walls of ice. The stratification is not arched in cross-section like that of the osar proper, but is horizontal, like the deposit I have elsewhere described as the osar plains of Maine."*

NORWAY AND SWEDEN

Giants' kettles referable to moulin waterfalls and subglacial stream erosion are known at many localities in Norway and Sweden, according to S. A. Sexe, Brögger and Reusch, Baron Gerard De Geer, and others.

In the close vicinity of Christiania numerous giants' kettles have been discovered and cleared of the glacial drift and water-rounded stones which filled them. The locality of greatest interest is Kongshavn, a southeastern suburb on the shore of the Christiania fjord, where, between the lines of low and high tide, a glacial pothole eroded in gneiss was found, on the removal of its drift contents, to be 16 feet deep, with a diameter of 5 feet. Another pothole, from which the drift was excavated under Professor Kjerulf's direction, measures 34 feet in depth on one side and 44 feet on its higher side, having a nearly cylindric but somewhat spiral or rifle-like form, 8 to 12 feet in diameter. The altitude of its mouth is 90 feet above the sea.†

Taking up the question of the probable epoch or stage of the Ice age in which the Christiania giants' kettles were eroded, we are confronted by the occurrence of marine shorelines and shells in deposits overlying the glacial drift, which demonstrate that during the time of the glacial recession there the land was depressed about 600 feet below its present height. It is impossible to ascribe the moulins and potholes to torrential agency so far beneath the sealevel, and consequently they must belong at Christiania to the earlier time of high land elevation and snow and ice accumulation.

THE GLACIER GARDEN, LUCERNE

Excavation in the glacial drift for a cellar, in the year 1872, first revealed a part of the very admirable group of giants' kettles which is now

* Amer. Jour. Sci., fourth series, vol. 9, pp. 9-12, January, 1900.

† "Giants' kettles at Christiania," by W. C. Brögger and H. H. Reusch, in Quart. Jour. Geol. Soc., London, vol. 30, 1874, pp. 750-771.

one of the chief attractions of sight-seers in Lucerne, Switzerland. This town, visited by the writer in 1897, is in many respects the most fascinating one for tourists in the Alps, and the most convenient for many neighboring excursions, as to mounts Rigi and Pilatus, and the sail on the wildly picturesque and historic Lake of the Four Forest Cantons. The Glacier garden, containing the giants' kettles, is about 100 feet above the lake, and is only a few steps from the Lion monument, designed by Thorvaldsen, which was chiseled from the solid rock fifty years earlier (in 1821). Thirty-two potholes of moulin torrent erosion are counted in the garden, occurring irregularly grouped upon a remarkably furrowed, waterworn, and glacially striated rock area about eight rods long and four rods wide, which was originally so drift-covered that its wonderful torrential and glacial sculpture was concealed. The covering of soil and drift has been removed since 1872, and many rounded stones, which served as grinders rapidly whirled around by the falling waters, from those of small size up to others of huge dimension, five feet or more in diameter, have been removed with the gravel, sand, and clay that filled these rock kettles.

The largest pothole of Lucerne, on the northwest border of the group, has a diameter of 26 feet and depth of 31 feet. Its southern side overhangs, probably because the northwardly flowing current of the overlying glacier carried the moulin slightly forward while the rock erosion was taking place. The movement was least at the base of the glacier, and increased differentially upward. The moulin therefore became inclined, and discharged its torrent somewhat backwardly into the rock kettle, hollowing it thus with an overhanging wall. The same feature is observable in others of these potholes, and several of them display spiral wearing. In some instances the potholes have irregular and composite forms, showing apparently that successive and independent moulins, probably of different years, contributed to their erosion. They range in size from the largest to others 9 or 10 feet deep and 4 or 5 feet in diameter, and to small cylindric or hemispherical kettles only 1 or 2 feet deep.

It is also to be noted that the rock at two or three places is waterworn in broad and somewhat crooked grooves, varying in depth to 6 or 7 feet, and extending 20 or 30 feet in length, where the moulin torrent was less concentrated and more variable than usual; or, more probably, these grooves may have been made by a very inclined and powerful englacial and subglacial stream there impinging on the rock floor. Perpendicular potholes of the usual form, but of small size, occur occasionally in the grooves. It is especially noteworthy, both here and in other localities of Europe and America, that generally the edge or lip of the giants'

kettles, whether large or small, is abruptly cut in the rock surface, perhaps sometimes because of their partial removal by glaciation subsequent to the moulin erosion. They seldom have a flaringly curved mouth, such as more frequently characterizes potholes seen at the present time in the process of erosion by cascades in brooks and rivers.

CONDITIONS OF EROSION OF GIANTS' KETTLES

According to these observations and records of glacial potholes in their best known localities on two continents, it seems to me most probable that the time of their excavation in many cases was the early part of the Glacial period, or some stage of glacial extension, when the ice-sheet was being formed upon the land by snowfall. On any hilly country the ice must have attained an average depth somewhat exceeding the altitude of the hills above the adjoining lowlands before any general motion of the ice-sheet could begin. During the process of slow accumulation of the ice-sheet, the summer melting upon its *névé* surface would produce multitudes of rills, rivulets, and brooks, which might unite into a large stream; and this, pouring through a crevasse and melting out a cylindric moulin, might fall perhaps 100 or 200 feet or more on a moderately hilly region, but probably sometimes 500 feet or more on a mountainous district, while yet the ice motion, though sufficient to permit the formation of the crevasse, might not have gained a definite current to carry the crevasse, moulin, and waterfall away from the spot where they were first formed. We may thus explain the continuation of a glacial waterfall in one place while it was excavating one of these giants' kettles.

After the ice-sheet acquired a current because of the greater thickness and pressure of its mass, such deep cylindric excavations in the bed rock could not be made, because the ice and moulin were in motion; and during the final dissolution of the ice-sheet it seems probable that its receding border had generally steeper gradients and consequently even more rapid motion than during the culmination of the Glacial period.

Moreover, the streams formed on the surface of the ice-sheet by the summer melting before it was so thick as to have motion would be free from drift or any load, excepting what might be derived from projecting hills or mountains, so that their waters could readily find a way through crevasses, forming potholes in the rock beneath by means of detached blocks from the same rock bed, and thence flowing away in subglacial courses. On the contrary, the superglacial streams during the departure of the ice, which then became more or less covered with the previously englacial drift, laid bare by ablation, were heavily freighted with the

gravel, sand, and clay of the modified drift, which must have soon choked up the passages wherever these drift-laden streams found crevasses, causing them to flow in superficial channels walled and underlain by ice, until, near their mouths, the ice was melted through to the ground and kames and eskers there received the coarser part of the river's burden.

In some places, however, we may better ascribe the moulin torrents forming giants' kettles to the closing stage of glaciation, at the time of final melting of that part of the ice-sheet, because this appears to be strongly indicated by a general lack of drift deposits to fill the potholes, as in the Interstate park, most particularly described in this paper. If we can affirm for such tracts of the ice margin, while it was finally melting away, a nearly or quite stagnant condition, allowing a moulin to remain without advance during a series of years, it seems to account for these deep but mainly empty potholes more satisfactorily. Therefore I am inclined to refer the giants' kettles of this park in the Saint Croix valley to the latest recession of the ice-sheet from this area.

The rock gorges of the Lower and Upper Dalles seem to me, as noted in the preceding paper, to have been eroded by the river, even to a great depth beneath its present level, during the long Buchanan interglacial stage or epoch of the Ice age. At the same time a wide reach of the valley, now partly occupied by Thaxter lake, was eroded between these narrow gorges, and a gradually descending ravine was channeled at the east side of the Upper Dalles, slightly north of the angle.

During the later and long envelopment of this area for a second time by ice, drift may have been deposited in this valley, on an average, to a nearly similar amount as on the adjoining higher ground—that is, to depths of 10 to 20 feet, more or less—but its scantiness on the trap outcrops, and the many empty potholes, suggest that there very little drift had accumulated. When the ice was melted back so far as to leave the valley open above the Upper Dalles, its next mile northward to the Saint Croix rapids became filled, to the height of about 60 feet above the present river, by a sand and gravel plain, now forming a terrace on each side, and in part, especially on the east, by coarse boulder drift. Upon these deposits the river ran during many years, smoothly wearing the boulders of its bed, which, as the river cut down its central channel to the present level, have fallen in great numbers from the upper part of the river bank to the water's edge.

GLACIAL STREAMS OF GIANTS' KETTLES AND ESKERS COMPARED

The rate of erosion of the giants' kettles, referred in most localities to a stage of incipient glaciation, and the rate of formation of kame knolls

and hills and esker ridges during the wane of an ice-sheet, were surprisingly rapid, in comparison with the generally very slow rates of geologic action. Watch the artificial processes of granite and marble abrasion and polishing, and there will be no need to doubt that the largest rock kettle of the Interstate park, of Archbald, Christiania, or Lucerne could be hollowed out during the warm months of even a single year by a stream 20 or 50 feet wide, and 2, 3, or 5 feet deep, falling down a moulin 200 or 500 feet deep, and well supplied at the bottom with grinding boulders of granite and other very hard rocks. Crevasses and moulins would be formed in successive years at nearly the same situation, thus producing such a profusely kettled surface as in the Interstate park or the Glacier garden.

Although we have been able to cite many localities of giants' kettles due to moulins and their waterfalls, they are far exceeded in numbers by the gravel and sand deposits called kames and eskers, which are attributable mostly to larger glacial streams. From my observation, it seems clearly within the limits of truth to estimate that we have records of hundreds of kame and esker streams for every one that is known to have formed a giants' kettle by plunging down a moulin or by flowing in any cascade or rapid along its subglacial passage.

If the retreat of the ice-fields under ablation was so rapid as a tenth of a mile yearly, which was apparently its rate near Stockholm, according to observations by De Geer, or about half a mile each year during centuries, as was probably true of the area of the glacial lake Agassiz and the vast plains of the Saskatchewan and Winnipeg country, we can not doubt that the most massive esker ridges, as in Sweden, or in Maine, and the highest kame hills, as the Devil's Heart hill, 175 feet high, in North Dakota, could be formed within a few years for any single section, or perhaps even within one summer for the great kame mentioned. Some of these gravel-depositing rivers, as shown by the widths of esker ridges and plateaus, were two to five or ten times larger than those of the moulins and rock kettles.

The streams flowing in the summers from the border of the ice-sheet were doubtless of larger size and greater numbers during the final disappearance of the ice, when they formed the kames and eskers, than at any previous stage of the Glacial period. Many of the giants' kettles, if not all, are clearly referable to an early or intermediate stage. For example, they are found in Maine and in Scandinavia on coastal tracts that were depressed and submerged beneath the sea to the depths of hundreds of feet when the ice was finally melted away, as is demonstrated by the relations of the glacial drift and the overlying marine deposits, which contain molluscan shells such as now exist only in the

cold waters adjoining glaciers in the arctic regions. As erosion of the bed rock cannot be supposed to have occurred at the bottom of a moulin extending so far below the sealevel, we are compelled to ascribe these glacial potholes, some of them small and others of great diameter and very deep, to some earlier part of the Ice age. I have thought them referable to the time of great continental uplift, proved by submerged valleys, when a severely wintry and snowy climate, resulting from the high land elevation, caused these great areas to become first enveloped by ice-sheets. Afterward, wherever glaciation was interrupted and again renewed, previous to the general subsidence of the land which terminated the Glacial period, moulin torrents might erode potholes during the later stage of snow and ice accumulation. Near the coast and at low levels they would lie under the sea during the departure of the ice-sheet, and the washing of sea waves may in some instances have removed the drift with which they had been filled.

While it is most probable that in some localities, as the Interstate park, giants' kettles originated during the final retreat of the ice, they seem predominantly referable to the beginning of glaciation or to a stage of its renewal. In many places, therefore, the bed rock containing them would be deeply worn away by ensuing glacial erosion, the potholes being spared only where they were protected by deposits of drift or where the rock was little worn by the later glaciation. According to this view, the infrequency of discoveries of these records of moulin waterfalls has been due to their present concealment by drift and elsewhere to their erasure by glacial planation of the bed rock. Kames and eskers, on the other hand, belonging to the time of glacial recession and to the surface of the drift, have been abundantly preserved, testifying of the formation of more numerous and larger streams fed by the glacial ablation and rains and carrying much sand and waterworn gravel.