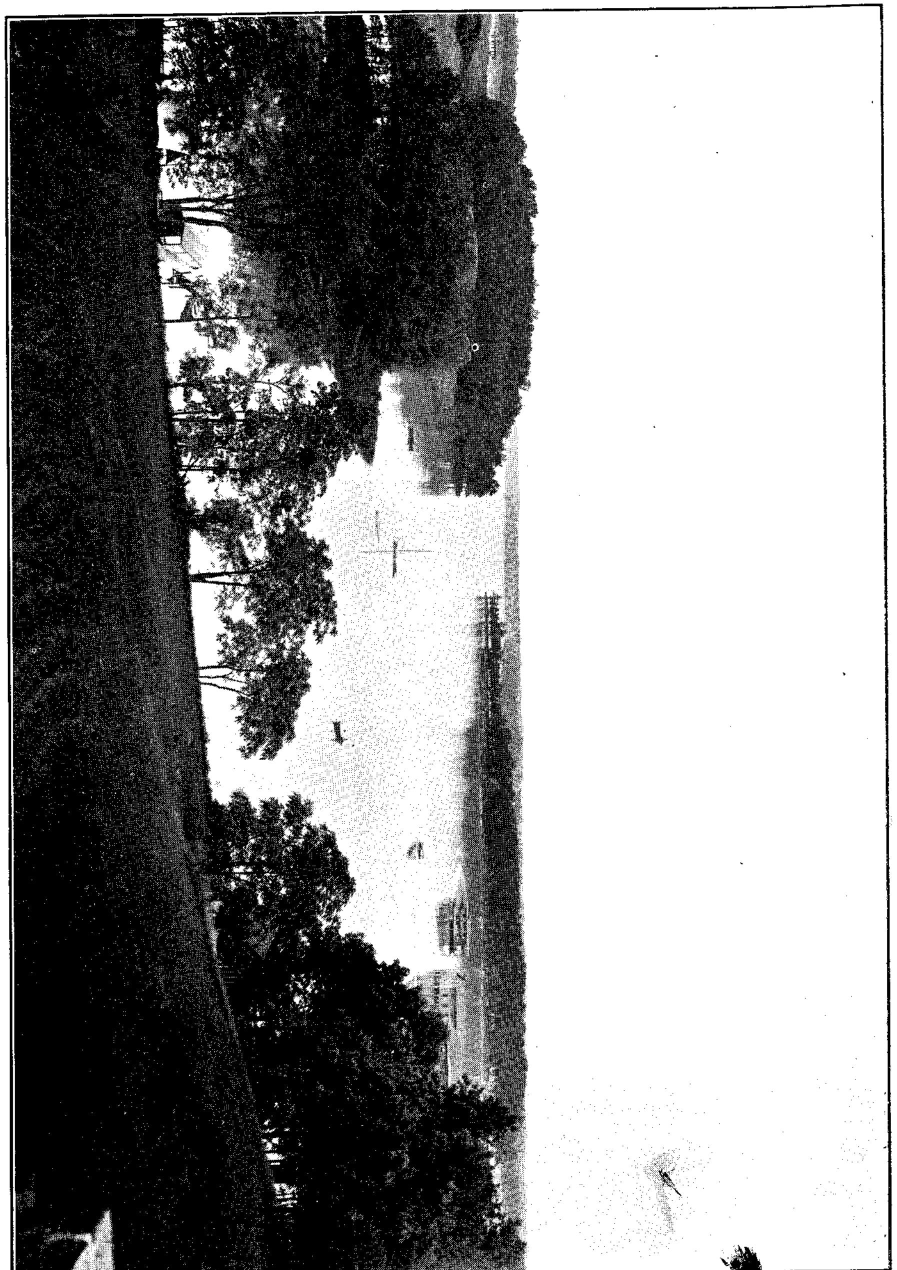
INLAND LAKES

OF

MICHIGAN

—

I. D. SCOTT



GULL LAKE, KALAMAZOO COUNTY

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MICHIGAN GEOLOGICAL AND BIOLOGICAL SURVEY

Publication 30
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INLAND LAKES OF MICHIGAN

By

I. D. SCOTT

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BOARD OF GEOLOGICAL AND BIOLOGICAL SURVEY, 1920.

LETTER OF TRANSMITTAL.

To the Honorable, the Board of Geological and Biological Survey of the State of Michigan:

Governor Albert E. Sleeper
Hon. Fred Jeffers
Hon. Thomas E. Johnson

Gentlemen: I have the honor to submit herewith a monographic report on the Inland Lakes of Michigan, by Dr. I. D. Scott with the recommendation that it be published and bound as Publication 30, Geological Series 25.

This monograph is the result of several years of field study and its object is to describe and explain the large lakes whose history is a part of the history of the Great Lakes, as well as those smaller lakes having an economic or aesthetic value. The book should be of value to students and teachers of physiography, to tourists and those desiring to attract tourists to the State, to State, city and town officials seeking park sites and municipal water supplies, as well as to the fisherman and those who seek recreation.

The field work upon which the greater part of the report is based was made during the summer months of 1913 and 1914. Progress on the writing of the report was interrupted by the War and further field studies and a reconnaisance of a greater number of the smaller lakes were made in the spring and summer of 1920. Earlier publication was desired but compensation for the delay is afforded in the more comprehensive report of a greater number of small but locally important lakes.

Very respectfully yours,
R. A. SMITH,
Director.

Lansing, Michigan, Dec. 11, 1920.

PREFACE.

The number of inland lakes in the State of Michigan is not definitely known but has been placed by some at greater than five thousand. They range in area from thirty-one square miles down to small, unnamed ponds and, in the Southern Peninsula alone, more than seventy have an area of one square mile or more. This number is considerably increased when the lakes of the Northern Peninsula are added. It has been estimated that lakes constitute about one-fiftieth of the total area of the State, a percentage so large that one may, with justice, entertain doubt as to their value to the commonwealth.

This doubt becomes almost a conviction if one considers the well-known fact that most lakes cover land of very high fertility. A classic example of the value of such land is the bed of former Lake Agassiz upon which is grown a large part of the enormous wheat crops of the Dakotas and Minnesota. Assuming that all of the inland lakes of the State could be drained, more than twelve hundred square miles of land of exceptional value would be opened to cultivation. In addition, it is probable that many nearby swampy areas would likewise be made available for use, and sanitary conditions be greatly improved by the extinction of the breeding places for disease-spreading insects. Also lake deposits, such as marl and peat, are frequently of considerable value and their exploitation, which is usually destructive to the lake, may be a legitimate enterprise. But our initial assumption that all of these lakes can be drained is impossible and, inasmuch as the data at hand is not sufficient for a fair estimate of the areas that can be reclaimed in this way, no attempt is made to state definitely their value. It is obvious, however, that it would be enormous.

Yet, on the other hand, lakes in themselves are a very useful resource and function in such varied ways that, although a statement as to their monetary value is impossible, there are many who consider their presence, within limits, a valuable asset. Among the functions performed by lakes may be mentioned their service as natural reservoirs. They accommodate the waters of spring freshets and melting snows with comparatively small rise in water level and thus lessen the flooded condition of streams and hinder the stripping of the land. Also, by throwing dams across the outlets the outflow of the lakes may be controlled for a number of purposes, for example,—power, irrigation, logging operations, city water supply, etc. The consideration of lakes as a source of food supply, as highways of commerce and as a tempering effect on climate applies more particularly to the larger lakes and inland seas and is, therefore, mentioned only in passing.

But the most important function of lakes is, however, not commercial but lies rather in their unique advantages for the recreation of man. Here one may rest

> "Escaped awhile,
> From cares that wear the life away,
> To eat the lotus of the Nile,
> And drink the poppies of Cathay,
> To fling the loads of custom down,
> Like driftweed, on the sand slopes brown,
> And in the sea waves drown the restless pack
> Of duties, claims and needs that barked upon their track."
>
> *Whittier.*

The pure air, cool temperatures and simple conditions of life stimulate renewed physical and mental vigor. Yet, lakes would fail in their service as recreational centers were opportunities for expression of the revived faculties lacking. This, however, appears contrary to fact, as shown by the ever-increasing numbers which migrate to them each summer.

The mere mention of the familiar water-sports should be sufficient to emphasize the appeal of lakes to our physical natures. But the appeal is deeper. Lakes are attractive not alone for their beauty but to a large extent because they portray so faithfully our own emotions and intensify the condition of our physical environment. During periods of calm, winter's solitude is accentuated by the ice-bound expanse and, in summer, tranquility is reflected from the unbroken surface. At times its leaden waters appear sullen, fortelling impending storms, at others boisterous and jubilant, and again, whipped to a state of fury.

Nor, is the intellectual side wanting. Of the various phases of the study of nature none is more easily observed and readily interpreted than Earth Science from the physiographic viewpoint and that part devoted to the study of lakes is one of the most interesting. From this viewpoint undrained areas are considered as one of the early phases in the wearing away of a land surface by streams. As the streams deepen their valleys and stretch out tributaries, all parts of the basin become completely drained and lakes are, therefore, considered as transient features of the land-

scape. From a physiographic standpoint one may study the entire life history of such bodies of water. In this work the principle events to be deciphered are the origin of the basin, its development by the various agencies active upon it and finally its extinction or death. In addition, the study has a much wider application, for lakes are but oceans in miniature, except for tides, and present similar problems on a more convenient scale.

From a practical standpoint the physiographic study of a lake gives a more intimate knowledge of and a closer acquaintance with the conditions not only of the shores but the surrounding country. This knowledge and familiarity cannot fail to be of service to the resorter both in the selection of the lake and the site on it. To illustrate, the larger lakes, although they may often be treacherous in times of storm, have advantages over smaller ones. The summer temperatures are apt to be lower and the very factors which make the lake dangerous, inasmuch as they work on a large scale, are beneficial in various ways. Thus, better and cleaner beaches are built and the submerged terrace is broader and drops into deep water from depths usually greater than a man's height, lessening the danger of accidents due to walking off the "drop off" or "channel bank". The situation of the lake is important and proximity to other large bodies of water is favorable. The ideal location is to the east of a large lake because the winds, prevailingly from the west, are cooled in their passage over the large expanse of water which has a lower temperature than the air in summer.

It would seem axiomatic that the shores and surrounding country should be well drained, if the lake is to be useful for summer homes, in order to secure healthful living conditions and to insure a minimum of pests. However, the writer has seen far too many resorts planned on a magnificent scale which exist only on plats executed for the use of distant real estate dealers and has helped in locating some of the properties only to find them situated on an insignificant lake in the midst of a swamp. Physiographic study would eliminate this. An ideal site, according to the writer, is to be found on lakes which have stood for a considerable time at an appreciably higher level—of which Michigan has many—for under these conditions a sandy terrace is now exposed high and dry above the level, surmounted by a cliff of varying height from the base of which springs of cool, pure water often flow.

As stated above, lakes have served a useful purpose in the storing of water for various projects which, in most cases, necessitates the building of a dam, thereby interfering with the natural level of the lake in question. This may involve a raising or lowering of the level, or both at different times of the year, and results in serious inconvenience and often damage to property along the shores. A lowering of the level means stranded docks and boat houses; a strip of the bottom exposed that often becomes foul from swampy conditions and decaying vegetation unless the lowering is permanent. A raising of the level is more serious and results in flooded shores and an increased activity of the waves. The latter is very noticeable on many lakes of the State and various means are employed to stop shore destruction by wave action. These, however, afford only temporary relief and are a source of expense and constant attention. In this case the physiographic principles seem to be ignored.

From the educational standpoint the study is also of importance. Physical Geography, in whole or in part, is quite generally taught in the schools of the State and it is truly educational in scope. Furthermore, the process of reasoning is complete. It puts new meaning in familiar things and only moderate teaching ability is demanded to arouse a lively interest on the part of the pupils. But it is not primarily a text book subject. Illustrative material is a necessity. Pictures may partially supply the need but by far the best illustrations are those obtained by direct observation. Exceptional indeed are the localities that do not furnish abundant accessible material for field study. Our lakes illustrate one phase of the subject of physiography and, on account of their number and distribution, should be a most valuable asset to the teachers of the State. Even the smallest pond is of some value in this respect and it is urged that advantage be taken of the opportunities.

It is hoped that from the brief statements concerning the points of view from which lakes may be considered it will be clear that both are well supported. As a matter of fact there are many lakes in our State that might well be exploited commercially but there are others which appear to be of greater value in their natural condition. Each lake, then, becomes a problem in itself and a physiographic study of the lake seems a prerequisite to its solution. The technicalities of such a study need not be overwhelming. No branch of earth science is more interesting that the study of lakes, and no special equipment other than an active brain and a reasonably vigorous physique is necessary. It provides both physical and mental recreation of the best type and is profitable as well as interesting. Familiar features take on new meaning and the changes taking place are a source of continued interest. The writer is convinced that the report of the studies of Michigan's inland lakes, undertaken during the summers of 1913, 1914 and 1920, will be of

greatest service if the needs of the increasing number of summer visitors and of those engaged in educational work are kept in mind. Therefore, the attempt has been made to present the essentials of the subject in as untechnical a way as possible in the introductory chapters. Following the introductory work are detailed descriptions and discussions of the physiography of some of the more important lakes.

It is obvious that all of the lakes of the State could not be included in this study and therefore a selection was made based on the importance, accessibility, distribution and promise of scientific results. Mistakes, both of omission and commission, appear in this selection as the work progressed, the principal difficulty being in the matter of distribution. In order to improve this, it was decided to include a large number of lakes in a reconnaisance study during the summer of 1920 and the results of this work are given in the final chapters. In these brief reports an attempt has been made to classify the lake basins and to state the type of the adjustments that have taken place on the shores. Also some information as to the accessibility of the lake, localities where the adjustments may be easily recognized, and the desirability of the lake as a summer resort may be included.

It is recognized that there will be some disappointment in the selection of the lakes described in detail but this need not be serious if one of the objects of this report is attained, namely, to present the underlying principles in such a way that they may be applied by those who may study these pages. Often the difficulty is in getting a start and it is felt that the final chapters may be of service in this respect.

The first essential in undertaking a study of this kind is to have a reasonably accurate map of the lake and its surroundings. Preferably this should show relief features; and the best to be obtained are the topographic maps made by the United States Geological Survey in co-operation with the State. These maps are about thirteen by seventeen inches in size and are made on a scale of approximately one inch to one mile for most districts, thus including and area of nearly 220 square miles. They are sold by the Director of the United States Geological Survey, and by the Michigan Geological Survey, at a nominal cost of ten cents and by all means should be procured, if they are available. Unfortunately much of the State is as yet unmapped, but encouraging progress has been made recently and we look forward to a more rapid production of these most useful maps as the demand increases.

Other maps that are useful are those issued by the United States Lake Survey, Detroit, Mich. They are very accurate, both as to shores and depth of water, but only a limited amount of the surroundings is included in the map. These maps are made for navigation purposes and represent navigable waters directly connected with the Great Lakes with one exception, the map of the Inland Route including Crooked, Burt and Mullet Lakes.

In most cases the only maps available are the United States Land Survey plats which give only the outline of the lake, and this is not accurate. Those used in this report were corrected in a rough way and, although far from satisfactory, are sufficiently reliable for the purpose. Most county maps and atlases are compiled from these plats and may be relied upon to the same extent.

The three main problems to be studied are, as indicated above, the origin of the basin, its subsequent development, and its extinction. The first of these involves a knowledge of the topographic features of the region and necessitates an examination of the surrounding country. It is often the most difficult to decide, and valuable information will be found in a publication of the Michigan Geological and Biological Survey by Frank Leverett: Publication 25, Geological Series 21, Surface Geology of Michigan.* The inserted maps are especially valuable and should be mounted on cloth to save wear and tear.

The development of the basin and causes working towards extinction are best discovered by making a detailed study of the shores and the off-shore lake bottom. The use of a boat is necessary for the latter and may be serviceable for a traverse of the shores if the lake is large. In general, however, a traverse on foot does away with the inconvenience of landing and gives more satisfactory results for the beginner. The sounding of the shallow water requires some apparatus. The writer found an exhausted dry cell a convenient weight but does not recommend any weight under twenty pounds for deep water. Accurate soundings involve both depths and locations. The process is tedious, and expensive instruments are necessary, therefore this is not recommended. For our purposes the depths of the water over the terrace and the width of the terrace are desirable. The width is the more difficult to obtain but an estimation will answer the purpose unless a detailed and serious study is to be undertaken.

If this report is successful, the physiographic study of lakes will

*Publication 25 is a revision of two earlier publications, viz.: Pub. 7, Surface Geology of the Northern Peninsula and Pub. 9, Surface Geology of the Southern Peninsula of Michigan. Both these publications are now out of print.

be the result. Workers may benefit themselves and others as well if their results are known, and the writer will be glad to receive suggestions, criticisms, and new developments concerning any lakes of the State whether included in this report or not. The use of the camera is strongly recommended also.

The illustrations in the report are from drawings and photogaphs by the author unless otherwise accredited. Acknowledgments are due to the many individuals who by information and services made much of the field work possible. Mr. Frank Leverett, United States Geologist, has aided the writer in glacial problems both by personal communication and by placing at his disposal valuable data, at the time unpublished. The advice and assistnce of Mr. R. C. Allen, former Director of the Michigan Geological Survey and Mr. R. A. Smith, present Director, have been of especial service in the prosecution of the field work and the preparation of this report.

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I. D. SCOTT

CHAPTER I

THE ORIGIN AND CLASSIFICATION OF LAKE BASINS

Lakes are numerous and the types of basins are many. If the basins are classified according to their manner of formation, complications may arise on account of several factors entering into the formation of a single basin. As the study is extended all of the agencies which are shaping the land surfaces of the earth are involved and it is, therefore, necessary to become familiar with the broader phases of the work and results of these agents.

To the beginner, one of the striking facts derived from the study of earth science is that the surface of the earth is slowly but constantly changing. Uplift and subsidence of the land are fundamental conceptions and no longer is the expression "terra firma" strictly applicable. Elevation has lifted the continents higher above the seas, while depression has served to deepen the ocean basins. On the first land waves, currents, and the atmosphere began their work, and with further elevation other agents—running water, ground water, winds, glaciers—became active. In general, the work of these agents is to wear down the land and transport the material elsewhere, eventually to the oceans. The continents occupy only one-fourth of the surface of the earth and are low in average elevation compared to the depth of the oceans, therefore, if elevation were inefficient or not active, they would soon be worn down nearly to sea level. But the continents have stood for ages far beyond the scope of human experience and, with the land assured, our interest centers on the agents which are fashioning its surface. The agents which are of most importance for our purposes are the atmosphere, running water, wind, ground water, and glaciers.

The Atmosphere. One class of work done by the atmosphere has been given the descriptive term *weathering*. Under weathering is included the action of such agencies as frost, temperature changes, plants, animals, abrasion by the wind, and the chemical action of the gases of the atmosphere, all of which tend to break up the solid rock into smaller and smaller fragments. The comminution continues until the particles are small enough to be removed by the various agents of transportation and, hence, may be considered a process preparatory to transportation.

The lateral movement of the air, or wind, serves as a transporting agent in addition to its action in the process of weathering. In regions where the earthy material is loosely consolidated and whose surface is unprotected by vegetation, e. g., deserts, sand plains, and the shores of bodies of water, the wind is especially active. The finest particles are picked up and often carried great distances while the coarser sand grains are rolled along the surface, collecting here and there in hills which are called *dunes*. The material of the dunes is clean sand, irregularly stratified, and the slopes are gentle on the windward side but steep on the lee. Whereever the sand is widely distributed, as on the sand plains in our State, the dunes tend to assume a crescentic form, but along the shores of lakes the supply is local and the dunes are heaped in wild confusion, with little regularity except that the slopes are characteristic. The latter are well illustrated along the western cost of the Southern Peninsula from Michigan City to the Straits, and the crescentic type may be seen relieving the monotony of the swampy plains of the eastern portion of the Northern Peninsula.

Running Water. Running water is one of the most important agents at work on the surface of the land. Wherever rainfall is sufficient the water collects in channels and flows onward, joining other streams, until it reaches a trunk stream which carries it to the sea. On account of their flow streams are able to pick up and to transport the solid material supplied them by weathering. The more swiftly flowing streams are able to carry larger particles and greater amounts of all sizes. It is usually the case that active streams are not supplied with enough disintegrated material to tax their energy to the limit and some of this unexpended energy is used by the suspended particles in filing, or abrading, the beds of the streams. In addition, the solvent action of the water removes material and the two processes working together deepen the stream beds. Early in the formation of valleys the process of weathering attacks the sides and reduces the slopes until tributaries develop along them, repeating the process. Also both the main streams and the tributaries tend to work headward and increase their length, pushing their tentacles farther and farther into the land and tapping the undrained areas. Eventually the headward extension is halted by encountering streams flowing in the opposite direction, forming divides and limiting the size of the basin. In this manner streams expand into great river systems which occupy definite

basins, and the basins are dissected and lowered by the constant removal of material.

Probably the most important factor in determining the velocity of a stream is the slope of its bed, and it is obvious that the slope, and consequently the velocity, must gradually decrease as the downward cutting proceeds, since the mouth of the stream is fixed at sea level. Eventually the transporting power is taxed to its limit and the stream can no longer cut downward because all of its energy is used in transporting suspended material and in friction. This condition is reached first near its mouth and develops upstream, although there may be local exceptions due to more easily eroded rocks.

After the limit of downward cutting has been reached any further reduction in velocity is accompanied by a deposition of some of the load. The largest particles are dropped first and, if the decrease in velocity continues, layers of increasingly fine material are added, forming a deposit composed of layers whose constituent particles are assorted in size and graded from coarse at the bottom to fine at the top. The ideal condition is where a stream enters a body of standing water, in which case the velocity begins to decrease at the mouth and becomes zero at some point out in the lake. But the velocity of streams varies at different times of the year, being greatest at the spring floods, and enables the stream to transport coarser material at this time. Thus, instead of a single layer becoming finer in size of particles off shore, there is formed a verticle series of strata showing the assortment and gradation mentioned above. This assortment and regular stratification are characteristic of deposits by running water.

It must not be assumed that the degrading work of a stream is finished when the downward cutting ceases, for, at about this time, the stream begins to swing laterally, or meander, and develops a flat on both sides which is flooded during high water and is called a flood plain, or better, a *valley flat*. Also the valley sides are being flattened by rain wash and other agencies until finally, after long periods of time, the areas between the water courses have slopes so flat that the material is not removed. At this time there is the broad valley flat adjacent to the stream and on either side low gently rolling plains stretch outward with almost imperceptible slope toward the sea. Such a region is called a *peneplain* (almost a plain) and represents the cessation of erosion by running water.

Complete peneplanation is an ideal condition never realized as far as we know because of interruptions of the process by uplift and by the varying resistence of the rocks, some of which stand in relief above the peneplain and are called *monadnocks*. In case of uplift of the land the power of the streams is revived and they renew their attack on the land. It is interesting to note in this connection that the peneplains that have been recognized up to the present time have all been elevated above their normal position, but erosion has not as yet obliterated their features.

GROUND WATER. In some regions underground water is a powerful eroding force, although generally not so effective as surface streams. It is always present in the rocks and its source is rain. Much of the rainfall sinks into the earth and percolates through the interstices and fissures in the rocks until its downward passage is interrupted, when it flows or seeps laterally, finally reaching the surface again. It is interesting and important to note that water is the greatest solvent known and its action is greatly increased when it contains other substances in solution. Thus, limestone is quite readily soluble in water containing carbon dioxide, one of the atmospheric gases, in solution, and in this way funnels are formed in the surface of the earth through which the water passes underground. The water sooner or later assumes a lateral flow, which is usually localized along the fissures and the beds of the limestone, and dissolves definite channels for itself which are called *caves* or *caverns*. As the process continues the interlacing channels enlarge and the roofs become weaker until finally they fall, blocking the cave with rubble.

The surface effects are at first a number of depressions, known as *sink holes*, which increase in number and extent, forming extremely rough ravines with occasional remnants of the roof standing as *natural bridges*. The sinks are often clogged with fine material and become lakes.

GLACIERS. Under this heading we wish to include only the work of the great ice masses which spread over the land and replace the variegated landscape with a cold, white, monotonous solitude,—an absolute desert. These continental glaciers advance and retreat over thousands of square miles of the land, grinding and plucking the solid rock, incorporating and carrying forward the disintegrated material, and depositing it near their borders as they melt. The movement is outward from centers and is to some extent independent of the slope of the land. However, large depressions like those occupied by the Great Lakes serve as channels along which the ice movement is accelerated, forming great projections, or lobes, in the ice front. See Fig. 1. Such an ice mass covered northeastern North America in recent geological times and advanced and retreated over

the area of the State of Michigan at least five times. The form and distribution of the material deposited by the ice during its last retreat have determined the present land surface to a very great extent and, since the basins of the inland lakes almost without exception occur in glacial formations, some further consideration of the work of glaciers seems necessary.

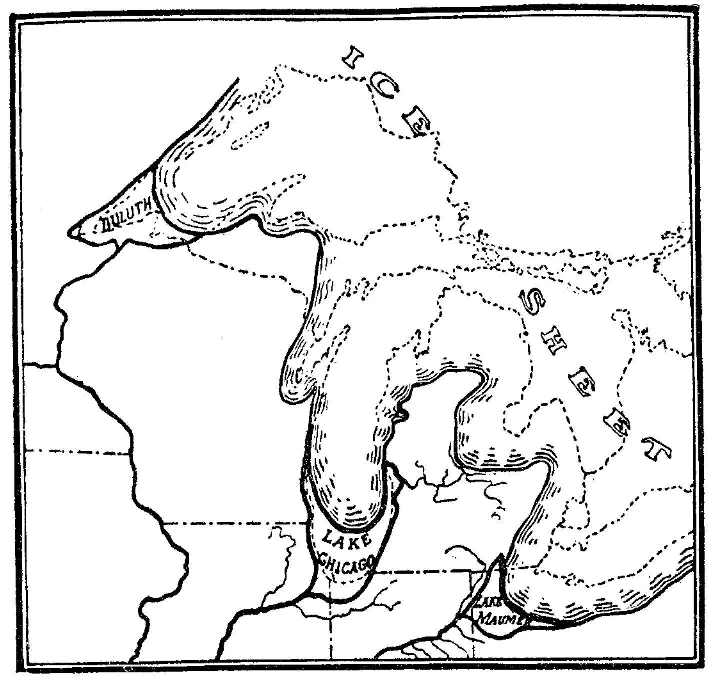


Fig. 1. A stage of the Wisconsin glacier showing lobate character of the ice front, (after Taylor and Leverett)

It is essential to remember that the ice moves forward constantly. The forward movement continues until temperatures are encountered which are warm enough to melt the ice effectively and this determines the position of the margin of the ice. Thus, at the border there are two factors active, the forward movement of the ice tending to advance the ice edge, and the melting which has the opposite effect. Whenever the forward movement exceeds the melting, the ice front advances and a continuance of this process causes an extension of the glacier. On the other hand, excessive melting causes a retreat of the ice front and when both factors are equal it remains stationary. The movement of the ice particles and the shifting of the ice front should not be confused.

Glaciers of this type profoundly affect the land which they override, in places wearing away the rock and in others depositing great quantities of material which is so characteristic in constitution and form as to be readily recognized. Ice itself has little or no power to wear away the rock over which it passes but, by sinking into the fissures which are universally present in rocks, it grasps the separated blocks and plucks them away in its forward movement. Such blocks of rock when firmly frozen in the base of the glacier become powerful abrading tools which grind away the solid rock leaving smoothed, polished, striated, and grooved surfaces.

The various glacial deposits to which the general term *drift* has been given, although differing greatly in form and material, have one predominating characteristic, that of heterogeneity. By this is meant that the material is composed of many different kinds of rock. It is the direct result of the immense size of the glacier which traverses great distances, encountering many different rock formations all of which contributed to its load. Some of the deposits are laid down by the ice alone and these, although varying in form and relief, are readily recognized by the character and disposition of the material. In addition to its heterogeneous constitution, this material, known as *boulder clay* or *till,* is of all sizes from the finest "flour" to immense boulders, with no indication of assortment or stratification as described for stream deposits. However, stratified and assorted glacial deposits are common and these indicate that the glacial material was worked over by running water. Such deposits offer no difficulty of explanation when it is realized that the melting of the ice furnished a great volume of water which flowed away from the ice or was ponded in front of it.

The characteristics and manner of formation of the glacial deposits may be best understood by imagining the existence of a glacier. Whenever the ice front remains stationary for a period of time, the constantly forward moving ice with its load of earthy material may be likened to a belt conveyor except that, instead of returning empty, it melts. The earthy material, unevenly distributed in the ice, is carried forward and deposited in hummocks at the margin. The resulting land form, known as a *moraine,* is a long, curved ridge of till whose surface is composed of irregularly distributed knobs and basins. Its width is relatively narrow but its length may be hundreds of miles.

At the same time the waters from the melting ice flow forward carrying great quantities of material which is deposited either among the moranic knobs in rounded hills of irregularly stratified sand and gravel, called *kames,* or just in front of the moraine. In the latter case the streams are often heavily clogged with drift and

tend to braid rather than keep to definite channels. Under these conditions broad plains are formed which slope gently away from the ice and are composed of assorted and often stratified material. They are known as *outwash plains.*

If the ice advances, the forms discussed above will be overridden by the ice and obliterated or covered, but if the margin of the ice retreats these forms will remain and, in addition, others which were covered by the ice are revealed. Of these the *ground moraine,* or *till plain,* is the most common. As the names signify, it is composed of *boulder clay* and has some of the characteristics of the moraines. Its surface has a knob and basin topography but the slopes are much more gentle and the relief lower. The expression swell and sag is commonly used in describing these features.

Another topographic form bared by the ice is the *drumlin.* These elliptical hills, composed of compact boulder clay, have a smooth, rounded surface and, when viewed from the side, resemble very closely a plano-convex lens which is resting on the flat side. Their length varies but is usually a mile or less and the relation of the dimensions to each other will be clear from the statement that the height may be measured in feet, the breadth in yards, and the length in rods. An interesting relationship is that of their longer axes which are apparently parallel for local areas but show a radial distribution over larger tracts, indicating an alignment along the direction of ice movement. The theories advanced for the manner of their formation are diverse and need not be considered here.

The last of the forms uncovered by the ice to be considered is the *esker,* a low serpentine ridge rising above the till plain. It is composed of imperfectly stratified sand and gravel and is usually a few feet high, yards in width, but may extend for miles. It is thought to have been formed by deposition by streams running in definite channels underneath the ice.

The forms discussed above may all, with the exception of drumlins, be referred to a definite position of the ice front. When the ice border is stationary a moraine is piled up, the strength depending on the length of the halt and the amount of material in the ice. At the same time the forms deposited by the water from melting—outwash plains, kames, eskers—are developed locally in their respective positions in front, near-by, and back of the ice margin, and may or may not be present in a given locality. Underneath is the till plain on which drumlins may be formed. The relative position of these forms is shown in Fig. 2.

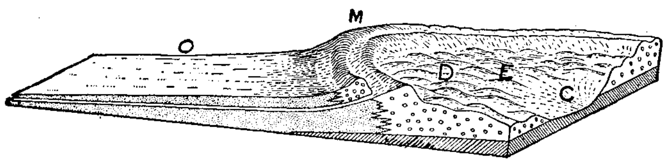


Fig. 2. Relative positions of glacial deposits, (after Tarr and Martin).

As stated above, most of the surface of the State is composed of glacial deposits left by the great ice sheet during its final retreat in recent geological time, and some idea of the nature of this retreat may be gained by a consideration of the distribution of the deposits. The accompanying outline map, Fig. 3, shows the posi-

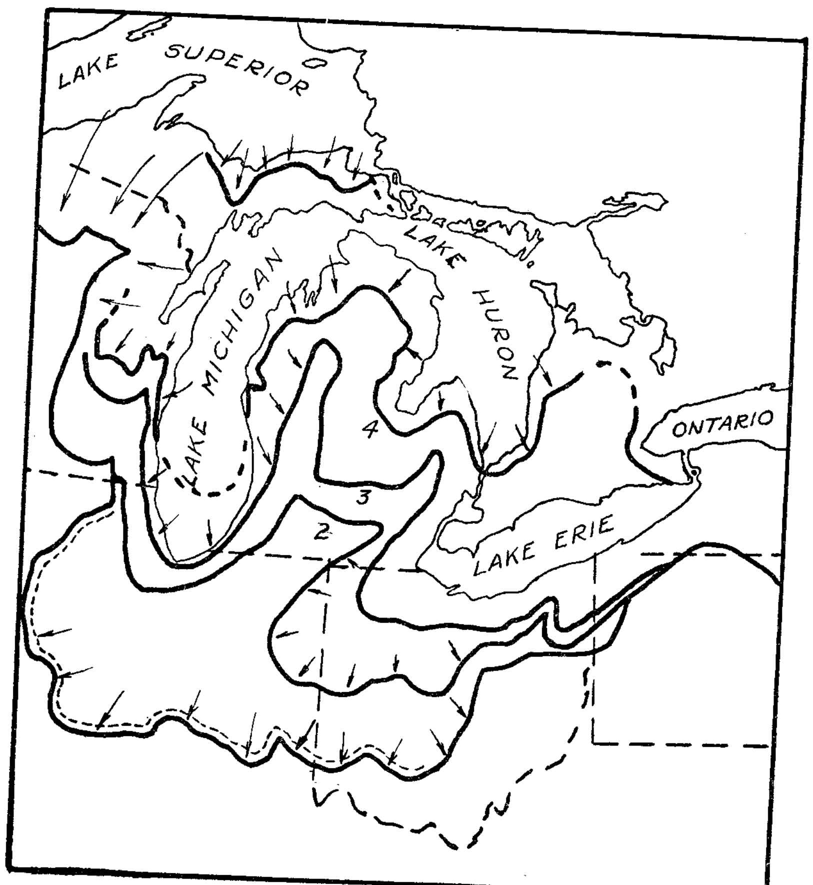


Fig. 3. Map of the principal moranic systems of Michigan. On this map are shown the southern limits of the Wisconsin stage of glaciation; 2, the Kalamazoo-Mississinawa moranic system; 3, the Valpariso-Charlotte moranic system; 4, Port Huron moranic system.

tions of some of the stronger moraines of the Michigan and Huron-Erie lobes, numbered in the order of their formation. Two things are plainly evident, the lobation of the ice and the duplication of the moraines in roughly parallel sequence. The lobation became more pronounced as the ice retreated and the narrow interlobate areas, areas which lie in the angle made by the junction of two lobes, were regions of excessive accumulation due to the presence of two ice margins in close proximity.

The duplication of the moraines, a few of which are shown on the map, indicates a gigantic and thoroughly contested struggle between the forward movement and the warmer temperatures which caused the melting of the ice, with the latter victorious. Thus, the ice advanced overwhelming everything in its path until checked by melting, when it entrenched by building a moraine. This position was held until the margin was forced back to another stand where the process of entrenching was repeated. Again and again this occurred with occasional minor advances which served only to prolong the struggle, and the ice retreated haltingly before the onslaught of the weather.

Another effect of the recession of the ice was the ponding of great bodies of water between the ice front and the divides. It is readily seen that, once the divide had been uncovered, a flat trough-like depression stood in front of the ice edge whose margins were the divide on one side and the ice on the other. The filling of such depressions with water gave rise to a series of lakes adjacent to or filling the present basins of the Great Lakes. As the ice receded, larger and larger depressions were uncovered and lower outlets were found, forming a succession of lakes each of which, with some exceptions, was larger but stood at a lower level than its predecessor. The history of these lakes is complicated and has been fully described in the publications of the Michigan Geological Survey and elsewhere. Yet the history of many of the inland lakes is closely connected with the two stages preceding the present Great Lakes, and a brief description of these is added.

The earlier of these lakes is known as Lake Algonquin and included all of the Great Lakes except Ontario, which was covered by the waters of a lake called Iroquois. The relation of its outline to those of the present lakes is shown in Fig. 4. Its shores now stand at elevations varying from 596 feet above sea level along the southern borders of Lake Huron to 720 feet at the Garden Peninsula, Big Bay de Noc, Lake Michigan, and 940 feet in the vicinity of Marquette, that is, above and at varying distances back from the shores of the present lakes. The map shows that a relatively narrow strip along the Superior shore of the western part of the Northern Peninsula was covered by these waters and that only a small portion of the eastern part was uncovered at this time, the land areas being islands. In the Southern Peninsula a considerable area in the northern part was covered by Lake Algonquin and the shore was very irregular consisting of many bays, promontories, and islands. Farther south the areas covered were narrow strips of land adjacent to the present shores of Lakes Huron and Michigan.

The stage immediately preceding the present is known as Lake Nipissing which occupied the same basins as Lake Algonquin but stood at a lower level and was somewhat smaller, in fact was but little larger than the present lakes. Its outlines are shown in Fig 5.

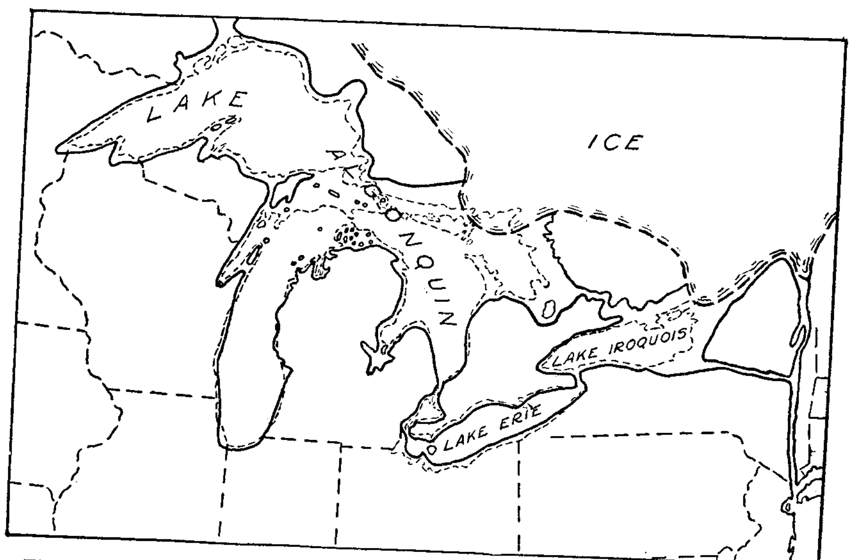


Fig. 4. Map of Lake Algonquin showing relation to present Great Lakes, (after Taylor and Leverett).

On the borders of the Northern Peninsula the Nipissing beaches stand at elevations from 10 to 60 feet above Lake Superior and are usually found a short distance inland. In the Southern Peninsula the beaches drop in level and the areas covered by this lake become smaller to the south. As in the case of Algonquin time, the northwestern part of this peninsula was an archipelago, and many of the inland lakes in this region have the shore lines and terraces of Lake Nipissing standing above their present shores.

It is hoped that the brief statement of the work of these agents given above will enable the reader to comprehend more easily the

forces at work on the land, and also aid in understanding the technical terms that are necessary in a report of this nature.

PHYSIOGRAPHY OF THE STATE OF MICHIGAN

The State of Michigan is divided naturally into two distinct parts which have been named the Southern and Northern Peninsulas on account of their positions with reference to Lakes Michigan,

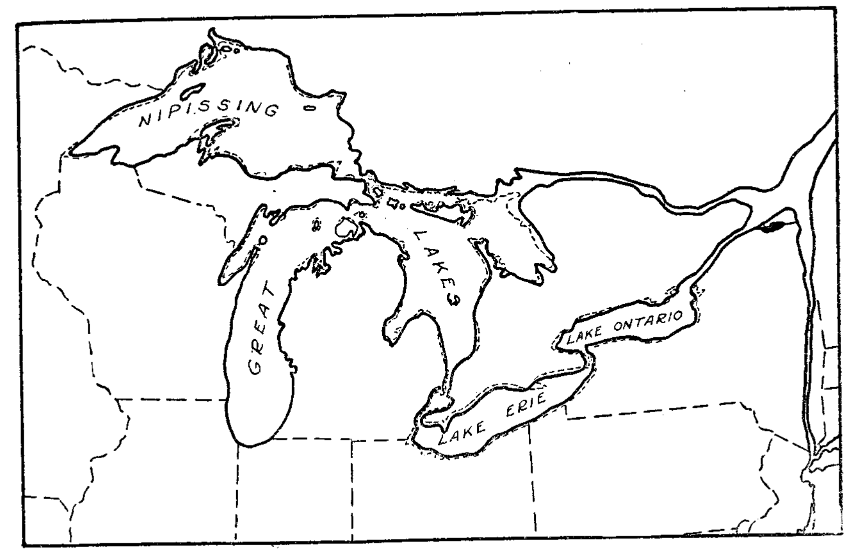


Fig. 5. Map of Lake Nipissing, showing relation to present Great Lakes, (after Taylor and Leverett)

Superior, Huron, and Erie. Thus, the Northern Peninsula is bounded to a large extent by Lake Superior, St. Mary's River, and Lake Michigan, and the eastern part is truly a peninsula. See Fig. 6. Construing the term peninsula rather loosely, the Menominee and Montreal rivers may be included with the lakes, making the land connection less than 70 miles in width for the entire peninsula.

The Southern Peninsula, surrounded on all sides except the southern by the waters of Lakes Michigan, Huron, Erie and their connections, is a broad peninsula which bears a resemblance to a great hand with the thumb just east of Saginaw Bay. See Fig. 7.

Northern Peninsula. The Northern Peninsula, Fig. 6, is a rather narrow strip of land about 330 miles in length and has an average width that is estimated at less than 50 miles. Its outline

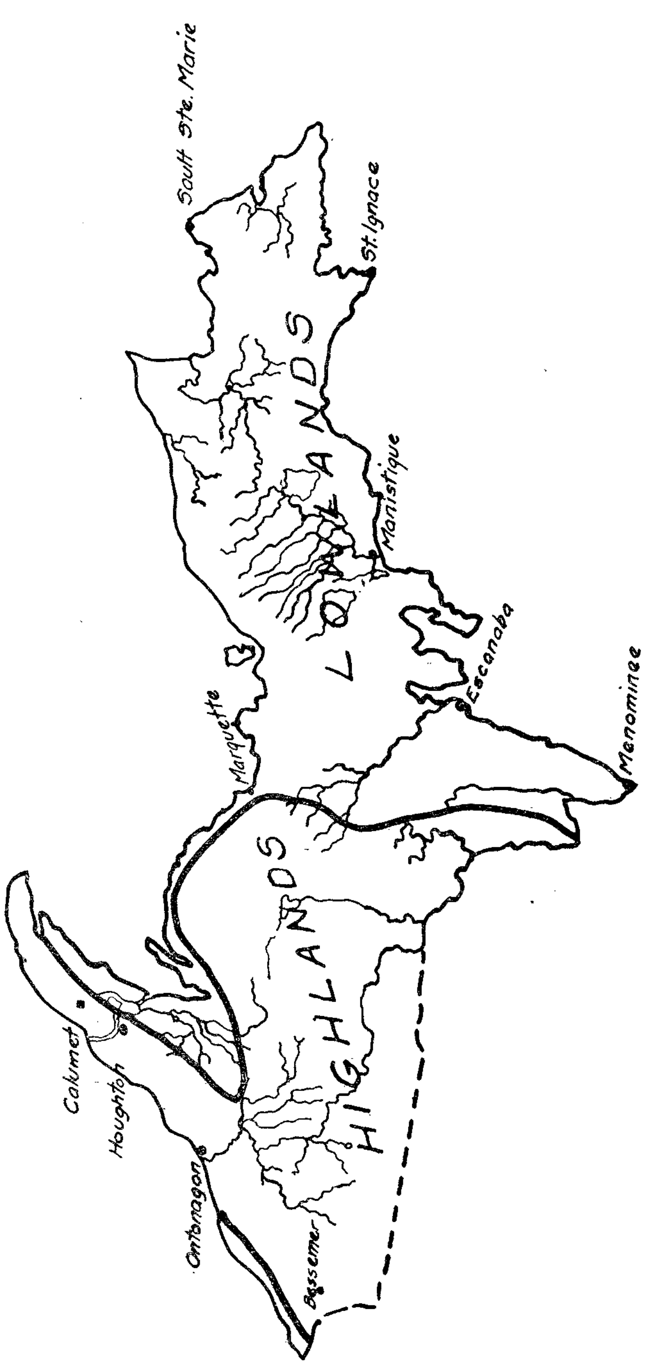


Fig. 6. Map showing physiographic provinces of the Northern Peninsula.

is irregular, having two prominent projections—Keweenaw peninsula on the north and the Menominee district on the south—and numerous smaller points and bays as well.

The altitude ranges from 580 feet above tide at the shores of Lake Michigan to more than 2,000 feet at the Porcupine Mountains in the northwestern part of the Peninsula. On the basis of elevation and underlying rocks, the area may be divided into two definite provinces: One, the Highlands, which is underlain by rocks largely of Pre-Paleozoic* age, lies west of a north-south line passing through Marquette, and the other, the Lowlands, extends eastward from this line and is underlain by Paleozoic* rocks. Glacial drift has been deposited over almost all of the Peninsula, the exceptions being more numerous in the Highland province.

HIGHLAND PROVINCE. This province extends from the meridian of Marquette westward and southward beyond the boundaries of the State, and stands at an average elevation of 1600-1800 feet above sea level, or 1000-1200 feet above Lake Superior. The region is a table-land which rises rapidly from the Lowlands on the east and north and its surface is covered with a variable thickness of glacial drift through which a relatively small number of hard rock knobs projects. The relief is moderate with differences in elevation which probably do not exceed 500 feet locally and are 100-300 feet on the average. The greatest elevations are rock hills which reach a maximum height of 2023 feet in the Porcupine Mountains.

The Highlands are a part of a great uplifted peneplain which was formed in ancient times. The underlying rocks are mainly of Pre-Paleozoic age and consist of crystalline masses and banded rocks the distribution of which greatly influenced the action of streams, causing, thereby, characteristic topographic forms. The erosion was profound and interrupted by several uplifts but, throughout the vast interval of time during which peneplanation was accomplished, the crystalline masses resisted erosion and stood in relief above the peneplain as monadnocks. The banded rocks were tipped on edge and presented alternately weak and resistant layers to the action of the streams. The hard layers resisted erosion and stood as monadnock ridges whose longer axes are roughly parallel to Lake Superior, while the softer layers were bevelled by the surface of the peneplain. The ridges were not continuous but

*Cenozoic	includes Present and Glacial times
Mesozoic	
Paleozoic	
Proterozoic	Pre-Paleozoic
Archeozoic	Pre-Paleozoic

The geological time scale, the main divisions of which are given, is tabulated to give the effect of a great column of superposed rocks, the oldest at the bottom and the youngest above in the order of formation. The position in the scale gives the relative age. It will be seen that the rocks under discussion and of all of Michigan as well, except the glacial deposits, stand low in the scale and are, therefore, ancient.

were crossed by streams, forming gaps which served as channels for the advancing ice of glacial times. Upon the peneplain and about the monadnocks were deposited paleozoic sediments which were largely removed by erosion before the advent of the ice.

The effect of the ice action was to scour out the gaps, round off the hills, and fill the valleys with heavy deposits of drift obscuring most of the former surface. Thus, we find today an area covered for the most part with glacial material through which rock knobs, either rounded or linear in form, project. The more important regions where such knobs are found are the Porcupine Mountains, Gogebic Range, Keweenaw Range, Huron Mountains, Marquette Range, Iron River district, and the Menominee district. Of these, Sheridan Hill in the Iron River district and some limestone capped hills in the Menominee district, are composed of Paleozoic rocks.

The glacial deposits of this province were laid down for the most part during the last recession of the ice by the lobes that extended into Lake Superior and Michigan with their subsidiary lobes, Keweenaw and Green Bay. The part first uncovered by the ice is in southern Iron County, an area of till deposits with drumlins or drumlin-like hills. A great moraine swings around this area, formed on the north by the ice of the Superior lobe and on the east by that of the Michigan lobe. The succeeding moraines show the same directions. Thus, the moraines, the inter-moranic till plains, and outwash run roughly parallel to Lake Superior in the western part of this province, except where influenced by the Keweenaw lobe. They have a nearly north-south trend in the eastern part which was covered by the Michigan lobe.

The Highlands are drained to Lakes Superior and Michigan with the exception of a small area in southern Gogebic County which is tapped by the Wisconsin river. The drainage is controlled both by the glacial formations and the pre-glacial topography. In the western part a strong moraine forms the divide, and in the vicinity of Watersmeet are situated the headwaters of the Wisconsin, Ontonagon, and Menominee rivers. To the east the divide shifts northward to a watershed north of Michigamme composed of thinly drift-covered crystalline rocks from which streams flow in all directions. The drainage is incomplete and small lakes and swamps are abundant, especially in the morainic districts and the thinly drift covered area north of Michigamme. There are several lakes of considerable size in this province whose basins are of exceptional interest and will be discussed later.

Lowland Province. The Lowlands extend from the meridian of Marquette eastward to the Sault Ste. Marie and swing to the southwest into Wisconsin and Minnesota in a broad semicircle. The greatest extension of the Lowlands along the northern edge of the Highland region is found in the continuation of Keweenaw Bay to the southwest and this is connected to the main Lowland area to the east by a narrow coastal strip.

This region is on the average more than 1000 feet lower than the Highlands and its general elevation does not exceed 250 feet above the Great Lakes, although in places it rises considerably above this. It is underlain by Paleozoic rocks which slope gently in a southerly direction. The bevelling of these rocks by stream action in pre-glacial times gave rise to a plain arranged in belts which mark the surface exposures of the various layers of dipping rocks. These belts run roughly parallel to the curve of the north shores of Lakes Huron and Michigan.

The hardness of the different layers varies, and the softer were worn into broad valleys whereas the harder stood in relief in forms peculiar to this type of structure. They consist of low, linear ridges which slope gently on the side formed by the surface of the rock layers but are more abrupt on the side which cuts across the layers. Such forms are known as *cuestas*. In this region they have almost imperceptible southerly slopes but stand usually about 100 feet above the plain to the north, although in places bluff-like escarpments with altitudes of 200-300 feet are found, for example, Burnt Bluff, Big Bay de Noc. Two cuestas are present in this province, one near the south shore of Lake Superior in the vicinity of Munising which swings to the south in its eastward extension, and another just north of the Michigan and Huron shores. Both are largely obscured by glacial deposits but the southern is the better developed. It begins with the Garden Peninsula at Big Bay de Noc and continues across the Lowlands to Drummond Island and eastward across Lake Huron as a great series of islands which partially isolate the North Channel and Georgian Bay from Lake Huron.

The recession of the ice in this region was from south to north and there is in general an east-west trend to the deposits. As shown in Fig. 3, a low moraine runs the length of this province. A large morainic tract is also found at the junction of Luce, Schoolcraft, and Mackinac counties and another important topographic feature, aside from the thinly drift covered southern cuesta, is the great swampy plains. The two most important are those which form the major part of the drainage basins of the Manistique and Tahquamenon rivers. These sandy plains have very gentle slopes and are almost featureless, the greatest relief being the small, but frequent sand dunes each crested with a clump of pines which accentuate the grass covered plain. These plains are the result of stream deposition and may be referred in part to the waters escaping from the ice border.

The drainage of the Lowlands is very poor and a large percentage of the area is covered by swamps and lakes. In the western part the divide is far to the north, giving a drainage area for the Manistique river of 1,400 square miles. To the east the divide swings southward and separates extensive basins on either side which are drained by the Tahquamenon and Carp rivers. The portion of the Peninsula east of St. Ignace and White Fish Bay is drained mainly into the St. Mary's River and Lake Huron. The inland lakes are found among the moraines, on the outwash plains, and along the shores of the Great Lakes, the largest being situated in the low morainic tract south of Seney and McMillan, and along the shores of Lake Michigan near Manistique and St. Ignace.

Southern Peninsula. The altitude of the Southern Peninsula, Fig. 7, is, in general, much lower than that of the Highlands of the Northern Peninsula and corresponds more nearly with that of the Lowland province. The highest points are found in Osceola county where elevations in excess of 1700 feet have been noted. The lowest altitudes are obviously determined by the level of Lake Erie, 572 feet, in the southeastern part of the peninsula. Ninety-six per cent of the area stands below 1200 feet, and probably the average elevation is not greatly in excess of 800 feet above the sea. The highest area is situated in the northern half of the peninsula, embracing about 1500 square miles largely within Osceola, Wexford, Missaukee, Crawford, and Otsego counties, and exceeds 1200 feet in elevation. Other elevated areas are found in the southern part, chiefly in Hillsdale county.

The Southern Peninsula has been divided into several physiographic provinces which have a diagonal trend in a northeast-southwesterly direction. See Fig. 7. Beginning in the southeastern part is a low plain, the Erie Lowland, bordering Lake Erie and to the northwest is the Thumb Upland, extending in a northeasterly direction from Hillsdale county to the Thumb. This gives way to the Saginaw Lowland, to the north of which lies the Northern Upland. The Michigan Lowland follows the Lake Michigan shore and is an exception to the diagonal trend.

The underlying rocks are of Paleozoic age and are closely associated with those of the Lowlands of the Northern Peninsula. Structually the rocks dip towards the center of the State and form a shallow basin which has been bevelled by erosion, distributing the

edges of the various formations in concentric ovals, that is, one within the other. The formations are of different resistances and the sandstone in particular yielded slowly to the erosive agents. The general relief features of this area before the advent of the

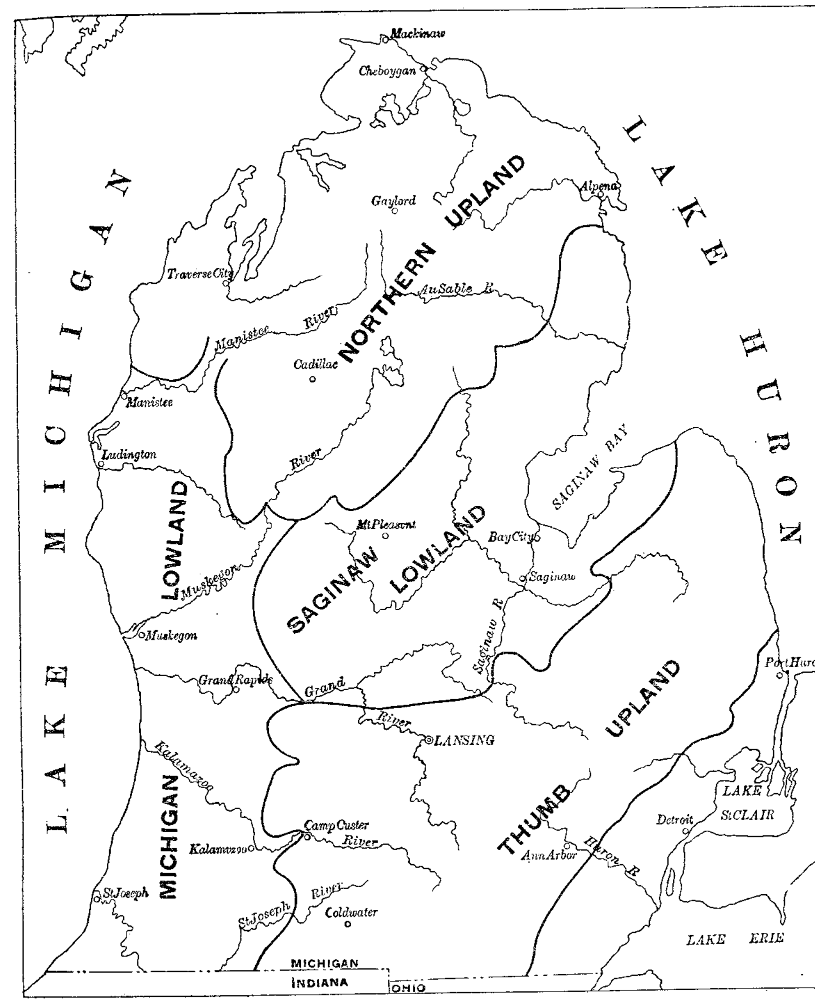


Fig. 7. Map showing physiographic provinces of the Southern Peninsula, (after Leverett). Note: Erie Lowland not designated.

glacier bore a striking resemblance to the present in that the larger features were similar in kind and distribution. Thus, there were upland areas in the northern and the southern parts with lowlands between and on either side. The low area in the northwestern part between Ludington and Frankfort would now be below sea level if the glacial deposits were removed.

In contrast to the Northern Peninsula, the glacial deposits of the Southern are largely those of an ice invasion just previous to the Wisconsin, or last stage, and form not only the main filling of the valleys but in places prominent ridges. The lobation of the ice of the earlier glaciation was similar to that of the Wisconsin stage and the same areas were, in general, regions of accumulation. It is of interest to one engaged in the study of lakes to know that the present surface features are largely due to the veneer of drift left by the last ice recession.

During its maximum extension the ice of the Wisconsin stage covered the entire Southern Peninsula and its recession uncovered first an area in the southern part of the State. See Fig. 3. Inspection of the moraine numbered 2 on the map shows this area to have been interlobate between the Michigan and the Huron-Erie lobes. With further recession two narrow interlobate areas were formed on either side of the small Saginaw Lobe, as shown by moraines 3 and 4 on the map. Thus, there were areas of excessive accumulation in the southeastern part, more or less coincident with the Thumb Upland, and in the northern part, coincident with the Northern Upland. The latter was an area of especially great accumulation, and here are found extensive moraines, till plains, and broad outwash aprons, the latter constituting the great sand plains.

The apparent coincidence of the pre-glacial physiographic provinces of this peninsula with those of the present time would lead one to infer that the pre-glacial topography controls the present relief but such is not the case, since the corresponding areas do not actually coincide except possibly in the Thumb Upland. It is probable, however, that the main influence was the indirect one of determining the positions of the ice lobes and thus the moraines, and that the present topography is due, for the most part, to the distribution of the drift, and near the shores of the large lakes to the working over of this material by the waters of Lakes Algonquin and Nipissing. However, it may be that some of the topography in Hillsdale County and in the region northwest of Thunder Bay is referable to the underlying rocks. Stream action since glacial times has modified the surface so slightly that it is negligible.

The drainage of the Southern Peninsula is determined in its larger aspects by the physiographic provinces discussed above, and the sources of the main streams are found in the high interior portions. In the northern part the divide is situated near the center of the Northern Upland and the streams flow outward to Lakes Michigan and Huron. In this locality the headwaters of the Muskegon, Manistee, and Au Sable rivers are in close proximity. Many of the smaller streams, however, have their sources on the slopes of the upland province and flow more or less directly into the lakes.

In the southern part the long Thumb Upland forms a veritable watershed and on this are located the sources of the St. Joseph, Kalamazoo, Saginaw (south branches), Huron, and Raisin rivers. As in the northern section, the minor streams head on the slopes of this province and flow directly to the lakes. Between the two upland areas lies the Saginaw Lowland which is drained by the Grand and Saginaw Rivers.

Notable and peculiar drainage patterns are shown by some of the streams, especially the Saginaw and Black (Thumb region), but these are due to the distribution of glacial material, more especially the moraines and the uplifted beaches of the predecessors of the Great Lakes. In Alpena and Presque Isle counties are many sink holes, and the surface drainage is interrupted by these in some cases. From the distribution of the sinks and the presence of "fountains" in parts of Thunder Bay, it has been inferred that there is an extensive underground drainage system, reaching from this region to the vicinity of Black Lake in Cheboygan County, but this has not been carefully worked out as yet.

The abundance of lakes in the Southern Peninsula is an indication of the incompleteness of the drainage, and it is noteworthy that many of the larger as well as the smaller lakes are to be found in the morainic districts, for example, in the northern and southern interlobate areas and in the morainic region within Calhoun, Barry, and Kent counties. Aside from the lakes due to the irregular distribution of the glacial material, there are those bordering Lakes Michigan and Huron which are more important in the extreme northern part of the peninsula.

ORIGIN OF LAKE BASINS

A physiographic study of lakes has as its starting point the origin of the basins, and studies in the past have resulted in a classification according to manner of formation which includes many types. The list given, although not complete, will serve to illustrate the diversity of types.

Diastrophism (movements of the earth's crust)	
Slow movements	New-land lakes
	Ponded lakes
Rapid movements (faulting)	Basin range lakes
	Rift-valley lakes
	Earthquake lakes
Vulcanism	Coullee Lakes
	Crater lakes
Gradation	
Rivers	Ox-bow lakes
	Alluvial dam lakes
	Saucer lakes
	Crescentic levee lakes
	Raft lakes
	Delta lakes
	Side-delta lakes
Waves and currents	Lagoons
Wind	Dune lakes
Glaciers	
Mountain	Rock basin lakes
	Valley moraine lakes
Continental	Border lakes
	Morainal lakes
	Marginal
	Ground
	Morainal dam lakes
	Inter-morainic lakes
	Pit lakes
	Glint lakes
	Ice dam lakes
	Glacial lobe lakes
	Glacial scour lakes
	Fosse lakes
Ground water	Sink lakes
	Karst lakes
Gravity	Landslide lakes

It is seen from the list that diastrophism and the gradational processes of rivers and glaciers produce the greater number of types of basins, but of these, glaciers are productive of the greater number of examples, and the lakes thus formed are of greater importance. Although it is comparatively simple in most cases to assign the general cause of origin, there are many cases where it is difficult to determine the specific cause, inasmuch as several factors, each of which may be sufficient to form a lake basin, have been active. For example, basins due to deposition by continental glaciers are easily recognized but it is often a perplexing study to determine which of the various deposits plays the most important part. In cases where several factors enter the most important must be decided upon and the lake classified accordingly. Within the State of Michigan lake basins of the following types have been recognized:

Graciers	
Continental	Glacial scour
	Morainal
	Morainal dam
	Pit
	Inter-morainic
	Fosse
Waves and currents	Lagoons
Diastrophism	Rift-valley
	Ponded
Ground water	Sinks
Rivers	Ox-bow

It is clear from this list that a considerable number of types have been recognized but by far the greater number of examples is due either wholly or in part to glacial action. In fact, there are but few that can be referred to other causes but they are interesting in that they are exceptional, for this State at least, and their characteristics as well as those of glacial origin will be given.

RIVERS. OX-BOWS. Lakes of this class are found in the vicinity of streams which have reached the limit of downward cutting and are meandering. In streams of this age the adjustment between the carrying power and the material in transport is so close that even a slight decrease in velocity will cause deposition of some of the suspended material and, on the other hand, any increase will cause removal. The current of a stream that is meandering on a valley flat is increased on the outside (convex) side of the bend and cor-

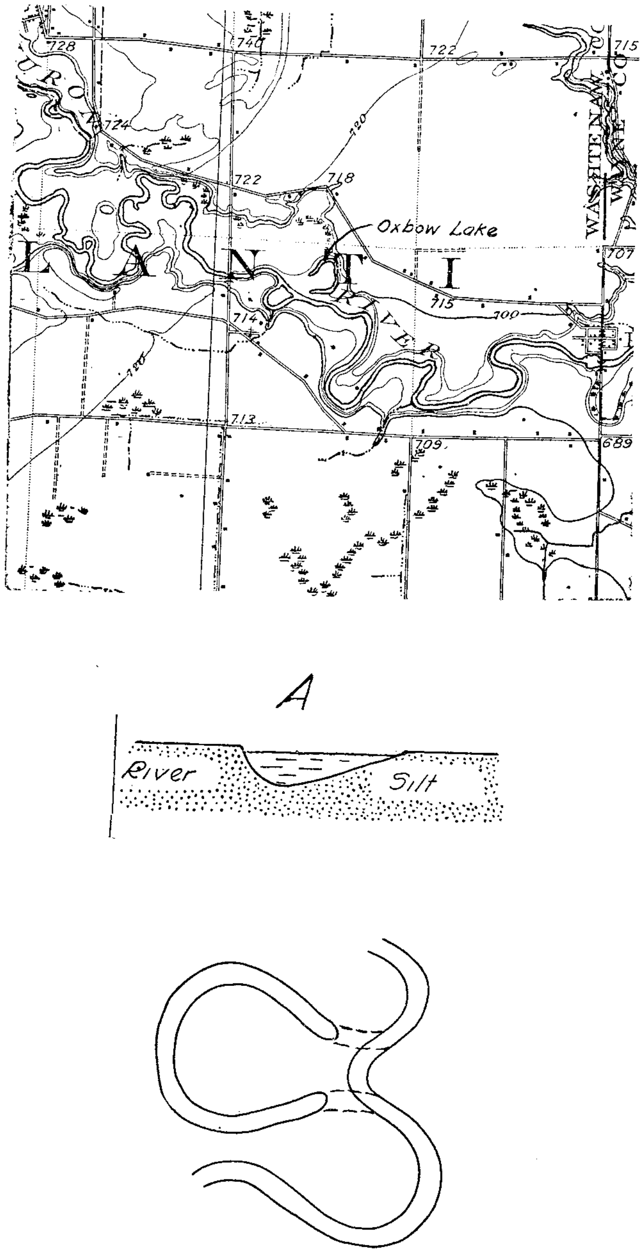


Fig. 8. Map and diagrams showing characteristics of oxbow lakes. Map a part of the Ypsilanti quadrangle.

respondingly deceased on the inside (concave). Therefore cutting takes place on the outside and deposition on the inside and at the same rate. This causes the meander to increase in swing, the width of the stream remaining constant, and also deepens the channel next the outside bank. In addition to the increase in width, meanders tend to work downstream, due to the fact that the stream is running down a slope. The neck of the meander is gradually worn away and the stream eventually straightens its course. The ends of the abandoned channel are soon filled by deposition and a lake formed. The characteristics of such lakes are: Its position on a valley flat composed of alluvium, crescentic shape, and greater depth near the convex side. See Fig. 8. An excellent example of an oxbow lake is that shown on the map in Fig. 8, and lies on the valley flat of the Huron River (Washtenaw County) about three miles below Ypsilanti.

Ground Water. Sinks. These lakes occur in regions underlain by limestone which is readily soluble in water containing carbonic acid gas in solution. The water with its dissolved gas seeps through the fissures and bedding planes of the rock and carries away much material in solution. The underground openings thus formed sometimes reach large dimensions and are called caves or caverns. The continuation of the process finally causes the roof of the cave to fall, forming a depression on the surface which may become filled with water. Such basins may be irregular in shape but are generally somewhat circular in outline and have no surface outlet, although they may have inlets. The characteristics are shown in Fig. 9.

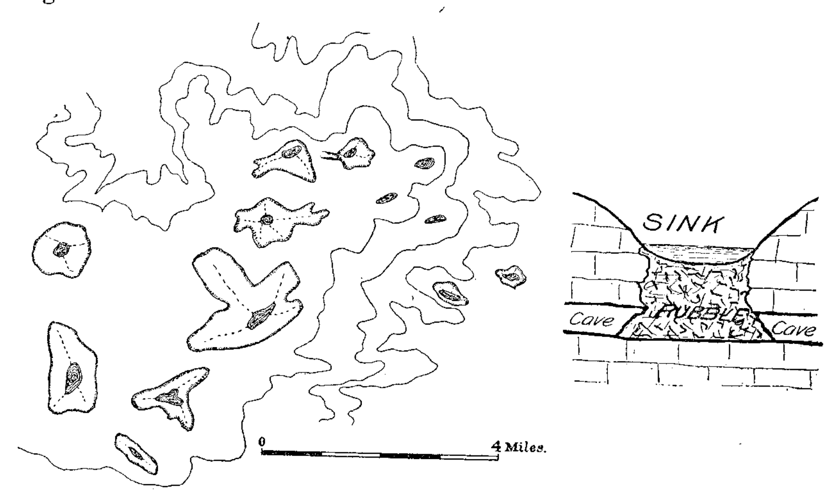


Fig. 9. Map and diagram to show manner of formation of lakes in sink-holes, (after Hobbs).

Lakes of this type are rare in this State and are confined to the Southern Peninsula as far as now known. Ottawa Lake in the southeastern part is ascribed by Lane to this cause. Numerous sinks occur in Alpena and Presque Isle counties but no lakes occupying true sink holes are known. Sunken Lake, a few miles south of Metz in Presque Isle County, is closely related to this type of lake and was visited by the writer. It has little interest except as a type of basin and is now permanently dry. It appears to be a stream channel about one fourth of a mile long which is cut off from the Upper South, a branch of Thunder River, by a dam at its upper end. It ends abuptly at the lower end in a sink which stands above the stream bed and ponded the water which formerly entered this basin at high water stage. A view of this lake bed in shown in Plate I.

Diastrophism. Faulting. Lake basins due to faulting are exceptional in Michigan and in no case known to the writer can the actual faults be detected. Canyon lake in the Huron Mountain group has characteristics which point so clearly to this origin that it is included in this class. This lake is too small to appear on the map, Fig. 84, but in reality is a most interesting and fascinating body of water. It is scarcely one-fourth mile in length and does not exceed one hundred feet in width. Nevertheless it possesses a charm which lies not in its size but rather in its picturesque location and surroundings. It lies in a narrow canyon of almost uniform width which cuts directly across a hard rock saddle. The shores at the ends are low and swampy but the sides are cliffs which

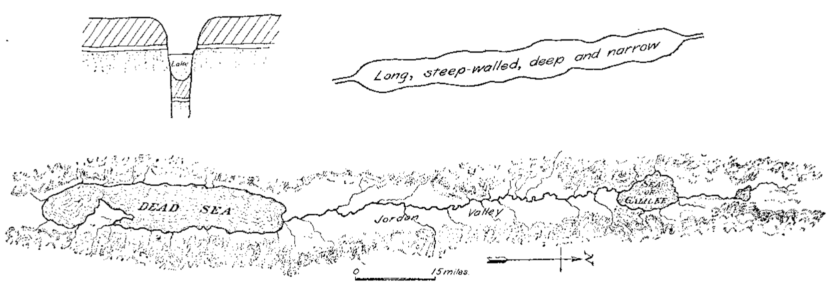
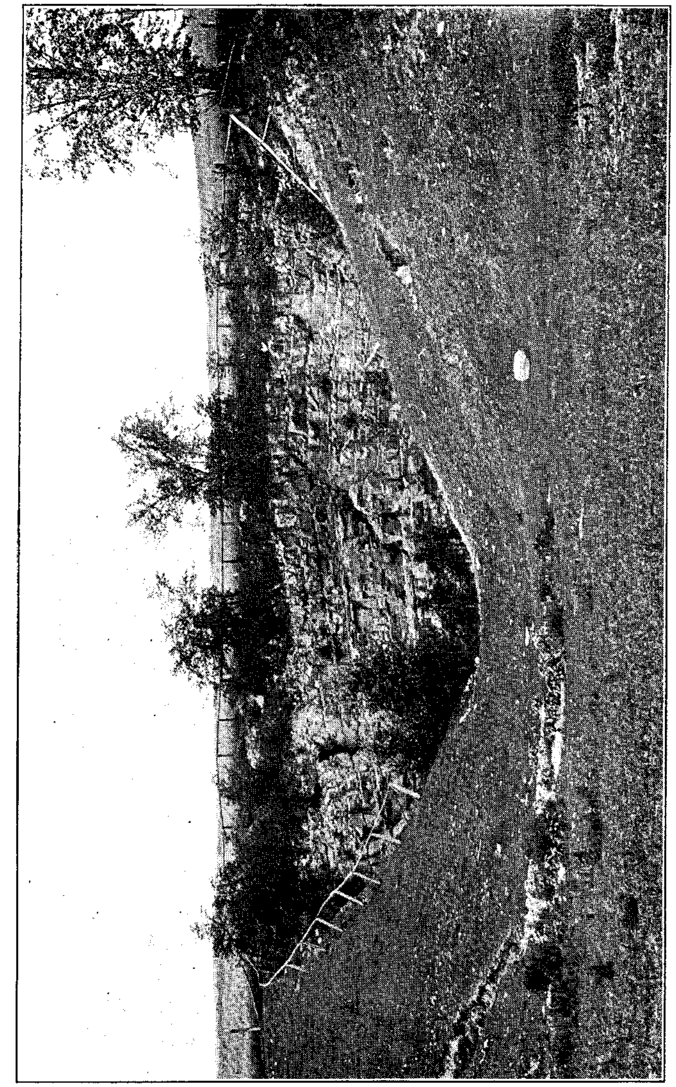


Fig. 10. Diagram and map showing characteristics of rift valley lakes, (After Hobbs).

increase in height from either end to a maximum in the center. The cliffs, while very steep, are not perpendicular but ascend in steps consisting of high risers and narrow treads upon which stand trees and shrubs in precarious positions. The outline of the sides is a somewhat regular zig-zag rather than a straight line, showing the presence of fractures. In addition, the depth of the lake is relatively great and the cliffs descend perpendicularly into the water.

Michigan Geological and Biological Survey

Publication 30, Geological Series 25, Plate I.



SINK HOLE, SUNKEN LAKE.

Such characteristics lead one to the conclusion that this basin was formed by the dropping of a portion of the earth's crust, not as one block but several long, narrow blocks, the amount of drop or displacement being progressively greater towards the center of the depression.

The general characteristics of such lakes are shown in Fig. 10 and may be enumerated as follows: Long and narrow, of great depth, and bounded on the sides by rock cliffs.

WARPING. Along the western coast of the Southern Peninsula south of Frankfort many of the streams broaden on approaching Lake Michigan, and the expansion is sufficient to warrant their being classed as lakes, since they have been separated from the main lake by the development of bars. Their separate existence is due to the work of waves and currents but the expansion of the river mouths—the lake basins—is due to a warping of the earth's crust. The warping consists in an uplift of the land to the north-east which is raising the outlets of the Great Lakes and, in the

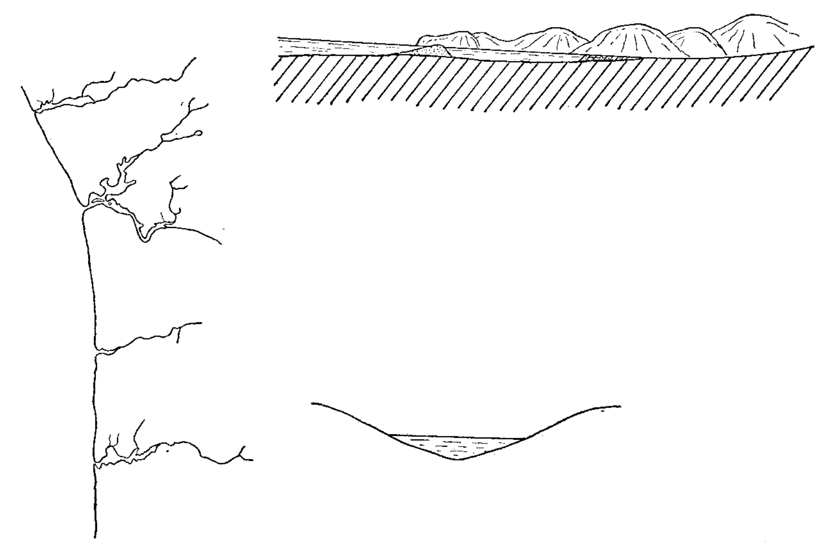


Fig. 11. Diagrams showing characteristics of lagoons of the drowned stream type.

case of Lake Michigan, is causing the water to encroach on the land in the region referred to. This is flooding or drowning the river mouths and, in conjunction with shore action which forms the bars across their mouths, forming lakes of moderate depth whose beds slope gently to a channel formerly occupied by the stream. The shape is usually irregular due to the flooding of main stream and tributaries. In case a single stream is flooded the shape is roughly triangular with the upstream point truncated by a delta-like deposit made by the entering stream. Fig. 11 illustrates these characteristics.

Glacial Lakes. Scour. In some localities the scour of the ice is responsible to a large extent for depressions, although other factors may be important. The scour was a planing action accomplished by rocks held in the base of the ice and was localized according to the topography, structure, and hardness of the rocks over which the ice flowed. Topographic depressions, such as stream valleys running in the same direction as the ice, were deepened by an increase in flow and a greater thickness of ice. Gaps in ridges running transverse to the direction of ice movement were both widened and deepened because of increased flow somwhat analogous to the greater velocity in river narrows. Once through a gap, the ice spread and in some cases flowed along the transverse valley on the far side of the ridge, deepening it locally. It is probable also that the ice in these depressions was the last to melt and outwash was deposited at the ends which accentuated the basin formed by scour. Such lakes are usually long and narrow and the evidence of glacial scour is the presence of striations on the exposed rock surfaces running parallel to the length of the lake. Another structure which facilitates glacial wear is an abundance of fissures in the rocks. Rocks which are easily abraded also were more rapidly worn down by the ice, but regions underlain by such rocks were the locations of stream courses previous to glacial times and the ice merely increased the pre-existing relief.

Deposition. Morainal. This term is reserved for the small basins caused by irregularities in the surface of marginal and ground moraines. In marginal moraines the surface is characteristically hummocky and the knobs and basins vary in size and regularity. The size and shape of the lakes occupying moranic depressions are determined not alone by the nature of the individual basins but by the amount of water draining into them. If sufficient water is available to cover several adjoining basins, a lake is formed which is irregular in outline and usually of moderate size. In case a single basin is flooded, the lake conforms to this basin and is often oval in outline and small in extent. The smallest of these are mere ponds without outlets and few, if any, inlets, and are rapidly being filled with vegetation. The depth of such lakes is not great and corresponds roughly with the relief of the surrounding country. The shores are frequently strewn with boulders and cobbles and the bottom is composed of a clay mud, where not covered with peat.

In the ground moraines the relief is less pronounced and the lakes are usually very shallow, although they may be of considérable

Fig. 12. Diagrams and map showing characteristics of morainal (marginal) lakes. (Diagrams after Hobbs. Map a part of the Three Rivers, Mich., Quadrangle.)

extent. Houghton Lake in Roscommon County, one of the largest inland lakes in the State, lies mainly on ground moraine and the depth does not exceed 25 feet. The characteristics of morainal lakes are shown in Fig. 12.

Inter-Morainal. During the recession of the glacier it sometimes happened that the halts of the ice border were close together, leaving parallel morainic ridges with a narrow depression between, composed of ground moraine or outwash. Often such depressions are below the general drainage level and, if the ends are blocked, become the sites of lakes of considerable extent. Such lakes are elongate in the direction of the flanking moraines whose slopes have the characteristic knob and basin topography, and the ends are frequently blocked with outwash. The presence of outwash may be explained by assuming a block of ice which filled the depression and from whose sides outwash developed in either direction; or that the outwash aprons developed locally at various places along

Fig. 13. Lake Antoine, a lake of the morainal dam type, (from the Menominee Special Quadrangle).

the ice front but did not coalesce. This type of basin is very similar to that of morainal lakes situated on ground moraine and perhaps should be considered as a special case rather than a distinct type.

Moranial Dam. Although the general statement that continental ice masses such as covered northeastern North America assume a form that is largely independent of the relief of the land is true, yet it is a significant fact that the ice border in its details was extremely sensitive to the topography over which is flowed. At the ice border hills served to divert the flow, and depressions became locations of increased movement especially when their direction was parallel to that of the ice flow. In this way minor tongues were formed in valleys which deposited a series of moranic dams as they receded and above these dams lakes now lie. The valleys must have been present before the final retreat of the ice and may have been pre-glacial or inter-glacial. Lakes of this type are often elongated in the direction of the valley but may be circular or even run transverse to the valley if the dams are close together or low in elevation above the valley floor. They occur frequently in series in the same valley.

In the Iron River district of the Northern Peninsula there are some lakes which are held by drift dams thrown across the valleys between drumlinoidal hills, for example, Fortune, Chicagon, Stanley, while in the vicinity of Iron Mountain an irregular moraine across a pre-glacial valley forms the west border of Lake Antoine, see Fig. 13.

Fosse. Fosse, as used in this connection, refers to a long, narrow depression that is sometimes found between a moraine and an outwash plain. It is a remnant of ground moraine upon which the ice stood when the outwash was being formed. The outwash was built up along the steep ice front partially burying it, and when the ice retreated part of the material at the inner edge of the outwash fell back on the ground moraine, forming a very steep slope. A short distance back the moraine was piled up, leaving a depression, as shown in Fig. 14.

Such lakes may be distinguished by the attenuated form, the presence of moraine on one side and outwash with steep edge on the other, and the absence of outlet or inlets of importance. The water of the lake seeps readily through the sand and gravel of the outwash in lieu of an outlet. Inlets may develop on the side slopes of the moraine but the more important will run in the unoccupied portion of the fosse. Inasmuch as the fosse is a local development, the inlets must necessarily be of little importance and the lake fed principally by ground water. An excellent example of this type of lake is Crooked lake, situated in the group of lakes a few miles west of Chelsea, Washtenaw County.

PITS. The term pit, as here used, signifies a depression in an outwash plain. It was probably formed by the isolation of an ice block which became covered with debris and melted later, allowing

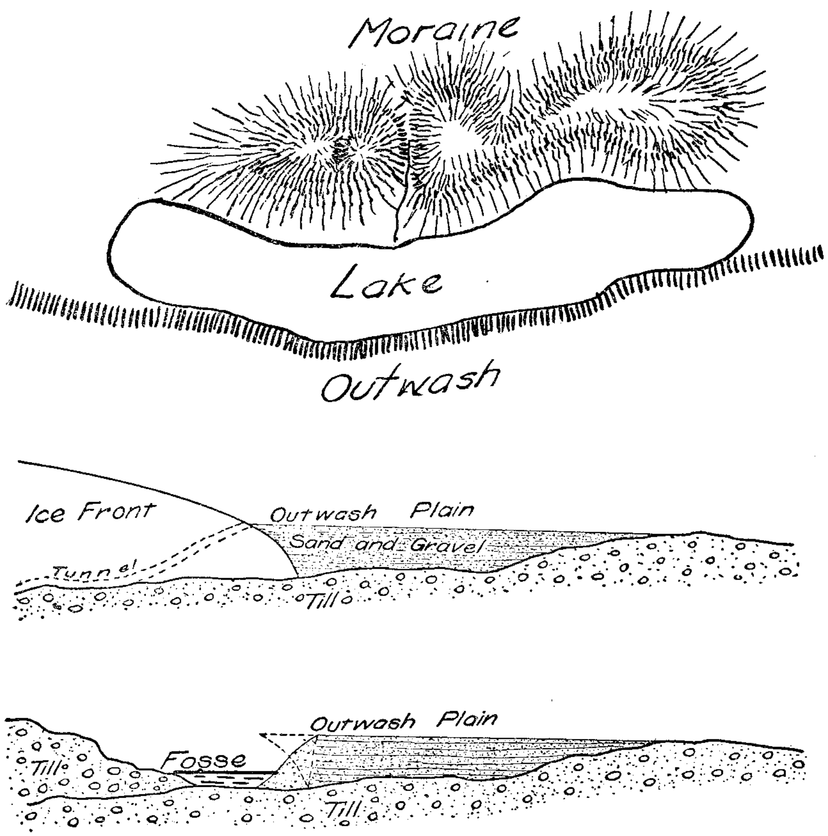


Fig. 14. Sketch and diagrams to illustrate manner of formation of fosse lakes, (diagrams after Hobbs).

the material above to settle. The important thing in the formation of these depressions is the protective effect of a coating of earthy material on the ice. A small rock fragment on the surface of the ice absorbs enough heat from the sun's rays to become heated through and melts a depression for itself in the ice. Larger fragments or an accumulation of small ones are not able to conduct the heat to the under side and, therefore, protect the ice, and the greater the thickness of the earthy material the slower the melting.

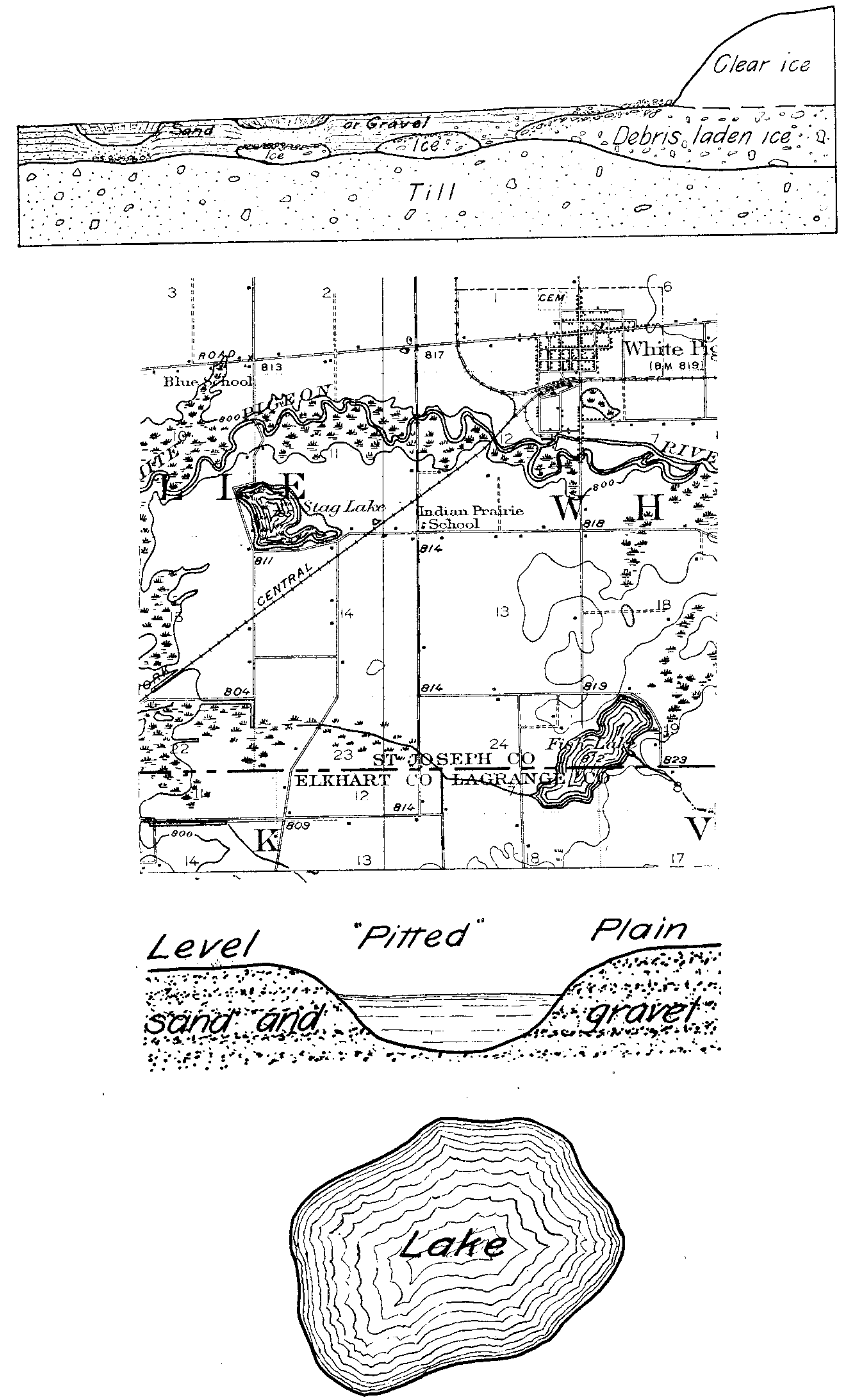


Fig. 15. Map and diagrams to illustrate characteristics of pit lakes. Map a part of Three River Quadrangle. Lower diagram after Hobbs.)

Continental glaciers are characteristically divided into two distinct zones, an upper one comparatively clean and free from debris and a lower which is heavily clogged with rock fragments. Under the sun's rays the clear ice of the upper zone melts rapidly but, when the lower zone is reached, the rock fragments protect the ice directly below them. The portions of the surface not covered with debris melt until earthy material is uncovered and finally a complete rock cover is formed which soon becomes so thick that melting proceeds at a very slow rate. This difference in the rate of melting of the upper and lower zones caused the ice of the upper zone to recede possibly several miles while that of the lower remains stagnant. Wherever the drainage from the ice was vigorous, the protective cover was removed from the stagnant ice and it melted, but where sluggish streams were depositing material, the ice was deeply buried in an outwash plain with an unbroken surface sloping gently away from the ice. The ice blocks did not underlie all of the outwash plain but were more in the nature of scattered fragments, due probably to the uneven distribution of debris in the lower zone of the glacier. Where the load was exceptionally heavy the debris accumulated on the surface until a cover was formed which protected the ice beneath so effectively that it persisted until covered with outwash. At some time subsequent to the formation of the outwash the ice blocks melted and allowed the material above to subside slowly, causing pits or depressions in the surface of the outwash. This process is illustrated in Fig. 15.

The distinguishing features are: The basin is a depression in a plain, the materials of the plain are water deposits and, therefore, assorted and sometimes stratified, the slope from the plain to the water level is steep, the outline is roughly circular, and there is often no outlet and no important inlets, the lake being supplied and drained by the seepage of ground water through the sandy material of the outwash plain.

Waves and Currents. Lagoons. Shore action often isolates a depression forming a new and usually smaller, detached body of water. The original depression is due to other causes and the shore action is responsible for the isolation only. The work of waves and currents is fully described in Chapter II and needs no discussion here.

It must be stated that some of the inland lakes studied by the writer cannot be definitely included in the classes described above because of the complexity of the origin of the basins and the lack of data concerning them. In particular, attention is called to a series of elongated lake basins along the coast of the northwestern part of the Southern Peninsula—Pine, Torchlight, Elk, Walloon, etc. These lakes exist in long, narrow valleys whose bottoms are filled with thick deposits of loose sand. However, on the sides of the flanking hills at elevations from 100-300 feet above the level of Lake Michigan are found exposures of clay varying in thickness from a few feet to more than 100. These deposits have been buried by till, showing that they were formed prior to the last advance of the ice over this region. The clays are interpreted by Leverett as lake beds, inasmuch as they are distinctly laminated, nearly free from pebbles, and, in places show sandy partings between the layers of clay. The data are incomplete but indicate the presence of great lakes in this vicinity previous to the last advance of the ice, the extent and duration of which we have merely a suspicion. The puzzling thing is the relation of the valleys in which the present lakes lie to the ancient lakes as signified by the clays. The heavy deposits of sand in the valleys preclude the possibility of determining by direct observation whether or not the sand is underlain by the lake clays found higher on the hills, and it is essential to know this. If underlain by the clays, the basins would be classed as enormous pits since it would indicate that the clays had sunk from the higher elevation. If not underlain by the clays, it may be assumed that the deposits have been removed or were never formed in the present lake basins. If the material has been removed, streams, ice, or both may have been the eroding agents. If the clays were not deposited in these depressions, we may assume the depressions to have been filled with blocks of ice, probably stagnant, while the clays were settling on the beds of lakes which bordered these ice masses.

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CHAPTER II

THE DEVELOPMENT OF LAKE SHORES AND THE EXTINCTION OF LAKES

CHARACTERISTICS OF WAVES AND CURRENTS

WAVES. Coincident with the filling of a lake basin with water there begins a development of its shores and, to some extent, its bed. Conditions of absolute calm are exceptional and it is seldom that roughened patches do not appear, travel forward, and die out on the otherwise unruffled water surface. It is a matter of common knowledge that for the most part these patches are caused by the wind, and examination shows them to be composed of a pattern of wavelets which run with the wind and whose crests are at right angles to the wind direction. See Plate II, A. If the wind fails, they disappear but with a freshening breeze the area of the ruffled water soon spreads over the entire lake.

From this we might conclude that waves are caused by the friction of the wind on the surface of the water, and further observation will strengthen this conclusion. At any one point, with a freshening wind, it is readily noted that the waves not only increase in height but in length and velocity as well. This continues until a maximum development is reached which is largely dependent on the strength of the wind and the time it has been blowing. However, a trip along the shore discloses the fact that the waves increase in development toward the lee side of the lake and, if several lakes are observed, it becomes evident that the larger the lake the greater are the waves formed by winds of the same velocity. Thus, in addition to the velocity of the wind and the length of time it has been effective, may be added the factor of the expanse of water across which it blows, or *reach,* in the development of wind driven waves. This development of the wave in height, length, and velocity is due to the fact that an almost continuous push by the wind is effective on the wave from one end of the lake to the other and is, therefore, cumulative. It continues until the friction caused by the differential movement of the water particles is equal to the energy supplied by the wind. Inasmuch as the storm winds usually steady down at a maximum velocity which is somewhat uniform, a maximum wave development which is exceeded only during exceptionally strong winds, may be postulated for a given lake. On the other hand a decrease in velocity or cessation of the wind allows the waves to flatten and gradually die out.

Other causes of water waves are possible but it is the wind driven wave that is effective on the smaller bodies of water. In waves of this type there are two motions to be considered, the forward motion of the wave itself and the motion of the particles of water affected by the wave. Whenever a wave is running in deep water where its motions will not be interfered with, it is called a *free wave* and the motion of the particles is theoretically in circular, vertical orbits which do not move forward with the wave, the revolution being in the same direction as the movement of the wave. Thus, in waves of *oscillation,* there is a forward movement of the particles through the upper half of the orbit during the passage of the crest of the wave and a backward semi-circle with the trough. This may readily be observed by watching the movement of a floating object, and is illustrated in Fig. 16. If all the particles occupied

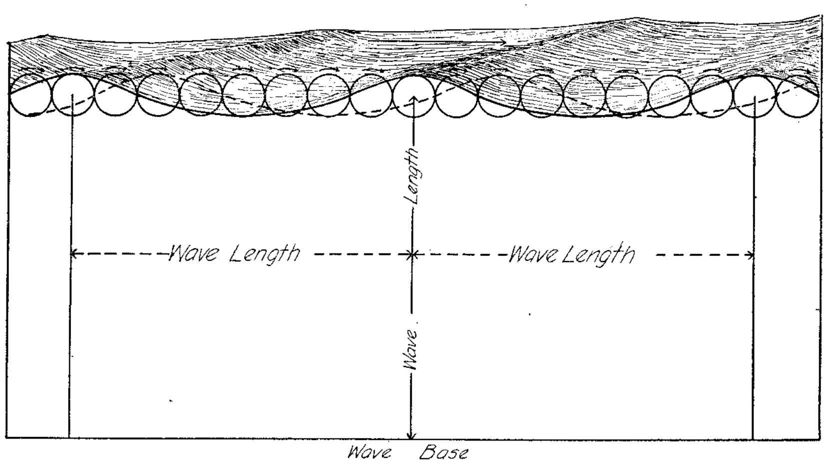


Fig. 16. Movement of water particles in waves of oscillation.

the same relative position in their orbits, or *phase,* e. g., all at the top, and continued to revolve, the result would be a raising and lowering of the entire surface of the lake accompanied by a forward and backward movement. This is not the case and the wave progresses because each impulse is communicated from one particle to the next adjoining on the lee side. It follows, then, that no two particles in any wave are in the same phase but are more advanced in their orbits to the windward. This is represented in Fig. 16 in which the orbits of conveniently spaced particles have been drawn

and must be considered as representative, the intervening spaces being filled with particles revolving similarly. The particles are represented as revolving in a clockwise direction and, beginning at the left, each particle is more advanced in its orbit (has a more advanced phase) than the next to the right by one-eighth of the circumference of the orbit. By connecting these points a curve is obtained which represents the form of the wave in cross section. This curve* shows the steeper crests and wide troughs, and from this it will be seen that the upper half of the revolution of a particle described during the passage of the crest of the wave must be accomplished in a shorter time and with greater velocity than the lower half, since the forward movement of the wave is uniform.

Both the height and the length of the wave may vary and great variations in the dimensions and velocity of waves are possible. Observation has shown, however, that in general there is a more or less definite relation in fully developed waves between the height, length, and velocity. This varies somewhat in different bodies of water but may be approximately stated as follows: Wave length is five and one-eighth times the square of the period (time between two crests) and the length fifteen times the height. The relationship is shown in Fig 17 in which the phasal difference is the same but the size of the orbits increased.

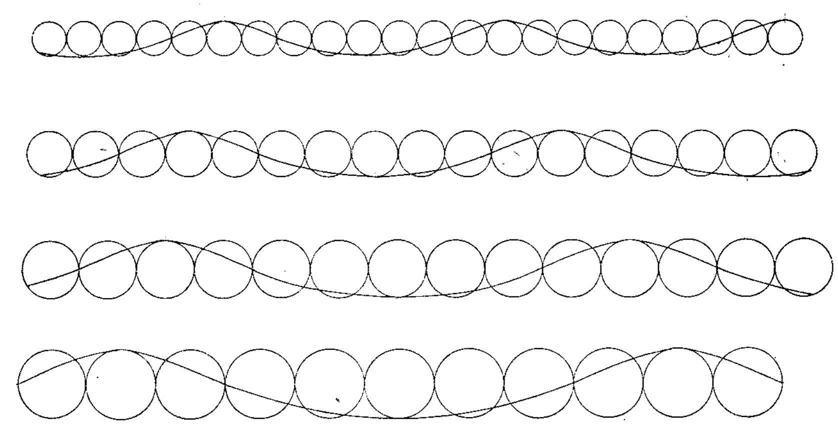


Fig. 17. Diagram illustrating the ideal development of waves.

The agitation of the water particles at the surface is communicated to the particles below, but the motion decreases very rapidly and practically dies out at a very limited depth. See Fig. 18. It is usually stated that the size of the orbits is halved for each in-

*The curve here shown is a trochoid and is obtained from the trace of a point inside the circumference of a rolling circle. A cycloid is formed if the point is on the circumference.

crease in depth equal to one-ninth of the wave length, but this is only a rough approximation. An illustration may give a better idea of the rapidity of the decrease in motion with depth. A free wave which has a height of three feet at the surface is approximately forty-five feet long and the time of passage about three seconds. At a depth equal to the wave length the diameter of the orbits is less than one five-hundredth of that at the surface, or in the case cited seven-tenths of an inch and the time three seconds. The rate at which the water moves in describing an orbit of this size is about two-thirds of an inch per second, a very feeble current and incapable of geologic work except possibly the transportation of the very finest sediment. The depth of a wave length below the surface has, therefore, been called the *wave base,* that is, the lower limit of effective wave action, but observations show that this depth

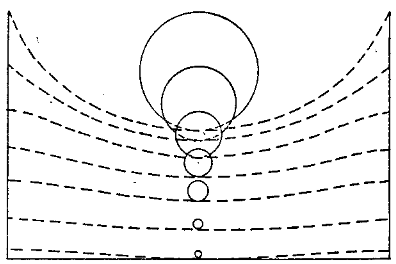


Fig. 18. Diagram illustrating rapid decrease, with depth, of motion of water particles in a wave, (after Fenniman).

is excessive and probably should be placed at less than half the wave length.

The relationship in the dimensions of the wave does not hold under a freshening breeze. Under this condition the height increases faster than the length, and the wave gradually becomes steeper until a limit is reached which, if exceeded, would cause the water to describe a loop at the crest of the wave, a condition obviously impossible. Fig. 19, which shows the effect of increasing the height while the length remains constant, illustrates this point. The wave is then said to break into a *whitecap,* but it is probable that the wind which is moving much more rapidly than the wave blows the crest over into whitecaps before the theoretical limit of steepness is reached.

As stated previously, from a theoretical standpoint there is no permanent forward movement of the particles of water in waves but, due to the constant forward push by the wind, it happens, in reality, that each revolution of a particle finds it slightly advanced from its former position and there results a drift with the wind. It is probable that the wind has a greater push on the crest of the

wave than on the trough because the wind and water are moving in the same direction and the steepness of the crest allows the force to be applied to better advantage. Consequently, most of the forward movement occurs during the passage of the crest and an attempt has been made to show this in Fig. 20. By following the course of this continuous line it will be noted that all of the for-

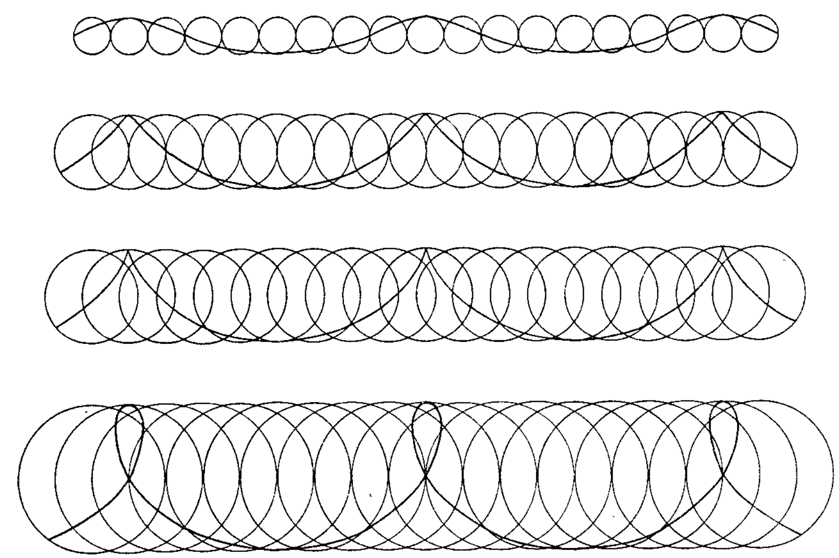


Fig. 19. Diagram to illustrate the formation of whitecaps. For convenience the wave length is kept constant.

ward motion is represented as taking place in the upper half of the orbit. The curve is not accurately drawn principally because there are no data from which to construct it but is presented merely to give some idea of the manner in which a forward drift is set up by the wind.

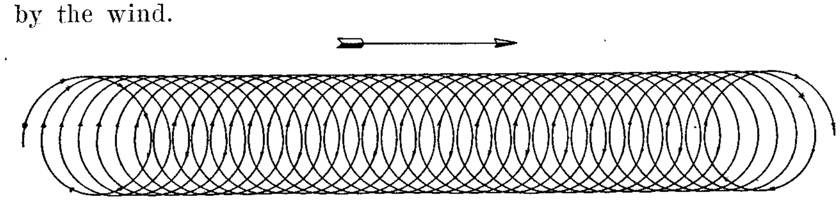
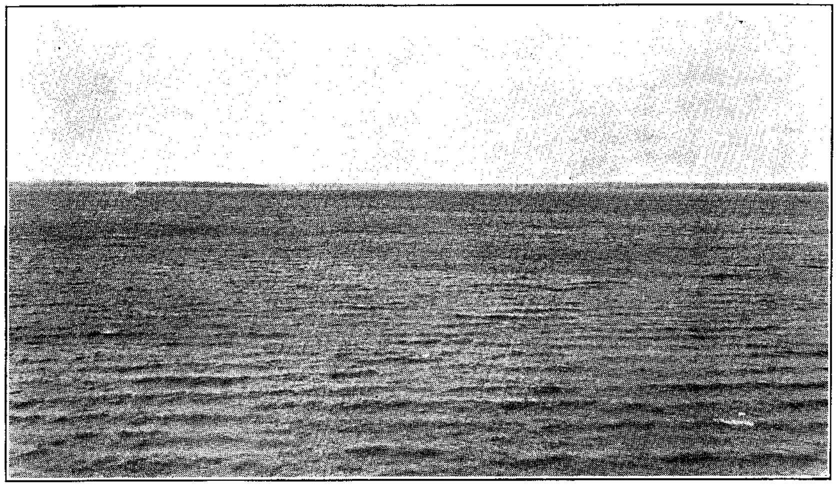


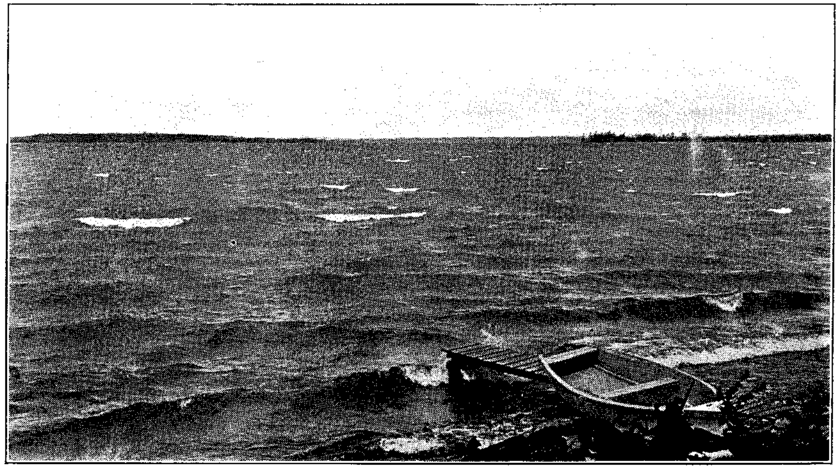
Fig. 20. Diagram of the path of a particle of water affected by a number of successive waves.

In addition to the drift, there are other positive forward movements. Of these whitecaps have already been considered. Another takes place when the waves approach the shore. As the water becomes shallower the agitation extends to the bottom and the lower portion of the wave is retarded by friction. The orbits of the water particles are no longer circles but are deformed into ovals. These are more nearly circular at the surface but become flattened with depth until the bottom is reached where the motion is a horizontal oscillation. The retardation of the lower part of the wave is shared by the upper but not in the same degree and results in a decrease in velocity which is less pronounced at the surface. The velocity of the wave is continuously reduced as it approaches the beach and is necessarily accompanied by a corresponding decrease in wave length and a steepening of the crests. In addition, the wave height is actually increased, due to the transmission of the motion to a continuously smaller quantity of water as the depth decreases, and the form of the wave becomes steeper on the front or shore side because of the more rapid forward movement near the surface. The variations are all progressive and continue until the crest topples forward into foam, or *breaks*, see Plate II, B, which reduces the height of the wave. The storm waves break first at a more or less uniform distance off shore, called the off-shore breaker line, and the reduction in height by breaking is sufficient to allow them to regain their true wave form. They then proceed for some distance, in some cases to the shore, without further breaking. It is possible to have the slope of the bottom so flat that the waves may break at the off-shore line and continue to the shore with crests a mass of foam, but this usually does not occur. In such a case the waves may be dissipated before they reach the shore.

Under the conditions stated above—a very gentle off-shore slope—waves of oscillation are not only modified in the manner described but may in some cases change their character and become a different type, called waves of *translation*. The motion of the particles, instead of being in orbits, may become a definite advance accompanied by a lifting and sinking, together making a semi-elliptical path for each particle which does not return to its former position. Each particle from top to bottom starts simultaneously with the approach of the wave, moves forward and upward until the crest arrives, then sinks in its forward movement, and finally comes to rest when the wave has passed. The forward movement is the same for all particles but the verticle movement is greatest at the surface and decreases downward to the bottom where it becomes zero, that is the movement is horizontal. Fig. 21 shows the paths of the particles in a wave of this type and Fig. 22 the forward and upward movement in the front portion and the forward and downward motion of the particles as influenced by the back of the wave. The velocity increases in the forward half of its path from zero



A. WAVES, BURT LAKE.



B. WHITECAPS AND BREAKERS, HIGGINS LAKE.

to a maximum at the middle and then decreases until it comes to rest.

Waves of translation are caused by a sudden addition of a volume of water to a lake or other body of water, each wave representing an addition. Obviously, they are independent of each other and consist merely of crests of water moving forward at a uniform rate of speed. They have neither length nor trough as the terms are used with reference to waves of oscillation, the surface between the crests being flat and the distance variable according to the regularity of the additions of water. When formed in a lake they are caused by the plunging crests at the off-shore breaker line which supplies the additional volume of water and usually run in to the shore in apparently related series because of the regularity with which the waves from the lake enter the breaker zone.

All waves, whether of oscillation or translation, are eventually dissipated on the shore, except in the possible case of an excessively

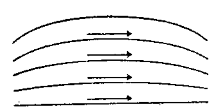


Fig. 21. Diagram showing paths of water particle in waves of translation, (after Fenneman).

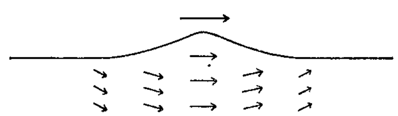


Fig. 22. Diagram showing upward and forward movement in the front part (right) and downward and forward movement in the back part (left of a wave of translation, (after Fenneman).

wide breaker zone. With the final plunge on the shore the true wave motion is lost and the water rushes forward and back over the shore, which acts as an inclined plane. The outgoing water running down the inclined shore meets the next incoming wave but succeeds only in modifying its front, which becomes increasingly convex toward the shore, and increasing its height until it wavers, curls forward, and crashes on the beach. This final breaking of the wave is popularly known as *comber*.

Currents. In the preceding pages it has been pointed out that there is a forward drift of the water in wind driven waves which is further increased within the breaker zone by the partial or total conversion of the waves of oscillation into waves of translation, and that this forward movement occurs mainly at the surface. This transfer of water from the windward to the lee side of lakes necessitates a return. This is accomplished by means of currents, although in large lakes, as Erie and Superior, a small amount of the transfer is accommodated by a piling up of the water at the lee end. The currents are set up when the waves strike the shore and may be horizontal currents along the shore, *shore currents,* or a vertical return into the main body of the lake along the bottom which is called the *undertow,* or both. The nature of the current is determined by the angle at which the waves strike the shore.

When the waves strike the shore at exactly 90 degrees the incoming water runs up on the shore and returns underneath without lateral movement along the shore, forming undertow only. As stated above, the agitation of the water by waves within the breaker zone extends to the bottom where it is a forward and backward horizontal movement having a maximum velocity midway between two periods of rest. Hence the undertow must be a pulsating current in which the particles move to and fro but advance slightly out into the lake with each oscillation. Its strength depends on the height of the waves and the steepness of the off-shore slope but decreases as it advances into the lake because it is distributed through larger amounts of water as the depth increases. In this way it loses its indentity but may continue throughout the entire length of small lakes as an inappreciable drift.

But it is impossible for waves to approach all shores at an angle of 90 degrees. When the waves strike at oblique angles the paths of the particles of water are as shown in Fig. 23. Instead of a to

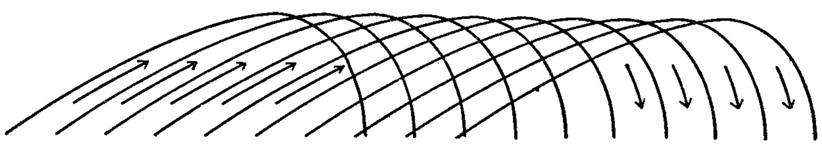


Fig. 23. Diagram to show actual motion of water particles striking shore at an oblique angle.

and fro motion along a straight line as in the case of the undertow, the motion is an oscillation on the shore accompanied by a lateral movement and results in a current along the shore which may reverse its direction because of the variable wind directions. Shore currents should reach their greatest development when the waves are running nearly parallel to the shore but this seldom happens. It may occur where the off-shore slope is very steep and the wind direction favorable. But where the off-shore slope is gentle the shore end of the wave is retarded within the breaker zone and the retardation increases with nearness to the shore. There is, then, a tendency for the crest of the wave to bend and swing towards a direction more nearly parallel to the shore, that is strike at 90 degrees. This change in direction may cause oblique waves to strike the shore at 90 degrees if the obliquity is slight and the off-shore slope wide.

Two currents, then, are set up on a shore upon which the waves are pounding, the undertow and the shore current, and the relative importance of each varies according to the angle at which the waves strike. With waves running on shore perpendicularly the undertow only is present but any appreciable variation of this angle sets up a shore current which increases at the expense of the undertow as the angle departs from perpendicularity. Considering the entire shore of a lake, the development of waves and currents varies at any given time due to the varying relations between the directions of the shore and the wind at different parts of the lake, and over a period of time, because of changes in wind direction and velocity. Thus, with shifting winds all the shores of the lake may be affected but not equally because the storm winds come usually from a prevailing direction. Under the influence of a wind constant in direction the location of the shore, and the size and shape of the lake are important.

Obviously, the windward side is least affected and the effects increase towards the lee. The size of the lake is important in that as the reach is greater the waves are better developed. As regards shape, the simplest case is a lake of circular outline. The middle of the lee side, A. Fig. 24, receives the strongest waves and at an

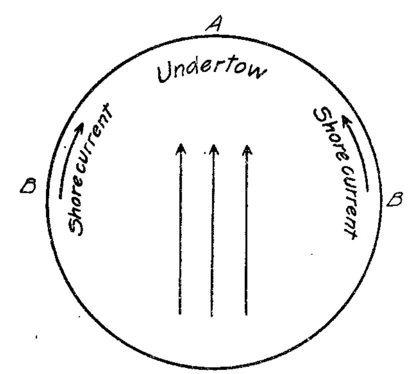


Fig. 24. Diagram to show currents set up on a circular lake.

angle of 90 degrees, therefore undertow only is developed on this shore, and at the sides, B, shore currents are formed. Along the intermediate stretches both shore currents and undertow are present but the former merge into the undertow as they approach A and return underneath. To the windward the waves are inactive and the only current possible is the return below the surface, the continuation of the undertow. On the other hand, if the lake is long and narrow, the condition is not so simple. The most effective winds are those which blow lengthwise of the lake because of the excessive reach and develop waves and currents similar to those established on a lake of circular outline. Cross winds, on account of their short reach, produce effects of minor significance but similar in character. However, when the wind crosses the lake diagonally, only a short stretch of the shore can be perpendicular to the wave movement and strong shore currents are developed on the lee side but the undertow is of minor importance. In this case the shore current turns the end of the lake and skirts the windward shore as a return current which has lost its intermittent character and therefore much of its effectiveness. See Fig. 25.

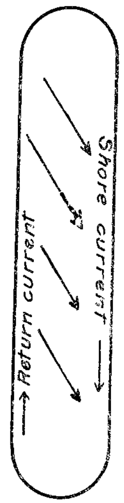


Fig. 25. Diagram showing conditions under which a return shore current is formed.

THE WORK OF WAVES AND CURRENTS

Waves and currents in the neighborhood of the shores are very effective erosive agents. They are active not only in tearing down the land but also in removing and depositing the disintegrated material. The resemblance to rivers is close and is strengthened when it is realized that they are, in fact, nothing but bodies of water in motion, obeying the same laws but with strikingly different results. Thus, the transporting power of running water is involved and with it the presence of tools—suspended material—which are important in the degrading process. In general, it may be stated that the waves are the active agents of destruction, and the currents the agents of transportation and deposition. In the final analysis both are due to the same cause, the wind, and they occur together. As regards the work accomplished, they may be said to

supplement each other, that is, the currents are dependent on the waves to furnish material for transportation and, on the other hand, the waves would soon lose their force if the material were not removed.

The Work of Waves. When a wave strikes the shore, there is agitation of the water from the plunge of the wave and at the same time currents are set up, except where a verticle cliff extends into the water to a depth greater than wave base. The range of the direct action of the wave extends approximately from wave base below water level to the greatest height that the waves splash above water level but the effectiveness varies within these limits. The action is greater above water level than below and is greatest at or a little above the water level. The movement of the water is greatest as it makes its final plunge on the shore and during the succeeding in-and-out rush along the inclined beach. Here also is the source of the suspended earthy material which is broken from the shores by the force of the waves with the co-operation of the weathering process. The suspended material is thrown violently against the shore with each incoming wave and acts as a powerful abrasive, which is limited in its action to a narrow zone near the water level. Within this zone cutting is most rapid and the effects are more pronounced where the shores are steep. At first a low cliff develops which recedes and at the same time increases in height. The cliff soon extends above the upper limit of the direct action of the waves and becomes undercut. The overhanging portion must sooner or later fall and, thus, extends the action of the waves indirectly to the top of the cliff and allows the recession to continue. See Fig. 26.

Fig. 26. Farwell's Point, an undercut notched cliff on Lake Mendota, Wisconsin. After a time the overhanging portion will fall by gravity to produce blocks like those in the foreground, (after Fenneman).

Coincident with the recession of the cliff there is formed at its base and below water level a terrace cut in the material of which the cliff is composed and, therefore, known as a *cut terrace*. The terrace itself furnishes the condition necessary for currents which modify its surface to some extent. The tools which are so effective in the cutting process are at first too heavy to be carried out of the zone of action of the surf but the continual pounding against the cliff and each other gradually reduces their size until they are carried lakeward by the undertow or along the shore.

The distribution of this material along the shore constitutes a *beach* which tends to become smoothed out into straight lines or almost perfect curves. See Plates XII, A and XIII. The material of the beach is rounded, except for particles of extreme sizes, and shows a rather close assortment. The rounding of the particles is due to the mutual abrasion caused by rubbing. Manifestly those particles too large to be moved by waves are unaffected and small particles, such as sand, are so buoyed up by the water that abrasion is not effective. Both waves and currents are active in assorting the beach materials. All of the particles which can be moved are picked up and tossed shoreward by the incoming waves but only the finer material is carried away as the water runs back. There is, then, a minimum size of particles to be found on a beach but not necessarily a maximum because rocks too large to be moved may be present. During exceptionally heavy storms coarse material is sometimes built into surprisingly strong ridges which stand some distance from the shore under normal conditions and are known as *storm beaches*. See Plate XIX.

Other factors in determining the character of beach material are nearness to the source of supply and the nature of the material. Where the material is quarried from a headland, the size decreases and the assortment is better with distance from the source. This is due to the more effective wave action on the exposed headland and reduction in size of the particles by abrasion as they progress along the beach. If solid rock is quarried, structures such as fractures and bedding are important. Thus, with thin beds closely fractured, small flat blocks are supplied which are soon rounded off and constitute a *shingle beach*. In Michigan the nature of the glacial deposits is important in determining beach materials, since little solid rock is exposed on the shores of the inland lakes. The clay of the till is readily washed away, leaving a strand of cobbles and boulders, while sand and gravel, unless clearly a current deposit, are significant of outwash.

The outward passage in the undertow is a series of backward and

forward movements which are far more effective than a steady current of the same average velocity would be. Abundant tools of fine texture enable the undertow to wear down somewhat and smooth off the cut terrace. The modification of the terrace in this way seems to be dependent largely on the time that the process has been active and, therefore, is greatest at the outer edge and decreases to the shore. Consequently the surface of the terrace slopes gradually out to its edge and then drops steeply into deep water. But when the edge of the cut terrace is encountered by the undertow, the current loses its effectiveness due to the sudden deepening and drops its suspended material. This accumulates beyond the edge of the terrace until it reaches the general level of its surface at which time the undertow again becomes effective and extends the terrace into the lake by deposition. Thus, there is formed a *cut-and-built* terrace which is constantly being widened by cutting along the shore and by deposition on the lake side. See Figs. 27 and 28.

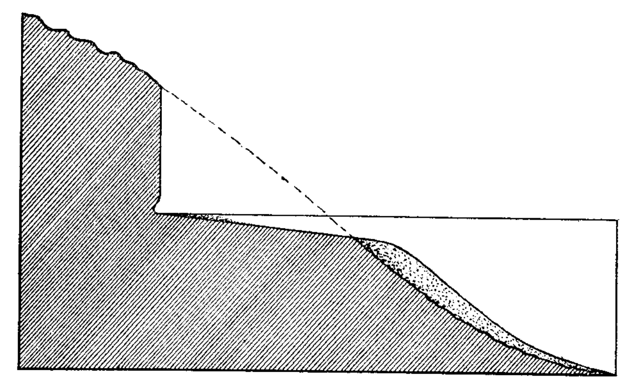


Fig. 27. Profile of a cut and built terrace on a steep rocky shore. The cliff is verticle and notched at the base, (after Hobbs).

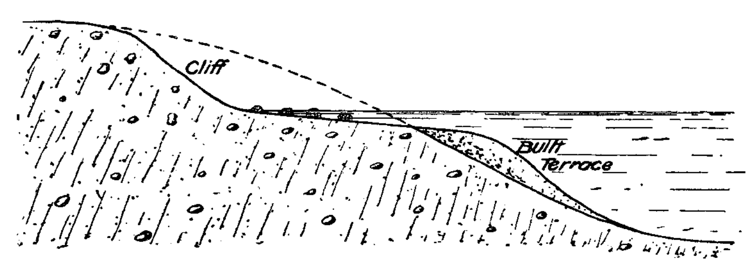


Fig. 28. Profile of cut and built terrace on a steep shore formed of loose material. Note inclination of cliff and the stranded boulders in front, (after Hobbs).

It has a gentle slope away from the shore and drops suddenly into deep water at its outer edge which is limited by the depth at which the water, agitated by the larger waves, loses its effectiveness as a transporting agent—one-half wave length or less. For a given locality this depth is fixed by the size of the largest waves and subsequent widening of the terrace serves only to flatten its slope which, in turn, reduces the action of the waves and currents. The process, then, is self limiting and the shore eventually becomes *adjusted,* at which time the highest waves lose their force as the shore is reached.

On well developed cut-and-built terraces it is not uncommon to find a perceptible shoaling of the water just before the "drop off" is reached, indicating the presence of a sand ridge which may reach almost or quite to the water level. These sand ridges are nearly coincident with the off-shore breaker line and their manner of formation has been referred to the violent agitation of the water during the breaking of the waves followed by more quiet conditions as the waves regain their true form. In this way the conditions of transportation and deposition are satisfactorily fulfilled. Similar forms have been described extending above the water level in large bodies of water and are called *barrier beaches* but in all cases a lowering of the water level (or elevation of the land) is involved. It is plausible that the waves might pound such forms above the water level but as yet no such case has ever been observed. Barrier beaches are not necessarily attached to the shore, are composed of sand, and have gentle slopes on the lake side while on the opposite side the slopes are steeper, Fig. 29. Between the land and the barrier is a narrow, shallow *lagoon.*

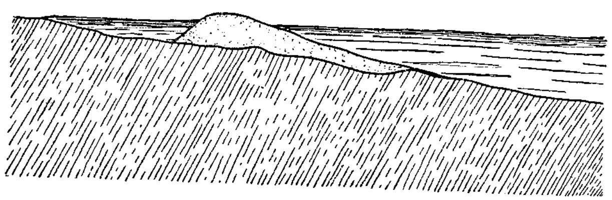


Fig. 29. Section of a barrier with characteristic steep landward and gentle seaward slope, (after Hobbs).

In the discussion above it has been assumed that the material of the shore was uniform but this seldom, if ever, occurs on all shores even of a small lake. The different kinds of rock vary greatly in the resistance they offer to the erosive agents and the same kind of rock may vary from place to place. In addition, certain structures in the rock serve as lines of weakness along which the erosion proceeds more rapidly. The more important of these are divisional planes between beds of stratified rock and joints which are the vertical cracks so commonly present in all rocks. These variations

in the rocks give rise to a number of transitory forms during the progress of erosion.

Under the conditions stated above (steep slope), cliff formation is one of the first results of wave action. The steepness of the cliff depends very largely on the firmness or consolidation of the rock. The great deposits of sand and gravel which are very numerous and extensive in glaciated regions offer little resistence to the waves and, being but loosely held together, form cliffs of moderate steepness which are not undercut. See Fig. 28. The same statement may be applied to the cliffs cut in clay except that the cliffs are somewhat more steep. However, in solid rock the cliffs may be vertical and overhang the zone of undercutting at the water's edge, Fig. 27.

Of the various forms which are due to wave erosion the under-cut cliff is perhaps the most common wherever hard rock is encountered. In massive rocks the face of the cliff may be very ragged and the undercutting excessive. The same may be true of stratified rocks where the layers are of different degrees of hardness and many picturesque forms result. Wherever a local weakness is present the cutting naturally proceeds more rapidly and a *sea cave,* Fig. 30,

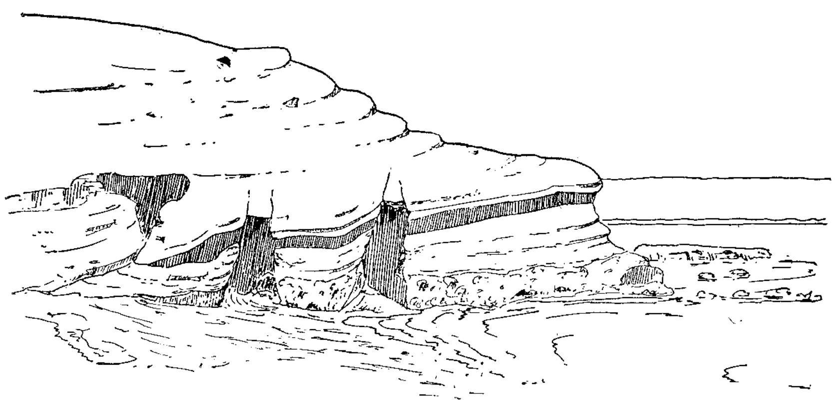


Fig. 30. Sea-caves in process of formation along joints, (after a photograph by C. W. Cook).

is the result. The weakness may be due to a difference in the rock or to the presence of fractures. The fractures or joints may run for long distances along a straight line and often have extremely smooth walls. They apparently run in all directions but study has shown that the more important are grouped in systems which cross each other at right angles. Joints running approximately parallel to the shore may cause smooth-faced cliffs, often without undercutting if the joints are close together and well developed. They may run oblique to the shore and in this case the cliffs have a buttressed effect. When the joints running at right angles to the shore are followed, caves may develop. Often the joints converge back from the shore and in time a channel is cut through. As the channel enlarges this form is appropriately called an *arch*. Fig. 31.

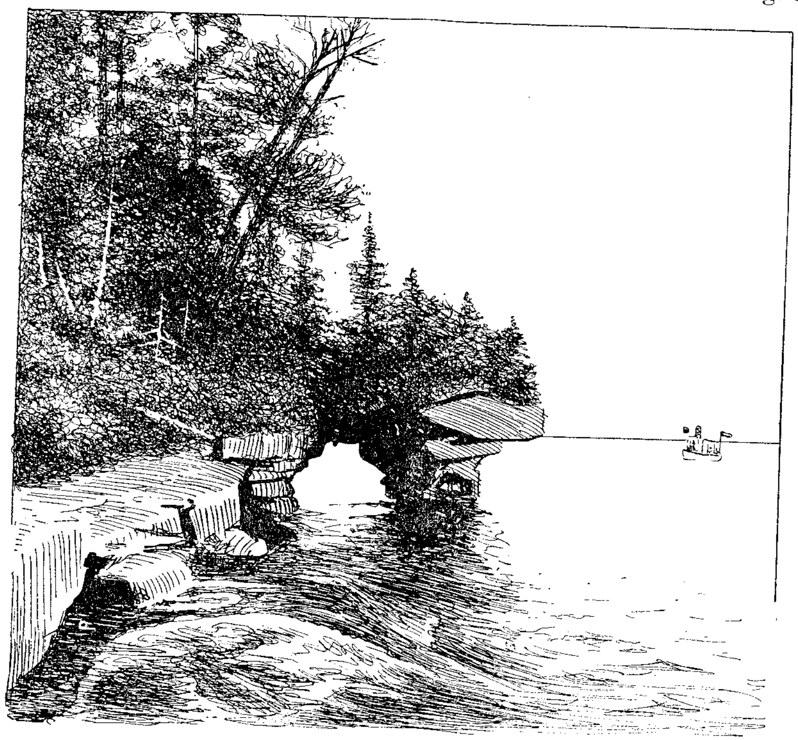


Fig. 31. A sea arch and small caves on the shore of one of the Apostle Islands, Lake Superior, (after a photograph by the Detroit Photographic Company).

But eventually the arch must fall as the action proceeds and a *stack*, Fig. 32, is left standing entirely separated from the main cliff. And this, too, must give way in time to the irresistable attack of the waves. These forms are all evanescent and represent the early scenes in the development of this particular type of landscape. They are very common features of sea coasts and the shores of large lakes and are an indication therefore, that much of the adjustment of the shores is yet to be accomplished. Inasmuch as the inland lakes lie largely in glacial basins, these features are seldom found.

Waves, as we have seen, are most active on shores with steep off-shore slope but conditions along the shores of any considerable body of water vary and with them the effectiveness of the waves. Headlands are almost universally subject to attack by the waves

and to these may be added shores with notable relief, for the surface of the surrounding land is to a great extent an indication of the topography of the bottom, that is steep slopes on land indicate similar slopes beneath the water.

THE WORK OF CURRENTS

On lakes of irregular outline shore currents must necessarily encounter numerous changes in direction of the shore. The current is able to accommodate itself to many of these but where the bend is abrupt it leaves the shore in the direction it had before the

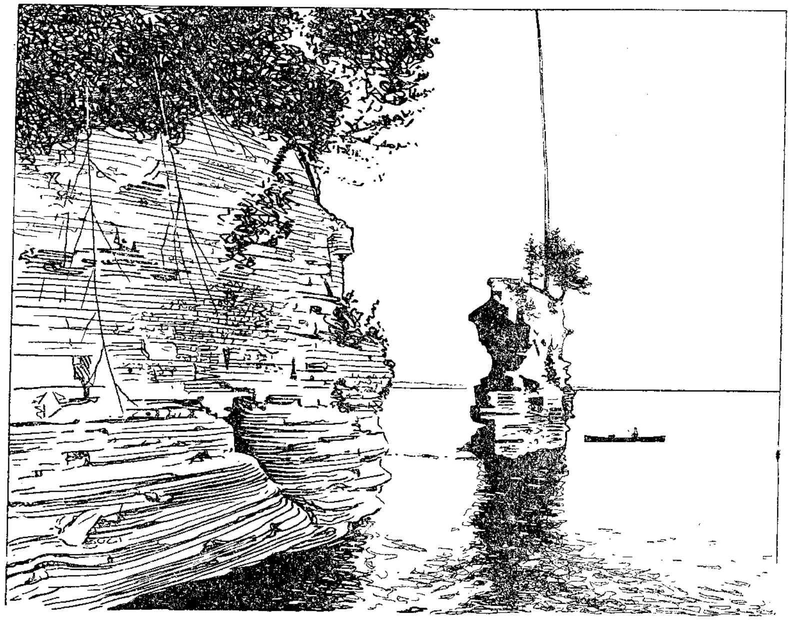


Fig. 32. A stack on the shore of Lake Superior, (after a photograph by the Detroit Photographic Company).

bend was reached. As the current leaves the shore its velocity is rapidly decreased because its motive power—waves striking the shore at an oblique angle—is lost and friction is present between the current and the still water of the lake. Deposition, therefore, takes place and is greatest near the point of departure from the shore.

If the bend is caused by a small indentation, the current may carry across the mouth but the velocity is decreased nevertheless and deposition takes place along its path in the form of a narrow submerged *bar*, best developed near the shore. Inasmuch as the currents may reverse their direction along the shore, due to shifting winds, the bar develops from both sides. As the submerged bar develops it first reaches the surface of the water at its land connections and is then pounded above the water level by the waves into pointed sand ridges, called *spits*, on either side of the indentation. (See Figs. 49 and 50.) Spits do not usually develop equally on both sides because of the prevailing direction of storm winds and the varying reach of the waves on different parts of the lake. With the formation of spits the currents are able to continue farther beyond the shore and the indentation is rapidly closed by a complete bar which is above the water level. This is called a sub-aerial bar or simply a *bar*. Plates IX, A, IX, B, XI and XIV. If a considerable amount of water drains into the lagoon, as the cut off indentation is called, a current is set up across the bar which may maintain an open channel. It sometimes happens that an island is encountered by the current after leaving the shore and it becomes tied to the land by the bar which developes. Fig. 65. It is then called a *land-tied island* and the bar is designated as a *tombolo*. Bars are composed almost entirely of sand and have a gentle slope on the lake side, due to the action of the waves and undertow, and a steep slope, often as much as one to one, on the lagoon side where wave action is much less intense.

In case the indentation is wide the currents may not persist across the mouth and a *hook* or re-curved spit is formed. Hooks are closely related to spits in that the material and the manner of formation is the same. The difference is in form, the hook curving back towards the shore. See Plate VII. Under the conditions necessary for the formation of hooks, the velocity of the current dies out rapidly after leaving the shore and the waves are able to turn it landward. The change in curvature is due in part to a shifting of the wind so that the waves strike the hook more directly or even from the opposite quarter and thus modify its form. Also the tendency of waves which are running oblique to the shore to swing to a direction more nearly parallel to the shore may be important in this process. The writer has seen waves break along a hook when the retardation of the shore end of the wave was sufficient to swing the crests around the end of the hook and even on the lee side in the opposite direction to the waves on the lake.

In the growth of spits and hooks the varying direction of the winds often causes minor developments in form which are not in harmony with the general growth. As has been stated previously, most of the storm winds come from a quarter which causes currents in one direction along a shore and the general development of

hooks and spits is in accord with this. However, high winds do occur from other quarters and the end of the hook or spit often grows rapidly during a single storm at an abrupt angle to the general direction. Such forms are usually very transient, often being destroyed by the next storm, but may persist on hooks as prongs extending landward from the sheltered side. See Plate VII. In reality, spits and hooks represent a balance between the currents set up in either direction along a shore and in the normal development one current usually greatly predominates. All gradations are possible and do occur. The clearest case is where evenly balanced currents from either direction are forced to leave the shore at some point. Spits develop from both directions and join in a point out in the lake forming a triangular or *V-bar*—also known as *cuspate foreland*—whose base is the shore and whose sides are equal. If the currents are not equally effective, one side grows at the expense of the other, the better developed often being a hook and the smaller a spit. The material is typical shore drift and the slopes are characteristic except at the tip of the V-bar where it drops suddenly into deep water. The whole embankment encloses a shallow depression similar in shape and normally filled with water. Such cuspate forelands seen by the writer were on long, narrow lakes running north-south and, at present, no reason for the currents leaving the shore can be assigned.

Another case of deposition by currents sometimes occurs along the shores of wide, shallow embayments between headlands. In such cases much of the material from the headlands is transported along the beach by currents into the bay. On account of the shallowness of the bay, the undertow is not effective, and this material accumulates about the head of the indentation. In this way a sand flat is built which gradually widens and reduces the indentation.

GENERAL EFFECT OF WAVES AND CURRENTS

In general the tendency of both waves and currents is to make the outline of the lake more regular. The work of waves has been described as a process of cutting, which insofar as headlands are reduced, removes the irregularities which project into the lake. On the other hand, currents are agents of removal and deposition. Deposition is favored by indentations which are cut off or filled thereby. However, it must not be inferred that a circular or oval outline is the final outcome of the work of these agents on all lakes, although this would seem to be the logical conclusion. The process of cutting is self limiting and may stop before the headlands are completely reduced. Also many indentations are too wide to be crossed by currents, and hooks develop rather than bars, serving merely to make the bends less abrupt. V-bars seem to disturb the symmetry of the shores and their complete development would carry them across the lake and divide it into smaller and more nearly circular bodies of water. This, however, is unlikely unless great quantities of material are supplied from extraneous sources. Another factor is the instability of conditions under which the lake exists. The development of lake shores requires long periods of time and changes in conditions may cause new levels or even the extinction of a lake before the work of adjustment is finished.

THE WORK OF ICE ON LAKE SHORES

ICE RAMPARTS. On the shores of lakes in regions having cold winters, ice is an effective agent of transportation and deposition. Its action is mainly that of a shoreward movement, accomplished slowly but with great force, which not only carries material forward to the shore but is able to shove heavy rocks in front. As the ice disappears in the spring the material affected by it is either piled up in a wall on the shores known as an *ice rampart,* Plate XVII, A. Figs. 51 and 61, or is left stranded on the terrace, to be moved subsequently. The ramparts are best described as walls of rock material and are located a short distance back from the shore. They are usually a single ridge but may be compound and the material is of all sizes, including boulders of large size. The slopes are steep on both sides with a tendency for the front slope to be the steeper.

The shove on the shore by the ice is exerted in two ways, by expansion and by ice jams. Expansion occurs during the winter when the lake is completely frozen. Water is rather exceptional in its properties and behavior under various conditions but, once frozen, acts as any other solid at ordinary temperatures and pressures. Thus, it expands or contracts with a rise or fall in temperature, and this property is involved in the formation of ice ramparts. When a lake first freezes it is enveloped with a layer of ice which completely covers its surface. If the temperature remains constant below the freezing point, the ice merely increases in thickness. But temperatures do not remain constant and the changes are often great and rapid. There is always a lowering at night followed by a daily rise and, in addition, there are the cold and warm waves which sweep over the country. With each drop in temperature the ice contracts but does not pull away from the shores. It cracks instead and the cracks are soon healed by freezing, since the temperature is below the freezing point. In this way the ice cover is kept intact but actually contains more ice that it did at the higher temperature. If such a condition is followed by a rise in temperature, the ice must expand and it will then be greater in extent than the surface of the lake. Repeated alternations in temperature serve to exaggerate this condition. The expansion may be accommodated either by overriding the shores or by buckling. In the latter case pressure ridges in the ice are formed out from the shore and usually occur in the same places year after year. Buckling takes place when the ice is not thick enough to withstand the pressures exerted by the expansion and where the shores are steep enough to prevent a landward movement of the ice edge. Even under this condition a slight amount of movement may be possible if the water level is low when the action takes place. In glacial material, at least, this results in a cliff embedded with boulders at its base or a boulder lined strand. See Plate VIII, B.

On sloping shores the ice is free to move and, if conditions are favorable, pushes up a rampart. The size of the material plays an important part both in their formation and permanancy. As a rule fine grained material such as sand does not freeze into a solid mass and the ice slides over it with little accumulation of debris. Also sandy shores are more commonly low and well-developed ramparts are not formed. However, if binding material, such as the roots of trees and mats of grass, is present, the material is pushed into ramparts, Fig. 61, but they are soon destroyed by the waves. During the winter of 1914-15 the sandy shore at the north end of Whitmore Lake, Washtenaw County, was pushed into a rampart about four feet high but by August of the following summer the rampart was less than a foot in height. Where coarse material is present it offers a good purchase to the ice which carries and pushes it on the shore forming ramparts which resist wave action and are relatively permanent. The fact that fine material is so generally mixed with coarse in ramparts indicates that the shoving action is important. The maximum size of particles moved in this way is not known but boulders of several tons in weight are found in ramparts.

Ramparts, formed by expansion, although very common on the shores of lakes in Michigan, require rather specific conditions for their formation and are formed only in winters when these conditions are fulfilled. The conditions involve the climatic factor, shore conditions, and the size of the lake. Shore conditions have already been discussed. Other conditions being equal, the size of the lake determines the amount of expansion. On small lakes, possibly less than a half mile in diameter, the amount of expansion is so small that the ramparts, if formed, are insignificant and soon destroyed. Larger lakes permit greater expansion but the ice becomes less able to transmit the thrusts caused by expansion, as the diameters are greater, and it buckles. The ability to transmit the thrusts depends on the thickness of the ice in relation to its expanse and is thus controlled by the climate. In this region the maximum size of lake upon which such ramparts are formed is not definitely known but probably does not greatly exceed a mile and a half.

The climatic factor includes both temperature and snowfall. temperature changes are essential but they must be large and rapid, and quickly transmitted to the ice. The excessive temperature changes of cold and warm waves which occur in this latitude during winter fulfill the temperature conditions perfectly but the daily rise and fall does not seem to be adequate. The rate at which the air temperatures are communicated to the ice depends on the thickness of the snow covering which may form an effective blanket. Absence of snow is, therefore, the most favorable condition.

The position of the rampart with reference to the shore is determined by the size of the lake and by the amount and number of the temperature changes. In general, it is situated just back of the shore which marks the high water stage. The size depends on the supply of available material and the number of times the ice shoves across the shore. If we assume that the ice moves a definite amount of material at each invasion, it is obvious that the development of the rampart is dependent on the number of invasions. As a rule, the ice encroaches on the shore but once each winter, each drop and rise in temperature serving only to push the ice farther on the shore. More than one advance is possible if the ice thaws during the winter and loses its continuity, but the total movement in the several advances is the same as that in a single advance and, therefore, less effective for each. Within limits, large particles are more readily moved by the ice than small ones and a preponderance of such material assures a strong rampart. However, the supply of this material on a shore may be limited and, after repeated invasions, may become exhausted, thus limiting the growth of the rampart.

Inasmuch as the climatic factor is relatively constant over a period of years, the typical rampart is a single ridge. If the available material is sufficient, the ridge develops until it becomes strong

enough to resist successfully the push of the ice and any further expansion is relieved by buckling of the ice sheet. The growth from this time on, if any, must be in width and from the lake side. On lakes whose levels are gradually lowering the overriding of the shores by the ice is not materially decreased but the position of the ice edge after expansion becomes less and less advanced as the shores recede and a series of ramparts are formed to which the name *ice-push terrace* has been given. Another factor in their formation is that with the lowering in level fresh areas of the bottom are brought into the zone of ice action and the supply of material is replenished.

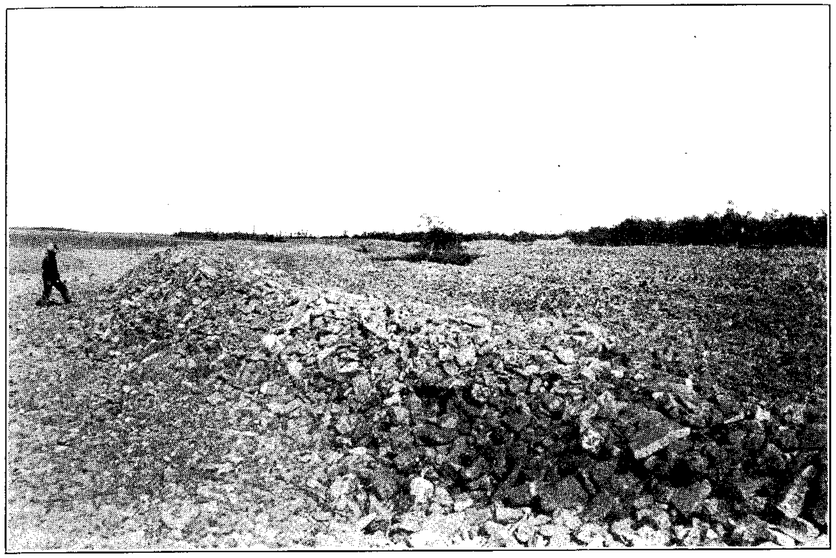
Ice ramparts of the expansion type, then, are limited to regions whose winters are severe and are punctuated by frequent cold and warm waves and to lakes of moderate size with absence of snow covering. Of these conditions the frequency and amount of the effective temperature changes, the amount of snow, and even the thickness of ice vary considerably, and it is only during winters when all of these factors are favorable that the expansion is effective in forming ramparts.

Ice Jam. The explanation of ice ramparts on the basis of expansion is only half of the story. Ramparts almost identical with those known to have been formed by expansion are common on lakes which do not fulfill the conditions necessary for this type. These lakes may exceed the maximum diameter postulated for expansion many times and are covered for the entire winter with a thicklayer of snow. In fact, it is known from observation that the ice does not expand on the shores of the larger lakes, and the ramparts have been accounted for by the action of ice jams which occur during the final melting of the ice in the spring.

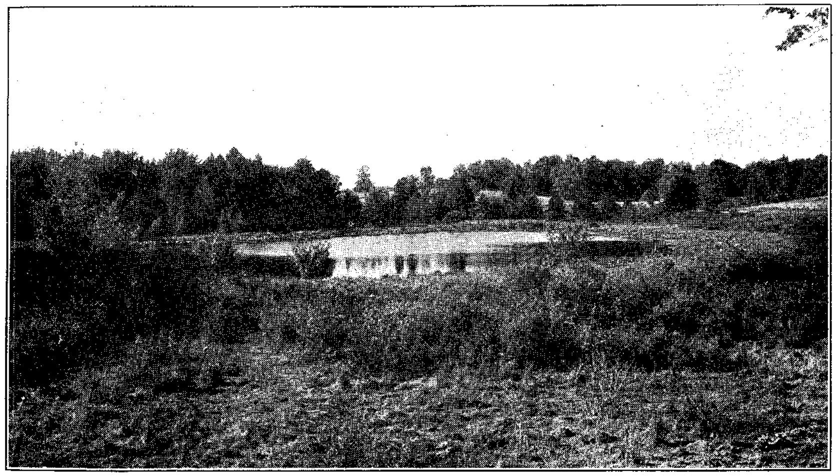
The melting of the ice at this time proceeds most rapidly at the shores, due to the more rapid heating of the land than the water under the influence of the rays of the sun, and a lane of open water of considerable width is formed next the shore. After the lane is formed weather conditions are of great importance. Some springs a prolonged warm spell is accompanied by calms or light breezes and the ice melts rapidly with little disturbance. It may disappear entirely in this way or become porous or "rotten" so that subsequent winds reduce it to slush. If, however, a storm develops after a lane is formed but before the ice has becomes porous, the mass of ice is blown before the wind and moves slowly to the shore with an almost irresistable force which carries everything in its path. See Plates X, A and XII, B. The storms in this latitude are cyclonic in nature and may best be described as vast whirlwinds which revolve in a counter-clockwise direction and at the same time travel from west to east across the country. They are especially frequent in Michigan because most of the storms tracks unite in the Great Lakes region. They are accompanied by winds which shift from an easterly direction usually through the south to the west and northwest, but occasionally in southern Michigan shift through the northern half of the circle. The velocity of the winds increases with the shifting and reaches its maximum with the westerly and northwesterly winds at which time it often reaches the intensity of a gale. These storms travel eastward at the average rate of about 700 miles a day but the rate is variable and they may halt for 24 hours or more. Inasmuch as they affect areas often 1500 and more miles across, their effects may be felt for several days in a given locality. All shores of a lake may thus feel their influence but the eastern and northeastern sides are in the lee of the strongest winds, at least for southern Michigan.

Where shore conditions are favorable ice jams bring in and pile up material in ramparts almost identical with those formed by expansion. Boulders of several tons in weight are moved shoreward in this way, leaving a trench between them and the lake and having a pile of rubble in front. Several such rocks were found on the northeast shore of Long Lake, Alpena County, (See Figs. 77 and 78.) As in the case of expansion ramparts, those formed by ice jam are self limiting for they finally must reach a strength which is able to stop the advance in the lower portion of the ice and the top shears over. Repetition of the process may form an ice push terrace, see Plate III (Athabaska), and this may possibly occur during one season as the ice is buffeted back and forth by the shifting winds or by a close succession of storms.

The size of the lake is also of importance. Permanent ramparts of this type are not found on very small lakes because the momentum of the small ice masses is not sufficient for large effects. On very large lakes they are formed but the material of the shores is usually fine and wave action excessive so they are soon destroyed, e. g., on the Great Lakes. The size of lakes on which the maximum push is exerted is not known but it is much larger than that for the expansion type. Practically all of the larger inland lakes of Michigan show evidence of ice action which is roughly proportional to the size. On many of the lakes of intermediate size it is certain that the push is exerted in both ways and the ramparts are thus intensified.



A. ICE-PUSH TERRACE. ATHABASCA.
Courtesy Canadian Geological Survey.



B. LAKE NEARING EXTINCTION BY VEGETATION, SECOND SISTER LAKE, NEAR ANN ARBOR.

Another effect of ice occurs when a great number of floating cakes of ice are present. These drift with the wind to the shores and, instead of being pushed up on the shore, some drift along the shore with the waves and currents. The action of these agents is increased by the ice especially as regards the transportation of large material. Some of the material may be supplied by rocks frozen into the ice which are released on melting but some shore material is moved along by the ice blocks and arranged into forms similar to spits or V-bars. A V-bar formed in this way was noted on Long Lake, Alpena County, Plate XIV, B. The form, the depression in the center, and the slopes are characteristic of current action but the material is angular limestone blocks having in some cases a largest dimension of as much as eighteen inches.

A similar form is shown in Plate XV, A. This feature resembles a spit in its position at the neck of an indentation but differs in form and material. Normally the outline of a spit is very regular but in this case the curvature is serpentine in character (the main body of the lake is to the left of the spit in plate). Also the material is angular and of relatively large size on its surface, although much of the submerged portion is composed of sand. It is probable that current action is largely responsible for its formation but floating ice blocks have added some material and have succeeded in modifying its form.

THE EXTINCTION OF LAKES

With the birth of a lake the forces which were responsible for its formation leave it unprotected to the action of certain agents which remodel its outlines and, to some extent, its bed. In addition, another set of agents becomes active which inevitably results in the extinction of the lake if existing conditions prevail. All of these agents work rapidly from a physiographic standpoint and support the idea that lakes are temporary features of the earth's surface.

The processes which are working towards the extinction of lakes are filling, draining, and evaporation. The filling of a lake basin may be achieved by sedimentation, by animal and vegetal remains, and by chemical precipitation. Sedimentation is active in lakes whose entering streams bring in great quantities of silt which is deposited near the shores to be worked over later by waves and currents, and to which may be added the material torn from the cliffs by the waves. The working over of this material into bars and barriers also favors the accumulation of vegetation.

Some of the lakes are inhabited by innumerable minute animal organisms whose hard parts are composed of calcium carbonate. When the animals die the fine shells drop to the bottom and become a part of beds of a white, powdery substance known as marl. Marl is usually considered to be a mixture of calcium carbonate material from several sources which, in addition to animals, include vegetation and chemical precipitates. Marl beds as much as forty feet in thickness have been found in Michigan lakes and are being utilized in the manufacture of Portland cement. The bed shown in Plate IV, B, is from three to four feet thick and is exposed along the artificial channel of the Sturgeon River near Indian River. Thicknesses of seventeen feet obtained by borings have been reported along Crooked River in the same vicinity.

Vegetation is another source of filling. Numerous water loving plants analogous to the leaves and stems of deciduous trees die at the close of the growing season and sink to the bottom. These dead parts, being covered with water, are protected from the gases of the atmosphere and only partially decompose. The yearly residue accumulates as deposits of peat, a light-brown to black porous substance composed very largely of vegetal remains, many of which are well preserved. This material burns readily but with poor heat values and is not used to any great extent as fuel in this country at the present time. The abundance of better fuel has held back the exploitation of peat but, as the supply of coal diminishes, the importance of the great peat deposits will become more and more appreciated.

The plants which enter into the formation of peat may or may not be attached to the bottom but in either case probably do not grow in water exceeding twenty-five feet in depth, due to unfavorable conditions of heat and light, and usually are within from two to six feet of the surface. The floating forms are important in lakes which are protected from strong winds and may sink and form a deposit over the entire lake bottom. Those attached to the bottom start in the shallow water along the shores and grow outward into the lake as the accumulation of their remains decreases the depth. However, these forms, growing most abundantly near the surface of the water, are not entirely dependent on shallow water but extend outward over the surface as a floating bog, composed of the felted and intertwined stems and roots. These bogs, often tenacious, are elastic and give under pressure, hence the name quaking bogs. They may develop so rapidly as to cover the surface of the lake before the basin is completely filled and are thus underlain by clear water. The development from this time on is accom-

plished by droppings from the under side of the bog, and in this way the water is crowded out of the space below. The bog becomes firm, first along the shore and progressively outward. When a lake is filled with peat the growth of vegetation on its surface continues for a time. But exposure to the air is unfavorable for preservation of the plant remains and the accumulation ceases a short distance above the former water level.

The encroachment from the shores in typical cases is quite regular and shows an interesting zonal relationship between the different kinds of plants. The constitution of the zones may vary but for southern Michigan the first plants to develop are the floating forms and the pond weeds. As these grow outward a zone of water lillies starts at the shore and is closely followed by the floating sedges which form the floating bog. With the filling of the clear water

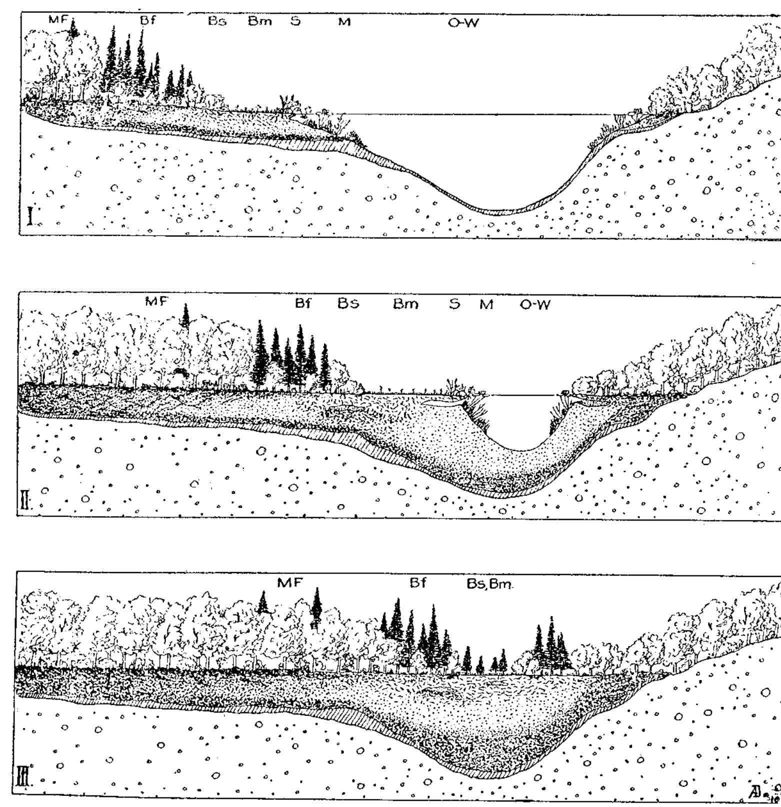


Fig. 33. Diagrams illustrating the filling of a lake by vegetation. The several plant associations of the Bog series, displacing one another, belong to the following major groups:—(1) O. W.—open water succession; (2) M.—marginal succession; (3) S.—shore succession; (4) B.—bog succession, comprising the bog meadow (B. m), bog shrub (B. s) and bog forest (B. f); and (5) M. F.—mesophytic forest succession. (Reproduced from Bulletin 16, Geological Survey of Ohio.)

under the floating matt, shrubs and other plants develop on the surface of the matt which crowd out the sedges. Next come the conifers, usually tamarack and spruce, and the last to propagate are the deciduous trees, especially poplar, willow, and maple. See Fig. 33 and Plate III, B. Such is the typical succession when fully developed but in the intermediate stages the later zones are absent.

In this manner lakes are filled by vegetation but the process varies in importance in different lakes. Quiet water is essential for plant growth, hence small lakes and lagoons are most affected. Shore conditions also have an effect. Gentle off-shore slopes are favorable because wave action is less intense and depths are suitable for vegetation, but are often composed of sand in which plants take hold with difficulty. Frequently there is found a heavy growth of weeds in the mud just beyond the edge of the terrace but the sandy terrace itself supports a sparse growth of reeds. Dead lakes, as lakes filled with vegetation are frequently called, are characterized by a monotonously flat surface composed of black soil and covered with a thick carpet of moss and shrubs above which is growing a thin stand of timber. See Plate XVIII.

Lakes may become filled to some extent by chemical precipitation but this process is limited in its application. In this climate it may have been of importance in the formation of marl where cold springs enter the lakes, but in dry regions it plays a more important role. In such regions the lakes are typically without outlets, due to the fact that evaporation is excessive and prevents the waters from rising to an avenue of escape. The loss of the water by evaporation allows the dissolved material brought in by streams to accumulate and, when sufficient concentration is reached, to precipitate on the shores and bottom. Among the substances deposited in this way are salt, borax, calcium carbonate, etc.

The draining of a lake is accomplished by cutting down of the outlet. Inasmuch as lakes act as settling basins, the outlets are relatively free from sediment and in general cut very slowly. The size and velocity of the outlet, and the resistance that the material over which it flows offers to abrasion, determine the rate of down cutting. Certain lakes, on account of their depth reaching below sea level, cannot be drained under existing conditions but, with the cooperation of filling, extinction is always a possibility.

Changes in climate are necessary for the extinction of lakes by evaporation and the change must be such that the supply of water is decreased or the evaporation greatly increased. A more arid

climate supplies both conditions and is usually accompanied by an increase in temperature. Many examples of partial or total extinction from this cause are to be found in the arid west but none in Michigan. Great Salt Lake, which has been greatly lowered in level in this way, is one of the best known examples.

The relative importance of the different methods of extinction varies greatly in different regions and with individual lakes. In general, the outlet is deepened rapidly in unconsolidated rocks, but even in hard rock this may be true if the down-cutting is due to the recession of a waterfall, such as Niagara Falls in the outlet of Lake Erie. As a rule deposition is more important than draining but in Michigan this is probably not the case. Down-cutting of the outlet is important because the great majority of the outlet streams run over unconsolidated glacial material which is readily eroded without the help of tools. On the other hand deposition has been slight. Many of the lakes are fed by springs and the drift deposits have as yet been only slightly trenched by streams, in most areas the original slopes being almost intact. In addition, the streams are usually short and the areas draining into the lakes small. An exceptional case is Torch Lake near Houghton where the Sturgeon river has built a large delta at the southern end of the lake. A more important source of material in our lakes is the cliffs which sometimes form a large part of the shores. The cliffs, composed almost entirely of unconsolidated material, are easily eroded by the waves and the debris is distributed along the shores and bottom. It is possible that the enlargement of the lake by shore recession may equal the amount of filling. Where cliffs form a considerable part of the shores the filling must be greater; and the ratio increases according to the height and preponderance of the cliffs. It is probable, however, that the amount of deposition in the lakes of Michigan so far has been a matter of a few inches only on the bottom.

At the present time, draining is probably more important than filling, but with future development the down-cutting of the outlets will gradually decrease as the streams approach grade, and the sediment brought in by tributary streams must increase as these streams extend their courses. At the same time the material deposited by waves and currents will decrease as the terraces widen. The deposition of part of this material in shore-forms reduces the size of the lake by cutting off indentations and thus facilitates filling, both in the main body of the lake and in the lagoons.

Vegetal accumulation seems to be more important in the extinction of lakes in Michigan than either of the two processes discussed above and is especially effective in the smaller lakes and lagoons. It is impossible to give an estimate of the amount of filling that has been accomplished in this way, but the prevalence of "dead lakes" and quaking bogs indicates that vegetal accumulations are of frequent occurence. All peat deposits are not necessarily evidence that a lake basin has been filled, and it is only by a determination of the depth and distribution of the peat and in some cases a recognition of plant zones that the extinction can be proven.

As regards chemical precipitation, marl is practically the only deposit of any significance in the lakes of the State and it may be formed in other ways. Three factors may be active in its formation, plants, animals, and chemical precipitation, and their relative importance is not known. In general, marl is one of the first deposits to be formed on a lake bottom and is often covered with peat. It may be sufficient in itself to fill a lake basin but no cases of such filling have been described in the knowledge of the writer.

THE CYCLE OF SHORE DEVELOPMENT

In the preceding pages the development of lake shores under the influence of waves and currents has been traced. This development is gradual and systematic, and the various stages are marked by definite topographic forms. In other words, the shores pass through a cycle of events which begin with the birth of the lake and terminate when the waves and currents are impotent to further modify them. A change in water level, either up or down, institutes a new cycle which may or may not interrupt the previous one before it is completed. Following the practice with regard to streams, the stages in the cycle have been likened to the life cycle and are termed youth, maturity, and old age. These terms, in a general way only, indicate corresponding lengths of time during which the forces have been active, but conditions, both as to the constitution of the shores and the force of the waves and currents, are so variable that the emphasis should be placed on the stage of development rather than on the time element.

The youthful stage is a period of active erosion. The shore is marked by irregularities above and below water level, and a general lack of adjustment to the movements of the water. The presence of frequent headlands necessitates numerous bays with sharp curves and the shore currents are consequently poorly defined and discontinuous. As the headlands are reduced and irregularities of the bottom filled, the currents increase in strength and continuity, and

eventually simplify the shoreline by cutting off re-entrants. Youth, then, is a time of relatively rapid changes and is brought to a close when all possible cut-offs have been accomplished.

The progress from this time on is gradual in contrast to the rapid changes of youth and characterizes maturity. The shore line as a whole either shifts landward or lakeward depending on the efficiency of the currents and the material available. Where abundant material is supplied by incoming streams, the shore will advance lakeward. If little or no material is supplied, the shore must progress landward but the recession becomes increasingly slower until an end point is reached. Shores of most lakes probably never reach a stage beyond maturity because of the interference of the process by extinction or by the inauguration of a new cycle. The inauguration of a new cycle by a rise in level gives conditions of the same nature as those present when the lake basin was first flooded. In case the water level sinks, shore action will be influenced more or less by the topographic forms developed during the previous stage, and the development may consist largely in a remodeling of these features. The latter condition is of common occurrence on the inland lakes of Michigan. On practically all the lakes, at least one higher level may be recognized, unless the level has been raised by dams, and in some cases as many as four have been found.

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CHAPTER III

LAKES OF THE CHEBOYGAN RIVER BASIN

In the basin of the Cheboygan River lie several of the larger inland lakes of the State, which, on account of their grouping and manner of formation, may well be discussed together. See Fig. 34. About three miles upstream from the city of Cheboygan the river branches, one branch leading from Black Lake on the borders of Cheboygan and Presque Isle counties, and the other draining a chain of lakes known as the "Inland Route." The lakes of the Inland Route and their connections are navigable for boats of small draught and a regular passenger service is maintained during the summer months from Cheboygan on the Straits of Mackinaw to Conway on Crooked Lake about three miles from Little Traverse Bay. The lakes included in this route are Mullet, Burt, and Crooked. Douglass, another lake of considerable size and importance, lies directly north of Burt, and is also included in this drainage system.

So far as known these basins lie entirely in glacial deposits which are somewhat complicated in this interlobate region. On the northeast side the moraines deposited by the ice of the Michigan and Huron lobes have a northwest-southeast trend and consist of a number of ridges which overlap in some cases. The best defined is probably a narrow ridge which parallels the shore of Lake Huron from Mackinaw to beyond Cheboygan, the only break being that through which the Cheboygan River flows. On the western side the moraines were deposited by the Michigan lobe and should be more nearly north-south in trend but are poorly developed. Little Traverse Bay caused a small lobe of the ice which penetrated as far as Crooked Lake and left the weak morainic ridges that cross this lake. The puzzling topographic feature is the extensive lowland area which is irregular in outline and extends from the head of Little Traverse Bay nearly to Cheboygan. This depression is crossed by similar depressions running northwest-southeast. The latter apparently lie between the moraines but the main depression runs transverse from Little Traverse Bay to Cheboygan, near which place the depression is terminated by the Cheboygan moraine mentioned above. It seems certain that the depressions existed

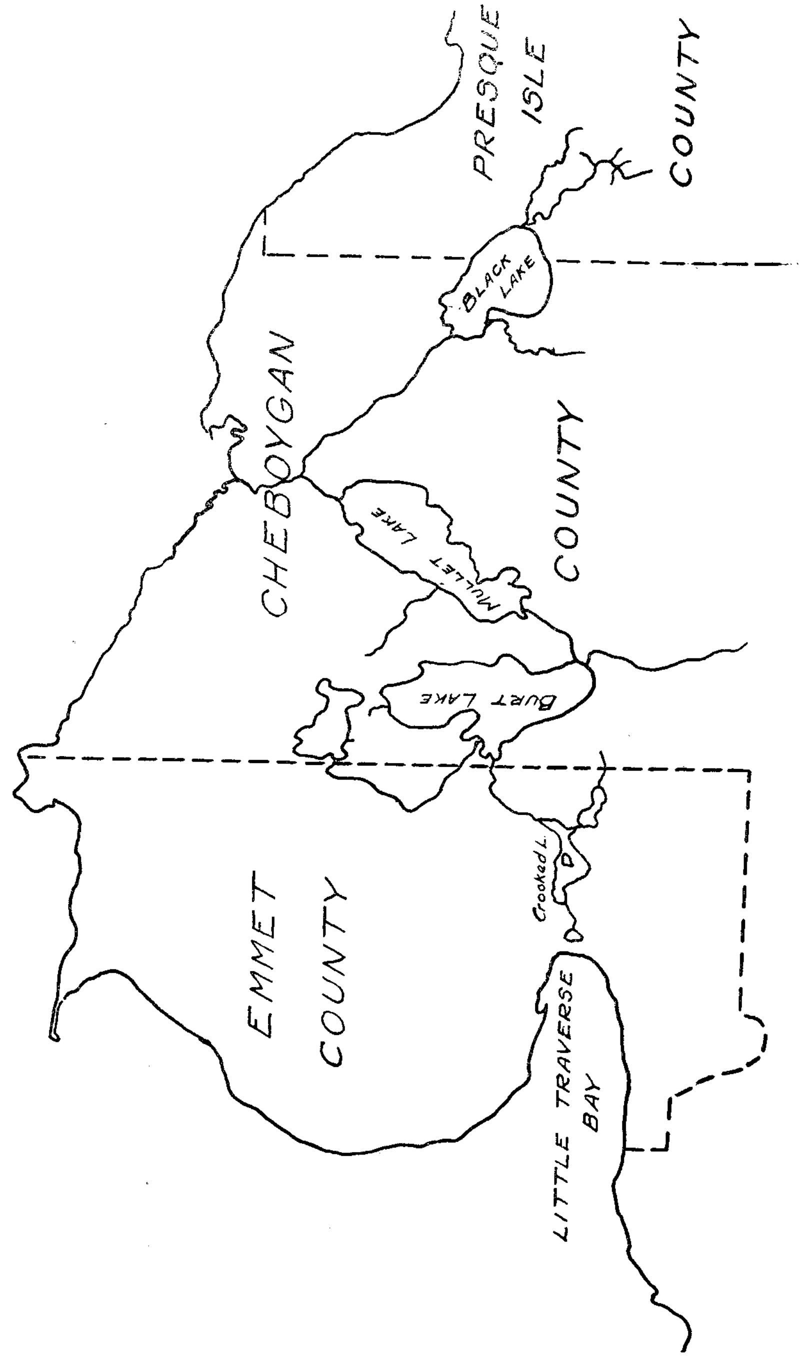


Fig. 34. Outline map showing lakes of the Cheboygan River Basin. Note: Douglass Lake, north of Burt Lake, is undesignated.

prior to the last retreat of the glacier and may have been caused by stream action previous to the advance of the ice, by the scour of the ice in its advance, or by both. During the retreat of the ice these depressions were filled with small lobes of ice which melted more slowly than the main ice sheet and prevented heavy deposition in or across them. Also this region is underlain by a pure limestone which has been dissolved to a considerable extent east of this locality forming numerous sinks, and it is probable that some of the deep holes in these lakes were formed in this manner.

All of these lakes lie in parts of this irregular depression whose slopes are strikingly marked by shore lines of former lake levels higher than the present. One of these shores stands on the average about 90 feet above Lakes Michigan and Huron and marks the borders of Lake Algonquin which in this region may best be described as a great archipelago. This archipelago covered all of the present inland lakes of this group and large areas of the adjacent lowland as well, leaving a heavy veneer of sand on the slopes now exposed. Below the Algonquin beaches at elevations varying from thirty-five to forty-five feet above Lakes Michigan and Huron, is another well defined shore line, that of Lake Nipissing. It stands below the level of Douglass and Black Lakes but is present around Burt, Mullet, and Crooked Lakes, a short distance back from the shores and at elevations varying from fifteen feet above Crooked Lake to twenty-five feet above the Cheboygan River at Cheboygan. Thus, with the sinking of the level of Lake Algonquin, Douglass and Black Lakes become isolated basins while the lower part of the depression, in which the lakes of the "Inland Route" lie, was still submerged and separated a large island to the northwest from the mainland. During Nipissing time the opening at Little Traverse Bay was partially closed by a bar the sands of which have been heaped into dunes, see Plate IV, A. These dunes rise gently on the western sides to heights of one hundred thirty to one hundred forty feet and then drop steeply on the eastern sides, showing clearly the predominance of westerly winds. Near the shore of the bay small dunes are now in process of formation and are migrating eastward. Farther inland, however, the large dunes have been clothed with vegetation which has prevented further movement. This row of dunes forms the divide which forces the water to run eastward into Lake Huron and is narrowest and lowest at Kegomic, having a width of slightly more than one-fourth mile and a height of thirty-four feet above Lake Michigan.

The recession of Lake Nipissing to the present Great Lakes level isolated a large inland lake which at first occupied all of the depression between the bar at the head of Little Traverse Bay and Cheboygan. Later it was divided by a bar at Indian River and then lowered to the present condition as the Cheboygan River deepened its channel. The variation in elevation in this part of the Cheboygan River drainage is very small, the total drop being less than twenty feet in thirty miles, and most of this occurs in the last mile of the river. The difference in elevation between Crooked and Mullet lakes is less than sixteen inches but this is in part due to a ponding of the water by a dam across the river at the mill of the Cheboygan Paper Co.

CROOKED LAKE

Crooked lake is the western member of the "Inland Route" and is readily reached by the G. R. & I. R. R. which skirts its northern shore. The name is none too appropriate if applied to its outline, which is roughly triangular and is nearly divided by Oden Island slightly east of the center. The lake is shallow for the most part but contains a good sized basin which drops to sixty-one feet in depth west of the island.

The irregular basin of Crooked Lake lies in a trough which crosses the general trend of the morainic ridges having northwest-southeasterly trend. The constriction in the outline caused by Cincinnati Point is due also to morainic material. This persists as a submerged ridge across the lake, with a maximum depth of less than twelve feet, and is flanked by deeper water. A similar ridge but better developed almost divides the lake at Oden Island. It seems probable, then, that the main depression existed before the last retreat of the glacier and may have been formed by a small lobe of ice which pushed through Little Traverse Bay. As the ice retreated, small morainic ridges were deposited across the trough and are largely submerged at the present time. The deep basin west of Oden Island was probably filled by a protected mass of ice which left this depression on melting. The whole depression was later covered by the waters of Lakes Algonquin and Nipissing, which deposited a veneer of sand over the morainic material. In fact, this sand covers the lowlands bordering the lake, and the till is exposed only where the sand has been removed along the headlands by wave action.

Three former levels are easily recognized along the shores of Crooked Lake. The Algonquin and Nipissing lakes have already been mentioned and their shores are found at levels of seventy and

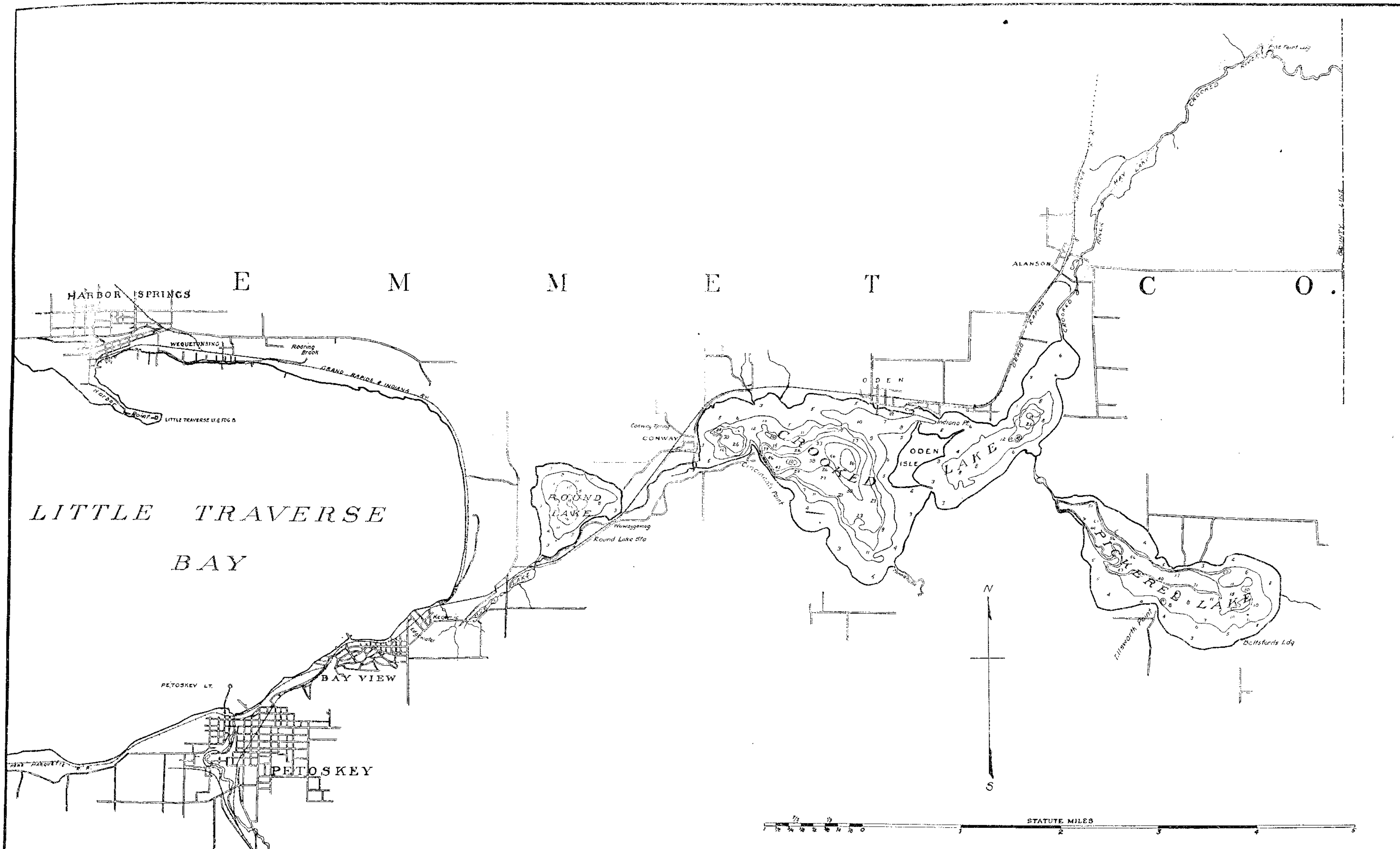
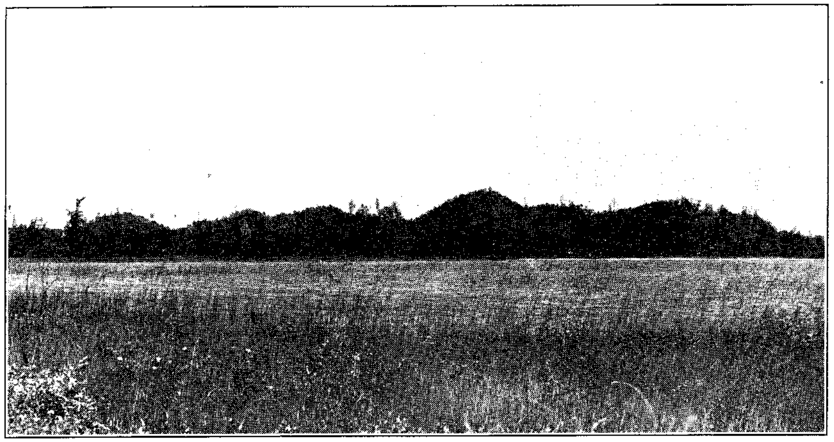
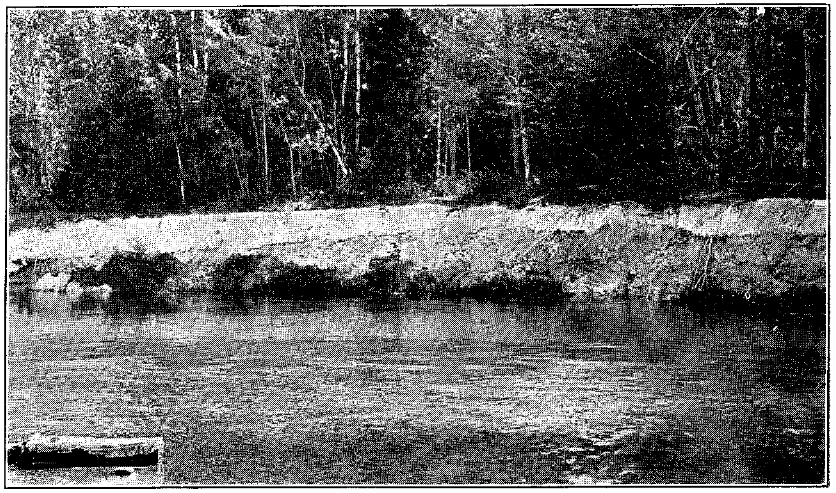


Fig. 35. Map of Crooked Lake, Emmet County, showing configuration of bottom, (after U. S. Lake Survey Chart).



A. SAND DUNES, LITTLE TRAVERSE BAY, ROUND LAKE IN FOREGROUND.



B. MARL BED, STURGEON RIVER NEAR BURT LAKE.

fourteen feet respectively above the present level. The third level occurs between four and five feet above the present and is but moderately developed, in places dropping out entirely. The faintness of the shore lines of this Post-Nipissing level may be due in part to the greatly reduced size of the lake and the consequent weakened shore action, but also to the fact that this level was maintained for a short period of time. The drop to the present level was due to the cutting down of the outlet, which runs through loose sands and therefore worked rapidly.

The shore adjustments of this lake are interesting and have taken place largely at the lower levels. Much work was done during the Post-Nipissing stage but adjustments are still taking place that will make important changes in the lake if allowed to continue. These may best be appreciated by a description of the shores in the order of a traverse.

Conway, situated at the west end of the lake, see Fig. 35, lies on a sand flat but slightly above the level of the lake. This flat is interrupted by a shallow, swampy trench through which the outlet of Round Lake reaches Crooked. The beach at this end is of sand and the lake bottom slopes gently outward, making an excellent and safe bathing beach. South of the outlet of Round Lake, the land slopes gradually upward to the Nipissing beach which follows the lake shore to Cincinnati Point. Along this shore the Nipissing terrace is well developed at an elevation of fourteen feet above the lake, averaging about one hundred yards in width, and above this an abrupt cliff fifty to fifty-five feet in height rises to the Algonquin terrace. The beach is of clear sand and even in contour except where littered with drift wood. The material of this beach is working eastward and is being deposited in a spit attached to the west side of Cincinnati Point.

The point is caused by a till knoll which stood as an island at the beginning of the Post-Nipissing stage but was connected with the mainland by a bar along the western side behind which was a lagoon. This bar now stands from eight to one hundred feet back from the beach. Inasmuch as the present wave action on the east side of the point is slight, in place of a bar a terrace is found. Along this side the ice has pushed a strong rampart where shore conditions were favorable. It is especially noticeable at the end of the point and near the mainland, but fails between these places. East of Cincinnati Point the Nipissing terrace is narrow, but of sufficient width to allow the building of a wagon road. Above this terrace a steep cliff, fifty feet high, rises to the Algonquin terrace which ends in a well defined shore line one hundred or more yards to the south. Along the present shore there is no indication of the Post-Nipissing level and the beach is of coarse material as far as the blunt swell which marks the southeastern limit of the point. Here the Nipissing terrace widens and slopes gently to the shore.

The bay beyond Cincinnati Point is caused by a long, narrow, swamp which swings back towards Round Lake. Beginning on the point and extending about one-third the distance around the bay is a continuous rampart which reaches a height of six feet in places and was formed during the Post-Nipissing stage. Near its southeastern extremity it encloses a lagoon, indicating that both currents and ice have been active in its formation. The bay terminates in a broad point which is lined with a beach of coarse material, an indication that the material is still covered with sand. Along this point the ice has pushed up a rampart which continues around the southern end of the lake as the most prominent shore feature as far as the Minnehaha River. North of the river the land is low and flat but not swampy. The rampart is present, but poorly developed along this shore. A short distance inland a faint terrace and shore of the Post-Nipissing stage can be distinguished. Shore action has been slight here, in spite of the fact that the waves which strike this shore have the longest reach on the lake and are driven by the strongest winds. The explanation is that the off-shore slope is very gentle around the entire southern end of the lake and the force of the waves is largely dissipated before they reach the shore. The adjustment is not complete, however, because currents are actively transporting the shore material northward and have built a spit more than one hundred yards in length opposite Oden Island. This spit extends outward under water and meets a long slender spit which has grown from the southeastern end of the island. The opening between the island and the mainland, which was originally more than one-fourth mile in width, is now less than two hundred feet and is so shallow that only boats of very small draught can pass. The two spits are not exactly in line at present, the direction of that attached to the island being almost due east. They will eventually swing into line, and, once this is accomplished, the tying of the island to the mainland to the south will be a matter of a few years only.

The till of the island is largely masked with sand, but an indication of its presence is found in the cobble beach along the south shore. This island was evidently a shoal during Nipissing time but was partly above water during the Post-Nipissing stage. At this time most of the area was planed off to a sand terrace with the exception of a small part near the south side. At the Post-Nipissing stage the lake ice was very active on the small island and pushed up a prominent rampart on all shores. Wave action has been especially active on the west shore and to a lesser extent on the south shore. This resulted in the transportation of the shore material around the north and south ends and its deposition in the form of spits, of which the one at the southeast corner has already been described. The counterpart of this spit occurs on the northwest corner and is actively growing at the present time. It has extended some distance beyond the original shore of the island and encloses a lagoon to the east. The outline of the tip of this spit as shown in Fig. 36, presents a sudden jog to the east. Undoubtedly this jog represents a slight elevation of the level of the lake or at least a holding up of the water to a more uniform level throughout the year than it naturally would have. The only explanation the writer can offer is that the waters are ponded to some extent and kept at a more constant level by the presence of the dam at Cheboygan, which is but five feet lower than the level of Crooked Lake. Unless the channel at this point is kept open artificially, the island will be tied to the mainland from this end as well as the south. No data could be obtained concerning the date of construction of the dam, and this is very unfortunate for, with this at hand, some estimate of the time necessary for the completion of the bar might be made, if the interpretation of the break in the outline of the spit is correct.

Fig. 36. Spit offset near distal end. Northwest end of Oden Island, Crooked Lake.

East of the island the shore is low and shows a faint beach of the Post-Nipissing level some distance back from the shore. Wave action is slight here, but currents are set up which have formed a spit about one hundred feet long on the south side of the small bay into which the outlet of Pickerel Lake enters. Beyond this bay the land rises to the Nipissing terrace which is rather wide and slopes gently toward the lake. The beach is of sand which is being carried northward and deposited in a well developed hook at the somewhat prominent projection. Along this hook the trees line the shore in places, and the roots are gradually being swept free from sand, which is added evidence of an abnormally high level for the lake. Back of the hook just mentioned stands a lagoon which connects with the north end of the lake and is in process of filling by vegetation.

Crooked River, which discharges the water of this lake into Burt, is a very sluggish stream, having a drop of slightly more than six inches in over four miles. The valley runs between the edges of the Nipissing terrace and gradually narrows until at Alanson it just allows the passage of the stream. This is the only place on the river where a road-crossing has been made. Below Alanson the depression widens somewhat and the river expands into Hay Lake, now so filled with vegetation that it has been necessary to dredge a channel. Leaving Hay Lake the stream takes a straight course through a low sand flat, but suddenly begins to meander at the Devil's Elbow. This seems to be the highest place in the depression between Crooked and Burt lakes, and the banks correspond closely in elevation with the Post-Nipissing level as found on Crooked Lake. It is evident from this that the drop to the present level is due to the cutting of the outlet through these sands. The stream with its present current could hardly have cut this channel, but at the higher level the gradient was somewhat steeper and there were no artificial obstructions in the drainage system.

Returning to the lake, the north shore presents little of interest until Ponshewaing is reached. Here the Post-Nipissing terrace is well shown, and upon this an ice rampart is found somewhat west of the point. Currents from the west have been active along this shore, but the resulting forms are obscured by docks and "made ground." However, at Oden a well developed spit was formed at the Post-Nipissing level, running to the east and partially enclosing a narrow lagoon which has been dredged and is now used as a harbor for small boats. The town of Oden is built on the Nipissing terrace, the front slope of which has been cut into low cliffs by the waves of the present lake. Farther to the west, this terrace is relatively narrow and the Algonquin terrace above is the more prominent. As the west end of the lake is approached, both terraces leave the lake and continue to the north side of Little Traverse Bay. Along this shore the terrace of the Post-Nipissing stage stretches from the foot of the Nipissing terrace to the beach and is wet and swampy.

From the description above it should be clear that Crooked Lake as an isolated basin has stood at a level some four feet higher than at present. Considerable adjustment of the shores has taken place at the higher level and is still going on. A notable change that may be expected is the tying of the island to the mainland both at the southeast and northwest ends. This will probably be accomplished first at the southeast and later will have to be prevented artificially at the northwest end of the island if the lake continues to be navigable to its western end. The "drop off" is well defined on shores exposed to the storm winds, such as the west side of the island, the large embayment on the south shore, and the north shore near Oden. The depth at the "drop off" is approximately four feet, and in most places it is evident that the slope of the submerged terrace is very flat. This depth seems very small for a lake of this size, and it is probable that this terrace is largely the result of wave and current action during the Post-Pipissing stage, at which time the depth over the terrace was double that at present. This flat off-shore slope must greatly reduce the force of the waves, but complete adjustment has not been accomplished as yet. In the future, more is to be expected from deposition than from cutting, although the slight flooding of the lake has increased the latter. Ice action has been of some importance, and in several cases excellent ramparts have been formed. Yet, as a rule, the material and topography of the shores are not favorable for their development.

As to the extinction of this lake, it is certain that it cannot be drained unless the level of Lake Huron is materially lowered. It stands 14.6 feet higher than Lake Huron and there are three "holes" which have greater depths than this. Tributary streams are few and deposit little sediment, so this method of extinction may be considered of slight importance. Filling by vegetation is of much greater importance. In many places marl is being deposited, and beds of seventeen feet in thickness have been reported in the outlet south of Alanson. In addition, heavy stands of reed grow each season on parts of the submerged terrace, particularly in the east arm and along the south shore where some protection from the waves is afforded, and aid the process of filling.

BURT LAKE

The second member in this group of lakes is Burt Lake, which with an area of 26.5 square miles is one of the largest inland lakes of the State. This lake is oblong in shape and extends north-south. Its length is slightly less than ten miles and its width reaches about five miles, although the average is probably nearer three. See map, Fig. 37. It is easily reached by the Michigan Central R. R. which crosses the outlet at the town of Indian River, situated on the outlet one-half mile from the lake.

As far as known, no hard rock outcrops on the shores of this lake, the surrounding land being composed entirely of glacial deposits. In general, it is flanked with moraines which run slightly oblique to the length of the lake. One of these moraines, which causes Colonial Point on the west side, ends abruptly at the point, and irregular deposition of the morainic deposits on the east side has given rise to Greenman point near the head of the lake. The north end of the lake heads in a swamp beyond which is the outwash plain extending to the east end of Douglass Lake. On the west side, Crooked River enters the lake through a low sand plain and Indian River drains the lake through a similar depression at the south end. The basin is consistently regular, usually reaching depths of forty to forty-five feet, but is somewhat deeper towards the south end. Two exceptions to the evenness of the bottom are present: A small pit east of Colonial Point which drops to more than seventy feet in depth, and a shallow depression near the south end fifteen to twenty feet below the general level. This basin seems to lie in a depression between morainic ridges which on the west side especially are irregular in distribution and continuity, and were deposited by the ice from the Lake Huron basin. The ice in this locality did little abrading, and this basin probably existed before the last retreat of the ice. The complication of the morainic system makes it seem plausible that Burt Lake was filled with ice after the general ice front had retreated, and around parts of its borders outwash was deposited which now lies well above the lake level, e. g., the outwash at the north end. The "holes" in the bottom of the basin may be due to exceptional thickness of the ice or may possibly be sink holes.

Burt Lake, on account of its size, the excellent development of the Nipissing terrace and cliff, freedom from swampy shores, and

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