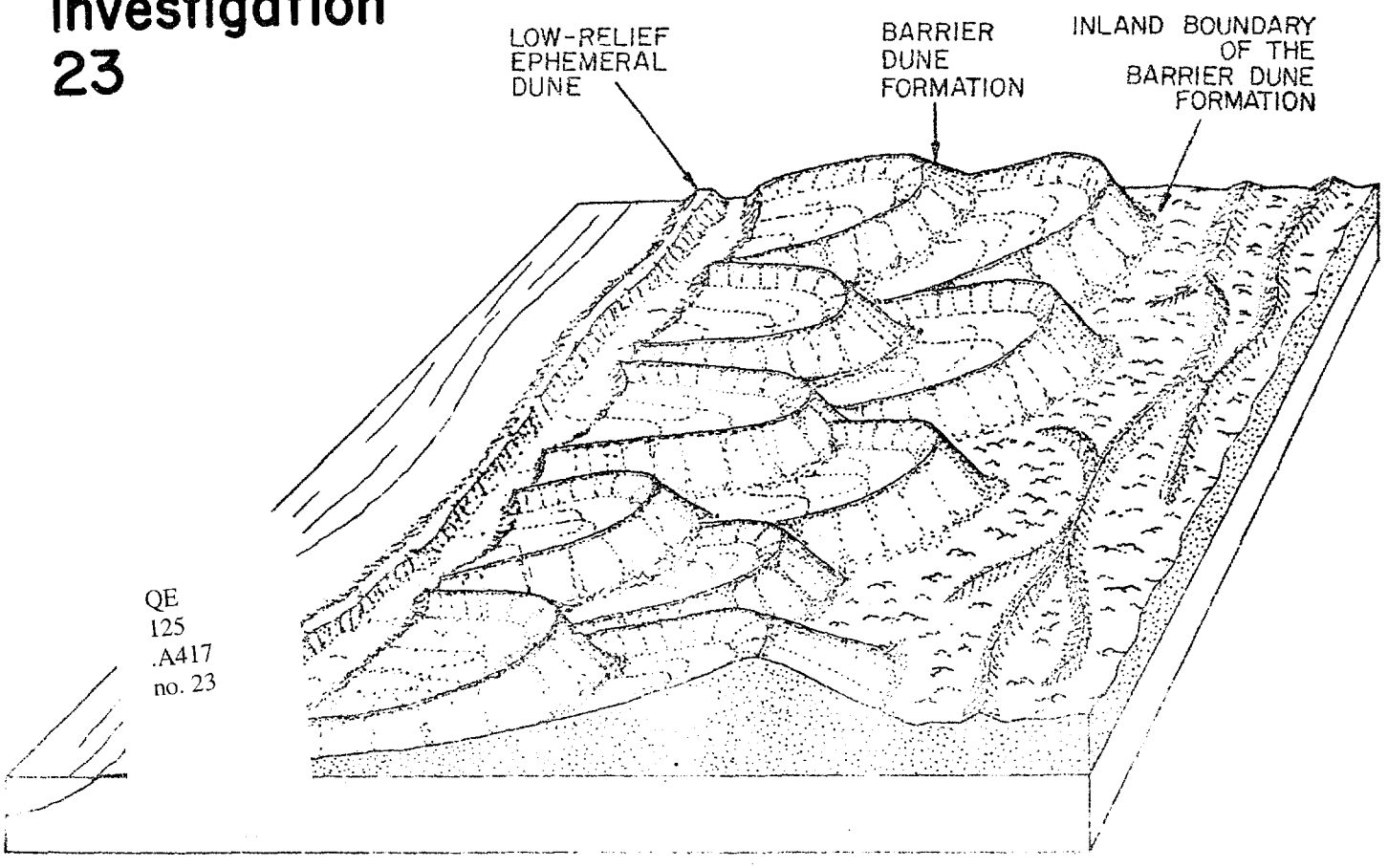
DUNE TYPE INVENTORY AND BARRIER DUNE CLASSIFICATION STUDY OF MICHIGAN'S LAKE MICHIGAN SHORE

Report
Of
Investigation
23



QE
125
.A417
no. 23

Geological Survey Division
Michigan Department of Natural Resources

Property of CSC Library

Geological Survey Division

Report of Investigation 23

DUNE TYPE INVENTORY AND BARRIER DUNE CLASSIFICATION STUDY of MICHIGAN'S LAKE MICHIGAN SHORE

U.S. DEPARTMENT OF COMMERCE NOAA
COASTAL SERVICES CENTER
2234 SOUTH HOBSON AVENUE
CHARLESTON, SC 29405-2413

by

William R. Buckler

Lansing, Michigan

1979

QE125 .A417 no.23 c.2
7169387
APR 03 1997

STATE OF MICHIGAN
Governor
William G. Milliken

DEPARTMENT OF NATURAL RESOURCES
Director
Howard A. Tanner

GEOLOGICAL SURVEY DIVISION
Chief and State Geologist
Arthur E. Slaughter

NATURAL RESOURCES COMMISSION
Hilary F. Snell, CHAIRMAN, Grand Rapids
Jacob A. Hoefer, East Lansing
Carl T. Johnson, Cadillac
E. M. Laitala, Hancock
Harry H. Whiteley, Rogers City
(Mrs.) Joan L. Wolfe, Belmont
Charles G. Younglove, Allen Park
John M. Robertson, Executive Assistant

Published by authority of State of Michigan
Compiled Laws of 1970 section 321.6

On deposit in many libraries in Michigan
and other selected locations
ISSN: 0543-8497

Copies of this and other DNR Geological Survey Division publications
are available from:

Information Services Center
Michigan Department of Natural Resources
Box 30028
Lansing, Michigan 48909

PREFACE

The "Dune Type Inventory and Barrier Dune Classification Study", as mandated under the "Sand Dune Protection and Management Act" (Act No. 222, P.A. 1976), was contracted to the Remote Sensing Project, Michigan State University in November, 1978. The purpose of the study was to develop a dune-type classification system to be used as baseline information in the sand dune mining permit decision-making process.

The information developed for dune-type classification was to be utilized in making a recommendation to the Department of Natural Resources to further define and identify "barrier dunes". The barrier dune as defined by the Sand Dune Protection and Management Act is "the first landward sand dune formation along the shoreline of a Great Lake or a sand dune formation designated by the Department."

The recommendations as identified in this report were, for the most part, accepted by the Natural Resources Commission as Guidelines (pursuant to the Administrative Procedures Act) and are included herein as an Appendix. Barrier dune formations (defined and referenced within the statute) have a special significance and therefore careful evaluation must be made of any proposed sand dune mining projects within barrier dunes.

In addition, the information developed in this report was used to delineate each dune type and barrier dune on black and white aerial imagery and U.S. topographic maps. The imagery and maps are available for public inspection at the Geological Survey Division Lansing office.

R. Thomas Segall
Geologist-in-Charge
Reclamation and Mining Control Unit
Geological Survey Division

ILLUSTRATIONS

Page		Figures
4	Figure 1.	Contractual high priority sand dune areas.
6	Figure 2.	Dune morphology classification of the Lake Michigan shore.
8	Figure 3.	Diagram of an idealized parabolic dune.
8	Figure 4.	Diagram of en echelon and overlapping parabolic dunes.
9	Figure 5.	High-relief parabolic dunes, Hoffmaster State Park.
9	Figure 6.	High-relief parabolic dunes and low-relief marginal sand apron, Warren Dunes State Park.
10	Figure 7.	Low-relief linear dune ridge parallel to the shoreline, Hoffmaster State Park.
10	Figure 8.	Moderate-relief linear dune ridge, Ludington State Park.
10	Figure 9.	Narrow low-relief dune terrace parallel to the shoreline.
11	Figure 10.	Diagram of a dune platform.
12	Figure 11.	Low-relief dune platform parallel to the shoreline.
11	Figure 12.	Diagram of domal dunes.
12	Figure 13.	Moderate-relief domal dune, undergoing shoreline erosion.
12	Figure 14.	Low- to moderate-relief complex dune field and high-relief parabolic dunes, Ludington State Park.
12	Figure 15.	Low-relief marginal sand apron.
13	Figure 16.	Inter-dune lowland, Warren Dunes State Park.
13	Figure 17.	Inter-dune lowland.
13	Figure 18.	Perched dunes, Sleeping Bear National Lakeshore.
14	Figure 19.	Perched dunes, Empire Bluffs.
14	Figure 20.	Diagram of an overriding dune.
15	Figure 21.	Diagram of dune assemblages with arcuate orientations within the Platte Lake Embayment, Benzie County.
18	Figure 22.	Diagram illustrating one type (parabolic) of barrier dune formation, its inland boundary and a low-relief ephemeral dune adjacent to its lakeward margin.
18	Figure 23.	Overlay on a topographic map base showing the outline of various dune assemblages.

Page		Tables
3	Table 1.	Boundary limits of the contractual high priority Sand Dune Areas (SDA).
5	Table 2.	Tague's (1946) main dune types for the Grand Marais Embayment, Berrien County.
7	Table 3.	Code for the dune morphology classification of the Lake Michigan shore.
17	Table 4.	Major stages of Glacial Lake Michigan.
19	Table 5.	Land cover/use categories used in the DNR-RSP Michigan lakeshore dune type inventory and barrier dune classification and the sand dune mining monitoring studies.

Page CONTENTS

iii PREFACE
v ILLUSTRATIONS
1 ABSTRACT
1 INTRODUCTION
1 Acknowledgments
2 PROJECT SCOPE AND PURPOSE
2 PROJECT STUDY AREAS
2 LITERATURE REVIEW
3 COASTAL AND SHOREZONE DUNE CLASSIFICATION
6 THE DUNE MORPHOLOGY CLASSIFICATION OF THE LAKE MICHIGAN SHORE
7 Dune Forms
7 Parabolic Dunes
9 Linear Dune Ridges
9 Dune Terrace
10 Dune Platform
10 Domal Dune
10 Complex Dune Field
12 Dune Flat
12 Marginal Sand Apron
12 Interdune Lowland
13 Relation of the Dune Form to the Underlying Formation
13 Nonelevated Position
13 Perched Position
13 Overriding Position
14 Relative Relief of the Surface Expression
15 Orientation of the Dune Form
15 Arrangement of the Dune Form within the Assemblage
15 Underlying and/or Associated Landforms
15 Boundaries and Identification of Dune Types
16 Interpretation Problems
16 THE BARRIER DUNE
18 LAND COVER/USE
18 PRODUCTS PROVIDED TO THE MICHIGAN DEPARTMENT OF NATURAL RESOURCES
18 Photo Overlays
20 Map Overlays
20 BIBLIOGRAPHY
29 APPENDICES
I IMAGERY USED
II LAND COVER/USE CLASSIFICATION
III BARRIER DUNES GUIDELINES ADOPTED BY THE NATURAL RESOURCES COMMISSION

DUNE TYPE INVENTORY AND BARRIER DUNE CLASSIFICATION STUDY of MICHIGAN'S LAKE MICHIGAN SHORE

by

William R. Buckler

ABSTRACT

This study has developed a dune morphology classification for the shorezone of Lake Michigan, and other Great Lakes adjacent to Michigan. The scheme is based on dune form, relative relief, orientation, arrangement and the relationship of the dune form to the underlying formation. Dune assemblages were identified and mapped according to this classification in seven priority sand dune areas along Lake Michigan.

Dune forms identified and described in this report include parabolic dunes, linear dune ridges, dune terraces, dune platforms, domal dunes, complex dune fields, dune flats, marginal sand aprons, and interdune lowlands.

Identification of barrier dunes cannot be accommodated in the classification scheme because dune types vary along the shore, and therefore, so does the form of the barrier dune. Consequently, the designation of the barrier dune assemblage is generally assigned to the dune assemblage whose forms display the greatest relative relief within the officially designated sand dune areas; this assemblage is adjacent to the beach or to the ephemeral low-relief dunes which are adjacent to the upper beach zone.

INTRODUCTION

The sand dunes along the shorezone of Michigan's Great Lakes are among the youngest geomorphic features in the state. Most are related to shoreline positions of higher glacial lakes during the last 13,000 years, although some are associated with the modern lakes. The largest dunes found today formed approximately 3,000 to 4,000 years ago at the time and during waning of the Nippissing lake stage. Water level of Lake Nipissing was 25 feet higher than present Lake Michigan. The dunes have undergone considerable change since then. Because of favorable conditions, nowhere were they better developed than on the eastern and southern shores of Lake Michigan. These dunes are somewhat unique and collectively probably represent the largest accumulation of sand dunes along any fresh water body in the world. They are valued by many as an aesthetically pleasing backdrop to the lakeshore, for the ecological communities which they support and for the recreational potential they provide. The environmental (climatic and geomorphic) conditions under which they formed no longer exist; once destroyed, these dunes are not likely ever to regain their present significant size and extent.

Nonetheless, the shorezone dunes are being destroyed. Loss due to storm wave erosion and associated processes is natural and has been going on since, and even occurred during, their formation. It will be thousands of years, however, before the major dunes are consumed by waves. A more rapid loss along some lakeshore segments is due to extraction for foundry core and molding sands, and glass making, as well as other uses. Sand mining along Michigan's western shore dates back to the last century and for much of this time has been a center of controversy. Severe restrictions have been placed on the use of most coastal dune areas in other states and in European countries. In Michigan, however, the dunes have mostly been under local government control which has proven to be largely ineffective in regulating mining operations.

Following concerted efforts by numerous individuals, organizations and units of government to preserve the present quality of the state's dunal topography, the Sand Dune Protection and Management Act (Act No. 222, P.A. 1976; M.C.L. 281.651-281.664) was passed in 1976. This act provides authority to the Michigan Department of Natural Resources (DNR) to undertake specified steps to ensure the wise use and protection of Michigan's sand dunes within two miles of the ordinary high water mark along all of its Great Lakes shorelines. The Act also stipulates that the Department is to make or cause to be made several types of comprehensive studies and inventories relating to the dunes and their values for environmental, recreational and industrial purposes. This document is a report of a study authorized under the provisions of the Sand Dune Management and Protection Act and contracted between the Geological Survey Division of the DNR and the Remote Sensing Project (RSP) at Michigan State University.

Acknowledgments. Special thanks are expressed to Professor Dieter Brunnschweiler for his critical comments during development of the dune classification and for his input to the initial RSP study proposal to the DNR. Appreciation is extended to Ger Schultink for coordinating various projects under contract with the DNR and for flying the photo missions. Valerie Stipe provided the line sketches, which were the basis for the final figures drawn by Donald R. Raymond. Other Michigan Geological Survey Division personnel were instrumental in helping to bring this report to publication. Jon Roethele and Mike Chapman were most helpful and cooperative as liaison with the Survey. Final editing was accomplished by Beverly L. Champion; layout, graphics and word processing were coordinated by Steven E. Wilson; and final manuscript typing was done by Lois J. DeClaire.

PROJECT SCOPE AND PURPOSE

The specific objectives of this study are:

1. To develop a classification system by which the various coastal dune types of the State, especially those of Lake Michigan, can be defined on the basis of morphology.

2. To inventory all dune types within designated high priority areas along the Lake Michigan shore.

3. To identify and designate "barrier dunes" within the designated high priority areas.

4. To inventory land cover/use within the designated high priority areas (in connection with another DNR - RSP study).

This study has been coordinated with two other projects under contract to Michigan State University. The Remote Sensing Project involves research aimed at developing procedures to inventory and monitor sand dune mining activities, whereas the Department of Resource Development is assessing the effects and impacts of "barrier dunes" in the sand dune areas upon aesthetic, environmental, economic, industrial and agricultural interests.

PROJECT STUDY AREAS

The study was conducted within seven high priority areas consisting of nine shoreline segments along Michigan's Lake Michigan shoreline. The boundaries of the segments designated under this contract largely coincide with those more recently determined by the DNR for the Series I Designated Sand Dune Areas (Michigan Department of Natural Resources, 1978). Each segment herein has been given the same code letter as listed in the DNR - RSP contract; and the segments are not in sequence along the shore (Figure 1; Table 1)

LITERATURE REVIEW

Literature on sand dunes is extensive, but all except a small part has been published in Europe. Most of the important contributions on coastal dunes have come from Germany, Denmark, Holland and Belgium, although some are from Australia, New Zealand, Argentina and Peru. In relation to desert dunes, the main studies have been conducted in the Sahara, with the western part favored by French investigators and the eastern by British. Bagnold's (1941) comprehensive work on the physics of blown sand, based on experiments and long field experience in Egypt and Libya, is the most notable contribution in its field.

In North America the list of important contributions is meager. Inland dunes have been studied more than coastal dunes. Contributions by H.T.U. Smith (1940, 1949, 1951, 1965), Melton (1940), Hack (1941) and Cooper (1935, 1938) are noted. Coastal dunes in particular have been neglected, although they cover a great extent of shoreline and in many places are imposing. The dunes along the west coast of the U.S. have been studied best (Cooper, 1958, 1967); but little has yet been published on the dunes along the Atlantic and Gulf coasts.

Although the sand dunes along Lake Michigan shores cover extensive area, relatively little scientific research, especially in the last several decades, has been published regarding them. Early emphasis was placed on the ecological relationship between vegetation and dunes. Cowles (1899) contributed the first major study, a classic dealing primarily with the dunes of northwestern Indiana. Waterman (1917, 1919, 1922a, 1922b, 1926) and Fuller (1912, 1918) centered their attention principally on Michigan. Cressey (1928) provided another early classic in his attempt to explain the origin of the lakeshore dunes. In the late 1920's, 1930's and into the 1940's, I. D. Scott (1920, 1927, 1930, 1934, 1938, 1939, 1942; Scott and Dow, 1936) concentrated extensive field research on the origin and evolution of Michigan's shoreline dunes. Considering the great amount of work he accomplished, very little was actually published. His field notebooks are available at the Michigan Geological Survey, as is an unfinished and incomplete manuscript dealing with his research. Several of his students centered their research on specific areas along the shore (Tague, 1946; Colver, 1946; Dow, 1937; Stevenson, 1931).

The Sleeping Bear dunes attracted the attention of many workers (Thompson, 1967; Gillis and Bakeman, 1963; National Park Service, 1961; Johnson, 1957; Martin, 1942; Dow, 1937, 1940; Waterman, 1922b, 1926), whereas Evans (1936, 1937) was interested in the origin of the coastal lakes of western Michigan. Since Olson's 1958 series of three articles on dune development, however, there has been no publication of major significance on the geologic aspects of Lake Michigan shoreline dunes.

Several less technical references are available (Kelley, 1971; Dorr and Eschman, 1970) as are numerous references on coastal marine dunes in general (Davies, 1973; King, 1972; Bird, 1969; Zenkovich, 1967; Steers, 1964; Gresswell, 1957). Kelley (1962) compiled a map of the sand dunes of Michigan; dunes were mapped along Lake Michigan by Hand (1970), Gifford and Humphrys (1966), Powers (1958), Humphrys, Horner and Rogers (1958), Martin (1955) and Leverett and Taylor (1915). Additional references are cited in the bibliography.

COASTAL AND SHOREZONE DUNE CLASSIFICATION

A comprehensive scheme of classifying all types of coastal and shorezone dune forms is not yet available, to the author's knowledge, in the geomorphic literature. Likely, this is because the forms of dunes and their evolution are subject to great variability in relation to local environmental conditions. Overall classification schemes developed for desert or continental dunes (Bagnold, 1941; Melton, 1940; Hack, 1941; Smith, 1965; McKee, et al., 1977; and others) are not applicable to dunes formed under marine or lakeshore conditions. Numerous coastal dune classifications have been devised (Briquet, 1923; van Dieren, 1934; Steers, 1946; Smith, 1954, 1960; Cooper, 1958, Table 1). 1967; Davies, 1973; and others). Some are based on dune genesis, others on dune morphology, and still others on a combination of the two. Nevertheless, none are particularly appropriate to the shorezone dune forms of the Great Lakes, and more specifically, Lake Michigan. All classifications were based on marine conditions and not on the special circumstances related to the Great Lakes. The majority of the dunes of the Lake Michigan shorezone were formed at the time and during waning of higher glacial lake levels; eolian sand accumulation was favored because abundant source material (from eroding unconsolidated Pleistocene and Recent sediments), a predominantly westerly wind flow, a semi-arid climate and a potential depositional zone prevailed.

High Priority Sand Dune Area		Northern Limit/Southern Limit
A1 [a]	Lincoln-Lake-Chikaming SDA (R 281.401)[b]	North Line-Sec 9 - T5S, R19W/ South Line-Sec. 9 - T7S, R20W
A2	South Haven-Covert-Hagar SDA (R 281.402)	North Line-Sec. 21 - T1S, R17W/ South Line-Sec. 16 - T3S, R18W
B	Golden-Benona-Claybanks SDA (R 281.405)	North Line-Sec. 4 - T15N, R18W/ South Line-Sec. 8 - T13N, R18W
C	Summit-Pentwater SDA[c]	North Line-Sec. 23 - T17N, R18W/ South Line-Sec. 27 - T16N, R18W
D	Grant-Hamlin-Pere Marquette SDA (R 281.406)	Magoon Creek, north of South Line-Sec. 28 - T21N, R17W/ South Line-Sec. 9 - T18N, R18W
E	Hendricks-Moran SDA (R 281.407)	West Line-Sec. 8 - T42N, R7W/ East Line-Sec. 23 - T41N, R5W
F1	Fruitland SDA[c]	Centerline-Sec. 11 - T11N, R18W/ East Line-Sec. 25 - T11N, R18W
F2	Laketon-Fruitport-Spring Lake-Grand Haven SDA (R 281.404)	S 1/16 Line-Sec. 7 - T10N, R18W/ South Line-Sec. 21 - T7N, R16W
G	Grand Haven-Port Sheldon SDA[c]	North Line-Sec. 28 - T7N, R16W/ Centerline-Sec. 28 - T6N, R16W

a These code letters refer to the priority sand dune areas as listed in the initial DNR-RSP contract and are used informally to identify the areas.

b These names and rule numbers refer to the legally designated sand dune areas of Series I as promulgated under authority of the Sand Dune Protection and Management Act (Act No. 222, P.A. 1976); in accordance with the Administrative Procedures Act (Act No. 306, P.A. 1969 as amended).

c These are priority sand dune areas listed in the initial DNR-RSP contract which are not legally designated Series I sand dune areas; they will be included in the Series II areas.

Table 1. Boundary limits of the contractual high priority Sand Dune Areas (SDA).

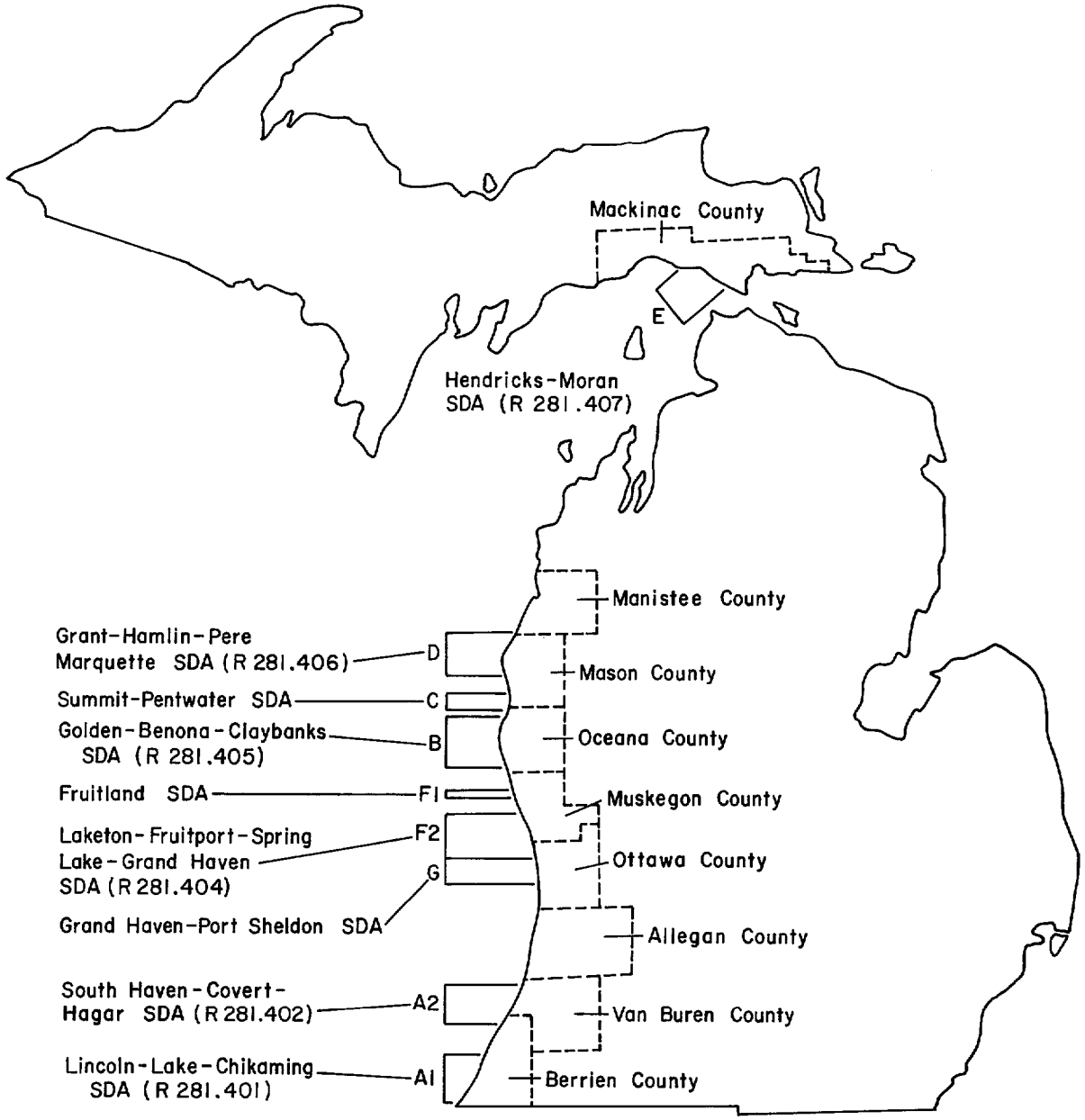


Figure 1. Contractual high priority sand dune areas.

Cressey (1928) recognized two characteristic dune types at the southern end of Lake Michigan:

> The foredune is essentially a ridge parallel to the shore and built just beyond the reach of the highest waves. Its linear character is due in part to the influence of the lake winds, in part to the belt of vegetation which springs up beyond the beach margin, and largely to the supply of sand. Blowout dunes are commonly developed along the shore by the action of the wind in scouring out through the established dunes a passage which later is widened, deepened, and extended inland. At their maximum development their windward slopes resemble large amphitheaters. (p. 38).

In a study of the Grand Marais Embayment of Berrien County, Tague (1946) classified dunes as being primary or 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. (p. 25).

His description of each dune form is listed in Table 2.

Fuller (1918) recognized perched dunes on the islands in the northern part of Lake Michigan and on the adjacent mainland. These dunes

> ...are developed upon substrata elevated some distance above the beach. They may have been formed either by a wind eddy at the top of a short cliff, or have travelled inland from the beach over higher land. The term also applies to dunes formed on an old beach which from the subsidence of the lake level finds itself much above the level of existing waters. (p. 111-112; also see Dow, 1937; Bergquist, 1936; Waterman, 1922, 1926).

Although various shoreline segments have been investigated in detail and dune types designated in these studies, a complete inventory of eolian deposits along the Lake Michigan shore has not been made. An objective of this study was to devise a dune classification based on morphology

Table 2. Tague's (1946) main dune types for the Grand Marais Embayment, Berrien County.

→

FOREDUNE

Foredune ridges are the first dunes to become established along a shore. 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 of 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.

DUNE RIDGE

Foredune ridges may blow out due to the removal of protective vegetation by fires, lumbering, building of roads or by wave cutting 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, 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 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.

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.

which is appropriate for the Lake Michigan and other Great Lakes shorelines. Some of the terminology expressed by earlier researchers is not applicable in the proposed new classification. For example, there are three recognizable dune forms which are commonly accepted as foredunes. Tague's (1946) use of the term longitudinal dune is inappropriate as it is generally restricted to a desert type. Dunes may be perched but the term gives no indication as to their form and stratigraphic relation to the underlying non-dune formation. The proposed scheme attempts to eliminate such ambiguous or conflicting terminology.

THE DUNE MORPHOLOGY CLASSIFICATION OF THE LAKE MICHIGAN SHORE

The suggested classification of dune types along the shore of Lake Michigan (Figure 2) is based on dune form, relative relief, orientation, arrangement, and the relationship of the dune assemblage to the underlying formation. The scheme is objective in that it relies on morphologic and geometric patterns which can be interpreted from aerial imagery at a scale of 1:20,000 and larger. The classification is not meant to express dune genesis.

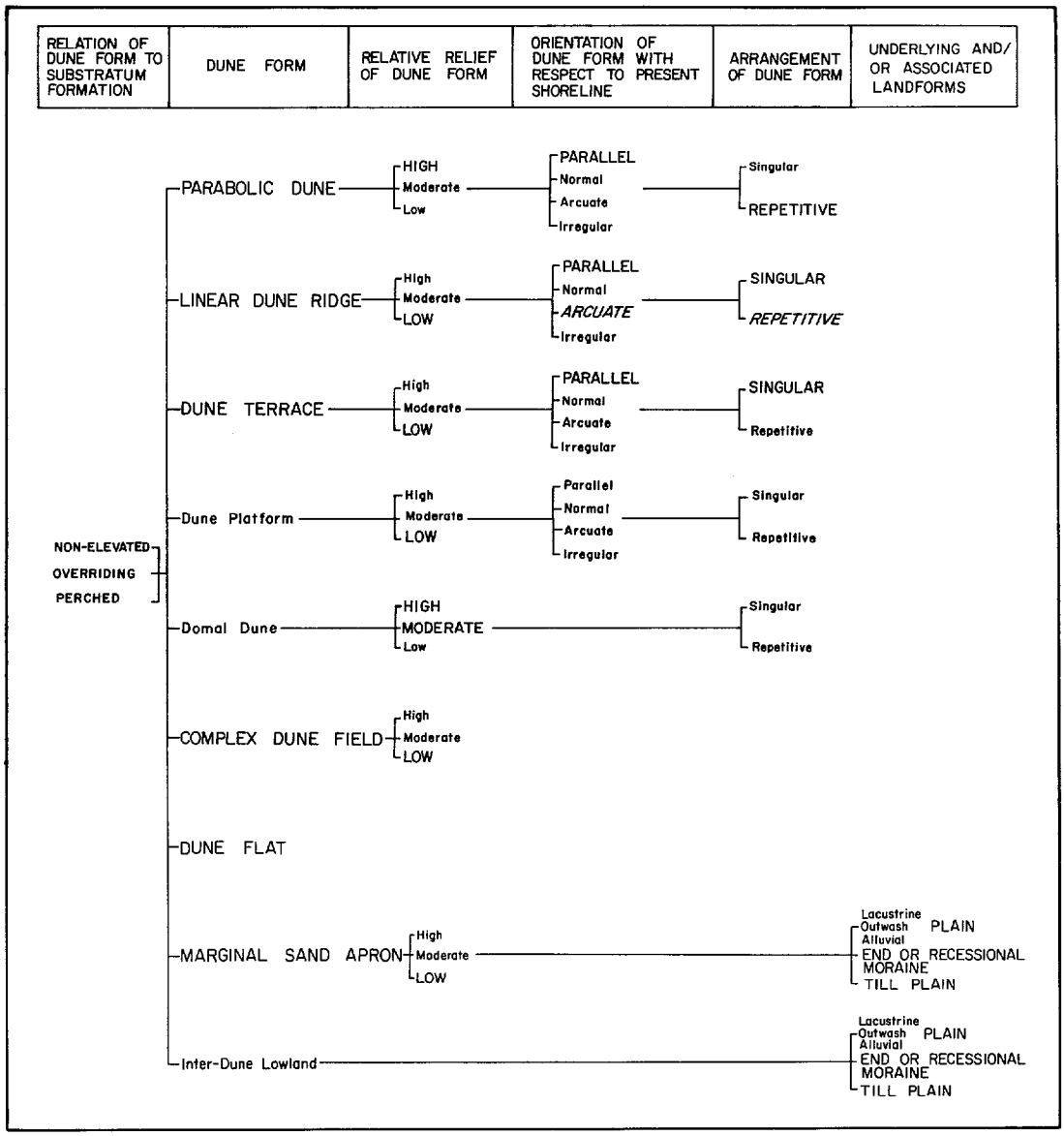


Figure 2. Dune morphology classification of the Lake Michigan shore. Dune forms and correlated characteristics which are more common or dominant are indicated by capitization.

Nine different dune forms are recognized in this classification[1]. Each assemblage of these forms may be expressed as having high, moderate, or low relative relief. With respect to the present shoreline, parallel, perpendicular, arcuate or irregularly oriented forms are possible. And within each area a single or multiple number of individual dune forms of the same type may be designated. Dune assemblages may be nonelevated, or they may be perched on top of, or override a steep slope of a nondune formation. Each characteristic under the various classification headings has a distinct alphabetic notation (Table 3). The dune type or assemblage may then be identified by a series of alphabetic symbols. For instance, a single dune ridge of approximately nine feet in height adjacent and parallel to the upper reach of the beach may be identified as Rlps (dune Ridge, low relative relief, parallel to the shore, a singular arrangement). A complex dune field with relative relief of approximately 48' perched on top of a nondune formation whose surface is 120' above Lake Michigan is indicated by Cm/700' (Lake Michigan is assumed to be at an elevation of 580' above sea level; therefore, the surface of the nondune formation, being 120' above the lake, stands at 700' above sea level). The scheme is designed to be somewhat flexible and can accomodate a wide variety of dune types which may be encountered along the Lake Michigan and other Great Lakes shorezones.

Dune Forms

Parabolic Dunes

Individual parabolic dunes have ground plans which are bow-, U- or hairpin-shaped (Figures 3 through 6, 17). They generally have sharply defined limbs that increase in height inland, and are oriented perpendicularly to somewhat obliquely relative to the shoreline. The concave, or open, side of the dune faces the shore and exhibits a relatively gentle slope, steepening somewhat near the crest and apex. The slope of the convex, or inland, portion is characteristically steep and descends abruptly from the crest at the angle of repose. It is not uncommon to find other types of low- to moderate-relief dunes between the limbs of, or between individual, parabolic dunes.

[1] The classification was developed specifically for this project study. Because Act 222 defines a "sand dune area" more broadly than is generally accepted in the geologic and geomorphic literature, several minor modifications of the classification would be needed before it could stand alone. For example, a dune flat was incorporated into the scheme to cover certain features designated under the Act as "sand dune areas" but which are, genetically, lacustrine and not eolian sand deposits.

First Letter (Dune Form)
- A Marginal Sand Apron
- C Complex Dune Field
- D Domal Dune
- F Dune Flat
- L Inter-Dune Lowland
- P Parabolic Dune
- PL Dune Platform
- R Linear Dune Ridge
- T Dune Terrace

Second Letter (Relative Relief)
- l low (0-20')
- m moderate (20'-80')
- h high (80'+)

Third Letter (Orientation)
- a arcuate
- i irregular
- n normal (perpendicular)
- p parallel

Fourth Letter (Arrangement)
- r repetitive (multiple)
- s singular

Relation of dune form to substratum formation

Xxxx[a]	non-elevated
$\frac{\text{Xxxx}}{\#}$[b]	perched
Xxxx/[c]	overriding

a Non-elevated dunes are represented by only the four (or less) code letters.

b Perched dunes are represented by the four (or less) letter code over a horizontal bar below which is the height above sea level of the surface of the underlying non-dune formation (the Lake Michigan surface is approximately 580' above mean sea level).

c Overriding dunes are represented by the four (or less) letter code followed by a slash.

Table 3. Code for the dune morphology classification of the Lake Michigan shore.

Widths typical of parabolic dunes are up to one-quarter of a mile, with lengths in some cases greater than one-half mile; heights may be more than 150 feet. Generally, the highest relief of these dunes is at the apex, although within an assemblage the apexes are not necessarily accordant. Blowouts are frequently found between

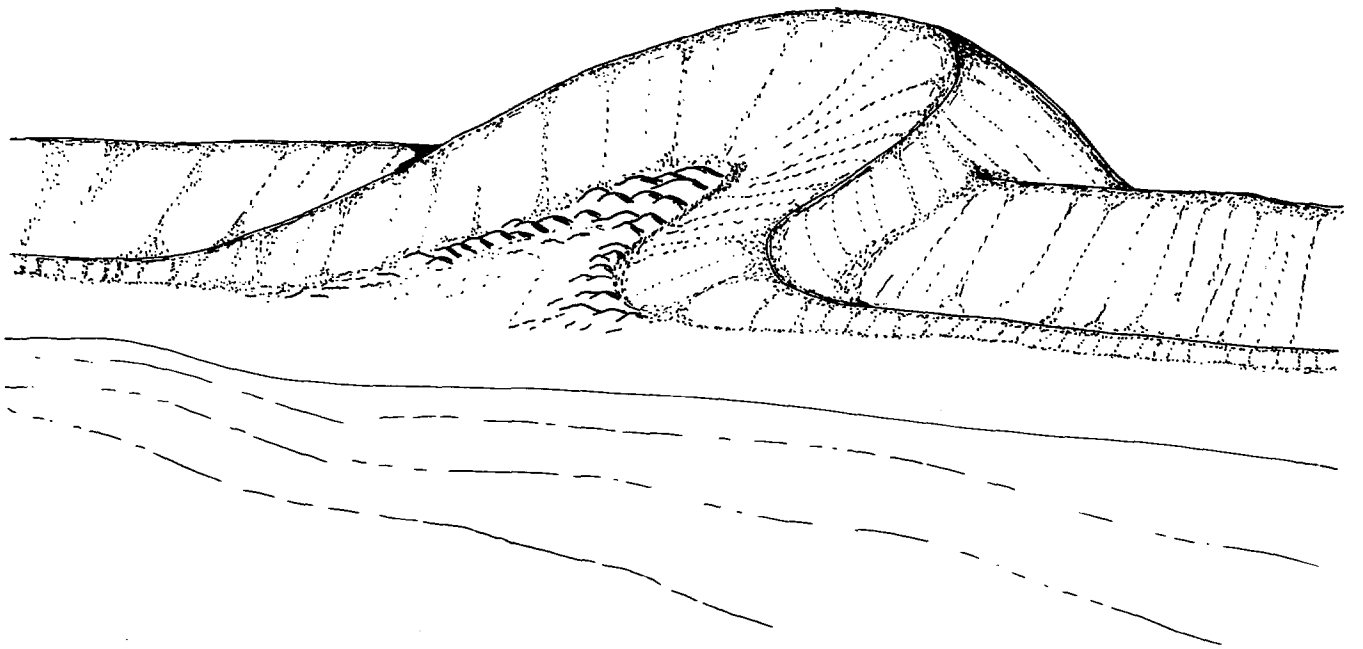


Figure 3. Diagram of an idealized parabolic dune.

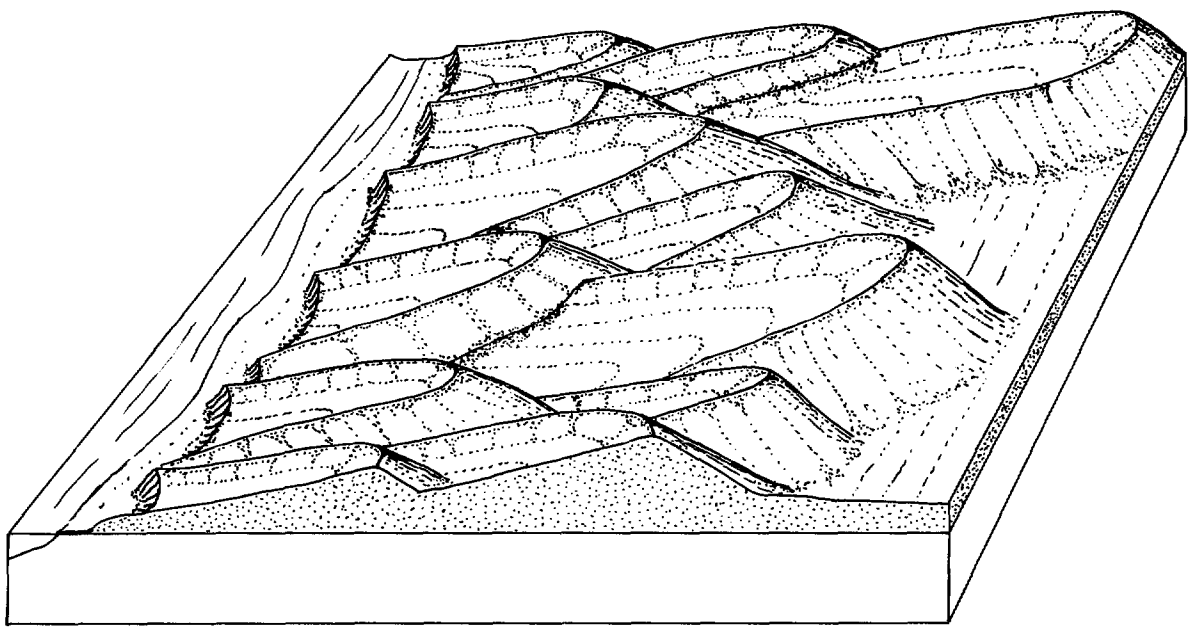


Figure 4. Diagram of en echelon and overlapping parabolic dunes.

the limbs and on the open concave slope. These dunes are typically grouped into an assemblage which trends PARALLEL to the shore; the individual forms, though, are often arranged en echelon (Figure 4) and not uncommonly overlap. In some cases, the trend of the dune assemblage takes on a broadly ARCUATE outline. Commonly, two generations of parabolic dunes may be found adjacent to each other. The shoreward group tends to be higher, more compact, and to display better-defined individual forms. The inland group generally is lower in overall height and the individual forms are somewhat more dispersed and less distinctive. Sometimes only portions of their "ideal" form are evident and their overall pattern occasionally resembles rather sinuous irregular ridge topography[2]; en echelon arrangement seldom exists. Because of shoreline erosion, it is not unusual to encounter numerous examples where only remnants of parabolic dunes remain.

Linear Dune Ridges

Linear dune ridges are elongated sand ridges whose overall trend is PARALLEL, ARCUATE, or, in rare cases, NORMAL (perpendicular) to the present shoreline. Some, especially those associated with older, higher, glacial lakes, have an IRREGULAR trend with respect to the present shore (Figures 7 & 8). The parallel and arcuate varieties are frequently asymmetrical in cross profile, with a gentler slope lakeward and a steeper slope on the inland side. However, this may not hold true if the lakeward slope is adjacent to the shoreline and is undergoing wave erosion. The normal and irregular varieties are typically more symmetrical, with the former type generally crested and the latter displaying a more arching convex topographic expression. Linear ridges may be found as single features or in multiples (repetitive) with intervening swales, the latter varying in width. In plan view the ridge may vary from rather straight to somewhat sinuous and in longitudinal profile the crest may not be accordant. The crests may be sharp or rather rounded. In places they may be breached, often due to natural blowouts or artificial leveling. Where small blowouts exist, the crest line may mimic a "parabolic trend" for a short distance (although, because of its small nature and limited extent, it is not classified as a parabolic dune).

[2] It is thought by most researchers that parabolic dunes are derived from repeated blowouts in dune ridges; "the central extensions of the blowouts...develop in height, length and breadth from repeated blowing and by addition of sand from the shores" (Tague, 1946).

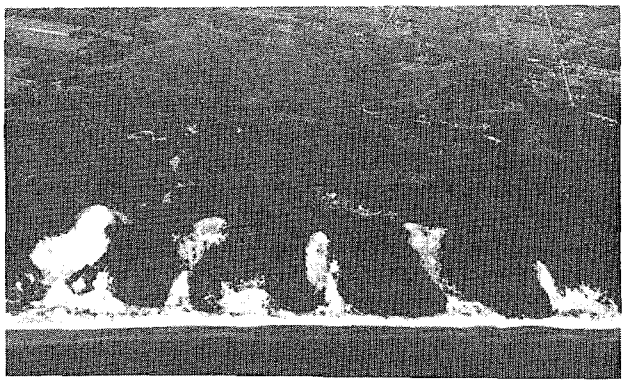


Figure 5. High-relief parabolic dunes, Hoffmaster State Park (Section 36, T9 N, R17W and Section 1, T8N, R17W; Muskegon-Oceana County line).

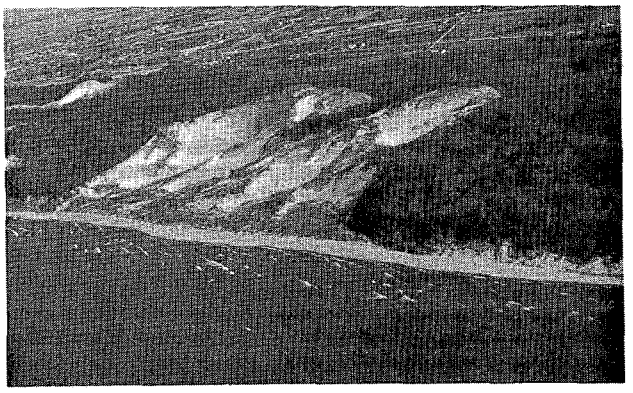


Figure 6. High-relief parabolic dunes (center ground) and low-relief marginal sand apron (background), Warren Dunes State Park (Section 26, T6S, R20W; Berrien County).

Not uncommonly, the end segments of the dune ridges have subdued elevations and are somewhat broadened. Adjacent ridges are not necessarily of the same elevation and local relief between crests and adjacent swales need not be similar. The toe of the dune on opposite sides of a single ridge crest may or may not be at the same elevation. The low-relief arcuate type and some low ridges associated with older, higher, glacial lakeshores may represent beach ridges of lacustrine sand and gravel, veneered by eolian sand.

Dune Terrace

A dune terrace almost always follows a distinctly linear shoreline trend maintained over an appreciable distance. It is bounded on one side by a higher bluff slope (for example, that of another dune form, a moraine or another terrace) and on the opposite side by lower relief topography

Figure 7. Low-relief linear dune ridge parallel to the shoreline, Hoffmaster State Park (Section 36, T9N, R17W; Muskegon County).

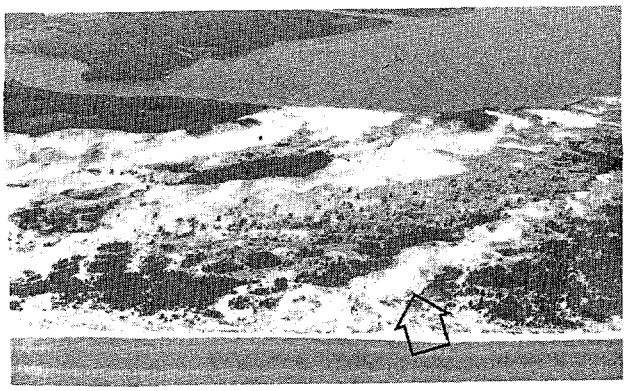


Figure 8. Moderate-relief linear dune ridge, Ludington State Park (Sections 6 & 7, T19N, R18W; Mason County).

(Figure 9). In profile, the majority of the dune surface is more or less level, but may display some hummocky relief. The slope rising from the lower elevation (generally the beach) to the terrace surface may be gentle to rather abrupt, especially if undergoing wave erosion. The terrace is almost always elevated less than 25 feet, and typically less than 15 feet, above the lower level. If more than one terrace is present, the topography will have a step-like profile. These dunes are generally PARALLEL to the present shoreline; occasionally, however, they may display a broad ARCUATE outline. Dune terraces are typically located at or near the upper reaches of the beach. Sometimes, a terrace of somewhat IRREGULAR outline and limited extent may be found associated with the margin of another dune type. For example, a terrace-like configuration may exist on the inland boundary of a parabolic dune area, overlooking the shoreward facing margin of a lower-relief complex dune area.

Figure 9. Narrow low-relief dune terrace parallel to the shoreline (South Line, Section 22, T16N, R18W; Oceana County).

Dune Platform

A dune platform is typically somewhat linear shoreline-trending with a rather level or slightly hummocky surface, elevated above the adjacent shoreward and landward areas (Figures 10, 11). Slopes rising from the adjoining lower areas to the platform surface may be gentle or, if undergoing wave erosion, rather abrupt. These dunes generally trend PARALLEL to the shoreline; occasionally, however, they may display a broad ARCUATE outline with respect to the present shore. In rare cases, the trend may be irregular or normal to the shoreline. A typical dune platform is located at or near the upper limit of the beach and is separated from higher landward topography by a narrow furrow or swale.

Domal Dune

A domal dune displays a circular or subcircular plan view and a hemispheric (domal) or conical (peaked) profile; occasionally, it will be multi-peaked (Figures 12, 13).

Complex Dune Field

A complex dune field is an area of nonoriented dunes, generally of a hummocky, chaotic nature (Figure 14). Slopes vary from gentle to steep. Local relief may be rugged, varying abruptly from hillock to depression, or it may assume an undulating appearance. The hillocks need not have accordant elevations and some of the depressions may reach the substratum on which the dune field rests; and sometimes the depressions are ponded. Locations classified as complex may be transition zones, either areally or evolutionary, between two different dune types.

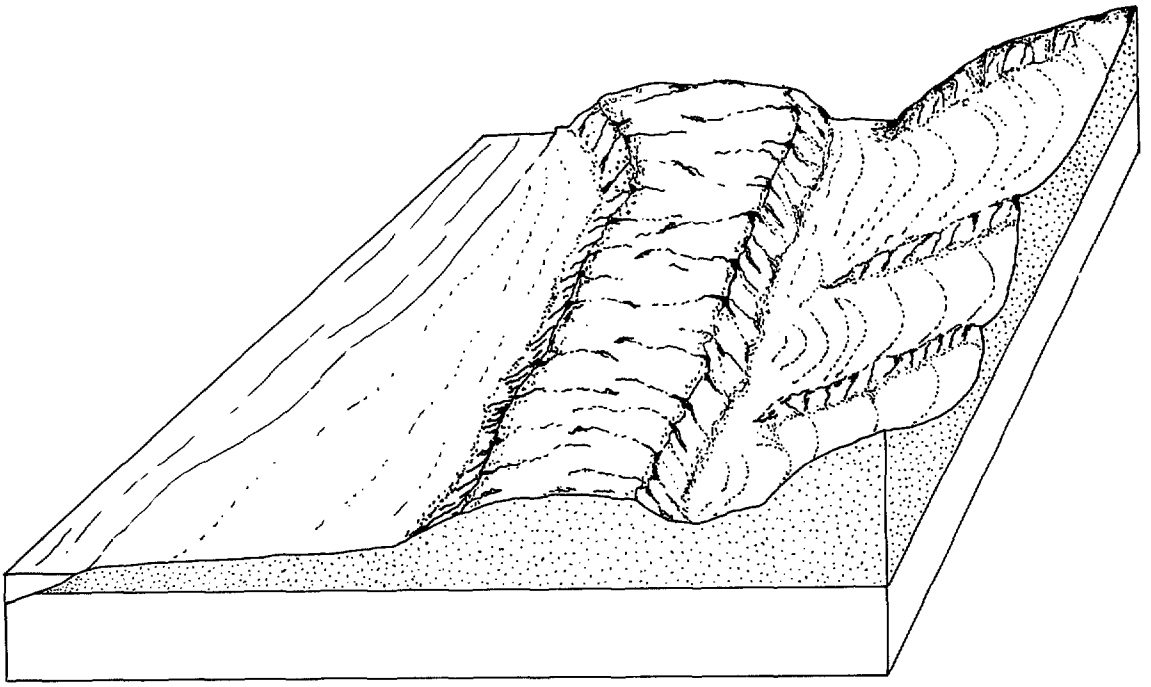


Figure 10. Diagram of a dune platform.

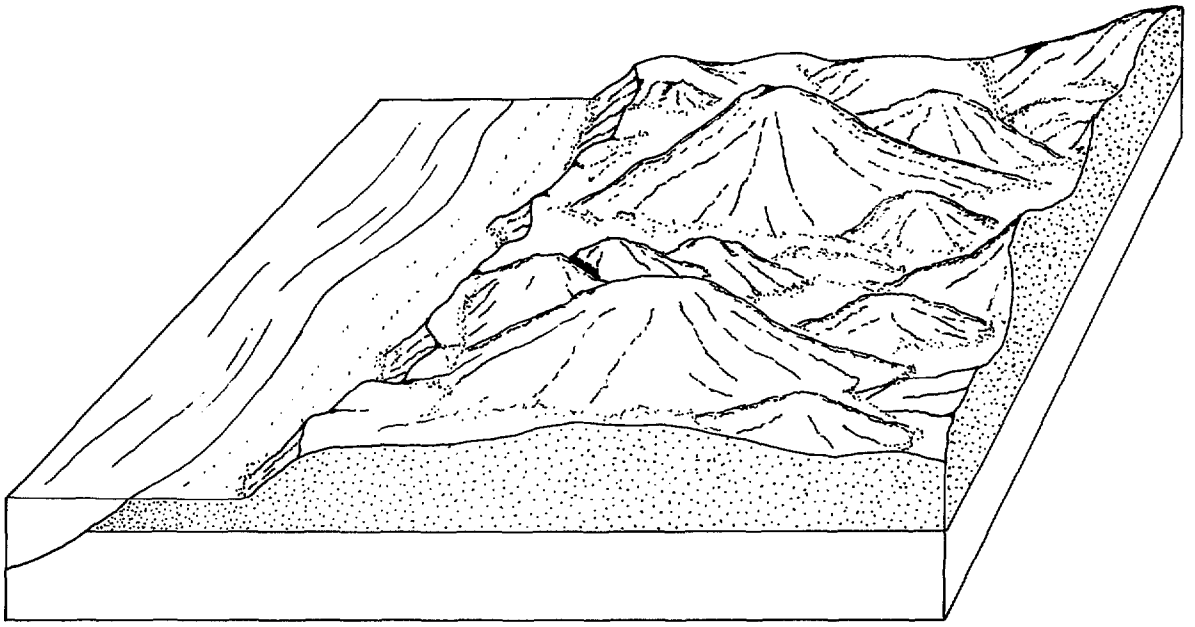


Figure 12. Diagram of domal dunes.

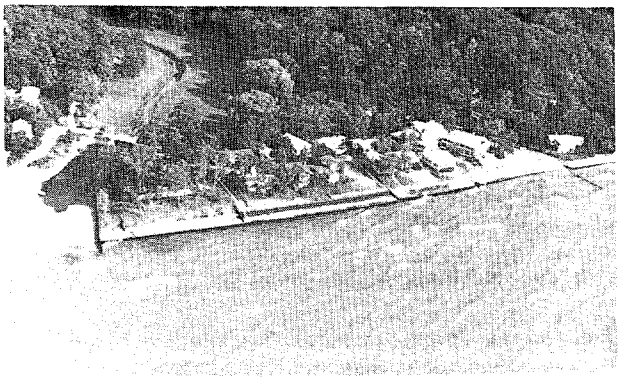


Figure 11. Low-relief dune platform parallel to the shoreline (NW 1/4, Section 8, T2S, R17W; Palisades Park, Van Buren County).

Figure 13. Moderate-relief domal dune, undergoing shoreline erosion (Centerline, Section 10, T3S, R18W; Berrien County).

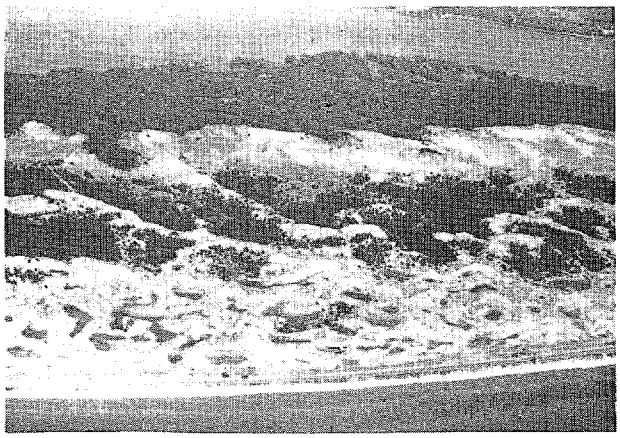


Figure 14. Low- to moderate-relief complex dune field (foreground) and high-relief parabolic dunes (background), Ludington State Park (Sections 28 & 29, T19N, R18W; Mason County).

Dune Flat

A dune flat is an accumulation form which displays few distinct relief features; its surface is essentially smooth and horizontal or gently sloping. This classification is largely applied to extensive sandy deposits of lacustrine origin which the Michigan Department of Natural Resources may designate as a "sand dune area."

Marginal Sand Apron

The transitional zone along the landward margin of the sand dune area is designated as a marginal sand apron (Figures 15, 6). Dune sand may only veneer the surface and may or may not be continuous. Typically, local relief is determined by the underlying formation and not by the dune sand itself. In some cases, however, isolated dune types, often low rounded ridges, may be found on the sand apron. Small deflation hollows or excavation pits may pocket the surface in limited portions. It is generally difficult to delineate the landward boundary of this apron; likewise, the exact thickness of dune sand seldom can be interpreted from aerial imagery.

Figure 15. Low-relief marginal sand apron (foreground and center ground). This view is toward the west and higher-relief dune forms (Section 5, T8N, R16W; Ottawa County).

Interdune Lowland

Interdune lowlands may exist either between two or more distinct dune assemblages or within a single dune type area (Figures 16, 17). Their surfaces are relatively flat to gently undulating and may contain small isolated low-relief hillocks, ridges or depressions. Dune sand may or may not cover the surface; where it does, even though the lowland surface is appreciably lower than the surrounding dunal topography, it may be distinctly elevated above the foundation upon which it rests. Furthermore, small borrow pits may pocket the surface of the lowland.

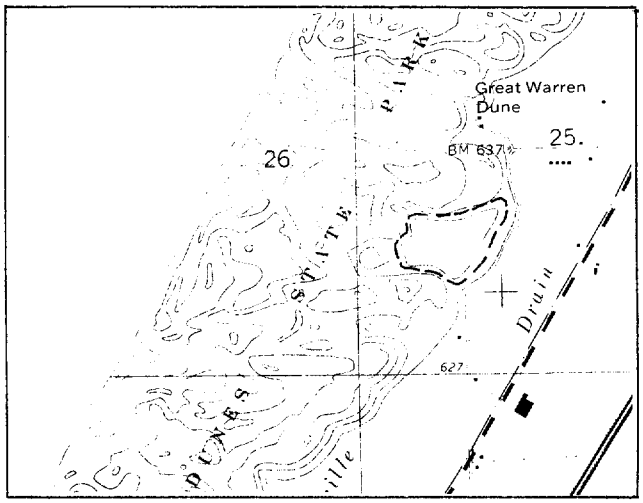


Figure 16. Inter-dune lowland, Warren Dunes State Park, as seen on a portion of the Bridgman 1:24,000-Scale Topographic Map.

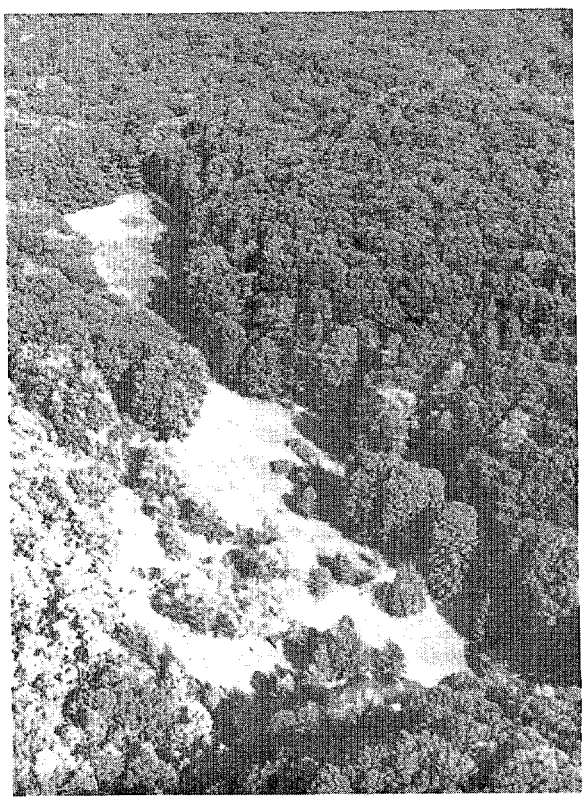


Figure 17. Inter-dune lowland (Centerline, Section 25, T2S, R18W; Van Buren County).

Relation of the Dune Form to the Underlying Formation

Nonelevated Position

Nonelevated dunes occur on a substratum base which is either near present lake level or at a level closely corresponding to the water elevation at the time the dune was formed, and which has not undergone significant uplift due to crustal rebound following deglaciation. This substratum may exhibit a gently rising incline away from the shoreline. Essentially, nonelevated dunes include all dune types not recognized as perched or overriding. In some cases, it is difficult to distinguish between the three varieties based on aerial-photo interpretation. In places where extensive wave erosion has cut back into the gently inclined substratum on which the dunes formed, it is not uncommon to find nondune sediments, often lacustrine sand and gravel, exposed near the upper beach surface. If this exposed substratum material is only a few feet in thickness, the dune assemblage is still classified as nonelevated. However, where an appreciable thickness of nondune sediment is recognized, the dune assemblage is classified as perched, even though no crustal uplift has occurred. Where mass-wasting of the overlying dune sand obscures the nondune basal material, these perched dunes may inadvertently be classified as nonelevated.

Perched Position

Perched dunes are situated on the upper surface of a nondune formation adjacent to, but elevated appreciably above, the PRESENT lake level (Figures 18, 19). The underlying nondune formation may rise to several hundred feet above the lake level. Perched dunes may take on the same forms as nonelevated dunes.

Figure 18. Perched dunes, Sleeping Bear National Lakeshore (T29N, R15W; Leelanau County).

Overriding Position

Overriding dunes are dunes which are encroaching upon relatively steeply sloping nondune formations, beginning more or less at present lake level, but rising distinctly above it (Figure 20). They may be thought of as being

DEPARTMENT OF NATURAL RESOURCES GEOLOGICAL SURVEY DIVISION GUIDELINES: DESIGNATED BARRIER DUNES LYING WITHIN DESIGNATED SAND DUNE AREAS

Adopted by the Natural Resources Commission on December 8, 1978 in accordance with the Sand Dune Protection and Management Act (Act No. 222, P.A. 1976) and the Administrative Procedures Act (Act No. 306, P.A. 1969, as amended).

I. Statement of Purpose: To delineate and illustrate the inland boundary of barrier dune formations within designated sand dune areas. The designation of a barrier dune does not restrict or regulate any person, organization, unit of government or other entity in any manner. Its relevance is in the following statutory language contained within the Sand Dune Protection and Management Act (Sec. 8(3)):

"In granting a permit, if the Department allows for the removal of all or a portion of the barrier dune pursuant to the act, it shall submit to the commission written reasons for permitting the removal."

II. Relationship of the Guideline to the Provision of the Authorizing Legislation: The Sand Dune Protection and Management Act authorizes the Department to regulate sand dune mining activities within designated sand dune areas. The designation of a sand dune area is accomplished through the promulgation of administrative rules in accordance with the Administrative Procedures Act.

The Statutory Definition of a Barrier Dune Is: "The first landward sand dune formation along a shoreline of a Great Lake or a sand dune formation designated by the Department of Natural Resources." Therefore, a barrier dune formation may be an integral portion of a designated sand dune area. The Department has identified, through indepth research efforts, criteria which shall be applied in determining the specific location of barrier dune formations and their boundary limitations within specific sand dune areas. This delineation shall be applicable to the review of those proposed sand dune mining activities within a barrier dune complex.

III. Criteria of Barrier Dune Boundary Determination:

A. A barrier dune is a relatively permanent feature.

B. The inland boundary of a barrier dune formation is that landward boundary line at the most landward base of the first sand dune formation from the great Lake Shoreline which displays the greatest relative relief within a designated sand dune area.

C. The shoreland boundary is that boundary line at the most shoreward base of the first sand dune formation from the Great Lake Shoreline that is not ephemeral (temporary) in nature.

D. The boundary of a barrier dune shall be easily recognized and delineated on aerial photographs (stereo-paired aerial imagery).

E. A barrier dune is a landform (geomorphic feature) whose relief and location restrict and impede interaction between the Great Lakes shoreline and inland oriented activities. Barrier Dunes frequently exhibit recognizable aesthetic values.

APPENDIX II

LAND COVER/USE CLASSIFICATION used in the Lakeshore Dune Type Inventory and Barrier Dune Classification and Sand Dune Mining Monitoring Studies

In broad terms, the classification system used in this study was modeled after the Michigan Land Cover/Use Classification System adopted by the Land Resource Programs Division, Michigan Department of Natural Resources. However, where that system was deemed incompatible with the objectives of the sand dune study, or where different kinds of information were required, it was modified. Most changes involved redefinition of, or additions to, categories in Level III of that system and they are summarized below. For a complete description of other categories, refer to the document cited above.

Category Descriptions

11 Residential:
Housing density was considered to be an important factor in assessing environmental conditions and was therefore mapped.

111 Medium and high density:
This category comprised tracts with a density exceeding one dwelling unit per acre and usually denotes well built-up regions. Also included, however, were linear areas--"strip development"--along roads where houses exist immediately adjacent to each other on both sides of the street.

112 Low density:
Dwelling units with a density of less than one per acre and "strip development" not meeting the medium and high density criteria were classified as low density. It should be noted that not all dwellings were mapped. If dwelling density was diffuse, the area was mapped according to predominant cover type. For example, farmsteads were usually mapped as agricultural land.

12 Commercial, services and institutional:
No notable changes.

13 Industrial:
No notable changes.

14 Transportation, communication and utilities:
No notable changes.

17 Extractive, open-pit mine:
This category includes only sand and/or gravel operations. The status of these mines (active or inactive) was not mapped initially. Based on that:

171 will refer to active sites.

172 will refer to inactive sites.

18 Cemeteries:
This number was used, rather than that of the Michigan System (194), so it would not be confused with the recreation category.

19 Recreation:
This category included such uses as golf courses, parks, boat docks, etc.

191 Public.

192 Private.

21 Cultivated cropland and permanent pasture:
No notable changes.

22 Specialty crops:
Essentially no changes were made in this category, but Christmas tree farms were specifically included.

31 Herbaceous groundcover:
No notable changes.

32 Shrub groundcover:
No notable changes.

41 Deciduous forest:
No notable changes.

42 Coniferous forest:
No notable changes.

43 Mixed forest:
No notable changes.

44 Dune grasses:
Discontinuous grassy cover on dunes and/or blow-outs was mapped in this category. The classification indicates a stable enough environment, at least recently, to allow growth of the grasses.

5 Water:
No further breakdown of this category was mapped. Thus, it includes lakes, rivers, ponds, etc.

61 Forested wetlands:
Poorly drained areas with a tree cover, either deciduous or coniferous, were mapped in this category.

62 Non-forested wetlands:
Included were brush swamps and/or marshes.

63 Vegetated open water:
This category includes stagnant water covered by vegetation such as lily pads, algae, etc.

72 Beaches:
No notable changes.

73 Sand other than beaches:
No notable changes, but it should be noted that blow-outs along the shore of Lake Michigan are specifically included in this category.

75 Transitional areas:
No notable changes.

APPENDIX I

IMAGERY USED in the Land Cover/Use Mapping Phase of the Lakeshore Dune Type Inventory and Barrier Dune Classification and the Sand Dune Mining Monitoring Studies (by Priority Area)

A1. Lincoln-Lake-Chikaming Sand Dune Area (R 281.401)

Source: Southwest Michigan Regional Planning Commission
2907 Division Street
St. Joseph, Michigan 49085

Type: CIR positive transparencies

Scale: approx. 1:36,000

Date: 6-3-77

A2. South Haven-Covert-Hagar Sand Dune Area (R 281.402)

Source: NASA/Remote Sensing Project, Michigan State University
201 UPLA Building
East Lansing, Michigan 48823

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 6-1-74

B. Golden-Benona-Claybanks Sand Dune Area (R 281.405)

Source: Western Michigan Shoreline Regional Development Commission
Torrent House
315 West Webster
Muskegon, Michigan 48440

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 10-4-75

C. Summit-Pentwater Sand Dune Area

Source: Western Michigan Shoreline Regional Development Commission (see above) and
Western Michigan Regional Planning Commission
1102 Peoples Building
Grand Rapids, Michigan 49506

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 10-4-75

D. Grant-Hamlin-Pere Marquette Sand Dune Area (R 281.406)

Source: Department of Transportation, State of Michigan
Photogrammetry Division
Box 30050
Lansing, Michigan 48909

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 7-11-73

E. Hendricks-Moran Sand Dune Area (R 281.407)

Source: Department of Transportation, State of Michigan
Photogrammetry Division
(see above)

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 6-13-73

F1. Fruitland Sand Dune Area

Source: Western Michigan Shoreline Regional Development Commission
(see above)

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 10-4-75

F2. Laketon-Fruitport-Spring Lake-Grand Haven Sand Dune Area (R 281.404)

Source: Western Michigan Shoreline Regional Development Commission
(see above)

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 10-4-75

G. Grand Haven-Port Sheldon Sand Dune Area

Source: Western Michigan Shoreline Regional Development Commission
(see above)

Type: CIR positive transparencies

Scale: approx. 1:32,000

Date: 10-4-75

7 Terasmae, J. and R. J. Mott, 1959,
NOTES ON SAND DUNES NEAR PRESCOTT, ONTARIO,
Revue Canadienne de Geographie 13(3-4), p. 135-141.

1 Terwilliger, F. W., 1954
THE GLACIAL GEOLOGY AND GROUND WATER RESOURCES OF VAN BUREN COUNTY, MICHIGAN,
Michigan Geological Survey Publication 48, pt. 1, 95 p.

3 Thompson, P. W., 1967,
VEGETATION AND COMMON PLANTS OF SLEEPING BEAR,
Cranbrook Institute of Science Bulletin no. 52, 47 p.

3, 5
Urban and Environmental Studies Institute, 1977,
KITCHEL DUNE PRESERVE--FEASIBILITY STUDY,
Grand Valley State College, Allendale, Michigan, 67 p.

4 Van Denack, J. M., 1961,
AN ECOLOGICAL ANALYSIS OF THE SAND DUNE COMPLEX IN POINT BEACH STATE PARK, TWO RIVERS, WISCONSIN,
Botanical Gazette 122(3), p. 155-174.

9 Van Dieren, J. W., 1934,
ORGANOGENE DUNENBILDUNG EINE GEOMORPHOLOGISCHE ANALYSE DER DUNENLANDSCHAFT DER WEST-FREESISCHEN ANSEL TERSCHELINY MIT PFLANZENSOZIOLOGISCHEN METHODEN,
Haag: Martinus Nijhoff, 304 p.

10 Verstappen, H. T., 1972,
ON DUNE TYPES, FAMILIES AND SEQUENCES IN AREAS OF UNIDIRECTIONAL WINDS,
Gottinger Geographische Abhandlungen 60, p. 341-362.

1, 13
Verway, D. I., and Grier, W., 1977,
MICHIGAN STATISTICAL ABSTRACTS,
Michigan State University: East Lansing, Michigan.

3 Waterman, W. G., 1917,
ECOLOGY OF NORTHERN MICHIGAN DUNES: CRYSTAL LAKE BAR REGION,
Report of the Michigan Academy of Science 19, p. 197-208.

3 ___, 1919,
DEVELOPMENT OF ROOT SYSTEMS UNDER DUNE CONDITIONS,
Botanical Gazette 68(1), p.22-53.

3 ___, 1922a,
DEVELOPMENT OF PLANT COMMUNITIES ON A SAND RIDGE REGION IN MICHIGAN,
Botanical Gazette 74(1), p. 1-31.

1, 3
___, 1922b,
FORESTS AND DUNES FROM POINT BETSIE TO SLEEPING BEAR, BENZIE AND LEELANAU COUNTIES, MICHIGAN,
Northwestern University: Evanston, Illinois, 20 p.

1, 3
___, 1926,
ECOLOGY OF GLEN LAKE AND SLEEPING BEAR REGION,
Michigan Academy of Science, Arts and Letters Papers 6, p. 351-376.

11, 13
Wright, R. and W. Ritchie, 1975
THE SURVEY AND PHOTO-INTERPRETATION OF THE SANDS OF FORVIE, ABERDEENSHIRE,
O'Dell Memorial Monograph no. 4, Department of Geography, University of Aberdeen: Scotland, 13 p.

8, 9
Zenkovich, V. P., 1967,
AEOLIAN PROCESSES ON SEA COASTS, in; PROCESSES OF COASTAL DEVELOPMENT,
Edinburgh and London: Oliver and Boyd, Limited, p. 586-617.

1 ___, 1939,
METHODS OF CORRELATION OF SAND DUNES OF THE LAKE MICHIGAN BASIN (Abstract),
Geological Society of America Bulletin 50(12), p. 2008-2009.

1 ___, 1942,
THE DUNES OF LAKE MICHIGAN AND CORRELATED PROBLEMS,
44th Annual Report, Michigan Academy of Science, Arts and Letters, p. 53-61.

1 ___, no date,
UNFINISHED AND INCOMPLETE STUDY ON SAND DUNES ALONG LAKE MICHIGAN,
Unpublished manuscript in files of Michigan Geological Survey, Department of Natural Resources.

1 ___, and K. W. Dow, 1936,
DUNES OF THE HERRING LAKE EMBAYMENT, MICHIGAN.
Michigan Academy of Science, Arts and Letters Papers 22, p. 437-450.

6 Shannon, C. W., 1911,
THE SAND AREAS OF INDIANA,
Indiana Academy of Science Proceedings (of 1911), p. 197-210.

10 Smith, H. T. U., 1940a,
GEOLOGIC STUDIES IN SOUTHWESTERN KANSAS,
State Geological Survey of Kansas Bulletin No. 34, 212 p.

2, 9
___, 1940b,
DUNE FORM AND WIND DIRECTION ALONG THE SOUTHERN SHORE OF LAKE MICHIGAN (Abstract),
Geological Society of America Bulletin 51(12), p. 1947.

11 ___, 1941,
AERIAL PHOTOGRAPHS IN GEOMORPHIC STUDIES,
Journal of Geomorphology 4(3), p. 171-205; Photogrammetric Engineering 8(2), p. 129-155.

10 ___, 1949,
PHYSICAL EFFECTS OF PLEISTOCENE CLIMATIC CHANGES IN NON-GLACIATED AREAS: EOLIAN PHENOMENA, FROST ACTION AND STREAM TERRACING,
Geological Society of America Bulletin 60, p. 1485-1516.

10 ___, 1951,
PHOTO-INTERPRETATION STUDIES IN THE SAND HILLS OF WESTERN NEBRASKA,
Naval Research Project, NR 089-016.

8, 9, 11
___, 1954,
COASTAL DUNES,
First Coastal Geography Conference, Office of Naval Research, Geography Program, p. 51-56.

8, 9
___, 1960,
PHYSIOGRAPHY AND PHOTO-INTERPRETATION OF COASTAL SAND DUNES,
Final Report, Contract no. Nonr-2242(00), Office of Naval Research, Geography Branch, 26 p.

10 ___, 1965,
DUNE MORPHOLOGY AND CHRONOLOGY IN CENTRAL AND WESTERN NEBRASKA,
Journal of Geology 73(4), p. 557-578.

1, 8, 9
Smith, R. A., 1914,
NON-METALLIC MINERALS, In; MINERAL RESOURCES OF MICHIGAN, R. C. Allen (Compiler),
Michigan Geological Survey, Publication 16, Geological Ser. 13, p. 88-89.

1, 8, 9
Squire, G. R., 1972,
A FIELD GUIDE TO THE GEOLOGY OF SOUTHWESTERN MICHIGAN,
Western Michigan University, Department of Geology Publication ES-1: Kalamazoo, Michigan.

5 Stace, A. W., 1939,
MICHIGAN'S MYSTIC DUNES,
Ann Arbor News, July 12-August 17 (series of daily articles).

8, 9
Steers, J. A., 1946,
THE COASTLINE OF ENGLAND AND WALES,
Cambridge: Cambridge University Press.

1, 7
Stevenson, E. G., 1931,
THE DUNES OF THE MANISTIQUE AREA,
Michigan Academy of Science, Arts and Letters Papers 14, p. 475-485.

4 Stomps, T. J., 1915,
THE DUNES OF LAKE MICHIGAN,
Plant World 18, p. 205-216.

1, 9
Tague, G. C., 1946,
THE POST-GLACIAL GEOLOGY OF GRAND MARAIS EMBAYMENT, BERRIEN COUNTY, MICHIGAN,
Michigan Department of Conservation, Publication 45, Geological ser. 38, pt. 1, p. 1-82.

12 Otvos, E. G., 1970,
DEVELOPMENT AND MIGRATION OF BARRIER ISLANDS, NORTHERN GULF OF MEXICO,
Geological Society of America Bulletin 81, p. 241-246.

1 Parkins, A. E., 1926,
THE SAND DUNES OF LAKE MICHIGAN,
Tennessee Academy of Science Journal 1(3), p. 12, 15.

1, 8, 9
Pettijohn, F. J., P. E. Potter and R. Siever, 1972,
SAND AND SANDSTONE,
New York, New York: Springer-Verlag.

1,2,9,13
Powers, W. E., 1958,
GEOMORPHOLOGY OF THE LAKE MICHIGAN SHORELINE,
Final Report of Contract No. Nonr-1228(07), Project No. NR387-015, Geography Branch, Earth Science Division, Office of Naval Research, United States Department of the Navy, 103 p.

1,9
Price, W. A., 1950,
SAND DUNES OF LAKE MICHIGAN AND DUNE TERMINOLOGY,
Geographical Review 40(3), p. 470-472.

5 Reber, L. B., 1928,
VANISHED VILLAGES OF BERRIEN COUNTY,
Michigan History Magazine 12(2), p. 322-326.

6 Reed, E. H., 1912,
VOICES OF THE DUNES,
Chicago, Illinois: Aldebunk Press.

6 ___, 1916,
THE DUNE COUNTY,
New York: John Land Company, 287 p.

6 ___, 1918,
SKETCHES IN DUNELAND,
New York: John Lane and Company.

1 Richardson, W. D., 1919,
THE SINGING SANDS OF LAKE MICHIGAN,
Science, new ser., 50(28), p. 493-495.

1 ___, 1920,
LAKE MICHIGAN'S SINGING SANDS,
Literary Digest 64(1), p. 93-95.

6 Ross, H. H., 1963,
THE DUNES LAND HERITAGE OF ILLINOIS,
Illinois Natural History Survey Circular no. 49, 28 p.

1 Russell, I. C., 1904,
A GEOLOGICAL RECONNAISSANCE ALONG THE NORTH SHORE OF LAKES HURON AND MICHIGAN,
Michigan Geological Survey Annual Report, p. 94-98.

7 Ruthven, A. G., 1911,
A BIOLOGICAL SURVEY OF THE SAND DUNE REGION ON THE SOUTH SHORE OF SAGINAW BAY, MICHIGAN,
Michigan Geological and Biological Survey Publication 4, 347 p.

2 Salisbury, R. D. and W. C. Alden, 1920,
THE GEOGRAPHY OF CHICAGO AND ITS ENVIRONS,
Geographic Society of Chicago Bulletin No. 1.

2 Sander, P., 1969,
KENOSHA SAND DUNES,
Wisconsin Academy Review 16(3), p. 2-6.

6 Schantz, O. M. 1919,
INDIANA'S UNRIVALLED SAND DUNES,
National Geographic Magazine 35, p. 430-441.

12 Schwartz, M. L., (Editor), 1973,
BARRIER ISLANDS,
Benchmark Papers in Geology, v. 9. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross, Inc., 451 p.

1, 7
Scott, I. D., 1920,
INLAND LAKES OF MICHIGAN,
Michigan Geological Survey Publication 30, p. 4, 18, 71, 102, 142-144, 165, 170-172, 269, 284, 355, 358, 361.

1 ___, 1927,
PHYSIOGRAPHY OF SOME MICHIGAN DUNES (Abstract),
Geological Society of America Bulletin 38, p. 140-141; Pan-Am Geologist 47(2), p. 149-150

1 ___, 1930,
DUNES OF LAKE MICHIGAN (Abstract),
Geological Society of America Bulletin 41(1), p. 83; Pan-Am Geologist 53(2), p. 128.

1 ___, 1934,
HISTORY OF THE SAND DUNES OF THE MICHIGAN BASIN (Abstract),
Geological Society of America Proceedings (of 1933), p. 107.

1 ___, 1938,
SIGNIFICANCE OF FORM AND ARRANGEMENT OF SAND DUNES (Abstract),
Geological Society of America Bulletin 49(12), p. 1899.

1 Leverett, F. and F. Taylor, 1915,
THE PLEISTOCENE OF INDIANA AND MICHIGAN.
United States Geological Survey Monograph 53, Washington, D.C.: Government Printing Office, 529 p.

1, 13
Lewis, J. D., 1975,
MICHIGAN'S INDUSTRIAL SAND RESOURCES,
Michigan Department of Natural Resources, Geological Survey Division Circular 11, 33 p.

1 Lutz, H. J., 1941,
THE NATURE AND ORIGIN OF LAYERS OF FINE-TEXTURED MATERIAL IN SAND DUNES,
Journal of Sedimentary Petrology 11 (3), p. 105-123.

5 Martin, H. M., 1942,
SLEEPING BEAR DUNE,
Michigan Conservation 11 (11), p. 12.

1 ___, 1955,
MAP OF THE SURFACE FORMATIONS OF THE SOUTHERN PENINSULA OF MICHIGAN,
Michigan Geological Survey Division Publication 49, Department of Natural Resources.

1, 13
McClaws, I. J., 1971,
USES AND SPECIFICATIONS OF SILICA SAND,
Research Council of Alberta Report 714.

2 McKay, B. R., 1917,
TOPOGRAPHIC MAPS OF THE DUNE PARK REGION,
with Explanation by R. D. Salisbury, Chicago: Geographic Society of Chicago.

10,11
McKee, E. D., C. S. Breed, and S. G. Fryberger, 1977,
DESERT SAND SEAS, In ; NASA LYNDON B. JOHNSON SPACE CENTER, SKYLAB EXPLORES THE EARTH,
NASA SP-380, National Aeronautic and Space Administration Scientific and Technical Information Office, Washington, D.C., p. 5-47.

5 McKee, R., 1956,
DUNES COUNTRY,
Michigan Conservation 24(4), p. 2-7.

10,11
Melton, F. A., 1940,
A TENTATIVE CLASSIFICATION OF SAND DUNES: ITS APPLICATION TO DUNE HISTORY IN THE SOUTHERN HIGH PLAINS,
Journal of Geology 48 (2), p. 113-145.

13 Michigan Department of Natural Resources, 1978,
PROPOSED DESIGNATED DUNE AREAS: SERIES 1,
Lansing, Michigan, 18 p.

13 Michigan Legislature, 1976,
SAND DUNE PROTECTION AND MANAGEMENT ACT,
Public Act No. 222, 78th Legislature, Regular Session of 1976.

5 National Park Service, United States Department of the Interior, 1961,
SLEEPING BEAR NATIONAL SEASHORE--A PROPOSAL,
Washington, D.C., 26 p.

6 National Park Service, United States Department of the Interior, 1966,
THE INDIANA DUNES NATIONAL LAKESHORE, A PROPOSAL,
Washington, D.C., 15 p.

4 Pealtie, D.C., 1930,
FLORA OF THE INDIANA DUNES,
Chicago, Illinois: Field Museum of Natural History, 432 p.

4 Olson, J. S., 1951,
VEGETATION--SUBSTRATE RELATIONS IN THE LAKE MICHIGAN SAND DUNES,
Dissertation, University of Chicago: Chicago, Illinois.

1,2
___, 1958a,
LAKE MICHIGAN DUNE DEVELOPMENT--1. WIND-VELOCITY PROFILES,
Journal of Geology 66 (3), p. 254-262.

1,2
___, 1958b,
LAKE MICHIGAN DUNE DEVELOPMENT--2. PLANTS AS AGENTS AND TOOLS IN GEOMORPHOLOGY,
Journal of Geology 66(4), p. 345-351.

1,2
___, 1958c,
LAKE MICHIGAN DUNE DEVELOPMENT--3. LAKE-LEVEL, BEACH AND DUNE OSCILLATIONS,
Journal of Geology 66(5), p. 473-483.

4 ___, 1958d,
RATES OF SUCCESSION AND SOIL CHANGES ON SOUTHERN LAKE MICHIGAN SAND DUNES,
Botanical Gazette 119, p. 125-170.

8 Olsson-Seffer, P., 1910,
GENESIS AND DEVELOPMENT OF SAND FORMATIONS ON MARINE COASTS,
Augustana Library Publication No. 7, p.10-41.

3 Henricks, M. M., 1975,
ECOLOGICAL RECONNAISSANCE OF THE GRAND HAVEN NORTH SHORE DUNES,
Unpublished report, Grand Haven, Michigan

4 Hill, E. J., 1893,
SAND-DUNE FLORA OF LAKE MICHIGAN,
Garden and Forest 6, p. 15.

2, 4
Hill, John R., 1974,
THE INDIANA DUNES--LEGACY OF SAND,
Geological Survey Special Report No. 8, Indiana Department of Natural Resources, 9 p.

10 Holm, D. A., 1968,
SAND DUNES, In: Fairbridge, R.W. (Editor), THE ENCLOPEDIA OF GEOMORPHOLOGY,
New York: Reinhold Book Corporation, p. 973-979.

12 Hoyt, J. H., 1967,
BARRIER ISLAND FORMATION,
Geological Society of America Bulletin 78 (9), p. 1125-1136.

1,7,9,13
Humphrys, C. R., R. N. Horner, and J. H. Rogers, 1958,
SHORETYPE BULLETINS no. 1-29,
Department of Resource Development and Agricultural Experiment Station, Michigan State University: East Lansing, Michigan.

1, 11
Johnson, K. G., 1957,
AN AERIAL PHOTOGRAPHIC STUDY OF THE GLEN LAKE-SLEEPING BEAR POINT AREA, LEELANAU COUNTY, MICHIGAN,
Master of Science Thesis, Michigan State University: East Lansing, Michigan, 32 p.

3 Kadlec, J. A., 1962,
PLANTS IN THE SAND,
Michigan Conservation 31(4), p. 33-37.

1, 9
Kelley, R. W., 1962a,
THE DUNES,
Michigan Conservation 31(4), p. 10-16.

1 ___, 1962b,
SAND DUNES OF MICHIGAN,
Map No. 3575, Michigan Department of Natural Resources, Geological Survey Division.

___, 1967,
MORAINIC SYSTEMS OF MICHIGAN,
Michigan Geological Survey, Small Scale Map 1.

___, 1968,
BEDROCK OF MICHIGAN,
Michigan Geological Survey, Small Scale Map 2.

1, 9
___, 1971,
GEOLOGIC SKETCH OF MICHIGAN SAND DUNES,
Michigan Department of Natural Resources, Geological Survey Pamphlet No. 5, 20 p.

1, 9
___, and W. R. Farrand, 1967,
THE GLACIAL LAKES AROUND MICHIGAN,
Michigan Geological Survey Bulletin 4.

7 Kenoyer, L. A., 1929,
SAND DUNE PLANTS OF KALAMAZOO COUNTY, MICHIGAN,
Michigan Academy of Science, Arts and Letters Papers 9, p. 219-221.

8, 9
King, C. A. M., 1972,
THE EFFECT OF WIND, In; BEACHES AND COASTS,
New York: St. Martins Press, p. 165-190.

8 Knutson, P. L., 1977,
FEDERAL LABORATORY BEGINS DUNE-BUILDING EXPERIMENT,
Great Lakes Basin Commission Communicator 7(14), p. 5-6.

6, 5
Komaiko, J. and N. Schaeffer, 1973,
DOING THE DUNES,
Beverly Shores, Indiana: Dune Enterprise, 231 p.

4 Laing, C, 1954,
THE ECOLOGICAL LIFE HISTORY OF THE MARRAM GRASS COMMUNITY ON LAKE MICHIGAN DUNES,
Dissertation, University of Chicago: Chicago, Illinois.

1 Landsberg, H. and N. A. Riley, 1943,
WIND INFLUENCES ON THE TRANSPORTATION OF SAND OVER A MICHIGAN SAND DUNE,
Proceedings of the Second Hydraulics Conference, Bulletin no. 27, University of Iowa Studies in Engineering: Ames, Iowa.

7 Lane, A. C., 1900,
GEOLOGICAL REPORT ON HURON COUNTY, MICHIGAN,
Michigan Geological Survey, vol. VII, pt. 2, p. 9, 40, 51, 56, 143, 204, 210, 235, 237, 239-241.

3 Lehotsky, K., 1941,
SAND FIXATION IN MICHIGAN,
Journal of Forestry 39, p. 993-1004.

1 Evans, O. F., 1936,
ORIGIN OF THE HARBOR LAKES OF WESTERN MICHIGAN (Abstract),
Oklahoma Academy of Science Proceedings (of 1935) 16, p. 74.

1 ___, 1937,
ORIGIN OF THE COASTAL LAKES OF WESTERN MICHIGAN,
Geographical Review 27(1), p. 136-137.

1 Fairchild, H. L., 1920,
MUSICAL SANDS,
Science, new ser., 51, p. 62.

11 Fezer, F., 1971,
PHOTO-INTERPRETATION APPLIED TO GEOMORPHOLOGY--A REVIEW,
Photogrammetria 27(1): p. 7-53.

1 Firpin, E. O.,
SINGING SANDS,
Science, new ser., 51, p. 64.

1 Franz, H., 1946,
FULGURITES IN MICHIGAN,
Rocks and Minerals 21(6), p. 354-355.

13 Free, E. E., 1911,
THE MOVEMENT OF SOIL MATERIAL BY THE WIND, WITH A BIBLIOGRAPHY OF AEOLIAN GEOLOGY BY S. G. STUNTZ AND E. E. FREE,
United States Bureau of Soils Bulletin no. 68, p. 1-173.

4 Fuller, G. D., 1912,
GERMINATION AND GROWTH OF THE COTTONWOOD UPON THE SAND DUNES OF LAKE MICHIGAN NEAR CHICAGO,
Illinois Academy of Science Transaction 5, p. 137-143.

1, 3
___, 1918,
SOME PERCHED DUNES OF NORTHERN LAKE MICHIGAN AND THEIR VEGETATION,
Illinois Academy of Science Transaction 11, p. 111-112.

3 Furlow, J. T., no date,
ECOLOGY OF THE LAKE MICHIGAN SAND DUNES--INTRODUCTION FOR A FIELD TRIP TO THE SAUGATUCK DUNES,
Department of Botany, Michigan State University, (Mimeographed): Lansing, Michigan, 9 p.

1, 3
Gates, F. C., 1950,
THE DISAPPEARING SLEEPING BEAR DUNES,
Ecology 31(3), p. 386-392.

1, 9
Gere, M. A., Jr., 1978,
MICHIGAN MINERAL PRODUCERS, 1976,
Michigan Geological Survey, Annual Directory 11.

9, 13
Gifford, A. R. and C. R. Humphrys, 1966,
LAKE SHORE CLASSIFICATION--SOUTHERN PENINSULA OF MICHIGAN,
Department of Resource Development, Michigan State University: East Lansing, Michigan.

1, 3
Gillis, W. T. anad K. I. Bakeman, 1963,
THE DISAPPEARING SLEEPING BEAR SAND DUNES,
The Michigan Botanist 2(1), p. 45-54.

6 Goodman, P. S., 1920,
THE INDIANA SAND DUNES,
Chicago, Illinois: Rand McNally Company.

7 Gordon, C. H., 1900,
GEOLOGICAL REPORT ON SANILAC COUNTY, MICHIGAN,
Michigan Geological Survey, v. VII, pt. 3, p. 18.

8 Gresswell, R. K., 1957,
SAND DUNES AND SALT MARSHES, In; THE PHYSICAL GEOGRAPHY OF BEACHES AND COASTLINES,
London: Hulton Educational Publications, Ltd., p. 87-99.

10 Hack, J. T., 1941,
DUNES OF THE WESTERN NAVAJO COUNTRY,
Geographical Review 31 (2), p. 240-263.

Hamblin, W. K., 1958,
THE CAMBRIAN SANDSTONES OF NORTHERN MICHIGAN,
Michigan Geological Survey Publication 51.

11, 13
Hands, E. B., 1970,
A GEOMORPHIC MAP OF LAKE MICHIGAN SHORELINE,
Proceedings of the Thirteenth Conference on Great Lakes Research, International Association for Great Lakes Research, Ann Arbor, Michigan, p. 250-265.

3 Hartz, M. K. and J. Kane, 1976,
ECOLOGICAL SURVEY OF THE SILVER LAKE SAND MINING SITE,
Report prepared for Hart Packing Company, Golden Township, Oceana County, Michigan, by Muskegon Community College.

Heinrich, E. Wm., 1979,
ECONOMIC GEOLOGY OF SAND AND SANDSTONE RESOURCES OF MICHIGAN,
Michigan Geological Survey, Report of Investigation 21.

8, 9
Cornish, V., 1897,
ON THE FORMATION OF SAND DUNES,
Geographical Journal, v. 9, no. 3,
p. 278-309.

6 Cottman, G. S., 1930,
INDIANA DUNES STATE PARK: A
HISTORY AND DESCRIPTION,
Indiana Department of Conservation
Publication no. 97.

4, 2
Cowles, H. C., 1899,
THE ECOLOGICAL RELATIONS OF THE
VEGETATION ON THE SAND DUNES OF
LAKE MICHIGAN,
Botanical Gazette, v. 27, p. 95-117,
167-202, 281-308, 361-391

4 ___, 1911,
A FIFTEEN-YEAR STUDY OF
ADVANCING SAND DUNES (Abstract),
British Association for the Advancement
of Science Annual Report, p. 565.

2 Cressey, G. B., 1921,
STUDIES IN THE SAND DUNES OF
NORTHWESTERN INDIANA,
Master of Science Thesis, University of
Chicago: Chicago, Illinois.

2 ___, 1922,
NOTES ON THE SAND DUNES OF
NORTHWESTERN INDIANA,
Journal of Geology, v. 30, no. 3,
p. 248-251.

2 ___, 1928,
THE INDIANA SAND DUNES AND
SHORELINES OF LAKE MICHIGAN BASIN,
Geographical Society of Chicago Bulletin
no. 8, Chicago, Illinois: University of
Chicago Press, 80 p.

12 Curray, J. R., 1969,
SHOREZONE SAND BODIES: BARRIERS,
CHENIERS, AND BEACH RIDGES, In; NEW
CONCEPTS OF CONTINENTAL MARGIN
SEDIMENTATION,
AGI Short Course Notes, American
Geological Institute, Washington, D.C.,
pt. JC-11, p. 1-18.

6 Daniel, G., 1977,
DUNE COUNTRY--A GUIDE FOR HIKERS
AND NATURALISTS,
Chicago, Illinois: Shallow Press, Inc., 167p.

7 Davies, C. A., 1908,
GEOLOGY OF TUSCOLA COUNTY,
MICHIGAN,
Michigan Geological Survey Annual
Report, Lansing, p. 144, 169-172.

8, 9
Davies, J. L., 1973,
GEOGRAPHICAL VARIATIONS IN
COASTAL DEVELOPMENT,
New York, New York: Hafner Publishing
Co., p. 146-161.

7 Desor, E., 1851,
ON THE SUPERFICIAL DEPOSITS OF THIS
DISTRICT, In; Foster, J. W. and Whitney, J.
D., REPORT ON THE GEOLOGY OF THE
LAKE SUPERIOR LAND DISTRICT, P. II,
32nd Congress, Special Session, Senate
Executive Document no. 4, p. 232-270.

7 ___,
ON THE SAND DUNES OF LAKE
SUPERIOR,
Boston Society of Natural History
Proceedings (1848-1851), v. 3, p. 207.

7 ___, 1854,
ON THE EXISTENCE OF DUNES ON THE
SHORES OF THE UPPER AMERICAN
LAKES,
Boston Society of Natural History
Proceedings (1851-1854), v. 4, p. 41-42.

1,8,9
Dorr, J. A., Jr. and D. F. Eschman, 1970,
GEOLOGY OF MICHIGAN,
Ann Arbor, Michigan: The University of
Michigan Press, p. 180-227.

1 Dow, K. W., 1937,
THE ORIGIN OF PERCHED DUNES ON
THE MANISTEE MORAINE, MICHIGAN,
Michigan Academy of Science, Arts and
Letters Papers, v. 23, p. 427-440.

1 ___, 1940,
SOME EXAMPLES OF VENTIFACTS FROM
SLEEPING BEAR POINT, LEELANAU
COUNTY, MICHIGAN,
Michigan Academy of Science, Arts and
Letters Papers, v. 25, p. 473-476.

6 Eifrig, C. W. G., 1918,
THE BIRDS OF THE SAND DUNES OF
NORTHWESTERN INDIANA,
1918 Proceedings of the Indiana Academy
of Science, p. 280-303.

Enyert, R. L., 1949,
MIDDLE DEVONIAN SANDSTONES OF
THE MICHIGAN BASIN,
Dissertation, University of Michigan: Ann
Arbor, Michigan.

2 Espenshade, E. B., Jr., 1932,
AN INTENSIVE STUDY OF THE
SPHERICITY AND ROUNDNESS OF
BEACH AND DUNE SANDS OF THE
SOUTH OF LAKE MICHIGAN,
Master of Science Thesis, University of
Chicago: Chicago, Illinois.

6 Bailey, E. S., 1917,
THE SAND DUNES OF INDIANA: THE STORY OF AN AMERICAN WONDERLAND TOLD BY CAMERA AND PEN,
Chicago: A. C. McClurg and Company, 165p.

2 Barrett, E., 1916,
THE DUNES OF NORTHWESTERN INDIANA,
41st Annual Report, Indiana Department of Geology and Natural Resources, p. 11-27.

1, 7
Bergquist, S. G., 1936,
AEOLIAN ACTIVITY IN THE PLEISTOCENE HISTORY OF THE TAHQUAMENON AND MANISTIQUE DRAINAGE REGION OF THE NORTHERN PENINSULA OF MICHIGAN,
Michigan Department of Conservation, Geological Survey Publication 40, Part 1, p. 113-137.

7 ___, 1935,
THE GRAND SABLE DUNES ON LAKE SUPERIOR, ALGER COUNTY, MICHIGAN,
Michigan Academy of Science, Arts and Letters Papers, v. 21, p. 429-438.

2 Bieber, C. L., 1952,
INDUSTRIAL SANDS OF THE INDIANA DUNES,
Indiana Geological Survey Bulletin no. 7, 31 p.

8, 9
Bird, E. C. F., 1969,
COASTS,
Cambridge, Massachusetts: M.I.T. Press, p. 128-146.

2 Blatchley, W. S., 1897,
THE GEOLOGY OF LAKE AND PORTER COUNTIES,
22nd Annual Report, Indiana Department of Geology and Natural Resources, p. 38-41.

1 Bolton, H. C. and A. A. Julien, 1885,
MUSICAL SAND, ITS DISTRIBUTION AND PROPERTIES (Abstract),
American Association for the Advancement of Science Proceedings, v. 33, p. 408-413.

3 Bowers, N. M., K. C. McMurry, and K. M. Stahl, 1941,
LAKESHORE INVENTORY AND CLASSIFICATION,
Michigan Academy of Science, Arts and Letters Papers, v. 27, p. 337-344.

6 Brennan, G. A., 1923,
THE WONDERS OF THE DUNES,
Indianapolis, Indiana: Bobbs-Merrill Company, 326 p.

9 Briquet, A., 1923,
LES DUNES LITTORALES,
Annales de Geographic 32, p. 385-394.

5, 7
Brown, G. G., 1936,
MOLDING SANDS OF MICHIGAN AND THEIR USE,
Michigan Department of Conservation, Geological Survey Publication 41, p. 23-24, 27.

1 Burroughs, R. D., 1953,
DUNE COUNTRY,
Michigan Conservation Magazine, v. 22(4), inside rear cover.

1 Calver, J. L., 1940,
ROUNDNESS OF GRAINS IN WESTERN MICHIGAN DUNE SANDS,
Michigan Academy of Science, Arts and Letters Papers, v. 25, p. 465-471.

1 ___, 1946,
THE GLACIAL AND POST-GLACIAL HISTORY OF THE PLATTE AND CRYSTAL LAKE DEPRESSION, BENZIE COUNTY, MICHIGAN,
Michigan Department of Conservation, Geological Survey Publication 45, Geological Series no. 38, Part II, 70 p.

5 Carlisle, N., 1960,
MICHIGAN'S MARCHING DUNES,
Coronet Magazine, June 1960, p. 159-162.

2 Chamberlin, T. C., 1877,
GEOLOGY OF EASTERN WISCONSIN, In; GEOLOGY OF WISCONSIN: SURVEY OF 1873-1877, II,
Wisconsin Geological and Natural History Survey, p. 233.

Clemens, R. H., 1976,
THE ROLE OF VEGETATION IN SHORELINE MANAGEMENT,
Great Lakes Basin Commission, 32 p.

10 Cooper, W. S., 1935,
THE HISTORY OF THE UPPER MISSISSIPPI RIVER IN LAKE WISCONSIN AND POST-GLACIAL TIME,
Minnesota Geological Survey Bulletin no. 26, 116 p.

10 ___, 1938,
ANCIENT DUNES OF THE UPPER MISSISSIPPI VALLEY AS POSSIBLE CLIMATIC INDICATORS,
American Meteorological Society Bulletin 19, p. 193-204.

8, 9
___, 1958,
COASTAL SAND DUNES OF OREGON AND WASHINGTON,
Geological Society of America Memoir no. 72, 169 p.

8, 9
___, 1967,
COASTAL DUNES OF CALIFORNIA,
Geological Society of America Memoir no. 104, 131 p.

2. Barrier dune boundaries.

3. Discernible dune crest lines.

4. Land-water boundaries at the time the photos were taken.

5. Beach zones.

6. Distinctive bluff crests of river valleys and older, higher glacial lake shorelines.

7. Locational indicators (section corners and selected roads).

Map Overlays

In conjunction with the proposed sand dune mining monitoring procedure study, 50% screened 1:24,000 USGS topographic maps were reproduced on mylar to serve as base maps for several different informational overlays. For priority areas not covered by 1:24,000-scale maps, enlarged quarter sections of 1:62,500 topographic quadrangles were used to reproduce equivalent 1:24,000-scale mylar base maps. Overlays are clear acetate, and are positioned on the mylar base maps by means of registration pins.

Map overlays produced for the two projects delineate (in the contractual priority areas):

1. Boundaries of the various types of dune assemblages, including barrier dunes, with appropriate identifying codes.

2. Land cover/use information, including active and nonactive sand dune mining operations.

3. Locations of active and many no - longer - active sand dune mining sites, for which color 70mm, large scale aerial photos were taken in the spring and early summer of 1978.

4. Boundaries of all public lands.

BIBLIOGRAPHY

A number or numbers corresponding to the listing below appear in the left margin of each entry. The numbers indicate the emphasis of the publication's content. Several references can be cited as particularly effective statements or overviews concerning the Lake Michigan coastal sand dunes. These are Dorr and Eschman, 1970; Scott, 1942, n.d.; Cressey, 1928; and Cowles, 1899.

1 geological emphasis on Lake Michigan coastal dunes in Michigan

2 geological emphasis on Lake Michigan coastal dunes in Indiana, Illinois or Wisconsin

3 botanical or ecological emphasis on Lake Michigan coastal dunes in Michigan

4 botanical or ecological emphasis on Lake Michigan coastal dunes in Indiana, Illinois or Wisconsin

5 general, popular or other emphasis on Lake Michigan coastal dunes in Michigan

6 general, popular or other emphasis on Lake Michigan coastal dunes in Indiana, Illinois or Wisconsin

7 emphasis on non-Lake Michigan coastal dunes in the Great Lakes region

8 emphasis on coastal dunes in general

9 emphasis on coastal dune terminology and classifications

10 emphasis on inland dunes and/or their terminology and classification

11 emphasis on remote sensing of dunes and shorelines

12 emphasis on barrier islands and dunes

13 miscellaneous

2 Alden, W. C., 1902,
THE CHICAGO FOLIO,
United States Geological Survey Folio no. 81.

13 American Geological Institute, 1974,
DICTIONARY OF GEOLOGICAL TERMS,
Garden City. New York: Anchor Books, 545 p.

8 Amos, W. H., 1959,
THE LIFE OF A SAND DUNE,
Scientific American, v. 201, no. 1, p. 91-99.

2 Atwood, W. W. and J. W. Goldthwart, 1908,
PHYSICAL GEOGRAPHY OF THE EVANSTON-WAUKEGAN REGION,
Illinois State Geological Survey Bulletin no. 7, 102 p.

Bagnold, R. A., 1941,
THE PHYSICS OF BLOWN SAND AND DESERT DUNES,
London: Methuen and Company, Limited, 265 p.

11 Residential
- 111 Medium and high density
- 112 Low density (less than 1 development unit/acre)

12 Commercial, services and institution

13 Industrial

14 Transportation, communication and utilities

17 Extractive, open pit mine
- 171 Active status, Spring, 1978[a]
- 172 Inactive status, Spring, 1978
- 173 Sand storage

18 Cemetery

19 Recreational
- 191 Public
- 192 Private

21 Cultivated cropland and improved pasture

22 Specialty crops (orchards, bushfruits, vineyards, ornamental horticulture, christmas tree farms and other specialty crops)

31 Herbaceous ground cover

32 Shrub ground cover

41 Deciduous forest

42 Coniferous forest

43 Mixed forest

44 Dune grass

5 Water

61 Forested wetlands

62 Non-forested wetlands (bush swamp)

63 Vegetated open water

7 Barren
- 72 Beaches
- 73 Sand other than beaches
- 74 Transitional areas

[a] Aerial surveillance is an on-going biannual program of the DNR

Table 5. Land cover/use categories used in the DNR-RSP Michigan lakeshore dune type inventory and barrier dune classification and the sand dune mining monitoring studies. The interpretation is based on predominant land use/cover type of one hectare (100 x 100 meters, approximately 2.5 acres).

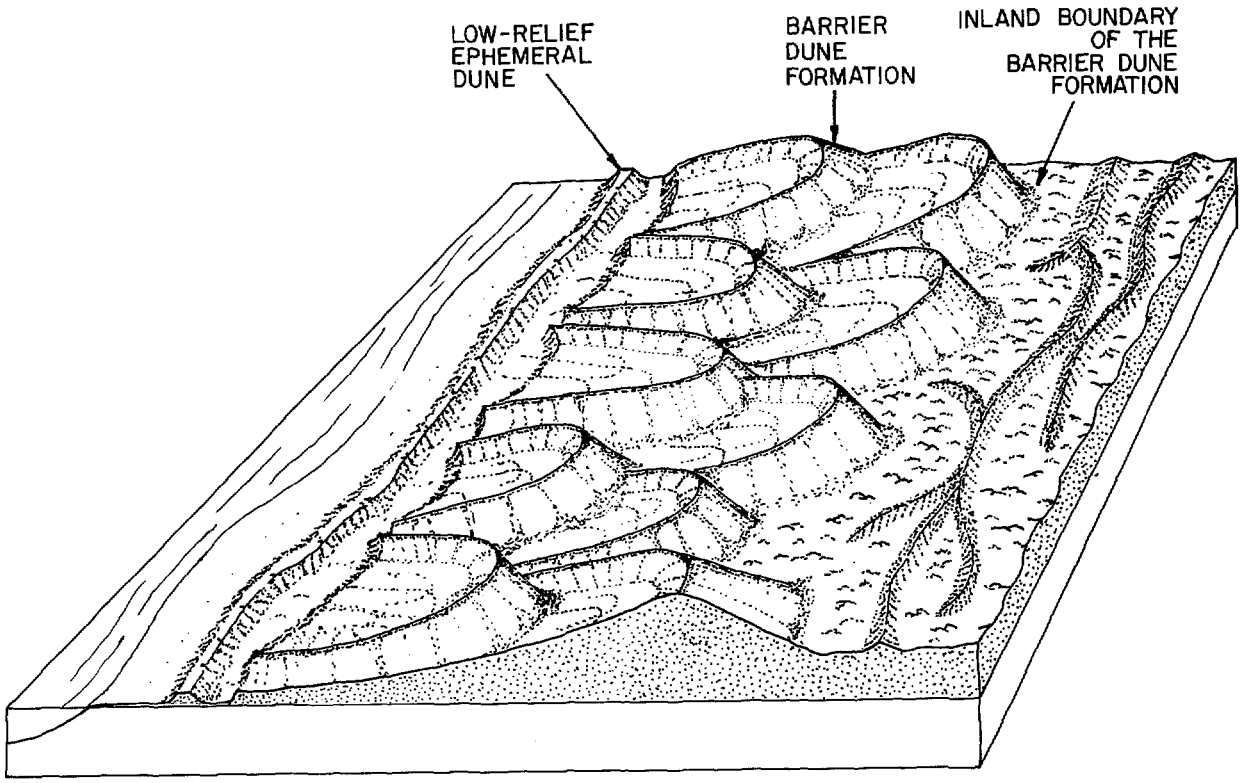


Figure 22. Diagram illustrating one type (parabolic) of barrier dune formation, its inland boundary and a low-relief ephemeral dune adjacent to its lakeward margin.

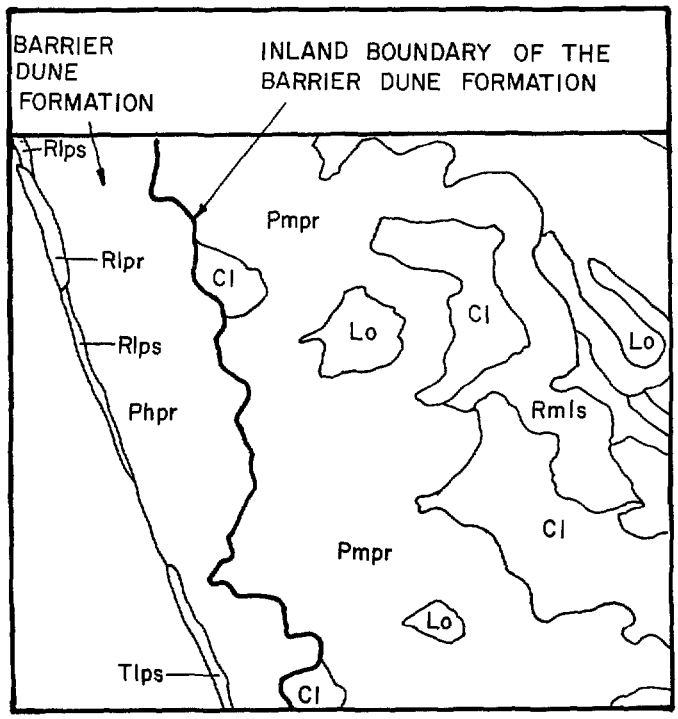


Figure 23. Overlay on a topographic map base showing the outline of various dune assemblages. The landward boundary of the barrier dune formation is the heaviest line. See Table 3 for an explanation of the codes used. Map base is a portion of the Grand Haven 1:24,000 scale topographic map.

LAND COVER/USE

Land cover/use mapping is discussed more fully in a related DNR - RSP contract study report entitled "Monitoring and Inventory Procedures for Sand Dune Mining Operations In Michigan - A Sand Mining Surveillance Manual Using Remote Sensing Techniques," authored by Ger Schultink. The most recent available aerial imagery (Appendix A) was used for delineating land cover/use information and for identifying and inventorying sand dune mining sites within the contractual sand dune areas. The classification scheme was modeled after the Michigan Land Cover/Use Classification System (Table 5 and Appendix B).

PRODUCTS PROVIDED TO THE MICHIGAN DEPARTMENT OF NATURAL RESOURCES

Photo Overlays

Identification of dune assemblages within the contractual priority areas was made by interpretation of the most recent 1:20,000-scale panchromatic ASCS aerial photography. Dates of the photo coverage range from 1965 to 1976. Overlays were produced using the photos as a base. The following features are displayed on the overlays:

1. Boundaries of the individual dune assemblages, with appropriate identifying codes.

Many shorezone features, therefore, are only ephemeral. Low dunes, for instance, which are presently found adjacent to the shoreline (in the literature generally referred to as foredunes) are not necessarily permanent features. During high lake levels they tend to erode, whereas during low water levels they may be accreting (Scott, 1942; Cressey, 1928); and over a long period, erosion exceeds accretion. Many foredunes were completely eroded during the last ten years along Lake Michigan by storm waves, as a consequence of prolonged high water levels. Hence, to ensure relative permanence, the designated barrier dune assemblage must not be part of the presently active, or potentially active, shorezone region; its life expectancy must be long-lasting.

Where significant dune accumulations exist along the Lake Michigan and other Great Lakes shorelines, several different zones or assemblages of dune types typically are encountered in a traverse inland from the water's edge. Except for the modern dunes adjacent to the shoreline, each zone is generally related to a former, higher glacial Lake Michigan (Table 4), and its topography varies as to relative relief, age, form and evolutionary stage. Usually, the older the dune is, the greater its distance inland. The most extensive period of dune formation occurred at the time and during waning of the Nipissing glacial lake stage (Scott, 1934; Tague, 1946; Dorr and Eschman, 1970), and most of the largest dunes recognized today are believed to be associated with this period. Dune assemblages of this age are commonly found adjacent to the present shoreline or ephemeral shoreline foredunes. Much of the dunes associated with the younger, and lower, Algoma stage (Table 4), being less developed and more limited in extent,has been eroded away over the last several thousand years by wave action; and other Algoma stage dunes have become superimposed on Nipissing dunes and often are not easily recognized as Algoma. Because of their position and tendency toward great relative relief and expanse, Nipissing dune assemblages are comparatively permanent, even though small portions may be lost to wave erosion during prolonged high water periods if the fronting foredune is removed. The Nipissing dunes commonly appear as impressive barriers separating the shoreline and inland environments.

In reality, however, problems exist in designating barrier dune formations on the basis of age or their association with a previous glacial lake. Because of the morphologic complexity of evolving dunes of different ages, it is most difficult to establish the age of individual dunes

Y.B.P.*	Glacial Lake	Water Elevation**
PRESENT	Lake Michigan	580
3,000	Lake Algoma	595
4,000	Lake Nipissing	605
9,500	Lake Chippewa	230
11,500	Lake Algonquin	605
12,000	Lake Kirkfield	565 (?)
13,000	Lake Chicago	
	Toleston Stage	605
	Calumet Stage	620
	Glenwood Stage	640

* Y.B.P. = Years Before the Present (approximate)
** above current sea level

Table 4. Major stages of Glacial Lake Michigan

conclusively without extensive field work. Furthermore, dunes of a given age may not necessarily be found in every shoreline segment where dunes presently exist. Instead of an age criterion, it seems more reasonable to delimit the barrier dune formation on the basis of relative relief. Relative relief of the various dune assemblages can be determined objectively through interpretation of stereo-paired aerial photographs and corresponding topographic maps.

As a practical definition, this study has identified the BARRIER SAND DUNE FORMATION as:

> that first dune assemblage whose forms display the greatest relative relief within the officially designated "sand dune areas" ; its inland boundary is at the base of the assemblage's landward limit. (Michigan Department of Natural Resources, 1978)[3].

This dune assemblage will generally be the first dune assemblage inland from the beach, or adjacent to the more or less ephemeral, or potentially active, low-relief dune form or assemblage which itself is adjacent to the upper beach zone (Figures 22, 23). Of course, the Sand Dune Protection and Management Act still allows the Michigan Department of Natural Resources to designate any other sand feature a "barrier sand dune formation."

[3] In cases where two different dune assemblages within the sand dune area have similar relative relief, the most lakeward assemblage would normally be the recognized barrier sand dune formation.

Interpretation Problems

Sand dune classification and subsequent delineation have been accomplished through the utilization of 1:20,000-scale ASCS panchromatic aerial imagery. If the dune feature is largely bare and devoid of vegetation, reflectivity, glare and washout on the photo often make it difficult or impossible to distinguish between low dune ridges, narrow dune terraces and/or narrow dune platforms; likewise, wide dune platforms and dune terraces are often indistinguishable. Furthermore, low-relief dune ridges, terraces and platforms adjacent to the shoreline which are recognized on the photos may represent only ephemeral features. They may form during times of low water but may be removed by wave erosion during periods of high lake levels.

Dense vegetative cover obscures topographic details on some stero-paired photos, and minor errors in placing boundary lines for certain dune assemblages very likely have occurred on the photo overlays. Many or most of these errors, however, were corrected when the boundary lines from the photo overlays were transferred to the topographic map overlays. The assemblage outlines are often expressed by specific contour lines or characteristic changes in the spacing and pattern of the contour lines.

Low-relief ridges, often segmented, are commonly detected inland from the major higher-relief dune assemblages. It is difficult to distinguish whether they represent relic shorezone dune features of the older glacial lakes or are actually relic beach ridges or offshore bars. If the soils map indicates that they are composed of fine sand, they are mapped as dune ridges.

THE BARRIER DUNE

The Sand Dune Protection and Management Act (Michigan Legislature, 1976) defines a barrier dune as "the first landward sand dune formation along the shoreline of a Great Lake or a sand dune formation designated by the department" (Michigan Department of Natural Resources, 1978). This definition is somewhat ambiguous, and it is most difficult, if not impossible, to designate clearly a barrier dune from a morphological point of view, given the types, arrangements, ages and evolutionary processes of the lakeshore dunes.

The delineation of the barrier dune, therefore, is not included in the scheme of the Dune Morphology Classification of the Lake Michigan Shore. It must be defined as a separate entity. Dune types vary along the shoreline and so must the morphologic and geometric characteristic of the barrier dune.

Unfortunately, the term "barrier dune" has a geologic connotation of long standing which is contrary to the definition in Public Act 222. A study of the pertinent literature conveys the idea that a barrier dune is formed on a barrier island, i.e., an offshore marine feature. It consists of multiple elongate sand ridges rising above high-tide level and extending generally parallel with the coast, but separated from it by a lagoon. Dunes, interspersed with vegetated zones and swampy terraces, commonly extend lagoonward from the open ocean beach (American Geological Institute, 1974; Schwartz, 1973; Otvos, 1970; Curray, 1969; Hoyt, 1967).

In the spirit of P.A. 222, the barrier dune seems to refer to a dune assemblage which separates the present-day shorezone and interior environments. It is the landward edge of the recreationally oriented, "aesthetically pleasing" shoreland and the lakeward edge of inland oriented activities. It is a sand formation whose location and relief impede interaction between the two areas. In essence, the barrier dune is a buffer zone; but it seems to be more important and unique to the littoral rather than the terrestrial environment. In this study, the barrier dune assemblage is generally the largest and best developed of the relic shorezone eolian sand features which formed 3,000 to 13,000 years ago. Along Lake Michigan, these features probably represent the largest collection of freshwater-associated dunes in the world. Once destroyed, they will not regenerate under present climatic and geomorphic conditions.

To delimit the barrier dune formation realistically, the following prerequisites were assumed:

1. Logical criteria should be established to permit defining the formation as objectively as possible.

2. Definition must allow for variation in morphologic and geometric characteristics.

3. Boundaries, and especially the landward limits, should be relatively easily recognized and delineated on stereo-paired aerial imagery at a scale of 1:20,000 and larger.

4. The dune should be a relatively permanent formation.

The latter characteristic is especially important. The shorezone environment, by its very nature, is dynamic; it is a geologically active zone. Waves, currents, wind and the effects of changing lake levels continually modify the shorelands.

The following local relief classes are recognized:

Low Relief:	less than 20 feet
Moderate Relief:	20 through 80 feet
High Relief:	over 80 feet

Orientation of the Dune Form

Some of the dune types may display a distinct orientation with respect to the present shoreline. If the trend of the dunes within the assemblage coincides or nearly coincides with the orientation of the shoreline, the complex is said to be PARALLEL to the shore (Figures 7, 9,). If the forms are oriented perpendicular or nearly perpendicular to the shore, the assemblage is said to be NORMAL to the shore. In some cases, the trend of the dune form is broadly ARCUATE (Figure 21), with the concave portion facing lakeward; the trend of individual dune segments, therefore, varies depending upon the location within the area. Typically, this arcuate trend exists where dunes had formed along a shore of a previous lake embayment which subsequently had been filled. Not uncommonly, low dune ridges associated with older higher glacial lakeshores will display more or less IRREGULAR orientation with respect to the present shoreline.

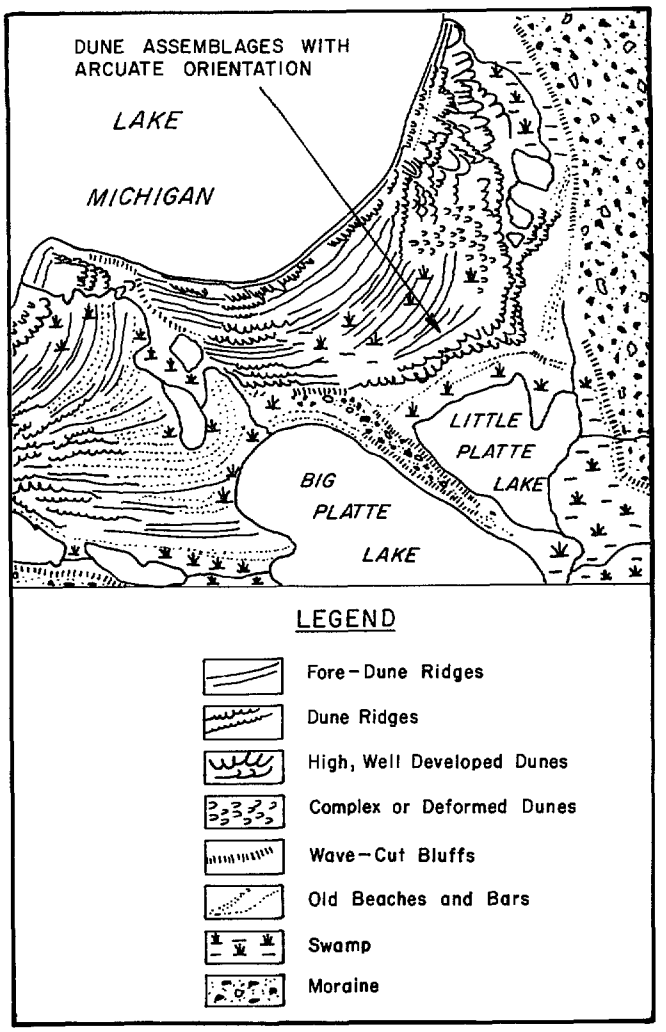


Figure 21. Diagram of dune assemblages with arcuate orientations within the Platte Lake Embayment, Benzie County (from Calver, 1946).

Arrangement of the Dune Form Within the Assemblage

Within a type area, the dune form may have a SINGULAR expression or it may be REPETITIVE in nature.

Underlying and/or Associated Landforms

The surface expression and other physical characteristics of the marginal sand apron and the interdune lowland commonly reflect the underlying formation. Thus, the recognition and identification of this formation is important. This classification scheme recognizes the following underlying formations: lacustrine, outwash or alluvial plain, till plain, and end or recessional moraine.

Boundaries and Identification of Dune Types

H. T. U. Smith (1954, p. 52) states:

> The simpler types of dunes, whether active or stabilized, exhibit a wide range of modifications and variations, and the overall characteristics of dune assemblages are subject to innumerable complications by the crowding or merging of individual dune forms, by alternations between activity and stabilization, by the juxtaposition or superposition of one type or scale of dune form on others of different type or scale, by shifts in wind direction during dune building, by wave erosion, and by other factors.

This introductory statement indicates that boundaries of the designated dune assemblages are not always precise lines, although they appear drawn as such on the photo and map overlays; in actuality, these boundaries may be transitional zones. By its very nature each dune form is going through an evolutionary process. Therefore, a designated dune assemblage may contain dunes which do not exactly fit an "ideal" form; nevertheless, the assemblage fits one class better than any other in the classification scheme.

Figure 19. Perched dunes, Empire Bluffs (Section 25, T28N, R15W; Leelanau County).

deposited on the sloping side of the formation. Their thicknesses vary. Overriding dunes may have the same forms as nonelevated dunes.

Relative Relief of the Surface Expression

A dune assemblage may display low, moderate or high relative relief. Except for the marginal sand apron, relative relief is based on the local elevational difference between the lowest and highest parts within the assemblage. It refers to the local surface expression of the dune sand itself and does not necessarily infer the assemblage's relative position above lake level. The value is meant to give an impression of the overall relief characteristics of the sand dune forms within the assemblage; consequently, it is possible in some instances to find small portions with differences in relief slightly below or above the relative relief value for the complex as a whole. The relative relief displayed by the marginal sand apron may be mainly an expression of the underlying nondune formation.

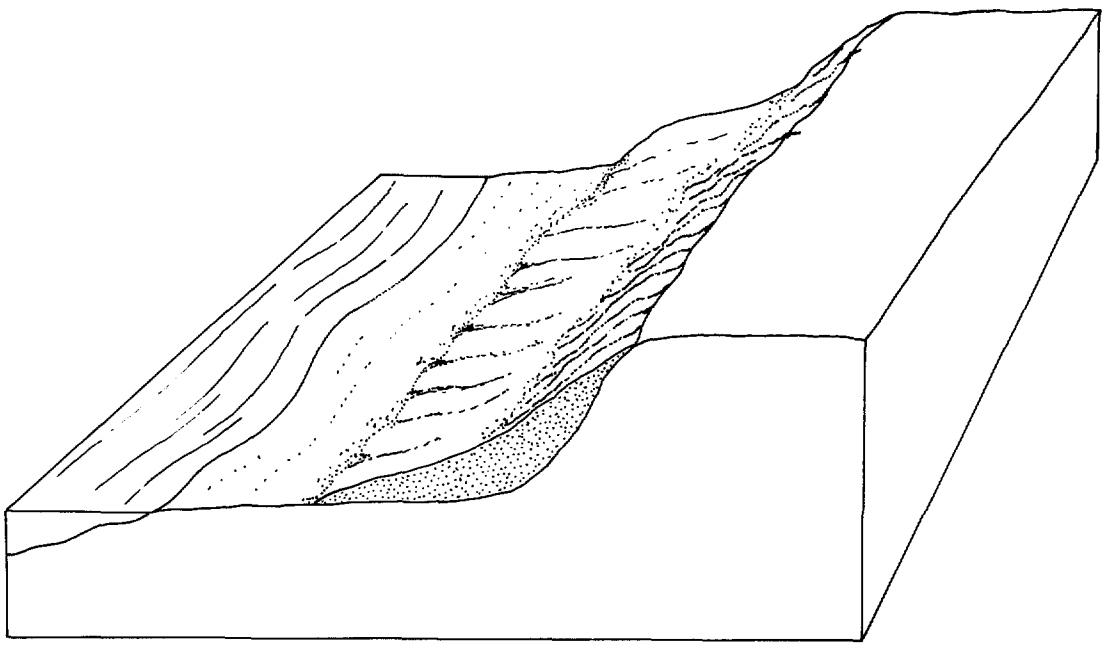


Figure 20. Diagram of an overriding dune.