PROCEEDINGS OF THE ROCHESTER ACADEMY OF SCIENCE
VOL. 5, PP. 161-240, PLATES 11-16. JUNE, 1918.

ESKERS IN THE VICINITY OF ROCHESTER, NEW YORK

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Presented for publication and read by title before the Academy, January 14, 1918

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Introduction.

During the spring of 1910 the writer made a study of several eskers in territory adjacent to Rochester, New York, in connection with graduate work for the degree of Master of Science at the University of Rochester. The results of this study were incorporated in a paper which was submitted as a Master's thesis. The matter was then dropped until the winter of 1916-17, when the general discussion of the paper was revised and rewritten. During the past summer (1917) the eskers described in the early paper were revisited, and several additional occurrences not originally examined were studied. The results are incorporated in the following paper.* It is hoped that it will make some contribution to the subject of eskers and to the general subject of glacial geology. The bibliography at the end of the paper the writer has tried to make as complete as possible.

Eskers represent an interesting type of glacial phenomena. Their peculiar form and trend excite interest even in the casual and superficial observer, and a great deal has been written regarding them.

Definition. Eskers may be defined as long, winding ridges of gravel and sand, commonly stratified, with steep slopes and narrow crests, trending in the general direction of former ice movement. They may strikingly resemble artificial railway embankments.

Popular names of eskers. People familiar with these interesting ridges have accorded them a great variety of names, some of them indicative of their supposed origin, such as, horsebacks, hogbacks, serpent kames, serpentine kames, whalebacks, ridges, windrows, turnpikes, back furrows, ridge furrows, morriners, Indian roads (99).

Technical nomenclature. Esker is the technical name now long used in this country for this class of glacial phenomena. The term is of Irish origin (44). The Swedish word "os", plural "osar", sometimes written "as (asar)", has priority, but has never come into use in America. In Scotland the term "kame" has been used to designate these ridges, the word being probably derived from the Teutonic "kam", meaning ridge (44) By general agreement the term "kam", is now restricted to mounds and short ridges, features developed perpendicular to the direction of ice movement, while the word "esker" is applied to ridges extending in the general direction of ice movement (10).

History. In the early part of the last century, when attention was first directed to these singular esker ridges, various explanations

* I wish to express my appreciation of assistance by Professor Fairchild in connection with this paper. He first suggested the subject to the writer as one worthy of study; he has made many suggestions during the progress of the work; and has placed the facilities of the Geological Laboratory of the University of Rochester at the disposal of the writer. Finally he has contributed of his experience and time in the immediate preparation of the paper for the press.

were advanced to account for them. By some they were explained as ancient sea shores (Hisinger, Martins (69), Chambers (15), Erdman (33), Torell, etc.). Ramsay refers to them as "those marine gravelly mounds, called kames or eskers" (78). Another idea was that a "vast deposit of sand and mud covering the country which had been cut thru by rivers, whose beds were gradually filled with stones and gravel. Later the sand and mud were washed away, leaving the stone and gravel deposits of the rivers in the shape of ridges"(109). They were also regarded as being due to a great diluvial flood (91). Again they were thought to have been formed by marine currents during the submergence of the land (117). Another very early idea compared them to the submarine banks formed in the pathway of tidal currents near the shore. Under the old idea of the aqueous origin of the drift they were referred to iceberg action (73). Jamieson explained both kames and eskers as moraines of gravelly debris deposited at the edge of an oscillating icesheet; the ridge-like form he considered due partially to the ice on its advance pushing the material before it (58). In certain localities in this country they are popularly believed to represent the work of the aborigines, hence the name "Indian roads" applied to them.

Hummel of the Geological Survey of Sweden seems to have been the first one to recognize the fact that the existence of an inland ice sheet must be presupposed as the indispensable agent in forming such ridges. He regarded them as being formed beneath the ice in tunnels excavated by percolating waters (1874) (57). In 1876 Holst, another Scandinavian, published his theory of their origin in the beds of supra-glacial rivers (56). The same view was advocated by Upham in 1878 in this country (115,117). Dana regarded eskers as being subglacial moraines. The idea of glacio-fluvial origin of this type of glacial phenomena has long been entertained, and there is general agreement on this point by all glacialists.

Geologists in this country who have made notable contributions to the subject are N. H. Winchell, I. C. Russell, Warren Upham, G. H. Stone, W. O. Crosby, T. C. Chamberlin, R. D. Salisbury, W. M. Davis, Frank Leverett and J. B. Woodworth.

Occurrence of Eskers. General Occurrence. Eskers occur only in glaciated regions and are limited to areas that were covered by the ice, they never occur beyond the terminal moraine in the marginal zone of outwash. They occur at all elevations above sea level.

Eskers find their best development in Sweden, where they were first recognized as being a distinct phase of the glacial drift. However in south Sweden, Germany, and Denmark, they are almost entirely absent. They are wanting or rare in many regions where other glacial phenomena are strongly developed, as in Switzerland, Norway, and southern Greenland. They are especially numerous in central Ireland, and occur also in Scotland, Finland, and northwest Russia.

In the United States they are best developed in Maine (99). They are common in New England, but rare over the interior states (61, 62, 63).

Occurrence in the New York area. In New York they are infrequent in occurrence, widely distributed, and are low short ridges. They occur in much the same way as over the whole glaciated area to the west.

General Description.

Dimensions. Eskers vary greatly in dimensions. In height they may be from 3 feet to 150 or even 200 feet. One in the Connecticut river valley has been described as being 250 feet high (117). In most cases they are less than 50 feet in height.

Eskers vary in length from a fraction of a mile to 100 miles or more. Several of the esker systems of Maine attain a length of 130 to 140 miles (99).

In breadth at the base they are in most cases only a score or a few score of feet, less than 75 or 100 feet, but locally they may broaden to 500 feet, and a basal width of over a mile has been recorded. The height exceeds one-eighth, and may reach one-fourth or one-third the width of the base. Width may increase as height diminishes or vice versa. They are neither constant in width nor uniform in height. One esker has been described as one-eighth of a mile wide throughout its whole length (63, p. 203). Eskers tend to be small near their point of origin, becoming larger toward their termination.

Segmentation and intervals. Eskers tend to occur in segments, separated by intervals of varying width. Discontinuity is the rule, not the exception. No esker ridge may be traced for 100 miles, or even 10 miles without interruption, the individual segments being but a few miles long, rarely greater than 5 miles, and in many cases only a fraction of a mile in length. In fact segments may be so short as to be mistaken for elongated kames. Stone has stated that in the long esker systems of Maine the eskers are seldom continuous for more than 10 miles without a break (99). The segments may or may not be in alignment.

The intervals between segments are in many cases less than a mile in length, but they may be 2 or 3 miles or even more in extent. These intervals are apt to be occupied by scourways or drainage creases (122). Again gravels more or less spread out and kames are found in these stretches.

Tributaries. Tributaries are an uncommon feature and, where they occur, they are apt to enter the main course at a high angle. They are in the vast majority of cases inferior in development to the main ridge.

Direction. In direction eskers trend with the general direction of ice movement for the general locality in which they occur. Hence their courses tend to parallel the striae, boulder trains and drumlins of the surrounding region. There are however some notable departures from this direction, in fact some have been observed to extend for miles in a direction transverse to the direction of ice flow. Some have their entire course in a direction at nearly right angles to the direction of local ice movement, again part of the course will be transverse and a part conformable to the direction of the ice movement. Some ridges have been observed that apparently extended nearly to the edge of the ice, then turned abruptly through a large angle and ran for miles parallel to the ice edge.

Relations at point of origin. Esker ridges rise abruptly from the general surface. This is true not only at the point of origin of the esker, but also at the beginning of each segment. As a rule the ridges attain their full height within a few rods. They may arise in a kame area, they may continue outward from a recessional moraine, again they may originate in a bouldery field of irregularly heaped till, or from a swampy area of thin till. They exhibit a tendency to originate in places favorable to a large accumulation of water, as level plains, broad basins, and near the top of low divides. They may arise from the lee end of a drumlin.

Character of course. The course, as already indicated, pursues commonly a sinuous direction; rarely is an esker straight for any distance. It meanders, the long deflections, sometimes a mile or several miles in length, appear to obey the topography, the short deflections, only a few feet to a fraction of a mile long, resemble stream meanders. Further, esker courses are unsymmetrical, abrupt turns and sharp angles being a not uncommon feature. Maxima changes in the course may be accompanied by maxima changes in the elevation of the crest line (122).

The crest may remain as narrow as a wagon road, again it may spread out into terrace-like flats, in conformity with a similar increase in the breadth of the base, and become higher than the rest of the esker. In the case of the eskers of the interior these flat areas are rarely more than 500 feet wide, in the case of the Maine eskers they may be exceptionally a mile or more in width. These broad "plains" may contain kettle holes, variously known as basins, sinks, funnels, hoppers, punch bowls, and Roman theaters (99). These kettles may be as deep as the esker is high, and may contain water indicating an impervious bottom. These broad places may show evidences of stream erosion, and boiling springs may occur along their flanks.

The esker ridge may divide, and two parallel ridges may unite to form one ridge. The main ridge may break up to form several distributary ridges, every one of which exhibits the same height and width as the main ridge. These distributary ridges may interlace complexly, enclosing numerous kettle holes, which may have outlets; again they may contain water, and may be floored with till. Such a system of meandering and anastomosing ridges may be connected by lateral and transverse branches enclosing large areas of the country. The width of such complexes may be as great as 5 miles, and the length 10 to 20 miles, the whole often representing a jumble of heaps, mounds, cones and ridges. Such reticulated eskers find their best development in this country in southwest Maine, where they lie in broad valleys (99). They are most liable to development near the terminus of the individual eskers.

Eskers find their fullest development on a long gentle slope. In crossing divides they are apt to be low and their materials coarse (92). They may be represented in such situations merely by scattered pebbles or they may be absent with ridges on both the up and down slopes on either side of the divide. On long gentle up slopes there is a slight tendency toward increase in size, while on short slopes there is no material change in size. On long steep down slopes there may be no deposit, or only a string of large boulders, while at the base of the slope large ridges or, in some places, "plains" are formed.

They may be conspicuously developed in valleys, and then passing onto plains become so faint as to be difficultly traced. The ridges are apt to broaden in the direction of their termination. In Maine they may broaden southward to plains one-half a mile in width. These very broad eskers behave as do the narrow ridges and may change back again to the narrow ridge type (99). Their sides tend to become pitted with small hollows, branches may diverge from them, and the adjacent lowlands become covered with small kames (99). These broad esker plains may constitute valley filling for a distance, or even a narrow marine delta (99).

"Buttress-like deposits" may lie against the base of an esker ridge; sometimes a fan-like spreading of debris from a similar position has been observed (88).

Relation to surroundings. Eskers show no particular regard for topography, they tend however to follow valleys, especilaly if such valleys parallel the direction of ice. movement. Rarely they may follow the axis of a valley transverse to the direction of ice movement, and in such cases are likely to lie along the side of the valley toward which the ice moved. They may cross valleys and pursue their direction across neighboring divides. Rarely do they cross ridges more than 200 feet high that lie athwart their courses; in the case of higher ridges the eskers pass through gaps which are not always the lowest or the most direct. One may turn aside to avoid a hill 100 feet high and in another part of its course cross a hill of greater height.

Eskers may follow the bottom of a valley; in the majority of cases however they lie along the sides of the valley and above its bottom. They may cross from one side of the valley to the other, often they trend toward the bordering hills on the one side or the other. If the latter are more than 200 feet high the eskers never leave the valley; if less, after following the valley for some distance they may break across the low divide and wind across areas of considerable relief. An esker may divide, one ridge maintaining its position in the axis of the valley, or along the side and above the valley bottom, the other ridge paralleling the first along the opposite side. A single ridge may break up into several ridges that follow along the valley, especially if it is a broad valley. If the valley lies in the general direction of ice movement, eskers will not leave it even if adjoining divides are considerably less than 200 feet in height. They often enter and leave valleys of other trend. They are more strongly developed throughout their courses in the valley than when crossing the neighboring uplands.

They show discordance in most cases with existing drainage. They may pass through lakes and their courses be traced beneath the water; they may pass from the land surface to beneath the level of the ocean (99).

They are more common in rough regions than in regions of slight relief, more numerous in Maine than over the upper Mississippi plains.

Leverett has noted the frequent occurrence of eskers in river-like channels cut into the till sheets (61, 62, 63). These troughs may be almost as narrow as the esker ridge at its base, commonly they are several times as broad, the individual trough may not be occupied by the esker throughout its whole length.

In Western New York they lie in narrow valleys between the drumlins. Instances have been recorded when they are known to pass over drumlins (125). They are bordered on either side by wet-swampy places. In fact lakes, ponds or swamps bordering eskers on one side or both sides, elongated in the direction of the esker are common features (29, 122).

Large eskers are apt to be found in large drainage basins, and to be composed of coarser material.

At higher altitudes eskers are confined to valleys chiefly, thus in Sweden at elevations greater than 300 feet they lie in valleys.

Relations at termination. Eskers frequently terminate in kame areas. They may also end in marine and lacustrine deltas and outwash plains. The esker ridges widen as they approach these, and merge with them gradually. Their termination may also be very abrupt without regard to the character of the surroundings. This may take place in an uneven bouldery field, or in a morainal surface. When eskers terminate in recessional or terminal moraines, they tend to advance toward them at nearly right angles.

Eskers may split up near their southern termini into several distinct branches or distributaries, like the mouths of a stream in a delta. These distributaries may be connected by cross-ridges giving a decidedly complex, reticulated appearance.

In case a single ridge has broken up into a number of ridges some distance from its termination the latter ridges are often found to converge and unite just above the termination. Again these diverging ridges may terminate miles from each other in separate deltas, kame areas, fans, etc.

The burial of the lower ends of esker ridges by lacustrine silts, marine sediments, outwash and delta materials, has been observed repeatedly.

Association with moraines. There is no denying the fact that many eskers, possibly most eskers, are associated with either terminal or recessional moraines. Their courses lie north of these moraines in which they terminate. This intimate relationship seems to indicate a close connection in the formation of the two types of glacial deposits.

Composition. Eskers are composed chiefly of sand and gravel. The sand is coarse for the greater part. Gravel is considerably the more abundant material and may be very coarse. It probably makes up the greater part of most eskers, while some eskers are composed entirely of gravel (38, 99,). Very fine material, such as "rock flour", is absent and clay is rare, and when present occurs only in thin beds. Boulders several feet in diameter may be present, embedded in the sand and gravel, some with a diameter of over 5 feet have been observed (99). The pebbles of the gravel are well rounded, rarely are striae preserved upon their surfaces, if once present water action has completely removed their traces. They are rounded not like those of ordinary stream beds, but like those of pot holes or beach shingle (99). The boulders are for the most part subangular, and many preserve striae upon their surfaces. However at times boulders 2 to 4 feet in diameter occur that are well rounded.

The ridges are entirely unfossiliferous, the waters in which they were formed being apparently destitute of life. However the individual component rock fragments may carry fossils indicative of the time which they were formed.

The material may be compact, even firmly cemented into a true conglomerate, again it may be so loose as to be readily dislodged by a stroke of the hammer. Davis has described the esker material as "open work gravels" (27). In certain places fine material has all been carried out from between the gravels, however, adjoining layers may contain plenty of fine material, such as sand.

A few ridges have been described that are composed entirely of till (29, 126, 62, 88, 63). The till has been more or less washed apparently, for the fine material is largely removed, and the coarser material locally shows some degree of water action. The famous Bird's Hill esker contains till incorporated within its mass (112). This will probably be found to be true of a large number of eskers when sufficient exposures are available to examine their interiors fully. Till interbedded with the sand and gravel may be considered then a rather common feature in many eskers.

Near the point of origin of eskers the materials are coarser, and less rounded. Proceeding toward their termination the materials became finer, and well rounded. In the longer Maine eskers Stone states that their north ends are composed of material barely water-worn, the finer material having been entirely removed (99). Toward the crest of the esker the materials are apt to be less rounded than in the lower portion.

One part of an esker may be composed of sand, another part of the ridge may be gravel. Steeper sided ridges are composed of coarse gravel, possibly blocks, angular and subanguler debris mixed with sand and earthy grit (40). The size and distribution of material are influenced by several factors, the nature of the underlying rock, the supply of water in which the esker material was deposited, and chiefly the slope on which the esker lies. Where the slope is steep all of the fine material seems to have been washed out, where gentle only the finer material was transported (102).

In the broad places, the "plains" of the esker courses, the central portion is of coarser material and more water worn. The lateral portions are chiefly sand, in fact most of the sand and finest materials are located in the wide flat-topped portions of the esker. Clay in a few instances makes up the lateral portions, but in most cases it is apparent that the water possessed sufficient current to carry out the very fine materials. Coarser materials are also apt to be near the top and the finer near the bottom in these broad areas.

Reticulated ridges show little change in composition throughout their length, on a whole their materials are coarser and not so well rounded as in the single ridges. The material becomes finer where the ridges grow broader and where they finally become coalescent in a rolling plain (99).

The gravel and sand, the materials of the esker, do not spread out laterally over the adjacent lowland, but are strictly confined to the ridge itself.

Source of materials. The materials composing eskers are largely local in origin, that is, they have been derived for the most part from formations immediately beyond the point of origin of the esker in the direction from which the ice came. The material has been transported somewhat farther than the till adjacent to the esker, but still it is largely local in origin. Hershey states that in the case of the eskers he studied 90 per cent. of the materials have come from less than 60 miles from the eskers themselves (48). The larger material, such as boulders, is more apt to be far-traveled than the smaller, yet a large proportion of these has been transported only a short distance from the place of origin. It is safe to say that in many eskers 90 per cent. of the materials have come from within a few miles to the north of the esker in question, in a majority of eskers 75 per cent. or more of the material is of similar local derivation.

Stratification. The materials of eskers,, being water-lain, are stratified almost without exception. This stratification is rude, chaotic, with cross-bedding common, the cross-bedding planes dipping toward the side or toward the lee end of the esker. The beds may dip from 5° to 60° or more.

There is a tendency toward an anticlinal arched arrangement of the beds, a feature exhibited in most eskers to a notable degree when viewed in cross-section. The layers may be curved, twisted, or distorted markedly. The beds not only tend to dip outward from the center toward the sides, giving the anticlinal appearance, but they are also inclined in the direction of the trend of the esker, they dip away from the point of origin toward the place of termination of the ridge or segment. A single bed may be of fine material, adjacent beds of very coarse material, and vice versa. The larger materials may show an imbricated arrangement observable often among the stones and coarse shingle of streams and rivers.

One part of a ridge may show good stratification, another part poor, obscure stratification. A few eskers exhibit no stratification, they have a "pell-mell" structure, as it has been described, a confused arrangement of materials all of which are rounded. An esker may exhibit stratification in one part of its course, and a "pell-mell" structure in another part. "Pell-mell" structure is characteristic of those eskers especially that are more irregular and hummocky in external form.

In the broad "plains" characteristic of many esker courses the strata are nearly horizontal, or gently dipping toward the southern termination of the esker.

Slopes. The lateral slopes of eskers are as steep as the materials will lie, being the angle of rest for the material of which the esker is composed. This slope varies from 25° to 35° from the horizontal. In cross-section the narrow crest and steep slopes give the appearance of an isosceles triangle, with the cross-sections in any section of a ridge tending to uniformity. The steepness of the slope is an indication of the character of the esker material, the steeper slopes indicating coarser material. Often where the high knolls, characteristic of many esker crests, appear, the declivity is very pronounced, and where the cols appear the angle of slope is somewhat less. Sometimes the slopes of both the cols and the knolls remain the same, the width of the base changing so as to maintain the usual degree of slope.

The ends of esker ridges and of the individual segments are, like the sides, as steep as the materials will lie. In few cases do the ends tend to trail out with a gentle slope and blend with the ground moraine.

Surface characters. Many eskers preserve a uniform crest line throughout their whole length or a greater part of their length. This is in many instances remarkably level, similar to a railroad grade, however such long stretches are in truth slightly curved. Again the crest may be very uneven, thrown into a series of alternating knobs and depressions. This type of crest may characterize the entire course of the esker. Again eskers may have a uniform crest for part of their length, and an uneven crest characteristic of the remaining part. Also the two types may alternate throughout the esker course, each type persisting for some little distance. Knobs above the crest are particularly apt to occur at termini and at ridge intersections (88). The knobs vary in height from 3 or 4 feet to 10 or 20 feet and rarely may be 50 feet above the general level of the crest. They may be so high and pronounced that the esker resembles a series of kames more or less connected. Where they occur the esker ridge tends to broaden.

The materials on the surface are of the same nature as the materials of the esker—sand and gravel, with gravel more common by far. While most eskers have no till on their surfaces, yet its occurrence on a part of the surface or over the whole surface of a number of eskers has been noted. Scheffel describes eskers mantled with till to the depth of 5 or 6 feet (88), and Leverett describes a number of eskers from the interior with till present upon their surfaces (62, 63).

Boulders with a diameter of several feet may be present upon the surfaces of eskers, their occurrence here however is not common. They may be sparingly distributed over the surface, they may be confined to certain restricted areas, again they may cover the surfaces of certain eskers quite profusely (117).

River silt may bury eskers that lie in valleys, as is the case with the series of eskers of the Connecticut valley. They may be buried by outwash carried out by streams from the front of the receding ice edge (28). Along the coast of Maine marine sediments cover the surfaces of eskers (99). Upham has described eskers in New Hampshire covered with alluvium (115). Valley terraces and delta materials may bury them also (21).

Till, as well as large boulders, is very rare over the surfaces of the broad places, the "plains", of esker courses.

Relation to the rock surface beneath. The relation of the esker to the surface upon which it rests is an unknown quantity in most cases, the lack of knowledge being due to the paucity of sections that reveal the bases of the eskers. Where examination is possible it has been found that in the case of a large number of eskers the gravels either penetrate to the bed rock beneath, or below the surface of the till on either hand. However, a number of eskers rest on the till directly with little or no evidence of erosion of the till beneath. Geikie states that eskers rest often on boulder clay, but more often perhaps on solid rock (40). Leverett has mentioned a number of examples of till erosion beneath eskers in the glaciated portion of the interior (62, 63).

Time of Formation.

It is universally conceded that eskers were formed during the waning stage of the continental ice mass. It is probable that the eskers were formed for the most part after the formation of the drumlins.

Condition of the ice at the time of esker formation. The ice at the time of esker formation was thin, having a thickness of but 300 feet or even less (99). High hills, ridges and divides probably projected above the ice as nunataks. Movement was slight or lacking altogether, surface ablation was rapid with the consequent formation of considerable volumes of water (45, 46), a "general recession of a nearly stagnant sheet of ice" was taking place (61).

Rate of Growth.

It is generally admitted that the rate of esker growth was rapid, very rapid. The streams in which the eskers were formed while torrential in character deposited the gravels and sands rapidly. The character of the stratification, the cross-bedding and irregular bedding, the rapid changes in dip and steep dips, all point to conditions of rapid sedimentation. The "open work" gravels, the coarse angular materials near the point of origin, point to rapid growth. Further the nature of the deposits indicate a more rapid flow of water in some parts than in other parts of the stream's course.

Theories of Origin.

The manner of formation of eskers has long been a matter of dispute. That streams associated with the melting glacial ice were responsible for the origin of the typical esker is beyond question, but just what that association was has been the "bone of contention." There have been two opposing ideas advanced, one maintains that eskers originated in streams beneath the ice, the subglacial view, the other idea maintains that eskers were deposited in streams on the surface of the ice, the superglacial view. Students of glacial geology have been advocates of the one or the other idea. Recently there has been another view advanced that has gained a few adherents. This holds that eskers were made at the edge of the ice or in reentrants back from the edge. Again some have entertained the idea of esker formation in ice-walled, earth-bottomed canyons open to the sky. Further, some eskers have undoubtedly been formed in ways in which the active agency of water has been lacking. The large question hinges upon what was the predominant method. These various theories will next be considered.

Subglacial Hypothesis. Statement. This view, advanced at an early date, and followed to-day by the majority of glacialists, attempts to explain the origin of eskers by the activity of subglacial streams. These streams flowed in tunnels beneath the ice mass. The water was under considerable pressure or "head," due to the crowding of the ice, if it possessed movement, against the stream, and due to the height of the tributary waters of the stream at their point of origin on top of the rapidly melting ice miles back from the place of deposition of the esker ridge. The water, derived by surface ablation, flowed along the glacier surface until it plunged into a crevasse or moulin where its course became englacial for a distance or subglacial. These subglacial waters, closely pent, followed a crevasse or a series of crevasses, or some other line of least resistance. The course once established was maintained, even if the ice possessed some movement, and the tunnel gradually enlarged by the melting of the ice adjacent to the stream and by mechanical erosion, Tributary tunnels were developed and maintained in the same way as the main course. The subglacial streams issued from beneath the ice into ponded glacial waters, in some cases as along the New England coast; beneath marine waters, or onto surfaces sloping away from the ice front. In any case there resulted decrease in velocity at the edge of the ice, through loss of "head," and consequent deposition from the waters heavily charged with debris. This clogged the mouth of the tunnel and caused the water to flow at a higher level in the tunnel, eroding and melting the upper surface of the tunnel. As the tunnel got larger and the mouth more and more clogged with debris the main current of the subglacial stream would vary in position and in load leading to aggradation. At first the deposition would be only local, here and there in the channel, but as the tunnel enlarged the deposition would be more frequent to a perfect or nearly perfect ridge development. By reason of the velocity the coarser materials would be left, the finer carried out into the deltas, outwash plains, kames, etc., that were forming at the edge of the ice. Subglacial streams issuing into standing water would have had their velocities checked some distance back from the edge of the ice without regard to aggradation at the mouth of the tunnels, thus leading to deposition in the tunnels.

The supply of debris was obtained from the surface, from englacial material, from the basal portion of the ice heavily laden with material, from tributaries, from the flow of the ice in case it possessed movement, by the erosion of any till in the upper reaches of the stream's course and in the tributary courses that already had been deposited beneath the ice.

These subglacial streams were for the most part short lived. They maintained their courses for brief periods only. They may have been diverted in part or wholly by the closing of the tunnel through ice movement, by the collapse of the tunnel, by the opening of an easier passage for the escape of the waters, possibly by finding exit to the surface or to an englacial position, and flowing there for some distance before plunging into another crevasse.

Some subglacial streams may have formed no deposits in their channels before diversion of their waters, in some cases apparently a low ridge or only a partially completed ridge was formed, again a ridge fully developed may have been formed before the waters were diverted. Such a ridge by clogging the channel and making great "head" necessary to continue the flow may have led to the diversion of the waters. Again the stream may have maintained its course along the crest of the esker until the tunnel became roofless, and even subsequently if the front of the ice was bathed in waters, the presence of which caused the tributary stream to flow sluggishly, thus preventing erosion of the ridge. With the recession of the front of the ice the ridge became a subaqueous embankment. This may have been covered by delta deposits or by a sand plain built into the glacial lake as in the case of the Auburndale esker, Mass. (28). It is evident that if the ice possessed vigorous movement tunnels could not exist, or if it was very thick tunnels would be closed by its weight.

Eskers were doubtlessly formed near the ice edge, within a few miles at most of the receding ice front. The most favorable position for esker development was under the stagnant front of the glacier, or beneath a detached ice block, conditions that were common along the front of the receding ice sheets. "Doubtless also esker development was favored along the margin of valley glaciers, or glacier lobes, when the ice was thin, the motion slight and the volume of water great. It is from such places that glacier torrents issue from living glaciers, and doubtless eskers are forming in some of them, as, for example, in Alaska, where small eskers are found on ground from which the glaciers have receded within a century" (105).

Such were the conditions under which typical eskers were formed according to the subglacial view. In the argument that follows the attempt is made to explain the peculiarities exhibited by eskers in terms of this hypothesis. Following this argument there is a list of all the objections that have been raised against this manner of esker origin. Most of these objections will be found to have been adequately answered in the argument.

Argument. The length of many esker systems has been urged as an objection to the subglacial hypothesis, it being maintained that correspondingly long tunnels could not exist beneath a mass of moving glacial ice. However, in the case of the longest eskers, eskers 100 miles or more in length, no part of the esker ridge was formed until the ice front had receded to within a few miles of that part, in most cases 2 or 3 miles at most, the part already formed extending beyond the ice edge to its leeward termination. In the case of segmentation, characteristic of practically all eskers of any length, the ice may have stood at or near the end of each segment as it was forming, see Fig. I.

As already indicated patches of gravel and sand are very characteristic of intervals between segments, and were carried out by the subglacial stream in which the segments were forming beyond the edge of the ice and spread out.

Thus an esker 100 miles long doesn't mean that deposition was going on in a subglacial channel beneath the ice for 100 miles back from the ice edge, but instead it means that conditions were favorable for fairly continuous deposition near the edge of the ice while the ice front was receding for a distance of 100 miles.

Eskers are especially apt to be developed in rough, hilly, rugged regions, such as Maine, for here the ice would be crevassed affording initial passage ways for the subglacial waters. Here also the ice flow would be likely to cease sooner while the ice was still thick, the melting of which would afford a large body of water to be contributed to the subglacial streams and its thickness furnish the requisite "head" for such streams. On peneplain tracts crevasses might develop as a result of tension thus giving opportunity of exit for subglacial waters. However this point is not of prime importance, since the pent-up subglacial waters must find exit, crevasses or no crevasses.

That till beneath the ice was eroded by subglacial waters has been repeatedly observed. Hershey has described the erosion of till and water laid drift within a short distance of a glacial lake, where the erosion must have taken place beneath the ice (48). Lack of evidence of erosion of till between esker segments and back of the point of origin of the esker by the subglacial waters may be expected, for subsequent deposition of till would tend to obliterate all such evidence. The above observer describes the erosion of rock ridges, more or less broken by the ice probably, that existed just behind the

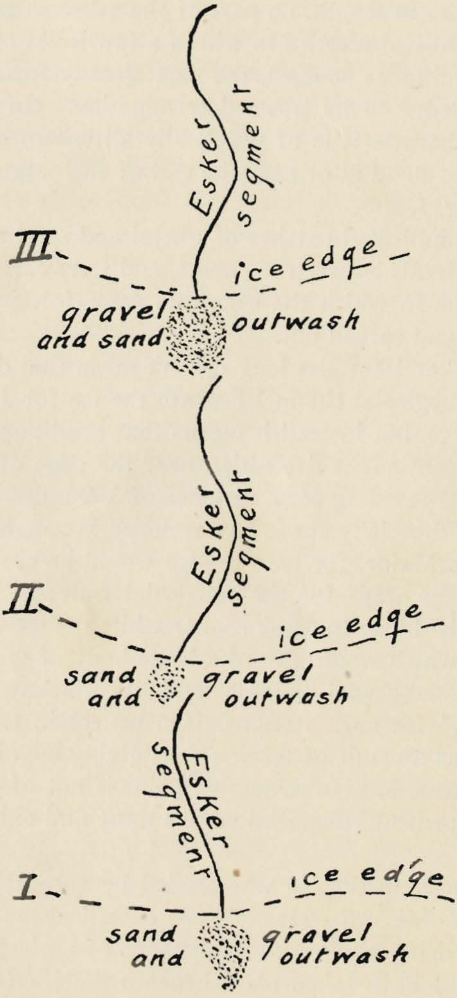

Fig. 1. Relation of the segments of an esker system to the ice front at the time of their formation. I, II, III indicate successive positions of the ice front, the segment just north being formed when the ice front was stationary in each one of these positions.

growing eskers which are composed largely of their fragments. The streams must have been subglacial to get at these ridges, and further, materials from the neighboring hills are absent from the eskers showing that the esker streams did not have access to those hills and did not get possession of drift they may have contributed to the englacial and surface portions of the ice. This hypothesis also accounts for the occurrence of eskers in troughs, so frequently noted by Leverett. These troughs were eroded by the same subglacial streams in which the esker ridges were deposited.

Tributaries to eskers are rare, for if the ice possessed movement it would obliterate such features inasmuch as they would be for the most part transverse to the direction of ice flow.

Double ridges may be accounted for by the formation of a broad arch which, unable to support itself, bent downward dividing the tunnel into two parts in each of which deposition took place, or locally a deposit was formed in a superglacial or englacial channel which, protecting the ice beneath from melting, slid down both sides of the resulting ridge.

Accordant levels of delta and feeding esker are significant. Eskers are never greater in height, and rarely of less altitude than the delta to which they are tributary. This is to be expected under this hypothesis for aggradation would cease in the subglacial tunnel when the upper level of the material clogging its mouth was attained, the upper level of the delta (27, 28).

Gaps in esker courses may be accounted for by subsequent erosion, by glacial erosion of the once continuous ridge, by lack of deposition resulting from lack of confinement of the subglacial stream to a definite channel where the gap occurs, by an ice-block falling into channel with deposition behind and in front of it, but the water possessing too great velocity in passing around it or not definitely confined to channels resulting in no deposition. Stone suggests that the ratio of the volume of water and the size of the tunnel varies in such a way that deposition takes place where the stream is small and the tunnel large and the velocity is therefore low, and that deposition fails where the ratio is reversed and the velocity high (98).

The fact that the stream was under high pressure accounts for esker courses across divides, across valleys, over rough topography, etc., as shown in the courses of existing eskers. The absence or poor development of eskers on divides and on steep downslopes is due to the greater velocity of the subglacial streams in those situations. Yet velocity on downslopes was not excessive, we have here to deal with something analogous to a tube of flow. Hence some deposition may have taken place on downslopes, the water not possessing sufficient velocity to carry the heavier material and excessive load to the front of the ice. Further, streams with sharpest gradient did not develop the highest esker ridges. The low ridges as well as the ridges having low, lateral slopes have the higher gradient as a rule (7). On long gentle slopes and across plains the eskers have their strongest development.

Courses transverse to the direction of ice movement may be accounted for by the formation of eskers after ice movement had ceased, or by assuming a change in the direction of ice flow near the closing stage of the ice epoch, the movement being in the general direction of the esker trend and not being recorded on the till coated surface beneath the ice, or by the stream maintaining its course against the ice flow. This theory accounts for the tendency of the esker ridge to bend in the direction of ice movement as when crossing a valley in which the motion of the ice was obviously down the valley axis (7).

Eskers are also strongly developed beyond localities where the ice had crossed easily eroded rocks, thus getting a large basal load to be contributed to the subglacial waters.

This method of origin accounts for the character of the stratification, its chaotic arrangement of layers, its cross-bedding, the tendency to dip toward the terminus of the eskers, the anticlinal structure due to sliding and slipping of the beds as the restraining ice walls on either hand were removed. "Pell-mell" structure may be explained by the excessive slipping and irregular sliding of the materials coming to rest, by ice push subsequent to the formation of the esker (102), or by collapse of the subglacial tunnel in which the esker ridge was deposited (40). Variations in supply of water from day to day, and from season to season would account for many modifications in bedding (40).

This theory also accounts satisfactorily for the character of the materials, their subangularity near the origin of many eskers when they had been transported but a short distance, their rotundity in the lower part of esker courses, the rounding of large boulders, 2 to 4 feet in diameter, indicating rapid, violent flow under great "head" of a stream acting upon subangular glacial materials. The presence of large boulders in the gravels may be explained as being derived from the basal ice, in which they were occluded, either by lateral melting revealing the boulders, or by being crowded in by ice push or by overriding ice, possibly some fell from the roof as the level of the stream rose in the growing subglacial channel. Large boulders on esker surfaces may be accounted for in these several ways. The presence of till on the surface and distributed through the esker mass may likewise be explained.

The absence of till from the surface of many eskers may be accounted for by subsequent erosion, especially during the time just following ice retreat when the surfaces of the easily eroded materials were unprotected by vegetation or other covering, or by the subglacial tunnel becoming roofless by surface ablation before the esker-forming stream was diverted, or by the esker becoming so high that it rose above or nearly above the upper limit of the zone of till in the basal part of the ice. Subsequent sliding may have concealed till present upon the fresh esker surface. Also the surface of the ice may have been kept free of debris by its washing toward the ice edge or into moulins continuously till the ice surface was lowered to the top of the esker leaving little to be deposited on it from the ice surface. Absence of outwash on surface may be accounted for in similar ways: Removal by subsequent erosion, never deposited if subglacial stream flowed along crest of esker deposit till the channel was open to the sky, or if the stream was diverted after the esker formation, outwash would not have been likely to have been carried out onto the esker surface, at the edge of the ice.

The knolls characteristic of the crests of eskers may be explained by local enlargements in the roof of the tunnel in which deposition took place, or by superglacial material falling through holes in the ice onto the partially uncovered ridge, or by being added by superglacial or englacial streams cascading downward from the surface. Also they may be explained by irregularities in the surface on which the esker rests, or by irregular sliding of the esker material on removal of the ice walls, or by subsequent erosion, or by melting out of occluded ice masses in the esker gravels, or by slight difference in the velocity of the subglacial stream leading to difference in the amount of deposition. Woodworth has advanced another explanation to account for irregularities in the crest (122). He says, "if in a channel at the base of a stagnant and disappearing ice sheet, detritus be laid down with a constructional surface relatively even, but with a width varying within short distances, so that at one point the width is less than the thickness, and at another point greater than the thickness of the deposit, the ultimate crest line of the deposit, when the ice melts away, will vary. The caving of the sides will produce slopes whose intersection will take place above the constructional surface when the deposit is wider than it is high in the ratio of one to one and one-half (about). When this ratio or a greater one obtains, the constructional surface along its median line will not be lowered. When the thickness is equal to or exceeds the width of the deposit, then the slopes will intersect below the constructional surface and bring down the crestline beneath the original surface. Where this readjustment has taken place, it follows that an esker channel was originally narrow where the esker is now low, and wide where the esker is high. This gravitative arrangement of the crestline would not be produced in deposits whose thickness did not equal or exceed the width of the channel. The application of this prin-

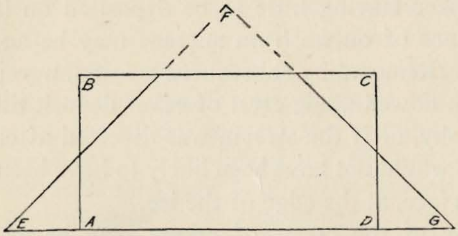

Fig. 2.

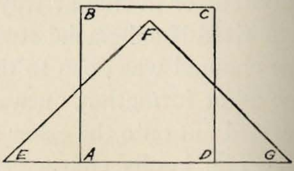

Fig. 3.

Diagrams illustrating one method by means of which an uneven crestline originates. Where the constructional width is greater than the thickness (Figure 2), the readjustment upon the melting of the ice will not result in the lowering of the crest; when the width is less than the thickness (Figure 3) the readjustment will bring down the crestline beneath the original surface (After Woodworth).

cipal to variations of the crest-line is made possible by the uniform limitation of eskers to a cross-section within the range of this action." See figures 2 and 3. Woodworth also has stated that maxima changes in the width of the channel occur at points of maxima change in direction.

"In these figures ABCD represents the assumed cross-section of the gravels and sands deposited in a tunnel of varying width before the ice has melted from the sides. EFG represents the cross-section after the sides of the original deposit have slidden down. In Fig. 2 F is above the constructional height, and the crest line is there unchanged; in Fig. 3, F is below the constructional height and the crest is lowered." After Woodworth.

Inasmuch as an ice arch more than 200 feet wide cannot support itself, wide places, so-called "plains," in eskers may be cited as in objection to this hypothesis. They may be explained variously: (1) The ice arch bent downward in the center and rested upon the surface of the accumulated deposit, however, the evidence of this in existing eskers has rarely been noted; (2) in such places in the subglacial stream courses the tunnel may have become roofless and the ice melted back to afford the required width, there being first the narrow ridge, and as the channel widened this central ridge was more or less spread out and finer material characteristic of these broad areas was brought in; (3) they may have been formed at the edge of the ice beyond the subglacial tunnel; (4) they may represent pools in the ice at the bottom of large moulins (99); (5) or possibly the ice floated on slack water above the deposit.

This theory accounts for the lateral projections from the sides of eskers. "These irregularities probably mark the entrance to the major line of small tributary streams, or as an alternative, the opposite condition, leakage from the major lines" (88). They may also represent alcoves in the ice bordering the stream (99).

Reticulated ridges may also be explained under this hypothesis. They may be considered as distinct ridges formed in branching, interlacing subglacial tunnels. Rapid melting of the ice yielded an excess of water heavily charged with sediment, especially in regions of easily eroded rocks, which choked the subglacial channels faster than the water could erode them, this and the excess of water formed many new channels, particularly on long gentle slopes where this type is apt to occur. "In this way large numbers of narrow channels were formed, connected at frequent intervals with one another by transverse channels". (Stone). They may represent ridges formed where streams debouched into open standing water from the ice front (97). Here they would be comparable to the distributaries of modern deltas, enclosing basins, kettles, etc. Lacustrine deltas formed in glacial lakes have been observed to be more or less reticulated toward their landward extremity. This feature may also have been formed as a lacustrine delta in a local enlargement of a subglacial stream, possibly roofless. Every stream flowing into the lake would build its lateral ridges, kettles would be enclosed by these growing ridges, and ice block inclusion would form others. On the north side of divides uncovered by ice ablation lakes might form and its numerous more or less connected subglacial tributaries northward give rise to reticulated ridges. As a result of clogged subglacial channels, the water might become superglacial and the resulting superglacial deposits become a jumble of ridges, cones and hollows on the melting of the ice beneath, these would constitute a narrow area of reticulation. They also may have been formed in an excessively crevassed ice front not bathed in glacial lake waters. Such crevasses might be produced by tension.

Ice movement probably destroyed eskers. Their almost universal absence from the glaciated interior and from other glaciated regions, with possibly here and there an isolated occurrence, except in especially favored localities such as Maine, may be explained not so much from lack of deposition in subglacial channels, or absence of subglacial drainage, but by the fact that subsequent or persistent ice movement destroyed the majority of those already formed. Ice advance might destroy eskers already uncovered by ice retreat as well as those formed or partially formed still beneath the ice. Vigorous drainage at the ice front may also have been a contributing factor in esker destruction as soon as they were uncovered. Stone explains the absence of glacial gravels near the coast of Maine as a result of "a small acceleration in the ice flow near the coast and limited enlargement of the subglacial tunnels over the area whose basal ice was submerged in the sea"(99). Eskers may have been destroyed as a result of subsequent erosion by the same stream that built them.

Objections. Various objections have been urged against this hypothesis of esker origin. They are indicated below:

(1) The enormous thickness of the ice, measured in terms of hundreds, even thousands, of feet would not permit of tunnels beneath itself (111).

(2) Swift streams do not deposit under ordinary conditions, much less deposit sand, gravel and boulders altogether (111).

(3) Eskers and kames are composed of the same materials. Kames are deposited at the edge of the ice where the issuing waters have lost their "head." If this be true it is reasonable to suppose that eskers should be composed of coarser materials than kames (111).

(4) Eskers could hardly escape destruction by the ice constantly moving over them, especially those 50 to 100 miles long extending far back from the ice border (111).

(5) This theory does not adequately explain the discontinuity of eskers. They cannot be due to irregular glacial erosion of an originally continuous ridge for the ends of segments are depositional rather than erosional. Further, breaks are common where the trend of the ridge was parallel to the direction of ice movement and glacial erosion at a minimum therefore. Also the absence of stratified materials in the intervals, and the abruptness with which the ridges pick up on either side of a break seem to militate against the idea that these discontinuities are due to lack of confinement of the stream to a definite channel where these breaks occur. It is urged that a stream so separated as not to be able to transport a load could hardly build a ridge 100 feet high and of proportionate breadth just beyond the point where the stream had had no definite channel to which it had been confined, and further what was the source of supply of the materials if the stream had not been definitely organized as a transporting stream above this ridge. If the suggestion by Stone (99) be valid the appearance of the esker ridge below the interval must represent a sudden change in the character of the tunnel (from small to large), and that large tunnels carrying water of low velocity can exist beneath ice masses 100 miles back from their terminals (111).

(6) Eskers are not found between the Malaspina glacier and the shore across which the ice has recently receded, although num-

erous subglacial streams issue from the ice along its margin here and present conditions apparently favorable for esker formation (111, 80, 81).

(7) Eskers should show drift covered surfaces frequently, they do not however.

(8) Eskers trend in the direction of ice movement. There is no reason why streams should flow in that direction, especially as topography is often adverse. Crevasses would not be in that direction often (21, 111).

(9) Why did subglacial streams follow rough topography and parallel valleys both broad and deep? Also the presence of eskers in a lateral position on the sides of valleys is inconsistent, the subglacial waters would tend to work toward the axis of the valley.

(10) Deposits should be swept away as fast as formed when parallel to ice movement.

(11) It is difficult to account for broad areas, "plains", because requisite arch would be too broad to support itself. Also heat of water and erosion would be inadequate to form the broad channels except late in ice epoch when there was no movement, and then the whole channel would be worn to uniform width.

(12) It is difficult to account for knobs along the crest-line. The crest should be even, uniform, sloping upward from the terminal plain.

(13) Branches can be accounted for only with difficulty. They would be erased by glacial movement. They often make oblique angles with the major ridge, they should make large angles.

(14) Double and reticulated ridges are likewise difficult to account for under this hypothesis.

(15) As soon as the channel became partially filled with a deposit there would be a strong tendency for the waters to be drawn off through a side crevasse.

(16) Eskers should be composed of coarse material and be stronger and more perfectly aggraded on up slopes.

(17) Mountain topography is apparently not favorable for the development of eskers, yet it is rough leading to extensive crevassing with opportunities for subglacial flow. On the other hand dissected peneplain tracts are favorable (111).

(18) More frequent trenching of the ground moraine, and the more frequent occurrence of eskers in troughs in the ground moraine would be expected under this hypothesis. Stone found little evidence of subglacial stream work except near the coast in his study of Maine eskers (101).

(19) In order to preserve the esker the subglacial stream had to be diverted when the ridge was completed. How was it diverted, and why was no esker formed in the new channel? Also erosion channels of such streams after their diversion are very rare (21).

(20) The trend of the subglacial stream demands ice control and a long life, its deposits demand a short and intensely active life, followed by a sudden disappearance from the scene of its labors (21). The two ideas are inconsistent.

(21) Deltas and outwash plains should show more tributary eskers than they do. They have not been ice removed, for ice contact slopes of the sand plains are intact, there is no evidence of disturbance due to ice push.

(22) Eskers should be well-stratified if subglacial, yet there is found extremely chaotic stratification with "pell-mell" structure.

(23) Absence of an adequate supply of material since the ice sheet protected till already deposited from erosion except where the subglacial tunnels were located constitutes an objection. All of the material must come from subglacial stream erosion of till, from debris in the basal portion of the ice and a little englacial and superglacial material, this must form eskers miles in length and extensive outwash plains. This source seems inadequate entirely.

(24) Crevasses are too few after cessation or near the time of cessation of ice movement to afford new subglacial tunnels, and those already existing are too few to accommodate sudden floods formed by melting during the warm summer season, this excess of water must therefore pass off in superglacial streams, hence few eskers would be formed subglacially.

(25) Eskers should tend to show a more uniform cross-section than they do, for with a given thickness and weight of ice any enlargement of tunnel would be precluded by creep of ice inward.

(26) Under this theory one would expect to find more large boulders on the surfaces of eskers.

(27) Eskers should be located in large preglacial valleys, instead they cross valleys repeatedly.

(28) Eskers pass along plains where there is little chance for crevassing, zigzag across valleys without regard to the direction that crevasses (29) would naturally follow. There is little or no evidence of erosion of till back of the point of origin of the esker.

Conclusion. Most of these objections have already been answered in the argument given above. Objections 5, 11, 14 are the most vital and important, and apparently can be answered only in part as yet, or in a manner not thoroughly satisfactory.

Superglacial hypothesis. The superglacial hypothesis of the origin of eskers has been most ably advanced by Crosby (21). Stone was an early exponent but later was converted to the subglacial idea. Holst has already been mentioned in connection with the early advocacy of this theory of esker origin. The hypothesis has found few supporters in this country.

Statement. Crosby states "this explanation of eskers assumes a stagnant marginal zone of the ice sheet at least 100 miles in maximum width, practically free from crevasses, sufficiently wasted by ablation to be more or less abundantly covered by englacial drift which has become superglacial, with a general southward slope, and toward the southern border at least, thin enough to reflect in its surface contours, in some degree, the underlying topography" (21). Crevasses, if present, would be sealed in the final stages of movement, or filled with debris; it is significant in this connection to note the rarity or lack of crevasses in the Greenland glacier except near the margin. Water divides on the ice must be sufficiently far apart so that the water supply may be great enough to form large rivers, hence over broad valleys and lowlands of the pre-existing topography are places favorable to the formation of eskers (66).

At the margin of the ice the superglacial stream's elevation is controlled by the level of a glacial lake, bank of till, or detrital cone (21). The stream grades itself with reference to this control. It may have tributaries—in fact a river system upon the surface of the ice, comparable to a river system on a land surface. At first the streams of the system will possess such high velocities that no material will accumulate in their channels, but as grade approaches corrasion will gradually cease, and aggradation will take its place, building an esker ridge in the stream channel. The stream will derive its supply of debris from subglacial or englacial drift that has become superglacial by shearing, by the overriding of the sedentary ice cap that had accumulated previous to the invasion by the ice from the center of ice dispersion, the latter carrying upward its basal load, by the upturning of layers, phenomena observed especially along the front of the Greenland glacier, by surface ablation revealing the englacial and basal material in the ice, and by erosion of nunataks projecting through the ice and of ledges projecting into the ice. Upham has thought that much drift has become englacial even in a short distance from the point of origin on a relatively flat surface. Stone formerly entertained the idea that much of the drift of the Maine eskers was englacial in source.

With the cessation of corrasion the esker channels may be 50, 100 or more feet above the ground. The question now arises as to how to get the esker down on the ground without the destruction of its ridge-like character. It is necessary that the banks of the channel—the retaining ice walls—be preserved if the esker form is to be maintained. Hence the bottom of the channel must be lowered as rapidly as surface ablation lowers the neighboring ice surface. Corrasion has ceased so recourse must be had to the melting of the ice at the bottom of the channel by the sluggish waters of the stream percolating downward through the porous gravels. Russell has described lakelets on the moraine-covered marginal zone of the Malaspina glacier, 50 to 100 feet deep, rarely more than 100 feet in diameter, with bottoms covered with drift constantly augmented by the addition of fresh material from top and sides. These lakelets are deepened as fast or faster than the surface of the ice is melted, by convection, the warmer, denser (near 39° F.) waters of the surface sinking and percolating through the porous materials covering the bottom displacing the colder lighter water, near the freezing point, at the bottom. Thus the lake bottom is lowered, and the walls of ice undercut even below the water surface. In a similar manner the bottom of the esker channel is lowered by the melting of the ice as the warmer surface waters percolate through the esker deposit, and the ridge finally comes to rest upon the ground. This is in brief the mechanics of the process of esker formation according to the superglacial view.

Argument. The esker having come to rest upon the ground will show the normal disregard for topography, its course being that of the superglacial stream.

Tributaries will be rare for aggradation will be confined to the main channel for the most part by reason of the high gradient of tributary channels.

The general absence of eskers in mountain regions may be explained because of excessive crevassing of ice not permitting the extensive development of superglacial streams (66). Thus Holst explains their absence in south Greenland (66). In regions of plains they are also apt to be absent because of the absence of large drainage basins (66).

Knolls are explained by the dumping of material into the main superglacial valleys from hanging tributary valleys, by unevenness in the surface upon which the esker ridge is deposited, and by irregularities induced by the gradual lowering of the esker deposit to the base of the ice due to the unequal melting of the ice beneath the esker.

The widening of eskers toward their terminations is due to the normal widening of the ice valley as it approaches a body of standing water in which its walls are bathed. Wide places in the esker course, the "plains", are due to the development of wide places in the superglacial valley.

In case the esker channel is drained before subsidence is completed, the debris so left will protect the ice beneath from melting and, becoming elevated on an ice ridge, will slide down both sides thus forming a double esker.

The trend of eskers is in general conformity with the direction of ice movements; the slope of the upper surface of the ice is in that direction so the esker streams naturally flowed in that direction.

Reticulated eskers represent delta-like branching in broad places in the superglacial channels, or a broad deposit split up into a network of ridges while being let down upon the ground.

The esker deposits may protect vast bodies of ice beneath from melting after being aggregated into ridges by the superglacial streams. From the ice ridges so formed material may slide down irregularly to form kames.

This manner of formation would explain the general absence ot till from esker surfaces. Large boulders on esker surfaces and within the gravels may have been floated in on icebergs, may have fallen from the steep ice walls at the side of the deposit, or may have been incorporated in the base of the gravels from the basal ice as the deposit was slowly being let down to the ground.

The chaotic stratification, evidences of sliding, and "pell mell" structure are explained by the irregularities induced in getting the ridges down upon the ground.

Segmentation is due to the occurrence of rapids in the superglacial stream with consequent lack of deposition, or to distribution of that portion of the ridge in being let down upon the ground.

This method of origin also accounts for eskers resting directly upon the till, and the absence of till erosion beneath the esker and back of the point of origin of the esker.

Objections. (1) Insuperable difficulties stand in the way of getting the ridge down on the ground according to the method postulated. Porosity of ice would drain off the water from the sluggish stream's course before the esker deposit could be let down on the ground. Russell's observations on the lakelets of the Malaspina glacier show that they are frequently drained even on stagnant ice, their deposits becoming cones due to the protection afforded to the ice beneath from melting. There is no instance recorded of the material on the bottom of these lakes getting down to the ground by this process.

(2) Eskers occur that are 100 miles long or more, it is doubtful if that expanse of glacial ice can exist without crevasses which would limit length of esker ridges. The extensive crevassing of the margin of the Greenland glacier in the zone of esker formation reinforces this point. Further streams of the length required here would be apt to have their upper courses in the region of névé and not on debris covered ice. These long eskers probably could not be formed close to the ice margin during its retreat for the rapidly melting ice would not permit of the stream coming to grade, a condition essential for aggradation.

(3) Glacial debris is almost entirely confined to the base of the ice. Little of it is englacial or superglacial. By far the greater amount of material is located within 50 feet of the base of the ice (9). This would leave little accessible to superglacial streams.

(4) Existing glaciers show that the drainage of ice sheets is almost entirely subglacial, streams flow but a short distance on the surface before they plunge into a crevasse or moulin. The presence of pot holes in glaciated regions shows that moulins were as characteristic of former ice sheets as present ones.

(5) The rapidity of currents of superglacial streams and the smoothness of their channels are directly opposed to the lodgment of materials in them.

(6) The materials of eskers are essentially local in character. Davis has shown that the materials of the Newtonville and Auburndale eskers have only come from two to four miles to the northward (27). To oppose this fact it has been suggested that the upturning of the layers of ice as noted in Greenland would bring up basal materials within a short distance of their source, however, this upturning of ice layers is merely a terminal phenomena and cannot find application here. Further this material would have to rise to a height of 50 to 100 feet in the case of high eskers, too great a rise especially on level ground. If the ice moved over a sedentary ice cap some of the surface debris at the time of esker formation must have been far traveled material, yet even the large boulders of eskers are local in origin for the most part.

(7) If eskers are let down from a superglacial position across divides they should show evidences of stretching—relation of chord to the arc—however they do not exhibit evidences of stretching in these situations but exhibit uniform preservation throughout the length of the segment (122).

(8) Ice is so easily eroded that deposits would not be restrained to definite narrow channels, especially after the stream had become graded, hence narrow ridges could not be formed with characteristic uniform cross-sections.

(9) Ponds and swamps bordering esker courses point to ice block inclusion and show that the ice lingered there longest. If the esker ridges were superglacial they would tend to slide off the surfaces of these blocks to either side.

(10) Numerous large boulders on esker surfaces and in the upper part of esker ridges are difficult to explain under this hypothesis (125).

(11) Eskers are often observed to lie in shallow troughs excavated in the till apparently by the same streams in which the eskers were formed (61, 62).

(12) Chadwick has noted several eskers in the vicinity of Ogdensburg, N. Y. If these eskers are superglacial in origin it is difficult to see how they were preserved with the vigorous waves and currents of the glacial lake Iroquois laving the ice edge, and the waters advancing into the superglacial channels with the recession of the ice front. In his study of the glacial features in the Thousand Islands district Professor Fairchild has reinforced this argument (34A; 34B. p. 149).

(13) Eskers exhibit a tendency to pass through gaps in crossing divides, a feature not easily accounted for under this hypothesis, since they should show little relation to these smaller features of the underlying topography.

(14) If eskers are superglacial in origin they are not likely to exhibit accordant relations with delta and outwash surfaces, as they usually do.

(15) No large lakes are known to form on ice sheets, comparable to such lakes as those in which esker "plains" are supposed to have been formed.

(16) This theory of esker origin is inconsistent with the "open work" structure observed so commonly in esker gravels (27), for where the stream became graded and the current sluggish the spaces within the gravels would have been filled by the slowly percolating waters.

(17) If eskers had been let down from a superglacial position to their present attitude, the bedding would have been much more greatly disturbed than the present sections indicate (27).

(18) Also if eskers had been let down from a superglacial position the material should slip outward more or less, the downthrow should always be toward the margins. Eskers exhibit displacements with downthrow toward the crest line, as well as dislocations with downthrow in the opposite direction.

(19) Amount of material on the Malaspina glacier cannot be taken as an index of the surface conditions of continental glaciers, for much of the superglacial material of the Malaspina is due to avalanching.

(20) Not enough debris would be brought in after the superglacial stream had reached the graded condition necessary to deposition to build eskers possessing such large dimensions as are frequently observed.

(21) Warm waters would have to penetrate deposits 50 or more feet thick and warm the ice beneath sufficiently to melt it, and in the case of broad eskers and "plains" penetrate a deposit of 500 feet or more wide and 25 to 100 feet or more thick, apparently an impossibility.

(22) Superglacial streams must always have had an obstruction at their mouth to permit aggradation, otherwise they would not have reached grade till the stream bottom rested upon the ground.

23) Shearing is little effective in getting material up into the ice, it is opposed by basal drag of the ice and the resulting more rapid movement of the upper portions of the ice.

Conclusion. Of the numerous objections noted several appear to be absolutely fatal to the theory and preclude the possibility of the majority of eskers having been formed in this manner. The local character of the esker materials, the confinement of debris to the basal portion of ice masses, the swiftness of superglacial streams, their smooth channels and short lengths, and the difficulty of getting ridges so formed down upon the ground without their destruction, are perhaps the most serious difficulties in the way of acceptance of the theory. A well known glacialist once remarked in the presence of the writer, "no one who has ever visited an ice sheet would entertain for a minute the idea of superglacial origin of eskers."

Hypothesis of origin at the edge of the ice. Baron De Geer of Sweden early stated his conviction that eskers were laid down where a glacial river emerged from the ice sheet and deposited its material as a fluvio-glacial fan. As the ice front receded the deposits of successive years formed a continuous gravel ridge, which followed the retreating mouth of the river.

Hershey in his study of Illinois eskers seems to have come to a similar conclusion regarding their origin (48). He thinks that the drainage was largely subglacial, and that the tunnels, being small, could not carry the amount of water provided by the rapid melting of the ice, the excess being ponded in the crevasses of the ice adjacent to the subglacial streams for considerable distances back from the border of the ice. This ponded water created great "head" in the subglacial streams, which therefore eroded rock ridges beneath the ice, and other deposits encountered, sweeping the materials forward and suddenly dropping them at or near the mouth of the tunnel, where the pressure was removed (48).

Gregory says that an esker is a "fluvioglacial ridge formed of sand and gravel which has been laid down along the course of a glacial river. The deposition has taken place mainly where the river emerged from the glacier, and the course of the esker is usually at a high angle to the edge of the glacier." "They have been built up into long ridges by the overlapping of successive delta fans" (44).

Still more recently Trowbridge has advocated essentially the same idea that of esker formation at the edge of the ice or within a re-entrant back from the edge (111). In the following statement the important details in this method of esker formation have been taken from a recent paper by the latter writer (111).

Statement. Trowbridge believes "that most eskers are simply kames drawn out into long lines by the slow retreat of the edge of the ice while kame deposition is in progress. If a kame is being formed at the edge of an ice sheet, and the edge retreats slowly, deposition will continue so long as the re-entrant remains and the stream continues to issue there, and the kame will be drawn out into a long ridge or esker." Discontinuities would result if "during the recession of the edge of the ice the re-entrant ceased to exist, or the stream ceased to issue there; when a re-entrant and the mouth of a subglacial stream again coincided deposition would begin again. This would make a break in the esker whose length would be determined by the rate of recession of the ice and the length of time during which deposition was not in progress. Such changes as these would take place suddenly," and would account for the abrupt termination of esker ridges. A slowly retreating ice edge would form a high, thick esker, rapid retreat would form a "thinner, lower one; rapidly changing rates of recession would cause an esker of varying thickness and of considerable surface relief." The esker knobs would result from a temporary halt in the ice recession. "Crooked re-entrants or shifting stream mouths would result in crooked ridges. Where there was one re-entrant, or one stream, there would be one ridge formed; where the ice edge was badly broken up and streams ran through all the cracks, the result would be a kame area drawn out into an intricate series of ridges, rather than a single ridge. Converging cracks would result in converging ridges, diverging cracks in diverging ridges, and crossing and recrossing cracks in intricate reticulated ridges. Where the ice edge retreated uphill, the ridges would be extended uphill. Where the ice receded across valleys and divides, the esker would be made to follow a course across a surface of high relief. The rougher the region, the more likely the presence of cracks in the edge of the ice, which explains the greater abundance of eskers in rough than in smooth regions" (111).

Hershey regards the "plains," areas of "special development" in esker courses, as formed at the terminus of the ice when it has remained stationary for some time (48). It is also suggested that they may be due to the overlapping of several individual deposits. He further states that esker deposits are not generally overriden but exhibit some evidence of ice push.

Objections. (1) Many eskers and most of the New York eskers do not show an uneven crestline but rather a uniform crest. To produce this condition by this method of origin it would seem essential that the recession of the ice front be very regular, and that the volume and velocity and load of the esker making streams remain constant, a series of conditions that would not be likely to obtain along the borders of receding ice sheets.

(2) An interval in the course of an esker should be represented by a ridge, or at least by gravels, elsewhere, which is not the case usually.

(3) Many eskers have till on their surfaces, a fact difficult to explain if the esker was built at the edge and not beneath the ice. The presence of large boulders on the surface encounters a similar difficulty in explanation under this idea.

(4) If eskers were formed in re-entrants in the ice front, such re-entrants would have to maintain their position while the ice front was receding for 100 miles or more in the case of the longer eskers, such as those of Maine, a condition not likely to occur.

(5) If eskers had been deposited in re-entrants into the ice their sides would be expected to show evidences of erosion in many cases by the stream which contributed to their formation. Eskers do not generally exhibit such erosional features, even on steep down slopes.

(6) Eskers occur where it would be impossible for a re-entrant to exist, situations in which the ice is wedged against a high cliff, the pressure on which would close the re-entrant (122).

Fig. 4. Outline map, showing the eskers of Finland, trending south-easterly toward the terminal moraines that were built at the margin of the ice. The segmented character of eskers and the intimate relations they display to terminal moraines are excellently displayed (After J. J. Sederholm).

(7) This theory does not explain adequately or satisfactorily the derivation of reticulated ridges, also the derivation of eskers whose direction was transverse to the direction of ice movement, or the meanders often quite symmetrical that are frequently exhibited by eskers.

(8) Esker ridges formed in this way should be banded in structure. The coarse wash deposited by spring floods should be followed by layers of finer material as the volume of the river diminished in the summer, thus there should result a passage from cannon shot gravel through fine gravel to sand. Eskers do not show this feature (44).

(9) The constant association of eskers with terminal and recessional moraines indicates their formation at a time when the ice front was nearly or quite stationary building the moraine, not at a time when it was in rapid retreat. See figure 4.

Conclusion. Of these several objections 1, 3, 4, 7, 8 and 9 are the most weighty, and especially the last, 9. This one alone would seem to preclude the possibility of the theory as applied to the formation of the vast majority of eskers.

Englacial hypothesis. This hypothesis has never been seriously entertained or advocated. It is subject to essentially the same objections as the superglacial hypothesis, and while it is possible that nearly stagnant ice may be traversed by tunnels above its base, as indicated by observation (80), yet it is improbable that any deposits of significance have ever accumulated in such tunnels.

Ice canyon hypothesis. The ice canyon theory has been elaborated particularly by Upham. N. H. Winchell seems to have entertained similar views earlier than Upham (120).

Statement. It is maintained that superglacial melting was rapid during summer but subglacial melting was slow both winter and summer. During the warm season the subglacial courses were inadequate for the transportation of all the water derived by ablation, and further tended to be "obstructed and closed by the transportation and deposition of modified drift." The melting ice border then became deeply incised by superglacial streams for a distance of 50 to 200 miles back from the ice edge. These numerous streams had steep gradients and, corrading rapidly, soon came to flow in deep canyons cut back from the ice front. These may have been ice floored or again cut entirely through the ice sheet with bottoms on the terrane beneath. In these ice-walled channels deposition of the esker gravels took place, the materials being derived from the surface of the ice, from the basal and englacial debris, and from the stream's floor.

Objections. The greatest objection to the theory is the disregard that the normal esker manifests for the topography. The appearance of an esker first on one side of a valley then on the other, the courses of eskers up long gentle slopes, could only be explained under this idea by the canyons being ice floored and sloping upward from the edge of the ice. In this case the theory meets the same objections as the superglacial hypothesis.

Conclusion. An occasional esker may have been deposited in an ice canyon, but the majority of eskers have arisen in other ways. Tarr has stated that "it is by no means impossible that in favorable situations, rapidly moving, heavily laden marginal streams may have flowed in valleys or tunnels cut in the ice, making deposits which, on the melting of the ice, took the esker form" (107).

Other views. Eskers may have arisen in other ways. Wright has described the formation of an esker ridge of the Muir glacier as follows: "The formation of kames, and of the knobs and kettle holes characteristic both of kames and terminal moraines, is illustrated in various places about the mouth of the Muir glacier, but especially near the southwest corner just above the shoulder of the mountain where the last lateral branch comes in from the west. This branch is retreating, and has already begun to separate from the main glacier at its lower side, where the subglacial stream passing the buried forest emerges. Here a vast amount of water-worn debris covers the ice extending up the glacier in the line of motion for a long distance. It is evident from the situation, that when the ice stream was a little fuller than now, and the subglacial stream emerged considerably farther down, a great mass of debris was spread out on the ice at an elevation considerably above the bottom. Now that the front is retreating, this subglacial stream occupies a long tunnel, 25 or 30 feet high, in a stratum of ice that is overlaid to a depth in some places, of 15 or 20 feet of water-worn glacial debris. In numerous places the roof of this tunnel has broken in and the tunnel itself is now deserted for some distance by the stream, so that the debris is caving down into the bed of the old tunnel as the edges of the ice melt away, thus forming a tortuous ridge, with projecting knolls where the funnels into the tunnel are oldest and largest. At the same time, the ice on the sides at some distance from the tunnel, where the superficial debris was thinner, has melted down much below the level of that which was protected by the thicker deposits; and so the debris is sliding down the sides as well as into the tunnel through the center. Thus three ridges approximately parallel are simultaneously forming—one in the middle of the tunnel and one on each side. When the ice has fully melted away, this debris will present all the complications of interlacing ridges with numerous kettle holes and knobs characterizing the kames; and these will be approximately parallel with the line of glacial motion. The same condition of things exists about the head of the subglacial stream on the east side, also near the junction of the first branch glacier on the east with the main stream, as also about the mouth of the independent glacier shown on the map lower down on the west side of the inlet" (126, pp. 65-66).

Eskers may have been formed between hill slopes and the steep edge of the ice. Upon the melting of the ice such deposits would tend to slide down and in some places be preserved with decidedly esker form.

An esker near Polmont in the south of Scotland, described as glacio-fluvial by Gregory, is unstratified, made up of angular materials, contains no bands of sand and appears to have been formed as a bank of wash quietly deposited along the margin of a melting glacier at one stage of its retreat.

Ridges may also be formed subaerially as natural levees, the current being bordered by slacker water. Likewise when streams enter standing water they tend to build up ridges at either side. Subaqueous ridges may be formed at the mouth of streams, and also in the lee of islands or other obstructions in the midst of sediment bearing streams (99).

Testimony of Existing Glaciers.

Existing glaciers do not throw a great deal of light on the problem of esker origin. The remoteness of continental ice masses and the paucity of observations on them have been unfavorable factors in this connection. The continent of Antarctica is covered by a continental glacier that approaches most nearly the great continental ice sheets of past time. Unfortunately it is not well known, and furthermore it does not furnish the requisite conditions necessary for the study of esker formation, its edge being nearly everywhere buried beneath sea waters.

Chamberlin has made a study of the Greenland glacier (9). He states that the drainage was largely confined to streams running along the sides of the glacial lobes, sometimes tunneling under the ice, or buried beneath snow drifts. On the disappearance of the snow and ice, deposits in such streams will resemble the terraces and eskers of our drift, but nothing typical in the way of esker formation was noted. However, it was observed, and this has repeatedly been confirmed, that the debris of the ice was confined to its lowest portion, with few exceptions at heights not greater than the heights of kames and eskers, a fact directly antagonistic to the superglacial method of esker origin, as already pointed out.

Holst found on the ice in south Greenland a stream 5 feet wide and 5 feet deep flowing on the surface for some distance, separating into two branches in one place enclosing an island of ice, before plunging into a moulin (66).

A. Kornerup in the published report of his travels, 1879, published 1881, states that he found in the Ausalik valley of Holsteinborg, "a typical gravel-ose about 4 miles long, parallel to the present direction of the motion of the inland ice, and having a roof-shaped top, and even sides, inclined 20° to 25° to the plane of the valley over which it extended in a meandering course." Further he states that the valley is "an unusually large plain, bounded by even, gently-sloping foot hills."

Alpine glaciers afford evidence of little significance in this connection. Their high gradients and paucity of materials are not favorable for the development of eskers. Materials are insufficient in amount to clog the subglacial channels at their lower ends thus leading to aggradation. Furthermore the high gradient of the valleys cause such rapid flow that only small deposition occurs, the outwash being carried on down the valley.

A deposit of the nature of an esker is described as occurring on a small glacier on Mt. St. Helena, Washington. "It was perfectly straight and regular in form, about 300 feet long, 20 feet wide at the base, 5 feet high and with a slightly convex crown of about 4 feet." Its materials were like those of the moraines associated with the glacier, "but worn, rounded and all of much smaller and more uniform size." At the foot of the side slopes the demarcation was clear and well defined, at its upper end it terminated against a lateral moraine into which it appeared to grade. Its lower end was abrupt, with no gradation and no dump. Russell suggests that it appears to have been formed in a tunnel by an englacial stream and afterwards brought to the surface by the melting of the ice (77). Tarr and Martin as a result of their Alaskan studies in the Yakutat Bay region state that eskers are subglacial deposits mainly, if not entirely, associated with stagnant ice conditions. However, in the bases of stagnant moraine-covered glaciers of this region, no eskers were observed in the process of formation on account of the dearth of streams. Some eskers buried by outwash were observed (106). Tarr has noted small eskers in Alaska on ground from which the glaciers have receded within a century (105).

Russell's study of the Malaspina glacier constitutes a classic in geology (80, 81, 82, 83). He states that the drainage of the Malaspina glacier is almost entirely interglacial or subglacial. There is no surface drainage except very locally, here the streams are short and soon plunge into a crevasse or moulin. On the Alpine glaciers tributary to the Malaspina there are a few short streams confined to their lower portions, but they soon disappear from view.

He further states that the lakes on the moraine-covered portion of the glacier "last from year to year," but are finally drained, usually through a crevasse or opening of some sort at the bottom, and the basins are left with a deep filling of boulders and stones. They protect the ice beneath from melting and eventually come to stand out on pedestals as a result of the ablation of the surrounding surface (83).

Russell also observes that the three principal streams along the eastern margin of the Malaspina glacier in 1891 issued from beneath the ice as subglacial streams. Each flows for some distance between walls of ice and is actively aggrading its channel. One, the Osar, has a ridge of gravel running parallel with it which was deposited on the ice during a former stage when the water flowed about 100 feet higher. No other instance of esker formation was directly observed (80).

"The formation of osars seems fully explained by the subglacial drainage of the Malaspina ice sheet." Streams flowing into the tunnels on the north side of the glacier are carrying already large quantities of sand, gravel and mud, and on emerging from the eastern and southern sides bring out large quantities of water-worn material. A part of the overload is dropped here. These cones obstruct the mouth of the tunnels and thus slackening the flow of water within the tunnel may lead to deposition. The water is consequently forced to a higher level in the tunnel, eroding the ice roof as it slowly rises and leading to further deposition on the gravel deposit beneath. When the ice melts, the supporting walls being removed, the gravel will slide down to a position of stability giving the arched, anticlinal structure of eskers. The process would go on in a stagnant ice mass till the waters found new channels (80).

Russell notes that in the case of the Muir glacier where debris is abundant and of large size, the channel frequently becomes clogged, and the subglacial waters are forced to find a new outlet. Some subglacial streams have formed re-entrants, others not, the condition of formation seeming to depend on volume and swiftness of stream and on amount and size of debris on the ice (79).

General Conclusion Regarding Origin.

The testimony of existing glaciers, while probably insufficient to warrant a firm and definite conclusion, yet unquestionably points to the subglacial origin for the typical esker and for the vast majority of eskers. A critical study of eskers themselves results in this same conclusion. Objections may be urged against this theory, but they are fewer in number, less vital, and more satisfactorily answered than is the case with any other theory so far formulated. It is significant that those geologists most familiar with existing ice fields, with Pleistocene phenomena and with the particular type of glacial deposits under discussion here, are in accord in the acceptance of the subglacial hypothesis for the origin of the vast majority of eskers. Such men as Chamberlin, Salisbury, Russell, Leverett, Davis, Woodworth, Tarr, Fairchild, Stone and others, all agree that the subglacial hypothesis best explains the facts.

Economic Importance of Eskers.

The sand and gravel these ridges afford are of economic importance and there is scarcely an esker that does not show one or more excavations for these materials. In some cases a large part of the esker has been removed, its materials being utilized for building purposes, road construction, and ballast, manufacture of concrete blocks, filling, etc. From a scientific standpoint this is unfortunate, and yet as a resource their materials should be utilized.

The ridges themselves may be used as roads to cross swampy ground, to afford suitable grade, and to save to the agriculturist arable land by utilizing that least arable. Such roads are level and dry.

Their surfaces are unsuited to agriculture, and are in most cases untilled, usually being forested.

Description of Western New York Eskers.

General statement. The description of the individual eskers that are readily accessible around Rochester follows. In every case the descriptions are in detail and it is hoped that they will serve as a guide for students and others interested in glacial geology who may visit the eskers in the future. The descriptions are followed in each case by a brief summary of the characteristics which tend to throw light upon the origin of the esker in question.

A contour map of each esker studied was made and this accompanies the descriptions. The contour interval was purposely made small, 5 feet, in order to bring out the details of the surface configuration. The linear scale and direction (magnetic) are indicated on each map. A larger scale was used for the width, approximately twice that of the linear scale. This is the first time that eskers have been mapped in so great detail, but it is felt that the results obtained amply repay the greater effort required.

Rush esker. Figure 5, plate XI. On going by train from Rochester to Rochester Junction on the Lehigh Valley railroad, one passes close beside this esker throughout its entire length, it being distinctly visible from the car windows. The esker makes its appearance one and one-half miles south of Henrietta on the west side of the railroad and continues in a more or less interrupted course until its termination is reached where the railroad turns southeast for the straight stretch into Rochester Junction.

The direction of the esker is nearly north and south in conformity with the direction of ice movement in this locality.

It varies in height from 5 to 25 feet, the greater part of its course being below 20 feet in elevation so that its representation on the Rochester quadrangle fails to portray its true linear proportions.

It rises from swampy ground at its origin and pursues a course southward along the swampy forested bottom of a narrow valley that is flanked on either side by drumlins. The northern portion of the esker from its point of origin to the small station called Cedar Swamp is composed of isolated mounds not more than 2 or 3 rods long or more than 10 feet high. From Cedar Swamp southward the ridge is fairly continuous for a distance of about 1¼ miles. There are interruptions in its course, creeks wind across, in places it fades out and disappears, however, the places of discontinuity are few and widely separated. Throughout this distance the crest is comparatively even, interrupted in but few places by low knolls. Its course is of the winding, serpentine character peculiar to eskers.

This part of the esker terminates in a kame area. From these kames a well defined ridge trends southward a short distance and then divides to form a complex of interlacing ridges, with steep slopes and stony surfaces, enclosing numerous kettles. The accompanying figure illustrates these conditions and indicates further that streams have succeeded in crossing this complex in two places. The terminal portion of the esker south of the reticulated complex consists of three distinct ridges, the one toward the west having a large kame extending from its western flank. These three ridges end in a kame topography which ceases abruptly southward at the margin of the deep east-west valley through which the Buffalo branch of the Lehigh Valley railroad passes.

Three-fourths of a mile south of Cedar Swamp there occurs a low but well-defined esker which may be regarded as a tributary. It is on the east side of the railroad and extends at almost right angles to the course of the main esker. It is several rods long but nowhere more than 10 feet in vertical section with uniform gentle slopes. There is no evidence of its continuation west of the railroad track where it might be expected to join the main esker ridge.

An excavation near the southern terminus of the esker reveals something regarding its internal character. Here boulders rounded and of all sizes occur in profusion. The gravel is for the most part of poor quality by reason of the large quantity of coarse materials, that of better grade being located in the center of the pit extending from the base of the excavation to the crest of the esker. On each side of this coarse materials predominate. At least 50 per cent. of the material is Medina, while 15 to 20 per cent. is crystalline. Stratification is not apparent. The base of the pit does not go below the adjoining surface so that it is impossible to tell how deeply the esker characters penetrate.

Origin. There are few features of this esker that shed light upon the manner of origin, the steep slopes and gravelly surfaces are characteristic of practically all eskers, the composition and character of course are likewise typical of the majority of eskers. The long interruptions at the north end of the esker may be due to subsequent erosion or to lack of deposition in the glacial stream. The short tributary is likewise noncommittal as to origin, the absence of till from the esker surface may be due to subsequent erosion or lack of deposition at the time of esker formation, or possibly to other causes. Its trend along the axis of a narrow valley in the direction of ice movement would seem to indicate its formation in a subglacial stream following the lowest part of the valley during or just after the accumulation of the heavy drumlin masses on either side.

Cartersville esker. Figure 6. The best known and one of the most magnificent eskers in Western New York lies nearly opposite Cartersville and north of Bushnells Basin. It has been briefly mentioned by Dr. Dryer (30), and more recently more fully described

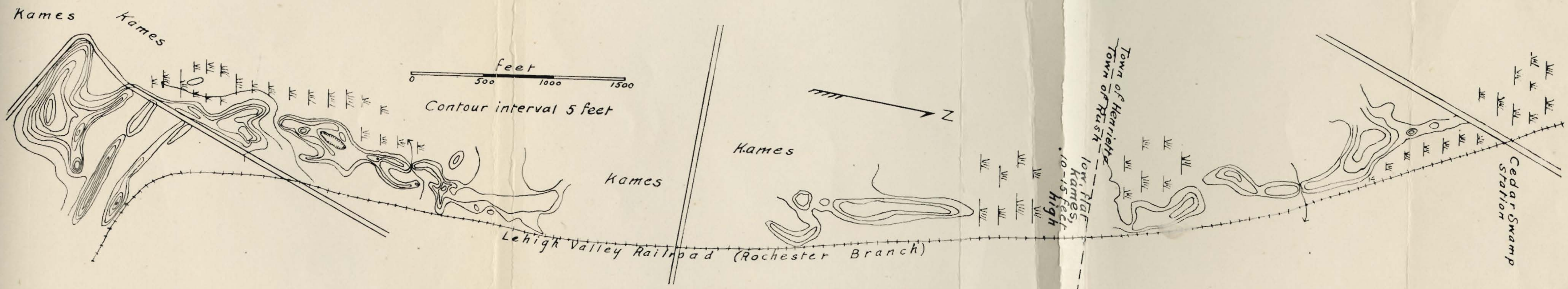

Fig. 5. Rush esker. This esker extends in an interrupted course from Henrietta to within one mile of Rochester Junction, closely paralleling the Lehigh Valley railway on the west

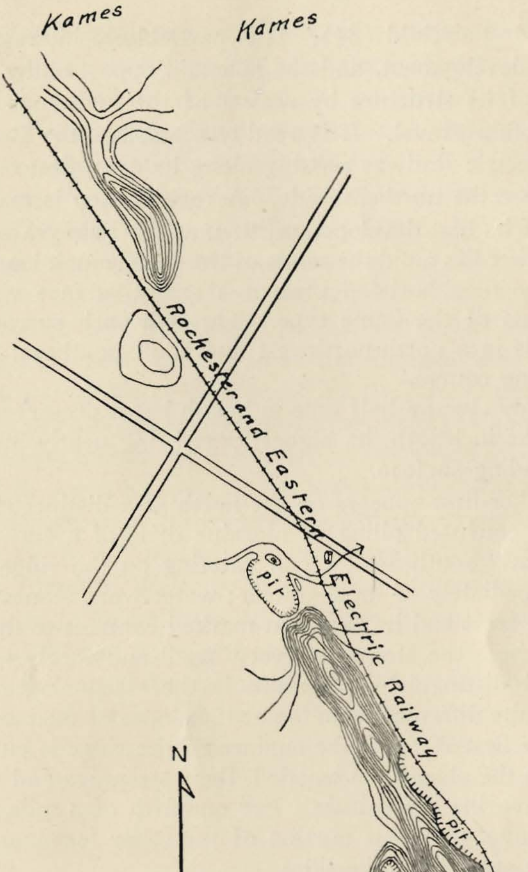

Fig. 6. Cartersville esker. One mile southeast of Pittsford, situated by the side of the Rochester & Eastern Electric Railway, and readily observed from the State road, occurs this magnificent esker.

by Professor Fairchild (34). It is particularly interesting because of its fine development, and the splendid opportunities offered for the study of its structure by reason of the numerous excavations made to obtain gravel. It is readily accessible, the Rochester and Eastern Electric Railway passing along its foot, first on the southwest, then on the northeast side. A regular stop is made within a few rods of its best developed portion, at the Palmyra road.

This esker lies amid the sands of the Irondequoit kame area. The fields in the neighborhood present a sandy surface with moraine developments of the kame type. Through such surroundings the esker trends in a north-northwest and south-southeast direction in a meandering course.

It is only about a half mile in length but it preserves in altitude what it lacks in length, its highest part being nearly 80 feet above the surrounding surface.

The esker first appears on the north as a distinct ridge emerging from a confused piling of moraine drift of a silty nature and extends nearly southeast. Upon entering on the ridge one is appraised immediately of its character; water-worn stones of all sizes marking its crest and its slopes in marked contrast to the neighboring area, where the stones are very small and rarely encountered. The second distinguishing feature is the steep slopes (about 30 degrees), quite different from the gentle slopes of the morainic drift.

For the first 200 feet the surface of the ridge is cultivated but beyond that the slopes are wooded, their steepness and stony character not favoring agriculture. For one-fifth of a mile these characters continue, then this portion of the esker terminates abruptly with a slope as steep as the sides.

Within a few feet of this abrupt termination, it is again resumed in a cultivated field. The gap thus left has been utilized for the line of the Rochester and Eastern railway. The length of this portion is but a few rods and its trend is in a more southerly direction than the segment described above. It has very gentle slopes here and is of low altitude only 10 or 12 feet above its surroundings. At the southern portion of this section of the esker there is a decided increase in width with a shallow depression in its surface, which slopes toward the west, the eastern side of the ridge acting as its rim. This segment terminates just north of the crossing of the two roads (see figure 6).

About 1,000 feet southeast of this portion of the esker it is again resumed, sloping upward from the plain until a height of 50 feet is attained. Here occurs a large gravel pit, the whole end of the esker being cut away, affording a fine exposure of the internal structure. From here the ridge continues southeastward for 1/3 of a mile with a crest showing frequent knolls and saddles and with a width of 15 or 20 feet. The base of the esker here is 100 to 200 feet in width, this width together with the narrow crest and lofty height give steep slopes that become gentler where the knolls occur along the crest line. Sand seems to be common in the saddles, gravel comprises the knolls along this crest line. It is in this segment that the highest knoll occurs, its top rising 80 feet above the surrounding country. Twenty-five rods beyond this knoll the ridge curves abruptly westward. Its course may be traced as far as the Erie Canal 1,000 feet or more to the west, however, this portion of the course has been almost entirely cut away for its gravel. This excavation affords the finest exposure of the internal structure and materials of an esker that is to be found in Western New York. Originally this portion of the ridge was of insignificant development, being but about 15 feet high and 25 to 30 feet wide at the base.

Beyond the canal the continuation of the esker has not been found if it exists. It is possible that it is buried beneath the well-defined kames that are excellently developed here. However, the topography has been much altered due to extensive excavations for the kame sands.

The internal structure of the esker is well displayed by the numerous gravel excavations already mentioned. The gravel pit at the north end of the southern segment presents the structure in a most satisfactory way. It exhibits the rude anticlinal structure so common in eskers. The stratification is indistinct. The materials vary greatly in size, Medina sandstone making up the larger proportion of both the fine and the coarser materials. Perhaps 90 per cent. of the mass is of local origin. Boulders 1 foot in diameter occur distributed through the gravels; boulders larger than this are rare. All of the materials are well rounded by water action.

At the bottom of the pit the gravel is of the finest character of the whole esker. Much of it is but little coarser than coarse sand.

Here the stratification is scarcely discernible, being best brought out by layers of small well rounded pebbles occurring in the fine gravel deposit. The stratification is most irregular, now dipping one way, again in another direction. At each side of the pit the dip is outward at an angle of about 10 degrees. The gravel here extends considerably below the general surface on either side of the esker.

At about 10 feet above the floor of the pit there is a peculiar development decidedly unusual in eskers so far observed. This consists of a layer of almost uniform thickness, of about 3 feet, which extends across the whole esker in a horizontal plane. It is composed almost entirely of small pebbles of uniform size, with few larger stones or boulders. The whole mass is so firmly cemented that it is almost impossible to break it with a sledge. It is necessary to dislodge it with dynamite to get at the gravel underneath. Great masses of this layer have been left strewn about the floor of the pit and in the adjoining field. This cemented layer lies in the plane of the latest and highest Iroquois waters. It is suggested that the calcareous cement was carried down by leaching atmospheric waters and was deposited when the zone of the standing waters was reached. The layer is the most striking feature of the excavation and immediately attracts attention.

At the southeast end of this excavation, of which this peculiar layer forms the floor, is found much the same features. Here the stratification is indistinct and appears frequently to be entirely wanting. The materials are unassorted, the coarser being mingled in profusion with the finer. This is especially true near the extreme top of the ridge. Here coarse boulders, 8 to 10 inches in diameter, occur in profusion.

On either flank of the ridge, as revealed in this excavation, a layer of fine sand occurs, 4 to 8 feet in thickness, extending from a line 15 feet from the crest half way down the slopes. This probably represents wind blown accumulations subsequent to the formation of the esker.

Southeast of this extensive excavation along the railway track there is another gravel pit which affords a good quality of gravel of uniform size. The exposure exhibits distinct stratification, the strata dipping outward.

As already indicated the finest exposure is found at the southern end of the esker. Here the whole ridge has been practically cut away for more than 1,000 feet. At the east end of the excavation the material is coarse at the top grading into fine gravel below. The bedding is horizontal. Southwest 60 feet from here a layer of sand 6 feet thick occurs upon the remnant of the western flang of the esker, which probably represents sand blown upon the esker subsequent to its formation. Four hundred feet farther southwest this sand layer has disappeared entirely, the surface layers being coarse gravel and rounded boulders, with finer gravel and some coarse sand below, cross-bedding being very characteristic here. Southwest of the north and south road the remnant of the esker remaining is composed of coarse gravel chiefly. Sand occurs here again on the surface of the slopes, and cross-bedding is excellently exhibited. A study of the material throughout this whole excavation reveals the fact that it is largely local in origin.

It seems probable from recent study that the esker described above represents only a portion of a very much longer esker system. Chadwick in a recent paper, "Lake Deposits and Evolution of the Lower Irondequoit Valley," describes a gravel ridge lying in the Irondequoit valley that may well be a part of this esker. This ridge divides the valley into two parts and extends southward to East Rochester where extensive sand plains occur, probably representing an esker fan. Three miles southeast of this fan lies the esker that is described in this paper. Two or three miles beyond Bushnells Basin southeast of Cartersville occurs another typical esker fan which is probably associated with this esker system. The continuation of the portion of the esker studied to this outwash plain has not been traced as yet. It is further possible that this esker system may continue north of Irondequoit Bay and lie concealed beneath the waters of Lake Ontario. At any rate if all these features are to be considered as a single esker system, which seems to be the correct interpretation, then the Cartersville esker is the longest esker system in Western New York.

Origin. Some features exhibited by this esker throw light upon its origin. The depression of the esker gravels below the general surface on either hand, the preponderance of local material, and the depression in the middle segment signifying the weight of an ice arch upon its surface, all point to the subglacial origin of the ridge. Likewise the kettles that parallel its course are evidence of the weight of ice masses bordering the esker (122). One gap in the course of the esker has been due to stream erosion and is now occupied by a vigorous stream. The other gaps may be due to stream erosion but more probably they represent lack of deposition in the subglacial tunnel.

Palmyra eskers. Figures 7-9, plate XII. Near Palmyra occur several eskers lying in the valleys between the drumlins. Three of these gravel ridges may be seen in going from Palmyra to Marion, closely paralleling on the west the road that connects the two villages; the fourth lies one and one-half miles northwest of Marion. All are of sufficient height to be indicated on the Palmyra topographic quadrangle. In length the ridges are short, each being from one-half to three-fourths of a mile long. Their north-south alignment would seem to indicate that they represent the activity of a single glacial stream flowing southward in a course parallel to the drumlins and to the direction of ice movement. In figures 7-9, plate XII, the ridges are designated A, B, C and D. A being the one nearest Palmyra, D being the one farthest north, lying northwest of Marion. A distance of about six miles separates the ridge near Palmyra from the one near Marion.

Ridge A. This esker, or esker segment, is of average height, being about 25 or 30 feet for the greater part of its course. It has a rather broad crest with relatively gentle slopes, which locally are exceedingly stony and elsewhere quite free from stones. Its crest supports no knolls, being thrown into a series of gentle grades. Its course is not characterized by meanders which were found to be a pronounced feature in a number of eskers studied that are shorter than this. Near the northern portion of the esker several gaps occur, one of which is traversed by a stream, the largest gap being occupied by a number of low kames. In the course of this esker excavations have been made in one place only. But little was gained in the examination of this excavation. It had not been worked for a long time, and the action of the weather had obscured its features. In the accumulated debris at this point coarser stones appeared to be lacking entirely.

The greater portion of this esker is under cultivation, in fact its surface is better suited to cultivation than the adjoining wet swampy ground, with its small ponds containing stagnant water. The ridge terminates northward in a comparatively flat swampy area, southward it gradually fades out and blends with the ground moraine.

East of the southern half of the esker and between it and the highway occurs a series of knolls resembling kames. The topographic sheet indicates several of them. They are joined by low intervening ridges except in one or two instances where deposition between the knolls apparently was lacking. The northernmost of these knobs is separated from the rest by a swamp and is attached to the eastern slope of the esker. Its surface is under cultivation as in the case of the knolls, and it is not excessively stony. This series of knolls may be regarded as a parallel esker or as a series of kames originating as a result of the deposition of detritus (formed by a superficial or subglacial stream) at the edge of the ice or in a reentrance of the ice, the localization of accumulation being due to the wavering retreat of the ice.

Ridge B. About one mile north of Ridge A occurs another esker segment closely paralleling the base of a lofty drumlin, to which it is joined in two places. For the most part it is low, being less than 20 feet high. Several gaps occur in its course, one or two of which are probably due to stream erosion. Near the northern portion of the ridge a shallow kettle occurs in its highest part; here the ridge is about 50 feet wide across its crest.

The southern portion of this ridge exhibits a notable tendency to meander. It terminates southward in a kame area, the surface of which is very stony. Some of these stones may have been derived from the erosion of the esker itself.

The northern portion of Ridge B is its highest part. Here a detached segment 500 feet long and 25 to 30 feet high rests upon an elevated surface which is apparently of till, possibly being a broad flat drumlin.

This segment is densely wooded, its crest is unusually level and rather broad, its termination on the south is very abrupt and its initiation northward is of equal abruptness. It is succeeded northward by a kame area that is bounded on the east by a steep slope about 20 feet high.

Ridge B is bordered on the east for a considerable part of its course by a long parallel ridge of about 25 feet in height.

Ridge C. One-fourth to one-half of a mile north of Ridge B occurs the third part of the esker. It proceeds northward from the kame area that terminates Ridge B on the north, the steep eastern edge of the kame area forming the eastern side of Ridge C.

This portion of the esker system trends northward for one-fourth of a mile or more as a well-defined ridge 15 to 25 feet high with steep slopes and a meandering course through swampy ground. Knolls along its crest are common. The excavations for gravel here show material of uniform grade and medium size. Sand is lacking, and few large boulders occur.

In the northern part of the esker two shallow kettles are depressed into the ridge. Where these kettles occur the ridge exhibits a tendency to become low and broad, while on either side the esker rises abruptly to the normal height. The slopes leading into the kettles and outward from their rims are very gentle.

Northward the esker terminates rather abruptly in a swamp.

Ridge D. This northermost segment of the esker system lies between two high drumlins bordered by swampy land with small ponds on either side. It is short, only about one-quarter of a mile long, with a meandering course throughout its entire length. Nowhere is its height greater than 30 feet.

The southern portion of the ridge is of low altitude with uneven crest, the northern part reaches a height of nearly 30 feet and has a remarkably even level crest with steep and stony slopes that are under cultivation. Northward this level-crested ridge terminates abruptly in a flat field, southward the esker blends with the high drumlin that parallels its course on the west.

Where the stream cuts through the esker there is an old excavation which reveals a rude indistinct stratification. At least three-fourths of the materials are from local formations. There is some sand here on the eastern side of the excavation in which are embedded numerous rounded stones. On the opposite side of the excavation occurs sand near the surface, with numerous embedded rounded stones.

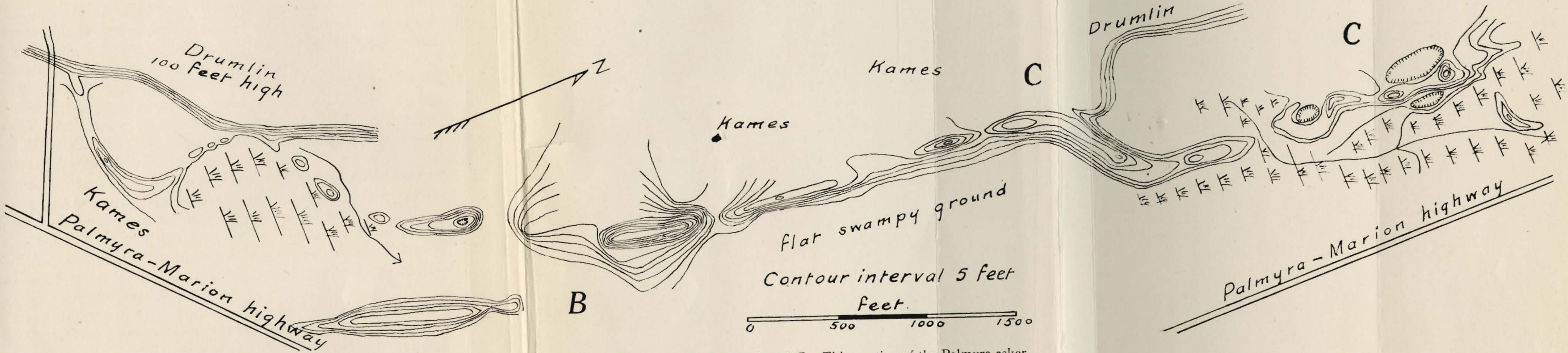

Fig. 8. Palmyra esker, Ridges B and C. This portion of the Palmyra esker lies one mile north of the northern termination of Ridge A.

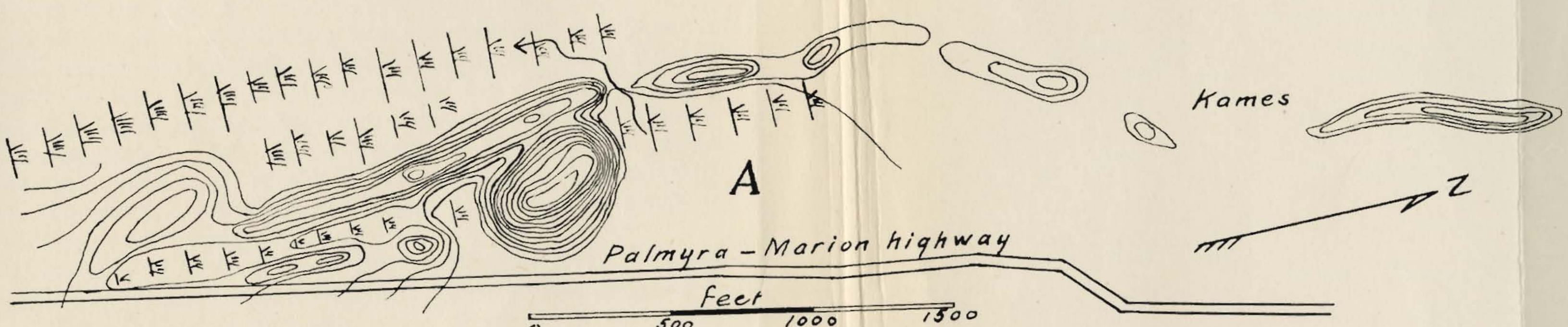

Fig. 7. Palmyra esker, Ridge A. This esker lies one mile north of Palmyra paralleling the Palmyra-Marion highway on the west.

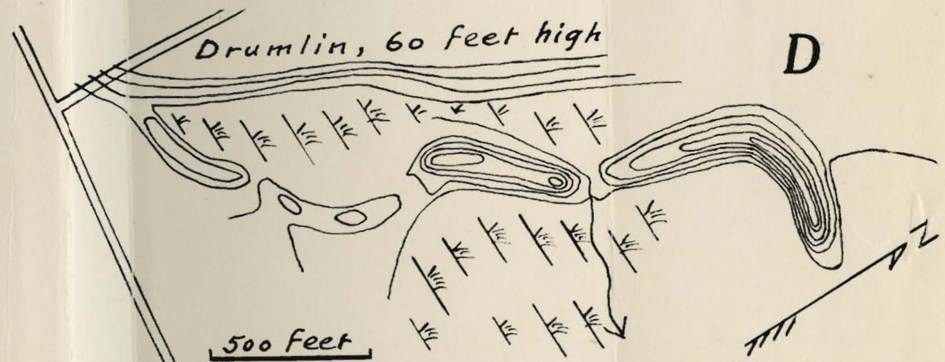

Fig. 9. Palmyra esker, Ridge D. This short segment of the Palmyra esker occurs about one and one-half miles northwest of Marion.

Origin. There was little developed in the study of these Palmyra esker segments that throws light on the precise manner of origin. If the broad elevation on which the northern and highest part of Ridge B is located is to be interpreted as till and possibly as a drumlin then the esker was deposited after the deposition of this till. However, that does not necessarily mean that the esker stream was superglacial even in this part of its course.

The presence of several kettles depressed into the crest of the eskers would indicate ice block inclusion with subsequent melting leaving the depression, or possibly the places of rest of the sagging ice arch over the broad subglacial tunnel, either interpretation favoring the subglacial origin of the esker.

Probably each ridge was built when the ice front stood near its southern terminus. In each case this was followed by ice recession and the building of the next ridge northward followed. The presence of kame areas near the ends of the individual ridges would seem to indicate this, the kames representing the outwash beyond the stagnant ice front from the stream in which the individual esker ridges were being deposited.

The trend of this esker system along the axis of a valley reinforces the idea of its origin in a subglacial stream.

Eskers of the Mendon kame area. Figures 10-11, plates XIII, XIV. The Mendon kame area lies about 12 miles south of Rochester. It has been described by Prof. Fairchild (34), who mentions briefly the eskers of the area.

All of the eskers of this kame area are excellently developed, in fact the one on the east side of the area east of Mendon pond is probably the finest esker in Western New York. The Rochester topographic quadrangle indicates the eskers of this region, although very inadequately. They all trend north and south and pursue meandering courses. They are of historic interest because their crests were utilized as trails by the Indians in passing northward to the vicinity of the present village of Pittsford.

Esker west of Mendon pond. Figure 10, plate XIII. West of Mendon pond occurs an esker that is nearly two miles long and in places attains a height of 100 feet.

On the north it rises from a low swampy tract and passes westward for about 600 feet with a height of less than 5 feet. Turning toward the southwest it broadens and gradually attains a height of 25 feet and then rapidly decreases in height until it is nearly lost again in the swampy ground. Pursuing its meandering course farther southwestward it gradually broadens and rises to a height of 45 feet, then drops off slightly with hummocky, narrow, meandering crest, to be continued onward in an abrupt rise of more than 40 feet followed by a level stretch and then a further gradual rise of 50 feet to a high elevation that rises about 125 feet above the swamp on either side of the esker. This elevation has a very stony surface, all of the stones being small, and well rounded. The slope toward the west from this elevation is gradual into rolling farm land. The elevation itself is under cultivation, although the esker from the point of origin to this elevation is wooded and bordered by swamps on either hand.

Southward from this high elevation the esker is very broad and indefinite. On the west is located a large deep kettle, on the east a steep slope leads from the esker crest to the swamp.

After crossing the road the esker rapidly narrows southwestward to its typical form, with hummocky crest, meandering course, and steep sides 60 to 75 feet high. A long deep kettle borders the esker on the west throughout this portion of its course.

At the second road crossing the esker turns abruptly southward making a right angle with its former course. For the next half mile its course is toward the southeast with narrow hummocky crest, meandering course and sides as steep as the materials will lie. All of this southern portion is wooded and bordered by swamps on both sides. About 1,000 feet south of the road just mentioned a ridge extends eastward from the esker that may possibly be interpreted as a tributary. It has a broad crest, with slopes more gentle than those of the main esker, and is under cultivation. Its surface is less stony than the surface of the main esker and apparently is composed largely of till.

South of this tributary 600 feet, the steep east slope of the esker is succeeded by a gentle slope that passes down to the edge of Mendon pond, the base of this portion of the esker being 500 to 600 feet in width.

One thousand feet south of this broad place occurs a conical elevation 100 feet high, one of the most conspicuous elevations of the Mendon kame area. It is east of the main course of the esker although intimately connected with the esker itself and overlooks both Mendon pond and the small pond to the south, lying between the two. Its surface is composed of sand and fine gravel. Near its summit a partly buried boulder occurs with an edge exposed that will measure 8 feet, and another edge that will measure 6 feet in length. It is not wooded. Southwest from this high mound the esker continues for 1,000 feet with a height of 75 feet or more, and with a hummocky meandering course. It then abruptly broadens into an excellent example of an esker fan, which slopes with uneven surface gradually toward the southeast, south and west, and is covered with small rounded stones and under cultivation.

There was little information obtained as to the composition of this esker. Its surface is typical of eskers in being mantled with gravel. An old excavation occurs north of the road that crosses the esker nearly a mile from its southern termination, which discloses gravel both coarse and fine and also some sand on its north side.

The northern portion of this esker is paralleled by another ridge on its south side. This second ridge is of about the same height as the esker itself, with the same degree of slope on the flank facing the esker. This slope is wooded. The opposite side toward the southeast is much more gentle and is under cultivation. This ridge is separated by a narrow swamp from the esker described above. Its northward termination is more abrupt and its northern portion is higher than the esker mapped. Otherwise it possesses the same general features as the one studied in detail. These two ridges are to be interpreted probably as a double or reticulated esker.

Origin. Little can be said regarding the origin of this esker. Near the top of the excavation mentioned above a large boulder was observed lying partly buried in the sand. It could hardly have gotten into such a position if the esker had been superglacial in origin. The prominent elevation near the south end of the esker was formed at the edge of the ice or more probably in a slight re-entrance, or possibly in an area surrounded by ice at a time when the esker northward was being formed beneath the ice and probably after the formation of the greater portion of the esker to the south of it. The eminence near the north end of the esker was formed in a similar manner, but after the esker to the south of it had been built and uncovered by the melting of the ice. During its formation the portion of the esker to the northeast of it was being formed beneath the ice. The elevation itself and the gentle slope westward from it represent outwash at the time this northern portion of the esker was forming, and the kettle to the south probably represents ice block inclusion, the block remaining while the elevation itself was being formed.

Esker east of Mendon pond. Figure 11, plate XIV. On the east side of Mendon pond is found the finest esker of the Mendon kame area. In many respects it is the finest example of this type of glacial development that was studied. For a distance of 2½ miles it continues its course through the eastern half of the kame area bordered by kames on either hand. It meanders freely, possesses an uneven hummocky crestline, and on either side at its base occurs a succession of kettles formed by ridges passing off from the side of the esker and connecting with the adjacent kames. These kettles may contain water forming small ponds and swamps. In altitude it equals or surpasses the other eskers studied, in places rising 100 to 125 feet above its base, with very steep slopes and narrow crest.

The esker begins on the north in one of the highest elevations in Monroe county. This elevation is well shown on the Rochester topographic sheet lying about 1 mile northeast of Mendon pond, with an altitude of 850 feet above sea level. The accompanying figure exhibits only the higher portion of this eminence from the upper surface of which there is a gentle rolling slope outward in all directions except where the esker joins on the south.

The surface of this elevation is thickly mantled with waterworn stones of all sizes and apparently the greater part of the whole hill is water lain material. Southward from this elevation the esker pursues its meandering course toward the southwest with hummocky crest and steep lateral slopes. About one mile south the ridge terminates in a high knoll bordered by a long deep kettle on the east side. Southwest of this knoll and joined to it occurs another higher knob that forms one of the most conspicuous elevations along the whole esker course. A short distance south of this high elevation the esker turns abruptly toward the west and continues nearly a half mile in that direction. The best view of the esker from the Pitts-

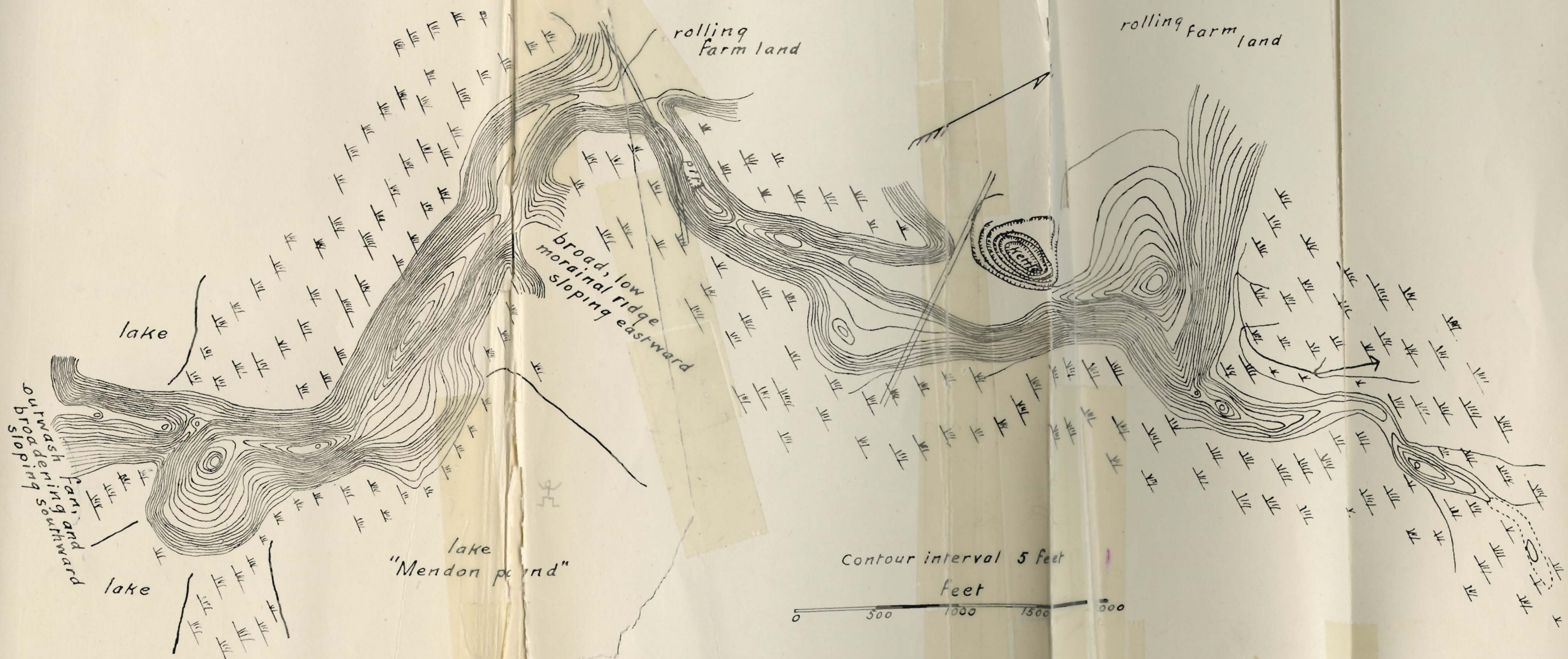

Fig. 10. Esker west of Mendon Pond in the Mendon kame area.

ford road may be obtained at the point where it makes this turn, its base being but about 250 feet distant from the road.

Swinging toward the southwest again from its westerly course the esker pursues its meandering course for another half mile, its narrow, hummocky crest, steep slopes, with numerous kettles on either flank, being its distinguishing features. In one portion of its course here it appears as if three or four kames had been tied together by short low ridges to form a part of the main ridge. From the summit of any one of these a fine view may be had of a large part of the esker and of practically the whole kame area. Near the southern end of this southwesterly trending part of the esker the ridge itself becomes inconspicuous and is bordered by a beautiful little lake on the west. Turning toward the southeast it continues onward for more than one-half a mile, preserving the same characters that distinguish the northern part of its course. As is the case with the esker on the west side of the Mendon kame area this esker terminates southward in an excellently developed esker fan that spreads out and slopes southward gently with a rolling surface well sprinkled with small rounded stones.

An interesting feature in connection with this esker is that it is in no place completely discontinuous throughout its whole course. In one or two places it is only 5 feet above the adjacent swamp, yet even here it does not lose its character as a distinct ridge.

Its northern portion is nearly all forested, its southern portion is entirely so.

Excavations occur in two places in the course of the esker. Both are small and have not been worked recently. One about a mile from the north end exhibits coarse gravel and many good sized boulders. The stratification is poorly preserved. Near the south end of the esker on its east slope occurs an old gravel pit. The material is considerably finer than that found in the excavation near the north end of the esker. In both excavations the material is almost entirely local in character having been derived from formations between the north end of the esker and Lake Ontario.

Origin. Very few features observed in the study of this esker throw light upon the way in which it originated. That part of its course which appeared to be a succession of kames tied to each other by connecting ridges may represent formation at the ice front or within a re-entrance into the ice, the point where the kame occurs representing a halt in the withdrawal of the ice front, the connecting ridge representing a time of slow, steady retreat of the ice edge. The high knob described above that is located about a mile from the north end of the esker was probably formed at the ice edge, after the formation and uncovering of the esker south of it and while the portion of the esker to the north of it was being built beneath the ice. The numerous kettles that parallel the course of the esker may represent the melting out of ice blocks that lingered adjacent to the sides of the esker, or unequal deposition at the ice front.

The high elevation occurring at the north end of the esker probably represents deposition at the ice edge or within a broad re-entrance back into the ice by a powerful stream pouring from the ice and carrying a large quantity of material with it. It was this same stream that built the esker extending southward from the elevation, the one just described. The formation of the elevation itself was not begun until after the building of the esker had been completed. Why there should not be an esker continuing northward from this elevation and built beneath the ice at the time the elevation was forming is an interesting question. Apparently all the material was carried out and dropped to make up the large mass of the elevation itself.

The local character of the materials of these Mendon eskers constitute a strong argument in favor of the subglacial hypothesis. It would seem impossible for this material to have gotten up on top of the ice in such a short distance especially when this ice was advancing over a level plain.

Further the occurrence of the high knolls in the course of these eskers is antagonistic to the idea of esker origin at the edge of the ice or in re-entrants from the edge; the knolls themselves represent the deposits forming in these situations, while the eskers stretching northward from them were being deposited in the subglacial streams at the same time the materials were being contributed by these streams to form the knolls. The latter doubtlessly clogged the exits of the tunnels leading to erosion of the roof of the tunnel and deposition in the slacker water in the lower part of the stream. The resulting strong development of the esker ridges north of the knolls and the upward trend of their crests toward these knolls are in line with this idea.

Esker south of Mendon kame area. A third esker occurs beyond the southern extremity of the Mendon kame area, shown on the Honeoye topographic quadrangle.. It has been described by Professor Fairchild (34). He says: "One mile south of the kame area occurs a singular group of knolls that must be regarded as an esker. This lies one-half mile south of Mud pond and three-fourths of a mile west of Mendon center. The north end of the esker is cut by the east and west highway. This esker consists of four connected knolls, in a north and south line, making altogether a length of about one-eighth of a mile. The local name of the knolls is the 'Dumpling Hills.' The summit and slopes of the ridge and the road cutting show only a fine, stiff or silty sand, similar to much of the surface of the region southward. A few stones were observed in the sand. The esker is thirty to fifty feet high but surmounting a ridge probably drumloid, it is conspicuous over a considerable area. Its altitude is 762 feet (aneroid). The sides of the esker are very steep and ridges of sand stretch away from it at right angles" (34).

Origin. These knolls probably represent deposition at the edge of the ice or within a re-entrant by a heavily laden stream flowing from the ice. They may best be interpreted as a series of kames that have been connected by deposition, the individual kames representing successive halts in the ice retreat with resulting localization of deposition, the connecting ridges indicating slow continuous retreat of the ice front between the periods of halting.

Le Roy esker. Figure 12. The LeRoy esker lies in Genesee County, situated partly in the town of LeRoy and partly in the town of Stafford. It is about one-half mile north of the main or State road that connects the village of LeRoy with the city of Batavia, and is crossed by the north and south highway forming the boundary between the two towns mentioned. It parallels in a general way both the New York Central Railroad (Batavia and Canandaigua Branch) and the Erie (Attica Branch), and lies about half way between the two. The northeastern part of the Batavia topographic

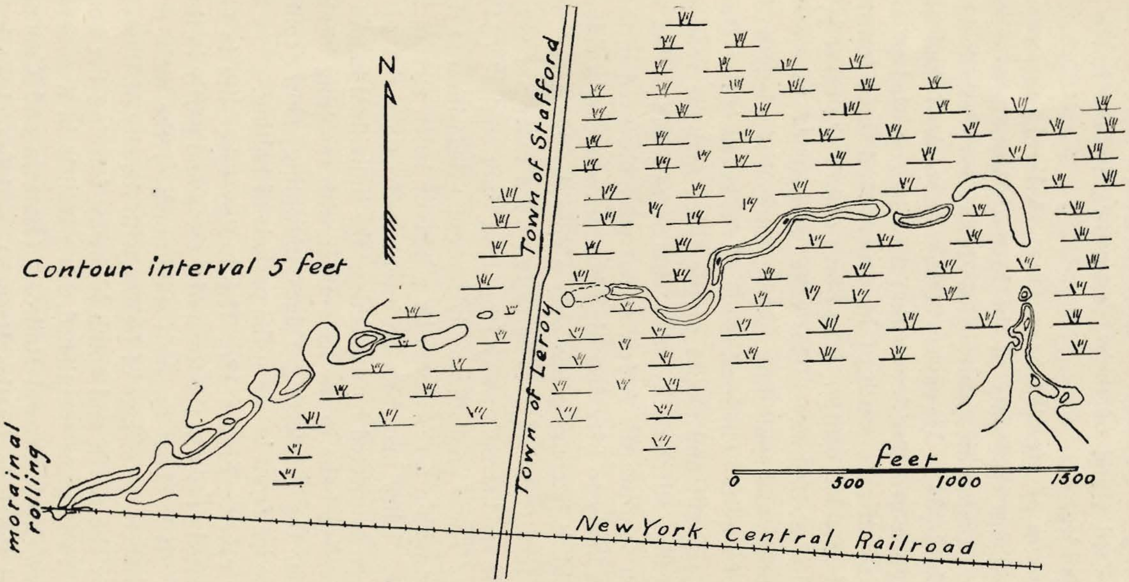

Fig. 12. Leroy esker. This esker crosses the township line between Stafford and Leroy, 2 miles west of the village of Leroy.

quadrangle indicates the character of the general area, the esker itself being too inferior to find expression on the map. This esker has already been described (20).

It is not a large type of its class, being less than a mile long and rarely reaching a height of 15 feet. The most striking feature observed in its study was its direction, this being not far from east to west, or at nearly right angles to the direction of ice movement in this region. However the striae locally do not indicate such a disparity between the direction of the ice movement and the trend of the esker. Apparently at least during the closing stages of the ice invasion the local ice movement was toward the southwest.

The esker begins on the east in a cultivated field with characteristic rolling morainal topography. The distinctly ridge form is scarcely assumed before it is abruptly terminated and succeeded by swampy ground, and then 500 feet farther north it picks up as abruptly and continues onward curving rather sharply toward the westward. Two short breaks, each but a few feet wide, follow in rapid succession and then its course is continuous, till the north-south highway is reached. West of the highway it is much more discontinuous and segmented (see figure) until finally it blends with the heavy morainal features just beyond the railroad.

It traverses swampy ground throughout its entire course, east of the road the adjacent swamp being wooded, west of the road it being sufficiently dry to be under cultivation. It is quite possible that the breaks are due to stream erosion, although the sluggishness of the illy-defined drainage lines through the swamp would seem to antagonize that idea.

Several excavations have been made at various places in the esker, though none are recent. Just east of the road such an excavation occurs and also one about 600 feet west of the road, and near the eastern termination of the ridge three excavations are found which exhibit the materials and structure to best advantage. Here the material is very fine for the most part, although little sand is present, with bedding indistinct. Just east of the north-south road the excavation is old and so thoroughly washed down as to be of little value. However, there is some sand here, and the fact that the excavation was continued below the level of the surrounding surface seems to indicate that the stratified materials continue below the general till surface. This excavation is now occupied in its deeper part by a pond. The excavation west of the road exhibits fine gravel only.

The slopes of the esker are gentle and the gravelly surface has developed sufficient soil to support vegetation. Its base rarely reaches a width of 50 feet.

About one-half mile west of the termination of the esker and just north of the railroad a ridge starts abruptly from the level surface and rapidly gains in height until an altitude of 50 feet is attained. This ridge continues northwestward for more than 1,000 feet and then turns northward and ceases rather abruptly. Its surface is of gravel with an excavation near its summit in fine gravel, these features together with its steep sides and change in direction give this ridge a decidedly esker appearance.

Northeastward this ridge is succeeded within a few hundred feet by another ridge that abruptly rises to a height equal to that of the first and as abruptly declines nearly to the level of the adjacent topography where it is succeeded by a low broad ridge. This last ridge is nowhere more than 20 or 30 feet above the adjacent surface, and continues for a half mile or more toward the northeast. Possibly these developments may be interpreted as the main esker, the one mapped and described above being considered a small tributary to it. This may help to explain the unusual direction of the latter. Further study will be necessary to bring out the relationships and to determine if the high disconnected ridges are really a part of an esker system. The topographic map very imperfectly exhibits these features.

Origin. The manner of origin of the ridge shown on the accompanying map (Fig. 12) is not demonstrated by the field study. The fact that the gravels continue below the general surrounding surface where one of the excavations occurs (see above) would seem to indicate that the esker materials were deposited not later than the deposition of the till which would favor the subglacial method of origin.

Eagle Harbor esker. Figures 13-14, plates XV, XVI. Three miles south of Eagle Harbor, a small station on the Falls branch of the New York Central railroad, occurs an esker several miles in length. Its northern portion is indicated on the Albion topographic quadrangle, the remaining part lying in the territory covered by the Medina quadrangle. The esker is associated with the Barre moraine, its southern end being about 1 mile north of the main east-west ridge of the moraine. The country through this section is rolling. In the midst of this rolling plain, occupying a rather low swampy stretch, the esker pursues its course. Its trend is nearly north and south, although both its northern and southern extremities depart appreciably from this general direction. Its height is nowhere excessive, for the greater part of its course only 15 to 30 feet, but its length is notable, being about four miles, with but one or two short gaps in this entire distance.

Leverett has mapped and described briefly this esker (62), the northern part of the ridge shown in the accompanying figure (Fig. 13), he apparently regards as moraine, and has so mapped it (62, plate III).

On the north the esker sets in as a very broad low ridge, the width of the base being several times the height. Arising from swampy land it continues southwestward for more than a mile, its gentle slopes and broad crest not revealing its true character to the casual observer. In places in this portion of the course the esker may broaden until its base is nearly one-quarter of a mile in width. This part of the esker lies banked against the Niagara escarpment, the trend of which has probably influenced its direction.

One or two exposures occur here. Very little sand is present, chiefly fine to coarse gravel, Medina sandstone pebbles comprising by far the greater part of the material.

The surface of the esker everywhere in this northern portion is exceedingly stony, the stones being small, about the coarseness of fine gravel, and mantling the surface everywhere. Notwithstanding this feature the esker is under cultivation and its slopes are fairly productive.

Near the southern terminus of this northern portion a distinct ridge joins it from the northwest. This is probably to be interpreted as a tributary to the main ridge. It is a broad, level-topped, gentle-sided elongation, about 700 to 800 feet in length and terminates northwestward in a broad flat-topped elevation with very gentle slopes.

From the point where this tributary joins the main ridge a road follows the broad crest of the esker until the latter ceases at a stream crossing 600 feet or more beyond this point of junction. The portion from this interruption to the southern terminus of the esker may be regarded as the southern part of the esker. (Figure 14, plate XVI). This southern portion possesses typical esker characters, much more so than the northern portion. Here the esker has a narrow, hummocky crest, steep sides, as steep as the materials will lie, and a meandering course.

In places the esker reaches a height of 50 to 60 feet, however, for the greater part of its course it is but 20 to 30 feet in height. It is continuous, but one short gap occurring and that near its northern terminus. Swamps occur on both sides throughout its whole extent, the ground being much too wet for cultivation; kames rise from these swampy tracts in several places.

This portion of the esker has a short low eastern prolongation just south of the east-west road. It continues eastward for 500 or 600 feet before gradually disappearing. It is very possibly a small tributary.

This part of the esker is further characterized by a very broad place in its course. It is flat-topped, several hundred feet across and rises 50 to 60 feet above the base of the esker. The sides have gentle slopes which are scarred by numerous gullies. In the southeast section of this elevated level space occur three large blocks of weathered Medina, the largest of which will measure 10 or 12 feet on its edges, the other two being but little smaller. Other large boulders are lacking on the surface, but gravel occurs everywhere.

After pursuing a meandering course for nearly a quarter of a mile beyond this broad portion the esker terminates abruptly in a level-topped loaf-shaped hill whose surface is covered by stones of all sizes. All are well-rounded, with crystalline material forming a conspicuous but minor portion, the greater part being Medina. Its sides are as steep as those of the esker ridge proper except the side on the west which slopes more gently toward the road.

East of the terminal loaf-shaped hill occurs another larger hill with gentle slopes. Its slopes are comparatively free from stones and apparently are of till. It is probably morainal in origin.

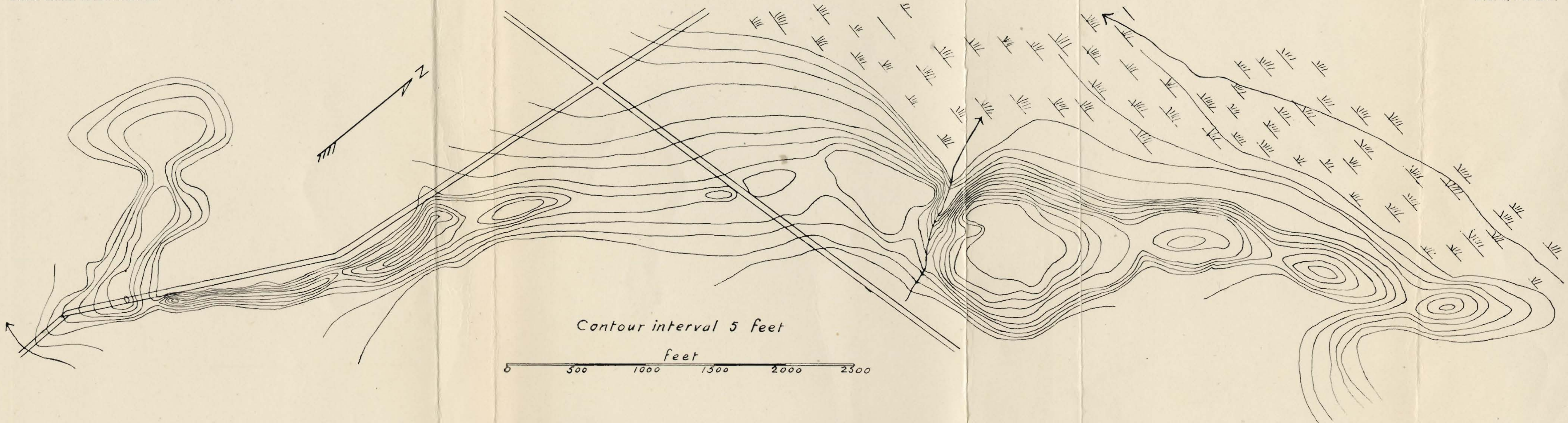

Fig. 13. Northern half of the Eagle Harbor esker. This esker originates about 3 miles south of Eagle Harbor and continues in an almost uninterrupted course for 4 miles southward nearly to West Barre. This map joins Figure 14.

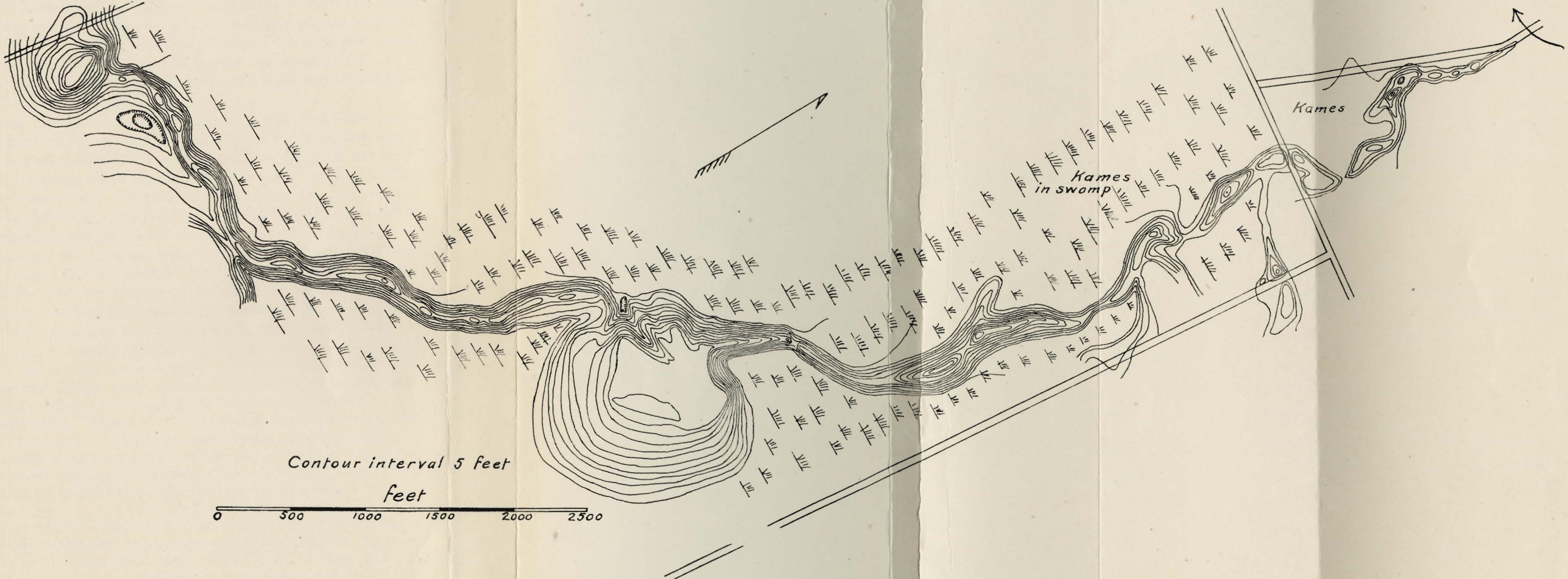

Fig. 14. Southern half of the Eagle Harbor esker. This map joins Figure 13.

Leverett has mapped two eskers as terminating in this loaf-shaped hill (62, plate III). The second one he indicates as paralleling on the west the one figured and described in this paper. Elevated ground occurs beyond the swamp that borders this esker on the west but its breadth and its other characters are not at all like those of eskers. It is half a mile wide, irregular in form, 20 to 60 feet above the swampy ground on the east and extensively dissected by drainage lines. Everywhere it is under cultivation. Its surface is rolling and not excessively stony, and is largely composed of till. It is undoubtedly to be regarded as morainic, and a northward continuation of the Barre moraine.

Origin. Several features in connection with this esker throw light upon its origin. Its position north of the Barre moraine would seem to suggest that it was forming beneath the ice while the Barre moraine was being built at the ice front. The large blocks of Medina on the surface of the wide portion of the esker near its southern terminus could not have gotten there if the esker was being built in a superglacial stream, and could with difficulty be accounted for in that position, if the esker was being built in a re-entrance back from the ice front. The influence of the Lockport escarpment on the trend of the northern portion of the esker shows that the esker stream must have been subglacial in this portion of its course at least to have been affected by this feature whose relief was certainly not great enough to extend through the ice and affect a superglacial stream. The swampy strips on either side of the esker bordered by higher ground farther away indicate the pressure of the ice blocks immediately adjacent to the subglacial stream on either side.

Holley esker. Figure 15. This esker is situated between Holley and Clarendon. It originates about a mile southwest of Holley and continues southwestward to within one-half mile of Clarendon. The improved highway that connects the two villages passes along the crest of the esker over the northern part of its course.

The ridge is over a mile long, it is very broad and near its southern extremity it reaches its greatest height, being 80 feet above the marshy flat ground that borders the whole length of the esker on either side. From the summit of this knoll, "Indian Hill", an excellent view is to be had of the entire surrounding country and particularly over Clarendon and to the southward.

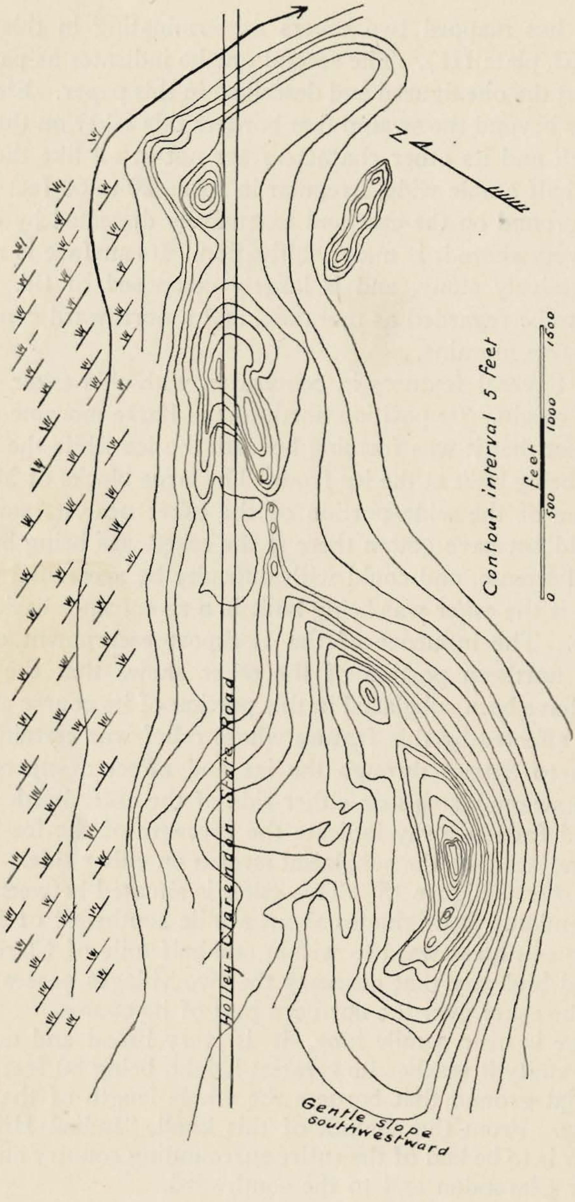

Fig. 15. Holley esker. This esker is situated between the villages of Holley and Clarendon and is traversed for the larger part of its course by the Holley-Clarendon improved highway.

It is associated with the Albion moraine, lying to the north of it, the moraine making a jog southward from its regular trend and passing through Clarendon beyond the southend of the esker (62). The Albion topographic map exhibits the esker and associated features clearly.

The esker ridge rises rather abruptly at its north end, the country north of its place of origin being uneven with gravelly knolls abounding. In fact these knolls parallel its course on either side and are especially numerous beyond its southern termination around Clarendon.

Its course is of the meandering type, the meanders being long and conspicuous. The ridge is unusually broad at its base, a feature not characteristic of Western New York eskers, and its crest is likewise unusually broad. Its lateral slopes are gentle, much more so than those of the ordinary esker. They are stony yet yield a fairly good soil consequently the ridge is under cultivation its entire length, part of it being in orchard. The crest-line is uneven or hummocky, the highest one being "Indian Hill" which rises 45 feet above the adjoining portion of the ridge on the north.

From the point of origin to the place of termination no interruptions occur in the course of the esker, it being continuous throughout its entire length.

Its termination is gradual. From "Indian Hill" it slopes southwestward, first rapidly and then more gently until it has ceased to appear as a distinct ridge among the irregularities of the ground moraine on either hand.

At least two gravel pits occur in its course. Neither has been worked recently so that their features are obscured by weathering. The bedding is imperfect and indistinct near the surface, becoming more distinct with rude anticlinal structure with depth. The materials are fine, chiefly gravel of good grade. This is composed almost entirely of Medina sandstone, a formation that is extensively worked at Holley for building stone. Leverett states that Medina makes up 90 per cent. of the pebbles by actual count (62).

One small tributary esker occurs just east of the north end of the main ridge. It is about 800 feet long with a hummocky crest, the hummocks rising to a height of 20 feet above the surface on either side of the tributary.

Origin. Little can be said as to the origin of this esker. The abundance of local material in its composition is antagonistic to the idea of superglacial origin. The small amount of sand observed in its course is certainly unfavorable to the idea of origin at the ice-front or within a re-entrance into the ice, for under these conditions a composition comparable to that of kames might be expected. Further it was apparently formed at a time when the Albion moraine with its associated kames was forming at the ice front around Clarendon south of the southern terminus of the esker. Its width seems to be the only feature opposed to the idea of subglacial origin. "Indian Hill" at the terminus of the esker may very likely represent a kame that was forming at the edge of the ice when the esker was being deposited beneath the ice toward the north in the subglacial feeding stream.

Ogden esker. Three miles south of Adams Basin and one-half mile east of Ogden occur several glacial features that Leverett has interpreted as constituting an esker (62). These features are well exhibited on the Brockport topographic quadrangle. An inspection of this part of the map discloses a broad interrupted ridge trending southwestward, 40 to 60 feet above the general level of the surrounding country, with low wet ground on either side. On the quadrangle this ridge is represented as about one mile in length, however it is in reality twice that length, fully half of it being too low to find representation with the contour interval used.

The ridge begins on the north as a low broad quite inconspicuous feature just south of the first east-west road north of Ogden. For one-fourth of a mile it preserves this character, then rises gradually to a height sufficient to take its first 20 foot contour. Just east of Ogden on the cross road the ridge is 50 feet high and one-quarter of a mile wide. It diminishes in height southward from this locality and nearly ceases. Again it increases in height and turning more to the southwest continues to the east-west road one mile south of Ogden. The highest part of this portion of the ridge is 60 feet above the surrounding country. It is broad, being nearly one-half a mile in width at this highest point with very gentle slopes.

Throughout the entire course the ridge is under cultivation. Its surface is sandy, here and there gravel occurs mixed with the sand. Large boulders are rare. Till occurs locally. Excavations have been made in several places, the most recent of which exhibit fine gravel, poorly stratified, covered by till to a depth of four feet. This excavation occurs along the north-south road at the north end of the southern half of the esker.

This ridge lies north of the Barre moraine which is very indefinite through this portion of Monroe County and the adjacent part of Orleans county, consisting chiefly of low, irregularly distributed mounds and short ridges.

Origin. It is quite possible that this ridge may be interpreted in another way rather than as constituting an esker. Its width, its very gentle slopes and its material are not typical of eskers. In fact the southern segment resembles a drumlin as seen from the north and from the sides. It has the same trend as the drumlins of this area. The topographic map exhibits this similarity very strikingly, however, its composition of sand with some gravel is opposed to this interpretation of its origin.

Again this feature may be considered as a morainic spur extending northward from the Barre moraine.

Finally it may be interpreted as an esker built in a very broad subglacial stream at the time of the deposition of the Barre moraine, or, less likely, the filling by a powerful stream of a broad re-entrant of the ice extending back from the Barre moraine.

Conclusion.

The study of the eskers in the vicinity of Rochester has developed few new facts and the observations recorded exhibit few new features. Each esker possesses its individual peculiarities which are largely a matter of detail. The relations at the point of origin, the relation at the termination, the character of the course, the relation to surroundings, the composition, are essentially the same with the New York eskers as characterize eskers in other regions.

The features exhibited by the western New York eskers seem to indicate in a vast majority of instances an origin in a tunnel beneath the ice. It is true that the characteristics of some eskers do not throw much light upon the manner of their origin, yet in the case of most eskers, if they are studied carefully, there will be revealed, very often in their minor details, the way in which they were formed. The relation they bear to moraines, their relations at the point of origin, their occurrence between the drumlins, the presence of lakes or swamps on either side, their composition largely of gravel, their relation to kames, the local character of their materials, the presence of till and large boulders on their surfaces, and of kettles depressed into their crests, their occurrence in trenches in the till sheet, their chaotic stratification, all seem to indicate a subglacial origin for the Rochester eskers.

While the preceding descriptions aim to include all of the eskers near Rochester, New York, very possibly some occurrences have been overlooked. Eskers of inferior dimensions are very likely to be missed. One such occurs two miles northwest of Scottsville. It is but a few hundred yards in length, 10 to 15 feet high, and lies between two high drumlins, with swampy ground on either hand. The topographic map (Rochester quadrangle) gives no indication of it and as it occurs some distance from the highway it might be very readily overlooked. Probably there are a number of such isolated examples of eskers in the area under consideration which are not high enough to be indicated on the topographic maps and the occurrence of which is not known to the scientific public.

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