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OUTLINE OF GLACIAL GEOLOGY

F. T. Thwaites, Department of Geology, University of Wisconsin

CONTENTS

(1934?)

<u>Introduction.</u> The following outline is a revision of a briefer one prepared in 1922. It is not a text book and does not treat specific areas in detail No attempt has been made to include references to reports on limited areas, such as Folios, unless they illustrate principles. Not all the references have been read. Mountain and modern glaciation is not discussed,

DISCOVERY AND EVIDENCE OF PLEISTOCENE GLACIATION

Discovery. Glacial deposits first attracted attention because they contain rocks unlike the adjacent bed rock; as these evidently had been transported from distant localities the deposits were called "drift". This term has survived to the present day as one which includes all deposits directly or indirectly due to glaciation. The term "diluvium" was also used.

Early explanations. Different early geologists ascribed the drift to transportation by (a) floods, (b) great waves, and (c) ice bergs in standing water; attempts were made to harmonize the facts with the Biblical flood. These theories in all asuming a submergance show the influence of the early study of marine deposits.

Glacial theory. The glacial theory of Agassiz was first applied in this country by Hitchcock in 1841 but was later retracted as the phenomena differed from those in the Alps where the theory had been first evolved. In 1863 Dana published the glacial explanation in his "Manual of Geology" since when it has been accepted by all save a few cranks.

Fundamental characteristics of the drift. The agent which transported the drift was able to (a) carry and deposit material without regard to size or weight, (b) move large stones for hundreds of miles, (c) remove the normal residual soils and weathered surface of the bed rock, (d) plane, striate, and polish both bed rock and transported stones, (e) leave deposits which terminate along a line of considerable relief which could not possibly be explained as a deformed shore line even with subsequent warping, (f) be directed by the position of the larger lowlands, (g) in some places fill up lowlands and in other places avoid or leave open comparatively low tracts, (h) produce a deposit in large part the result of mechanical forces alone, (i) leave an irregular constructional topography with inclosed basins, (j) make basins in the surface of the bed rock, (k) account for the presence of water in quantities and in locations where such is now impossible and (l) elevate material to considerable heights above its source. Glacial ice of continental extent alone answers these conditions.

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All textbooks of geology.

CENTERS OF DISPERSION.

<u>How Known</u>. The centers of dispersion of Pleistocene glaciers are known by (a) radiating strae, (b) radiating transportation of stones, (c) concentric distribution of terminal moraines, (d) comparison with present conditions in Greenland and Antarctica.

<u>Location</u>. Glacial centers were located in (a) Greenland, (b) Newfoundland (c) Labrador, (d) the relatively low tract west of Hudson Bay (Keewatin center) (e) the Height of land north of Lake Superior (Patrician center), (f) the northern mountains of the Cordillera, (g) a number of mountain ranges as far south as Arizona. Knowledge in Canada is still imperfect owing to the uninhabited nature of the country and the fact that geological surveys have been made primarily for other purposes.

<u>Time of Occupation</u>. During the last or Wisconsin stage of glaciation there can hardly be any question that the centers were occupied essentially simultaneously but opinions have varied especially in the case of the earlier stages from (a) contemperaneous maxima to (b) progressive maxima from both east to west and west to east. Survival of glaciers in Greenland and climatic considerations rather favor a growth from east to west at least in the eastern part of Canada but the question is best left open until more data has been collected.

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STRIAE AND ASSOCIATED PHENOMENA

Definition. Striae are scratches produced by glacial action on both bed rock and transported stones; associated phenomena are gouges, polishing, faceting of stones, and chatter marks.

Distribution. Striae are found (a) on all kinds of rocks but mainly on soft varieties, (b) on all kinds of surfaces, level, sloping in all directions with reference to the direction of ice flow, even vertical and overhanging, (c) on loose stones in the drift, (d) on bowlder pavements, (e) in all parts of the glaciated area where conditions of preservation were favorable. On the whole, striae are best found on surfaces exposed to the brunt of the ice and where preserved by a covering of drift. Chatter marks are found mainly on brittle rock like quartzite.

Origin. Striae were caused by (a) stones in the bottom of the ice, (b) grains of sand and small pebbles caught between large stones and the bed rock, and (c) shearing between layers of ice causing stones to rub within the glacier. Polishing was due to rock flour and clay at the bottom of the ice. Large gouges were mainly due to long continued abrasion of pre-existing grooves in the surface of the bed rock or of lines of weak rock. Scratching stopped when (a) cutting stone was worn out or broken up, (b) stone rotated to a smooth face, (c) the ice yielded instead of the rock and pressure was reduced, (d) the overriding stone was removed by ice motion. New tools were constantly supplied by (a) rotation of new faces of stones, (b) lowering of stones by melting, (c) falling of stones down crevasses, (d) tearing off of fragments of the bed rock, and (e) shearing motion within the ice. Chatter marks were caused by percussion of stones held loosely by the ice. Crescentic cracks formed behind the blow where there was a tensional strain, except in the case of a very powerful blow when the crack formed all around the point of impact.

Time of Formation. Most observed striae were formed by the last movement of the ice in that area; this is especially true on hilltops and on slightly covered ledges. Striae of older glacial stages can be found (a) in shelter of protecting ledges where ice direction later changed and (b) where deeply buried under the older drift. Great care should be used in ascribing any striae to an older ice invasion than the last, particularly in the case of striae on the same ledge which run in different directions (crossing striae). It would have taken too delicate a balance between deposition and erosion to assign such to glaciations separated by an interglacial interval. The phenomena are adequately explained by normal changes in the growth and wasting of an ice sheet: (a) motion of the ice normal to its border bringing about changes in direction at any given point as the position of the border moved, (b) changes in the relative strength of the different centers of accumulation, (c) local variations in rate of wastage of the ice causing change in direction of motion at a given point, (d) changes in ice thickness causing variation in relative amount of control of flow by topography, (e) changes in flow due to erosion of obstructions or to deposition of drift. These phenomena are most marked in tracts where two lobes abutted.

Faceted Stones. While glacial abrasion wears flat faces on stones it is well to remember that many observed facets may have been bedding planes or joints in the original rock. Faceting is best developed on previously water-worn stones. Striae are occasionally found on subsequently water-transported stones.

Direction of ice movement along striae. The direction in which the ice moved in forming any given striae may be ascertained by (a) abrasion of the exposed or stoss sides of large or small projections on the bed rock called roche moutonees, (b) U-shaped grooves around hard spots in the rock with open end pointing in direction of movement, (c) greater abrasion of fa sides of cavities in surface of the bed rock, (d) chipping of crossed striae side toward ice source, (e) plucking on rear or lee sides of prominences, (f) sudden ending or dividing of striae in direction of ice movement, and (g) chatter marks which generally have convex dide toward source of the ice.

Other Scratches. Glacial striae may be confused with (a) slickensides, (b) work of silt-laden water, (c) iceberg scratches, (d) some forms of wind work, (e) landslide scratches, and (f) artificial scratches. Slickensides are found in disturbed rocks, extend down into the bed rock, are finer, generally rougher and more frayed, and are more exactly parallel, and in many cases are associated with rock flowage and secondary platy minerals. Shearing has often produced scratches on both pebbles and adjacent rocks of conglomerates and evidence of ancient glaciation based on such alone should be received with caution. While gravel-laden streams only polish, silt-laden waters can produce surfaces which somewhat resemble those due to glaciation, particularly where there are small hard spots in the rock; the scratches are not deep and are parallel to river courses and associated with stream deposits. Ice in streams locally produces scratches. Iceberg scratches are zig-zag, irregular, and discontinuous. Shore ice locally scratches the rocks of beaches. Where the wind is constant in direction short choppy indentations may result. Scratches due to creep and to landslides are explainable by the topography and the derivation of the materials. Artificial scratches are due mainly to road grading, stripping with scrapers, cultivation, and use of sleds; freshness, parallelism to roads and furroughs, and relation to disturbed soils serve to distinguish.

Field Points. Striae may be found on all firm bed rocks where they are or have recently been covered by soil or drift. Where there are no recent exposures one must dig. Carry a small broom, or if soil is very heavy, a sponge and water. Use a compass to read the direction of the striae; it is best to sight along the linew rather than to lay the compass on the rock. Read the direction in which the ice moved. Be sure you read the north end of t needle, plot approximately on the map, and record if bearing is true to magnetic. Look for and describe as many evidences as you can find to demonstrate the direction of motion along the striae, even if at the time this appears obvious. Failure to do this, or to search for striae, is prima facie evidence of careless work. Remember that while striae on bed rock are conclusive evidence of glaciation, you must eliminate the possibility of another mode of origin.

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GLACIAL EROSION

Theoretical. The subject of glacial erosion has been much debated. Insmuch as a glacier is a moving body provided with tools it is capable of causing erosion; the only possible difference of opinion is the relative efficiency of water and ice erosion. A glacier has a greater width and depth and a less speed than a river carrying off the same amount of precipitation. Ice therefore works over a wider area with greater pressure, and on a lower base level than would equivalent streams. The total amount of energy is the same but losses from internal friction are probably greater in the glacier. Low temperature and saturation with cold water of the ground beneath a glacier are factors very unfavorable to chemical weathering. Glaciers hold their tools somewhat more firmly than do rivers; they work by grinding and polishing with some tearing and plowing rather than by rolling and crushing as do rivers. The internal heat of the earth is generally too great for freezing of the ice to the ground but an irregular mass of loose material may readily be plowed up by a glacier.

Observations Showing Glacial Erosion. The following are proofs of more or less glacial erosion: (a) the general absence of residual soil and weathered bed rock beneath the drift in most glaciated regions, (b) scratching and polishing of bed rock, (c) plucking, (d) disturbed loose rock and drift, (e) bowlders of drift and gravel, (f) rock flour produced by glacial grinding, (g) the large proportion of the drift made by mechanical forces from fresh bed rock, roche moutonees or ice worn hills many with long axis parallel to the direction of ice movement, (h) rock basins, (i) smooth outlines of escarpments, and (j) rarity of caves in glaciated regions. In addition, mountain glaciers show fiords deeper than the continental shelf, hanging valleys, cirques, and U-shaped valleys.

<u>Objections to glacial erosion</u>. The following observations may be urged as objections to unqualified acceptance of glacial erosion as a major agent: (a) glaciers have overridden uncondolidated deposits for scores of miles without disrupting them except where the upper surface was irregular, (b) the preglacial soil was not everywhere removed nor is the upper surface of the bed rock everywhere sound, (c) not all rock valleys parallel to the direction of ice movement are different from those which are not, (d) not all rock hills were shaped by the ice and some apparent cases demonstrably due to drift accumulation and not to erosion, (e) many deep lakes are certainly not in rock basins, (f) accumulation of excessive amounts of drift in the basal ice would cause shearing over the supercharged portion, and (g) rough topography would also cause shearing over the stagnant basal portion of the ice. In making comparisons with unglaciated regions care must be taken that the materials and other conditions are the same, for instance absence of caves may really be due to difference in nature of the limestone rather than to glacial erosion. In the case of mountain glaciers some features are open to question because the materials are not open for inspection as for instance in the case of submerged hanging valleys; many so-called hanging valleys may be large cirques which never were accordant with the main valley.

<u>Conclusion</u>. Many of the foregoing objections may be accounted for by either (a) thinness of the ice, (b) protection in lee of hills, (c) stagnation of basal ice, or (d) relative brevity of ice occupation. The reverse of these conditions were necessary for a maximum of glacial erosion. On the whole, it is clear that neither extreme view is tenable but that glacial erosion is a factor to be reckoned with wherever thick ice had a free flow for a long time. The best studied examples in the United States are (a) the Finger Lakes in New York and (b) the Great Lakes.

<u>(a) The Finger Lakes</u>. The Finger Lakes of western New York occupy deep valleys in the north edge of the Appalachian plateau. These valleys are remarkable for their straighthess, length, steep sides, and depth of nearly 2000 feet; the bottoms of some of the lakes are below sea level, but are not lower than the bottom of Lake Ontario to the north. There are hanging tributary valleys with small drift-filled notches in their rock floors. These features have been explained as due to glacial erosion induced by concentration of flow in these valleys, with interglacial erosion of the bottoms of the tributaries. But it has been shown that (a) the lakes are not certainly in rock basins for there is over 1080 feet of drift at the head of one of the lakes, (b) some of the cliffs were formed by normal subaerial erosion and not by glacial erosion, (c) glacial erosion was very weak on the adjacent uplands, and (d) no lobes were formed south of the lakes as would have been had the ice motion been very much more rapid in the valleys than on the uplands. If present glacial erosion must have had a sharp upper limit and have been more active in pre-Wisconsin than during Wisconsin time. The second of these is far the more difficult to explain for there seems little reason to ascribe more power to a less extensive ice advance. It has been suggested that the hanging valleys were due to stream reversals in preglacial time from south to north flowing drainage. The question is therefore still open.

<u>(b) The Great Lakes. Relation to Geology.</u> The Great Lakes lie in lowlands due to weak rocks between and at the foot of the cuestas of the Central Plain. They can be divided into the following series: (a) Lake Superior on Keweenawan and Cambrian shales and sandstones at the foot of the Magnesian cuesta, and extending into the pre-Cambrian to the West,

(b) the main part of Lake Huron, Lakes Michigan, Erie, Manitoba, and Winnepegosis on Devonian shales and shaley limestones and Silurian salt and gypsum beds at the foot of the Onondaga and Dundee cuestas, (c) Lake Ontario, Georgian Bay, Green Bay, and Lake Winnebago on Ordovician shales at the foot of the Niagara cuesta, and (d) Lake Winnepeg on Ordovician sandstone at the foot of a cuesta. None of the lakes lies in a depression due solely to earth movements; the Lake Superior syncline and its associated rift valley were once filled with monoclinal sediments.

Relation to glacial Movement. Lakes Superior, Michigan, Winnebago, the Canadian Lakes, and Erie were traversed longitudinally by the ice; the others were all crossed by the glaciers. Not only the lake basins themselves, but the associated lowlands and cuestas of the entire region had a profound influence on the flow of the ice especially during the Wisconsin stage when the ice sheet was thinner as well as less extensive than earlier in the Pleistocene, thus being more readily influenced by the topography.

Shape of Basins. With the exceptions of Erie and the Canadian lakes, the bottoms of all the Great Lakes are below sea level, but the basins are so broad and flat bottomed (several hundred times as wide as deep) that they have no resemblance to U-shaped valleys. Apparent hanging valleys are open to question on account of lack of knowledge of the rock topography.

Relation to preglacial valleys. Well records fail to show any wide preglacial valleys leading out of the lake basins; for instance, an outlet to the Lake Superior basin would have to be 1000 to 1200 feet deep and only two miles wide. The only possible outlet to Lake Ontario is through the Dundas valley to Lake Erie and thence southwest across Ohio where no deep valley is known. There is no possible southern outlet to the Lake Michigan basin. Although probably deeply drift covered, the bottoms of the lakes are far deeper than the rock floor of the Mississippi valley. On the other hand, the very deep valleys at Black Creek and Brillion, Wisconsin and the deep gorge of Hudson River suggest that there may be undiscovered deep preglacial valleys, and that the lake basins are not rock bound. If so, it is difficult to explain why the outlets are so narrow as to have escaped detection. The post-glacial uplift of the region northeast of the lakes is also a confusing factor. Estimates of the amount of drift removed from the basins are virtually worthless.

Conclusion. It is apparent that the lake basins could not have been caused by streams alone for they are not at all in harmony with the preglacial features elsewhere along the same belts of rocks and are so deep compared with adjacent preglacial valleys, but whether glacial erosion alone, or northeastward uplift alone, or a combination of the two, explains the differences is not at all clear. The basins must have been preglacial lowlands due primarily to weak rocks and with bottoms nearer to sea level than to present lake levels. That some lakes were crossed at right angles does not exclude glacial erosion since the basins are so wide. It seems to be well established that glacial erosion did have something to do with their formation.

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DRAINAGE CHANGES DUE TO GLACIATION

General. Viewed broadly, the glacial drift is a relatively thin mantle, thickest in the lowlands, thinnest on highlands, and rarely forming in itself very large hills. Where the drift covered a rock surface of low relief the net result was in many places an increased relief; in regions where the preglacial hills were higher than the average thickness of the drift the opposite was always true. An important factor is the character of the drift; stony drifts made rugged hills while clayey drift formed plains and smooth, gentle hills. Outside the glaciated area the valleys were filled with outwash and their tributaries aggraded to meet the new conditions. Changes in drainage resulting from the deposition of the drift range from complete obliteration of the old drainage lines to local diversions of streams against the sides of their old valleys or across divides into other valleys. Where a plain was left by the ice the greater amount of settling over the preglacial valleys than where the drift was thinner on preglacial uplands caused the quite general reoccupation of the older lines of drainage. The problem of drainage changes is bound up with the determination of the preglacial topography which may in general be assumed to be the surface of the bed rock. This involves an error of relatively small magnitude since in few areas does any considerable part of the solid bed rock seem to have been removed by glacial erosion.

Mapping preglacial topography. Mapping the bed rock surface of a region requires collection of (a) locations and elevations of rock outcrops, (b) locations and elevations of wells of which a log may be obtained, and (c) data on the probable origin of topographic forms in order to discriminate between drift and rock-cored hills. In some regions the courses of preglacial valleys are evident from the present topography. Drift hills are in general smaller and less regular in form than are drift veneered rock hills; some glacial forms, like drumlins, are evident at once but morainic hills may be a very thin covering over an older topography. In general, the principal elevations are likely to be rock-cored. After collection of the foregoing data the elevations of the rock surface are platted on the map including the elevations of the bottoms of wells that do not reach rock, as these are valuable negative evidence. With a knowledge not only of erosion forms, but of the effect of different kinds of rocks upon them, contours should be drawn on the bed rock surface using an interval suited not only to scale and refief but to the fullness of the data. The largest single map of this character is that of southeastern Wisconsin by Alden.

Drainage changes in the young drift. The drainage of the young or Wisconsin drift area is very immature; lakes and swamps abound and except where conditions were very favorable, postglacial erosion has accomplished very little. Lake basins may be classified as (a) preglacial valleys irregularly blocked with either terminal or ground moraine, (b) kettle holes caused by melting of blocks of ice buried in the drift. (c) valleys blocked by greater amount of outwash in a connecting valley, (d) due to irregular scour by glacial streams, (e) due to differential glacial erosion mainly on areas of weak rock or deeply disintegrated rock, and (f) unclassified irregularities of glacial deposition. Many marshes were once shallow lakes and still preserve their shorefeatures. Falls and rapids, either over bed fock or bowlders, are characteristic of the streams of the young drift.

Drainage changes in the older drift. In the areas of older or pre-Wisconsin drift, postglacial erosion is marked and has almost everywhere drained the lakes and many of the marshes and locally has destroyed all vestiges of the original drift topography. Where drainage coincided with preglacial valleys they have been re-excavated and where streams were superimposed on rock ridges relatively narrow gorges have been formed, features in sharp contrast with the more mature preglacial forms. The abundance of such diversions is an index of the original depth of drift in the region.

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BOWLDER TRAINS

Definition. A bowlder train is the debris spread out from a particular rock area by glacial action.

Description. A bowlder train is fan-shaped, has its apex at the source of the material, and extends out in the direction of glacial movement. The bowlders become smaller and make up a lesser portion of the drift with incresing distance of transportation. The fan shape is the natural consequence of variation in the direction of glacial flow during growth and wastage of the ice sheet; it is similar to the case of crossing striae. Too far-reaching conclusions cannot be drawn from this normal phenomenon until other possibilities than separate stages of ice advance have been eliminated. The smaller stones may have been transported by water for a portion or all of their journey. Care must be taken that (a) there are no far-travelled stones of the same kind in the drift, (b) that the stones of the train are properly identified, and (c) that the drift does not conceal ledges of the same kind of rock at other points than at the apex of the fan.

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GLACIAL TRANSPORTATION

General. Material was transported (a) on top of the ice or superglacially, (b) in the ice or englacially, and (c) under the ice or subglacially. In the continental glaciers the first was operative only (a) near nunatacks and (b) near the margin where englacial debris melted out of the ice and covered the surface. Drift tends to move downward in a glacier by (a) falling down crevasses, and (b) burial by snow. Small particles which can be warmed through by the sun melt down into the ice but large stones or thick accumulations of drift tend to protect from the sun. Subglacial material becomes englacial and englacial drift rises because of shear in the ice over the basal portion a process largly induced by excessive debris in the basal ice which causes loss of plasticity and hence stagnation. This shearing caused the striation of somestones. Not all englacial drift came from the bottom by this means but was picked up from hills crossed by the ice. It is often said that glaciers differ from rivers in being able to elevate material above its source but this is due solely to the great thickness of glaciers which causes upward currents induced by bottom irregularities to be more conspicious in their effects than is the case with rivers.

How the ice obtained its load. The ice obtained its load by (a) plucking out of blocks of rock, (b) abrasion of rock by material in the ice, and (c) freezing to soil and loose rocks. Plowing up the the ground was doubtless rare except where material lay against the ice face or had a very irregular topography. Great masses of gravel, probably frozen when transported, are common in the drift; masses of clay and till are probably present but are not so readilly distinguished.

Zones of glacial action. Near the centers of ice accumulation the ice picked up much more drift than it deposited; this was the zone of drift accumulation. Near the glacial boundary the ice left more than it picked up there making the zone of drift deposition. At no place, however, did the glacier fail to pick up some local material although near the margin it did override much loose material. It is not possible for glacial drift deposits to have a distinctive assortment of pebbles save where the ice came from different directions. The idea that glacial drift deposits of differnt ages had distinctive lithologic characters is erronious.

Local origin of drift. While it is the far-traveled stones of the drift which attract much attention the greater portion of the determinable material was not carried very far. This was due to (a) spreading out of the ice away from the centers of accumulation, (b) deposition of many stones along the route of transportation, (c) wearing out and disruption of some of the far-traveled sstones, (d) origin of some of the ice away from the centers, (e) the relativly soft rocks south of the crystalline areas where the ice accumulated which were readilly picked up. In the northern United States except in northern Wisconsin, Michigan, Minnesota, New York, and all of New England which contain crystalline rocks, there is a sharp contrast between the far-traveled Canadian rocks and the local sedimentaries. Here the existance of glacial transportation is most evident. Most of the large bowlders of this region are of Canadian crystalline rocks. Attempts have been made to show that these bowlders traveled high in the ice and were therefore not disrupted. It is more plausible to suppose that they owe their ~~xx~~ size simply to their hardness and the rarity of joint planes as compared with most sedimentary rocks.

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GLACIAL DEPOSITS---TILL

Definition. Till is unstratified and unassorted glacial drift with particles ranging from clay to bowlders many feet in diameter. The term "bowlder clay" as synonemous with till is inapplicable to many regions and is virtually obsolete.

Material. On account of the local origin of glacial drift the character of glacial till depends on the character of the adjacent bed rock. Clay till is found in shale regions or where lake ~~x~~ clays were overridden; in sandstone regions the till is sandy, and in limestone and crystalline rock districts the drift is very stony. Striated and faceted stones are characteristic of till but water-worn shapes are not uncommon having been derived from overriden gravels and from conglomerates.

Bowlders are more conspicious on the surface than within the till; this is mainly due to concentration by erosion of the finer materials.

Structure. While most tills are entirly destitute of structure or stratification there are exceptions. These are: (a) sucessive layers of slightly different compositiön deposited under varying conditions, (b) pressure lamination which is best developed in clay tills and which extends around stones, and (c) contorted semi-lamination due to mud avalanches while the drift was still wet.

Similar deposits. The following materials may be mistaken for till: (a) bowlder beds or bowlder pavements formed by concentration of stones through rain, stream, and wave erosion, (b) coarse, ill-assorted, poorly stratified gravels, mainly those associated with terminal moraines, (c) gravels with ice-rafted bowlders, (d) lake clays with ice-rafted bowlders; these clays are laminated below the zone of weathering, (e) weathered and slumped gravels in which stratification has been obscured and with which in some cases loess has been mingled, and (f) talus and residual deposits. A very common error is to describe the weathered surface of gravels as till. The absence of either end of the series of different sizes of material is always strongly suggestive that the deposit in question is not till. If the material lacks clay and rock flour it certainly is not till. Presence of striated bed rock beneath a deposit is conclusive evidence that it is till.

Field and office study. Counts of not less than 100 pebbles selected at random are a valuable means of determining the source of the drift and therefore of checking the direction of movement of the ice. Such counts require that the bulk of the pebbles be of rocks whose outcrop area is known. In heavilly drift-covered areas or where the rock geology is imperfectly known pebble counts are of little value. Results differ with different sizes of material for pebbles fail to account for friable rocks like sandstone and shale. It seems best to take pebbles of from one to three inches in diameter. To determine the origin of the finer constituents mechanical analyses of the till are needed. A wet process of separation is necessay as the finer materials form aggregates. Mechanical analyses thus far published are mainly of soils which have been much altered by weathering. Analyses are capable of yielding much information as to the proportions of preglacial residual material and mechanically disrupted rock. Ground limestone and feldspar flour indicate the latter and red or brown clays the former. That so many tills are gray or blue below the zone of postglacial oxidation is not a certain indication that they were mainly derived from fresh rock for the color has doubtless been changed by (a) ground water action, and (b) reduction by organic matter in the drift.

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TERMINAL MORAINES

Definition. A terminal moraine is a deposit of drift which was formed at the margin of a glacier.

Classification. Terminal moraines are classified as (a) true terminal moraines or "end moraines" formed at the maximum of a glacial advance, (b) recessional moraines formed during the retreat of the ice margin from its maximum extent, (c) land moraines, (d) water-laid, kame, or delta moraines, and (e) interlobate moraines formed along the line of juncture of two separate lobes. Continental glaciers, save where divided into tongues in very rough topography, do not form lateral or medial moraines. Terminal moraines are frequently spoken of simply as moraines.

Material. Terminal moraines consist of (a) till, and (b) assorted material (sand and gravel). Moraines of the second class are described under glacio-fluvial deposits but in most cases there is intimate mingling of the two classes in the same moraine. The till of terminal moraines is somewhat more bowldery than the average; this is dueto steep slopes (a) where the bowlders are exposed by slope wash, and (b) removal of finer material by glacial waters.

Topography. Terminal moraines are ridges along the ice margin and run normal to the direction of ice motion. The course of a moraine swings outward from the glacial center in low tracts where the ice was thick and could flow freely and in the reverse directions on uplands which split the ice. Such protrusions of the glacial boundary are called glacial lobes. Clay till moraines are broad, relativly smooth ridges with the steeper side away from the ice side. The maximum slope is only a few degrees." Stony or gravelly moraines have slopes up to 25 degrees with complex "short hills", winding interconnecting ridges, sharp knolls, and many depressions which contain lakes, ponds, and marshes. It is this kind of topography which is most characteristic of marginal deposits.

Conditions of origin. Terminal moraines were the dumping grounds of the glaciers and the accumulated deposits were never subjected to the smoothing effect of ice passing over them. Blocks of ice up to several miles across were isolated from the main body of the glacier and buried in the terminal moraine. Later these melted and the drift fell in to form kettle holes. This fact together with the melting of the main ice body which supported drift against its face left many slopes at the angle of repose for wet drift. The slides of drift are frequently called mud avalanches. Steep slopes once against the ice margin are spoken of as ice-contact faces. Not all undrained depressions in a terminal moraine were caused by melting ice masses; many were caused by (a) spaces between ridges formed at successive minor retreats of the ice margin, (b) irregular settling of the drift, (c) slides of drift, (d) unclassified irregularities of deposition. The amount of water assorted drift in a moraine was determined by (a) the amount of stony and sandy material in the till which was [illegible] for assortment by water, [illegible] (b) the amount of [illegible] which was available for concentration by glacial waters, and (b) the amount of water present which was greatest where the ice margin stood in a lake or the sea. The stony till regions show much more sand and gravel than do clay till regions. There could have been no such thing as a "moraine-forming habit" which was possessed by certain ice advances and not by others. In order to be preserved moraines must have been deposited either (a) at the maximum stand of the ice front or (b) during the recession of the ice edge since marginal deposits made during the advance were overridden and destroyed. In order to form a moraine of any considerable bulk the ice margin must have remained essentially in the same place for some time, probably for a number of years. Till moraines imply that the ice was moving to bring up the material to the border; the material of assorted moraines may have been in large part carried to the ice margin by glacial streams so that the glacier may not always have been in motion to form such deposits. The margin of moving ice was kept stationary by melting equal to the rate of motion; in the case of stagnant ice the condition was caused by lack of melting and could therfore not last very long. Recessional moraines imply changes which produced halts in the retreat of the ice. These were caused by (a) lowering of the temperature for a certain lapse of time, (b) increase of snowfall on the ice, (c) recession of the ice margin to a point where the ice was protected by a range of hills, (d) retreat to where the ice was thick in valleys, and (e) in the case of a submerged ice front retreat to a point where the ice front was aground and bergs could not form so readilly as where the ice was floating, rapid retreat following upon thinning of the ice so that it could float, In many cases it is impossible to determine just which one of these causes was operative but it is evident that changes in climate will not account for all recessional moraines. The bulk of the moraine is proportionate to the duration of the halt other things being equal. Many moraines formed during a brief halt are weak and discontinuous; this is particularly noticable with kame and delta moraines which were formed only where streams left the ice. The extreme complexity of interlobate maoraines is due (a) to their double character for they are really two terminal moraines adjoining, and (b) to the concentration of glacial drainage with formation of gravels.

Similar topography. On the basis of topography alone terminal moraines might be confused with (a) sand dunes, (b) gullied unconsolidated material, (c) limestone sinks or "karst topography", (d) landslide topography, (e) flood plain topography, and (f) pitted outwash. In most of these the nature of the material is enough to make distinction easy. Gullies follow a definite law and unless blocked by recent landslides show no undrained depressions; pitted outwash will be discussed later.

Field mapping. The outer border of a terminal moraine is generally a fairly definite line which is not difficult to map. Where the region outside the moraine is unglaciated or thinly drift-covered, the mapping is very simple butin the case of recessional moraines or a moraine adjacent to a thick drift area the problem is more difficult. The map boundary should be drawn at the foot of the ridge and not at the edge of knobs and kettles where such are present; the same rule applies to the inner border of a terminal moraine which is a much less regular line. In general, morainic topography is distinguished by (a) linear trend normal to the ice movement, and (b) complexity of the smaller topographic feature which display steep slopes, undrained depressions, and no regularity of summit levels.

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DRUMLINS

Definition. A drumlin is an oval hill composed of till whose long axis is essentially parallel to the direction of glacial motion at that point.

Topographic form. Typical drumlins are several times as long as wide but there are all variations from nearly circular forms to very long ridges some of which have more than one crest. Most drumlins have the stoss or upstream end quite steep and the lee or downstream end a long tail but exceptions are not uncommon. The sides are steeper than the nose reaching in many localities a slope of 20 degrees. Drumlins seem to be limited to a maximum heigth of about 200 feet and most are not over 100 feet. The great majority are less than half a mile in length although a few are several miles long. There is every gradation from small elongate swells of drift to typical drumlins. Adjoining drumlins in many cases coalesce into twin, triple, or en echelon combinations; in places the tail of one drumlin forms a shelf along the side of the one to the rear. One large crest may branch into two or three tails. Many drumlins have scalloped sides or crests or both; some of the scallops are gullies but others are not.

Material. Drumlins are virtually all till similar in composition to the associated drift; where stratified beds are present they are in many cases folded or disturbed. Rock cores are rare but some rock hills have tails which resemble drumlins; these are termed "crag and tail or "rocdrumlins". Banding and concentric lamination parallel to the surface is not uncommon; it is best seen under proper moisture conditions.

Distribution. Drumlins are relativly rare. They are found in parts of Wisconsin, Michigan, New York, Minnesota, Iowa, New England, Ireland, England, Switzerland, and Germany. Those of Iowa are deeply loess-covered and were called"paha" by McGee. Drumlins occur in belts of a few miles width which are roughly parallel to the terminal moraines. They occur mainly on plains and do not extend within several miles of the drift border. Drumlins seem to bear little, if any, relation to (a) kind of till, (b) kind of underlying rock, or (c) preglacial topography. On the whole they are rare in both very stony and very clayey drifts. They occur in regions of vigorous ice movement due to shove from behind and not to descending of a slope at that point.

Relation to other drift. Drumlins are older than recessional moraines, kames, and eskers all of which bury them and whose location they have in large part controlled. Drumlins occur in belts each of which is a few miles in the rear of a recessional moraine. Recessional moraines are weakly developed in drumlin regions.

Origin. There are two rival theories of the origin of drumlins; (a) the destructional theory, and (b) the constructional theory. (a) The first view holds that drumlins are the ice-worn remnants of overridden moraines. In answer to this it may be said that (1) the position of the steeper end is exactly opposite to that of a roche moutonnee, (2) the drift of drumlins lacks the coarse kame gravels of terminal moraines, and (3) the width of the drumlin belts is far too great for moraines. Nevertheless, some drumlin-like hills may be of destructional origin. (b) The second view is supported by (1) concentric banding of the till which suggests plastering on rather than wearing off, (2) the topographic form which suggests accumulation rather than abrasion, (3) the distribution of drumlins where the ice was in motion clear to the bottom, (4) the fact that the relation of drumlin belts to sucessive moraines suggests control by ice thickness at a certain distance behind the ice margin, (5) the fact that drumlins are made only of moderately plastic till, (6) the apparent interrelation of drumlins and weak moraines which suggests lodgement of drift before it reached the ice margin, (7) the orientation of drumlin axes normal to the associated moraines and not to the outermost moraine, (8) the rarity of drumlins which suggests narrow limits within which the various forces must have operated to produce drumlins, and (9) the apparent relation of drumlins to areas of spreading out ice. The balanced forces were (1) amount of load in the ice, (2) character of drift, (3) vertical and horizontal pressures in the ice, and (4) speed of movement. Lodgement of drift seems to have been initiated along lines of either less pressure or less movement, possibly along longitudinal crevasses. However, the infinite variety of drumlin forms does not exclude the possibility of there being some destructional drumlins.

Field mapping. On account of the great variation in form the exact number of drumlins which should be shown on a map depends on the personal judgment of the geologist as well as on the scale of publication. The border of each drumlin should be shown at the edge of the drumlin form and not at the lowest elliptical contour; an interval of 20 feet is insufficient to show all the details of drumlin topography, and many drumlins lie on a sloping base. Well records must be collected in order to distinguish hills of similar shape which have rock cores.

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GROUND MORAINE

Definition. Ground moraine is that area of drift which is not definite terminal moraines, drumlins, or glacio-fluvial deposits; it is drift smoothed by ice cover.

Topography. Ground moraine varies from merely scattered drift over a rock topography to drift thick enough to conceal all traces of the proglacial topography. Wherever the drift is thick enough to influence the topography the slopes are low, gentle, and smooth, rarely exceeding 5 degrees, and in regions of clay drift the ground moraine is a dead level or "till plain". Where rock hills show through the drift the stoss sides are much gentler than the lee sides. There are few, if any, marked sags or hummocks. Lakes are not very common in ground moraine areas. Some authorities call drumlins a variety of ground moraine. Ground moraines average thinner drift than do terminal moraines and show more rock outcrops.

Material. Ground moraine consists of till with rare areas of water deposits and with layers of assorted material which do not show at the surface. Bowlders are somewhat less abundant than in terminal moraines.

Conditions of origin. Ground moraine is essentially an ice-smoothed topography. The materials accumulated both (a) under the ice by melting out, and (b) by the final melting of the ice when it left the region at places where the margin did not remain long enough to form a definite terminal moraine. Stratified deposits were smoothed over or buried under till. There is no known way of separating the deposits made in the two different ways.

Field mapping The chief difficulty in mapping is to separate ground moraine from weakly developed terminal moraine; the ridge form of the latter should serve to distinguish. It is well to remember that the ice margin stood at all parts of the glaciated area during its retreat and that therefore some faint indications of marginal deposits may be expected almost anywhere. Search for gravel in ground moraine topography is well nigh hopeless.

GLACIO-FLUVIAL DEPOSITS

Definition. Glacio-fluvial deposits are glacial drift worked over and redeposited by waters which were mainly derived from the melting of the ice.

Materials. Glacio-fluvial deposits are assorted according to size of particles; they consist of (a) gravel, (b) sand, and (c) clay. The following definitions will make this more definite: (a) bowlders are stones over a foot in diameter, (b) gravel is stones from a foot to 1/16 inch in diameter, (c) sand is particles from 1 mm. to 0.05 mm. in diameter, (d) silt or rock flour is particles from 0.05 to 0.005 mm. in diameter, and (e) clay is particles smaller than 0.005 mm. in diameter. Ice-rafted stones may be found in all classes of glacio-fluvial deposits. Commercial gravel is defined as material with more than half by ~~wt~~ weight larger than 1/16 inch particles. The word gravel should never be applied either (a) to scattered stones in sand, or (b) to non-aqueous deposits. It is the glacio-fluvial deposits which are of the most economic importance in the drift. Road material investigation is the applied geology of these deposits.

Conditions of origin. Glaciers give off floods of water under all save very exceptional conditions; these are (a) very severe climate like that of Antarctica, (b) thin ice covered with debris, and (c) underlying loose materials which cared for the water by percolation. Under thick ice the heat of the earth was undoubtedly enough to cause copious melting throughout the year as is the case in Greenland today. Melting was greatest in summer. Unconsolidated deposits could never have absorbed much water and a very moderate rate of melting would have been sufficient to raise the water table to the surface and to cause streams in all low tracts. That melting took place during the advance of the ice as well as at its maximum and during its period of wastage, although there naturally was the most water during the last named time, is shown by (a) lake and stream deposits buried under till with no evidence of a prolonged exposure to the atmosphere after their deposition, and (b) the absence of local glaciers in the Driftless Area which indicates that the conditions of glacial accumulation never extended very far south but that the ice was always in the zone of wastage in most of the United States. The glacial waters were probably added to by local precipitation. They formed streams and lakes in which glacial till was washed over and assored before deposition. The perfection of assortment and of water-wear depended upon the time and vigor of the water motion. The perfection of stratification depended upon the rapidity of variations in the velocity of the water. Glacio-fluvial deposits were formed (a) under the ice, (b) at the edge of the ice on land, (c) beyond the edge of the ice on land, (d) on the ice, (e) at the edge of the ice in standing water, (f) beyond the edge of the ice in standing water, and (g) where streams flowed off the land into standing water.

Classification. Glacio-fluvial deposits are commonly mapped as (a) outwash plains, (b) pitted outwash, (c) kames, (d) eskers, (e) deltas, (f) water-laid moraines, and (g) lake deposits.

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OUTWASH

Definition. Outwash (overwash in older literature) consists of material deposited by glacial streams on land.

Topography. Outwash forms plains with a slope decreasing from over 15 feet per mile near the source of the streams to one or two feet per mile farther from the ice front. Undisturbed outwash plains are nearly plane surfaces. Some outwash plains contain pits up to several miles in diameter; these have steep sides with a maximum slope of 35 degrees, and contain small hills, lakes, ponds, and swamps. These "pitted outwash plains" in many places resemble terminal moraines but the summits are many of them flat topped and the higher ones come up to a common level. Some elongated pits resemble valleys blocked by moraines and have deceived some geologists. Outwash plains in valleys leading from the ice front are called "valley trains."

Material. Outwash consists of sand and gravel and is, in general, the best sorted of all glacio-fluvial deposits. The average size of stones decreases away from the source of material, in other words in going downstream. Rounding increases in the same direction. Bowlders and striated stones are rare. Silt is present to some extent both scattered through the sand and gravel and in thin layers. The sand and gravel is horizontally bedded and occurs in irregular curving lenses with their long axes parallel to the average direction of the streams that deposited the plain. Cross-bedding is common and dips in all directions but mainly downstream. Near to pits bedding is inclined, disturbed, or absent.

Conditions of origin. Streams overloaded with debris came out of cracks and tunnels in the ice. They gathered together in valleys and, except where the grade was too steep or the valley too narrow, began to aggrade their beds at once. The material was laid down in order of size as the velocity decreased away from the ice. The slope of the stream decreased in the same way. The streams built up their beds until higher than adjacent areas; then shifts of course took place causing "braided" streams. Thus the entire plain was built. Silts from the milky waters were deposited in slack-water portions of the channels. As originally formed the surface of the outwash plain was furrowed with abandoned stream channels but subsequent wind work did much to even the surface. Loess, derived from floodplain silts and adjacent freshly uncovered drift, was deposited on many outwash areas. Sand dunes were formed on other plains; many of these are no longer active. Most of the streams were too shallow for large icebergs and hence ice-rafted bowlders are rare. Striated stones were smoothed by transportation. The quality of material in outwash plains was also conditioned on the character of the load that the glacial waters could get. In clay till there is little material for sand and gravel, a fact which accounts for the paucity of outwash in areas of that kind of till. Outwash plains formed outside of the maximum extent of the ice at any particular stage of glacial advance could not bury any large ice blocks but deposits formed in front of recessional moraines formed after relativly rapid retreat of the ice covered large and small ice masses that had not yet melted. Melting was delayed by the burial with sand and gravel. Elongated ice blocks were preserved in valleys and gave rise on melting to the pseudo-blocked valleys of some districts. The ice blocks contained till which was left in and around the kettles adding to the confusing appearance. Some outwash deposits contain bowlders derived by the streams from hills of drift within the area of the plain that were later buried by the sediments. Melting of ice blocks locally changed the grade of streams and caused them to change from depositing to eroding thus making valleys through the pitted plain. Presence of pitted outwash is indisputable proof that the ice was over that area not long before its formation for ice blocks could not survive a prolonged retreat of the glacier followed by a readvance, much less an interglacial interval. Outwash deposited during the advance of the ice was (a) buried to form lenses of sand and gravel in the drift, or (b) plowed up into gravel bowlders or incorporated into the till. The formation of gravel bowlders was favored by (a) position of the outwash on or against the ice, and (b) freezing of the material. The largest outwash deposits seem to have been formed at or near the maximum stand of a glacial stage for the ice front remained there for the longest time. That the outermost terminal moraine locally overlies the outwash deposits is no proof that they are much older than the ice maximum. During wastage of the ice sheet melting was slackened by the melting out of drift on top of the ice. In rough country outwash was deposited along the sides of ice tongues in deep valleys; these now form a species of outwash terraces.

Terraces. As the ice margin fell back the waters deposited their load farther and farther back and were thus adjusted to a lower grade than at the same place before. Lakes were formed and the waters cleared in them. As a result the outwash plains were eroded into terraces. Another change was the erosion of drift and rock barriers in the streams which changed their baselevel above those points. In some valleys the erosion has continued to the present time, the less loaded and shrunken streams eroding their formed deposits; in other cases reduction of volume caused aggradation. Mississippi River is building up its bed and receives more sediment from tributaries than it can now remove. This is indicated by then phenomenas of Lake Pepin and the swinging of the river away from the mouths of tributaries. Other causes of erosion of outwash plains into terraces were (a) recession of the ice front which opened lower avenues of drainage, and (b) melting of ice masses in the gravels. Postglacial and late glacial northeastward uplift of the land doubtless aided in producing terraces but its effects have as yet not been discriminated from the phenomena described above. Reworking of outwash in many cases concentrated the gravels.

Effects of outwash on non-glacial tributaries. Outwash plains extend far from the outermost drift into unglaciated areas. Aggradation of these valleys which carried the glacial floods raised the baselevel of their tributaries. At first lakes were formed in the lower parts of the latter; in time these lakes were filled up and the valleys adjusted to the new conditions. Those that were not filled have for the most part been drained by terracing of the main valleys. In some places similar results occured at the junction of two valleys both of which carried glacial drainage but distance from the ice front and volume differ

Field mapping. Outwash may be distinguished by (a) its relativly horizontal bedding, (b) good assortment, (c) continuity of beds, (d) level top even distinguishable where pitted or eroded. Some till may be found around the pit s of pitted outwash. Map boundaries should be drawn at the break in slope between the plain and any surrounding higher topography.

Exploitation. Outwash is the best form of glacio-fluvial deposit for commercial exploitation on account of the good assortment, comparativly wide extent of deposits of the same grade, rarity of weak stones, and the low silt content.

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KAMES

Definition. Kames are hills of sand and gravel which were formed at or near to the edge of the ice on land, in other words they are the assorted portion of land terminal moraines. Some authorities include similar deposits made under standing water but here these are treated separatly.

Topography. Kames are relativly small, abrupt hills which enclose many kettles. The angle of slope depends on the coarseness of material and reaches a maximum of over 30 degrees. Kames merge into (a) till moraines, (b) pitted outwash, (c) dissected outwash, and (d) eskers. In some valleys there are terraces of kames on the sides which are like outwash terraces. Kames have no regularity of summit levels and no flat tops.

Material. Kames vary from very bowldery, unassorted, poorly stratified gravel to fine sand. The arrangement of the different kinds of materials and the bedding are for the most part very confused and irregular. Assortment and rounding of pebbles is mainly very poor. Folding and faulting are not uncommon. Striated stones are found.

Conditions of origin. Kames are in one sense a form of outwash which was deposited on and close to the ice margin on land. In many places deposition took place in reentrants of the ice margin and around isolated ice blocks which later melted forming kettles. Many kames are alluvial fans which had ice walls on one or more sides. Melting of supporting ice led to slumping to the angle of repose with consequent disturbance of the bedding. Kames may have been formed either by moving or stagnant glaciers since streams brought up the material to the ice edge. Deltas are treated separatly but small ones may be found where pools of water existed among deposits otherwise formed on land.

Similar topography. Kames may be distinguished from deltas by the inclined bedding of the latter, from sand dunes by the stones, from eskers by the irregularity of form, and from outwash by the lack of regularity of summit level.

Field mapping. Kames have been mapped with terminal moraines by most geologists but owing to their economic importance deserve separation. In the absence of exposures kames may be distinguished by their steep slopes although this criterion fails in very stony moraines. Vegetation is sparse on most kames. Kames make up a large part of many moraines and are the most conspicuous features of morainic topography.

Exploitation. Kames are a much less satisfactory source of gravel than outwash deposits on account of the sudden variations in quality. Development should be preceded by thorough test pitting.

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ESKERS

Definition. An esker (osar of older literature) is a ridge of water-deposited drift which has its long axis more or less parallel to the direction of glacial motion.

Topography. Most eskers are steep-sided ridges much like railway embankments. The top, however, is not at all regular in elevation and most long eskers are divided into several distinct sections with considerable gaps between. The highest recorded esker in the United States is about 150 feet high and the longest is over 150 miles in length. The width of eskers varies more or less in proportion to the height; the recorded maximum is about a half a mile. The inclination of the sides varies with the coarseness of material up to a maximum of about 35 degrees. Many eskers are winding; some branch and reunite (reticulate). Eskers end in various ways: some die out to nothing, others join kames, deltas, or outwash, and others have these deposits in the breaks between sections. There is every gradation between eskers and kames and indeed they were once included with kames.

Material. Eskers are made of sand and gravel like that of the other glacio-fluvial deposits of the region. Bowlders are common throughout eskers and especially at the top, and till is not uncommon as a covering. The base of the assorted material in many eskers is lower than the till at the sides of the ridge. Assortment is very poor and subangular and striated stones are common. Bedding is rude, irregular, or entirely absent. "Open-work" gravels with too little sand to fill the voids are not uncommon. Faulting and disturbance of the beds are very common; some eskers show an anticlinal cross section. The grade of material varies very rapidly in most eskers.

Distribution. Eskers are common in regions of fair relief which have stony drift; they are rare in mountains. Most eskers lie in low ground but some disregard the topography and pass over hills up to 400 feet in height. Some eskers lie on valley sides and might be confused with kame or outwash terraces. In drumlin tracts the eskers avoid the drumlins. Eskers are buried by recessional moraines.

Conditions of origin. It is evident that eskers were the deposits of glacial streams within the limits of the ice but whether these streams deposited their load on, in, or under the glacier is not so apparent; there is no general agreement on the latter point. Eskers have not been observed in process of formation by modern glaciers. Most glaciers are drained by streams which flow in tunnels at the bottom of the ice, for there are too many crevasses to permit streams of great extent at higher levels. However, (a) caving of tunnels, (b) stagnation of ice with filling of crevasses with drift and possibly with standing water, and (c) irregularities in the bed rock are all possible causes for streams above the bottom of the ice. Near the margin of the continental glaciers superglacial streams could obtain a load as well as englacial and subglacial streams; away from the margin the first class of streams, if present, could have had nothing to deposit. All winding and branching eskers indicate either very slow-moving or stagnant ice; indeed the same conclusion seems probable for all eskers. The subglacial theory of eskers is favored by (a) their extension below adjoining till, (b) presence of well-preserved stratification except for slump of the sides, (c) presence of till or bowlders on top of many eskers, (d) the avoidance of hills by many eskers, (e) presence of open-work gravels, and (f) presence in some eskers of stones derived so near that they could hardly have been very high in the ice. Objections are (a) the great widths of some eskers, (b) meandering and branching eskers, (c) disregard of hills by many eskers, difficulty of understanding deposition on both ascending and descending slopes, (e) difficulty of accounting for the upward growth of a tunnel in exact proportion to the irregular summits of eskers, (f) difficulty of accounting for observed gradation of some eskers into kames or deltas, and (g) the lack of stratification in some eskers. All these facts favor the origin of the eskers in which they are found in cracks open to the sky which may or may not have reached to the bottom of the ice. It has been suggested that the gravels deposited by superglacial streams melted their way down to the ground before the ice disappeared on the sides, but this is opposed to the observed protection of ice by thick drift deposits. Others have urged that eskers are kames or deltas elongated by gradual retreat of the ice margin. Some have suggested that discharge of drainage into standing water is a necessary condition for the formation of eskers. Under these last views it is difficult to (a) explain very long unbroken eskers, or (b) explain the breaks with no outwash or typical deltas in them. The breaks in eskers were caused either by (a) constrictions in the stream, (b) rapids, or (c) positions of the retreating ice border. The contradictory nature of the evidence and the great variety of the phenomena strongly suggest that all eskers were not of the same origin and that examples of all the suggested modes of origin are present. In the Mississippi Valley most eskers appear to be either long kames or subglacial.

Field mapping. Eskers are mainly found in ground moraine areas. They are readily recognized by (a) shape, (b) orientation, and (c) sparse vegetation. The map boundary should be drawn at the base of the ridge and not at the first contour.

Exploitation. Eskers are almost the sole source of gravel over wide areas but the poor assortment and rapid changes in quality of the material makes them of indifferent quality. An idea of the coarseness of the material may be gained from the steepness of the sides but careful test pitting is required. Even a low esker may be of value if it extends into the till below.

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DELTAS AND WATER-LAID MORAINES

Definition. Delta moraines and water-laid moraines were deposited where the edge of the ice stood in standing water; deltas were also formed where glacial streams flowed from the land into standing water.

Topography. Water-laid moraines are smoother and much less conspicious than are moraines formed on land. Ice margin deltas vary from small cones to large, mesa-like hills with steep sides which are known in New England as "sand plains". The tops of large deltas slope gently away from the ice margin and may contain kettles. The sides of deltas have the slope of the angle of repose under water, a maximum of about 20 degrees. The outline of the front of a large delta is more or less lobate. On the ice side many detlas connect with eskers. Deltas differ from outwash fans in having a distinct break in slope between the top and the sides.

Material. Morainic deltas consist of very poorly sorted and rounded material; deltas at the mouths of land streams may be better sorted. Bowlders are common in the former and till deposits may be found on the side toward the ice. Subangular and striated stones are very common in the first class of deltas; sand with scattered stones is very common. The bedding is the most characteristic feature of a delta. Where undisturbed a delta may be divided into (a) bottomset horizontal beds of fine clay or sand, (b) foreset beds of sand and gravel dipping about 20 degrees toward deep water; these overlie the bottomset beds, (c) if the deposit is large enough topset beds which are nearly horizontal and overlie the inclined strata, and (d) in many cases backset beds on the ice side which rise to the topset beds, that is dip in the opposite direction from the foreset beds. Cross bedding is not uncommon in topset beds. Water-laid moraines are largely but not wholly assorted material but are for the most part covered by sand and gravel.

Water-laid moraines were smoothed by the work of waves and of streams which emerged from the ice. They merge into delta moraines just as deltas merge into land kames. When the ice margin stood in a lake or sea the streams were suddenly checked and deposited their load before they had time to assort or wear it to any great extent. At first the deltas were small cones that did not rise to the water level but as they grew they covered the bottomset beds. When the tops rose to the water level topset beds could be formed above the slanting foreset and backset beds. Morainic deltas were largely fed by subglacial streams for the most part but in the case of superglacial streams topset beds may locally have been laid down on top of the ice. Some supposed backset beds may be due to sliding of the material after removal of the supporting ice. Blocks of ice were buried in the deltas and some melted quickly enough for the streams to fill the kettles. In many places adjoining deltas coalesced into a species of outwash plain with a delta front. Deltas were deposited very rapidly; many show very little if any sign of motion of the ice edge during their formation and so may have been formed in a single summer. Many deltas were doubtless formed at the edge of stagnant ice. Deltas not formed at the ice front present no unusual features. They are free of the bowlders which rolled down from the ice into marginal deltas but might contain some ice-rafted bowlders.

Field mapping. Deltas may be recognized by (a) their characteristic forms, either conical or flat-topped, and (b) their inclined bedding. Care must be taken to see that exposures are deep enough to distinguish the latter from cross bedding in outwash or kames. Water-laid moraines are ridges normal to the ice flow that connect with ordinary moraines. Delta and water-laid moraines have generally been mapped along with other terminal moraines but distinction is desirable.

Exploitation. Deltas are in general very inferior sources of gravel although they may contain good sand. The deposits are very sandy and are poorly assorted and variable. The topset beds most resemble outwash and are therefore the best. Water may frequently be found in large deltas just above the impervious bottomset beds.

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MARGINAL LAKES

Definition. A marginal lake or true glacial lake is one where glacial ice acted as a dam to enclose the basin.

Topographic features. Ice-bound marginal lakes left traces in (a) wave-worn cliffs, (b) bowlder lines, (c) wave-built bars, spits, beaches, etc., (d) quiet water sediments, and (e) deltas. Any one of these is sufficient to prove the existence of a lake. Cliffs are steep slopes in drift and vertical cliffs in rock; they are scars on the smooth contours of glaciated topography. Bowlders line the bottoms of cliffs in the drift and lines of them are found even where there is no distinct cliff. Where the descent into deep water was relatively abrupt there is a terrace in front of the cliffs whose outer edge slopes steeply down into the lake basin. On gently sloping shores and in bays spits, hooks, barriers, and bars are found, all of them ridges with nearly level tops. The bottoms of lake basins are in most instances nearly flat or smooth slopes of up to 50 feet per mile. Deltas have been described above. Marginal lakes had outlets (a) on land, (b) over the ice, or (c) through the ice. Of these traces remain of the first in the form of valleys either (a) without streams, or (b) much too large for the present streams. The floors of these valleys contain shallow lakes and bowlder pavements. In some cases several lines of beaches at different levels are found. In some places these all lead into the same outlet and in other instances into different outlets. Rock ledges in outlets often contain large pot holes.

Material. On the cut portions of shore terraces there is little gravel; the outer built part is fairly well sorted gravels in beds which dip away from the shore at angles up to about 20 degrees. On account of the shuffling action of waves there is some tendancy toward tabular pebbles. The material of bars and spits is better assorted and is more water-worn. These features have a rude anticlinal section with beds dipping on both sides at a maximum of about 20 degrees. The angle is steepest on the inshore side. Silt and clay are found in deep lakes and sand alone in shallow water. The clays are laminated unlike glacio-marine clays which are massive. The laminae are in pairs of alternately coarse and fine material. The coarser material is rock flour like that of the associated tills. In dolomite regions the lake clays contrast sharply with the calcitic postglacial marls. The carbonates of the calcareous clays of the Lake Superior basin must have been derived from Keeweenawan shales. From Superior to Milwaukee the lake clays are red and contain up to 15 per cent of Fe_2O_3. The color was derived from the red rocks and iron ores of the Superior region and have no relation to postglacial weathering as it extends below water table and is not associated with leaching. Most lake clays are gray or blue, in part because of reduction by ground water. Colors depend upon the amount of water present and change markedly on drying. Silica is for the most part below 50 per cent and alumina is below 15 percent. Potassium oxide may exceed 3 per cent. Calcareous clays are leached near the surface and have carbonate concretions below. Ice-rafted stones are common but rarely obscure the lamination. Near the surface weathering has obscured the lamination. Sliding of clays both (a) during deposition, and (b) in postglacial time has caused many folds and faults. Grounding of ice bergs was responsible for some disturbances.

Conditions of origin. The work of waves on shores is described in all text books of geology and physiography and need not be repeated. Some lakes fail to display beach features because of (a) slight wave action on account of covering by floating and solid ice, (b) rapidly varying water level, (c) short life, or (d) subsequent burial or erosion of the features. In long-lived lakes the quiet water sediments were in part buried by deltas and shore gravels. Lowering of the water level led to covering with shallow water sediments. Changes in level were due to (a) erosion of outlets, and (b) changes in the position of the ice margin which when in retreat opened sucessivly lower and lower outlets, and when in advance blocked successive avenues of escape. Although the waves must at one time have stood at all levels in a basin it is only at those elevations where they remained for some time that marked shore features were developed. The quiet water sediments dip gently to the center of the basin and in many cases form the confining top of an artesian basin. The maximum number of ice bergs entered a lake during its early stages before the ice front had been masked by deltas. Wave work was at its maximum on islands and headlands; it must have been much interfered with by floating and solid ice. The glacial lake outlets have been much altered by aggradation by both main and tributary streams since the flow diminished; this has formed more lakes in the already uneven bottom.

Varves. Even where the ice margin stood in the sea the adjacent waters were quite fresh on account of the large volume of glacial water. Precipitation of clay and silt takes place very differently in fresh and in salt water. In the latter flocculation took place and the aggregates carried down fine and coarse material together to form massive clays. In fresh water the process was slower and the coarse material settled before the fine. Most of the supply of sediment came in summer when the ice melted fastest. The paired laminae of fresh water clays consist of a coarse and a fine layer; this combination is interpreted as an annual deposit, the coarse formed in the summer and the fine in the winter. Each pair is called a "varve." The fine layer is for the most part of darker color than the coarse layer. There is every gradation from massive clays to typical varve clays. While the seasonal origin of varves is well established it does not follow that all laminated glacio-fluvial deposits show annual layers. It has been shown by actual observation that somewhat similar laminae develop on flood plains in a short space of time. It is suggested that where deposition was very rapid several laminae due to changes in water velocity, storms, etc. may correspond to a single varve in deep water. In America the study of varves is in its infancy; although subject to some uncertainty it offers great possibilities in that it places geologic history in terms of years instead of indefinite stages, periods, etc. It is evident that no one exposure can show all the varves that were formed. Correlation of adjacent sections is based on the assumption that the thickness of sucessive varves is a function of temperature. The variations of sucessive varves is then a reflection of variation in climate and individual varves can therefore be correlated as explained below. This method has produced results that are reasonable but its validity has not met with universal acceptance. It fails to produce results under several conditions: (a) when the varves are all nearly of the same thickness with no distinctive succession of changes, (b) where local floods or storms upset or masked seasonal variations, (c) when too great a distance is involved, and (d) when the varves have been altered by creep or iceberg action.

Field mapping. Lake beaches and cliffs can be identified by their sharp outlines, levelness, and local origin of the gravel. Bars can be distinguished from eskers by their level tops and orientation. They are more uniform in composition and have better and less disturbed bedding. Elevations of the ancient water surfaces may be measured by (a) break in slope at the front of a delta, (b) top of a beach at the foot of a cliff, (c) upper limit of smooth lake-bottom topography, and (d) bars and beach ridges which extend some few feet above high water mark. In some basins the only evidence is the upper limit of lake sediments and ice-rafted bowlders. Elevations must be measured accurately; the hand level may be used if the distances are short and the slopes are steep but otherwise either the engineers level or the stadia must be employed. Lake clays may be distinguished from clay till by (a) lamination, and (b) ice-rafted stones; only clean fresh exposures can be considered, for slumping destroys lamination and also gives an exaggerated impression of the thickness of the clay. Clays below sands and gravels make a spring line. Varves are measured by cleaning off a face and marking the thicknesses on a long strip of paper. In the office these thicknesses are transferred to a graph with equal intervals for years and the thicknesses themselves as ordinates. The ends of the ordinates are then connected into a saw-tooth curve. The graphs of adjacent localities are moved up or down until correlation is established from similarity of the curves. As a check on this method laboratory study of the chemical and physical characters of the clays has been used so that lithologic correlations are also made in a manner similar to the lithologic correlation of marine formations. Samples of varve clays can be taken in long shallow metal boxes and glycerine substituted for the water in order to keep them.

Exploitation. Beach gravels generally do not bind well enough for road surfacing but may be used for concrete. Clays are mainly sought for clay products and for surfacing sandy roads. Elevations are useful in searching for beaches and clays.

ICE-BOUND LAKES OF THE UNITED STATES

Age. Marginal lakes were formed during the advance, maximum, and retreat of all ice invasions. Little trace is found of lakes of the first class since their beaches were destroyed and the bottom deposits either plowed up or buried by till. Such conditions gave rise to some of the very clayey tills. Pre-Wisconsin lake deposits within the area of the young drift also suffered the same fate. Outside of the terminal moraine traces of the older lakes have suffered much from (a) erosion, (b) burial by alluvium, and (c) burial by young outwash. Lakes whose only trace is ice-rafted stones have been discovered in southern Indiana and southern Wisconsin and some are suspected on the Great Plains.
The marginal lakes of the Wisconsin or young glaciation are much better known. Those which existed at the maximum of that invasion comprise Lake Passiac in New Jersey, Lake Wisconsin in Wisconsin, and a number of lakes on the Great Plains. More lakes were formed when the ice front had retreated into the Great Lake basins where the average slope of the land was toward instead of away from the glacier. Names have been given to the different levels of water in the several basins. Changes in level of the glacial Great Lakes were effected not only by (a) uncovering of different outlets by ice retreat but (b) by northeastward uplift of the land. The earlier lakes comprise Lake Agassiz in the valley of the Red River with its outlet via Minnesota River, Lake Duluth in the Superior basin with outlets to St. Croix River, Lake Chicago in the Michigan basin with an outlet to Illinois River, Lake Maumee in the Erie basin with

an outlet via the Wabash, and Lake Jean Nicollet in the Fox River Valley of Wisconsin with an outlet to Wisconsin River. Further recession of the ice opened lower outlets across the upper and lower peninsulas of Michigan and possibly north of Lake Superior until the lakes fell to something like their present level. A readvance of the ice known to have extended southwest of Superior and to Milwaukee and Port Huron then formed a second Lake Chicago, Lake Whittlesey, and Lake Warren. Lake Agassiz also suffered a low stage followed by a high level caused by an ice readvance. Renewed recession of the ice opened an outlet via Trent River in lower Ontario and caused Lake Algonquin which filled the basins of all three of the upper lakes. This vast lake drained into Lake Iroquois in the Erie basin which in turn discharged to the sea via Mohawk valley, New York. Complete disappearance of the ice from the Great Lakes left Lake Nippissing, a stage when the confluent upper lakes discharged via Ottawa River to the Champlain sea which then joined the Hudson and St. Lawrence Valleys and extended into the Ontario basin. Since then northeastward uplift of the land caused the abandonment of this outlet for the present one via Detroit and Niagara Falls. The story of the changes in volume of Niagara Falls is clearly told in the different widths of the gorge from place to place. The same uplift also caused the retirement of the sea to its present position.

LATE GLACIAL AND POSTGLACIAL EARTH MOVEMENTS

Field evidence. That there has been late glacial and postglacial movement of the earth's crust in the Great Lakes region and adjacent areas is shown by (a) the northeastward rise in the abandoned beaches, (b) abandonment of northern in favor of southern outlets in the Huron basin, (c) observed change in elevation of certain bench marks as referred to the lake levels, and (d) the drowning of postglacial valleys as at Superior. The slope of the beaches is of the magnitude of several feet per mile; it is (a) greatest in the case of the older high level shorelines, (b) greater to the northeast, and (c) absent to the soutwest, and (d) limited farther and farther to the southwest in sucessivly higher beaches. The limiting line of deformation is called a "hingeline." Lines connecting points of equal elevation of the beaches are called "isobases." The hinge lines and isobases, so far as determined, form smooth curves centering around the pre-Cambrian area or Laurentian highland. Tilting is still going on at the rate of less than six inches per century in the width of the lakes. If this uplift affected the terraces of streams like the Mississippi the fact has not yet been separated from other causes.

Cause. Most authors ascribe the uplift to isostatic conditions, that is as due to the removal of the load of ice. Some have even gone as far as to suggest that ice loading pushed up regions adjacent to the glaciated region, and others have endeavored to measure the thickness of the ice sheets from the amount of uplift. This view fails to take into account the facts (a) that uplift is still in progress long after all the ice has gone, (b) that the isobases are not closely related to the ice border but to the pre-Cambrian area, and (c) that the theory of isostacy has been strongly attacked on other grounds. In Europe, however, the above objections do not seem to have as much force. Mathematical study shows that attraction of the ice masses on the adjacent water was a very minor factor in producing warped water planes. It is probable that the earth movement was not directly associated with glaciation but was one of those known throughout geologic history whose origin is not yet clearly understood. The great amount of water locked up in the ice caps doubtless lowered the mean sea level during the Pleistocene glaciations.

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THE QUATERNARY LAKES OF THE GREAT BASIN

General. In the Great Basin of the western United States there are many enclosed depressions which show evidence of having contained extensive lakes in relatively recent geologic time. At present the basins are either dry most of the time or contain shallow salt lakes. The principal ancient lakes were (a) Lake Bonneville in the region of Great Salt Lake, and (b) Lake Lahontan whose principal survivor is Pyramid Lake, Nevada. Most of the basins have never been studied in detail.

Topography. The lake basins are all of structural origin and date from the late Tertiary uplifts of the western ranges. The shore features of the lakes are classic examples of such topographic forms since they have been so well preserved in the arid climate. Deltas, beaches, cliffs, bars, hooks, etc. are all displayed on a magnificent scale. Lake Bonnevill had an outlet channel to Snake River.

Deposits. The lake basins contain the following series of deposits: (a) older alluvial cones about 2000 feet thick, (b) older lakes beds, marls, clays, and chemical precipitates mainly the chloride and sulphate of sodium and calcium carbonate, (c) intermediate alluvial cones, (d) younger lake beds, and (e) modern alluvial cones.

History. The older alluvial deposits tell of a prolonged interval of arid climate after the formation of the basins. A climatic change, either an increase in precipitation or a lowering in temperature and therefore a decrease of evaporation or both, then caused lakes to form. The earlier Lake Bonneville did not overflow and was never fresh. No beaches of the older lakes are known. A period of aridity then followed which led to the complete drying up of the lakes; this is known from the differences in the character of the chemical sediments in the younger and older lakes. Lake Lahontan never had an outlet but the second Lake Bonneville rose higher than the first and overflowed. It was then fresh water. Erosion cut down the level of the outlet into the soft alluvial deposits to a depth of about 375 feet. The waters stood for a long time at this level and developed the Provo shoreline. A reversion to aridity with some fluctuations caused the lakes to shrink to modern conditions. The beaches are not horizontal but have suffered differential uplift with the maximum apparently at the centers of the basins; this fact has been ascribed to isostacy or relief following on the drying up of the waters.

Relation to glaciation. The relations of the high water stages to glacial advances in the adjacent mountains is best shown in Mono Lake California. Phenomena in the Lake Bonneville region also support the view that the lakes corresponded in time to episodes of maximum glaciation.

Keyes has recently urged that crustal warping cut off rivers from more humid regions thus leading to the variations in the lake levels. This idea is untenable as it could not possibly explain (a) the multitude of lakes throughout the Great Basin, or (b) the exact similarity of history of the lakes that have been studied. The evidence of the western Quaternary lakes is a very powerful argument that there were but two maxima of Pleistocene glaciation.

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LOESS

Definition. Loess is a homogeneous, unstratified silt, for the most part of eolian origin.

Topography. Loess forms a mantle over both rock and drift hills, river terraces, and sand dunes. Only rarely does it make a distinctive constructional topography. Loess is readily eroded and having a tendency to split vertically forms steep-sided ravines. Where these ravines are well developed, as on the banks of the Missouri, a very complex bad-land topography is formed. It is this fact, as well as the greater thickness of loess along stream bluffs which led the early geologists to call the loess the "bluff formation". Loess has a vertical range of about 1500 feet in the Mississippi basin and of much more in other regions.

Material. Loess is composed mainly of silt particles from 0.05 to 0.005 mm. in diameter with a lesser amount of clay particles smaller than 0.005 mm. in diameter. Sand is relatively unimportant except near the base of some deposits; some analyses report larger particles but these are evidently (a) aggregates, and (b) tubular and globular concretions of iron oxide and calcium carbonate. However, there are some stones in thin deposits of loess. Unweathered loess is gray and the weathered loess is yellow, buff, or red. There is a narrow zone of transition in color and iron oxide is particularly abundant there. Concretions are most abundant just below the weathered zone. The vertical cleavage of loes is due to numerous small vertical concretions of tubular form.

Fresh loess in the Mississippi Valley is highly calcareous. Leaching extends to depths of several feet and entirely through the thinner deposits. Toward the base of the oxidized zone there is in some places an alternation of light and dark bands which is due to weathering. While loess is mainly devoid of bedding or lamination there is some interbedding with sand at the base of some deposits. Loess is very sliiceous, 60 to 65 percent SiO_2 in the fresh phase and 65 to 78 percent in the leached zone. Alumina is correspondingly low and iron oxide is for the most part below 5 percent. The minerals of fresh loess are the product of mechanical disintegration; they comprise quartz, feldspar, ferromagnesian minerals, mica, calcite, and dolomite. Carbonaceous bands are rarely present.

Fossils. Unleached loess contains rather abundant irregularly distributed land snail shells; the species are all modern. There is little sign of vegetation except for the vertical concretions which are ascribed to roots. Mammalian bones are found but it is difficult to discriminate those deposited with the loess from those subsequently introduced.

Distribution. Loess is not confined to glaciated regions but is a formation of the desert borders, the steppes or high plains. It happens to overlap the outer portion of the glacial drift. It is found on the Columbia Plateau, and on the Great Plains from Montana east through the Dakotas and Nebraska to the Central Plains region. In the last named region loess is found on the outer glacial drift of Iowa, Missouri, Illinois, and Indiana and in the Driftless Area. The loess of Europe has the same relation to the glacial drift. The loess in both continents is mainly confined to the old, or pre-Wisconsin drift. Loess is absent in humid regions although there are deposits in Arkansas, Mississippi, and Louisiana.

Thickness. Loess is in few localities over 50 feet thick and is mainly only a few feet in thickness. It conceals the underlying formations over wide areas. Loess is thickest (a) along valleys, particularly on the east sides where it locally forms ridges and is associated with sand dunes, (b) on the east sides of hills, (c) in areas of broken topography, and (d) in areas which have or did have a cover of grass, brush, or timber. Loess is thin or absent (a) on open hill tops, (b) on broad plains, (c) on areas without any vegetation, and (d) on areas subject to flooding.

Conditions of origin. The unaltered minerals of loess imply an origin from deposits not affected by chemical weathering; such are present in (a) freshly deposited glacial drift, (b) floodplains of glacial streams, and (c) the arid regions. Loess was transported and assorted by an agent which (a) was capable of carrying only rather fine material, (b) worked without regard to elevation, (c) operated faster than erosion or leaching, (d) was associated with the formation of sand dunes, (e) was confined to regions adjacent to deserts, (f) was associated to some extent with glaciation, (b) buried land snail shells, (h) was to some extent affected by topography, (i) operated more vigorously near rivers, (j) did not produce bedding or lamination, and (k) operated in the presence of land vegetation. The agent which alone can meet these conditions is the wind in a climate rather drier than that which prevails in much of the loess region at the present time. Lodgement of loess was effected through checking of the wind by (a) vegetation, and (b) slopes. Of the former trees and brush were doubtless important and the objection that loess could not have accumulated in forests is invalid for it is prairie soils that contain the most organic matter and not woodland soils. Broken topography was more favorable than open plains since the wind was more interrupted. The loess-depositing winds appear to have been westerly and southwesterly as are the summer winds of the same region today. Indeed, loess is still being formed along the borders of the arid regions and adjacent to the flood plains of large rivers; the process has been much speeded up by the work of man in destroying vegetation. The buried sand dunes seem to tell of a gradually lessening vigor of wind work so that silt came tobe deposited over the sand. The fossils of loess also tell of a climate somewhat drier than that of today. While some loess-like deposits, especially those on floodplains, were doubtless deposited by water, it is now realized that water had no essential part in the formation of loess except in so far as it formed bare river flats from which the wind picked up the material. The outwash plains doubtless furnished much dust. Stones and bones of annimals were introduced into loess (a) by burrowing animals, (b) by uprooting of trees, (c) by slump and creep from higher land, (d) by human agency, and (e) by deposition of some loess on top of the ice followed by slumping.

Age. The earlier geologists ascribed loess to glacio-aqueous deposition and decided that as it is absent or rests on fresh drift in northeastern Iowa it was deposited when and soon after that area was glaciated. The drift of that region was ascribed to the Iowan stage of glaciation and the loess was therefore regarded as of Iowan age. That this cannot be true is shown by (a) the presence of two distinct loess deposits of which the older was much weathered before the deposition of the younger, (b) the existence of loess on some of the young drift, (c) the testimony of the fossil shells which indicate a mild climate during the formation of most of the loess, and (d) the occurence of buried loess deposits near to the base of the drift. Interglacial age is also suggested by the relation of the bulk of the loess to the drift; most of the loess lies upon deeply weathered and eroded drift with the contact in many places marked by concentrated pebbles. In the Driftless Area loess rests upon the preglacial residium with no intervening soil, a fact suggestive of aridity. In Illinois there are local swamp deposits between the loess and the drift; these are called the Sangamon formation. In some regions the loess lies on fresh till, a fact generally explicable by erosion of the weathered zone before the formation of the covering formation. Buried loess is common below the young or Wisconsin till but in many places it rests on fresh Wisconsin drift. It is evident that all loess deposits are not of the same age and that even where there is more than one age of loess no line of demarcation can be found in many sections. Attempts to place all yellow loess as decidedly younger than the gray loess are ill-founded as the differences may be explained by weathering, but the old leached red loess under the fresher calcareous loess is very much older than the bulk of the deposits. Loess was doubtless formed both (a) during a time of aridity during one or more stages of glacial retreat, and (b) during the retreat of the ice front when much fresh drift was uncovered. Deposits of the latter class might be less fossiliferous than those of the first kind. The loess cannot be used as an horizon marker in Pleistocene geology except in the most general manner; it is mainly pre-Wisconsin but that is all that can be said. Much of the loess came from the arid regions and not from the drift.

Exploitation. Loess is used for clay products and for surfacing sandy roads. It is an important soil comprising a large part of the Knox, Union, Wabash, Waukesha, LaCrosse, Marshall, Lintonia, Whitman, Antigo, Colby (?), Fox, and possibly other soil series.

Field mapping. Loess is distinguished by (a) its freedom from stones, (b) its silty texture, (c) its light color compared to residual clays, (d) its vertical cleavage, (e) porosity, (f) its lack of lamination, (g) lack of stickiness, and (h) the presence of fossil shells. Some of these features may be absent in some localities but enough of them are found everywhere to make discrimination easy. The irregular distribution of much of the loess makes detail mapping very difficult. A soil auger is very useful in loess regions to find out what lies beneath.

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GLACIAL AND INTERGLACIAL STAGES

Introduction. The extent to which Pleistocene glaciation was interrupted by interglacial intervals during which the ice largely or wholly melted away has been a vexed one. The opinions of the geologists of the last century on this question were affected by (a) their preference for certain theories of the cause of glaciation, and (b) the regions in which they had worked. The men who accepted elevation of the land as the cause of glaciation without exception favored a relatively brief single ice invasion; adherents of Croll's hypothesis sought eagerly for evidence of the several interglacial stages that it required. Students of marine sediments sought to reduce drift deposits to an orderly sequence of formations. Although unity of glaciation is no longer advocated by geologists who are familiar with field evidence there is still ample reason for believing that the complex Pleistocene succession urged by some geologists is in part based on errors of judgement and that it may be in need of some revision. Research in this field has been dominated for a long time by men from only one institution of learning and the following discussion aims at a complete rehearing of the subject from a standpoint unhampered by loyalty to any particular school of thought, institution, or individual, and particularly at a clear statement of the value of the criteria and their practical application in the field.

Definition. An interglacial interval is defined as a recession of the continental glaciers so far north that a temperate climate was restored to the United States. The problem is to find criteria by which the existence of such a time of deglaciation may be established with certainty, and distinguished from a less extensive oscillation of the ice margin. The following fundamental facts must be kept in mind: (a) it is probable that the southern ice margin was thrust forward into a fairly mild climate just as mountain glaciers descend into fertile valleys below timber-line, (b) the fact that the marginal drift is much older than the drift farther north is in itself no evidence whatever that an interglacial interval occured between the formation of the two deposits, (c) the evidence of deglaciation between successive glacial deposits is found mainly near the drift margin and is in itself no evidence of real interglacial intervals, (d) the question of how close to the ice vegetation and animals could have existed is in large part a matter of wind direction with reference to areas of bare ice and snow, for much of the margin of the ice sheets must have been mantled with drift, (e) the existence of an interglacial interval can only be proved by demonstrating that mild climate like that of today extended over a wide area, and (f) that the problem of the determination of interglacial intervals must not be confused with the correlation of drift deposits of the same age.

Climate near to the ice. The air becomes very cold over bare ice and snow and therefore sinks and flows away from the glacier. Anticyclonal winds of this type are present in Greenland and Antarctica and to some extent on all glaciers. The existing continental glaciers are all in high latitudes but in Alaska winds from the Pacific allow forests of hardy trees to grow close to or in drift upon the ice. The question of the prevailing winds in the United States during glacial time must rest upon the determination of the cause of glaciation but meantime there is some direct evidence as to how close to the ice vegetation did actually exist. This is : (a) the "forest bed" of northeastern Wisconsin which implies a recession of the ice as far as the Straits of Mackinac long enough for spruce trees to migrate into that region is admittedly an incident within the last stage of glaciation; (b) remains of plants and animals have been found in Iowa both in till and in lenses of outwash gravels within the drift thus strongly suggesting that they lived near to the ice, and (c) with the exception of a portion of one locality all of the known vegetal remains buried in situ in the drift are subarctic or arctic species which might have lived close to the ice. Any difference in elevation of the land that can reasonably be assumed could not influence the climate near to the ice to a material extent.

Climatic evidence of the DriftlessArea and adjacent regions. There is positive evidence that no local glaciers were formed in either (a) the Driftless Area, or (b) the Appalachian mountains south of the border of the continental drift. All evidence purporting to indicate the former existance of local glaciers in these regions has been found to be worthless by geologists who were familiar with mountain glaciers. This fact definitely demonstrates that conditions for glacial accumulation did not extend as far south as central Wisconsin and that the southern extension of the ice sheets was in the zone of wastage.

Buried vegetation or "forest beds". Vegetal remains occur in the drift (a) as transported fragments similar to erratic stones in both till and assorted deposits, (b) buried between two tills, and (c) buried between till and overlying water or wind deposits. Material of the first class means little as it may have been carried a long distance. The last class [illegible] as well as vegetation beneath all of the drift has little bearing on the question of interglacial conditions. Some vegetation has also been buried by (a) landslides in ravines, (b) slopewash, and (c) human agency. Evidence of buried forest or swamp deposits based only on well records is uncertain for it is difficult to discriminate materials of the different modes of origin, particularly stray transported fragments. Vegetation buried in situ may be distinguished by (a) leaching of the subsoil in case of long exposure of the region to the atmosphere, (b) stumps and roots in the subsoil, and (c) comparatively wide extent at the same level. Material of this kind is sometimes called a "forest bed". Forest beds in some cases lack a leached subsoil and then indicate merely a minor recession of the ice border.

Buried animal remains. Animal remains in the drift are capable of the same classification as that of vegetal remains. Presence of animals implies vegetation to supply food to at least some of the species. Remains that were not transported far may be distinguished by (a) complete skeletons, (b) paired shells, (c) lack of abrasion, and (d) original fragility. Shells are common in buried loess but are very rare in water deposits. Glacial lake clays do not owe their carbonate content to organisms.

Distribution of organic remains buried in situ. Organic remains buried in situ between tills have been reported from the Dakotas southeastward through Minnesota, Iowa, Illinois, Indiana, and Ohio. It seems clear that many of the occurences reported in the older literature do not belong in this class. Beds of lignite are found between two tills near to James Bay in Canada and many organic remains are found in lake and stream deposits between tills at Toronto, Canada. Loess with fossils is found between tills in Iowa and Illinois. With the exception of these and a portion of the Toronto deposits the determinal remains are of northern species now of arctic and subarctic habitat. Forms now common only in more southerly latitudes have been found only at Toronto although McGee described temperate vegetation from northeastern Iowa and some authorities have ascribed some of the Pleistocene mammals of southwestern Iowa to a mild climate region. It must be recognized that in most instances there is little or no evidence as to how far the ice advanced in order to bury the vegetation; some forest beds may represent vegetation that grew some scores or even hundreds of miles from the ice.

Invalid criteria. Oxidation and leaching during a retreat of the ice front have been regarded by some as evidence of temperate climate but there is little definite evidence to support this view; all that is needed is for the soil to thaw some of the year. Evidence from erosion is also open to the same doubt. Erosion certainly must have gone on while regions slightly farther north were still ice-covered; weathering must also have occurred at the same time. Glacial advances were formerly regarded as having been separated by interglacial intervals because (a) the direction of motion changed, (b) the younger drift has more assorted material and more accentuated topography, (c) there were supposed differences in "manner of action", vigor, or "drainage conditions" in different glacial stages, and (d) there were supposed differences in lithology in drifts of different ages. Most of these phenomena form incompetent and irrelavant evidence; they are better explained in other ways than by interglacial intervals. Supposed differences in elevation of the land so that some ice invasions deposited only gravel and others only loess, supposed selective action so that ice of certain ages carried certain kinds of bowlders or deposited only thin drift or only thick drift, and supposed differences in "moraine-forming habit", speed, or "vigor" must all be classed as outworn theories that had little if any validity.

Conclusion. The sole evidence in the eastern part of America that definitely proves a mild interglacial interval is the character of the vegetal remains at Toronto and the occurence of the lignite beds in the drift near James Bay. In the west the drying up of the lakes of the Great Basin strongly suggests a marked interglacial interval. All other evidence is inconclusive though it does prove (a) long duration of the Pleistocene, and (b) marked oscillations of the ice margin.

Evidence of long duration of the Pleistocene. That the Pleistocene period covered a long space of time is demonstrated by (a) the great amount of weathering suffered by some of the marginal drift, (b) the great amount of erosion in the same areas as compared with regions nearer to the centers of dispersion, (c) the extinction of many of the animals whose remains are found in the drift, (d) the time that must have been required for the migration of plants during some of the glacial recessions, and (e) the great distance that stones were carried by the slow-moving ice.

Evidence of oscillations of the ice border. Oscillations of the ice margin, some of them of long duration and of a magnitude of several hundred miles are shown by (a) the varying degrees of weathering of contiguous drift areas, (b) the varying degrees of erosion of the same areas, (c) overridden zones of weathered drift, (d) buried vegetal remains, (e) buried wind, stream, lake, and marine deposits, (f) overridden erosion surfaces on older drift. The major oscillations were once termed glacial epochs but growing conservatism has changed the nomenclature to "stage".

Correlation of glacial stages. The correlation of drift deposited in different glacial stages is an entirely different matter from the determination of the existance of mild interglacial intervals with complete disappearance of the ice caps. The following criteria alone have much value: (a) amount of erosion, (b) depth of weathering, and (c) stratigraphic relation of superimposed deposits. A number of other phenomena have been used as criteria in the past but have little or no value; these are: (a) assumed relation between age and lithologic composition of the drift, (b) assumed relation between age and direction or rate of ice movement, (c) conclusions on drainage conditions based either on the old aqueous theory of loess or on comparison of outwash from clay till with that from stony till, (d) discrimination as glacial deposits of scattered stone, bowlders mixed with loess, weathered gravel, bowlder beds due to stream work or to floating ice in lakes or the sea, or to wave work, including the assumption that certain glaciers deposited only assorted materials, (e) assumption that certain glaciers passed over delicate erosion forms in soft material without sensibly affecting them or changing the drainage, (f) assumption that the ice failed to leave any deposits at all in certain areas, (g) assumption that glaciers formed long narrow tongues or lobes with no topographic cause, (h) assumption that all loess was of the same age and was contemporaneous with a glacial stage, (i) confusion of long pits in outwash with valleys blocked by moraines, (j) assumption that different ages of ice differed in "manner of action", "moraine-forming habit", thickness of ice, and thickness of drift. It is now known that these phenomena are explainable in other ways than as evidences of drifts of different ages. Some geologists seem to have pinned their faith mainly to weathering phenomena, others to erosion features, while still others, particularly students of marine strata, have been most impressed by stratigraphic relations and endeavored to reduce the drift deposits to an orderly sequence.

Postglacial erosion. Postglacial erosion forms must be discriminated from preglacial topography thinly mantled with drift; the latter is, on the average, smoother and shows both (a) more or less obstruction of valleys, and (b) no sharp boundary between erosion slopes and glacial topography. Postglacial erosion forms are for the most part youthful to submature in the erosion cycle and are distinctly "topographically unconformable" with the untouched part of the glaciated landscape. Only in a few places has postglacial erosion removed all traces of glacial forms and approched the state of topographic old age. Where streams were diverted across rock divides gorges have been formed that contrast sharply with (a) the more mature preglacial topography, and (b) the more open valleys in drift. Where the drift is relatively thin the erosion phenomena are not difficult to interpret but where an erosion topography in thick drift was later overridden by the ice the matter is less simple. It seems highly improbable that ice could pass over an irregular drift tppography without considerable erosion of the sharper divides and blocking of the valleys. The discrimination of constructional drift topography from erosion forms is in places fraught with difficulty; where kettles are present the matter is settled but sand dunes and landslides are very confusing. Certain types of erosion spurs when viewed from below are deceptively like constructional knolls. Areas of scattered glacial stones if not due to ice rafting, are positive proof of erosion of the finer material. The original drift topography of clay drift areas was a nearly level plain which in the more eroded regions now forms tabular divides between the valleys.

Erosion as a time measure. In order to use the total amount of erosion as a measure of the length of postglacial time it is necessary to first consider the factors which govern the speed of erosion: (a) slope of original surface, (b) nature of material, (c) climate, and

(d) vegetation. The first is of immense importance since it regulates the velocity of streams whose carrying power increases much more rapidly than velocity. Erosion tends to start on steep slopes; in a plain the main valleys develop first. The drift was first stripped from (a) hillsides, and (b) main drainge lines; this explains the destruction of the outwash valley trains of the older drift. Total elevation of an area above sea level is unimportant in the interior of the continent since it takes an immense lapse of time for streams to deepen their valleys back from the coast so that the effect of change of level can be felt. Tilting of an area is important since it rejuvinates streams that flow down the new slope. Northeastward tilting of the land is known to have occured in late glacial time but its effect on streams has not been worked out. Explanations based on crustal movements should be used with caution; they are easy to assume but must be confirmed by more than one kind of evidence. The resistance of drift materials to erosion varies widely. Sand, sandy gravel, and sandy till yield to erosion very readily ; clays and clay tills are tenacious but slide readilly when wet. Gravel and stony tills are relatively resistant because the pebbles and bowlders are concentrated by removal of the finer material and thus form protecting residual gravels and bowlder pavements. The character of the drift affects the percentage of runnoff which is greatest in the case of clayey material. Where postglacial erosion has reached the bed rock the character of the latter must also be considered. A ledge of resistant rock in a stream bed fixes a local baselevel; above such erosion is on lower gradients than below making a smoother topography which may resemble old age forms. Erosion is favored by heavy rainfall especially when concentrated into violent storms. Vegetation is related to both climate and soil. Abundant vegetation increases runoff but retards erosion. After the sod or root layer has been penetrated erosion is rapid until grade is reached. Erosion is at a maximum rate in regions of scant vegetation with rainfall in occasional cloudbursts. This condition with soft material results in badlands as along Missouri River. A difference in climate such that one area had tree-covered slopes and another only grass would make a tremendous effect on the amount of erosion in a given space of time.

Work of glacial waters. Some of the older geologists referred much of the erosion of the marginal drift to the work of waters from the melting ice sheet. This process was unquestionably important along the main channels of glacial drainage beyond the zone of outwash deposition, especially where the streams had a high gradient or carried the flow from lakes. It resulted in over-development of these valleys as compared with their tributaries, a fact which serves to distinguish phenomena of this class from postglacial erosion due to local precipitation.

Practical application. Inasmuch as the sum total of postglacial erosion is the value of an equation with a number of factors besides time, erosion cannot be used to compare the age of two areas of drift without either (a) proof that the other factors are equal and can therfore be cancelled , or (b) making a quanitative estimate of the relative values of those factors. In this connection changes in climate are very difficult to evaluate for (a) they affected adjacent areas in varying degree, and (b) climate affected vegetation in unknown degree. Although it is clear that the drift outside the terminal moraine of the young or Wisconsin drift is very much older than the latter the subdivision of this old drift into several ages on the basis of erosion features is fraught with grave chances for error. Attempts to use erosion as a quanitative measure of age are open to the most serious question for neither (a) the proportion of the area affected by stream work nor (b) the total volume of material removed can have any direct or even approximately determinable ratio to the time involved. Rate of erosion unquestionably follows a declining curve with many variations due to changes in the factors noted above.

Postglacial weathering. Virtually all drift shows some postglacial weathering. Some geologists have claimed that the observed phenomena are due to admixture of preglacial weathered material and instances of this undoubtedly occurred. Proof that the alteration of most of the drift is postglacial lies in the observed downward gradation into fresh drift; in the case of very thin drift this cannot be observed since alteration has extended clear through and in many cases into the bed rock. The phenomena of weathering noted in the drift are: (a) oxidation, (b) solution, (c) disintegration, (d) cementation, and (e) under certain conditions reduction. Oxidation is mainly observed by the change of color of the iron-bearing compounds to yellow, brown, and red. These high colors extend gradually down to fresh drift, going deepest along cracks. Unaltered drift is for the most part gray or blue in color but there are exceptions like the red till of northern and northeastern Wisconsin which was made from red lake clays. The colored zone of oxidation is called "ferretto" by the Iowa geologists. A very confusing factor is introduced when there is a perched water table due to alternating pervious and impervious materials; in such a case oxidized material may be found beneath fresh thus suggesting an oxidized drift buried by a later fresh drift. The lowest limit of oxidation is normally fixed by the water table. Other confusing phenomena are (a) oxidation of gravels caused by escaping ground waters which carry iron in solution, and (b) abnormal amount of oxidation in and adjacent to materials which carry iron sulphides. Solution is best observed with the carbonates of calcium and magnesium since these dissolve readily in waters containing carbon dioxide. Iron is dissolved mainly in the zone of humus but beneath marshes iron is removed to a depth of several feet. Solution effects are also limited by the water table in most instances, but for the most part extend to much less depth than does oxidation. Rapidity of solution is favored by (a) small size of particles, (b) abundant carbondioxide and organic acids, and (c) moderate amount of water. Disintegration of pebbles and bowlders is conditioned mainly upon the character of the rock; it is particularly favored by even a very small amount of iron sulphide which sets free sulphuric acid when weathered. Stones exposed to the air dry rapidly and so may suffer less than those which are imbedded in the soil; a confusing factor is that easily disintegrated stones on the surface fall to pieces and are lost while those of the same kind in the drift are held together and can be seen in excavations. Coarse grained basic igneous rocks, schists, shales, and limestones suffer disintegration readily; quartzite, chert, and fine grained or very acidic igneous rocks last longest. Some stones that are now disintegrated may have been weathered in preglacial time and transported while frozen; that others were altered before transportation is shown by glacial facets that cut through to the fresher core. Cementation is caused by (a) evaporation of solutions either before reaching the water table or on escape to the surface, (b) chemical changes like loss of carbon dioxide, supersaturation, or introduction of oxygen, and (c) meeting with solid material of the same kind. The last process is in part the cause of concretions which are abundant in clays and loess just below the zone of solution. Iron and manganese oxides and calcium carbonate are the most common cements in the drift; they also occur as veins and in bands parralel to the surface. Some bands of manganese oxide have doubtless been mistaken for buried soils. Gravels have locally been cemented into conglomerate and tills into tillite. Reduction takes place (a) beneath the water table, and (b) in the presence of organic matter. This fact explai in part the gray or blue color of deeply buried drift and of drift close to buried forest beds, peat, and wood.

Gumbotil. The name gumbotil has been applied by Kay to a sticky, tenacious, gray to black, unstratified, gritty clay with a starchy fracture when dry. The clay contains sand and small pebbles of very resistant rocks as well as occasional disintegrated bowlders. It is non-calcareous and contains less iron and more alumina than do the adjacent clay tills. It lies upon leached oxidized till which grades downward through oxidized unleached till to the fresh unoxidized unleached till. The contac of the gumbotil with the brighter colored material below is a relativly abrupt gradation. The maximum known thickness of gumbotil is about 12 feet. There is every gradation from normal gumbotil to non-calcareous silts without any grit or stone but gumbotil is decidedly unlike flood-plain gumbos. Gumbotil is unquestionably the product of weathering of the till under swamp conditions before the present postglacial valleys had been developed to their present soze and extent. It must have required a very long time to form a gumbotil layer but not nearly as long as to form the same thickness of residual soil from solid rock. In some places slopewash added to the thickness of gumbotil; locally there is a pebble line below the gumbotil which suggests the transportation of the entire deposit at that particular spot. Gumbotil is found (a) on the remnants of the original drift surface, and (b) buried between tills. In age it is found on the older or pre-Wisconsin drift, buried in that drift, or buried under the young or Wisconsin drift. Its absence from the latter is explained by (a) the youth of the drift, and (b) its more stony composition; no gumbotil is found on sandy or stony old drift as in northern Wisconsin. It has been suggested that the gumbotil of Iowa was formed on a low-lying plain that was later uplifted and dissected but such an explanation hardly seems needed. Gumbotil is the best criterion so far discovered to demonstrate prolonged intervals of deglaciation but it is by no means certain that it demonstrates the existence of a temperate climate.

Weathering as a time measure. The only practicable measure of the amount of weathering suffered by a given deposit is to measure the depth of weathered material. To draw conclusions as to comparative ages it is necessary to consider two qualifications: (a) the factors that affected the speed of weathering, and (b) the factors which affected the amount of weathered material left in situ. The rapidity of weathering is governed by (a) kind of material, (b) structure of material, (c) climate, (d) topography, (e) position of the water table, and (f) vegetation. Drift that contains carbonates, sulphides, and other relativly soluble minerals shows weathering in less time than drift made of resistant materials. The amount of easily altererable material must be taken into consideration; for instance drift in regions of crystalline rocks is non-calcareous when fresh but it takes a long time to remove the carbonates from the very calcareous drift of a limestone region. Porosity is a vital factor; sandy drift weathers much faster than does clay drift. Gravel, however, although more porous than till, is made of harder, water-sorted stones and in many cases is so permiable that it dries out before much solution takes place; this is particularly the case with knolls of coarse gravel. Structural features include (a) beds and masses of assorted materials in till, and (b) joints. These features influence the amount and rate of water movement and locally they determine perched water tables. Buried vegetal material may cause solution in the underlying material on account of the unusual supply of acids and carbon dioxide. Such might be very hard to distinguish from weathering at the surface. Climat factors are (a) temperature, (b) amount and manner of precipitation, and (c) length of the frozen season. High temperature favors weathering but does not extend far into the soil. Too moist a climate is unfavorable as it means a high water table. Weathering is at a standstill while the ground is frozen but frequent freezing and thawing is very favorable. Percolation of water is least during the time of frost and after prolonged rains when the soil is saturated. Topography also governs the amount of runoff; the water table is nearest the surface in flat regions and in clay drift. Vegetation (a) breaks up the soil, (b) furnishes carbon dioxide etc., (c) retains weathered material in place, and (d) reduces percolation. Burrowing animals are important agents of weathering in some regions. The factors which affect the depth of weathered material left in place are those that regulate the speed of erosion for retention of residium and erosion are mutually antagonistic. Where erosion is at its maximum on steep slopes fresh drift may come to the surface while on adjacent flat uplands there is a thick mantle of weathered drift. Creep and slopewash are also confusing factors.on hillsides.

<u>Practical application</u>. The practical application of weathering phenomena to measuring the age of glacial drift involves essentially the same problems as does the use of erosion phenomena and is equally subject to the personal equation. In limestone regions the depth of leaching of the carbonates is the criterion used. This is determined by testing with hydrochloric acid. In regions of crystalline rocks recourse is had to depth of oxidation; this extends deeper than many cuts and is in general very variable and uncertain as a criterion. Observations that are at all accurate are possible only on the tops of divides and as exposures are rare in such positions recourse must be had to borings with a soils auger. Account must be taken of non-glacial materials like loess that may cover the till. Average depths of leaching and oxidation should be arrived at with caution since averages of figures that vary over a wide range mean very little. Above all no attempt should be made to apply averages either (a) to regions outside where they were worked out, or (b) to drift of different composition. The factors of past climates and of porosity are very hard to evaluate. It is little wonder, therefore, that conclusions based on weathering are very uncertain and that many errors have in all probability crept into the literature. The phenomena of weathering are valuable criteria only when used with care and in conjunction with other evidence.

<u>Stratigraphic relations</u>. Glacial deposits and associated glaciofluvial deposits are fundamentally different from marine sediments. They cannot be expected to form continuous sheets or formations with definite and distinctive lithology, fossils, or sequence. They were deposited on an irregular land surface; deposition was interrupted by the presence of ice. The materials were largely derived from the immediate vicinity and not from distant sources. Complete sequence formed by deposition of sucessive tills above one another is essentially a marginal phenomenon, for under deep ice glacial erosion removed much of the older drift. A stratigraphic habit of thought is therefore, a fundamental error in dealing with glacial deposits although it is true that in the flat states like Iowa and Illinois there is some approach to a definite sequence of drift materials. For instance, correlation of gravel beds found in wells is very hazardous since they are more likely not continious or contemporaneous; the practice of giving formational names to

such deposits is to be condemned. In fact, all evidence from logs of wells from which no samples have been examined is open to question; "hard pan" may mean till or compact gravel. The assignment of all aqueous beds between tills to interglacial intervals is very doubtful although it was once common practice. Interglacial streams were much more likely to erode than to form deposits of coarse gravels; gravels within or below till are much more likely to be glacial outwash than anything else. Attempts to distinguish tills of different ages in the same section by color, pebble content, or degree of cementation are very questionable since the phenomena may readily be explained as due to distance from the surface or other simple causes. Furthermore, it is evident that many deposits that have been described as till are not such and do not show a readvance of the ice. The difficulty of using vegetal remains reported in wells as a stratigraphic line of division has been pointed out. Swamp deposits can be correlated over limited distances by means of elevation as can also gumbotils. If the gaps are too long, however, this method may fail. Loess, gumbotil, and leached zones between tills are the only sure means of separating drifts of different ages in the same section. Forest or swamp deposits without leached subsoil may indicate a minor ice recession. Application of many of the criteria used in the past led only to absurdities and it is now evident that separation of drifts of different stages of glaciation by stratigraphic methods is not the simple task that it once appeared to be. Discrimination of erosion unconformities between tills is very difficult and it will not do to say that the later ice failed to leave any drift in some localities. It is probable that serious errors have been committed in the separation of drifts by the methods outlined above.

Field methods. Disintegration of stones is a poor and over-worked criterion of age. Leaching is determinable only in and near to limestone regions. Its determination involves testing with dilute hydrochloric acid preferably in sections made by boring. Borings should be located where erosion is least. Pebble counts should be made in both fresh and weathered drift with record taken of the depth from the surface. Oxidation is a poor criterion but must be observed. The soil auger must be over 6 feet long and provided with a chisel to get by stones. In studying sections care must be taken that (a) material overlying the supposed buried land surface is really till, (b) the differences of material above and below the zone in question is not due to ground water conditions, (c) no possibility exists that the overlying material was placed by landslides or slopewash, (d) black zones are not manganese oxide, (e) plant and animal remains are in situ, (f) plant and animal remains are collected and determined by a competent authority, (g) true gumbotil is distinguished from stream gumbo, and (h) that organic remains were not introduced by human agency, possibly as a hoax. Well records must be collected but inferences made from them with care. Above all, older publications should not be taken at face value but the problem should be approached from the begining.

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HISTORY OF THE DISCRIMINATION OF THE GLACIAL SUCCESSION

Pioneer exploration. The announcement of Croll's hypothesis of the cause of the glacial period took place in the late 60 s. It immediatly started a search for interglacial deposits since it required the presence of a number of rapidly recurrent stages of complete deglaciation and to find evidence of such was to demonstrate the validity of the theory. The earliest mentions of vegetal deposits in the drift as of interglacial age were by Winchell and by Orton in 1873. In 1875 McGee called the "forest bed" of northeastern Iowa an interglacial deposit which marked a very long interval between two glaciations. In the same year Chamberlin began to recognize the great difference of the drift within the terminal moraine from that without but his conclusions were not published until 1878. Hinde described the interglacial deposits at Toronto in 1878. In 1882 McGee and Call described the loess between two tills at Des Moines, Iowa, but failed to recognize its significance. In 1891 McGee announced in his final report on northeastern Iowa that the forest bed marked the principal division of the glacial period. In 1893 Salisbury published the only categorical summary of the criteria for the discrimination of different ages of drift that has ever appeared.

Naming of the stages. In 1894 Chamberlin began the practice of giving geographical names to the different ages of drift. The drift of southern Iowa and Illinois was called Kansan, that of northeastern Iowa the East Iowan, and the young drift the East Wisconsin. This established a tripartate division of the Pleistocene which combined McGee's forest bed and the terminal moraine as major divisions of the Pleistocene. In the following year Chamberlin dropped the prefixes East and named the Aftonian interglacial deposits which he placed between the Kansan and the Iowan drifts. This correlation placed the surface drift of southern Iowa as of Iowan age. In the same year Dawson named a supposed drift in western Canada the Albertan and placed it as older than the Kansan, that is older than the till beneath McGee's forest bed. In 1896 Calvin described and named the Buchanan gravels of northeastern Iowa; these he placed between the Iowan and the Kansan drifts. Later in the same year Chamberlin announced that it had been found that the uppermost till of northeastern Iowa was not the uppermost till of the southern part of that state, the till above the Aftonian deposits; this placed the Aftonian below the Kansan drift. A succession of five drifts was therefore announced: Albertan, Kansan, Illinoian, Iowan, and Wisconsin. Of these the Illinoian had been discovered by Leverett. The Toronto interglacial deposits were named the Toronto formation and placed just before the Wisconsin drift. In 1897 Leverett announced a subdivision of the Wisconsin drift into two distinct stages marked by a shifting of the ice lobes; this marked the introduction of the term stage instead of epoch in speaking of ice advances. In the succeeding year the same author named the "intervals of deglaciation or recession" so that there were no recognized six drifts and five intervals: Pre-Aftonian or Albertan drift, Aftonian interglacial interval, Kansan drift, Yarmouth interglacial interval, Illinoian drift, Sangamon interglacial interval, Iowan drift, Peoria interglacial interval, Early Wisconsin drift, unnamed interval, Late Wisconsin drift. In 1903 Fuller and Veatch attempted to transfer this column to the Atlantic seaboard. In 1906 Calhoun discovered that the so-called Albertan drift is not a glacial deposit and the term was accordingly dropped in favor of sub-Aftonian or pre-Kansan. In the same year Chamberlin and Salisbury first used the term Jersian for the old drift of New Jersey. In 1910 Shimek suggested the name Nebraskan for the pre-Kansan drift.

Modern conservatism. In 1909 Leverett, after finding only four drifts in the Alps, attacked the existence of the Iowan stage of glaciation or at least its separation from the Illinoian, and at the same time minimized the subdivision of the Wisconsin drift into two stages. This drew a vigorous reply from Calvin in 1911. In 1915 Leverett formally abandoned the use of the term Early Wisconsin as a stage designation. In 1917 Alden and Leighton reported in favor of the retention of the name Iowan. A few geologists, particularly G. F. Wright, always held out against the theory of separate glacial stages with interglacial intervals but their views met with little encouragment. The idea of multiple glaciation is now firmly established although there is still much room for divergance of opinion as to (a) the exact number of stages, (b) the extent of the recession of the ice during some of the intervals, and (c) the correlation of some particular areas.

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THE PLEISTOCENE GLACIAL SUCCESSION

Introduction. The Pleistocene glacial sucession is discussed under the following heads: Nebraskan drift, old drift of Pennsylvania and New Jersey, Aftonian interval, Kansan drift, Yarmouth interval, Illinoian drift, Sangamon interval, Iowan drift, Peorian interval, Toronto interglacial deposits, Wisconsin drift, subdivision of the Pleistocene drift in the eastern United States, with the conclusion that it has not been proved that (a) there was more than one mild interglacial interval, (b) the existence of the Iowan drift is questionable, and (c) some doubt may be entertained as to the separation of the Kansan and Illinoian stages. Some of the names, particularly Nebraskan, Sangamon, and Peorian are found to be inappropriate and misleading.

NEBRASKAN STAGE OF GLACIATION

Nomenclature. The name Nebraskan was first used by Shimek in 1910; previously the terms sub-Aftonian and pre-Kansan had been in use and for a time the correlation with Dawson's supposed Albertan was in vogue. The name Nebraskan is a misnomer in that no drift of that age in known in Nebraska.

Distribution. Nebraskan drift is definitly known in southwestern Iowa and possibly in northern Missouri. It nowhere forms the surface drift except where uncovered by postglacial erosion. Some geologists have claimed that the scattered stones on the bluffs of the Mississippi in Iowa and Wisconsin and some of the much eroded drift of central Wisconsin are Nebraskan drift. There is little if any evidence to prove this and some of these may be pre-Pleistocene.

Description. The Nebraskan drift of Iowa is for the most part a dense, dark greenish-blue clay till with relatively few pebbles or bowlders. It was formerly supposed that this lithologic character was a distinguishing feature but this has been shown to be an error and it is now known that the Nebraskan drift cannot be distinguished in this manner alone. The peculiar color and texture are mainly to be ascribed to (a) derivation from weathered shales and other residium, (b) reducing action of ground water on account of organic matter in the till and deep burial, and (c) pressure of the overlying drift. Some of the supposed till may prove to be stream or lake deposits. Lenses of sand and gravel occur, some of them formerly called Aftonian interglacial deposits. The scattered stones of the Mississippi region may not be remnants of an eroded till but may be either (a) outwash formed before the valleys were as deep as they are now or when the valleys were filled with ice, or (b) pre-Pleistocene stream gravels which antedate the erosion of the valleys.

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OLD DRIFT OF PENNSYLVANIA AND NEW JERSEY

Nomenclature. The old drift of Pennsyvania and New Jersey has been called (a) the fringe, (b) extra-morainic drift, and (c) Jersian drift. The last name was applied by Chamberlin and Salisbury in 1906.

Distribution. The old drift forms a relativly narrow strip outside of the terminal moraine of the young drift. The greatest width is about 25 miles and occurs in New Jersey. The tract is not areally continuous with the old drift of the Mississippi basin.

Description. The drift is thoroughly oxidized stony till which is too thin to show an unaltered zone. Undisturbed drift is confined to hill tops and much of the area shows either no drift or only scattered stones. There are no glacial topographic features.

Interpretation. Different observers have interpreted the old drift as (a) a deposit made by the first temporary advance of the ice that built the moraine and therefore composed mainly of preglacial residual material, and (b) a drift of far greater age than the morainic drift, presumably separated by a long interglacial interval. Advocates of the former view point out (a) the uniform oxidation of the drift from top to bottom, (b) the freshness of the underlying rock which in places carries striae, (c) the fact that some pebbles were striated after weathering, and (d) that drift locally extends to the bottoms of the valleys. Salisbury showed that the drift was very old by (a) the present disintegrated condition of some of the stones which must have been hard when transported, and (b) the erosional topography. The question was ably argued on both sides and it is possible that materials of both modes and times of origin are present. Correlation of this old drift with the deposits of the west hardly seems possible but some geologists seem to have assumed that the Jersian drift is the Labradorian correlative of the Nebraskan drift. While this might be correct there seems to be no justification for correlation over so long a distance of different materials in very different climates.

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AFTONIAN INTERVAL

Nomenclature. The type locality of the Aftonian is near Afton Junction, Union County, Iowa. The term was first used by Chamberlin in 1895, but the deposits were forst described by Bain in 1898.

Distribution. Aftonian deposits have been described througnout a large part of Iowa having for the most part been found only in wells. McGee's forest bed in northeastern Iowa is correlated with the Aftonian, and in 1908 Shimek extended the Aftonian to include gravels in the Missouri Valley.

Description. The Aftonian deposits of western Iowa are fluvial gravels, sands, and silts. In the type section these deposits are overlain, underlain, and interbedded with till. It is possible that some of the reported Aftonian beds are either (a) next to the rock below all the till, or (b) lie above the drift having been in places covered with slopewash or assumed to extend back into the bluffs where in fact they did not. The practice in western Iowa seems to have been to place the first gravel bed encountered in wells as of Aftonian age. In northeastern Iowa peat and soil are reffered to the Aftonian; these were what McGee called the forest bed. It is now known that there is a widespread gumbotil in Iowa that marks the top of the Nebraskan till and therfore represents the Aftonian interval.

Organic remains. The Aftonian gravels of Missouri Valley have yielded bones of the elephant, horse, deer, beaver, sloth, camel, etc as well as mollusks. The vertebrates are all extinct species but the shells are modern varieties. The condition of the remains shows that the animals lived near to the place of deposition of their remains. McGee reported a number of hardwoods, ash, hickory, oak, linden, maple, sumac, and walnut [illegible] among the more abundant spruce, pine, cedar, and willow. Later observers in northeastern Iowa, however, found only spruce and arctic species of moss. It seems possible that McGee either (a) had access to material no longer available, (b) made errors in identification, or (c) confused ancient and modern organic remains. At one point in Iowa a mastodon skeleton was found in till just above the Nebraskan gumbotil.

<u>Interpretation</u>At the type locality of the Aftonian there are several layers of sand and gravel separated by tills that contian much wood in small fragments. There is no evidence of weathering, erosion, or notable organic growth which might indicate a considerable lapse of time after the deposition of any of the fluvial beds before it was buried by a readvance of the ice but it is possible that trees grew on some of the gravels. The slight oxidized zones at the tops of some of the gravel beds were probably formed since ground waters escaped into the dry gravels, a process accelerated by the opening of the pits. The fossiliferous gravels of the Missouri Valley have the same characters; it is possible that some of them lie either (a) bielow all of the drift, or (b) above all of the drift and are covered by slumped till only. There is some dispute as to whether or not the animals whose remains are found in the gravels could have lived close to the ice border. It is thought possible that they did and that the greater abundance of organic remains in the gravels is due to (a) better preservation than in till, and (b) greater amount of excavation in the gravels. In any case there can be little doubt that a large part of the so-called Aftonian gravels are not interglacial but are glacial outwash lenses and masses in both the Kansan and Nebraskan tills; some may be interglacial stream terraces either of Aftonian or post-Kansan age and others might be proglacial. Although the type section of the Aftonian has lost its significance there is ample evidence of a prolonged stage of glacial recession if not complete deglaciation between the Nebraskan and Kansan ice advances. This consists of (a) gumbotil, (b) an erosion surface on top of the Nebraskan drift, and (c) peat and forest remains including McGee's forest bed in northeastern Iowa. In view of the conflict of evidence as to the organic remains of the forest bed no conclusion can be drawn as to climate during its formation. Trowbridge has claimed that the erosion of the major portion of the valleys in the Driftless Area took place during the Aftonian. This view seems extreme if not entirly untenable since (a) Nebraskan drift is present at quite low altitudes if not proved to extend into the bottoms of deep proglacial valleys, (b) the upland gravels of the Mississippi bluffs may be proglacial and have not been proved to antedate the valleys, (c) some true glacial drift in that region does enter the valleys and there is little evidence for two ages of drift at that locality, (d) even where drift is absent in the valleys it does not follow that the entire amount of erosion is post-drift for the drift may never have been thick enough to cause drainage diversions and have been entirely eroded on the valleys, (e) such a vast amount of erosion is out of harmony with the erosion of the buried Nebraskan area, and (f) postulated differences in climate and elevation are either incompetent or unsupported by other evidence. It is a stange fact that although the evidence on which the Aftonian was orignally defined is worthless, there is nevertheless, a real "Aftonian" interval of great length and possibly constituting a real interglacial stage. The name Aftonian should be dropped as inappropriate and another term used.

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KANSAN STAGE OF GLACIATION

Nomenclature. The name Kansan was given by Chamberlin in 1894 to what was then considered the oldest drift, the "Lower Till" of McGee. This placed the Kansan below the Aftonian gravels but in 1896 Calvin and Chamberlin split up McGee's "Upper Till" into Kansan and Iowan drifts, thus preserving the correlation of the "Forest Bed" with the Aftonian but making the surface till of southern Iowa the Kansan drift.

Distribution. Drift of the Kansan stage makes up the great bulk of the drift area outside of the terminal moraine of the young drift west of Mississippi River. Just how far west this drift extends is unknown but it seems to extend northeast into central Wisconsin. A small area of old drift in northwestern Pennsylvania has been tentatively correlated as Kansan.

Description. The Kansan drift lies mainly in an area of shales and shaley sandstones and is therefore a clay till with little sand and gravel The paucity of glacio -fluvial deposits has been exaggerated by the practic of assigning the stratified deposits to interglacial intervals and giving them formational names. Gravels within the till were called Aftonian and those above it Buchanan. Much of the Kansan till is a blue-gray color; it was once believed that this color was a distinctive feature and that there was also a characteristic assortment of erratics but both ideas have now been abandoned. Oxidation extends to a depth of about 30 feet in many places; some claim that the average is 20 feet but it is very difficult to see how this was arrived at. Leaching varies from nothing on slopes to from 6 to 12 feet on uplands; some claim an average of 12 feet. These figures neglect the gumbotil that covers many of the uplands and has a maximum thickness of 12 feet. The supposed Kansan drift of central Wisconsin is much more stony than the known Kansan of Iowa and must have in large part never had any limestone content; it is deeply weathered and oxidized. The Kansan drift west of the Mississippi is for the greater part covered with loess. Locally an old red leached loess is found beneath the fresher gray and buff calcareous loess; this Shimek called the "Loveland formation". The gumbotil was at one time called "Dallas deposits."

Topography. The original topography of the Kansan drift of Iowa, Nebraskan, and Missouri was a nearly level plain. There seems never to have been any terminal moraine at the drift border or any recessional moraines; at least there is now no trace of such. The drift plain has been eroded to the stage of advanced youth so that the only remnants are the narrow divide tops many of them capped with gumbotil.

Lenses and bowlders of gravel have resisted erosion better than the till and form ledges or knolls on the smoother slopes. Where erosion has touched the dense Nebraskan gumbotil benches have been formed. An exception to the foregoing type of topography is found in northwestern Iowa. There erosion has removed all of the original plain over considerable areas, reducing the country to the smooth curves of advanced maturity The loess instead of resting on gumbotil or the "feretto" (oxidized drift) lies on fresh till. In much of this region the streams have been rejuvinated and are now dissecting the older erosion surface so that two types of topography are present in the same area. In northeastern Iowa similar conditions seem to have obtained and long narrow strips of rolling country extend in one place to the banks of the Mississippi. These smooth tracts are on divides and are separated by rough erosion topography along the main streams. Within the smoother areas are some of the low, loess-covered drumlins called "paha" by McGee. The supposed Kansan of Wisconsin shows smooth erosion topography and that of Pennsylvania occurs in a rugged country of rock hills, a region quite unlike any of the western drift areas described above.

Interpretation. All of the recognized Kansan drift came from the Keewatin center. The questionable drift of Pennsylvania is Labradorian but correlation seems impossible with such great differences in conditions. It seems very strange that there should not be a Labradorian correlative of corresponding extent unless it should yet prove that the Illinoian drift really belongs to the same stage as the Kansan. This question is discussed in more detail under the heading of the Illinoian. It is impossible to ascribe the topography of the uneroded Kansan drift to a weakness of glacial action for so extensive an ice sheet must have had a fair rate of motion and have lasted a long time. Absence of moraines is rather to be explained by (a) clay drift which could not form steep slopes, (b) lack of prolonged halts of the ice margin, and (c) erosion of what ridges were formed. It may well have been that the far-flung southern margins of the ice was mantled with melted-out drift and loosing its motion wasted gradually away without forming either outwash or recessional moraines and that the outermost margin never remained stationary for very long. The amount of stratified drift, however, has been underestimated for (a) the till could not form much gravel, (b) many deposits have been misinterpreted as interglacial, and (c) erosion has destroyed the valley trains along the larger rivers. The old terraces of the Wisconsin, Ohio, and other rivers where the rock bottom of the valley has been since lowered scores or hundreds of feet belong in this class although some of them may well be of Nebraskan age. The great age of the Kansan drift is shown by its profound erosion and its deep weathering. Most of both processes were completed before the deposition of the younger loess. Just why portions of both northwestern and eastern Iowa differ in erosion features from southern Iowa and northern Missouri has never been explained. The reason doubtless lies in a combination of (a) altitude, (b) climate, and (c) underlying rock. The drumlins on some of the inter-stream tracts in eastern Iowa do not suggest deep erosion but rather remnants of an original drift topography. Many observers have sought to place these areas of smooth topography as younger than the Kansan; they have been ascribed to the Iowan and Illinoian stages by most, and by some to an early advance of the Wisconsin. Objections to this view are (a) the impossibility of explaining the boundaries of these tracts on a theory of long narrow ice lobes, and (b) the lack of evidence of any vertical division in the underlying drift deposits. The matter is similar to the question of the Iowa drift and is further considered under that head.

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YARMOUTH INTERVAL

Nomenclature. The term Yarmouth was first applied to the interval between the Kansan and Illinoian drifts by Leverett in 1898. The type locality is a well at Yarmouth, Des Moines County, Iowa.

Distribution. Yarmouth deposits have been recognized only in a narrow belt along Mississippi River in eastern Iowa and western Illinois where the Labradorian Illinoian drift overlaps Keewatin Kansan drift.

Description. The Yarmouth interval is mainly represented by gumbotil and oxidized drift; there is some peat and loess has been reported. The deposits are for the most part known only in wells. They lie at different elevations so that an erosion surface of the underlying drift has been deduced.

Organic remains. The recorded organic remains of the Yarmouth included arctic mosses, coniferous trees, rabbits, and skunks. The specimens were mainly not found in situ but were taken from the debris from wells; few specimens have been examined by experts.

Interpretation. The Yarmouth deposits were included by McGee with his forest bed but were placed in a younger horizgn by Leverett. His reasons seem to have been (a) elevation of the deposits at approximate level of the Kansan uplands to the west, and (b) position of the deposits at the border of the less eroded Labradorian drift whick lies upon the Kansan drift of Iowa. It was concluded that the Kansan drift had been eroded into broad shallow valleys before the coming of the eastern ice. The principal evidence of long duration of the Yarmouth interval is the presence of gumbotil to a thickness of several feet. The described organ remains tell little of the climate. It has never been proved that the Aftonian deposits underlie the Yarmouth. Too much of the published data rests on well records. Other objections will be considered under the head of the Illinoian droft.

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ILLINOIAN STAGE OF GLACIATION

Nomenclature. The term Illinoian (Illinois at first) was first applied by Chamberlin in 1896 on the basis of work by Leverett.

Distribution. The extra morainic tract of drift in Illinois, together with smaller areas in Indiana and eastern Iowa is classed as Illinoian drift. A small area in southern Wisconsin seems to be of the same age and efforts have been made to identify Illinoian drift in central Wisconsin and eastern Minnesota. Leverett has suggested that the Iowan drift of northeastern Iowa and a portion of the smoother Kansan area of northwestern Iowa are both of Illinoian age. So far these extensions which do not actually touch the original area have not met with general acceptance.

Description. The original Illinoian drift lies in a region of shales and shaley sandstones and is therefore a region of clay till. The surface is mainly a level plain which is in the stage of youth in the erosion cycle. There are some morainic ridges, some of them composed of kames but there is little evidence of a marginal moraine, except in part of southern Wisconsin where the drift is more stony than farther south. Gumbotil is present over a considerable portion of the uplands. It is several feet thick. Leaching varies from 6 to 20 feet and oxidation in few places extends to less than 20 feet from the surface; some claim averages of 7 and 15 feet respectively but such generalizations must be accepted "with reservation." Most of the original Illinoian is covered by loess which lies both on uplands and on erosion slopes. Throughout much of the area there is some evidence of a still older drift beneath the Illinoian separated by a soil and weathered zone.

Interpretation. The drift of both the original Illinoian area and the supposed Illinoian of northern Wisconsin and eastern Minnesota came from the Labradorian center. It is difficult to see why the maximum extension of that center should have taken place in a different glacial stage than did the maximum of the Keewatin center when the Kansan drift was deposited. It seems natural to suppose that the two centers would have essentially the same development at the same time for not only was this the case during the Wisconsin stage but the Labradorian center is much the nearer to a supply of moisture. Leverett placed the Illinoian in a different stage than the Kansan because of (a) the strikingly great amount of erosion of the latter, (b) the presence of well-marked moraines kames, and eskers in the Illinoian drift, and (c) the presence of the Yarmouth zone of weathering between the eastern and the western drifts. While there is no doubt that the Illinoian is very much less advanced in erosion than the Kansan, even on the banks of the Mississippi, still the following questions may be raised as to the validity of the commonly accepted correlation: (a) there is no proved Keewatin correlative of the Illinoian or Labradorian equivalent of the Kansan, (b) the supposed equivalence of the Iowan and Illinoian has little or no support as shown in considering the Iowan stage, (c) the supposed Illinoian of northwester Iowa has neither a mappable border nor a vertical line of division from an older drift beneath, (d) the difference in dissection of the two drif is not so great but that it might be explained by one or more of the fo lowing factors (1) the prevailingly higher elevation of southern Iowa an northern Missouri above local baselevel, (2) possible differences in climate and vegetation in past times, and (3) erosion of the western area while the ice still covered Illinois, (e) there is no certainty tha the Yarmouth gumbotil and weathered zone is not the Aftonian, for the two horizons have never been found in the same section, (f) the known organic remains of the Yarmouth do not prove an interglacial climate, (g) the known extent of the Yarmouth zone is too slight to demonstrate a major ice recession, (h) the differences in weathering between the two drifts are not very striking, (i) both drifts have gumbotil on them, (j) both drifts were covered by the main body of the loess after extensive erosion and oxidation, and (k) the greater irregularity of the topography of the Illinoian is capable of explanation by a greater amount of stone than in the very clayey Kansan drift. It is possible that none of these objections are valid and that the Labradorian Kansan is mainly concealed by younger drifts as is also the Keewatin Illinoian but it would seem that the matter will bear further investigation. An evidence that may favor a much greater age of the Kansan is the presence of the old red loess on that drift and not, so far as known, on the Illinoian. The supposed Illinoian of north central Wisconsin appears to lie in the class of errors due to the discrimination of kame gravels as younger than the associated till; no glacier ever deposited gravel alone but the differences in weathering and erosion are capable of easy explanation on the ground of the difference between gravels and till.

<u>Lake Calvin and the diversion of the Mississippi.</u> The name Lake Calvin has been applied to the supposed ponding of the lower courses of the Iowa and Cedar Rivers in eastern Iowa. This basin shows (a) silts and laminated clays in sloping, little-eroded terraces, (b) rounded bluff lines, (c) possible ice-rafted bowlders, (d) an inlet and an outlet through abandoned valleys which join the Mississippi north and south of the area of Labradorian drift in Iowa. These valleys have bottoms high above the present levle of the Mississippi and have been interpreted as the temporary course of that river during the Illinoian invasion. They contain no sand and gravel deposits, but a bowlder bed at one point indicates a form stream bed. This interpretation may be challenged on the following groun (a) the sediments are those of slack-water streams and not of a lake,

as made evident by the slope, (b) the deposits occur at so low a level that it requires the assumption of much more erosion before the Illinoian than otherwise seems reasonable, (c) the valleys in which the deposits lie were eroded after the formation of the gumbotil on the Illinoian, although it has been suggested that the lake lasted long enough to permit of the formation of the gumbotil upon its banks, a theory out of harmony with the transitory character of lakes. It is legitimate to suggest that the phenomena mean that there is no essential difference in age of the Kansan and the Illinoian drifts and that the so-called lake was merely the ponding of the rivers by outwash deposition in the Mississippi, possibly in the earlier part of theWisconsin stage. An outwash terrace on th basin would then be ascribed to the time of terracing of the Wisconsin outwash trains and not to the Iowan. Both rivers carried Wisconsin drain It may also be suggested that the extreme youthfulness of the topography of the Illinoian along the Mississippi bluffs is in part due to the widening and deepening of the valley by the waters from the advancing Wisconsin ice. It seems that Lake Calvin would bear reexamination.

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SANGAMON INTERVAL

Nomenclature. The name Sangamon was applied by Leverett in 1898 to certain organic remains and to the interval between the Illinoian drift and the loess. The type locality is Sangamon County, Illinois.

Distribution. Evidence of the Sangamon interval is found throughout the area of Illinoian drift but organic deposits are less common outside of the original locality in central Illinois.

Description. In most places the Sangamon interval is shown by the presence of gumbotil, leaching, and oxidation. There is some peat, sand, and silt, the last probably in part loess.

Organic remains. The Sangamon deposits contain remains of northern mosses, coniferous trees, beetles, and apparently some vertebrates like the mastodon. The only thorough study seems to have been that of Wickham on the beetles; these were found to indicate a cool climate.

Interpretation. As there is no known contact between the Illinoian and the Iowan drifts Leverett chose the Sangamon deposits to mark the interval assuming that the loess that overlies them was of Iowan age. Now that it is known that loess is not a glacio-fluvial deposit, that there is more than one age of loess, and that loess is for the most part of interglacial age the force of this assumtion has been lost. There is certainly no evidence in the Sangamon deposits that can demonstrate an interglacial climate. It seems possible that they represent the early part of a long interglacial interval in which increasing aridity caused the burial of both swamp deposits and weathered drift by the encroaching dust from the deserts to the west. The term Sangamon is useful in refering to a certain horizon of the Pleistocene of Illinois but should be discarded as meaning a distinct interglacial stage.

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IOWAN STAGE OF GLACIATION

Nomenclature. The name East Iowan was applied by Chamberlin in 1894 to McGee's "Upper Till" which was then supposed to be the surface drift of southern Iowa south of the terminal moraine. In the following year the prefix was dropped and in 1896 the "Upper Till" was divided into Iowan and Kansan. This confined the Iowan drift to northeastern

Iowa. In 1909 an attempt was made by Leverett to either abolish the Iowan stage or to correlate it with the Illinoian. In 1917 Alden and Leighton reported in favor of the retention of the term Iowan as a stage designation.

Distribution. The recognized Iowan drift area lies wholly in northeastern Iowa east of the Des Moines lobe of Wisconsin drift. Attempts have been made to identify Iowan drift (a) west of that lobe, (b) north and northeastward into Wisconsin, and (c) in northern Illinois.

Description. The surface till of the original Iowan area is yellow in contrast with the reddish-brown of the oxidized Kansan farther south. At depth the till is blue gray. Leaching extends to depths of from one to 8 feet; some claim that leaching averages 3 feet and oxidation 8 feet. The till is relatively stony with many large bowlders of coarse gray granite. Loess is very thin or absent; over much of the area it is so highly charged with organic matter that its origin is obscured. There is a distinct pebble line between the loess soil and the till. Where the loess is thick enough for the lower part to be unleached it rests upon unleached till. In some places, especially along streams, loess covers sand dunes so that the topography resembles that of a terminal moraine. There are some kames and many of the streams have gravel terraces. Formerly these stratified deposits were called Buchanan gravels.

Topography. The Iowan drift area has a distinctive type of topography, a smooth, gentle, almost flat in many places, erosional type, with broad, branching, indistinct valleys. The slopes and uplands which merge imperceptibly into the valley sides, are all bowlder-strewn where undisturbed by man. This type of country closely resembles some of northwestern Iowa. A striking feature is the irregular boundary of the smooth topography which runs out in long fingers pointing southeast, for the most part on divides but some seem to jump across the streams in a curious manner. An instance of this is the North Liberty plain near Iowa City. In the smooth areas are some "islands, of rough, loess-covered drift and low, loess-covered drumlins, the "paha" of McGee who supposed them to be wholly loess. There are also some outliers of smooth topography which are entirely surrounded by rough erosion forms. Some areas of kames have relatively steep slopes that have been interpreted by some as constructional topography.

Interpretation. The Iowa drift area offers more puzzling phenomena than almost any other region in North America. McGee originally divided the drift into two tills divided by the forest bed. He thought that the loess was a glacio-fluvial deposit which was accumulated while the ice still occupied parts of the region. This theory was worked out in a very ingenious manner but fell to the ground when the true nature of loess was discovered. However, even at the present it is held by many geologists that the loess was excluded from the Iowan drift area by ice occupancy at the time of its formation. Calvin then split up McGee's "Upper till" into Kansan and Iowan, the latter a thin veneer of loam, yellow till, and granite bowlders. The mapping in northeastern Iowa apparently used the following criteria: (a) absence of loess, (b) presence of large granite bowlders, and (c) smooth topography. The Iowan till was regarded as a distinct lithologic unit separated from the underlying Kansan by (a) a zone of weathering, and (b) the Buchanan gravels. The difficulty of the peculiar borders of the Iowan was explained by the theory that the ice was very thin and was floated by the waters that deposited the loess.

The pana and areas of rough, loess-covered drift were regarded as nunatak which rose through the ice. In recent years an effort has been made to abandon the long prongs and "islands" and to smooth the margin to one consistant with the known characteristics of glaciers. It has been found that the type locality of the Buchanan gravels has no till above the sediments; the same is true of many other areas of these deposits. The Buchanan gravels are now interpreted as (a) Iowan kames, (b) Kansan kames, (c) Iowa outwash, (d) Kansan outwash, and (e) Wisconsin outwash. The existence of valley trains from the Wisconsin drift to the west was ignored by the earlier geologists.

The Iowan controversy. The Iowan drift was accepted without question until Leverett returned from Europe where the German geologists had convinced him that there were but four glacial stages. In order to harmonize their results with the phenomena in this country Leverett eliminated the Early Wisconsin as a distinct stage and suggested that the Iowan drift either be eliminated or correlated with the Illinoian. These opinions met with strenuous opposition from Calvin and after the death of the latter Alden and Leighton were assigned to reinvestigate the question.

The case for the Iowan. Alden and Leighton reported that although no single line of evidence definitly proved the existence of the Iowan stage of glaciation a number of separate kinds of evidence suggested that such was the case and that the combined pull of these in the same direction convinced them that Calvin had been correct in principle although not in detail. The points are as follows: (a) the Iowan area is much less weathered than the adjacent Kansan, (b) although the loess was doubtless in part excluded from the Iowan area by its smooth topography it was thought that radiating winds from the ice may have been the cause, (c) where loess is present it rests on fresh drift without evidence of the Sangamon interval, (d) bowlders are no more numerous in valleys than on uplands suggesting that their presence is not due to erosion of the finer material, (e) terraces of comparatively fresh gravels, the valley phase of Calvin's Buchanan gravels, are present only in valleys that drained the Iowan area, (f) the peculiar Iowan topography can be explained by glaciation of an eroded drift, (g) locally the till lies upon and contains masses of gravels (Buchanan) which have been interpreted as having been weathered previous to the last ice advance of that region, (h) several exposures have been found where the surface, relatively fresh drift lies upon gumbotil and weathered drift which has been correlated mainly on the basis of elevation with the Kansan gumbotil plain to the south, and (i) the forest bed of McGee lies at lower levels than do these gumbotil remnants.

The case against the Iowan. On the other hand, a formidable array of evidence may be arrayed against the existence of the Iowan: (a) the mapped borders of the Iowan are fantastically impossible and are prima facie evidence that something is wrong in interpretations that lead to such absurdities, (b) large granite bowlders are not confined to the Iowan area but show there because of the thin loess, (c) the Iowan ice could not have had a selective action and deposited only a certain type of bowlders, (d) the bowlders are fresh simply because of a different variety of granite than are the weathered granites, (e) there could not have been any such thing as a "typical Iowan till", (f) much of the surface material formerly called Iowan till is not till but is slope-wash, loess, and weathered gravels with some bowlders, (g) the slight depth of oxidation and of leaching is associated with a high water table and much of the area was marshy before the extensive tile drainage, (h) the Iowan drift area is essentially the outcrop of the Devonian and Silurian limestones and therefore the drift is more stony and calcareous than the recognized Kansan drift, (i) the high water table, the absence of loess, and the presence in the stream valleys of ledges of resistant limestone coupled with the smooth character of the preglacial surface are adequate and plausible factors in producing the present surface contour, (j) the surface is not a fresh glacial topography but an erosional form, for it lacks blocked valleys, sags, and true constructional knolls, (k) the supposed constructional forms are, barring the drumlins, either sand dunes or eroded gravels, (l) the gumbotil remnants have been cut by the erosion surface of the present topography showing deep erosion since their burial, (m) the freshness of the drift and its relation to the loess are both explicable on the ground of more erosion rather than of less alteration, (n) The rock barriers in the streams have formed local baselevels which affected the type of erosion, (o) the correlation of the buried gumbotil as super-Kansan rather than Aftonian rests upon a rather uncertain basis, long-distance comparisons of elevation, especially in view of the paucity of exposures and the slight vertical distance between the two gumbotils in southern Iowa, (p) that some of McGee's forest bed lies lower than the gumbotil exposures is not decisive since they may have been formed in valleys eroded in the gumbotil plain and the two zones of weathering are nowhere known in the same section, (q) the paucity of loess is readily explained by the levelness of the land, (r) the fossils in the loess do not indicate that ice was present nearby at the time of its deposition, (s) the loess-covered paha and other elevations are too low for nunataks and must have caught their loess cover by reason of their rough topography and cover of vegetation, (t) the erosion form of the Iowan area may have been affected by the cover of prairie grass which differed from the light grass and trees of the region to the south, (u) it has been suggested that the valleys were blocked by the invasion of their lower parts by the Illinoian ice, (v) there is no topographic reason for the lobe of Iowan drift where it is and an ice sheet powerful enough to support so far-flung an extension would surely have extended beyond the border of the young drift at other points, (w) the topography and relations of drift to loess in the Iowa area are almost perfectly matched in northwestern Iowa where the drift is now believed to be of Kansan age, (x) the unmappable border of the Iowan area cannot be explained away by either assumption of thin drift nor by arbitrary smoothing, (y) the supposed Iowan outwash may be mainly of Wisconsin age, (z) no Iowan till has ever been found beneath the Wisconsin drift to the west, and (aa) it is admitted that no single kind of phenomena prove the existence of the Iowan stage of glaciation. The foregoing points prove that (a) the loess is not synonymous with Iowan in point of age, and (b) that the Iowan question is not yet solved.

Supposed extensions of the Iowan area. The Iowan drift mapped in northern Illinois was taken to be the Labradorian equivalent of the original Iowan. Later Alden showed that no account had been taken of topographic control of depth of weathered material, at least in the northern part of the district so that the drift was shown to be Illinoian clear to the glacial boundary. Even the little-eroded drumlin belt of eastern Rock County, Wisconsin, was included in this stage as the difference in topography was found to be explicable by differences in relief and in preglacial topography. Recently Leighton has suggested that a portion of the extramorainic drift in Rock River Valley, Illinois, shows deep enough weathering to be possibly of Iowan rather than of Wisconsin age. The conclusions are admittedly uncertain and are confused by differences in drift character and other factors which affect weathering. Weidman sought to distinguish Iowan drift in north-central Wisconsin but the deposits appear to be wholly stratified materials. Leverett has urged that the drift of part of northwestern Iowa is of the same age as that of northeastern Iowa and has suggested that both areas are of Illinoian age. Carman found no mappable border either horizontal or vertical. The exact cause for the differences in topography has not as yet been worked out but it is apparent that there are no definite constructional features associated with the smooth drift areas of northwestern Iowa. Recently Alden has suggested that the extra-morainic drift of the Dakotas may be of Iowan age since it is not much weathered and lies in the bottoms of valleys which appear to be younger than the first glaciation which diverted the streams to the Mississippi instead of their former course to Hudson Bay. None of the proposed extensions of the Iowa appear to have any definite proof of their existence.

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PEORIAN INTERVAL

Nomenclature. The name Peroian was applied by Leverett in 1898 to the interval between the Iowan and Wisconsin drifts. The type locality is seven miles east of Peoria, Illinois.

Distribution. Evidence of the Peorian interval has never been discovered between the Iowan and Wisconsin drifts in Iowa. The original definition was based on the conclusion that the loess was contemporaneous with the Iowan drft. Examples of loess buried by Wisconsin drift are common along the border of the young drift throughout Iowa and Illinois.

Description. The Peorian is not marked by extensive deposits but only by weathering unless the loess be regarded as of Peorian age as it is now coming to be. The younger loess of Illinois and Iowa is for the most part decidedly younger than the Illinoian and Kansan drifts, and older than the earliest Wisconsin drift. In many places, however, there is loess on the margin of the Wisconsin drift. There seems to be no known line of demarkation in loess sections on the old drift although the deposits must be of more than one period of formation. The relations of the loess to the equivocal Iowan drift have been noted with the conclusion that although the bulk of the loess was deposited during the time during which the Iowan drift was supposed to have been deposited, there is little definite evidence to fix its age in reference to that of the drift. If there is an Iowan stage of glaciation the main portion of the young loess is younger. The loess was weathered before the coming of the Wisconsin drift. Some peat beds found in wells in northern Illinois were once correlated as Peorian.

Interpretation. The Peorian was named when the loess was considered as a glacio-fluvial deposit of Iowan age. At the type locality the Sangamon gumbotil and peat are present below the loess and there is little reason to divide the deposits into two ages, separated by a stage of glaciation. Nothing is known of the vegetation or animal life of the Peorian but if the loess is regarded as belonging to that interval the climate was like that at present. The name Peorian is inappropriate although useful in referring to a definite horizon in the drift of Illinois. There is no sharp line between Peorian and Sangamon deposits in Illinois; they may both belong to the same interglacial interval, the loess having been caused by a period of aridity. In Iowa the presence of the two loess deposits separated by a long interval of time suggests either (a) that one is Sangamon and the other Peorian, or (b) that one is Yarmouth, and the other either Sangamon or Peorian. The separation of the Peorian and Sangamon is bound up with the question of the Iowan drift and cannot be settled until that is.

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WISCONSIN STAGE OF GLACIATION

Nomenclature. The striking difference between the drift inside the terminal moraine and that outside attracted the attention of Chamberlin in the early 70's and in 1878 he urged that the moraine marked a major line of division in the history of glaciation. The term East Wisconsin was applied by him in 1894 and the prefix dropped in the following year. In 1897 Leverett announced a subdivision of the Wisconsin into two distinct stages, Early Wisconsin and Late Wisconsin but in 1909 he minimized this conclusion and in 1915 repudiated it entirely. A tripartate division seems to have been considered at one time.

Distribution. Drift of Wisconsin age occupies a larger area than that of all the pre-Wisconsin stages put together; it extends from the Pacific to the Atlantic and came from all the centers at essentially the same time.

Description. Drift of Wisconsin age includes all varieties of till and of glacio-fluvial deposits. In such a variety of deposits and of climates weathering conditions have naturally been varied. On the whole weathering is very slight and in the climate of Wisconsin leaching varies from nothing in dense clay till to several feet in loose sandy deposits like sandy tills or outwash. In Iowa some have put leaching at nothing and oxidation at one and a half feet. In northern and northeastern Wisconsin there is a bright red till, evidently the product of ice passing over lake clays; this till is underlain by a forest bed.

Topography. As a whole, the Wisconsin drift is characterized by (a) much stratified drift, (b) pronounced moraines, and (c) little erosion. The topography is related to the character of the drift in different districts. The Wisconsin tills average a greater amount of stone than do the pre-Wisconsin tills; hence the difference in original forms. Erosion is slight save where conditions were very favorable as in some of the clay tills with a relatively steep slope. Most of the border of the Wisconsin drift is marked by a large terminal moraine but in some districts there is no moraine and the border of the young drift must be discriminated by (a) constructional topography, (b) little weathering, and (c) the thinness or absence of loess.

Interpretation. It is obvious that the Wisconsin drift is much younger than any of the pre-Wisconsin drifts with the possible exception of the Iowan. Its difference in topography is mainly explicable on this ground. There is no reason to suppose that the less extensive Wisconsin ice sheet had more vigor, was thicker, moved faster, or carried a greater load than its predecessors; nor was it the only ice sheet to form stratified drift. Much of the supposed difference in phenomena of the old and new drift was the result of comparing the stony drift of Wisconsin and northern Minnesota with the clay drift of Illinois and Iowa; where regions of the same kind of drift are compared the differences are less striking. The strongly accentuated terminal moraines of the Wisconsin drift are all very gravelly and stony. The relatively large amount of gravel in and associated with the Wisconsin drift is explicable by (a) youth of the deposits which have not yet been removed even along large streams, (b) great amount of stone in the till. There is no reason to assume either more vigorous drainage or different elevation of the land. The stony and sandy character of the Wisconsin tills is accounted for by (a) deposition of much of the Wisconsin drift in regions of limestone, sandstone, and crystalline rocks, (b) overriding of older outwash deposits, (c) picking up of residual gravels and bowlders from the eroded surface of the old drift, and (d) derivation of some of the drift from the northern regions that had been stripped of their preglacial soil by earlier ice action. That the Wisconsin drift shows more marked lobation than did the earlier glaciers is explained by (a) relative thinness of the ice, and (b) less extent of the later ice so that it was more nearly confined to the Great Lake basins that alone could form large lobes. The avoidance of the Mississippi Gorge by the Wisconsin ice is in large part explainable by pressure of the Labradorian or Patrician Lake Superior lobe against the Keewatin ice.

Possible subdivision. Leverett at one time divided the Wisconsin into two stages with the interval not indicated by either differential weathering and erosion or the presence of interglacial deposits but by shifting of the Erie and Illinois lobes. This view involved several objections: (a) the moraine correlative with the maximum extent of the Green Bay lobe of Wisconsin would have indicated an unreasonably small extent of the Illinois or Lake Michigan lobe, (b) the relations of the moraines near the Illinois-Wisconsin boundary, where stony and clay tills meet, would be peculiar and unreasonable, and (c) the phenomena of the Erie and Illinois lobes are explicable on the basis that the shifts took only a short length of time and that what erosion is present is the work of glacial waters alone. Leverett has now concluded that the data on which he made the discrimination of two stages in the Wisconsin were misinterpreted and has urged the abandonment of the term Early Wisconsin. Since then Leighton has shown that weathering seems to indicate that parts of the marginal Wisconsin drift is considerably older than the drift farther north but apparently did not use the term Early Wisconsin as meaning a separate stage. What seems to possibly be a better basis for a division of the Wisconsin into two sub-stages is the readvance of the ice that formed the drift above the forest bed of northeastern Wisconsin. This readvance has been traced from the Port Huron moraine in Michigan west into the Lake Superior basin. It followed upon an interval that was long enough to (a) permit of retreat of the ice at least as far north as the Straits of Mackinac, (b) permit the growth of spruce trees over 18 inches in diameter, and (c) not long enough for leaching of the subsoil. The red color of much of the till above the forest bed is confined to the regions near to the iron ore and other red beds of the Lake Superior region; it is original and not due to weathering for it is (a) independent of leaching, (b) extends to great depths beneath the water table, and (c) is explicable by the concentration of the iron oxide in the lake clays. This interval is evidently not comparable in length to those heretofore discussed.

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TORONTO INTERGLACIAL DEPOSITS

<u>Nomenclature</u>. The name Toronto was first used by Chamberlin in 1894. The subdivisions, Scarboro and Don, were first named by Coleman in 1901.

Distribution. The type locality of the Toronto deposits is near the city of that name in Ontario, Canada. Beds correlated with more or less certainty have been found near Lake Cayuga in western New York and near James Bay in northwestern Ontario. The co-called Saugeen and Erie clays of Ontario have been correlated by some with the Toronto interglacial formation.

Description. The original Toronto formation is a delta deposit of sand and laminated, non-calcareous clay. It lies upon a thin discontinuous till of northeastern origin. The rock surface below this till is not straited but glacial stones in the till leave no doubt of glaciation. The varves in the clays total several thousand. There are no ice-rafted stones. The total thickness of the Toronto is close to 200 feet. The top is irregular and in one place shows a deep and broad valley which is filled with the complex of tills and gravels that overlie the interglacial beds. The James Bay lignites with associated sands and clays lie between two tills and were greatly disturbed by the second ice invasion.

Organic remains. The lower part of the Toronto formation is designated as the Don beds; this member contains trees up to 18 inches in diameter and leaves of basswood, maple, ash, hickory, osage-orange, red cedar, elm, oak, and pawpaw, 35 species in all. The malluscan shells include Unios like those of the Mississippi region and the mammals include the deer, bison, elephant, etc. This fauna and flora definitly indicate a climate markedly warmer than that of Toronto at the present time, a climate like that of southern Pennsylvania. The upper member of the formation, however, which is called the Scarboro beds, contains beetles and vegetal remains that clearly show a cool climate like the present climate of Labrador. The James Bay lignites have not been carefully studied but have yielded balsam, cedar, and poplar trees up to 17 inches in diameter Fossils like those of the Don beds have been found in western New York.

Interpretation. The history of the Toronto deposits was as follows: (a) Labradorian glaciation, (b) erosion of drift, (c) formation of a lake from unknown causes but apparently not blocking of drainage by a glacier, (c) formation of the warm-climate Don beds, (e) conformable deposition of the Scarboro cool-climate beds, (f) lowering of lake levle, (g) erosion of broad valleys, and (h) Labradorian glaciation with possible erosion of the interglacial deposits by ice and several oscillations of the ice margin. The ice must have entirely disappeared from Labrador during the formation of the Don beds, a conclusion very much strengthened if the James Bay prove to be thesame age as the Toronto formation, for the former are only 300 miles from the glacial center. The Toronto deposits are unique among American Pleistocene deposits in proving a real interglacial interval by their nearness to the center of accumulation of ice.

Correlation. The correlation of the Toronto deposits with the Mississippi Valley succession is still an open question; they have at different times been assigned to the Peorian, Sangamon, and Aftonian. In recent years Coleman has urged correlation with the last, apparently basing his conclusion upon (a) the position of the deposits with only one till beneath, and (b) the character of some of the fossils. An effort was then made to subdivide the tills and gravels above the Toronto into several glacial and interglacial stages but there seems to be little if any evidence in favor of such a view for there is no published information that would lead one to conclude that there was any great lapse of time between successive deposits. According to the same author the Toronto marks an interval two or three times as long as all postglacial time, a large portion of which is accounted for by the second erosion interval. This conclusion appears to fail to take account of the possible broadening of the buried valleys by glacial erosion. In any case the Toronto deposits represent a very long lapse of interglacial time although the upper part might have been formed while the ice was advancing for the second time.

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PLEISTOCENE SUCCESSION IN EASTERN UNITED STATES

General. The extra-morainic drift of the eastern states was treated above; some geologists have sought to find in the east the same drift succession that has been worked out in the Mississippi Valley. In 1886 Merrill first suggested more than one age of drift on Long Island on account of the disturbed condition of the lower deposits. In 1889 Shaler discriminated interglacial fossils on Nantucket, although in the previous year he had correlated the folded beds of Marthas Vineyard as Tertiary. In 1890 he discussed the possible glacial origin of some of these disturbed beds and in 1894 ascribed the folding to earth movements. In 1896 Shaler and Woodworth first definitely expressed the idea of complexity of the glacial drift and announced the succession: (a) Nantucket bowlder bed, (b) Sankaty interglacial beds, folded, (c) Tisbury beds, glacial, horizontal, (d) Vineyard erosion interval, and (e) last ice invasion glacial deposits. A very long interval was deduced between the first two ice advances. In 1897 Woodworth concluded that the base of the Pleistocene was marked by the earliest appearance of undecomposed feldspar in the sands. In 1901 the same author gave the succession on Long Island as: (a) old Pleistocene sands and gravels with evidence of floating ice, (b) erosion of valleys, and (c) Wisconsin glaciation. Veatch, in 1903, went much farther and discriminated (a) Pensauken outwash gravels, (b) Jameco gravels, (c) Sankaty cool-climate beds, (d) Manhasset or Tisbury beds, glacial outwash, and (e) Wisconsin drift. Of these the Manhasset was described as unconformable over the older folded beds and was tentatively correlated with the Iowan; the Pensauken was assigned to the pre-Kansan and the Jameco to the Kansan. This column was further elaborated by Fuller in 1905 to read: (a) Manetto weathered outwash-Albertan, (b) erosion interval-Aftonian, (c) Jameco fresh outwash-Kansan, (d) Jacob sand and Gardiner clay-Yarmouth, (e) Montauk drift and Herod gravel-Illinoian, (f) erosion interval-Sangamon, Iowan, and Peorian, (g) Wisconsin drift. In 1906 Veatch used the same column with slightly different names. In 1906 Fuller extended the succession to the mainland and soon after Clapp endeavored to find evidence of several glacial stages in northeastern New England. The latter laid great stress on (a) tills which appeared old, (b) relations of moraines to marine clays, (c) differences in weathering and oxidation, (d) erosion unconformities, and (e) buried soils. He admitted that the evidence for complexity of the Pleistocene glaciation was far from conclusive and some of the conclusions appear to be open to doubt. For instance the assignment of the bulk of the drift including the Boston drumlins to the Illinoian is hardly possible for drift as old as that would certainly have lost all glacial topography in the climate of that region. Such a correlation reduced the Wisconsin drift to a mere veneer which illustrations show to really be slopewash and weathered drift. In general the evidence, especially in assuming the absence of glacial drift on top of some of the clays, is by no means convincing. In 1914 Fuller's final report on Long Island appeared but added little new. The illustrations of the so-called Montauk till of supposed Illinoian age show definitely that it is not till but a beach deposit in which bowlders were concentrated by wave work. The folding of the older beds was ascribed to overriding by ice.

Conclusion. There is good evidence that the ice front oscillated several times in the eastern state but there is little to prove which of the ice retreats were most extensive or marked interglacial intervals. Much of the work on the Pleistocene of this region was done by students of marine strata who attempted to apply the same methods to glacial deposits as they had used before. Their efforts to bridge the thousand-mile gap between the Atlantic seaboard and the Mississippi River involved methods that would never be accepted in the case of marine sediments. Only one geologist, Crosby, seems to have protested publicly but it appears best to accept the conclusions as to interglacial stages and particularly the correlations with the western section "with reservations." It seems fair to suggest that (a) the folding of strata by glacial action does not require overriding but is more likely due to shove against either an erosion escarpment or gravels banked against the front of the ice, (b) the lapse of time between folded and overlying horizontal beds may not mean a long period fo erosion for the truncation of the folds may have been accomplished by the sea, (c) subaerial erosion was very rapid on account of the loose sandy material, nearness to the sea, and the humid climate, (d) to attempt ot divide a complex of glacial outwash, beach, and deep water sediments into lithological units or to subdivide it on the basis of the presence and absence of folding is extremely hazardous, (e) no account seems to have been taken of ground water conditions in considering weathering, for instance the Manetto gravels are on high hills and the Jameco is wholly beneath the water table, (f) judging from maps the erosion forms of parts of Long Island are certainly postglacial and it is legitimate to suggest that only post-human erosion may have been called postglacial, (g) the attempt to confine the Wisconsin drift to a very thin discontinuous mantle seems improbable, (h) the fossils at Sankaty Head do not have very great significance as showing true interglacial conditions, and (i) the region would bear reexamination.

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GLACIATION IN THE WESTERN MOUNTAINS

Introduction. The western mountainous area is here treated as including both the foothill region adjacent to the Great Plains and the lowland of Puget Sound. The study of glacial geology is not well advanced in much of this vast region but studies are now in progress by Alden which may clear up some of the present uncertainty. There are many incidental references to glacial geology that have not been included in the references.

Distribution. Evidences of Pleistocene glaciation have been found on most of the higher ranges from Arizona northward; local glaciers still linger on many of the high mountains, mainly on the northern Rockies and the high peaks of the Cascades. The phenomena are those of mountain and piedmont glaciation, subjects not treated in detail in this outline.

Evidences of more than one glaciation. The glacial features of the mountains show wide variation in degree of alteration by weathering and erosion; they vary from fresh moraines abandoned by the ice only a few years ago to deposits which are nearly indistinguishable on account of age and might easily be confused with landslides. Division into different ages cannot be made by stratigraphic superposition of deposits except in the Puget Sound region. There an old till, called Admirality, is overlain by glacial outwash called the Puyallup formation, which was deeply weathered and eroded before the later Vashon glaciation. These main facts are well established but it appears improbable that some of the details are, for instance the assignment of certain kames to the Puyallup and the confining of the later drift to a veneer of scattered stones. In the same region is found a very peculiar phenomenon, the occurrence of small gravel mounds on the outwash plains whose origin is in large part undetermined. In the region of Glacier National Park Alden has found glacial drift on top of divides hundreds of feet above the intervening valleys. Although it is impossible to determine to what extent this drift entered the valleys and has since been removed this ice advance must have been very old, possibly as old as the Nebraskan glaciation.

The later or Wisconsin drift lies only in the valleys, and it is presumed that a long interglacial interval occurred between the two drifts.

Evidence of three stages of glacial expansion separated by long intervals of erosion have been found in the mountains of Wyoming and of southern Colorado. On the Columbia Plateau Bretz finds two ages of relatively recent drift which have no loess cover; these are discriminated by the comparative amounts of talus in the valleys eroded by their drainage.

There is also some evidence of an older, loess-covered drift. Indications of two drifts are common to many ranges. In attempting to correlate these phenomena with the events of continental glaciation, it is well to remember that (a) it is very difficult to tell if any particular valley or portion of a valley is later than drift on the divides for reasons explained above, (b) the great differences in material, slopes, climate, etc. make comparisons of weathering and erosion virtually impossible, (c) glaciation in the mountains may have been affected by uplift and the cutting off of winds by uplifts elsewhere to such an extent as to mask the effects of climatic changes, and (d) erosion has removed much of the evidence of early glaciations if present. Alden distinguishes one period of uplift just before the earliest glaciation and another at a later date in the Pleistocene. Correlation with the succession is premature at present.

A number of geologists have at different times confused non-glacial and glacial deposits in the mountain region; an instance is Dawson's Albertan drift which is now known to be stream gravels.

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SUMMARY

General. It has been shown that whatever the shortcomings of some of the criteria the complexity of the Pleistocene is firmly established. The only questions left are: (a) the number of major recessions of the ice, (b) the extent of these great recessions, (c) the climate during each, and (d) the correlation of drifts deposited during the several stages.

Number of glacial and interglacial stages. If we proceed outward from any of the centers of continental glaciation we find (a) Wisconsin drift, and then (b) pre-Wisconsin drift which conceals beneath it a still older drift. This is true in Iowa, Illinois, and apparently on the Atlantic coast. These facts early gave rise to a tripartate division of the Pleistocene, after it had been evident for some time that a dual division of the surface drift was demonstrable. Save for the equivocal Iowan [illegible] drift area, no sections outside the Wisconsin terminal moraine have been definitly proven to show more than two Pre-Wisconsin drifts at the same spot. If, however, we travel along the drift boundary or a line parallel to it the matter is less simple. In New England the last ice advanced farther than any previous stage. From New Jersey to western Pennsylvania the drift border is old drift, "Jerseyan", which farther west is overlapped by the young drift. Owing to differences in climate, material, and rock topography correlation with the drift farther west seems impossible. The same remark applies to the small area of supposed Kansan drift in western Pennsylvania west of the reentrant in the drift margin. From Indiana west the glacial boundary is old drift; the difference in erosion of Illinois and Iowa has been taken to prove that the drift of the former state is much younger than the marginal drift farther west, thus making three pre-Wisconsin drifts without including the Iowan. As shown above there is some reason to doubt this conclusion and more data must be collecte in order to remove this suspicion. Farther to the northwest in North Dakota and Montana the marginal drift occurs in the bottoms of valleys of streams diverted by a former glaciation and Alden has suggested that this drift may be younger than that of southern Iowa. The oldest mountain glaciation must surely be as old as the oldest buried drift, the Nebraskan. The evidence as studied in this fashion indicates four or possibly five, glacial stages but there is no point where all of these are found in a single section out from a glacial center or vertically above one another. If the Kansan and Illinoian should prove to be parts of the same stage then the number would be reduced to three.

Extent of recessions. The Toronto interglacial deposits are only 100 miles from the glacial margin and the gumbotils of Iowa are not known at much greater distances from the unglaciated region. The James Bay lignites alone indicate deglaciation in the far north. As pointed out great extent of such deposits could not be expected on account of glacial and interglacial erosion and long duration does not prove great extent of a recession. It is clear, however, that there was at least one complete or nearly complete deglaciation.

Climate during recessions of the ice. The Toronto deposits stand alone in definitly proving a very mild climate between two glacial stages. Remains of temperate vegetation could not be expected in the latitude of the James Bay lignites. There is some evidence that the Aftonian was an interval of temperate climate but the position of the deposits so near the southernmost extent of the ice reduces the significance of this. The position of the Toronto formation in the western section has never been determined; it may be Aftonian or it may belong at the time of the Sangamon, the great break between the young and the old drifts. The paleontological evidence, therefore, indicates one or two mild interglacial intervals.

Correlation of drifts. If there are four or five glacial stages then drifts of each have not been discriminated from all of the centers. This may mean either (a) that the natural difficulties of correlation have prevented the reaching of definite conclusions, or (b) that there are fewer than four separate stages. The case of the Kansan and Illinoian drifts is the best illustration of this point. The attempted correlations of the Pleistocene formations of the Atlantic coast with the section in the Mississippi Valley appear to have been over too great a distance to inspire confidence and such should be discouraged as tending to bring discredit upon the science of glacial geology. The same remark may be applied to the use of a considerable number of the criteria formerly in vogue.

Evidence of the western Quaternary lakes. The Quaternary lakes of the Great Basin have thus far disclosed evidence fo but one arid period which can be correlated with a time of complete deglaciation. If evidences of other humid periods corresponding to early Pleistocene glacial stages exist, they must be buried under the oldest alluvial cones. The phenomena are, therefore, not in harmony with the succession worked out to the east; this shows that either (a) there was but one real interglacial interval, the other recessions having been less extensive, or (b) there were older lakes remains of which have not yet been discovered. The former agrees with the paleontological evidence of the Mississippi Valley so far as the latter is known.

Summary. It has been shown that the evidence for complete or nearly complete deglaciation during the recessions of the ice between the glacial stages is not decisive for more than one or at most two of these intervals. The exact number of major recessions of very long duration is also open to some doubt; there must have been at least three principal glacial invasions of the northern states, if not four, and possibly five. Nothing that is said herein should be taken as showing that there were not several distinct glacial stages in these latitudes; the only question is how far the ice retired during the intervals. There may well have been only one mild interval of complete deglaciation without destroying the reality of the separate glacial stages in the United States. It is probable that some revision of the number of stages and the names applied to them and to the times of recession may be needed. Most criticism applies to matters of correlation of different areas rather than to the main conclusions as to the complexity of the Pleistocene glaciation. To quote a well-known foreign authority, W. B. Wright: " It is interesting to note that the apparent ease and definiteness with which the Americans have read the record of their glacial deposits is gradually becoming reduced to a state of agnosticism very similar to that of the European glacialists toward their northern drifts." (Quaternary Ice Age, p. 167, 1914.) European thought appears to be tending toward only one mild interglacial interval between two glaciations each with two maxima. It is possible that the same will eventually be found to hold true in this country. If so, the section might be revised to read: (a) older glaciation including Nebraskan, Kansan and Illinoian drifts, (b) true interglacial deposits, Toronto formation, etc., and (c) younger glaciation, including Iowan (?), and Wisconsin drifts. For the present, however, it is best to reserve judgment on this broad question and to confine ourselves to the task of eliminating the mistakes due to faulty criteria and to the changing of some of the names to ones more appropriate. The questions of the Pleistocene are far more difficult to solve than seemed the case thirty years ago.

LATE GLACIAL AND POSTGLACIAL PHENOMENA

General. The retreat of the last ice left the country bare of vegetation at first and with many undrained areas. Since the ice left and the last ice dams melted and broke destroying the ice-bound lakes, continental uplift, weathering, erosion, and sedimentation have all worked changes; similar phenomena occured during the major recessions of the ice earlier in the Pleistocene. In some of the higher mountains local glaciers survived, some of them to the present, and the ice cap has never been driven from Greenland. The work of man in cultivating fields and destroying forests has introduced changes of the first magnitude in the processes of erosion and sedimentation.

Postglacial uplift. The subject of late glacial and postglacial uplift of the land has been considered before.

Postglacial weathering and erosion. The subjects of postglacial weathering and erosion have been considered above. Post-Wisconsin weathering is by no means negligible for on sandy plains the limestone pebbles have been destroyed to a depth of several feet. The most conspicuous erosion features of postglacial time are those due to the waters from the retreating ice; of these may be mentioned the valleys of the St. Croix, Illinois, and Niagara Rivers. In favorable locations where gradients were steep, material soft and impervious considerable valleys have been formed by local precipitation alone; of these may be mentioned the valleys and ravines in the beds of some of the glacial Great Lakes. The work of man has enormously speeded up erosion by (a) substituting bare fields for grass and woodland, (b) tramping of ground by cattle, (c) substitution of grass land for forest mould, and (d) increasing the rate of run-off by draining marshes and lakes. The formation of shore lines is a phase of postglacial erosion; beach lines are not positive proof that the area they surround was once a lake. Some appear to have developed around marshes due to (a) drying and lesser plant growth in the margins, and (b) burning out of peat in the same situation, both of which cause a strip of open water whose level may be considerably above that of connecting lakes.

Postglacial sedimentation. Postglacial sedimentation has been both (a) inorganic, and (b) organic. Deposits of the former class have been made by (a) lakes, (b) streams, (c) slopewash, and (d) wind. Along the coasts there are late glacial and postglacial uplifted marine sediments. The conditions for the formation of sediments were best (a) immediatly after glacial retreat before vegetation obtained a foothold, and (b) since the work of man accelerated erosion. A conspicuous feature indirectly due to man is the formation of cattle and sheep trails on steep bluffs; as these are found on abandoned excavations and dumps, their recent origin is clear. An analagous feature is the hummocks of marsh borders; these should not be confused with grass tufts but are due to tramping of cattle between the tufts. Hummocks are absent where cattle have not been pastured and are known to have developed since the settlement of the country. Most forms of inorganic sediments have been treated before. Organic deposits consist of (a) peat, and (b) marl. The latter is confined to regions of hard water; in some cases the glacial transportation of limestone has caused hard water in regions where it was probably absent in preglacial time. Another postglacial feature is the formation of ice ramparts by expansion of the ice in lakes and wet marshes; this process is confined to a climate where winter snows melt off before the ice is weakened. Marl is calcitic even in dolomite regions.

Local glaciation. In the higher ranges of the eastern United States and Canada there are cirques made by local glaciers. Opinions differ as to the age of these in reference to the continental glaciation. Absence of moraines and the shapes of some of the cirques have been taken to indicate that the features are older but this has been disputed. There is almost everywhere the danger of confusing local moraines with landslides. Local glaciers probably existed at several times during the Pleistocene in this region. The Greenland ice cap lies on mountains and its border therfore takes on much of the character of mountain glaciation; it is not further discussed here.

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CAUSES OF THE GLACIAL PERIOD

Introduction. The problem of the cause of glaciation is one primarily of climatology and not of geology. For the benefit of those who have not studied climatology the following should be stated: (a) glaciation results from the carrying over of snow from one season to the next so that there is a net gain leading to snow drainage instead of water drainage, (b) condensation of moisture liberates latent heat which is immediately carried away and dissipated in the atmosphere, (c) melting of snow and ice uses an immense amount of heat, 8 tenths the amount needed to raise the same weight of water from the freezing point to the boiling point, (d) the temperature of the earth is maintained above that of space by solar radiation which enters the atmosphere as short waves and is changed to heat by contact with rock and earth, (e) radiation of heat from the earth is retarded by water vapor, dust, and carbon dioxide in the atmosphere, (f) snow fields reflect light and absorb little heat, (g) the air is generally clear above snow fields, (h) other things being equal the amount of precipitation at a given locality is determined largley by temperature decreasing with decrease in temperature, (i) heat is distributed on the earth by winds and oceaan currents, (j) precipitation and storm tracks in the belt of prevaliing westerly winds where the ice sheets accumulated are controlled by factors as yet imperfectly understood.

Distribution of glaciation. The centers of accumulation of Pleistocene and modern glaciation in the northern hemisphere are situated close to (a) the North Atlantic, (b) Hudson Bay, and (c) the North Pacific. Low pressure centers exist over both of the northern oceans and are best marked in winter when the lands are cold; they are centers of maximum storminess. Greenland, the only northern continental glacier at present, is occupied by a permanent high pressure center or anticyclone. There precipitation is from high levle cirrus clouds. In the areas of the Labradorian and Keewatin centers precipitation is due to cyclonic storms and on the western mountains to these and to winds from the ocean forced upward by the mountains. There never were any glaciers in the dry cold regions of northern Alaska and Siberia.

Pleistocene climate. Pleistocene climate differed from present conditions merely in degree. It still freezes in every month of the year in the locations of the glacial centers. The evidence of mountain glaciers shows that the Pleistocene snow line was lower in altitude and in latitude. Other phenomena of the Pleistocene ice ages were (a) high water levels in the streams and lakes of both glaciated and unglaciated regions for instance in the Great Basin, and (b) a lowered level of the oceans due to abstraction of the water needed to make the ice sheets. That the wind directions were essentially the same in the Pleistocene as they are today is shown by (a) parallelism of the older and the present snow lines, (b) the distribution of local glaciers on the leeward sides of mountains, (c) distribution of the loess, and (d) apparently by the distribution of plants and animals close to the southwestern margins of the ice sheets. Glaciation could have been caused by either (a) increas snowfall, (b) reduction of melting by low summer temperatures or short summers, or (c) reduction of melting by clouds and storms. A greatly increased precipitation is difficult to account for especially as the ice sheets themselves must have tended to reduce the carrying power of the winds. High water levels can be explained as well by reduction of evaporation, by lowering of temperature, as by increased precipitation. The first cause is, therefore, not proved. Decision between the other two causes is difficult. Large ice fields do not have a cover of clouds but tend to become anticyclones waith light precipitation, the snow being spread out by the radiating winds. A general lowering of mean temperature appears probable but whether (a) a flat reduction all over the world, or (b) reduction in certain areas due to changes in wind belts and storm tracks is difficult to decide. Most Pleistocene organic remains indicate a subarctic climate far to the south of where it now exists. Survivals of the Pleistocene life are found on (a) high mountains, and (b) on areas of poor soil from which the temperate forms have as yet been unable to push their predecessors. Computation shows that a reduction of only a few degrees Centegrade of the mean annual temperature could produce glaciation. The resistance of the ice to melting because of (a) the amount of heat needed, and (b) the cover of melted-out drift, enables the ice sheets to push far to the south of the centers of accumulation and probably enter the zone of forests.

Interglacial climate. The climate during at least one of the recessions of the ice appears to have been as warm or warmer than at present in the same latitude. The evidence in the case of the other intervals is uncertain but it hardly seems likely that the only known organic remains were deposited either at the begining or the end of the interval when the climate was cold. At the time of the formation of the main body of the loess between the Illinoian and the Wisconsin stages aridity must have prevailed, a fact which may serve to connect this interval with the drying up of the lakes of the Great Basin. The lack of a soil between the loess of the Driftless Area and the underlying residium indicates aridity in that region. The climatic problems suggested by the old loess of Iowa still await solution. The formation of the gumbotils suggests moist warm climates.

Postglacial climate. That the return to modern climatic conditions was not a continuous change is shown by (a) varying lake and stream levels in the unglaciated regions, (b) cessation of dune and loess formation in some areas, (c) variation in rate of growth of the big trees of California, and (d) observations during the term of human history. Some of the evidence on which these facts are based has been disputed, but the general fact of changes in climate is indisputable. Today glaciers are nearly everywhere fighting a loosing battle against the sun.

The problem. A theory which can explain the ice age must be able to (a) account for a general reduction of summer temperatures over a very long period of time and over a large portion of the globe, (b) account for several profound and long continued oscillations of the ice borders, (c) account for at least one very long mild interglacial interval during which the ice sheets disappeared entirely and the climate was if anything warmer than that of today, and (d) account for pronounced desert conditions during one of the intervals of ice recession, presumably that of the mild climate. The theory must take account of the very complex conditions which govern climates and must not confuse cause and effect.

Types of hypotheses. Hypotheses to explain the glacial period may be divided into (a) astronomical, or forces outside the earth itself, (b) terrestrial, or forces within the earth, and (c) atmospheric, or forces in the earth's atmosphere. Under the first may be listed (a) variation in the inclination of the axis of the earth, (b) passage of the earth through cold and warm regions of space, possibly explained by the amount of dust between the earth and the sun, (c) varaiation in the heat of the sun itself, (d) variation in the electrical activity of the sun, especially in that shown by sunspots, and (e) variation in the eccentricity of the orbit of the earth plus variation in the direction in space of theearth's axis, the precession of the equinoxes. The second class includes (a) changes in elevation of the lands, (b) changes in distribution of land and water thus affecting ocean currents and precipitation, (c) elevation of mountain ranges, (d) shift in the position of the earth's axis within the earth, and (e) cooling of the earth by reduction of the internal heat. The third class includes (a) changes in the atmosphere which affect the amount of radiation of heat from the earth, particularly variations in the amount of carbon dioxide, (b) changes in electrical conditions in the atmosphere, and (c) changes in storm tracks and storm frequency. It will be seen that the different classes overlap to a considerable extent.

Astronomic hypotheses. Variation of the inclination of the earth's axis is possible only within narrow limits; in any event it would increase the amount of summer heat in high latitudes if the value should be greater than at present which would be unfavorable to glaciation. A value less than at present would be still less favorable and there is no known cause for large variations in inclination. Changes in the temperature of space, in the amount of dust and in the radiation from the sun are possibilities but lack proof of cause; the dust theory is well-thought of by some. The relation between sunspots and weather has been debated and is doubted by some. The last named explanation, that based on changes in (a) eccentricity of the earth's orbit, and (b) precession of the equinoxes is the most famous; it is known as Croll's hypothesis and was announced in the late 60's. It has the great advantage of being founded on known facts which are capable of mathematical demonstration but this does not prove that the theory is competent to explain the facts. The primary idea is that changes in the accentuation of the seasons by reason of changes in the distance of the earth from the sun at different seasons will be alternatly favorable and unfavorable to glaciation. The orbit of the earth is elliptical with the sun at one focus; the degree of elepticity varies with the movement of the other planets and can be computed. High values occured approximatly 100,000 and 200,000 years ago and a very low one about 40,000 years ago. The prolongation of the axis of the earth' describes a circle in the heavens once in every 21,000 years; this is precession of the equinoxes. At present the northern winter occurs when the earth is nearest the sun and eccentricity is now rather low. It was concluded by Croll that, although the changes could in no way affect the total amount of heat received by the earth during a season, nevertheless the temperatures would be changed by the different relative lengths of summer and winter. Whenever one hemisphere had its winter when the earth was farthest from the sun that season would be long and cold; this condition would be reversed every 10,500 years so that the summers would be long and hot in the same hemisphere. The computed variations in mean daily heat are quite large and would be most marked in high latitudes. It was admitted that these differences would be in themselves incompetent to produce glaciation but it was believed that secondary effects would reenforce them until they did. The principal one of these was the assumption that the greater temperature gradient from pole to equator in the glaciated hemisphere would force the trade winds away from that region and thus on account of the shape of the east coast of South America deprive the hemisphere of much of the present warm ocean currents. Another, less open to question, was the self-perpetuating powers of growing ice sheets. Croll's hypothesis required alternations of glaciation between the two hemispheres with warm interglacial periods in the hemispheres opposite to that which was having glacial climate. One of the main objections to the hypothesis is the brief time allowed for such profound reversals, only 10,500 years, which is totally inadequate to permit of such large ice sheets as those of North America. Another objection is the lack of observed alternations of climate and of alternations in glacial conditions in the two hemispheres; glaciers are or have recently retreated in the southern as well as in the northern hemisphere. Attempts have been made to show that once glaciation became established it would persist through the unfavorable cycles thus giving two or three Pleistocene glacial stages, each with rhythmic oscillations, and separated by a prolonged mild interglacial interval or by two such intervals. This view would overcome some of the main objections and accord fairly well with the facts of Pleistocene history but lacks confirmation.

<u>Terrestrial hypotheses</u>. Elevation of the land around the glacial centers was long favored by some geologists as it unquestionably explains many areas of modern glaciation. Evidence for this theory laid much stress on the fiords and submerged valleys of many coasts. Some thought that isostatic sinking closed the ice age. The main difficulty is to account for oscillations of the ice border and for interglacial climates, and

indeed, the followers of the hypothesis fought long and violently in favor of a relatively brief single episode of glaciation. Attempts were also made to superpose Croll's theory on this one. Another difficulty is to account for world-wide elevation and the climatic changes of unglaciated regions. Changes in the distribution of land and water are for the most part unsupported by corroboratory evidence and attach an exaggerated importance to ocean currents; such a theory is no longer seriously entertained. Neither is the theory of glacaiation due to internal cooling of the earth any longer regarded seriously, for it could neither explain the oscillations of climate nor the known fact that internal temperature has little to do with surface temperature. A shift in the location of the north pole to somewhere near Iceland has been favored by a few. The theory finds several difficulties: (a) the known wind directions of the Pleistocene are the same as now, (b) there is no known cause for such a shift although some astronomers think it a possibility and others deny this, and (c) the occurrence of interglacial conditions.

Atmospheric hypotheses. Explanations of the glacial period by changes in the winds are open to the objection that such would be the result of glaciation rather than the cause. The same applies to changes in the amount of moisture in the atmosphere because that is a function of temperature however much it may affect radiation. Foremost among the atmospheric hypotheses is that of Arrhenius which is based on the conclusion that the carbon dioxide in the atmosphere has (a) great heat retaining power, and (b) great variations in amount due to terrestrial activities. The theory has been elaborated by Chamberlin but has never had much support outside of his followers. It is presumed that continental emergence during the Pliocene caused absorption of carbon dioxide through (a) carbonation of rocks, (b) solution in the ocean, (c) checking of liberation during formation of limestones, and (d) absorption by vegetation. When the carbon dioxide had been depleted enough to cause sufficient decrease in temperature to start glaciation, then other forces were called upon to reverse the process, such as (a) reduction of weathering by ice cover and cold, (b) return of CO_2 to the air on account of differences in vapor pressure, the air having been depleted until the ocean gave back part of what it had absorbed, and (c) lessening of use of CO_2 by vegetation. It was assumed that these complex factors would operate in such a manner as to cause a declining as to cause alternations of glacial and interglacial climates in an oscillating curve of declining vigor and intervals between glacial stages. Many features of the hypothesis are vague and incapable of proof but the worst feature is the opinion of a number of authorities that carbon dioxide is not the efficient thermal blanket it was supposed to be. A later theory is that of Huntington who postulates that not only storm frequency but the tracks of cyclones are governed by sunspots. He suggests long sunspot cycles, the existence of which is admittedly unproved, which might cause glaciation. The theory is attractive but unsupported. Another suggestion is that of changes in dust in the atmosphere on account of volcanic activity but this is open to the same objection, lack of confirming evidence.

Conclusion. There is now no generally accepted theory of the cause of Pleistocene glaciation and little apparent progress has been made in this direction in many years. The problem awaits solution through a fuller knowledge of the causes of weather conditions, especially of the very wet and cold seasons that occur at intervals. To quote Shaler "the student who forms a particular hypothesis is ever afterwards out of the search altogether. He cleaves to his idol, while fresh men pursue the trail. Finally, when many theories have in turn been held to be sufficient, it gradually appears that they were all, or many of them, in part true, and have to be united to make the whole explanation." Athough the above was written over 40 years ago, it holds true today and it seems probable that the true explanation of the glacial period will be found in the complex interaction of forces that we now understand only when viewed alone, the ofrces that govern the retention and distribution of the heat of the sun.

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DURATION OF THE QUATERNARY PERIOD

<u>The problem</u>. The first step in determination of the duration of the Quaternary is measurement of postglacial or Recent time. Such may be derived from measuring the rate at which some process is now operating and dividing the result into the sum total of its accomplishment since the retreat of the ice. The processes so far used for this purpose are (a) erosion, particularly the recession of water falls, (b) sedimentation, especially where varves are present, (c) weathering, and (d) migration of plants into the glaciated district. The principal difficulty in this measurement is in determining if the rate has been uniform and if it has not been, in determining quantitatively the lack of uniformity. The next step is to find out by comparison what fraction postglacial time is of the entire Quaternary period.

Erosional measurements. At first sight it might appear that the rate at which streams are removing material from a watershed might be divided into the total volume of the eroded valleys; both quantities are capable of accurate measurement but erosion does not proceed at a uniform rate. Even if (a) variations in climate, and (b) the effect of the work of man could be eliminated the process is still impossible. This method has, however, been employed by Bain, Chamberlin, Leverett, and others. Recession of falls, particularly Niagara Falls and St. Anthonys Falls, has been more of a favorite; the rates of recession of both are known within a small margin of error. The older geologists applied this rate to the total distance of retreat with results averaging less than 10,000 years. Later work has shown that (a) the quantity of water at Niagara has varied more than 1,000 per cent due to changes in outlets of the Great Lakes, a fact shown clearly in the varying widths of the gorge, (b) the height of the falls has diminished, (c) the amount of limestone has increased, and (d) a portion of the gorge was cut in drift and not in rock. Using estimates for these qualifications Taylor makes the time 20,000 to 35,000 years since the waters fell low enough for Niagara to begin to flow. Obviously this is only a fraction of the time since the maximum of the last ice. At St. Anthonys Falls there has also been (a) variation in flow, (b) change in amount of resistant rock, and (c) decrease of height. Cutting could not have commenced until the channel of the Mississippi below the junction of the Minnesota had been eroded by the waters from Lake Agassiz. The latest estimate places the age of the falls at 20,000 years. A number of computations have been based on wave erosion but are open to the objections that (a) the location of the original shore line is indeterminable, (b) the rate of cutting decreases with time, and (c) owing to changes of water level and climate the time measured is an indeterminate fraction of postglacial time. Although the erosion of the older drifts cannot be used as a quantitative measure of their age as compared to the last drift still it is clear that unless (a) there was much erosion while vegetation was absent, or (b) there were vast changes in climate, the oldest drift at the surface must be from 10 to 20 times as old as the last drift.

Sedimentary measurements. Most estimates based on mechanical sediments are open to the same objections as to the use of erosion; the rate has not been uniform and cannot be evaluated. It has been suggested that chemical or organic sediments be employed but in that case the rate varied on account of climate. The use of varves appears to be the only possible solution of the question. Antevs arrived at 4,000 years for the recession of the ice from part of New England but thus far no measurement of postglacial or interglacial time has been attempted in America. In Sweden De Geer found that postglacial time is about 12,000 years.

Weathering measurments. It is apparently impossible to use depth of weathering as a quanitative measure of age since the rate decreases with depth in an indeterminable manner and is conditioned on too many factors that have been subject to change. From a qualitative standpoint, however, the evidence of weathering, particularly the formation of gumbotil, is indubitable evidence of the age of the old drifts as compared with the Wisconsin drift. Indeed, the gumbotil, unless there are unknown factors in its formation, appears to indicate a much greater age of the Kansan and Illinoian drifts than would be warranted from erosion; one could readily believe the Kansan drift to be 50 times as old as the Wisconsin on this basis. The probability is that erosion did not get started until the gumbotil had been largely developed.

Vegetational estimates. The migration of vegetation into a glaciated region is slow in the case of plants that do not have their seeds carried by wind. The rate of migration can be measured near existing glaciers that have recently retreated but it seems doubtful if this rate can be applied to other regions with different soils and climate. Guesses based on the rate of migration of nut-bearing trees are interesting merely as showing the general order of magnitude of the time involved. The greatest proved distances of migration are (a) the James Bay interglacial beds, and (b) in postglacial time.

Conclusion. Although there is no generally accepted figure for the duration of postglacial or Recent time, it appears probable that it is less than the 80,000 years postulated by Croll since the maximum of the Wisconsin stage of glaciation; for the Mississippi Valley 50,000 years seems a fair estimate. Obviously, the time since the final disappearance of the Labrador and Keewatin ice caps is much less and the duration of the entire Pleistocene very much greater. Bain made the Kansan drift from 10 to 15 times as old as the Wisconsin using erosion alone as a basis; using weathering as a figure the result would surely have been much greater, possibly 50 times as old as the Wisconsin. If the Nebraskan drift is twice as old as the Kansan we would have possibly 5,000,000 years for the duration of the Pleistocene. This figure is far greater than the erosional estimates of Chamberlin the details of which have never been disclosed. They are admittedly mere guesses but when one considers that (a) many kinds of plants and animals have become extinct since the begining of the Quaternary, (b) valleys have been cut in solid rock to depths of several hundred feet, (c) the older drifts have been very deeply weathered, (d) plants have migrated over many hundreds of miles, (e) stones were transported over similar distances by slow creeping ice, and (f) glaciation was interrupted by one or more long interglacial intervals and several immense oscillations of the ice border, then these figures do not seem too great.

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LIFE OF THE PLEISTOCENE

<u>General</u>. The beginning of the Pleistocene was marked by a change from the mild Pliocene; this brought about a marked southward migration of plants and animals away from the oncoming ice sheets. During every recession of the ice front and particularly during the one or more intervals when the ice caps disappeared entirely from the North American continent, or at least from the United States, the direction of migration was reversed for a time. Apparently during at least one of those intervals the climate was somewhat warmer than today. During advances of the ice the climate was probably more severe than during recessions but the ice sheets were largely mantled with drift near the margins and so did not make as cold a climate along their southern margins as some seem to have supposed. In this way the [illegible] remains of a temperate climate could be buried by the advancing ice. Most of the organic remains in the Pleistocene of the United States are arctic and subarctic species which probably lived close to the ice. It is a mistake to regard the southern margins

as bordered by a desert save immediately after a rapid retreat. Water fossils are much better indices of climatic conditions than are land animals; the latter would approach the ice in the summer or could grow a thick coat of hair as did the Pleistocene elephants, but the cold of the glacial streams was without either much seasonal change or much increase in temperature with distance from the ice.

<u>Study of Pleistocene fossils</u>. Most Pleistocene glacial and glaciofluvial deposits are entirely barren of organic remains save fossils in fragments of hard rocks of far greater age than the drift. Some tills contain many fragments of wood which may have been carried a long distance. Most of the glacial lake beds also are devoid of fossils on account of the cold muddy waters at the time of deposition. Deposits of peat, stream, and lake deposits during the major recessions of the ice have yielded the most fossils. The loess although containing many mollusks, has thus far failed to show the abundant mammalian fauna that it carries in Europe. Many loess deposits contain no fossils because (a) they are so thin that leaching has destroyed the remains, (b) they accumulated so slowly that all organisms decayed before burial, or (c) they were deposited immediatly after glaciation when there was little life in the region. The study of Pleistocene fossils is in its infancy in America, for most geologists have not been experienced paleontologists and many have apparently not realized the importance of accurate determination of organic remains and the paleontologists have not been experienced geologists and have had to work with much material whose source was only vaguely known. Thus it happens that although the general nature of the Pleistocene faunas is known, exact correlations on the basis of fossils are not yet possible. Paleontological evidence appears to favor the equivalence of the Toronto and the Sangamon. The Aftonian fauna is distinctly older with a greater proportion of extinct species. A striking feature of the Pleistocene was the northward extent of the elephants; those creatures did not become extinct until postglacial times.

<u>Pleistocene man in America</u>. In spite of the efforts of many geologists, particularly the old-time hybrid archeologist-geologists, no proved instance of human relics has ever been discovered in the Pleistocene of America. The supposed occurrences are all explained by (a) burial by landslides or slopewash, (b) burial by human agency, (c) entry into animal burrows, decayed roots of trees, cracks, etc., (d) reworking of stream deposits by modern streams, and (e) frauds. Man certainly did not make his appearance until relatively recent times; in Europe glacial and interglacial human remains are proved.

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ECONOMIC GEOLOGY OF THE DRIFT

Introduction. The glacial drift is of economic importance (a) for the use of some of the materials in and associated with it, and (b) because it conceals other formations. The subjects here treated are (a) gravel, (b) sand, (c) clay, (d) miscellaneous substances, (e) soils, (f) water supplies, (g) excavation and drilling in drift, and (h) mapping of formations beneath the drift.

Gravel. Glacio-fluvial materials are sought for road and structural material. Gravel is desired for (a) road surfacing, (b) concrete, and (c) filters. Gravel for surfacing should contain (a) more stone than sand, (b) a downward gradation in sizes from two inches in diameter to sand in such proportion that voids are filled with the smaller material, and (c) a binder in the shape of weathered pebbles or clay not in sufficient amount to be sticky or slippery when wet. In some cases the last requirement may be met with either (a) shale, (b) clay, or (c) the clay of the subgrade; most gravels require crushing and screening to meet the other specifications. Gravel for concrete must contain no excess of sand over that required to fill the voids and must have no weathered rock or silt and very few chert pebbles if used in concrete pavement. Gravels with mainly limestone pebbles are best for the last purpose since the hardness of the pebbles is nearly the same as that of the cement between them. In order to meet modern specifications for concrete, gravels must be crushed, screened, and washed. Outwash, kames, and eskers are sources of drift gravels; they rank in merit in the order given. The localities where gravel is exposed at the surface have nearly all been developed to some extent but there are many deposits which are either (a) too coarse to use without crushing, or (b) are covered by more or less material of other character. The problem of the geologist is to (a) distinguish these undeveloped deposits by the criteria of topography, vegetations, and conditions of origin, and (b) forecast the probable extent and value of both discovered and undeveloped deposits on the basis of their origin. In this he must be guided by the engineering conditions of (a) maximum permissible depth of cover or stripping, (b) quality of the gravel for the purpose required, (c) availability of transportation, (d) distance from point of use, and (e) availability of water for washing if desired for concrete. Decision on the use of the deposits is in many cases left to the engineer or the contractor. Gravel exploration requires much test pitting, for slumped surfaces are very misleading. The soils auger is no use in gravel. Sometimes further test pitting is recommended before purchase of the deposit.

<u>Sand</u>. Sand is used for (a) fine aggregate in concrete, (b) mortar, (c) plaster, (e) moulding, (f) filters, (g) sand-lime brick, and (h) braking friction on rails. Requirements for (a), (b), (c), and (g) include both freedom from clay and angularity of grains. Moulding sand must have (a) variation in grain sufficient to allow of packing, (b) sufficient binder to hold its form, (c) freedom from fluxing or gas-forming minerals, and (d) porosity to allow escape of gas from the metal. Requirements for the other uses vary but are less rigid. The problem of the discovery of sand is much the same as in the case of gravel; sand deposits are much more abundant than gravel deposits.

<u>Clay</u>. Clay is used for (a) brick and tile, and (b) surfacing sandy roads. Both loess and lake clays can be used for these purposes. The value of clays for clay products depends largely upon chemical analysis but the availability of fuel and markets are much more important than quality of material alone; the modern tendency is toward the consolidation of clay product manufacturing near to large cities. The competetion of concrete has greatly reduced the clay product business in recent years. Clays may be studied with the soils auger.

<u>Miscellaneous</u>. Natural gas in small amounts is associated with buried vegetal deposits in the drift. Other substances sometimes of value are magnetite sands and copper fragments. A few diamonds have been found but have never been traced to their Canadian source. Associated with the drift are peat and marl; the former is of little value at present but the latter has been used to some extent for cement on account of its low content of magnesium and is now being largely employed as a soil neutralizer.

<u>Soils</u>. Soils mapping involves the consideration of (a) origin, (b) topography, (c) texture, and (c) chemical composition including amount of organic matter. Soils are classified in two ways: (a) by texture, and (b) by origin which determines soil series. The following table shows the definition of the soil series now mapped in Wisconsin. The nomenclature varies considerably and there seems to be no record of the type localities after which the series are named.

- Loess and residual.
    - Mainly residual.
        - Dark prairie
            - Shallow ridge top soil-Dodgeville
            - Deep soil on valley slopes-Bates
        - Light colored timbered
            - On limestone-Baxter
            - On granite-Marathon

- Mainly loessial
    - Dark prairie
        - Terrace
            - Poorly drained-Wabash
            - Well drained-Waukesha or LaCrosse
        - Ridgetop
            - Marshall
    - Light colored timbered
        - Terrace-Lintonia
        - Upland-Knox
- Glacial noncalcareous
    - Alluvial (outwash)
        - Wet Dark
            - Sandy-Duning
            - Heavy-Whitman
        - Light colored, well drained
            - Sandy-Plainfield
            - Heavy-Antigo
    - Till on sandstone or shale
        - Light colored
            - Deep sandy-Colona
            - Shallow heavy-Vesper
    - Till on crystalline rocks
        - Red
            - Iron range border-Mellen
        - Gray
            - Sandy-Vilas or Chelsea
            - Heavy with loose subsoil-Kennan
            - Heavy with tight mottled subsoil-Colby
- Glacial calcareous
    - Alluvial (outwash)
        - Light colored
            - Poorly drained-Genesee
            - Well drained, sandy-Plainfield
            - Well drained, heavy-Fox
        - Dark colored
            - Poorly drained-Clyde
            - Well drained-Waukesha
        - From red lake clay
            - Poorly drained-Poygan
            - Upland-Superior
    - Till
        - Light colored
            - Upland timbered-Miami
            - Thin, sandy and gravelly-Rodman
        - Dark
            - Upland prairie-Carrington

Field examination shows a number of errors and inconsistencies in the application of the above classification; for instance many of the areas shown on maps as till soils are either (a) mainly loess, or (b) lie on glacio-fluvial material. A number of the so-called alluvial soils are loess on outwash or on non-glacial alluvial valley filling. The borings have in general been carried only to three feet, a depth insufficient to determine the difference between sandy till and weathered gravel and little attention seems to have been paid to topography which betrays the origin of the drift. The Colby series has been described as due to weathering of an old drift but geological examination shows that it is probably for the most part an old loess. Soil textures are divided into (a) fine gravel, 2.0-1.0 mm., (b) coarse sand, 1.0-0.5 mm., (c) medium sand, 0.5-0.25 mm., (d) fine sand, 0.25-0.1 mm., (e) very fine sand, 0.1-0.05 mm., (f) silt, 0.05-0.005 mm., and (g) clay, less than 0.005 mm. Some of the soil series do not contain all textures. Textures are determined by the grade of material that is present in largest percentage. Soils maps, however useful for the purpose intended, have very limited value as substitutes for glacial maps.

Water supplies. Water supplies can be obtained from the sands and gravels of the drift. Outwash plains offer the best opportunities for development, but there are many gravel layers in the drift which do not show at the surface near the locality where water is desired. Many such outcrop at levels sufficiently high to furnish flowing wells. In order to secure a large yield of water it is necessary to have either metallic or gravel screens in the water-bearing stratum for only a small amount of water can enter the end of the casing. Properly constructed drift wells have a much higher specific capacity than do wells in rock on account of the high porosity of loose material. Failures to obtain water in the drift are due to (a) too clayey material, and (b) tapping of lenses of gravel that do not communicate with the surface. Drift waters are subject to (a) danger of contamination since the water may not travel far enough to be filtered, and (b) high iron content on account of nearness to the zone of solution of iron in the soil. The drift is almost the only source of water or the only source of potable water in regions of certain kinds of rock. The chemical quality of drift waters is very variable; near the surface the amount of mineral matter is low on account of leaching of the more soluble substances. Some deep drift waters are very highly mineralized, locally more so than the rock waters beneath; this is mainly due to the presence of fine material that is easily dissolved. In Wisconsin waters are tested bacteriologically for drinking purposes by the State Laboratory of Hygiene; this is done free. Tests for boiler use must be made by a commercial chemist; such analyses cost about $20; soap tests may be made for less but are not reliable.

Excavation and drilling. Excavation in dry sand and gravel is affected by the danger of caving; many lives are lost in sand and gravel pits, trenches, etc. from this cause. Mechanical excavators or hydraulic methods may be used. Slopes must be graded to about 30 degrees to stand permanently and much trouble is experienced with washing. Wet sands flow and are called quicksands. Most tills stand up well in excavations but bowlders give trouble when machines are used. Some tills are so dense and bowldery that only the heaviest steam shovels can handle them and that only after blasting; in such instances excavation may cost more than that of soft rock. Gumbotil makes much trouble on account of both its stickiness and propensity to slide; cuts must be very wide in such material. Loess is easy to cut and stands best in vertical faces, although in very wet seasons great slides may occur. Lake clays slide very badly when wet as do some clay tills. Drilling in drift may be carried on in two general ways: (a) methods where no casing is used until the hole is completed, and (b) methods where casing is driven down as the hole is deepened. Under the first method may be listed (a) augers which are useful in clay or very clayey till, (b) percussion tool methods, and (c) the rotary method with mud-laden fluid. The last is by far the cheapest and most rapid in loose, caving material of great depth. A bit is rotated on the end of a pipe down which mud is pumped; the fluid returns to surface outside of the drill pipe and serves to support the sides of the hole until casing can be inserted. The disadvantages of the method are (a) lack of accurate samples of material penetrated, and (b) "mudding off" of water-bear- [illegible] ing strata without noticing them. For this reason it is best to sink a small test boring by other methods before commencing a large well with the rotary. Casing methods include (a) those where pipe is driven with blows, and (b) those where pipe is pressed down with jacks, the California stovepipe method. On the basis of tools used the classification is (a) methods where material is forced to one side by a point, (b) methods where material is removed by bailing with a bucket or a sand pump, and (c) methods where material is washed up by a stream of water. Of these the first is adapted to shallow, small diameter drive wells which carry a sand point or screen with a point on the bottom. In the second case the tools are carried on either a cable or solid rods; they either stir up the material or catch it in a device like an open length of pipe. The last, or jet method, uses tools on hollow rods which carry water down or in some cases carry out the cuttings the drill acting as a pump. Cable tools with a bailer or sand pump are frequently spoken of as "standard tools." Jet methods have the advantage that recovery of lost tools is more readily effected in small holes than where cable is used. Solid rod or pole tools have the same advantage but are now little used. No method where the cuttings are washed out of the hole yields reliable samples; the best samples are from the auger and the bailer methods. Drilling to test the formation and to simply make hole rapidly are two different things and this fact should be impressed on the driller. In casing methods of drilling the only good samples are obtained by bailing close to the end of the pipe; material driven up into the pipe or obtained by bailing lower than the end is open to question. Difficulties in drilling in drift are mainly caused by (a) bowlders, (b) quicksand, and (c) certain kinds of clay that will not mix well or that form clay balls. Bowlders can be distinguished from bed rock by (a) springing under the drill, and (b) by their lithologic character. They are generally drilled through and then broken by blasting; this must be done with the casing several feet back to avoid damage to the pipe. In borings to determine depth to bed rock the rock should be entered a few feet to make certain what it is. Quicksand causes very hard driving of pipe and in many cases loss of tools due to sudden rise of sand in the pipe; it can be overcome by keeping the hole full of water, adding mortar, cement, or clay. Clay can be cut out in chunks with proper tools or caused to mix by adding stones or sand. Some sands can be picked up better if clay is added. Well drilling requires a working knowledge of applied geology and the geologist can learn much from experienced drillers and should be slow to criticize the methods employed by them.

Mapping of rock formations beneath the drift. In order to make any kind of a geological map, especially of horizontal sediments, it is necessary to study the thickness of the drift. The methods of mapping the bed rock topography have been given above. Much information can be obtained from studies of the composition of the drift providing that there are enough rock outcrops to enable the source of the stones to be fixed with fair accuracy. Care must be taken to consider only stones from the unweathered portion of the drift as otherwise the more soluble varieties may be absent.

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FIELD METHODS

Introduction. Glacial geological work may be divided into (a) reconnaissance, (b) detailed mapping, and (c) economic work. The first may be subdivided into (a) mapping of glacial geology alone, and (b) glacial mapping incidental to other work. Most of the glacial work in America has been of the last named type. The published maps are in many cases either very much generalized or are mere sketches which do not show anything but drifts of different stages.

Map units. Detailed maps should show (a) terminal and recessional moraines, generally including kames and ice-margin deltas, (b) ground moraine, (c) drumlins, (d) outwash, (e) terraces, (f) eskers, (g) areas of bare rock, (h) other rock exposures, (i) sand, gravel, and clay pits, (j) lake deposits including deltas not at ice margin, (k) abandoned drainage lines of glacial waters, (l) beaches, bars, and other shore line features,

(m) postglacial stream deposits, (n) marsh deposits, (o) sand dunes, (p) made-land, (q) striae, and (r) any other features of Pleistocene and Recent age. Generalized maps may omit some of these if the scale is too small to permit of showing them, but none whose presence is wide-spread or geologically important. If possible the map should show contours even if these are very rough but colors do not permit easy reading of contours so that a separate topographic map is desirable. A scale of four miles to the inch is sufficient to show considerable detail and even all the rock outcrops.

Ethics of field work. A geologist should remember that (a) he is not a partisan like a lawyer or a politician but is to present all sides of a question, (b) all his observations including field notes and maps are the property of his employer, (c) notes should be intelligible to everyone who is familiar with geological terms, (d) no feature should be neglected because difficult to reach, although the purpose of the work must be the guide to the permissible amount of time given to each feature, (e) examinations should be made systematically and without regard to the possibility of another visit to that spot, (f) dignity and courtesy always pay, for if in the public service the purpose of the work must be explained to all who ask, and if in private work entry on to property of other than the employer is at sufferance of the owner, (g) scrupulous care must be taken not to injure growing crops and fences and not to leave open gates, (h) in working with a car stops must not be made on the traveled portion of a highway and when the car is parked room must be left for two other cars to pass without danger, (i) he must not chase special features but observe and record all there can be found in the area, (j) he must stick at the job even if it is difficult until the work is finished or called off by the person in charge.

The field map. Glacial map boundaries must always be drawn on the map when in actual view of the geologist and never from contours or from notes alone. The field map must therefore be arranged so that it can be kept clean and can be readily used; maps are cheaper than time but when marked up must be kept neat. A topographic map of not less than 1:62,500 scale mounted on cloth in eight (8) sections is ideal. The number of sections is important as it permits of folding so that cloth is outside the map whatever section is in use and yet one motion will open the map for use; this seems inconsequential indoors but in the wind it is far from being such. Some prefer to cut up the map and paste the sections on pages of the notebook; this keeps the map cleaner and reduces chance of loss but unless a separate office map is used prevents a general view of the situation. Where no topographic survey has been made, or the published map is too inaccurate to use, then "white print" copies of either a good county map or of the original U. S. Land Survey on a scale of not less than a mile to an inch are the best substitutes. The maps of the U. S. Post Office Department are good but are rather generalized. Not only the boundaries of map units but abbreviated notes on (a) rock outcrops, (b) drift exposures, (c) topography, (d) well records, etc. should be neatly placed on the map with the use of the symbols and abbreviations given below. Use of the topographic symbols should be followed even on good topographic maps since few of these are detailed enough to show all of the diagnostic features of glacial deposits. If not shown on the map cultural features should be mapped approximately as they serve as a check on locations.

SYMBOLS AND ABBREVIATIONS USED BY WISCONSIN GEOLOGICAL SURVEY

Exposures, etc.

- Drift exposure, natural or road cut
- × × Bowlders or talus
- Outcrop of sedimentary rock, horizontal or unknown dip.
- Outcrop of sedimentary rock with dip and strike
- # Outcrop of igneous rock
- Outcrop of gneiss or schist

Cultural symbols

- ■ building
- church
- school
- ▴ camp
- ⚒ quarry
- pit in drift
- ○ well, non-flowing
- well, flowing, in drift
- well, flowing, in rock
- ⌀ well or drill hole, abandoned

Colors

bf	buff	gn	green
bk	black	gy	gray
br	brown	lt	light
bu	blue	rd	red
dk	dark	wh	white
dr	drab	yl	yellow

Topographic symbols

- ∼ gently undulating
- ∿ roughly undulating
- → gentle slope with direction
- > steep slope with direction
- cliff
- gentle sags and knobs
- pronounced sags and knobs
- — flat
- pitted plain
- marsh
- △ sand dunes
- spring

Surficial deposits

A	alluvial wash
B	bowlders
Cl	clay
D	drift
G	gravel
L	loess
M	marl
P	pebbles
Pt	peat
S	sand
T	till

Soils

cl-l	clay loam
sdy-l	sandy loam

Sedimentary rocks

cg	conglomerate	ct	chert
dl	dolomite	gd	greensand
ls	limestone	qz	quartzite
rk	rock	sh	shale
sl	slate	ss	sandstone

Igneous rocks

Bt	basalt	Db	diabase
Dr	diorite	Ga	gabbro
Gn	gneiss	Gr	granite
Gs	greenstone	Po	porphyry
St	schist	Tr	trap

wth	weathered	stk	sticky	cal	calcareous	crs	coarse	fne	fine	sft	soft
str	stratified	xb	crossbedded	lch	leached	frg	fragments	fer	ferruginous		

The geologist must know his exact location on the map at all times; if on foot he should pace from the nearest recognizable point and if in a car should use the speedometer. In the evenings the map should be carefully inked with India ink. If an office map is kept, and this is very desirable if more than one geologist is at work, the data should be transferred to that every evening. The office map is very desirable also because it (a) insures against loss of the field map, (b) combines the work in a way needed for general study, and (c) can be made on tracing cloth so that blue prints may be made if needed. Such a map can be colored but colored pencils should not be used for drawing boundaries. The Wisconsin Survey uses red for terminal moraine and blue for outwash because such colors can be obtained everywhere. The "pin prick" method of placing notes on the back of a map is almost impossible with mounted maps; it may be used with maps in a notebook but is desirable only with a very small scale base map, for otherwise it is more of a nuisance than a benefit.

The notebook. The use of map notes should not replace the use of a notebook; every important observation should also be recorded in the notes and any observation worth placing on the map is important. A loose-leaf book is very desirable as it permits the notes of different geologists to be put together in proper order, thus eliminating the use of indexes. In areas covered by the Land Survey the township is the unit in combining notes. Notes should be dated and carry the name of the writer, not of the chief of party. Notes must be connected with the map by land locations where there are such. If there are no townships and sections then a system of coordinates or of "locality numbers" is permissible. If one of these systems is used, it should be so standardized that it could be understood even if the field map should be lost. Remember that your work is not final but that someday, perhaps not far distant, somebody is going to retrace your work and will wish to find just where you went and what you saw; your successor will judge you by your notes. Locations by quarter-quarter section or "forty" are generally close enough; other information should be added such as distance and direction from nearest town, land ownership, relation to roads and houses, for it is very easy to get confused in noting section, township, and range numbers. The fraction, ¼, etc., can generally be omitted and a description written as NWSE 21, 47N-1W. Notes should be full, clear, and in ordinary words. Descriptions in terms of interpretation, as "old drift", or Kansan drift" instead of weathered till, should be carefully avoided. Descriptions must be clear as to directions, heights, slopes, colors, character of exposures, size of exposures, etc. Every effort should be made to be definite and exact. Fountain pen or medium hard pencil should be used; some ink in notes at night but the habit of having someone who may not know geology typewrite notes should be avoided.

Well records. Following the great drouth of the 90's well records could be obtained from almost every farmer, for drilled wells were still a novelty. Since that time farms have changed hands, drilling is a commonplace matter, and information must now be obtained from drillers. The geologist must first explain who he is and what he wants the information for. Some drillers are afraid to reveal trade secrets, but most of the younger men in the business are keenly interested in applied geology and if approached in the right way are only too glad to furnish data. If possible, recourse should be had to written notes and the geologist's notes should state if records are from such or from memory. Until you have finished asking direct questions avoid inquiries that can be answered by "yes" or "no"; the latter are called "leading questions". Much information on ownership of lands, changes in historic times, local names of geographic features, etc., can be obtained while seeking well records but you must be a good judge of human nature to decide as to its value. In general all that can be found out about wells is the depth to rock and the nature of the rock. Casing is in many places driven into the rock to depths of 15 to 20 feet. Information on depth to water is of value. Many drillers will furnish samples from wells in progress if bags are furnished. The Wisconsin Survey uses cloth mailing bags and pays drillers from $2.50 up for complete sets of samples.

Instruments and tools. The geologist is now generally equipped with a car and so can carry more equipment than formerly. He can use (a) hammer with chisel point for digging, (b) notebook, (c) map, (d) soils auger up to 18 feet long in three foot sections, (e) compass, (f) aneroid barometer, (g) hand level or if working on beaches an engineer's level and rod or transit and rod, (h) long handled shovel, (i) crow bar, (j) pick, (k) broom or sponge for cleaning striae, (l) field glass to examine distant cuts to see if worth a visit, (m) hydrochloric acid in rubber corked bottle, (n) camera, (o) tripod, and (p) exposure meter. Of these the first three and generally also the compass cannot be dispensed with.

Conclusion. While the above suggestions can be varied somewhat in accordance with the time available for the work it will be found that in the long run it takes less time to do things right than to do a sloppy job in the field and then either guess at what was not recorded or have to go back again. Economic work is very intensive but is confined to rather limited areas. Reconnaissance work will generally require the omission of visits to inaccessible points where the probability of finding anything is remote. It is vital to get over all roads on account of the cuttings but railroad cuts are now nearly all too heavily grass covered to be of any value. In judging the work of older geologists remember that they had railroad cuts but only a few shallow road cuts. Work in unsettled country is very difficult on account of the lack of cuts. The geologist should not be afraid to dig but must fill all pits when through and look out for slides in sand. The day's work should be planned to eliminate backtracking as far as possible. Some problems are insoluble at present but you should not be ashamed to admit it; remember that good descriptions of facts are worth more than unsupported theories. No fact should be neglected because you cannot explain it at the time.

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