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PART I

THE POST-GLACIAL GEOLOGY *of the* GRAND MARAIS EMBAYMENT, BERRIEN COUNTY, MICHIGAN

by
GLENN CHARLES TAGUE

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the University of Michigan.

April, 1942

CONTENTS

Introduction 3
- Nature and purpose of the study 3
- Location and extent of the area 4
- Methods 4
- Acknowledgments 5

Regional Glacial Geology 5
- Previous investigations 5
- Glacial geology of Western Berrien County 6
- Résumé of the lake history in the Lake Michigan basin 7

General Principles involved in the Formation of Coastal Dunes 11
- General discussion 11
- Forms and development of coastal dunes 12
- Methods of determining age of coastal dunes 15

Shore Lines of the Grand Marais Embayment 17
- General discussion 17
- Glenwood stage 19
- Calumet stage 21
- Algonquin stage 22
- Nipissing stage 25
- Algoma stage 27
- Present stage 28

Conclusions 32

References Cited 33

ILLUSTRATIONS

[Plates]

I. Aerial photograph of the northern part of the Grand Marais Embayment 3

IV. A. Gentle windward slope of foredune ridge west of Mt. Edward. 12

B. Early stage of foredune formation between Mt. Edward and First Church Camp. 12

V. A. Looking north along the foredune ridge west of Bald Top showing the depression behind the foredune and a wave cute bluff on the north arm of Bald Top. 13

B. Looking north at Grand Mere Beach showing low, grass covered, foredune ridge and beach cusps on the Lake Michigan shore. 13

VI. A. Panoramic view looking north from Blueberry Hill showing Wilkins Dune (W), Johnson Dune (J), Bald Top (B), South Lake (S), Covert Ridge (C), Lake Michigan (L), and an Algonquin dune passing beneath Wilkins Dune (A). 14

B. Looking from Bald Top showing apex of Johnson Dune (J), Covert Ridge (C), and apex of Wilkins Dune (W). 14

VII. A. Looking south from apex of Mt. Edward showing saddle of First Church Camp Dune in foreground and Great Warren Dune in background. 14

B. Looking east from foredune up blow of First Church Camp Dune showing three transverse ridges. 14

VIII. A. Looking southeast from Bald Top showing lee slope and apex of Johnson Dune, Covert Ridge in background and Algonquin level (road) left foreground. 14

B. Algonquin level along north base of Johnson Dune. Bald Top in background. 14

IX. A. Looking northeast up first modern blow south of the First Church Camp. 14

B. Foreset beds of a dune exposed by eolian erosion in first modern blow south of the First Church Camp. 15

X. A. Foredune ridge cut by waves at First Church Camp. Note roots of grass exposed along the cut bluff. 15

B. Tennis court at First Church Camp located on foredune ridge and covered by sand. 15

XI. A. Present blowing on north arm of Johnson Dune. Note two soil zones indicating three episodes of blowing. 15

B. Looking north at present blowing of north arm of Johnson Dune (J), and south arm of Bald Top (B). 15

XII. A. Looking north from Bald Top showing Dunham Dune (D) in the right background, and Covert Ridge headland (C) in the left background. 18

B. Looking southwest from Dunham Dune showing foredune ridge, and area of present blowing. 18

XIII. A. Cross section of the Algoma level looking south from a position west of Grande Vista. Note the more gentle lakeward slope. 19

B. View of Algoma level looking east from a position west of Grande Vista. 19

XIV. A. Looking east from second Algonquin bar (2) southwest of Grande Vista showing first Algonquin bar (1), Algonquin bluff (A), Calumet bar (C), and Covert Ridge (C). 21

B. Close view of Algonquin bluff southwest of Grande Vista. 21

XV. A. Looking south along the Calumet terrace north of the Riding Stable showing scattered boulders and narrowing of the terrace where it has been cut away by the Algonquin stage. 21

B. View of the Calumet terrace and the Algonquin bluff west of the Riding Stable. Man is standing on boulder lined Algonquin strand which resulted from ice push. 22

XVI. A. Calumet terrace south of the Riding Stable. 22

B. Calumet terrace north of the Riding Stable showing scattered boulders resulting from wave cutting of Covert Ridge. 22

XVII. Looking southwest from top of Covert Ridge at Stevensville road showing Blueberry Hill (H), Wilkins Dune (W), Johnson Dune (J), Bald Top (B), Dunham Dune (D), Middle Lake (M), and Nipissing beach (N). 24

XVIII. A. View of the apex and a portion of the arms of Johnson Dune as seen from the north arm of Wilkins Dune. 26

B. Looking east up the trough between the arms of Wilkins Dune. 26

XIX. Looking north across the mouth of the blows just north of the Great Warren Dune State Park entrance showing the lee slope and crest of well developed foredune ridge (F), and several longitudinal ridges (L) extending landward. 27

XX. A. Longitudinal ridge passing from foredune ridge upward into the first present blow north of the Warren Dune State Park Beach. 27

B. View south along the lee slope of the foredune ridge lakeward of the blow-out in Fig. 1 showing attachment of longitudinal ridge. 27

XXI. A. Blow-out between Bald Top and Johnson Dune as viewed from the Lake Michigan shore showing foredune ridge in the foreground. 29

B. View of the blow-out shown in A from its windward end. Note exhumed soil in foreground. 29

XXII. A. Southeast view from foredune showing longitudinal ridges in the middle blow of the Great Warren Dune. 30

B. Post-Nipissing beach (Algoma ?) exhumed near the north attachment of Great Warren Dune. 30

XXIII. A. Longitudinal furrow and ridge in Mt. Edward blow. 30

B. Lee slope of longitudinal ridge in Mt. Edward blow. 30

XXIV. A. Looking from foredune up north blow of Great Warren Dune. 31

B. View to the right and in panorama with Fig. 1 showing longitudinal ridge. 31

XXV. A. Looking east from the first transverse ridge in the first modern blow south of First Church Camp showing two transverse waves of sand in the background. 31

B. Looking west from the same position as in Fig. 1 showing foredune and area of wind erosion. 31

XXVI. A. General view looking northeast in the present blow north of the State Park showing transverse and longitudinal ridges. 31

B. Looking east through the saddle of modern dune north of Mt. Randall. 31

XXVII. A. Exhumed stumps with roots imbedded in soil of Nipissing dune on the blow of Great Warren Dune. 32

B. Close view of exhumed stump in A. 32

[Figures]

1. Geography of the Grand Marais Embayment 4

2. Map showing the surface geology of Southwestern Michigan 5

3. Diagrammatic cross sections between Covert Ridge and Lake Michigan in the Grand Marais Embayment 7

4. Map showing the location of the hinge line in Michigan 9

5. Lake Michigan bottle paper courses 1892, 1893, and 1894, special drifts and resultant currents 18

6. Plan diagram of the first Algonquin spits formed in the northern part of the embayment. 23

FOREWORD

To the Commissioners and Director of the Department of Conservation

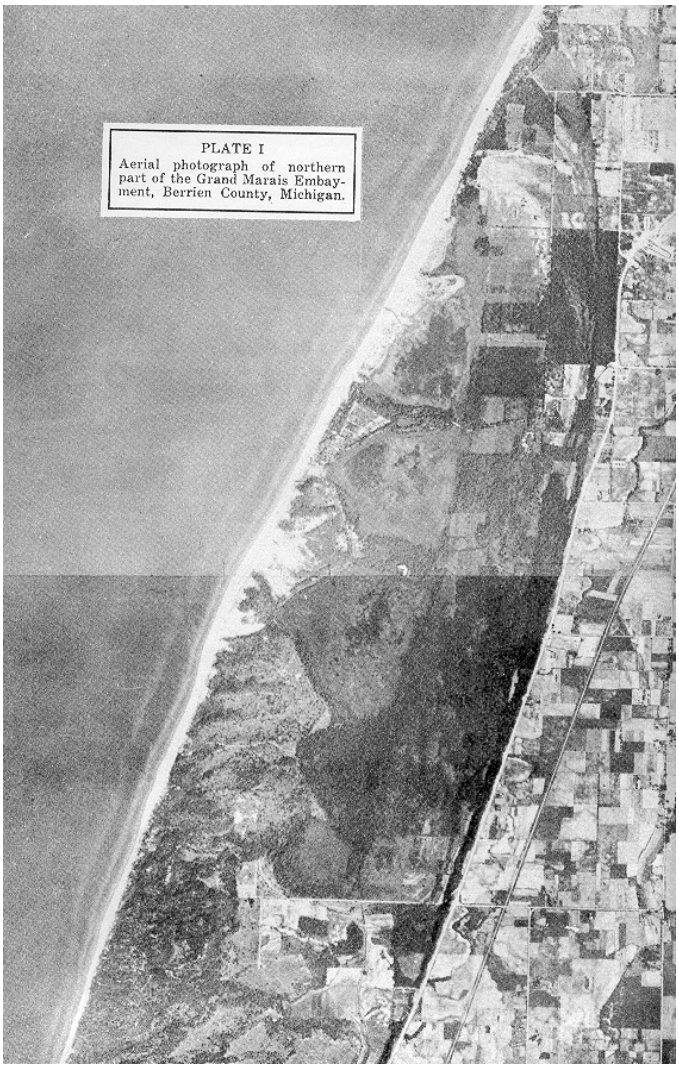
Gentlemen:

In compliance with Act No. 65 of 1869 as amended by Act No. 179 of 1871 of the Public Acts of Michigan under which the Geological Survey Division of the Department of Conservation operates, I have the honor to present herewith two reports on the geology of Michigan prepared under the direction of my predecessor, Dr. R. A. Smith, by Dr. Glenn C. Tague of Western Reserve University, and Dr. James L. Calver, Florida Geological Survey, and recommend that they be published as Publication 45, Geological Series 38 of the Geological Survey Division, Department of Conservation, as a part of the annual report for 1946.

Both reports are studies of dunes and old lake shore lines in type areas along the Lake Michigan shore. Dr. Tague's report deals with an area in Berrien County including the Warren dunes which is south of the so-called hinge line and, therefore, not deformed by continental uplift. It is also an area in which the early ancestral lakes of the Lake Michigan Basin were confined to the southern part of the basin. Dr. Calver's report deals with the dunes and old shore line area of Benzie County which is north of the hinge line in the region of continental uptilt and, therefore, is also a study of beach deformation in the region of Crystal Lake. In this area the ancestral lakes of the Lake Michigan Basin were greatly expanded and united with the expanded lakes in the Superior and Huron basins. Both reports discuss the origin of dunes and of ancient and modern shore features in the type areas and are further contributions to the studies of Great Lakes dunes, (A report on the Grand Sable dunes of the Northern Peninsula was published in Pub. 40, Geol. Series 34, 1936).

Both reports are profusely illustrated by maps and photographs and should be of interest and value not only to the student of glacial geology, soils, dune ecology and control, but also to the tourists. They are outstanding studies of, and contributions to the literature of sand dunes, and significant contributions to studies of former Great Lakes and the surface formations of Michigan.

Respectfully submitted,
[signed] Gerald E. Eddy
State Geologist



[I. Aerial photograph of the northern part of the Grand Marais Embayment]

INTRODUCTION

Nature and Purpose of the Study

Dunes on the east coast of Lake Michigan are among the best examples of this type of shore feature to be found anywhere. These coastal forms are but little understood in this country although voluminous works have been published by European authors concerning the coastal dunes in the Low Countries, the Baltic Sea area, and in Southwestern France. Scientific information relative to the dunes in this country, primarily in Michigan, has been published by Bergquist, Calver, Cowles, Cressey, Dow, Scott, Smith, Stevenson, and others.

The study of the area selected is closely related to the larger problem of post-glacial lake history. It is through detailed investigations of such isolated embayments of these ancestral lakes that a more thorough picture of their extent and duration may be obtained. Furthermore, it is only through such a careful study that one is able to

add to the information on post-glacial lake history as it has been worked out by Leverett, Taylor, Baker, Goldthwait, Bretz and others.

A discussion of the post-glacial[1] history of the Lake Michigan basin involves a study of the coastal dunes which are regarded primarily as shore features. Throughout much of the area selected for study the beach ridges of all except the oldest lake stages are covered in part at least by dunes of younger succeeding stages. Therefore, the significance and importance of the study of dunes, and in particular a determination of their ages, is an important adjunct in the study of lake history.

A detailed study of the dunes and of the beaches in this area was begun several years ago by I. D. Scott. Considerable difficulty was encountered in the field at that time due to high water which flooded a portion of the lower part of the embayment at its northern end. As a result of the high water only work of a reconnaissance nature could be carried out. The observations and conclusions presented in this paper result from a continuation of the study under the direction of the original investigator.

[1]"Post-glacial" used in this paper refers to the time from the first evacuation of the ice from the area up to the present.

Location and extent of the Area

The Grand Marais Embayment, (figs. 1 and 2) an area 16 miles long with an average width of one mile, lies parallel to the east coast of Lake Michigan in western Berrien County, Michigan. The northern end of the embayment terminates in a point one mile west of Glen Lord (5 miles south of St. Joseph), and the southern end extends south to the vicinity of Lakeside. The eastern side of this long, narrow embayment is roughly paralleled by United States Highway 12 and the Pere Marquette Railroad. The northern part of the embayment is mapped in the southern coastal area of the Benton Harbor Quadrangle, Michigan, and the southern and larger portion is mapped in the northern coastal area of the Three Oaks Quadrangle, Michigan-Indiana.

Methods

Field. Studies were made during the field seasons of 1940 and 1941. The early part of the 1940 season was spent in a reconnaissance survey of the west coast of Lake Michigan from a point just north of Chicago, Illinois, to Green Bay, Wisconsin, and in the Grand Marais Embayment. Hand levels were run in several localities along the west coast where low level beaches and terraces were found. These were believed to have a significant bearing on the younger lake stages represented in the Grand Marais Embayment.

The later part of the 1940 and the entire 1941 field seasons were spent in plane table mapping of the northern and most critical part of the embayment. In conjunction with the plane table mapping a detailed study of beaches and dunes was made. Great care was taken in checking elevations at known points, and inasmuch as the level of the water in Lake Michigan was frequently used as a datum, the margin of error should fall within one foot. The correct elevation of Lake Michigan was obtained from the United States Coast Guard station at St. Joseph.

The contour topographic map (plate I) was made on a scale of eight inches to one mile. A contour interval of five feet was used where the elevation was less than 600 feet above sea level in order that the low beach ridges might be more clearly defined. Above 600 feet the contour interval is 10 feet. The larger interval was found adequate to bring out the details of the higher beaches, wave cut bluffs, and forms of the dunes. The elevations of exposed beaches were determined by plane table or hand level in the area south of the area included in the contour map.

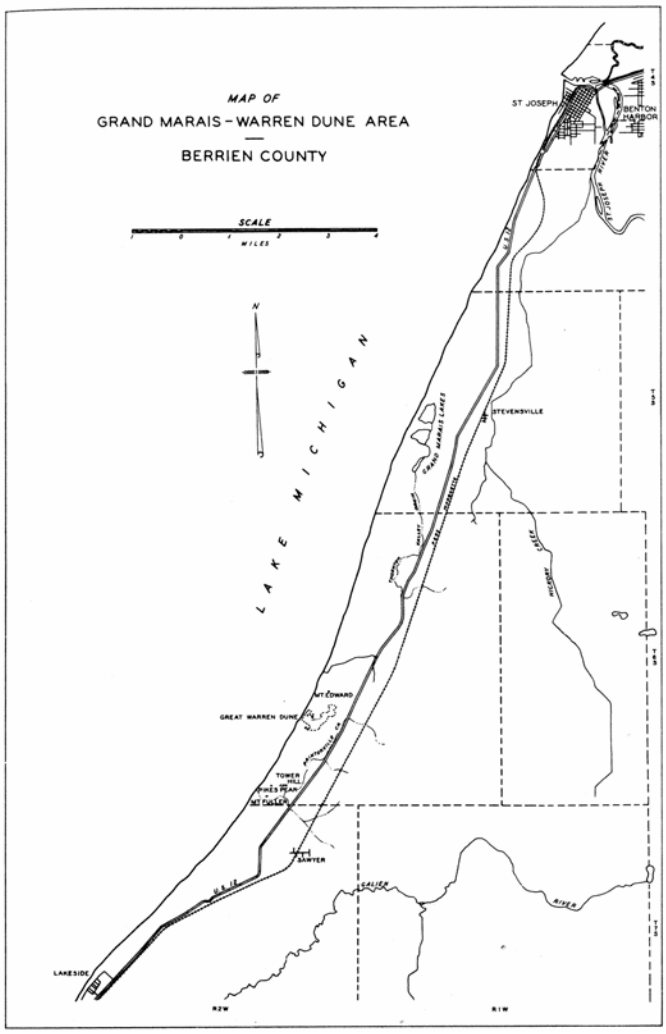


Figure 1

Beach ridges were traced on foot in order to establish their correlation and extent. Ridges of the dunes were likewise traced as an aid in determining their age and form. In addition, many four foot soil profiles were

studied as another criterion in fixing the ages of the dunes.

Office. The United States Geological Survey topographic maps of the area were used for office study in working out the broader aspects of the problem. These maps, however, proved inadequate for more careful work because, (a) they were constructed with a 20 foot contour interval which failed to show minor features, (b) they were drawn with little consideration of the true form of the dunes, and (c) they were reproduced on a scale of one inch to one mile and required magnification for detailed study.

The sections of the plane table map as drawn in the field were enlarged by photostatic methods from a scale of eight inches to one mile, to a scale of approximately 16 inches to one mile. The final drawing of the map was traced from an assembly of these enlargements and then reduced photostaticly.

Stereoscopic use of aerial photographs (plate II) was found to be invaluable to the investigator throughout the entire study. Contact prints were consulted from day to day as the plane table work progressed and this aided materially in establishing the forms of the dunes with reasonable accuracy. Overlapping contact prints were carried in the field and examined frequently by means of stereoscopic vision. This use of aerial photographs was an extremely important aid to the author in determining location, orientation, and form of both dunes and beaches.

A stereosketch map (plate III) of the southern eight miles of the Grand Marais Embayment was constructed by using 20 x 26 inch enlargements made from 8 x 10 inch negatives of vertical aerial photographs. By viewing pairs of these enlargements under an especially constructed mirror stereoscope, it was possible to draw with considerable accuracy the bases and crests of the dunes directly on the photographs. These lines were then traced and details of side lines and shading were drawn. Frequent reference to the enlargements under the stereoscope aided in working out the details. Shading was applied to the map with the light coming from the southwest. This was a departure from the conventional method of shading sketches, but it was thought to be more suited to the orientation and shape of both the embayment and the individual dunes. The orientation, shape, position, and relative heights, of the larger forms of the dunes are well shown on this sketch map. It was difficult, however, to observe the lowest forms with stereoscopic clarity where the forest vegetation was thick.

Acknowledgments

The writer will always be indebted to Professor Irving D. Scott, University of Michigan, for the many years of patient, understanding help that to a large degree made this study possible. His experience and knowledge of the subject, as well as his time and energy for checking field results were always available. The writer's information regarding the classification and development of coastal dunes was derived largely from study under Professor Scott. The untiring assistance in the field of Elizabeth Waldorf Tague was both an inspiration and material aid to the writer. Without her devoted help the contour map could not have been completed. To Professor Ralph L. Belknap, University of Michigan, many thanks are due for his assistance in checking field observations and, through the work of his students in field geology, in establishing control for plane table mapping. Professor Armand J. Eardley, University of Michigan, has been extremely helpful and generous with his time in the development of the technique for stereosketching. The writer is grateful to Professor George M. Stanley, University of Michigan, for his many kindly and helpful suggestions. Special thanks are due the Geological Survey Division of the Michigan Department of Conservation, under the direction of Dr. R. A. Smith, for cooperation in making available aerial photographs and for financing a portion of the field work. Thanks are likewise due Dr. James L. Calver who spent some time in the field with the writer and offered many helpful suggestions, and to Professor O. F. Evans, University of Oklahoma, who displayed a keen interest in the study and checked some of the observations with the writer in the field.

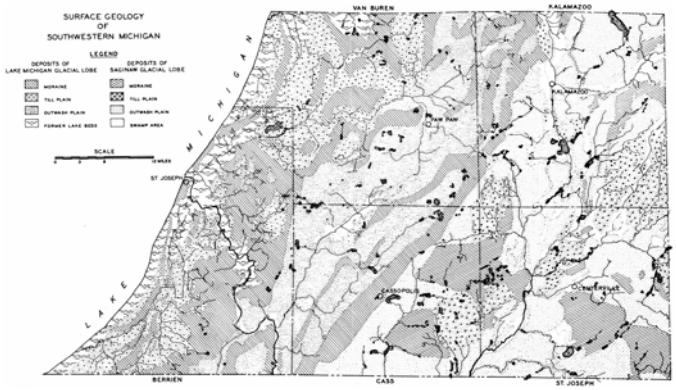


Figure 2

REGIONAL GLACIAL GEOLOGY

Previous Investigations

The glacial geology of the lower Lake Michigan basin which includes parts of Michigan, Indiana, Illinois, and Wisconsin has been studied by many investigators. The results of their studies have been recorded in publications dating from 1838. Much of this work was done by Leverett (1899, p. 339-453) who described the glacial deposits of the Lake Michigan lobe from northern Illinois, around the southern end of the Lake Michigan basin and northward into the State of Michigan. He also described the Chicago Outlet and the history of ancient Lake Chicago and commented on the shore development and currents of the modern lake. Later work by Leverett and Taylor (1915, p. 316-333, 350-357) gave more detailed information on the history of Lake

Chicago and the other ancestral lakes of the Great Lakes basins. The works of Leverett and Taylor are most frequently referred to in this paper.

Goldthwait (1907, pp. 9-42) reviewed the works of the early writers on the beaches of the ancient Great Lakes from 1838 to 1907. Among the earliest investigators cited by Goldthwait are Whittlesey, Desor, Banister, Andrews, Chamberlin, Gilbert, Leverett, Spencer, Taylor, Lane, Gordon, Russell and others. Goldthwait (1907, p. 41-98) also described the abandoned beaches in Wisconsin on the western shore of Lake Michigan and correlated them with the beaches studied by Leverett farther to the south in Illinois and Indiana. Alden (1918, p. 135-136, 326-338) in a later publication reviewed the history of glacial Lake Chicago and the post-glacial lakes of the Lake Michigan basin. Cressey (1928, p. 51-73) discussed the relationship of the shore dunes and lake beaches in Indiana at the head of the Lake Michigan basin. Stevenson (1931, p. 475-485) related the history of the dunes and beaches of the Manistique area along the north shore of Lake Michigan from Seul Choix Point westward into the City of Manistique. Scott and Dow (1936, p. 437-450) worked out the relationship of the dunes and beaches in the Herring Lake Embayment in the western part of Benzie County on the eastern shore of Lake Michigan. Bergquist (1936, p. 88-130) described dunes and beaches of the Tahquamenon and Manistique drainage region in the Northern Peninsula of Michigan. Stanley (1937, p. 1667-1686) (1938, p. 477-495) in two papers, discussed the Algonquin beaches of the Georgian Bay area and in a third paper (1938, p. 966-974) discussed the submerged valley through the Mackinac Straits. Bretz (1939, p. 99-116) outlined the glacial geology and shore features in Chicago and vicinity. The manuscript of the more recent study by Calver (part II of this publication) on the dunes and beaches of the Crystal Lake Embayment in western Benzie County was available to the writer for reference purposes.

Glacial Geology of Western Berrien County

Berrien County is located in the southwestern corner of the State of Michigan north of the Michigan-Indiana line. The western edge of the county is the shore of Lake Michigan, which here has a general northeast-southwest trend. On the east Berrien is bounded by Cass County and on the north and northeast by Van Buren County.

The surface of the western part of Berrien County was formed almost wholly by deposits laid down by the ice of the Lake Michigan lobe of the late Wisconsin glacier and by shore features and lake plains formed in and by waters impounded between the moraines to the east and the edge of the ice as the lobe retreated northward. The work of post-glacial streams has but slightly modified the glacial features.

Leverett (1899, p. 339-412) described two morainic systems, the Valparaiso and the Lake Border, (fig. 2) which extend from the Indiana border in a northeasterly direction through Berrien County. These morainic belts are nearly parallel to the Lake Michigan shore, and were deposited by the ice of the Lake Michigan lobe.

The Valparaiso system, farthest to the southeast, was built of deposits laid down while the ice front stood along its axis and the region to the west was ice covered. The Valparaiso moraine extends over 100 miles northward on both sides of Lake Michigan forming a giant U in the south at the head of the lake basin. Leverett (1899, p. 339) states, "The parallellism of the morainic system to the shore of Lake Michigan is one of its most striking features."

The Lake Border morainic system is between the Valparaiso system and the Lake Michigan shore and is roughly parallel to both. In Berrien County it consists of two parallel ridges extending from the Michigan-Indiana boundary to the vicinity of Benton Harbor, (fig. 2). The oldest ridge was called by Leverett, (1899, p. 389), "The outer ridge." This ridge can be traced from the west side of Lake Michigan southward around the head of the lake and northward along the east coast to the vicinity of Benton Harbor where it joins with the Valparaiso system and loses its identity. The younger ridge lying between the outer ridge and the shore of Lake Michigan has been called Covert Ridge (Leverett, 1899, p. 388) after the village of Covert in Van Buren County which is situated upon it. Covert Ridge joins with the Valparaiso morainic system to the north in northern Allegan County. This ridge has been traced southward by Leverett (1899, p. 389) from the point of its union with the Valparaiso system to a place about four miles east of Michigan City, Indiana, a distance of 80 miles down the eastern side of the lake basin. A third and still younger moraine north of Berrien County has been called Zeeland Ridge by Leverett (1899, p. 390).

In Berrien County (Leverett, 1899, p. 405) the Valparaiso morainic system is separated from the outer ridge of the Lake Border morainic system by a till plain (fig. 2) two to four miles in width. This plain has an elevation of 60 to 90 feet above Lake Michigan and slopes gently towards the lake. The outer ridge and Covert Ridge are likewise separated here by a gently sloping, narrow till plain, one to three miles in width, (fig. 2) which has an elevation between 50 and 75 feet above Lake Michigan.

The Valparaiso morainic system and the outer and Zeeland ridges of the Lake Border system are located well outside the area of the Grand Marais Embayment and consequently will not be discussed further. Covert Ridge, however, forms the eastern margin of the embayment and it was the main factor in establishing the limits and shape of the embayment.

Leverett, (1899, p. 406) states that, "Covert Ridge follows the shore of Lake Michigan so closely that a plain is present on its inner border along only a small part of its course from the state line northward to the Kalamazoo River. Where present it shows a descent of 20 or 30 feet per mile towards the lake. In places where the ridge is distant two or three miles and its inner border

stands 60-70 feet above the lake, the till surface drops down nearly to the lake level at the lake shore. Sand deposits have considerable depth on the lower parts of this plain and bring the surface up to a height of 35-40 feet or more above the lake." Covert Ridge can be traced southward from the mouth of the St. Joseph River along the lake shore to a point west of Glen Lord where it swings eastward away from the lake and passes along the western edge of the village of Stevensville, (fig. 2). Five miles farther south its crest is a short distance east of the village of Bridgman and farther south it lies east of the village of Sawyer. South of Sawyer the ridge returns southwestward to the lake shore at Lakeside and Union Pier where it has been deeply cut by wave action of Lake Michigan. From St. Joseph to Glen Lord it presents a steep bluff of till along the lake front; but farther south to Lakeside the easterly bend of the ridge forms the eastern side of the Grand Marais Embayment, and there only the three highest water stages of the Lake Michigan basin have made contact with it.

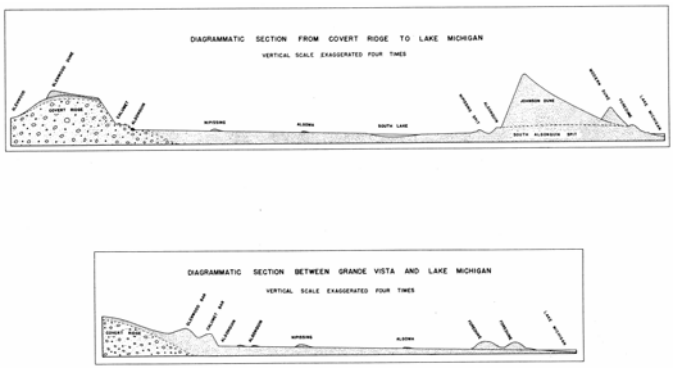


Figure 3

Where Covert Ridge forms the eastern boundary of the Grand Marais Embayment its surface is strikingly smooth and of slight relief. From the lake shore west of Glen Lord to a position just north of Livingston, the ridge has an elevation of approximately 120 feet above Lake Michigan. From Livingston southward, however, it is 60 to 75 feet above the lake, scarcely above the level of the highest of the lake stages. South of Livingston the ridge has a broad, even surface with gentle slopes to both east and west. North of Livingston the ridge becomes considerably sharper with the relatively steep slopes particularly on its eastern side. From Wildwood northward to Grande Vista, the western sloped of Covert Ridge is a bluff developed by the waves of the three highest lake stages.

Leverett (1899, p. 393-394) describes the material in Covert Ridge as: "The body of the ridge seems to be composed of blue till having a large clayey constitutent, and on the whole more compact than the blue till found in the Valparaiso morainic system. The till is also less stoney as a rule than typical till. This till is occasionally replaced by sand and gravel, and generally contains pockets and thin beds of sand and gravel of sufficient extent and convenient depth to supply the shallow wells. There are places where a nearly pebbleless laminated clay replaces the till. Boulders are found in moderate numbers along each of the ridges. They consist largely of granite, though there are many other classes of rocks present."

In the area of the Grand Marais Embayment Covert Ridge is covered by a veneer of sand blown into small dunes in places. Home owners along the ridge report that the sand cover ranges in thickness from 5 to 10 or more feet, (fig. 3). This observation is borne out by Leverett (1899, p. 393) who states that, "At many points on each of these ridges (Covert and outer) there is a thin coating of sand. It is usually drifted into low knobs and ridges, and was apparently deposited in large part by the wind."

Shore features of five and possibly six lake stages (including the present stage) of the Lake Michigan basin are in the area of Grand Marais Embayment. These forms were developed after the embayment became freed of the late Wisconsin ice and are described in another part of this paper.

Resume of the Lake History in the Michigan Basin

The post-glacial lakes, the ancestral lakes of the Lake Michigan basin, had a relatively simple history as compared with the histories of the lakes of the other Great Lakes basins. However, this history, is far from simple. The even trend of lake changes from the first lake to modern Lake Michigan was complicated by fluctuations of the ice border in the general retreat, by uncovering or closing of some of the outlets, and by the down-cutting of others. The rhythmic character of these changes resulted in a surprising number of alternating low and high water stages, but with a continuing lowering of the lake level. The high levels are of greatest importance in this study because of the exceptional shore features which were developed during high lake stages.

The highest and oldest lakes, Leverett (1899, p. 427) named collectively, Lake Chicago. The waters of these lakes drained south-westward through the Chicago Outlet, by way of the Sag and Des Plaines river to the Illinois River and thence to the Mississippi. This early lake, or more correctly, series of lakes is commonly considered as a glacial lake because the ice of the Lake Michigan lobe was in the northern part of the basin and effectively blocked a somewhat lower eastward outlet through the Straits of Mackinac. Later as the ice retreated to the northeast the lower channel of the straits of Mackinac was uncovered, and the waters of the Michigan, Superior, and Huron basins merged to form the greatest of all the ancestral Great Lakes, Lake Algonquin.

Shortly after the formation of Lake Algonquin, the waters abandoned the Chicago Outlet and began draining wholly to the east. This they continued to do during the succeeding lake stages known as the Nipissing and the Post-Nipissing stages.

When the Lake Michigan glacial lobe first retreated or melted away from the Valparaiso moraine, the melt waters from the ice were ponded in a small crescent-shaped lake between the ice front and the inner flank of the moraine at the extreme head of the Lake Michigan basin. The ice margin continued to retreat northward until two-thirds or three-quarters (Taylor, 1915, p. 326) of the basin was uncovered. Taylor (1915, p. 326) states that, "In all probability the retreating ice front performed here the same series of oscilliations, with strong marked steps of retreat and readvance, that took place in the Huron-Erie basin. The evidence of these oscillations, however, are not generally so well marked, because critical changes were not produced by them; but some of the stronger moraines mark readvances that override beach ridges which had been made just previously."

GLENWOOD STAGE. Of the intitial lake in the Lake Michigan basin Cressy (1928, p. 53) states, “The first appearance of the lake was at the inner margin of the Valparaiso Moraine. . . . The water then dropped to 60 feet above the present mean lake level (578), and shortly after to 55 feet, forming the Glenwood stage." The writer is unable to find further reference to this highest and intitial pre-Glenwood level and no figure is given by Cressy for its height above Lake Michigan. The first stage of Lake Chicago has been given the name Glenwood, (Leverett, 1899, p. 428) after a village located on its beach a short distance south of Chicago in Illinois.

The highest beach of the Glenwood stage stands 55 to 60 feet above the present level of Lake Michigan in the area of horizontality. The beach can be traced from the vicinity of Sheboygan, Wisconsin, where it is partially cut away by the modern lake, southward around the head of the Lake Michigan basin and northward through Michigan to a position north of Ludington where it terminates under a gravel plain and moraine, (Leverett, 1915, p. 350).

The level of the impounded water that formed the Glenwood stage was established by overflow at the lowest place in the Valparaiso moraine at a point in Chicago, Illinois. Thus the initial drainage of the Lake Michigan basin was established to the southwest through the Sag and Des Plaines rivers to the Illinois River and from there to the Mississippi, through what is now called the Chicago Outlet (Leverett, 1899, p. 420-426).

CALUMET STAGE. The next lower, or Calumet stage, is found at an elevation of 35 feet above Lake Michigan, and is shown by well developed beaches. The waters of this stage also drained south-westward through the Chicago Outlet. The Calumet stage probably was preceded by a low water stage, the Bowmanville. Leverett, (1915, p. 356) mentions peaty material found beneath the gravels of the Calumet beach in Evanston, Illinois, and Baker, (1910, p. 715) notes a similar deposit under the Calumet beach at Bowmanville. Cressy (1928, p. 53) calls this the Bowmanville low-level stage and indicates that the water level dropped to about the present level of Lake Michigan. Alden (1918, p. 136) believes that following Glenwood the lake level dropped to, "something like 50 feet below the present level of Lake Michigan.”"

The drop in water level from the Glenwood to the Calumet stage was accomplished by the erosion of the Chicago Outlet. Alden (1918, p. 136) states, "The Chicago Outlet had been gradually cut down, but the final drop to the Calumet level appears to have been rather sudden, as if due to giving way of the last obstruction to the overflow."

The Calumet beach is parallel with and below the Glenwood stage south of the hinge line and can be traced from Wisconsin through Illinois, Indiana and northward in Michigan beyond Big Sable Lake, Mason County, where according to Leverett (1915, p. 355), it seems to have been overridden by a moraine. Northward from Allegan, however, the Glenwood beach has been somewhat tilted. Throughout much of this distance on both the west and east sides of Lake Michigan the beach is fragmentary, having been cut away in many places by the waves of younger and lower lake levels.

TOLESTON AND ALGONQUIN STAGES—The Chicago Outlet continued to be cut down through glacial drift during Calumet time until it reached bed rock, and the next lower and last stage of Lake Chicago was ushered in. This is called the Toleston stage and its shore features are found at a level from 18 to 25 feet above modern Lake Michigan, or a little above the 600 foot contour. Leverett (1915, p. 356) states that the lake in the Toleston stage was, "barely high enough to open into the Chicago outlet."

The ice front retreated to the northeast in the northern part of the Lake Michigan basin and uncovered the Straits of Mackinac. When this occurred, the waters of the Lake Michigan basin merged with the waters of the Superior and Huron basins to form Lake Algonquin. Leverett (1915, p. 357) suggests that, "The Toleston beach may have been only partly formed by Lake Chicago. It has a level that was closely approximated if not reached by Lake Algonquin. The occurrence of a lake at this level in Algonquin time makes this beach a part of the Algonquin beach of the upper Great Lakes region." Taylor, (1915, p. 330) on the contrary believed that the Toleston beach was formed at the time of the two outlet discharge through the Chicago and Port Huron outlets following uplift of the Kirkfield outlet during Algonquin time. (p. 16) This view does not seem to be compatible with the researches of Leverett, Alden, Cressey, and Bretz.

The beach of the Toleston stage is well shown at the head of the Lake Michigan basin in Indiana and Illinois, but according to Leverett (1915, p. 356) it is generally cut away on both shores of Lake Michigan north of a line running from Evanston, Illinois to Michigan City, Indiana.

Following the formation of the Toleston beach the ice border retreated farther north, uncovered the Straits of Mackinac and allowed the waters of the Michigan basin

to join the lakes of the Superior and Huron basins, and at the same time exposed a much lower outlet to the east. This outlet extends from Kirkfield on Georgian Bay to the Ontario basin through the Trent River Valley. The drainage from the Ontario basin at that time was by way of the Mohawk and Hudson rivers to the Atlantic Ocean and perhaps marks the first time that the waters of the Michigan basin had drained eastward to the Atlantic Ocean.

The Kirkfield outlet was sufficiently low to bring the water of the Lake Michigan basin down to a level about 10 feet above the modern lake. This low level was called the "Kirkfield stage" by Taylor (1915, p. 328) and in the Lake Michigan basin the "Sag low-water" stage by Cressey (1928, p. 60). During the Kirkfield stage all discharge of the three upper lake basins was by way of the Kirkfield outlet.

While the last ice was retreating to the northeast from the Great Lakes basins a differential uplift (fig. 4) began north of the hinge line, (Taylor, p. 329) "a line running through the middle of the 'thumb" of Michigan and across the south arm of Lake Huron about S. 68 degrees E. and also . . . a line running westward across Lake Michigan from a point south of Frankfort." The area south of this hinge line was 4not elevated, but remained in a horizontal position as is proved by the fact that the abandoned shore lines of this area are not tilted but are horizontal.

The Kirkfield outlet was north of the hinge line and therefore was elevated during Algonquin time, until it stood higher than the Chicago and Port Huron outlets and lake water could not flow eastward but was spilled to the southwest. The outflow of water then abandoned the Kirkfield outlet and discharged through both the Chicago and Port Huron outlets. Perhaps during a short time all three outlets functioned before the continuing uplift raised the Kirkfield outlet completely above the others, (Taylor, 1915, p. 329) and (Bretz, 1939, p. 112).

As the Kirkfield outlet was uplifted the water level rose in the area of horizontality until in the Lake Michigan basin, it coincided with, or stood a little below the Toleston stage at an elevation of 600 feet. This is called the Hammond stage by Cressey (1928, p. 69) and it is correlated with the late Algonquin stage by Leverett. The Port Huron outlet was through glacial drift but the Chicago Outlet had been cut to bed rock, therefore the Port Huron outlet eroded rapidly and soon lowered the water level below the Chicago Outlet and it was abandoned. The Port Huron outlet then carried discharge of the Superior, Michigan and Huron lake basins.

NIPISSING STAGE—The continuing retreat of the ice border in late Algonquin time finally exposed an outlet lower than the Port Huron by way of the Mattawa and Ottawa rivers to the St. Lawrence depression. This is called the North Bay outlet after the city of North Bay on the northeastern side of Lake Nipissing. With the opening of the North Bay outlet the Port Huron outlet again became dry and the water level in lakes Michigan, Superior, and Huron basin again dropped, forming the Nipissing Great Lakes.

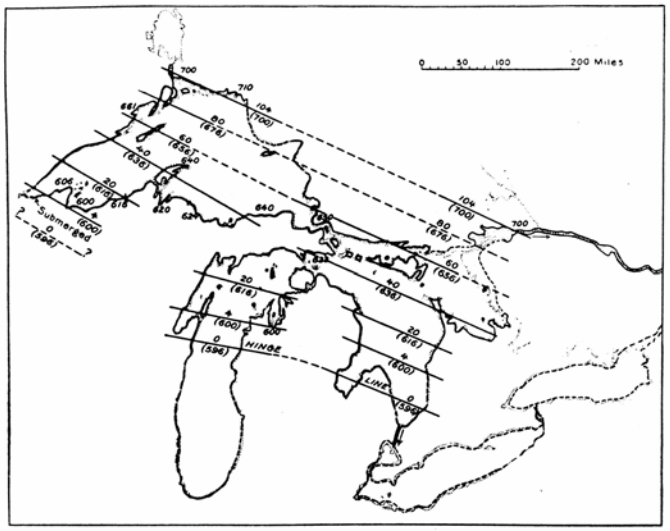


Fig. 4. Map showing the location of the hinge line in Michigan (after Leverett).

The amount of drop in the water level from the Algonquin to the Nipissing stage seems to have been considerable and in the Lake Michigan basin it was below the present level of the lake. Continued uplift north of the hinge line raised the North Bay outlet and caused a corresponding rise in the level of the lake south of the hinge line in the area of horizontality, until it was once again high enough to spill southward through the Port Huron outlet. Probably during a short period both the North Bay and Port Huron outlets were functioning simultaneously, but as the uplift continued, the North Bay outlet was finally abandoned. Also some discharge may have gone through the Chicago outlet accord-cording to Taylor (1915, p. 449), until the Port Huron outlet had cut down three or four feet.

The exact elevation of the initial stage of Lake Nipissing when the water first began to drain eastward through the North Bay outlet is apparently not known, because its beaches north of the hinge line have been elevated since, and those south of the hinge line are now submerged below the present lake levels. Stanley (1938, p. 973-974) presents evidence to show that the water level dropped considerably more than 300 feet below the level of the modern stage. He also indicates that the water level of the Lake Michigan basin dropped to about 150 feet below the present level, because there it was being held up by the depth of the channel at the Straits of Mackinac.

The Nipissing beaches north and south of the hinge line present quite different aspects in their relationship to the modern lakes. Taylor (1915, p. 332) states, "South of the hinge line the Nipissing beach is horizontal at about 15 feet above the present lake level. North of it the beach rises at the rate of about 7 inches to the mile in a direction about N. 22 degrees E. The Nipissing Beach is now 117 feet above Lake Huron at North Bay, about 70

feet above at Sault St. Marie, 48 or 50 feet above at Mackinac Island, and about 130 feet above (110 feet above Lake Superior) at Peninsula Harbor, near the north east angle of Lake Superior." Taylor further states that the Nipissing shows remarkably strong development in all of the northern parts of the basins, but that it declines in strength to the south until in the area of horizontality, it is of about the same strength as the Algonquin.

The Nipissing Great Lakes had practically the same outlines as the modern lakes Superior, Michigan and Huron. The Nipissing beach in the area of horizontality of the Lake Michigan basin can be traced from the head of the basin northward on both sides at an elevation averaging 15 feet above the present lake level. Here it is somewhat fragmentary as a result of wave erosion by Lake Michigan, and is found only in indentations. Above the hinge line it begins to rise gradually to the north.

ALGOMA STAGE—The Algoma beach represents an intermediate stage between the Nipissing level and the present lake level. Some investigators are skeptical as to the advisability of referring to this level as a stage. Of all that has been written on the history of the Great Lakes, very little attention has been given to the Algoma stage. Hobbs (1911, p. 62) mentions the Algoma beaches on the Garden Peninsula of Northern Michigan. Taylor (1915, p. 332) refers to the Algoma under his discussion of the Post-Nipissing Great Lakes, and states, "One beach, especially is slightly stronger than the rest and seems to mark a pause in the uplifting movement. This beach is called Algoma beach because of its development at Algoma Mills, Ontario, where it lies 50 feet above Lake Huron and 35 feet below the Nipissing beach. The Algoma has been found at many places farther south in a position a little more than half way up from the present shore to the Nipissing beach." He (Taylor, 1915, p. 464) further states, "In the area of horizontality a beach among several light ridges below the Nipissing and having an altitude of 591 to 592 feet (10 or 11 feet above the lake) is generally a little stronger than the rest and is regarded as the Algoma beach. The only basis for its identification, however, is the fact that it is a trifle stronger than the others above and below it" Taylor (1915, p. 469) in his table of glacial and non-glacial lakes of the Huron-Erie and Michigan basins, gives the elevation for the Algoma beach south of the hinge line as from 589 to 591 feet above sea level. There seems to be a slight difference in his figures for the elevation of this beach. This variation would give the Algoma a range of from 589 to 592 in the area of horizontality.

Localities other than Algoma Mills where the Algoma beach has been found are (Taylor, 1915, p. 464-465) Sault Ste. Marie where it was observed by Leverett, at Mackinac Island, Clam Shell Harbor, on the Garden Peninsula and a few places on the shore of Lake Superior. Stevenson (1931, p. 478-484) describes the beaches of the Algoma stage in and to the east of the City of Manistique. Bergquist (1936, p. 110-112) to corroborates these observations and states further, "The Algoma shore is not traceable as a continuous feature in Schoolcraft County, but occurs rather as more or less disconnected units sometimes widely separated, along the shore. In certain areas, the Algoma features are very definite, but in the main they are either obscured by low dune developments, or missing entirely as a consequence of later wave activity." Scott and Dow (1936, p. 443-447) describe dimes and bars of the Herring Lake embayment which they suggest may correlate with the Algoma stage. Calver (1941, Part II of this report) designates certain wave cut terraces and bluffs in the Crystal Lake area of Benzie County as belonging to the Algoma stage, Stanley[2] recognizes an Algoma beach on South Fox Island in Lake Michigan.

With the exception of the work by Scott and Dow the observations cited were all made in the area of uplift, north of the hinge line where the Post-Nipissing shore features are more readily differentiated than in the area of horizontality. Goldthwait (1907, p. 43-71) has made a study of the abandoned beaches south of the hinge line in Wisconsin. He describes beaches and terraces at several localities which are, according to the range fixed by Taylor, at the proper elevation for the Algoma. He observed a gravel bar north of Fox Point, between Milwaukee and Port Washington, which was 10 feet above Lake Michigan. East of Oostburg he found a gravel bar 11 feet above the lake, a "10 foot bar" east of the Black River, a "12 foot terrace" at Centerville, a "12 foot beach" two miles northeast of Two Rivers, a "9 foot bench with a bluff", and a "9 foot bench with a high steep bluff of remarkable strength" south of the village of Algoma,[3] and 12 and 9 foot levels north of Clay Banks.

The writer measured by hand-level, in 1940, several beaches and terraces along the Wisconsin shore between the southern state line and the village of Algoma, Wisconsin, to the north. These levels are close to, or within the vertical limits of the Algoma stage. Near the Kenosha Yacht Club there is a beach ridge six feet above the lake. In Racine, north of the gas works, a terrace was found which was 12 feet above the lake. A terrace eight feet above the lake is in the park at Port Washington. South of Sheboygan a wave cut bluff is at the back of a terrace 200 yards wide. The terrace is 10 feet above the lake at the base of the bluff, and a beach ridge on its outer edge is at the same elevation. A terrace 12 feet above the lake with a beach near its outer edge is south of the Sheboygan light house. This beach is also 10 feet above the present lake level. Farther north in Kewaunee a similar terrace, 100 yards wide stands at an elevation eight feet above the present level.

During the summer of 1941 hand-levels were run by O. F. Evans and the writer on a poorly developed beach on the north shore of Muskegon Bay. This beach, at an elevation of seven feet above the present lake, is just below a well developed, broad, Nipissing terrace. Levels were also run on a terrace 10 feet above the lake on the north shore of White Lake west of Montague and one

mile farther west along the shore of White Lake at the Sodony Boat Works where the terrace was found to be 7.5 feet above the lake.

The elevation of Lake Michigan was between 579 and 580 feet above sea level during the summers of 1940 and 1941. The time of Goldthwait's leveling was in the fall of 1905 and the U.S. Lake Survey has a record of 581 feet for October of that year.

Additional plane table work in the Grand Marias Embayment shows consistent shore features at an elevation of 586 to 591 feet or from eight to 12 feet above the Lake Michigan level (pl. I). Most of the elevations found for these features fall within or a little below the elevation range for the Algoma stage as given by Taylor for the area of horizontality. It would seem reasonable therefore, to suggest that they probably represent the Algoma stage of the Post-Nipissing Great Lakes.

LAKE MICHIGAN—With the complete abandonment of the North Bay outlet and the reoccupancy of the Port Huron outlet, the two outlet stage which developed the Nipissing beaches was over, and the post-Nipissing Great Lakes came into being. The outlet at Port Huron cut down fast enough so that despite the rise north of the hinge line, the lake level dropped until it reached the present position. With the exception of the Algoma beach which was probably developed either during a temporary halt in the uplift to the north of the hinge line, or as the result of a temporary stop of the down cutting of the Port Huron outlet, the drop in level to the present was relatively uniform.

Regular measurement of the levels of the Great Lakes was established in 1860, and since that time it has been observed that the Lakes average about one foot higher in summer than in winter. Lakes Michigan and Huron (considered as a single body of water) were, according to Bretz, (1939, p. 116) abnormally high in the summers of 1917 and 1918, when they reached an elevation of 582 feet above sea level. For the next ten years the level dropped steadily a total of approximately 4 feet. Cressey (1928, p. 71) lists a high water stage in 1838 when the elevation of Lakes Michigan and Huron stood at 584.69 feet above sea level. In 1929 (Bretz, 1939, p. 116) despite the diversion of 10,000 cubic feet of water per second through the Chicago Drainage Canal, the level was raised to 582 feet. During the summers of 1940 and 1941 the level was 579 plus feet. The United States Lake Survey Notice to Mariners of June 4,1940, states, "Based on past records the monthly mean level for June is likely to be about 579.1 and not less than 578.9".

The lowest level observed for Lake Michigan was a little below 579 feet and the highest level above 584.5 feet. On the basis of these figures it can be seen that the greatest known fluctuation for the level of the lake has been more than 5.5 feet.

[2]Report to Michigan Academy of Science, Geology Section on the Physiography of the Fox Island. 1947. Unpublished.

[3]Algoma, Wisconsin—Not the type locality for the Algoma beach.

GENERAL PRINCIPLES INVOLVED IN THE FORMATION OF COASTAL DUNES

General Discussion

Coastal dunes are found along the shores of the oceans and at intervals along the borders of most large lakes. Dunes of this type are especially common along the Great Lakes and are one of the characteristic features along the east side of Lake Michigan from Gary, Indiana northward to Mackinaw City. Coastal dunes are also present between St. Ignace and Manistique on the north side of Lake Michigan, and at Two Rivers, Terry Andrae State Park, and Kenosha, Wisconsin on the west shore of the lake. Some very prominent coastal dunes are also found on the south side of Lake Superior west of the village of Grand Marais. Dunes are found also along the east shore of Lake Huron, and at a few places on the south shores of lakes Erie and Ontario.

The material of which the Great Lakes coastal dunes are built is primarily sand that has been derived from shore erosion of morainic bluff's. This sand is carried by along-shore currents to the mouths of indentations where it is deposited on the beach by storm waves. The sand then dries out and is blown landward into dunes by on-shore winds. A study of the sand from dunes and beaches at the head of Lake Michigan indicates that it is made up primarily of well rounded quartz grains. Cressey (1928, p. 24-32) states, "sand both of the dunes and of the beach is almost entirely between one-half and one-eighth millimeters in diameter."

According to Bagnold (1941, p. 105), "of the total sand in motion in air about three-quarters moves in saltation and a quarter in surface creep." The finest material may be lifted and carried in suspension by the wind, but in coastal dunes nearly all of the fine material has been washed out by waves and currents before wind transportation begins.

The velocity of the wind at which the sand begins to move has been the subject of numerous investigations, which have considerable variation in results. According to Cressey who used a windmill-type anemometer, movement of sand begins when wind velocity reaches 6.8 miles per hour, but he admits a considerable inaccuracy in his method of observation. Work by Scott, Bergquist and the writer in 1931 indicates that the threshold velocity is between seven and eight miles per hour. Pitot tubes were used in this experiment for determining velocities in an especially constructed tunnel in which airflow was artificially controlled. Observations made in 1941 by Belknap, Rosby and Landsburg (personal communication) show that no appreciable movement of sand occurs until the wind attains an average velocity of 20 miles per hour. These

observations were made with the aid of four Biram type anemometers set at varying distances above the sand surface. This wide variation in results is probably due, among other factors, to variation of instruments, elevation of instruments above the sand surface, and to gustiness of the wind.

On-shore winds are essential for the development of coastal dunes. Calver (Part II) found that the dunes of the Crystal Lake area are at right angles to the shore from which they developed. The dunes of the Grand Marais Embayment, however, have an angle of approximately 35 degrees to the shore of Lake Michigan, with their long axes almost due east and west (pls. I and III).

The cause of deposition of air borne sand is not definitely known. It is suggested that a decrease in velocity brought about by some obstruction in the path of the wind such as a building, a fence, or vegetation, may be the cause of deposition. It is believed, further, that vegetation has played an important part in the initial formation of coastal dunes along Lake Michigan and was of particular importance in their later development.

Cressey (1928, p. 35) suggests as a possible explanation for the origin of dunes, that wind formed sand ripples overtake each other and join, and with each union of two ripples a growth in size occurs until a dune is formed. This supposition was not borne out by the wind tunnel observations made by Scott and Bergquist (personal communication) in 1932. They observed that ripples migrate with the wind and overtake each other, but show no tendency to increase in size. Their observations were recorded with a moving picture camera set to automatically expose one frame every five seconds. When projected this gave 80 times the normal speed to the ripple movement and showed them overtaking each other, but not increasing in size.

Ripple marks (pl. IV, B) are a characteristic feature associated with sand surfaces. They are unsymmetrical in cross section and a concentration of the coarse material on the crests is noticeable. According to Cressey (1928, p. 34) ripples begin to form when air speed is about seven miles per hour, the velocity at which sand first moves, and are destroyed by winds in excess of 20 miles per hour.

The windward slopes of some dunes are as little as 10 degrees, although steeper slopes are more common and some windward slopes are as much as 20 degrees. Under exceptional conditions, the windward slope, (pl. XI) may attain the angle of repose, as on those dunes where side arms are sapped by the winds, and on dunes so close to the lake shore that they are cut by waves. Lee slopes always stand at approximately the angle of repose for dry sand, that is between 30 and 33 degrees, unless modified later. However, lee slopes measured were found to have but little variation in degree of slope.

The structure of dunes depends upon the wind and varies according to wind direction and the stability of the dune. Stationary or fixed dunes developed by winds from one general direction, develop in length and height and in cross section display both windward (pl. IX, B) and lee bedding. On the other hand, dunes which have migrated at least a distance equal to their length but were formed by winds of a constant direction, show chiefly lee beds. Dunes effected by strong winds from several directions display a characteristic eolian cross bedding in which windward and lee beds cannot be differentiated. Dunes that migrate are largely limited to deserts, whereas dunes that develop without migration are characteristic of coastal areas. Coastal dunes may become fixed by vegetation.

PLATE IV. A. Gentle windward slope of foredune ridge west of Mt. Edward.

PLATE IV. B. Early stage of foredune formation between Mt. Edward and First Church Camp.

Forms and Development of Coastal Dunes

Coastal dunes have several forms which are all so related that the dune mass is a whole, that is, the various forms as a rule do not migrate as independent units. Dunes may be classified as primary and secondary. The sole representative of the primary dune is the foredune ridge. Secondary dunes are represented by such forms as dune ridges, parabolic dunes, and longitudinal dunes which are modifications of the original

primary form. Further classification is desirable due to the many modifications of the secondary dunes, but cannot be attempted at this time.

FOREDUNE. Foredune ridges are the first dunes to become established along a shore, (pls. IV, and V). These dunes are a few feet landward from and parallel to the shore and are almost universally present except where they have been destroyed by wind or water. They are relatively low and seldom attain a height of more than 30 feet above their base. The windward slopes of foredune ridges are rather gentle, usually not over 15 degrees. The lee slopes are somewhat steeper as a rule than the windward slopes, but only occasionally do they approach the angle of repose for dry sand. The crest of the foredune as a whole, is relatively uniform and even, but in places the crests are rounded and somewhat irregular and locally knobby. The characteristic vegetation on foredunes is various dune grasses such as calamovilfa and ammophila, and shrubs such as red osier, willows, poplars, and sand cherries.

PLATE V. A. Looking north along the foredune ridge west of Bald Top showing the depression behind the foredune and a wave cute bluff on the north arm of Bald Top.

PLATE V. B. Looking north at Grand Mere Beach showing low, grass covered, foredune ridge and beach cusps on the Lake Michigan shore.

DUNE RIDGE. Foredune ridges may blow out due to the removal of protective vegetation by fires, lumbering, building of roads or by wave cutting (pl. X, A) during high water periods. Where cut by waves the sand in the dune assumes a slope of the natural angle of repose and the bare exposed sand is blown up over the ridge locally, thus starting blow-outs through the ridge at various places. Wherever the vegetation cover is broken, by whatever cause, the sand is subject to wind blow. A series of small blow-outs along a foredune ridge develops a sinuous form which is called a "dune ridge."

PARABOLIC DUNES. Parabolic dunes (pls. I, and VI) which derive their name from their shape like a parabola, are probably the most characteristic and most frequently observed dunes in coastal regions. The windward (concave) side of the parabolic dune faces the shore. These dunes are central extensions of the blow-outs in dune ridges and develop in height, length, and breadth from repeated blowing and by addition of sand from the shore. They may attain a height of over 250 feet above the lake and a length of approximately one mile. The two arms of the parabolic dune remain attached to the source of sand as development progresses.

Two types of parabolic dunes are recognizable—the apex dune and the saddle dune. The parabolic apex dune, (pl. VI, B) rises to its highest point at the vertex of the parabola but in the parabolic saddle dune, (pl. VII, A) the apex has been cut down to form a low curved ridge beyond the saddle.

The windward slopes of parabolic dunes may be less than 10 degrees near the source of sand, but become considerably steeper near the apex. The lee slopes, (pl. VIII, A) of the parabolic dunes are at the angle of repose for dry sand. In many places waves or transverse ridges (pl. VII, B) of sand are within the arms of a parabolic dune at varying distances between the windward end and the apex. It is not uncommon to find as many as three waves in a single dune. Such waves are believed to be fore-dune ridges which are migrating landward through the opening between the two arms of the dune.

LONGITUDINAL DUNES. A ridge lying parallel to the direction of the prevailing wind is called a longitudinal dune. Longitudinal dunes are developed by a complete blowing through of the landward crest of an apex or saddle dune and the formation of a gap known as a wind rift or transection. Thus the apex or saddle dune is divided into a pair of longitudinal dunes.

SUGGESTED DEVELOPMENT. Through many years of study and observation in the field, Scott has concluded that the first dune to form is the foredune. This form, altered by numerous small blowouts may be changed to a dune ridge. Continued blowing, and the addition of more sand from the beach, brings about the development of parabolic dunes which in turn may be transected by further blowing to form longitudinal dunes.

PLATE VI. A. Panoramic view looking north from Blueberry Hill showing Wilkins Dune (W), Johnson Dune (J), Bald Top (B), South Lake (S), Covert Ridge (C), Lake Michigan (L), and an Algonquin dune passing beneath Wilkins Dune (A).

PLATE VI. B. Looking southeast from Bald Top showing apex of Johnson Dune (J), Covert Ridge (C), and apex of Wilkins Dune (W).

PLATE VII. A. Looking south from apex of Mt. Edward showing saddle of First Church Camp Dune in foreground and Great Warren Dune in background.

PLATE VII. B. Looking east from foredune up blow of First Church Camp Dune showing three transverse ridges.

PLATE VIII. A. Looking southeast from Bald Top showing lee slope and apex of Johnson Dune, Covert Ridge in background and Algonquin level (road) left foreground.

PLATE VIII. B. Algonquin level along north base of Johnson Dune. Bald Top in background.

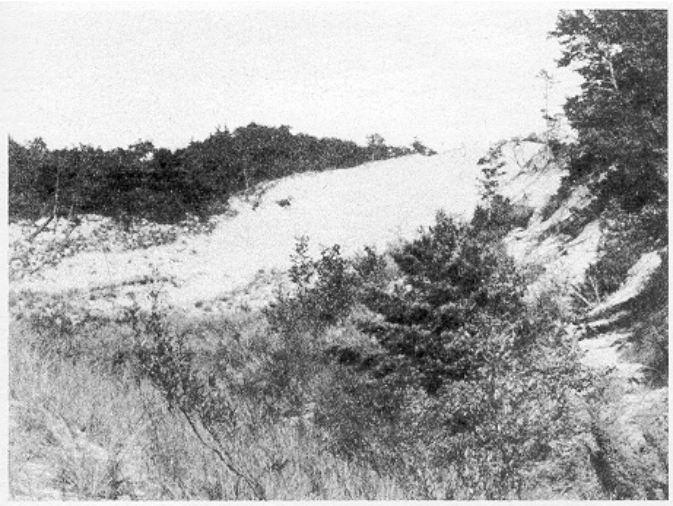


PLATE IX. A. Looking northeast up first modern blow south of the First Church Camp.

PLATE IX. B. Foreset beds of a dune exposed by eolian erosion in first modern blow south of the First Church Camp.

PLATE X. A. Foredune ridge cut by waves at First Church Camp. Note roots of grass exposed along the cut bluff.

PLATE X. B. Tennis court at First Church Camp located on foredune ridge and covered by sand.

PLATE XI. A. Present blowing on north arm of Johnson Dune. Note two soil zones indicating three episodes of blowing.

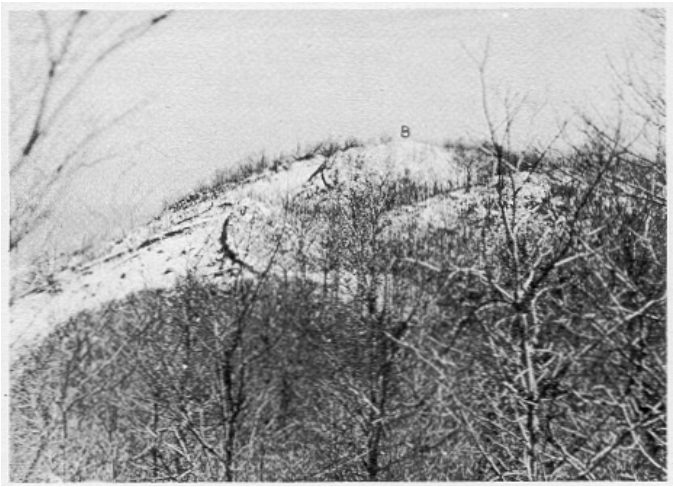


PLATE XI. B. Looking north at present blowing of north arm of Johnson Dune (J), and south arm of Bald Top (B).

Methods of Determining Age of Coastal Dunes

Beaches of the ancient lake stages in the Great Lakes basins are lacking in many places, due to shore erosion and where present they may be buried under coastal dunes. Such burial is characteristic along the Lake Michigan coast in the area of horizontality, (south of the hinge line), where for considerable distances the dunes alone show the presence and position of the higher and older abandoned shore lines. Since coastal dunes are essentially shore features, and may be readily differentiated as to relative age, they hold an important key to the details of the history of the Great Lakes.

The work of Scott, Stevenson, Dow and Calver has shown that the apparent confusion and complexity of coastal dunes, where dunes of several ages are present, is in reality far less complex than at first believed, and in many places is a relatively simple and orderly sequence. In the area of uplift where the rows of dunes of different ages are usually well separated at different elevations and distances from the modern shore, the problem of

differentiation is considerably less puzzling than in the area of horizontality where the abandoned strands are nearer together. South of the hinge line it is not uncommon to find dunes of the younger stages which completely cover dunes of older lake stages or at least overlap upon them.

The relative ages of the dunes within any given area can be determined by: (1) position of the dune, (2) elevation of the beaches, (3) soil profile, (4) topographic unconformity, (5) elevation of the base of the dune, (6) relative development, and (7) direction of elongation. No single fact ordinarily gives sufficient evidence to definitely establish the age of a dune, therefore, as many observations as possible should be utilized.

POSITION. Position of the dune is established by noting its location with reference to the dunes nearest to, and farthest from the present shore line. Normally the dunes farthest from the coast are considered to be the oldest dunes of the area and the dunes nearest to the coast are the youngest dunes. According to Scott and Dow (1936, p. 442), "This principle is based upon the assumption that there has been no dune migration." Relative position alone, however, is not sufficient evidence. Many younger dunes may be developed longitudinally until they stand with their lee bases considerably to the landward of the lee bases of older dunes on either side. This situation can be observed in the Grand Marais Embayment, one half mile north of the entrance to the Warren Dune State Park and farther north on the Great Warren Dune, (pl. III).

ELEVATION OF BEACHES. Elevation of beaches above the modern lake is a most important factor in determining the age of a dune where such an observation can be made. If it is possible to trace a row of dunes (all of the same age) to a place where they give way laterally to a beach it is assumed that the dunes are of the same age as the beach. Stevenson (1931, p. 479) was able to trace well developed beaches of Algoma age eastward from the City of Manistique, Michigan, to the place where they gave way to dunes. She (Stevenson 1931, p. 479) states, "At Manistique Point the beaches rest on bed rock and are composed of coarse rubble, which decreases in size northward along the beach, and finally as the dune area is approached, consists of sand in the form of a bar, then a foredune ridge, and, in the dune area proper, blown dunes."

The presence of a beach of known age immediately to the shoreward of, or to the landward of a dune is likewise an aid in establishing the age of the dune. Stevenson (1931, p. 483) observes an Algoma cut bluff developed on windward slopes of a Nipissing dune a few miles east of Manistique.

This method of age determination is excellent where the relationship of beaches and dunes can be observed. In the area of horizontality, however, such conditions rarely occur due to the close spacing of the abandoned beaches.

SOIL PROFILES. Soil profiles have been used as an aid in establishing the age of dunes. The method was first used by Scott and Stevenson during the field season of 1929, in studies in the Manistique area and later by Scott and Dow (1936, p. 442) in studying the Herring Lake Embayment.

The principle of the soil profile observation is that, the older the dune, (the longer the sand has remained in place) the greater the iron oxide concentration just below the surface of the ground. With age the zone of such iron oxide concentration becomes darker in color and reaches a greater depth. However, if the dune is blown out locally as in a "spot blow," the normal concentration of iron is disturbed and an abnormal considerably younger and lighter colored soil profile is developed. It is not at all uncommon to find that a dune, which according to all other available criteria belongs to an old stage, displays the soil profile of a young stage. This can be accounted for on the basis of a later episode of blowing, but it reduces the reliability of the soil profile as an age determining factor. The examination of many profiles, however, helps greatly in establishing age in local areas. A rule of thumb applicable to the use of such soil profiles is that the dune in question is at least as old as the oldest soil profile that can be found in it.

TOPOGRAPHIC UNCONFORMITY. Lahee (1941, p. 375) states that, "Topographic unconformity is a term applied to land surfaces which consist of two parts that are out of adjustment with one another. This condition is brought about by an interruption in the ordinary erosion cycle." By applying this principle to areas of dunes it is possible to determine breaks in the continuity between the dunes developed during each of the various glacial lake stages, since each change of lake level was an interruption in an erosion cycle and produced a topographic unconformity. Dunes of the different lake stages generally have distinctly different characteristics of form and size, and dunes of each succeeding lake stage are for the most part piled over their predecessors in varying degrees, especially in the area of horizontality. The line of demarkation between the stages is located at the lee base of the younger dunes and may be referred to as the "contact".

During the periods of high water or of static water level and a retrogressing shore, wave action cuts away shoreward portions of dunes producing cut bluffs. Wave-cut bluffs, and other indications of a former shore are also topographic unconformities which serve as contacts in the separation of the different stages of dunes and in determining their age.

ELEVATION OF BASE. The elevation of the base of a dune is an aid in determining age. Ordinarily the surface upon which a coastal dune is built is the exposed bed of the next earlier higher lake level. Therefore, the elevation of a dune at its base is likely to be the age of the next lower lake stage. This principle is well illustrated in the Grand Marias Embayment. West of Bridgman the Calumet dunes are standing on the older Glenwood lake bottom which has an elevation a little below Glenwood beach

level (635-640 feet), but higher than the level of the Calumet stage (615 feet). From Wildewood northward to the Algonquin bar (south of South Lake) the Algonquin dunes are located on the gently sloping Calumet lake bottom (pl. III). Southwest of South Lake, Johnson Dune, Wilkins Dune, Blueberry Hill, and Brinkman Dune, all of Nipissing age, are located on a surface 600 feet (pl. I) in elevation—the Algonquin level.

Dunes may be younger than the stage represented by the elevation of the land surface on which they are standing, but never older. Migrating dunes moreover, may move from a high land surface to a lower but older surface as shown by the migration of Glenwood dunes between Bridgman and New Troy. Here the Glenwood dunes have migrated eastward across Covert Ridge and down the eastern or outer slope of the ridge to a lower level, but the inland surface is an older glaciated land surface.

RELATIVE DEVELOPMENT OF DUNES. Simple ridges, deformed ridges, and size, as a means of determining age of a dune mass are discussed by Solger (1910, p. 40-50) and by Scott and Dow (1936, p. 442-443). According to Solger, the development of a series of undeformed ridges running approximately parallel to each other indicates a lowering of the water level along a shore whereas deformed ridges indicate rising or oscillating water conditions. On a shore that is being cut back due to a rising water level, deformation of dunes takes place, but these dunes are of moderate size because no large amount of sand is added. Wave action and current action remove most of the sand as cutting occurs.

Scott and Dow (1936, p. 443) state, "on the other hand, exceptionally large deformed dunes (150-250 feet high) are the result of the alternating addition and abstraction of sand along the shore of a lake whose level oscillates. 'Oscillation' in this sense refers to the normal short-period fluctuations. . . . dunes of this type are to be expected at the flood stages of both Algonquin and Nipissing Algoma possibly, and present." According to Scott[4] the largest dunes of the pre-Lake Michigan stages were developed during the Nipissing stage, a fact which holds true generally for the areas in which studies have been made, including the Grand Marais Embayment. Therefore, after checking all other factors of age identification, designating dunes which are consistently the largest as Nipissing, gives the investigator a control which aids in establishing the ages of both older and younger dunes.

It should be pointed out, however, that Nipissing dunes are not always the largest to be found in local areas. Consequently, it is necessary to utilize other methods as a check.

EXTENSION. Extension or direction according to Scott and Dow (1936, p. 442) refers to the direction in which ridges of the dunes run. A variation in the direction of the long axis or the amount of curvature in the dunes of various ages may supply clues to age and manner of formation.

[4](Personal communication.)

SHORE LINES OF THE GRAND MARAIS EMBAYMENT

General Discussion

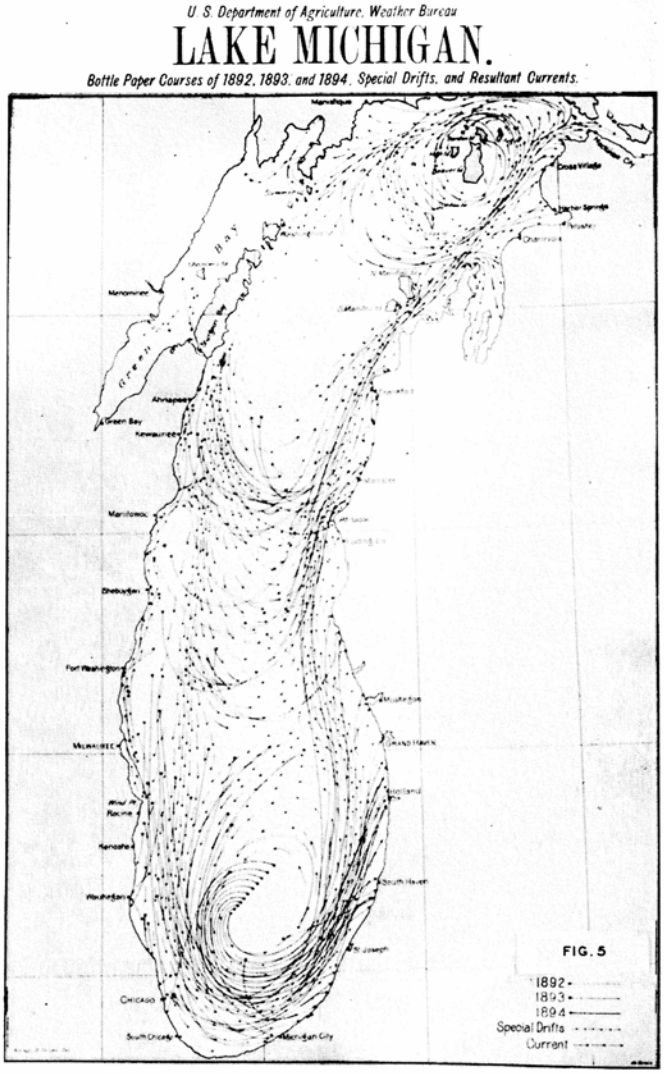
In the locality between Glen Lord on the north and Lakeside, 16 miles to the south, the Covert Ridge bends to the eastward from Lake Michigan, thus leaving a long narrow depression, a former lake bed, between it and the present shore. This depression is the object of this study and is hereafter referred to as the Grand Marais Embayment.

The Grand Marais Embayment was occupied by all of the glacial (ancestral Great Lakes) lakes from Glenwood time to the present. Lakes of the Glenwood and Calumet stages filled all the Embayment. Lakes of the Algonquin, Nipissing and Algoma stages were confined entirely to the deeper and more critical northern part (pls. I, II, III). This part of the embayment was the last to be abandoned by the predecessor of Lake Michigan as shown by the presence here of three shallow, swampy lakes, North, Middle, and South Lakes, — the Grand Marais Lakes. The shore features of the lake stages in the embayment consist of abandoned spits,[5] bars,[6] beaches, and wave cut bluffs, and dunes. They will be discussed in considerable detail. In reading the following discussion and studying the maps, it should always be kept in mind that the eastern part of the embayment—the modern lowland between Covert Ridge and the coastal dunes—was cut off from the main lake by shore features developed as the ancestral lakes retreated westward into the modern lake basin.

A spit may have started to develop from the south across the mouth of the embayment as early as Calumet time. Such an assumption, however, is entirely problematical and is based upon the fact that a fragment of a beach (surrounded by dunes) at the Calumet level is found a half mile north of the State Park entrance in the southern part of the embayment (pl. III). However, a strong spit began to develop northward across the bay in Algonquin time when the lake had subsided to the Algonquin level. At the same time a much weaker and much shorter spit was built southward from the headland (pl. XII, A) of Covert Ridge on the north, where the ridge approaches the lake west of Glen Lord.

It is evident from the greater development of the southern spit that the supply of sand was much greater and the currents were much stronger from the south than from the north. Modern conditions substantiate this conclusion as shown by Harrington (1892-93) who obtained evidence for strong currents from the south along the east coast of Lake Michigan by bottle paper investigations for the United States Weather Bureau.

Figure 5 is a map which shows the bottle paper courses recorded for several years of these investigations. Phil Church and Sherman Morre, of the U. S. Lake Survey, agree with this conclusion that strong currents come from the south along the eastern shore of Lake Michigan. Others (Leverett, 1899, p. 454-456), however, maintain that the chief movement of water is toward the south along the east shore.



[Figure 5. Lake Michigan bottle paper courses 1892, 1893, and 1894, special drifts and resultant currents.]

Apparently lowered lake levels did not alter conditions which caused the development of the opposed spits until they were finally joined forming a bar which cut off the embayment in post-Nipissing time, probably after the Algoma Lake stage. Evidence for this history can be shown by the fact that the Nipissing beach and the Algoma beach (pl. XIII), are both stronger opposite, and to the east of the place where the outlet of the embayment was finally closed north of North Lake (pl. I). Farther south these beaches diminish in strength and in some places become rather weak. The place of union was probably about 1000 feet north of the present outlet to North Lake. It is evident from the strong Algonquin cut bluff along the inner side of Covert Ridge east of North Lake, that the wide opening to the main lake was functioning during Algonquin time. North and south the bluff diminishes in strength until it becomes faint and dies out. This fact implies that the waves of Lake Algonquin had a free sweep through the opening of the bay and worked strongly on that part of Covert Ridge which is opposite the opening. As the spits built towards each other the opening became narrower. Eventually the cutting on Covert Ridge ceased either as a result of spit development or more likely as a result of a lowering of the water level to the Nipissing Lake stage.

The southern spit developed rapidly during Algonquin time, the period of its greatest extension, but the northern spit, due to weaker shore currents and a smaller supply of sand, grew more slowly.

PLATE XII. A. Looking north from Bald Top showing Dunham Dune (D) in the right background, and Covert Ridge headland (C) in the left background.

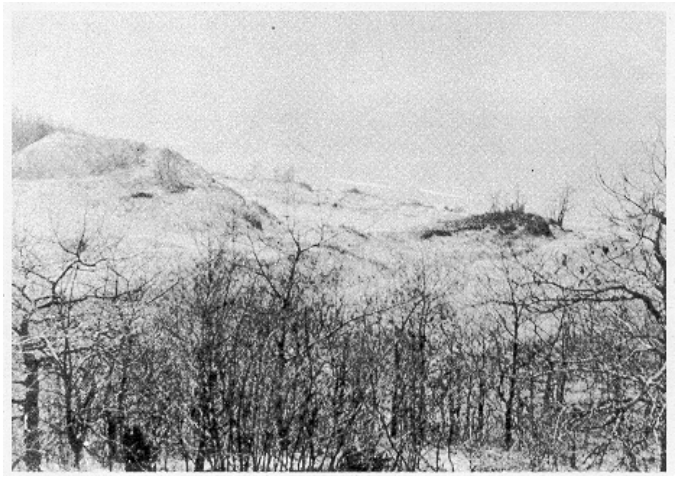


PLATE XII. B. Looking southwest from Dunham Dune showing foredune ridge, and area of present blowing.

Five prominent points may be observed on the east side of the southern spit (pls. I, II, III) between the Algonquin bar (AB, pl. I) and the place to the north where the embayment was finally closed. Points were developed only by the southern spit, apparently the result of a compound recurving of the spit as it developed intermittently northward. Johnson (1919, p. 290) says of

the formation of such a spit: “The forces supplying debris to the longshore current, the longshore current itself, and the contrary currents which tend to recurve the spit, do not always act with even approximate uniformity. One or more of these activities may have a very pronounced intermittent character. In such a case, the forces tending to elongate the spit in a straight or curved line may prevail for a period, after which the forces operating to recurve the spit may temporarily gain the ascendancy. The effect of this intermittent action will be to produce a spit whose inner side is diversified by a series of landward deflected points representing successive recurved termini. To this interesting form the name *compound recurved spit* may be applied."

PLATE XIII. A. Cross section of the Algoma level looking south from a position west of Grande Vista. Note the more gentle lakeward slope.

PLATE XIII. B. View of Algoma level looking east from a position west of Grande Vista.

It is also significant to note that the four southern points have an average elevation of 600 feet, therefore are the elevation of the Algonquin stage, but the fifth or northern point is lower and is either of Nipissing or post-Nipissing age. It is also significant that the size of the points and their recurvature decreases northward (pl. I). This fan arrangement of the five points is perhaps due to the narrowing of the opening between the main lake and the bay during Algonquin and later time. As the opening became constricted the effect of waves and currents sweeping into the embayment was decreased, thus the activity of recurving agents was reduced and cusps (points) rather than curved spits were developed.

The Grand Marais Embayment, south of the Algonquin bar, is covered with a complex series of coastal dunes. The Glenwood beach is wholly outside and to the east of this area of dunes, but the Calumet beach can be traced south of the Algonquin bar as far as Wildewood (pl. III) where it disappears beneath Algonquin dunes. It has therefore been necessary to differentiate between these dunes as to age in order that a more complete history of the embayment may be established.

[5]Spit—a bank of sand and/or gravel deposited by shore currents with one end attached to the land, the other in open water. Shifting currents may curve the outer (in water) point of the spit landward.

[6]Bar—a bank of sand and/or gravel deposited along a coast or across the mouth of a bay. Its ends may or may not be attached to the land. Some bars are produced by the union of two spits.

Glenwood Stage

The Glenwood shore is readily traceable except in one locality along the inner side of Covert Ridge from the northern end of the Grand Marais Embayment west of Glen Lord, to Lakeside on the south, a distance of approximately 16 miles. Between Stevensville Road and Livingston (pls. I and III), however, the Glenwood beach has been removed by wave and current action of the later and lower Calumet and Algonquin lake stages.

The water level of the Glenwood stage in the embayment stood between 635 and 640 feet above sea level and, therefore, is closely approximated by the 640 foot contour on the United States Geological Survey maps and on the contour map (pl. I) of the northern part of the embayment.

One quarter of a mile south of the Glen Lord Road in the northern end of the embayment the Glenwood shore is represented by a short sand bar or spit which extends from the present lake shore, where it has been truncated by Lake Michigan, to one quarter of a mile southeast where it ties into Covert Ridge. This bar probably represents a development very early in Glenwood time—a feature that was built from the southeast towards the northwest of material derived from the inner flank of Covert Ridge. It is impossible to determine that the small triangular shaped embayment to the northeast was or was not entirely cut off, but this depression was the earliest complete or partial separation of a part of the Grand Marais Embayment. Shall spot blows indicate some wind activity and it is evident that the bar has been somewhat modified by the wind since its formation. The landward end of the bar rises with a uniform slope to the top of Covert Ridge. It stands for the most part, however, from 10 to 20 feet above its base or 635 to 645 feet above sea level. Its landward slope approximates

the angle of repose for dry sand, but the lakeward slope is more gentle.

A second, wind-modified, Glenwood bar with its northern end likewise truncated by the lake is 1,000 feet farther south along the Lake Michigan shore. The bar parallels the earlier bar for a quarter mile, but gradually takes a more southerly course more nearly parallel to Covert Ridge and finally terminates in the ridge at a point just southwest of Grande Vista. The total length of the bar is approximately one and one quarter mile. West of Grande Vista it units with a bar of the Calumet level, the next lower lake stage, which here has been eroded by waves of the Algonquin stage (fig. 3).

This bar, like the bar to the north, developed from the south and is composed entirely of sand. It has been altered to some extent by wind, as can be seen by the presence of a parabolic dune (pl. I) near its midpoint. The apex of the dune rises 10 to 20 feet above the elevation of the crest of the bar.

The inner side of Covert Ridge, landward of these Glenwood bars, drops downward to the west with a uniformly decreasing slope, and nowhere does this surface show any indication of beach development. The implication is that these two bars formed early in Glenwood time thereby protecting the west side of Covert Ridge in this area from Glenwood and later wave erosion.

The Glenwood beach has been completely removed by the waves of the succeeding lake stages, from a point on Covert Ridge 1,000 feet southwest of Grande Vista (pl. I) to Livingston (pl. III[7]), except perhaps in one section one quarter mile south of the Riding Stable (pl. I) where a narrow bench is developed in the clay bluff above the Calumet terrace. This bench runs along the face of the bluff for about 50 feet and stands at the elevation of the Glenwood shore. It may be a fragment of the former Glenwood terrace which was not completely cut away by wave action during Calumet time.

The Glenwood shore appears again at Livingston and can be traced southward as a sandy beach through Bridgman just west of the tracks of the Pere Marquette Railroad. From Bridgman the Glenwood beach follows a course roughly parallel to the shore of Lake Michigan and passes through Browntown and Harbert. Southwest from Harbert it swings gradually back to the Lake Michigan shore in the vicinity of Lakeside where it has also been cut away by the modern lake.

From Livingston southward the Glenwood beach appears as a low, flat ridge of sand on the westward gently sloping inner side of Covert Ridge which in this area was barely above the level of Lake Glenwood.

Dunes of the Glenwood stage extend from the northern limit of the Grand Marais Embayment as far south as New Troy (about four and one-half miles east of Lake Michigan southeast of Sawyer). Southward from the northern end of the embayment to Livingston the Glenwood dunes are perched (fig. 2) on the crest of Covert Ridge and their sand was evidently blown up the relatively gentle inner slope of the ridge. Here the dunes are mainly small, low, parabolic and festoon forms having a soil sufficiently rich for the growing of fruit. Farming practice has rounded their crests, and reduced their height and distinctness of form. In places the steep lee slopes have been planted to vineyards. In many places the Calumet or the Algonquin bluff truncates the windward arms of these dunes.

The elevation of Covert Ridge decreases southward and its inner (lakeward) side has a very gentle slope in the vicinity of Livingston. Here the Glenwood dunes and the Glenwood beach are separated and diverge as they continue southward (pl. III). The divergence of the dunes and the beach increases southward to New Troy, the termination point of the dunes, where they are about three miles apart. The cause of this divergence is the migration of the dunes over Covert Ridge.

The migration of these Glenwood dunes is of special interest, as it is the only occurrence of migratory dunes known at the present time in the region of the Great Lakes. It is suggested that a deficiency in sand or scarcity of vegetation, or a combination of both, are responsible for this phenomenon. The migration begins in the area just north of Livingston where the top of Covert Ridge drops from an elevation of over 700 feet above sea level where it has relatively steep sides to an elevation of about 660 feet where it has gently sloping sides. In fact the inner slope from here southward is extremely flat.

During the time of Lake Glenwood, the shore was along the inner side of the Covert Ridge moraine. The lake was relatively small, occupying only the southern part of the Lake Michigan basin. It was probably also of comparatively short duration and shore adjustments were incomplete as little sand was available for transportation by shore agents. Therefore development of Glenwood beaches was weak.

One factor believed to be at least partially responsible for the migration of dunes, is a limited supply of replacement material to occupy the place of wind moved sand. Another suggestion to account for the migration of these Glenwood dunes is that the vegetation on Covert Ridge at the time of their formation was not enough to hold them in place. It is commonly believed that vegetation is an aid, if it is not the chief cause of coastal dune formation and also of dune stabilization. It seems probable that at the time of Lake Glenwood the ice front stood not far to the northwest in the Lake Michigan basin and as a result of the anticyclonic winds from the ice, the climate was not yet warm enough to produce sufficient vegetation on Covert Ridge to hold the sand in place (Baker, 1920, p. 216-219).

Whatever the cause, and it may be a combination of factors, the fact remains that Glenwood dunes in this area have migrated several miles inland from their beach source. It should likewise be noted that in the area of

greater migration the form of dunes has changed from parabolic to festoon and transverse types.

[7]The Glenwood beach shown on Plate III between the Pere Marquette railway and Keelo Creek east of Covert Ridge, marks the western shore of a lower embayment to the north which opened into Lake Chicago near St. Joseph, Michigan.

Calumet Stage

The Glenwood stage was closed by a lowering of the water level. Evidence of a low water stage, are peat deposits lying on Glenwood sand below the Calumet beach (Cressey, 1928, p. 59-62). Then lake level again rose and became readjusted at an elevation about 35 feet above Lake Michigan or between 615 and 620 feet above sea level. This stage is known as the Calumet. The outlet for the Calumet level was also by way of the Chicago outlet to the Mississippi River.

Calumet shore features of the Grand Marais Embayment are bars, beaches, wave cut bluffs, terraces, and dunes. Drop in water level of some 20 feet from the Glenwood stage caused a withdrawal of the water westward in the embayment and with the exception of the zone between Grande Vista and Livingston, the Calumet shore features are found well lakeward of the Glenwood beaches.

Three quarters of a mile south of the Glen Lord road a well developed Calumet bar (pl. I) emerges from under a festooned Algonquin dune. It can be easily traced south for three quarters of a mile where it merges with the second or latest Glenwood bar and eventually is cut off by the Algonquin bluff 200 feet north of the Stevensville road. It is composed entirely of sand and throughout most of its length it has an elevation a little above 630 feet. This bar may represent a Calumet foredune ridge, though its crest appears to be altogether too uniform and smooth for such a form. The smoothness, however, may be due to the fact that it is utilized in its entirety for horticulture, consequently, cultivation plus wind action may have removed its irregularities.

The Calumet shore has been completely removed by wave erosion of the next lower or Algonquin stage from a position west of Grande Vista, where it joins with the Algonquin bluff, southward for nearly one quarter of a mile along the inner side of Covert Ridge. (The location of the Algonquin shore is shown by the 600 foot contour (pl. I)). Farther southward to the Algonquin bar (Ab pl. I), however, the Calumet stage is represented by a strong wave cut bluff and terrace (pls. XV and XVI), cut in the glacial till of Covert Ridge. The terrace varies in width from a few feet on the north, where it has been chiefly cut away by waves of the next lower lake stage, to over 100 feet near the Algonquin bar (Ab pl. I) to the south where Algonquin wave activity was reduced by the protection of the spit building northward across the mouth of the embayment.

PLATE XIV. A. Looking east from second Algonquin bar (2) southwest of Grande Vista showing first Algonquin bar (1), Algonquin bluff (A), Calumet bar (C), and Covert Ridge (CR).

PLATE XIV. B. Close view of Algonquin bluff southwest of Grande Vista.

PLATE XV. A. Looking south along the Calumet terrace north of the Riding Stable showing scattered boulders and narrowing of the terrace where it has been cut away by the Algonquin stage.

PLATE XV. B. View of the Calumet terrace and the Algonquin bluff west of the Riding Stable. Man is standing on boulder lined Algonquin strand which resulted from ice push.

Numerous igneous rock boulders (pls. XV A, XVI B) having diameters of several feet, are on the Calumet terrace. They were concentrated on the terrace as the waves and currents of the Calumet stage removed the finer material from Covert Ridge.

The Calumet stage developed a beach and wave cut bluff from the Algonquin bar (Ab pl. I) to a point a few hundred feet south of Wildewood entrance (pl. III). South of Wildewood the bluff disappears, due to the lower elevation of the Covert Ridge, and the beach passes under the Algonquin dunes.

Southward from Wildewood to the vicinity of Bridgman the Calumet stage is represented by low parabolic, transverse, and festoon dunes (pl. Ill) which are nearly covered by dunes of Algonquin age. Between Bridgman and the south entrance to Warren Dune State Park, Calumet shore features have not been observed except at the north base of Tower Hill (pl. Ill) where a fragment of the dune buried Calumet beach has been uncovered by modern blowing.

Algonquin Stage

The Toleston stage (605 feet above sea level) has been described for areas in Indiana and Illinois at the head of the Lake Michigan basin, but this level was not observed in the Grand Marais Embayment. The next beach below the Calumet in this area stands 600 feet above sea level and represents the late Algonquin stage. The lake reached a low water stage, however, between the Calumet and the late Algonquin stage which has been called the Kirkfield stage of Lake Algonquin. The water level of the Lake Michigan basin at the time of the Kirkfield stage was about 10 feet (Cressey, 1928, p. 69) above the present level. Therefore, its beaches were covered and obliterated in the area of horizontality when the waters of late Algonquin rose to flood stage and 20 feet above the present lake level or 600 feet above sea level.

Shore features of the late Algonquin stage in the Embayment are spits, bars, wave cut bluffs, and dunes, — features that are among the strongest and most clearly shown in the entire area.

As the water level dropped from the Calumet stage to the Algonquin stage, large areas of the floor of the embayment were laid bare, and only the deeper northern part was covered by water, so that the water area of the embayment was only about one-fifth as large as in Glenwood time.

PLATE XVI. A. Calumet terrace south of the Riding Stable.

PLATE XVI. B. Calumet terrace north of the Riding Stable showing scattered boulders resulting from wave cutting of Covert Ridge.

The waters of the Algonquin stage occupied only a small lagoon, approximately one quarter of a mile in diameter, just south the Algonquin bar (Ab pl. I). This muck filled lagoon has a surface elevation slightly below 600 feet, but south of it the land is well above the Algonquin level. All of the bulky deposits of Algonquin dunes within the embayment were derived from the shore of the main lake.

An Algonquin bluff (pl. XIV) is a prominent feature along the western side of the Calumet bar (fig. 2) from a position northwest of Grande Vista to the end of the

Calumet bar at the Algonquin bluff 200 feet north of the Stevensville road. South of this point, the bluff is cut into the till of Covert Ridge and has a height of about 100 feet for a distance of 2,000 feet where it meets the Calumet terrace. From this point southward to the Algonquin bar (Ab pl. I), the Calumet terrace is continuous and the Algonquin bluff is cut from it. The bluff varies between three and 10 feet in height depending upon the amount of terrace that has been cut away. Near the Algonquin bar (Ab pl. I) the Algonquin wave action was relatively weak and here the Calumet terrace is broad with scarcely any Algonquin bluff. Boulders line the base of the Algonquin bluff for a distance of about two hundred yards, just west of the Riding Stable, and evidently were collected by ice push.

Both Algonquin and Calumet bluffs have undergone some stream erosion where they are cut in till. Many gullies have been cut in the bluff face and their associated fans or cones have been built out at the base. The largest development of gully and fan is at the base of the Algonquin bluff 50 feet south of the Grand Mere Beach road.

It should be noted that the amount of Algonquin shore erosion was considerably greater in some places than others along the Calumet terrace as indicated by the changing width of the terrace (pl. I). The unequal erosion is probably due to variations in the consolidation of the material constituting Covert Ridge. The stronger cutting east of North Lake is undoubtedly owing to the fact that the north and south Algonquin spits had not developed sufficiently to join and cut off the embayment, and that the opening from the main lake into the bay was relatively wide.

A little northwest of Grande Vista a series of five or more closely grouped Algonquin spits or bars (fig. 6) are outlined by the 600 foot contour (pl. I). These spits reach an elevation of approximately 605 feet on the west where they pass under the lee slopes of Nipissing dunes of the northern spit of the bay-mouth bar. From this location they make a gradual bend to the southeast approaching the Algonquin bluff on the Calumet bar and finally pinch out just short of the bluff. These spits were evidently built by northward moving shore currents along the east side of the embayment. They must have been developed and perhaps joined with the northern spit very soon after Lake Algonquin reached the 600 foot level. Development of the spits isolated a small triangular embayment northeast of the bar. The protection afforded by these bars accompanied by a lengthening of the northern spit resulted in a weaker development of the Algonquin bluff along the northern end of the Calumet bar. The bluff becomes less pronounced northward and toward the extreme northern part it dies out altogether and the Calumet bar has a gentle slope on its lakeward side.

Two later, narrower, and more southerly Algonquin bars (pl. XIV, A) extend from the base of the Algonquin bluff near the Grand Mere Beach road (pl. XVII, B), in a northerly direction to a position northwest of Grande Vista, where they bend sharply westward and near the Lake Michigan shore are covered by dunes of a later stage. These bars were evidently also formed along the east side of the embayment by shore currents from the south. They are considerably higher near the lake shore than they are near the Algonquin bluff where their elevation is barely above the 600 foot contour.

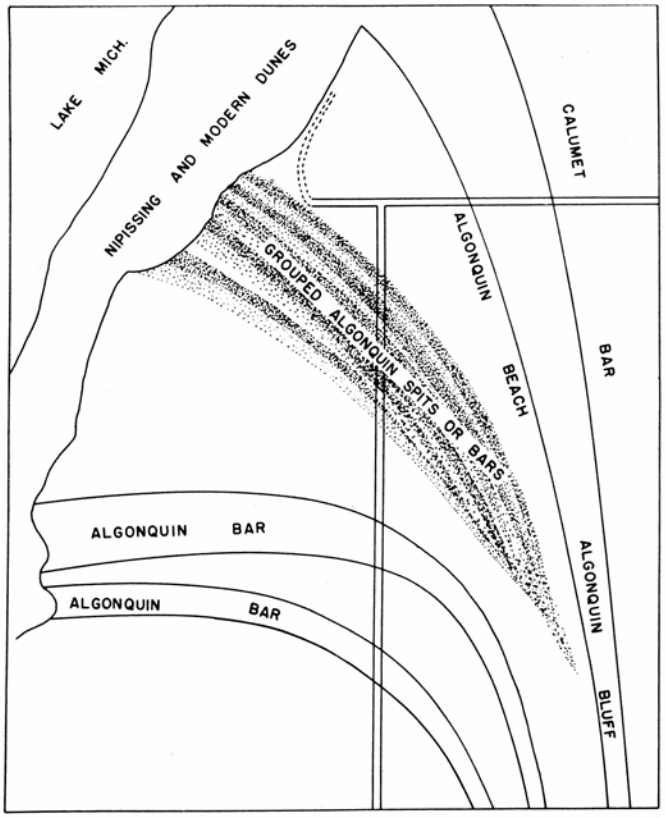


Fig. 6. Plan diagram of the first Algonquin spits formed in the northern part of the embayment.

The position of a well developed bar which early in Algonquin time was built across the embayment one mile south of South Lake, is shown by the 600 foot contour (Ab pl. I). This sand bar has a uniform crest about 605 feet above the sea, but is somewhat higher at its western terminal end. It forms a broad crescent from the Algonquin bluff, westward across the embayment and turns northward on the inside of the southern spit, which was developing northward at that time. Here it divides into two distinct ridges. The older ridge passes under a festoon Algonquin dune, 100 feet east of the Waverland Beach road, but the younger, bayward member apparently pinches out and was not dune covered.

The Algonquin beach again appears on the interdune area on the north of the festoon dune at the east base of Blueberry Hill, where it consists of three poorly defined beach ridges outlined by the 600 foot contour. These ridges converge a short distance to the northeast and form a single low ridge which can be traced around the end of the point east of Wilkins Dune. Here it makes a right angle turn and runs northwestward 300 feet. Beyond this point it has been cut away for a short

distance by the next lower lake level, the Nipissing. The Algonquin beach picks up again to the north and then passes under the lee base of Johnson Dune and Bald Top, but the elevation of the bench (pl. VIII) on which these dunes are built is 600 feet, the Algonquin level. From the lee base of Bald Top to Grand Mere Beach Point the Algonquin beach is fragmentary (pl. I) having been cut away for the most part during lower lake stages.

PLATE XVII. A. Looking southwest from top of Covert Ridge at Stevensville road showing Blueberry Hill (H), Wilkins Dune (W), Johnson Dune (J), Bald Top (B), Dunham Dune (D), Middle Lake (M), and Nipissing beach (N).

PLATE XVII. B. Looking north along the base of the Algonquin bluff (A) from Grand Mere Beach road showing Nipissing beach (N) and termination of first and second Algonquin bars (1 and 2).

The Algonquin beach can be traced around Grand Mere Beach point. On the north side it is covered by younger dunes near the Lake Michigan shore.

It is probable that most of the northern part of the southern compound recurved spit was repeatedly submerged and exposed during Algonquin time. Wherever the spit is not covered by dunes, its surface varies from a few feet above to a few feet below the 600 foot level. Small seasonal and periodical fluctuations in the level of Lake Algonquin would effect this condition.

The first series of Algonquin dunes was evidently developed as the water level dropped from the Calumet stage to the level of the Kirkfield low water stage of Lake Algonquin. These dunes are relatively low, having a maximum height of 30 to 40 feet. They consist primarily of a series of festoon dunes with many low longitudinal ridges, located on a wedge-shaped area of the Calumet lake bottom (pl. Ill) south of the Algonquin bar and between the Calumet bluff and higher parabolic dunes nearer the Lake Michigan shore. The widest part of this area is near the Algonquin bar but it narrows southward near the Bridgman-Weco Beach road. These dunes do not form a continuous cover for the Calumet lake bottom, which is the flat land exposed between them, but they have almost completely covered dunes of Calumet age in the area between the entrance to Wildewood and Bridgman, along U. S. Highway 12.

It is possible that these Algonquin dunes have migrated to some extent over the Calumet lake bed. They were formed during a period of lowering water level and receding shore which must have limited the available supply of material.

A row of complex parabolic dunes of the apex type and Algonquin age stands west, (pl. Ill), of the festoon Algonquin dunes. These dunes were formed and remodeled during the late Algonquin stage when the lake level stood at 600 feet. Many of the dunes show double ridges, an indication of two episodes of development. They can be traced southward as a compact row from the vicinity of Wildewood Beach, where they approach the present lake shore, to a large parabolic dune north of the First Church Camp road a short distance west of U. S. Highway 12 (pl. III). Farther south the Algonquin dunes have been almost entirely covered by younger Nipissing dunes and appear only where they extend out eastward, from beneath the lee bases of the younger dunes along the eastern edge of the area of dunes within the Embayment.

North of Wildewood Beach the later series of Algonquin dunes is somewhat fragmentary (pl. Ill), but on the whole they are larger and higher than the dunes south of the Beach. Two transected parabolic dunes southeast of Waverland Beach have only their south arms preserved. A large festoon dune which probably belongs to the later series is east of Brinkman Dune and Blueberry Hill. It can be shown to be of Algonquin age. This dune is especially interesting, because it is situated on the south spit which was forming across the embayment during Algonquin time; and it was truncated (pls. I and III) on its eastern or lee side during Nipissing time by the sapping action of waves in the bay.

The northernmost Algonquin dune on the south spit is between the lee ends of Wilkins Dune and Blueberry Hill. It is a parabolic apex dune showing two or more episodes of blowing near its apex. A festoon Algonquin dune built up 35 feet above its base, is on the north spit between the second Glenwood bar and the Calumet bar. It is the only dune of Algonquin age observed north of the outlet. The southern part of the dune covers the

northern end of the Calumet bar (pl. I), and both shoreward extensions have been truncated by waves of later lake stages.

Nipissing Stage

In late Algonquin time the ice was retreating to the northeast. It finally uncovered a lower outlet by way of North Bay, Canada, and the lake waters shifted from the three outlets of the final Algonquin stage—(1) Kirkfield-Trent River outlet that led southeastward to Lake Iroquois (now Lake Ontario), (2) the Port Huron, and (3) the Chicago Outlet. The new lower farther north North Bay outlet led to the Mattawa and Ottawa rivers to the St. Lawrence basin. The Port Huron outlet became dry as the water level dropped to a position considerably below the level of the modern lake. The shore features of this lowest Nipissing level are below the present level of Lake Michigan in the area south of the hinge line, which includes the Grand Marais Embayment; and consequently cannot be studied.

The North Bay outlet, however, was raised by continuing continental uplift north of the hinge line, and the Nipissing water level was once again elevated to the position of the Port Huron outlet. For a time both the North Bay and the Port Huron outlets functioned simultaneously. During this two outlet stage the strong Nipissing beaches and dunes were formed.

The Nipissing beach (late stage) in the Grand Marais Embayment stands about 5 feet lower (595-597 feet above sea level or 15 feet above Lake Michigan) than the 600 foot Algonquin beach and is closely followed by the 595 foot contour on the topographic map (pl. I). The strongest development of Nipissing time within the embayment is a strong foredune ridge which stands on the gently sloping bed of Lake Algonquin east of North Lake. This ridge, having an elevation above 600 feet, can be traced from near the Lake Michigan shore west of Grande Vista along a gentle southeastward curve to a position west of the junction of the Calumet bar and the Algonquin bluff north of the Grand Mere Beach road. Thence southward parallel to and about 300 feet from the base of the Algonquin bluff. Approximately 1200 feet south of the Grand Mere Beach road it swings southwestward away from the Algonquin bluff for a short distance and then southward, where it breaks up into an irregular crested foredune ridge most of which is below the 600 foot contour. South of the road between Middle and South lakes the ridge is difficult to trace and consists of a series of small, low, wind modified ridges with intervening gaps.

Near the Algonquin bar (Ab pl. I) the Nipissing shore is represented by a broad, flat swell or ridge which turns westward into the bar, and there forms a weak terrace. Near the western end of the Algonquin bar it takes the form of a well developed, low bar, extending northward, and is distinctly separated from the Algonquin bar by a small swampy depression (pl. I). North of this depression the Nipissing bar is attached to the southern end of a wave cut bluff on the lee slope of the truncated festooned Algonquin dune east of Brinkman Dune. The Nipissing beach extends northward along the western side of the embayment where Nipissing waves apparently truncated the lee slope of the festoon dune (pls. I and III). Northward from this bluff the Nipissing level is absent around the point east of Wilkins Dune and was evidently cut away by the waves of a lower post-Nipissing, perhaps the Algoma, level.

The Nipissing beach can again be identified along the northeast side of Wilkins Dune Point where waves have cut the eastern extension of Wilkins Dune and formed a low bluff between it and Johnson Dune to the north. The swamp road is located along the base of this bluff. Apparently the lee base of Johnson Dune was slightly cut by Nipissing waves, as a Nipissing spit that developed from the northeast corner of the lee base of Johnson Dune can be traced southeastward for several hundred feet.

A short break approximately 600 feet wide in the Nipissing beach occurs northward from the lee base of Johnson Dune. North of the break the beach appears as two small parallel ridges along the southeast side of Dunham Dune Point. During the Nipissing stage a well developed bluff in places 130 feet high was cut on the southeastern extension of Dunham Dune, but the Nipissing shore has been cut away from the Dunham Dune Point. During the Nipissing stage, however, the northeast extension of Dunham Dune along the northeast side of the point was truncated and in places a bluff 40 to 60 feet in height was developed. A well developed foredune ridge from four to eight feet high is in front (lakeside) of the cut bluff. Two spits developed from either end of the foredune ridge (pl. I); one from the southeast and the other from the northwest. Both spits die out rapidly from their places of origin.

It is probable that an opening to the main lake existed during Nipissing time between Dunham Dune point and Grand Mere Beach point. The present barrier between Lake Michigan and North Lake is a modified, modern foredune which has a maximum elevation of 618 feet and a minimum elevation only slightly above 600 feet. The curved dune along the south side of the abandoned channel shows definite evidence of having been cut by Nipissing waves along its curved northern side. A Nipissing beach containing some gravel is exposed in places at the base of the northern slope of the dune.

Grand Mere Beach point (between Middle and North lakes) shows no evidence of a Nipissing level, but On both the southeastern and northeastern sides it has a wall developed bluff from 15 to 20 feet high. The base of the bluff has an elevation from 587 to 590 feet above sea level, approximately the elevation range for the Algoma lake stage.

No definite evidence of the Nipissing shore can be observed between the north side of Grand Mere Beach point and the northern end of the Nipissing beach approximately three-quarters of a mile to the north. The

point just north of North Lake varies in elevation from 610 feet to less than 585 feet and is considered to be Algoma age. Since wind is actively modifying the dune at the present time, it undoubtedly has been considerably changed since its formation.

The Nipissing dunes on the whole, are the largest in the embayment, just as they are the largest in other areas in the Great Lakes region. Stevenson in discussing the Manistique area (1931, p. 485) states in conclusion, "the Nipissing has been the greatest stage of dune formation and has been productive of the largest dunes." Scott and Dow (1936, p. 446) found that Nipissing dunes are the largest in the Herring Lake area, and Calver reports them to be the largest in the Crystal Lake area.

During the development of the Nipissing dunes the lake level was high, transgressing on the shore, and forcing the shore line landward with the result that material available on the shore was actively remodelled by the wind.

The largest and best developed Nipissing dunes in the Grand Marais area are chiefly of the parabolic type as illustrated by Johnson Dune (pl. XVIII, A), Bald Top (pl. VI, A), Wilkins Dune (pl. XVIII, B), Blueberry Hill and Brinkman Dune (pls. I and III). These dunes are all on the southern Algonquin compound recurved spit near the northern end of the high dune area of the embayment. The highest of the group is Johnson Dune which rises 163 feet above its base to 763 feet above sea level. Bald Top rises 755 feet above sea level or 155 feet above its base. On the west side where it has been cut away by the lake it rises 175 feet above Lake Michigan. Wilkins Dune and Blueberry Hill have summits more than 150 feet above their bases. The apex of Brinkman Dune is 135 feet above its base.

Several dunes near the south end of the area (pl. III) reach elevations of more than 800 feet above sea level. These dunes, however, are standing on a surface approximately 640 feet above sea level, and consequently their actual heights above their bases seldom exceed 160 feet. Most notable of these high Nipissing dunes are Tower Hill, Mt. Fuller, and Mt. Randall, so named on the United States Geological Survey topographic map.

No Nipissing dunes are near the lake shore for approximately 1,000 feet north of Wildewood Beach (pl. III) where Algonquin dunes approach the lake. Opposite Wildewood Beach the Nipissing dunes reappear and can be traced southward as a series of complex, modified parabolic forms. In the vicinity of Wildewood Beach they are relatively small, but increase in size towards the south. Between Wildewood Beach and Weco Beach at least two episodes of development can be observed.

The Nipissing dunes have been modified and to some extent covered by modern dunes between Weco Beach and the State Park entrance (pl. III). Near the southern part of this area modern blows have extended eastward and completely engulfed and covered many Nipissing dunes.

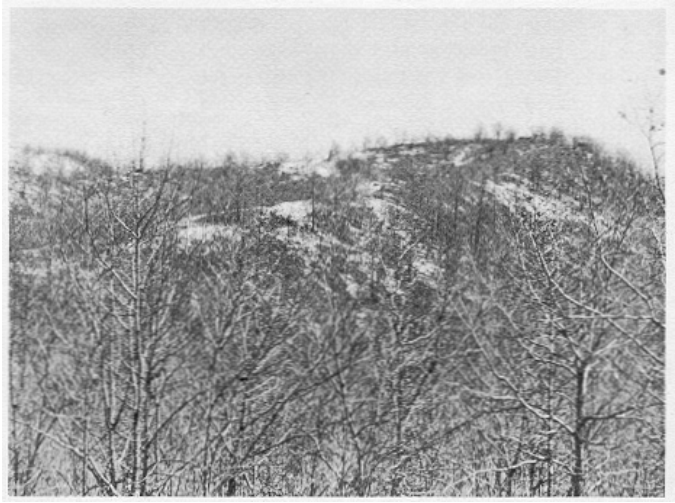


PLATE XVIII. A. View of the apex and a portion of the arms of Johnson Dune as seen from the north arm of Wilkins Dune.

PLATE XVIII. B. Looking east up the trough between the arms of Wilkins Dune.

North of North Lake on the northern Algonquin spit small Nipissing dunes have developed over the lakeward ends of the Algonquin spits (pl. I). The maximum height of these dunes is about 60 feet above their bases. They have been cut away to a large extent by Lake Michigan.

Dunhame Dune (pl. I) and its associated ridges appear to have been formed by the transection of a large Nipissing parabolic dune and subsequent removal of its southern arm by shore erosion within the bay and later modification by wind. The north arm of the dune is undergoing considerable eolian (wind) development at the present time.

Both Johnson and Wilkins dunes are excellent examples of parabolic dunes (pl. VI). Much of the north arm of Johnson Dune and of both arms of Bald Top (pl. XI) have been cut away by shore erosion of Lake Michigan. It seems probable that Bald Top was originally as long as Johnson and Wilkins dunes. A modern blowout (pl. XXI) is developing between Bald Top and Johnson Dune and is carrying sand nearly to the lee base of Bald Top where it has developed a 50 foot lee slope. This is the beginning of a new episode of blowing which may

develop to the magnitude of the modern blows north of the State Park entrance and may eventually completely destroy both Johnson Dune and Bald Top. Field investigations by Belknap, Landsberg and Rosby (1941, personal communication) indicate that large quantities of sand are being moved through this blow-out every year and that wind erosion is extremely active on the arms of Bald Top, Johnson Dune and in the windward part of the blow-out.

Both Johnson Dune and Wilkins Dune have a single wave of sand between their arms and part way up their windward slopes. This phenomenon is observed in other parabolic dunes, notably parabolic dunes of modern development between Weco Beach and the State Park entrance. These dunes have as many as three waves of sand between the foredune ridge near the lake shore and their crests. It has been suggested by Scott (personal communication) that such sand waves probably represent foredune ridges that have been blown landward into the mouths of the blow-outs, and that they have migrated to the positions where they are now found. This interpretation appears to be correct in view of the fact that many of these waves are still attached to the foredune ridges in the modern blow-outs, and that modern foredunes have a tendency to be bent landward into the mouths of the blow-outs (pl. XIX).

PLATE XIX. Looking north across the mouth of the blows just north of the Great Warren Dune State Park entrance showing the lee slope and crest of well developed foredune ridge (F), and several longitudinal ridges (L) extending landward.

Blueberry Hill has a rather complex form which apparently resulted from at least three episodes of blowing. The original parabolic dune developed, and was then partially transected and a saddle type parabolic dune was formed. A third episode of blowing developed the high apex of Blueberry Hill. A fourth episode of development seems probable in the shaping of the south arm of Blueberry Hill.

Brinkman Dune, likewise, shows three episodes of development with characteristics similar to Blueberry Hill. In Brinkman Dune, however, the undeformed arms of the succeeding dunes constitute a group having a final form of a gigantic clover leaf or a radiating pattern (pls. I, II). Such a multiple episode pattern may be due to varying directions of storm winds. Two other Nipissing dunes between Waverland Beach and Wildewood Beach (pl. III) have multiple episode pattern.

PLATE XX. A. Longitudinal ridge passing from foredune ridge upward into the first present blow north of the Warren Dune State Park Beach.

PLATE XX. B. View south along the lee slope of the foredune ridge lakeward of the blow-out in A showing attachment of longitudinal ridge.

Algoma Stage

The Algoma stage, and the presence of features at the correct level for that stage in the area south of the hinge line of the Lake Michigan basin have already been discussed. Within the northern, deeper part of the Grand Marais Embayment a continuous, low, sand beach ridge (pl. XIII) has been traced from near the Nipissing shore (1600 feet north of North Lake) southward along the east sides of North, Middle, and South lakes to the Algonquin bar (A pl. I). This sand beach is considerably stronger in its northern part where it lies east of the North Lake depression than farther to the south where it becomes somewhat flatter and more difficult to follow.

The location of the beach is well shown by the 585 foot contour on the topographic map (pl. I). The 585 foot contour, however, does not enter the southern-most basin next to the Algonquin bar (A pl. I). Opposite the points which separate North, Middle, and South lakes the beach is somewhat less prominent than where it stands directly east of the lake basins.

The Algoma beach has an elevation between 587 and 591 feet above sea level. A cross section which may be seen (pl. XIII, A) directly east of the point north of North Lake where a drainage ditch cuts through it shows a gently sloping lakeward side and a considerably steeper landward side.

Evidence of a level standing between 587 and 590 feet is found consistently all along the west side of the embayment on the eastern side of the southern, compound, recurved Algonquin spit. In places the evidence is a wave cut bluff, in others beach ridges, and in others bars and spits. An indication of a low, cut bluff is found along the swamp road south of the truncated festoon Algonquin dune (east of Brinkman Dune) and along the base of Brinkman Dune as far north as the point. The base is about 587 feet above sea level. A loop bar (Johnson, 1919, p. 109-111) (Scott, 1921, p. 151-153) shown on the topographic map (pl. I) stands for the most part a little above the 590 foot contour. The wave cut bluff can be traced from the north corner of the truncated festoon dune all the way to the southeastern Nipissing spit on the northeastern side of the point east of Dunham Dune. In places where the Nipissing level has been partially or completely cut away, the bluff is 10 or more feet high. On the southeast side of Dunham Dune point the bluff is 20 feet high. Opposite this point recurved spits and bars (pl. I) which extend eastward and separate Middle and South lakes have an elevation of from 587 feet to a little above 590 feet above sea level.

Both sides of the point east of Grand Mere Beach have been cut by the waves of the Algoma level to form a strong bluff 10 or more feet high on the southeast side and 20 feet high on the northeast side. A well developed beach and terrace are displayed along the northeast side of the point at the base of the bluff. East of the point a looped bar (pl. 1) has an elevation ranging from 585 feet to slightly more than 590 feet above sea level. Northward to the outlet of North Lake, the road is built on a 588 foot level along the lee base of a modern foredune ridge.

These features are all in the northern part of the embayment. The only other beach which stands at the elevation of the Algoma was found in the north blow of Great Warren Dune where a small fragment of a once buried beach (pl. XXII, B) has been exhumed, or uncovered, by wind erosion.

Heavily wooded dunes which may be of Algoma age cover the lakeward end of the south arm of Wilkins Dune, the north arm of Blueberry Hill, and the northern extension of the Brinkman Dune group. These dunes have a soil profile that is distinctly lighter in color than the soil of the Nipissing dunes and yet darker than the neutral soil profile of the modern dunes. The buff soil color disappears rapidly with depth. It seems, probable, therefore, that these dunes are somewhere between the Nipissing and modern dunes in age and may be correlated with a strong transverse ridge, (double in places), which parallels the Lake Michigan shore behind the foredune ridge, and can be traced more or less continuously (pl. Ill) southward past the State Park entrance. Modern blows have developed through this ridge between Weco Beach and the State Park entrance.

The lakeward sides of these dunes have been so severely cut by the waves of the modern lake that a high cut bluff is conspicuous along the lake shore. The bluff which is covered with vegetation was cut during recent high water stages of Lake Michigan. It is probable that this wave cutting established the conditions favorable to modern blowing.

Present Stage

The Lake Michigan shore at its present low water stage presents a remarkably broad, sandy beach, which is being constantly reworked by waves and currents for the entire length of the Grand Marais Embayment. During periods of relatively small waves the beach is building shoreward and forming well developed beach cusps (pl. X, A); (Evans, 1938, p. 615-627). During periods of storm, waves frequently cut away the beach ridge and attack the lakeward portion of the foredune ridge (pl. X, A). The off shore feature, "low and ball" described by Evans[8] (1940, p. 476-511), is particularly well shown on the aerial photographs (pl. II) of the embayment. The presence of "singing sand" (Cressey, 1928, p. 19-21) was frequently observed in the beach sand along the shore.

A modern foredune ridge (pl. V, A; pl. XIX, A) can be traced almost continuously from the Covert Ridge headland on the north to the southern extremity of the embayment. In places it reaches an elevation of 610 feet or about 30 feet above the lake, but on the whole it stands a little above or a little below the 600 foot contour (pl. 1). The windward slope (pl. IV, A) is generally between 10 and 15 degrees, except where cut by waves. Nearly everywhere on the lee side of the foredune the slope is between 20 and 30 degrees passing into a depression which may be as much as 10 feet deep. However, in many places the foredune is built against the base of a bluff cut in higher and older dunes to the landward, and the depression and lee slopes are absent.

A double foredune ridge is in several places along the embayment. The most notable example is between the outlet (North Lake to Lake Michigan) and the Nipissing beach on the north. There, two well developed foredunes parallel each other having a miximum depression of 15 feet between them (pl. I). The older,

landward foredune shows a distinctly older and more continuous covering of vegetation.

The foredune stands as a distinct ridge where it crosses the mouths of modern blow-outs. Examples are the bar west of North Lake, and in the areas of modern blowing (pl. XX, B; pl. XIX, A) between Weco Beach and the State Park entrance. However, the foredune ridges tend to bend landward wherever they cross these openings.

Dunes, other than foredunes, are forming on a large scale at several places in the embayment at the present time. Small active blow-outs and dunes may be observed in many places on the bar between Grand Mere Beach and the Covert Ridge headland to the north (pl. I), but the greatest present eolian (wind) activity is between Weco Beach and the State Park entrance.

A large area of freshly blown sand with a scanty cover of vegetation is between Dunham Dune and Bald Top (pls. I and XII) at an average elevation of 640 feet above sea level. This area is flanked with deep wind scoured troughs which have a minimum elevation of about 590 feet.

The blow-out between Bald Top and Johnson Dune has been discussed. The truncated, south arm (pl. XI, B) of Bald Top has a fresh blow where the sand, carried to the top of the dune, a vertical distance of more than 150 feet, has been deposited to form a gently curved dome which is visible for several miles in all directions.

No further blowing of present age and major significance has occurred from Bald Top to the vicinity of The First Church Camp, where two great parabolic dunes are in the process of development,—Mt. Edward, one quarter mile north, and another dune immediately north of the camp (pl. III). Mt. Edward, an apex type dune, has a maximum elevation more than 800 feet above sea level or 220 feet above Lake Michigan. The First Church Camp Dune (pl. VII, A) is about 160 feet above the lake and has a well developed saddle, Mt. Edward has two well formed longitudinal ridges (pl. XXIII) which extend from the foredune ridge toward the landward end of the trough. The northernmost ridge extends nearly to the apex and is attached to the south arm and the second or southern longitudinal ridge parallels the first, but extends only about half way up the trough. The First Church Camp Dune has three distinct transverse sand waves (pl. VII B. Two ridges show on pl. Ill): the first just landward of the foredune ridge at the mouth of the trough, the second about midway between the foredune ridge and the saddle, and the third in the saddle itself. These sand waves are believed to originate by migration of foredune ridges (pl. VII, B) up the trough of the blow-outs. It is suggested that high water stages and increased wave cutting may start the movement of these foredunes.

Great Warren Dune (pl. Ill) consists of a large area of present blowing which is some 2,000 feet wide and 2,000 feet long. Here the Nipissing dunes have been largely blown away and on the lee slope of the Great Warren Dune are being covered by modern sand. The blowing of Warren dune is taking place through a series of four large blow-outs (pl. XXIV) which have coalesced by lateral widening. Here again longitudinal and transverse ridges or waves of sand can be observed in the troughs. The transverse ridges are attached to the present foredune ridge, (pl. XXIV, B).

PLATE XXI. A. Blow-out between Bald Top and Johnson Dune as viewed from the Lake Michigan shore showing foredune ridge in the foreground.

PLATE XXI. B. View of the blow-out shown in A from its windward end. Note exhumed soil in foreground.

The development of two parabolic dunes is taking place at the present time just north of the Warren Dune State Park Beach (pl. III). The apexes of these dunes are about 120 to 130 feet above Lake Michigan. At the lower end of the northern dune (pl. IX, A) two longitudinal ridges are attached to the foredune ridge (pls. Ill and XXV, B) and three transverse ridges (pl. XXV, A) are in its upper two thirds. Leeward of the first bulky transverse ridge a great bowl shaped depression has been scoured by the wind. The bottom of the depression is below 600 feet in elevation and close to the water table as is shown by the damp sand floor and the more luxuriant growth of vegetation.

The southern dune has two longitudinal ridges which pass upwards along the trough of the blow where they

die out midway between the foredune ridge and the apex.

In an area about 3500 feet long and wide (pl. XIX, A) south of these two modern dunes and north of the State Park entrance (pl. XIX, A) the Nipissing dunes have been greatly blown out and deformed (pl. III). Fresh modern dunes are developing lee slopes considerably eastward of the bases of Nipissing dunes. Some of the highest points in the area are more than 800 feet above sea level. Mt. Fuller, Mt. Randall, Pikes Peak, and Tower Hill (pl. Ill), all within the area, are for the most part remnants of wind eroded Nipissing dunes. Three great troughs of active blowing are easily recognized. The northern trough (pl. XXVI, A) has three distinct transverse waves of sand and culminates in a saddle (pl. XXVI, B) just north of Mt. Randall. The middle trough, likewise, has three transverse sand ridges and terminates on the south side of Mt. Randall. Tower Hill and Pikes Peak form a high ridge along the south side of this trough. Opposite and north of Tower Hill a buried section of the Calumet beach has been exhumed by eolian erosion of a deep depression (pl. Ill). The third and southernmost trough passes between Mt. Fuller on the south and Pikes Peak on the north and terminates in a saddle south of Tower Hill. A single transverse sand ridge is in this trough.

[8]"Low and balls" constitute a series of troughs and ridges at various places along the shores of oceans and large lakes where the bottom slopes gently outward and where there exists an abundant supply of sandy sediment. These troughs and ridges lie roughly parallel to the shoreline and to each other and may extend continuously for many miles along the coast.

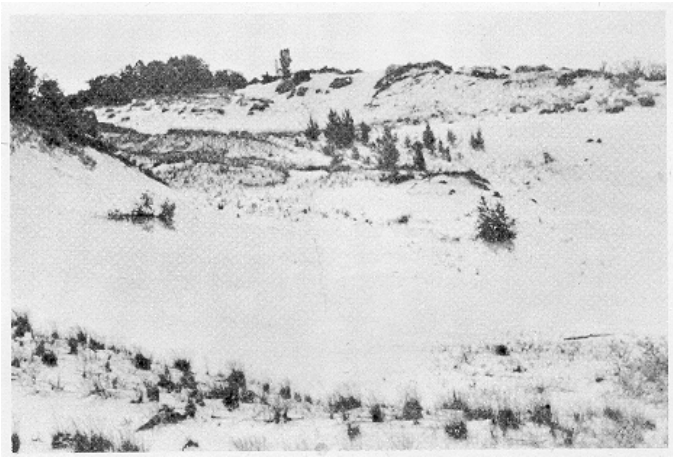


PLATE XXII. A. Southeast view from foredune showing longitudinal ridges in the middle blow of the Great Warren Dune.

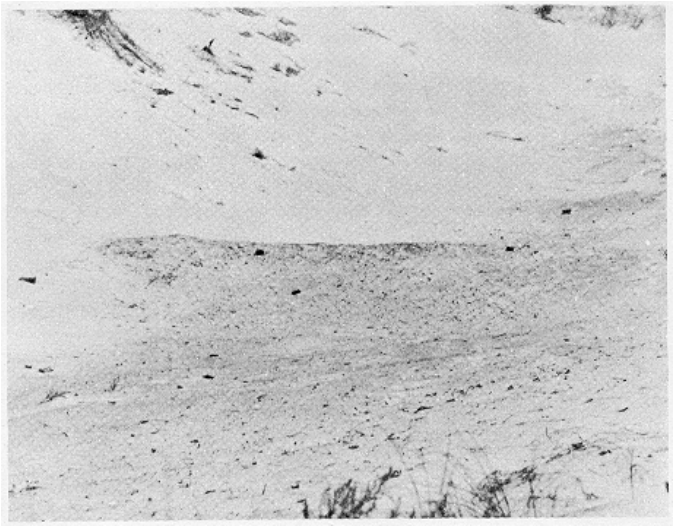


PLATE XXII. B. Post-Nipissing beach (Algoma ?) exhumed near the north attachment of Great Warren Dune.

PLATE XXIII. A. Longitudinal furrow and ridge in Mt. Edward blow.

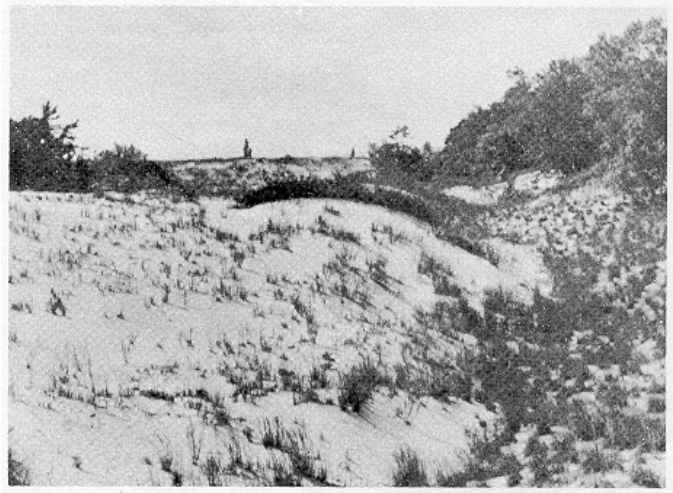


PLATE XXIII. B. Lee slope of longitudinal ridge in Mt. Edward blow.

PLATE XXIV. A. Looking from foredune up north blow of Great Warren Dune.

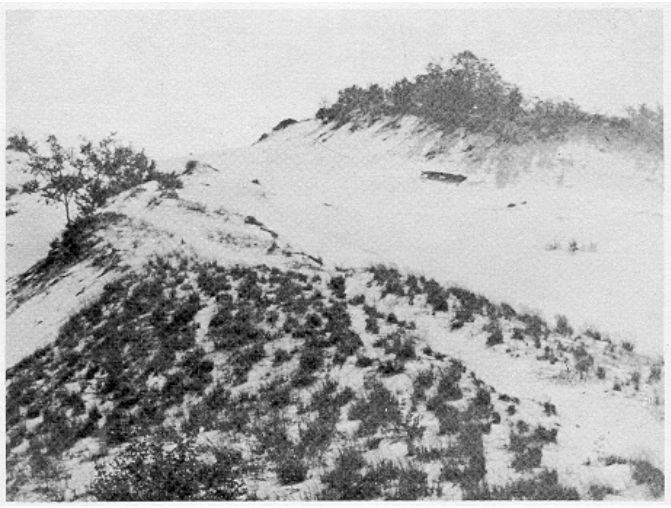


PLATE XXIV. B. View to the right and in panorama with A showing longitudinal ridge.

PLATE XXV. A. Looking east from the first transverse ridge in the first modern blow south of First Church Camp showing two transverse waves of sand in the background.

PLATE XXV. B. Looking west from the same position as in A showing foredune and area of wind erosion.

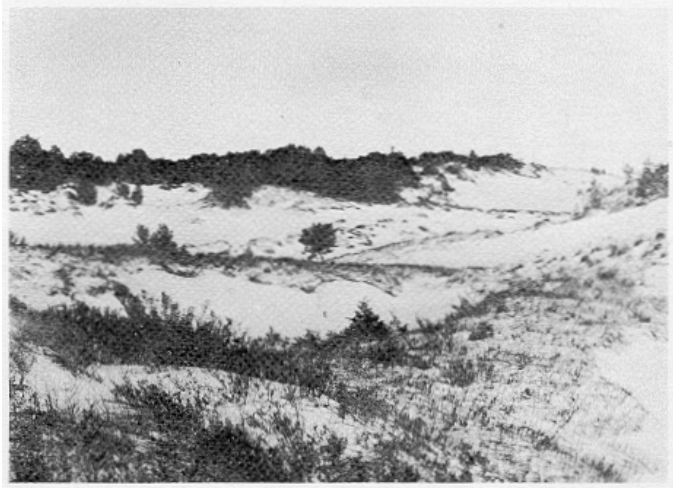


PLATE XXVI. A. General view looking northeast in the present blow north of the State Park showing transverse and longitudinal ridges.

PLATE XXVI. B. Looking east through the saddle of modern dune north of Mt. Randall.

PLATE XXVII. A. Exhumed stumps with roots imbedded in soil of Nipissing dune on the blow of Great Warren Dune.

PLATE XXVII. B. Close view of exhumed stump in A.

CONCLUSIONS

The Grand Marais Embayment lies between the Lake Michigan shore and the inner side of Covert Ridge. The easterly bend of Covert ridge in the locality is chiefly responsible for formation of the Embayment.

The pre-Lake Michigan lake stages—Glenwood, Calumet, Algonquin, Nipissing, and Algoma were present in the embayment and developed shore features. The waters of the Algonquin, Nipissing, and Algoma stages, however, were confined to the deeper, northern part of the embayment.

The Glenwood beach can be traced almost continuously along the landward side of the embayment; and the small dunes of this stage have migrated inland. They are the only migrating dunes known in the Great Lakes Region.

Shore forms of the Calumet stage can be traced from the northern end of the embayment to a position about midway between its north and south end. Southward Calumet shore features are primarily covered by dunes of younger lake stages.

The shore features of the Toleston stage are not recognized in the embayment. Algonquin shore features are the most prominent. Beaches, bars, and cut bluffs of the Algonquin stage are strongly developed in the northern part of the embayment where the waters of the stage were confined. Two ages of Algonquin dunes are recognized in the southern extension of the embayment. The earlier group was probably formed as the water lowered from the Calumet level and the higher and lakeward group were formed during the 600 foot stage. A compound recurved spit was built intermittently northward across the entrance to the bay during late Algonquin time. Its length and width implies that strong northerly currents were moving along the east shore of the lake. This bulky southern spit supplied sand for the large Nipissing dunes built on it. At the same time a much weaker and shorter spit was forming from the north across the embayment suggesting weak shore currents from the north. These two spits begun in Algonquin time did not join to cut off the embayment until post-Algoma time.

The late Nipissing beaches are rather weak in the embayment and are found only in the northern part. The largest dunes of the embayment chiefly of the parabolic type were developed at high water level of the Nipissing stage. All of these dunes were formed from the shore sands of the main lake.

A consistent level is found in the lower part of the embayment which corresponds to the elevation of the Algoma stage for the area of horizontality and is considered of that age. Numerous large dunes between Nipissing and present age cover the westward extensions of Nipissing dunes near the Lake Michigan shore and may be correlated with the Algoma Lake stage.

The present low water stage of Lake Michigan has a remarkably broad, sandy beach, and a well developed foredune ridge. Numerous modern blow-outs occur in the older dunes of the embayment and are actively forming large dunes. Initiation of these blow-outs probably is a result of erosion during recent high water levels of Lake Michigan.

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