Genesis and Development of Sand Formations on Marine Coasts

by

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Genesis and Development of Sand Formations on Marine Coasts.

By Pehr Olsson-Seffer, Ph. D.

Since the year 1891 I have been studying the sand formations on marine coasts and their flora and vegetation. During the years 1891 to 1899 my investigations were confined to the coasts of the Baltic. The last mentioned year I also investigated the dunes on the Danish North Sea Coast, in Holland, and in certain parts of Scotland and France. In 1900—1901 observations were made in Southern Sweden, in various places in Denmark, on the South Coast of England, in Southern Italy, at Port Said, in Egypt, in Western Australia, and in Queensland.

Various coasts in Australia, from Central Queensland to Western Australia, through New South Wales, Victoria and South Australia, were visited and re-visited during 1902. In New Zealand only part of the North Cape was made subject to a brief and hurried visit and notes of the strand vegetation were taken during stays in various islands of the Pacific, such as the New Hebrides, Solomon Islands, Samoa and Hawaii.

On the Pacific coast of North America the dunes at San Francisco and Monterey Bay were studied in 1903—05. During 1905, I also visited the coastal sands at Santa Barbara and Santa Monica, in Southern California, as well as several sand dune districts on the Pacific coast of Mexico, such as Salina Cruz, in the innermost part of the Gulf of Tehuantepec, and San Benito, near the Guatemalan border. The extensive sand dunes near Vera Cruz, in Mexico, on the Gulf side, were investigated in August of the same year. In December, sand strands were studied at Mazatlan, a Mexican port on the eastern shore of the Gulf of California, as well as at San Blas in Mexico and Champerico in Guatemala.

The large field these observations cover have given me ample opportunity to make comparisons of the coastal sands in various climates

and under the most different natural conditions. In the present paper I propose to deal briefly with some of the marine sand formations, their origin, development, and classification, so far as it is necessary to demonstrate the most fundamental facts of this subject and the principles on which they are based. I also give short comments upon the principal dune districts visited in the course of my studies.

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SAND FORMATIONS IN GENERAL.

When we consider the factors which have given rise to the formation of sand, the principal ones are the atmospheric and the aqueous agencies, which also are the most important in transportation and distribution of the material. It will therefore be convenient to distinguish between the following general classes of sand deposits:

1. Eolian sand formations.
2. Neptunian sand formations.

The term eolian in this connection was to my knowledge first used in 1835 by *R. J. Nelson*¹⁾ and it signifies the agency of wind. Eolian deposits exhibit a different composition and structure from the neptunian, those sediments which have been built up by the water. The transporting power of water being considerably greater than that of wind, it necessarily follows that the material moved by aqueous agencies varies more in size than that which is carried by the wind. We will have ample opportunity to note this difference as we proceed in our inquiry.

No rational nomenclature for the different kinds of soil constituents, neither of inorganic nor of organogenetic origin, has yet been agreed upon, and it will thus be necessary to give here the designations which have been used during my observations in the field.

1) Proceedings of Geological Society of London, Vol. II., p. 160.

Diameter of grains in millimeters.

Fine dust or silt.....	0.02—	0.03
Medium dust or silt.....	0.03—	0.05
Coarse dust or silt.....	0.05—	0.1
Finest sand	0.1 —	0.2
Fine sand	0.2 —	0.3
Medium sand	0.3 —	0.5
Coarse sand	0.5 —	1
Grits	1 —	2
Gravel	2 —	4
Coarse gravel	4 —	6
Pebbles	6 —	10
Coarse pebbles	10 —	20
Shingle	20 —	50
Stones	50 —	250
Boulders	250 —	Upwards.

The limit of the coarseness of sand grains is here considered as 0.2—0.1 mm. When the grains are finer than 0.05 mm., the soil ¹⁾ has lost the physical properties of sand. It does not feel gritty to the fingers, and if it is dropped on a level and hard surface the grains will not separate but congregate in small heaps. It needs several minutes to sink in water to the bottom of a test tube. When over 0.05 mm. the soil has, however, more of the characteristics of real sand. It is then gritty, when pulverized between the fingers. If scattered dry, it will separate into grains conspicuous to the naked eye. When mixed with water in the test tube, it sinks rapidly, usually in less than one minute, and it is to a noticeable degree conductive of water. It is difficult in practice to draw the lower limit for sand of a certain coarseness, because the soil is more or less mixed. On account of the difference in specific gravity of the grains many samples contain grains of different grades.

In the above table the measurements of diameter refer to the average sized grains in each class. The term sand has here been applied to soil, the grains of which are under 1 mm., while a coarseness of 1—2 mm. has entitled the soil to the name of grits. When the chief ingredient is particles larger than 2 mm. and below 6 mm. the soil has been designated as gravel.

Common sand is 2,100 times heavier than dry air, while only 2.5 to

1) The term soil is in this paper used in its broadest technical sense to designate the loose material constituting the disintegrated superficial layers of the earth's surface.

2.7 times heavier than water. A strong breeze is therefore required to raise the dust of a road for transportation by the wind, and a still stronger breeze to raise quartz sand; while large pebbles are seldom lifted from the ground. The winds are also extremely irregular in their movements and action. The trades over the ocean have a higher degree of uniformity than other winds, but the velocity is generally only 10 to 20 km. an hour. The winds that do the chief part of eolian geological work are those of storms, whose velocity per hour is from 50 to more than 100 km. Such winds are very unsteady in their action, blowing in gusts, in which there is a sudden increase to a maximum and a slower decline to a minimum. There is no constancy in force even for an hour, and no uniformity over large areas.

The transporting power of water, on the contrary, is very great; strong waves or torrents being able to move rocks weighing hundreds of tons. By experiments it has been found that a current moving at the rate of 25 cm. per second is able to carry fine sand, while a velocity of 50 cm. is sufficient to transport coarse gravel. The action of water is, moreover, very constant as a rule, and the waves on a long coast, for instance, exert their uniform influence over a considerable area.

We must not, however, confound the transporting power of these agencies, wind and water, with their erosive power. In one case it is the weight, in the other the cohesion, that offers the resistance. Neither wind nor water has any greater erosive power by itself. It is where mud or sand is carried by the wind or water, that a friction arises which removes the particles, loosened by decaying and other processes, from their original place.

Water is efficient in denudation by 1) dissolving of rocks, 2) transportation of the material which assists in the eroding work, and 3) carrying away the debris. The analogous functions of wind are: 1) transportation of the material which triturates and erodes all substances in its way, and 2) distribution.

A water current when overloaded with solids will deposit; when underloaded it will erode. A sandladen wind always both cuts and deposits. Dry sand, wind borne, is an unobtrusive agent, working silently but diligently on the task of paring away the surface. It leaves no monuments to show the magnitude of its results, as does denudation by water. River beds and sandbanks are examples of the excavating and building up through sedimentation by the water.

Water is a base leveler in the sense that it transfers material from higher places to lower; but where it erodes, it always works more rapidly

along the lowest lines and leaves ridges and islands, by which its results can be measured. The water currents have, at any one spot, but a single direction, and the furrows and mouldings of the curved surface are grouped in a single system; but the wind may blow in many directions, and produces series of corresponding complexity.

It is a well known law in dynamical geology that all sedimentary deposits are stratified. This lamination is somewhat different when caused by eolian influence than when resulting from the action of water. The sorting power of water is more distinct than that of wind, because of the greater regularity of water currents.

As a consequence of the rapid variations to which the transporting power of the wind is subjected, eolian deposits are generally straticulate, finer and coarser laminae succeeding each other in indefinite alterations. But there is not the evenness of layer characterizing aqueous deposits, even when made over level surfaces. To make beds without straticulation would require winds without these irregularities,—little varying and long continuing,—such as few regions have, except those that have winds of too moderate velocity to carry any but the finest particles. The gusty winds also tend, by their denuding as well as transporting work, to make wavy rather than plane upper surfaces. Moreover, any barrier, as a projecting rock or a stump, or a tuft of grasses, causes a heaping of the sands around the obstacle, and makes curving surfaces in the heaps, owing to the eddies in the air.

We must here consider the following kinds of lamination:

- 1) horizontal
- 2) oblique
- 3) flow- and plunge
- 4) irregular.

Horizontal strata are developed in water only, especially in non-running water. Each lamination here represents different conditions of the water in which the sediment is deposited, and oblique lamination or cross-bed structure is a result of deposition by rapid shifting currents, carrying material of varying coarseness. While strictly horizontal lamination cannot be formed by winds, obliquely laminated layers occur in eolian deposits, indicating that somewhat regular winds have blown for some time.

This cross-bed structure of the sediments is characterized by a lamination in a plane, oblique to the horizon. It results from the pushing along of the sand by currents, causing at first a little elevation, and

then the deposition of successive layers over the front slope of the elevation. If the currents are transient, alternating with conditions of still water, the obliquely laminated beds will alternate with others horizontally laminated. Such laminations may be due to changes of wind or tide, or to the periodical or occasional fluctuations in the volume of rivers.

The flow- and plunge structure has been caused by plunging waves accompanying the rapid flow of a current, through which action the oblique laminae have been broken up into short, wavelike parts. This lamination bears evidence of being the result of an agent less variable, and moving slower than that which has formed the irregular structure so characteristic of most eolian deposits.

THE DEVELOPMENT OF COASTAL SAND FORMATIONS.

The sand formations, which will come under discussion in connection with our present subject, all have their origin ultimately due to the action of the sea. We can conveniently divide these marine formations into following groups:

1. Submarine sand banks.
2. Sandy islands.
3. Sandy spits.
4. Sandy beaches.

1. The first class of formations or submarine sand banks are formed by the combined action of streams and the waves of the sea, or by the latter alone. Most of these accumulations contain more or less of river detritus, which is brought down to the sea during floods. The ocean's waves and currents meet it as the tide sets in, with a counter action, or one from the sea landward; between the two the waters, as they lose their velocity, drop the detritus over the bottom. Where the river is very large and the tides feeble, the banks and reefs extend far out to sea. Where the tide is strong, sand bars are formed, and the stronger the tide, the closer are the sand bars to the coast. Where the stream is small, the ocean may throw a sand bank quite across its mouth, so that there may be no egress to the river waters except by percolation through the sand; or, if a channel is left open, it may be only a shallow one.

In other cases the material constituting the sand banks is derived

from the land through the erosion and transportation of waves and currents. This material consists usually of coarse or fine sand, but may include some beds of pebbles or stones when the currents are strong. The stratification is comparatively regular and nearly horizontal.

2. When the accumulations just spoken of increase under wave-action in shallow water, until they rise above low tide level, they form sandy islands.

3. Sandy spits are the lengthwise extensions of beaches formed through the waves throwing material on shoals at the turn of the shore. Their composition is similar to that of the above formations.

4. Sandy beaches are made by material thrown up on the shore by waves. This material is coarse where the waves break heavily, because, although trituration is going on at all times, the powerful wave action and the undertow carry off the finer material seaward into the offshore shallow waters, where it settles over the bottom or is distributed by currents. It is fine where the waves are gentle in movement, as in sheltered bays, or estuaries, the triturerated material accumulating in such places near where it is made.

As soon as the accumulations of eroded material have increased so far as to rise above the surface of the water, the further growth is similar to that of the beaches, and from these latter other coastal sand formations such as dunes and sand fields are developed by the influence of wind. The development of these two kinds of eolian sand formations will be discussed in detail under separate headings.

It is a well known fact that the salts of seawater hasten the deposition of sediments, and consequently the shape and formation of sand banks and beaches on marine coasts is somewhat different from those of corresponding freshwater deposits. I have not been able to ascertain whether the seawater acts differently on siliceous material than on clay sediments. We usually find that deposits nearer the shore or the source of the material contain more silica than further out in the deep water, but this may depend on the usually large size and the greater weight of the siliceous fragments, which causes them to sink sooner.

In order to determine this, experiments were conducted in the laboratory. I tried ordinary seawater from the Baltic, of a salinity of 0.6% measured with areometer, and artificially prepared solutions of resp. 2.7% and 3% corresponding to the salt content of ocean water. Finely ground clay and beach sand were stirred in the water samples, and allowed to settle in vessels 25 cm., 50 cm., and 100 cm. deep, all being 42 cm. in diameter. The following results were obtained:

Depth of vessel.	No. of vessel.	Salinity of water per cent.	Hours for settling.	
			Silica.	Clay.
25 cm.	{ 1	fresh	29	38
	{ 2	0.6	10	12
	{ 3	2.7	2	2.5
	{ 4	3.0	1.75	2.25
50 cm.	{ 5	fresh	42	50
	{ 6	0.6	14	16
	{ 7	2.7	3	3.75
	{ 8	3.0	2.50	3.25
100 cm.	{ 9	fresh	68	84
	{ 10	0.6	24	30
	{ 11	2.7	5	6.25
	{ 12	3.0	4.25	5.25

As will be seen from this table, silica in all cases both in salt and fresh water settled faster than clay. Whether this fact was merely a result of a greater weight of the siliceous particles, or whether other factors influenced the sedimentation, I was unable to decide. At all events it was evident that the salt produces a considerable flocculation in the water. The primary cause of the growth of the deposit in water is sedimentation, but in many cases the rising of the level of the coast-line has to be taken into consideration as a secondary factor. It is often difficult to determine to what extent the rate of growth of a deposit is due to one of these factors or the other. Especially is this the case on a low coast, where the growth always takes place more rapidly than on a steeper shore. The horizontal growth of the deposit is also much greater on coasts protected by islands than on open coasts with deep water, where the material is more easily carried away.

With regard to the position of the marine sediments it will be noticed that they are apparently horizontal, and the tendency is to level the beds through filling all depressions. The coarser sediments are always nearer the shore in comparatively narrow lines, parallel to the coast, whereas the finer sediments are spread over a larger area further off the shore. Banks and beaches are always sloping gently seawards, and they are, perhaps, somewhat steeper on marine coasts than on fresh water shores, general conditions being equal.

We have here also to consider the peculiar results of the wave-action of both water and wind, which are generally known by the name of ripple marks, a term introduced by *Lyell*.

The phenomena of rippling have in recent times had a careful observer in *Cornish*, and the following statements are principally based on his studies of this problem, although the laws and facts presented by him have been subjected to a detailed investigation in the field by the present writer, and I am able in a few instances to bring forward some evidence in support of *Cornish's* theories.

The same factor which causes the wave formation of water has a similar influence on the sand. The resulting wave-forms or ripples consist of alternate ridges and furrows made by the wash of the waters over a sand flat or beach, or over the bottom within soundings. They may also be made by the action of wind on a surface of sand. When the ripples are formed through the action of water we can distinguish between

1. wave formed ripples,
2. current made ripple marks, and
3. tidal sand ripples.

The parallel formations of wind made sand waves are

4. eolian sand ripples, and
5. dunes.

Comparing waves of water with those of a more solid medium, such as sand, we find that, while in the case of water two kinds of waves, oscillatory and wind driven, can be recognized, wave formation in sand is always connected with onward movement of the particles. In oscillatory waves the water particles on the crest are moving forward, but those in the trough backward with the same velocity and consequently the water body as such does not move in either direction. It is customary to express this motion by saying that the particles move in a circular orbit. When the waves are wind driven the forward velocity is greater than the backward, and a bodily movement of the water in the direction of the acting force is the result. The curve described by the water particles is still closed, having a trochoidal form. In the case of drifting sand the particles from the crest of the wave move in curves, which are open.

Wave-formed sand ripples have an unsymmetrical form, always facing with the waves. Current made ripple marks are similarly unsymmetrical in form, the sheltered side being steeper, and the front facing the cur-

rent. Tidal sand ripples, first described by *Reynolds*¹⁾ and later by *Cornish*²⁾ occur in estuaries and also on some shores where the sand is exposed to waves as well as currents. *Cornish* is of the opinion that they do not require for their formation any cooperation between flood and ebb currents. The size and form of these ripples is constantly changing with the variations in the tide. *Cornish* describes this in the following words:

"At neap tides the sands were nearly smooth, and as the tides increased the tidal sand ripples appeared, short and relatively steep. The amplitude increased steadily, the average wave-length also increased, apparently by elimination of some of the ridges. When the highest spring tide was passed the amplitude rapidly diminished, the wave-length remaining nearly, but not quite constant, and the mean sand level remaining practically unchanged."

Tidal sand ripples sometimes attain a considerable size, *Cornish* giving the wave length of from 1 to 6.7 m. I have often noticed a finer rippling of the proper tidal ripples, and in two instances, on the eastern coast of Australia, I observed the tidal sand ripples crossed by another set of large ripples. These were formed by a sudden change of the direction of the tide current through the overflow of a neighboring stream. Both these sets of wave formations were then beautifully rippled in the usual way by little current marks, facing almost transversely the second set of larger ripples. *Cornish* attributes the formation of current marks to the pulsation of the fluid rather than to the current itself.

In the formation of eolian sand ripples it is the heterogeneity of the material which is of the greatest importance. The sorting action of wind is remarkable, and it is evident at the first glance on a group of ripples that the heavier grains always constitute the crest, the lighter the trough. A moderate range of sizes of grains seems therefore most favorable to the formation of ripples.

*Darwin*³⁾ remarked the uniformity of pattern in the ripples formed by wind, which uniformity, as a rule, is absent from ripples made in

1) Reports of committee appointed to investigate the action of waves and currents on the beds and foreshores of estuaries by means of working models. — British Association for Advancement of Science, Reports '89, '90, '91.

2) The formation of wave surfaces in sand.— Scot. Geogr. Mag. 17: 1—11. 1901.

3) *G. H. Darwin*: On ripple mark. — Proceedings of Royal Society, London, vol. 36. 1883.

water. When the wind blows upon the sand, a winnowing process takes place, the finer particles being carried farther away than the coarser material, which then produces the ridges of heavier grains mentioned above. This uniformity of pattern connected with the fact that the wave length increases with the time during which the force of the wind is acting upon the sand led *Cornish*¹⁾ to advance the following law for rippling by wind: *The rippling takes place when the eddy in the lee of the larger grains is of sufficient strength to lift the smaller.*

The systematically corrugated surface of loose sand can only be produced by a wind that is not too strong for the larger grains to remain on the ground. If the breeze is too strong no rippling whatever takes place as all the particles of sand then will be transported. If on the other hand the wind is too weak to make an eddy, the sand moves slowly, but does not form ripples.

The height of the waves and their distances from each other is larger the larger the grains are. The movement of the waves is of different rapidity and depends on the force of wind and the size of the grains. It is naturally more rapid when the wind is stronger and the sand fine. Following results were obtained by the author from a number of measurements of amplitude or height of ridge and wave-length of sand ripples made by wind on the coast of West Australia. All measurements are given in millimeters.

No.	Coarseness of grains.	Amplitude.	Wave length	Number of measure- ments of which sample is average.
1.	0.7	8.6	36	34
2.	0.6	3.1	29	6
3.	0.4	3.7	34	3
4.	0.3	2.5	47	14
5.	0.8	6.2	40	8
6.	0.6	4.4	39	6
7.	0.7	8.7	51	25
8.	0.8	8.3	68	21
9.	0.6	14.6	82	19

These measurements serve to support the results obtained by *Cornish* and the law advanced by him, that *amplitude and wave-length increase*

1) On the formation of sand dunes. — Geographical Journal, vol. IX: 280.

in same proportion. His other conclusion that regular rippling has an amplitude of three grains from trough to crest, seems to me rather hasty. I have, however, not made any regular observations to test this statement, it being of minor importance in connection with my present inquiry.

For the study of wave forms, which as a legitimate subject for investigation has attracted the attention of several scientists since the time of *Newton*, *Cornish* has proposed¹⁾ the term *Kumatology* ($\kappa\upsilon\mu\alpha$ -wave).

Accepting this name for the sake of convenience, the writer has to point out that the digressions here made into the domain of Kumatology have been necessary in order to arrive at a better understanding of the factors which control the movements of sand, the interpretation of which is in many respects still contradictory.

SANDY BEACHES.

The beach may be defined as that strip of the shore which is formed by the agency of waves. As a rule, it is situated between the lowest level of the water and the formations produced by other geological agents.

The method of beach formation has already been indicated. It was mentioned that the mechanical action of the sea is evidenced in the phenomena of erosion, transportation and sedimentation. The eroding action of the sea is especially prominent on steep rocky shores, and on places where the difference between low and high tide is great.

The material from the rocks eroded by the waves as well as the sand and silt carried down to the rivers, sinks to the bottom of the sea and is again transported by the waves and currents to the coast, there to be accumulated. Although the transporting power of the waves is immensely great, the distances to which rocks or even sand can be carried is limited. In sediments of a clastic nature a sifting takes place through the action of the waves against the shore, the finer material being carried farther away, while the coarser is left on the shore. On very steep shores, only larger pebbles and gravel are found, on lower fine sand, and on very low coasts, silt.

If we consider the movements of the sand on a low shore, we will

1) Geographical Journal, March 1897 and June 1898.

notice that the sand grains follow the movement of the waves, that is roll up and down. The deposit of sand takes place only when the returning current does not carry back all material brought forward by the wave. It follows that the velocity of the forward movement must be greater than that of the returning current which is possible only on very low strands, the sloping angle of which is not greater than five degrees. If the size of the grains is large, the angle naturally also changes. At the limit to which the wave reaches, an instantaneous absorption of the very thin strata of water takes place in the sand, so that the returning current does not begin at this limit, but at a place lower down. It is easy to determine the width of this belt in which the absorption takes place, as the sand surface first is shining by the water and then quickly turns dull. The width is always varying, and is in direct relation to the strength of the waves, and also to the sloping angle of the beach. During a strong gale and on a very low strand, this belt is from 2 m. upwards on the Baltic coast, and on the western coasts of Australia and the Pacific coast of America, where the mighty waves of the ocean strike the shore with all their force, this belt is still much broader. Secondly, deposits take place only on coasts, the sloping angle of which is not more than 5 to 10 degrees. This angle is about 5 degrees with a grain size of 0.5 to 1 mm. in diameter. With finer sand, under 0.5 mm., as is the case on many places on sheltered shores on the Baltic coasts, it sinks to between 1 and 2 degrees, while with larger grains, from 1 to 3 mm., an angle of 7 or even 8.5 degrees is formed. With a steeper slope, deposition does not take place, but a denudation is commenced.

Sandy beaches afford a certain protection of the coast line against the erosive action of waves and surf. During the constant landward urging of the sediments the coarser ingredients of the arenaceous material soon cease to roll, and come to rest, and as the deposits are augmented they will offer sufficient resistance to reduce the energy of the wave, and consequently the erosion is diminished.

That beach sands remain unworn depends to a great extent on the fact that the particles do not touch each other, as each one is surrounded by a film of water. The beating of the waves also compresses the interstitial water, and the solitary grains are thus not tossed about and therefore do not grind and wear.

The presence of a considerable amount of interstitial water in the beach sand washed by the waves is demonstrated when through the pressure of the foot on the sand this whitens because of the expulsion

of water, while as soon as the foot is lifted the original dull color is quickly resumed.

Very fine sand is angular, and the rounding by water is produced only when the strength of the current is not sufficient to keep the grains suspended, but yet capable of moving them. The specific gravity of the volume of sand is always smaller than that of the solitary grains. The latter leave between each other spaces which are filled with air and water; if all the grains were of the same size and exactly spherical, the specific gravity of the volume of sand would be independent of the absolute size of the grains, but as soon as grains of different sizes are mixed, the small grains fill the spaces between the larger and hence increase the specific gravity. This latter is also, the mineral character of the grains being equal, higher the more dissimilar the grains are.

The texture of the sand in each locality depends entirely upon the nature of the rocks from which it was originally derived. Through having a comparatively large mixture of different sizes, and consisting of the most different minerals of different specific gravity, beach sands exhibit considerable differences in texture. On almost every non-rocky coast, however, some kind of accumulation of fine grained quartz sand can be noticed.

By quartz sand we understand a soil consisting mainly of white or yellowish quartz grains, among which only very seldom any organic matter is distributed. Being conspicuously free from foreign constituents, quartz sand is very uniform. It is generally believed that the pure quartz sand on marine shore is a special result of the action of the sea. This is, however, not the case. I have examined many samples of the littoral sediments on different coasts, but never found the clean white quartz sand of the beach occurring on the bottom of the sea. On the contrary, the sandy sediment under water is impure, mixed with organic matter, and highly colored. As soon as the sand is thrown ashore by the wave and current action, and left at the water level, it is picked up by the wind and carried inland. And if we observe the sand of the beach from the edge of the water landward, we will find that it becomes cleaner the further it is from the sea. This fact is mentioned by several authors; for instance, *Serres*,¹⁾ who speaks of it in discussing the French Mediterranean coast. Beach formations are very irregular in stratification in their upper portions, where they are made by the toss

1) *Marcel de Serres*: Der Treib- und Flugsand des Mittelländischen Meeres. —*Peterm. Mitth.* V: 197—198. 1859.

of the waves combined with the drifting of the winds. But the sloping part swept by the waves below high-tide level is very evenly stratified parallel to the surface: This surface dips usually at an angle of 5° to 15° . Generally speaking the coarsest beaches have the steepest slopes. The sand of the beach is increased or decreased according to the weather and the seasons, it being thickest in summer and thinnest in winter, and sometimes the beach is almost stripped of sand after a series of gales. On the beach, there is formed a ridge of sand during offshore winds. The sand is readily raised by the breakers and usually an excavation or trough is found at the back of the ridge. This is similar to the excavation and elevation produced in ripples. When the wind goes down, a succession of low ridges are formed concave on the side toward the sea, but as soon as a wave reaches over the top of the ridge, the concavity is filled and an edge with uniformly sloping sides is formed. The height of this beach ridge is usually not very considerable on the Baltic coasts; seldom more than 1.5 m. over the general level of the beach, or 2.25 over the sea. On the Atlantic and Pacific coasts, the height is not much greater, although the ridge is formed by breakers of considerable strength.

When the breaker line has been stationary for some time, for instance during a high tide, an excavation is dredged out, and at ebb a lagoon is often left here. For our purposes the beach may be divided into the following belts: 1. *The submerged beach*; 2. *The front beach*; 3. *The middle beach*; and 4. *The upper beach*. The first belt includes that portion of the beach that lies below mean low tide, but which may be exposed by neap tides. It is normally covered with water, and is subjected to the constant beating of the waves, which carry the material ashore in their landward advance. Some of the detritus is deposited, while another part is returned seawards with the undertow. Where the carrying power of the surf is great, the beach is often built up by material containing a considerable amount of coarse gravel and pebbles. On such beaches there is always a residue of mud after a storm or an exceptionally high tide, while no such deposits occur on sand alone. The front beach is the belt between mean low tide and mean high tide, being alternately each day exposed to the air and submerged. It mostly passes without any marked break into the submerged belt. Situated on the border between the land and water the front beach offers very unfavorable conditions, not allowing the deposits to remain stable or resting, on account of the repeated washing of the waves and currents.

With the term middle beach we would designate that portion of the

shore which is continuously moistened by the spray from the sea, and it may even occasionally become inundated. The sand of this formation which has been piled up by the waves, is picked up by the wind and carried inland. It is usually of a light color. The upper layers are rapidly drying up, but the ground water keeps at a high level, and moisture is usually found at a very slight depth.

The upper beach is limited on one side by the line of debris that marks the highest water. This debris, cast up by the sea, consists of lumber and other wooden articles, fruits and seeds, fragments of marine plants, and a quantity of animal remains, rapidly decaying. The upper beach is also characterized by a greater rise in elevation and contains more organic matter than any other part of the beach. The development of this formation is modified to a greater extent by the wind than by water, and it is especially on this strip of the shore, where the sands commence to drift, and where they usually form the first ridges of sand parallel to the coast, which we know as dunes.

The windmade embankments on the beach have a remarkable construction, somewhat different from the usual. When the shifting of the sand is very rapid, the littoral dunes do not reach any remarkable height, and their existence is then very precarious.

DUNES.

The etymology of the word dune is somewhat obscure. Generally it is presumed that it is derived from the Celtic word *dun*, hill. In Latin it is called *dunum*, in Greek *δύνον*, and hence the modern languages have acquired the use of the same term in more or less changed dress. According to *Grewingk*, not every ridge of sand parallel to the coast is a dune, as they can in some cases originally be sand-banks formed under water, which later have been lifted above the surface of the water through the elevation of the shore. Dunes are formed especially where the sands are almost purely siliceous, and hence incoherent, and little fit for any kind of vegetation. They reach their greatest height on projecting coasts that receive the winds from different directions.

The source of the dune sand is usually either diluvial sand, which has been laid bare, or sand which has been brought ashore by the sea.

On the Dutch and Danish west coasts almost all the sand which forms the dunes traces its origin from the sea. It is here thrown up on the beach by the waves, and as soon as it has been dried by the sun,

the wind carries it further inland. On the coasts in question, the westerly winds are the prevailing, and therefore the sand wanders in an easterly direction.

Because of their extreme shiftiness of soil, the dunes do not attain any considerable elevation. The sand deposited by the wind on the summit of the hill is always in a state of unstable equilibrium. It has a constant tendency to be precipitated down the other side, and the higher the summit, the greater is this tendency, so that the dune arrives at last to a point when no further accumulation is possible. The dune, however, still continues to grow, extending its base and generally increasing in dimensions, but does not increase in elevation.

The size and the height of the dune depends on the distance from the sea and on the strength of the wind. In some cases it has been observed that during a strong wind a dune has decreased in height 5 cm., while other dunes have increased 25 cm. Every dune has one side placed against the prevailing wind. This front side has a lower grade than that on the lee side, which is always more abrupt. As long as the same wind prevails, and as long as the wind carries only so much sand as it is able to take away from the top of the dune, so long will the dune retain its position and form, just as a whirlpool in a river is constant, so long as the river maintains the same velocity and volume. Because the sand grains cannot be lifted to any greater height in the air, the dunes, when they have reached a certain elevation, would present to the sand grains an almost insurmountable obstacle, but they have very seldom time to cohere. The wind modifies its work incessantly and the height of the dune is very soon reduced by stronger winds.

The transporting power of the air is, as already mentioned, small compared with that of water, because of its lightness and want of cohesion. The size of the particles has, therefore, a great influence not only on the degree to which the sand is liable to drift, but also on the extent in which it may manifest properties relative to the texture of the soil, among others that of retaining moisture, which is so important to vegetation.

The amount of sand transportation is greatest, other things being equal, where there is no cover of vegetation to keep down the sands, and the deposits made are most extensive in the direction of the prevailing currents. The coarser dune sand particles are pushed along the ground, while the finer form clouds of dust in the air, and settle rapidly or slowly near to or remote from the source of supply according to the force of the wind and the size of the particles suspended.

The drifting of sand by wind takes place according to following principles: If the force of the wind is great, the grains do not move on the surface but are lifted by the wind to a certain height. The larger grains make jumps, and touch the ground from time to time, while the smaller grains often are carried forward in form of clouds at a considerable height from the ground. At a velocity of 4.5 m. in the second, grains of 0.25 mm. diameter slide on the ground, but at a velocity of 15 m., grains of 1 mm. diameter are lifted high in the air. As a corollary of this fact it follows that the movement of the grains depends on their volume. The greater part of the sand grains have an irregular flat form, and hence their movement is not rolling but sliding. That of the largest take place spasmodically and only during stronger gusts. According to *Sokoloff*, a wind of a velocity of 10—12 m. in a second cannot carry grains of 100—150 cubic mm. When the wind is not too strong, the grains slide along the surface, but when they are lifted up during the strong gusts, and fall down at a certain angle, they again rebound at the same angle. *Hagen* has proved that coarser sand grains are sometimes lifted up to 2 m. height, and in such a case they are carried up to 12 m. from their original place.

Ridges or rim formed ripples advance almost entirely by the sliding of the larger grains of the top layer of the crest, and *Cornish* estimates the progress of the ridges at one foot per hour. *Helmann* found in Chiwa that the ripples on the lee-side of the dunes move almost with the same rapidity as on the windward side, and he was not able to interpret this phenomenon. It has been ascertained that the movement of the dunes landward goes on at the average rate of 4.30 m. a year, and that the quantity of sand thus transported is about 75 cubic m. to the running m. of the length of the dune.

The winds have a greater power at a higher elevation than near the surface, and consequently more sand is removed from the summit than the wind is able to lift from the ground. This difference in the strength of wind exercises a modifying influence on the development of the dunes. The effect of the wind is to diminish the maximum slope, but as the formation of dunes is mainly regulated by the supply of sand, the varying angle of the windward slope depends upon the varying density of the sand shower pushed forth toward the summit. In cases where the supply of sand has become scarce or exhausted, the front slope of the dune soon will be almost as steep as the lee side, that is, approach the natural limit of the angle of rest.

The leeward slope of the dune varies but slightly, provided a reverse

of the dominant wind does not take place. It is the gravity which here exercises its force and reduces to the angle of rest any steeper slope caused by the air currents or other factors. The development of a dune is similar to that of a ripple, although it takes place on a larger scale. In lee of the dune crest there is an eddy, the upward motion of which lifts the fine sand particles, and in cooperation with the wind sends them flying from the summit. Gravity acts upon these particles, causing the fall across the stream lines of the air. The coarser sand falls more steeply, and this pitch is further increased by the backward motion of the eddy.

There are thus several factors which influence the formation of dunes. Of these operating factors the force and direction of the wind, the sand shower, the eddy in the lee of any obstacle, the gravity, the configuration of the surface, and the moisture are the principal ones. If the dune is formed at a certain constant sum-total of these factors, it retains its form as long as these factors are constant.

THE SCULPTURAL FORM OF DUNES.

The forms of dunes have a greater variety than those of ripples, because a dune is the result of many changing winds. While the dunes do not owe their origin to the action of the sand grains, like the ripples, still rippling plays a part in the shaping of every dune. Reversible winds produce dunes having both front and back slope very steep. The first effect of reverse of winds is to turn the top of the dune.¹⁾ During strong winds the troughs are always deeper.²⁾ On a hard ground, the windward slope can be as steep as the angle of rest, in case the sand supply fails and the wind is strong. If such is the case the dunes are widely separated.³⁾ This form differs from that of dunes produced in deep sand by dominant wind. The angle of the windward slope in this case decreases with the density of the sand shower, and increases with the power of the wind.

The amplitude of the dune does not exceed one third of the wavelength, and this limit is most nearly approached when the wind blows

1) *Sven Hedin*: A journey through the Takla-Makan Desert, Chinese Turkestan.—*Geogr. Journ.*, VIII: 264—278, 356—372. 1896.

2) *G. Grandjean*: Les Landes et les dunes de Gascogne.—*Bull. Soc. Géogr. Coml. de Bordeaux*, March 1896.

3) *V. Cornish*: On the formation of sand dunes.—*Geogr. Journ.* IX., p. 286. 1897.

alternately from opposite quarters, but does not hold in one quarter sufficiently long to reverse the work of preceding winds. *Cornish*¹⁾ remarks that in speaking of amplitude instead of height of dunes, one avoids the common confusion which results from the fact that the vertical distance from the bottom of the trough to the summit may increase even by raising of the crest or by deepening of the trough.

A dune sufficiently large is stationary, and it is an established law that as the amplitude increases, the velocity of the dune wave decreases. The velocity of the dune is the rate of advance of the crest which takes place by accumulation of sand upon the lee slope. There is also a group velocity of dunes to be recognized, that is, the rate of travel of the sand. Increase of wind will increase formation of new dunes to leeward rather than the rate of travel of the individual dune, and is usually accompanied by a considerable lowering of the general level, especially in the case of simultaneous diminution in the supply of sand.

The sorting action of wind already mentioned is supported by rain-water which washes the finer particles down into the trough, and consequently we find the summit of dunes to consist of coarser material. But on the other hand the lower part of the eddy is gouging out the trough and the finer material is carried away through the combined action of the eddy and the wind. The sand is therefore finer in the dunes generally than in the hollows between them. On a large sandy surface the particles are finer at the extremity towards which the wind blows.

Through this winnowing process the dust which consists of friable matter, having been reduced to the size of powder by grinding between the sands is carried away from the dune district and deposited beyond its limit. It is especially in desert regions, where aridity excludes vegetation and allows the wind to play with full force upon the finer particles of the soil, that we notice the development of sandy deserts covered with quartz sand, yet surrounded by grassy steppes consisting of clay dust. This remarkable distribution of the products of rock disintegration by wind and its effect on the physiography of Northern Africa has been eminently shown by *Walther*.²⁾ Already *Buway*³⁾ described the transition between the cultivated coast lands and the desert of Africa, which must be called a steppe, and the genetical relation of these formations is now a generally admitted fact.

1) l. c. p. 287.

2) *Die Denudation in der Wüste*.

3) *Zeitschr. für Allgemeine Erkunde*, Berlin, 1857, p. 290.

If we consider the general appearance and composition of the drift sands we find that they consist in a preponderating degree of somewhat rounded grains of quartz sand with only a very small percentage of other materials. The admixture consists primarily of felspar, of mica, and of various other minerals, such as hornblende, augite and granite, and to some extent of lime, mostly in form of fragments of shells.

In a crystalline rock, such as granite, we find that the different constituents, felspar, quartz and mica, are present in isolated crystals. As soon as these elements are separated from each other, they acquire a granulated form and constitute what we call quartz sand. The grains of felspar and mica act, however, in a different way than those of quartz, the latter representing crystallographically only one or a few individuals, while felspar and mica consist of many thin lamellae. Hence, when exposed to the decomposing agencies, disintegration of felspar and mica is much more intensive than that of quartz. The different particles of sand are moved more rapidly by the wind the lesser their gravity in proportion to their surface. Mica is so light that the least gust of wind carries its thin lamellae away, and it is further so brittle that it is easily broken into small fragments against other sand particles. The same can be said of felspar, although, perhaps, in a less degree. Here we also have to consider the chemical facility for decomposition. During the night and in the dewy mornings, the felspar which has been opened through the many capillary spaces is chemically decomposed by the moisture, while the quartz has a greater resistance against this agency. Consequently the older the dune sand is and the longer time and water have exerted their influence, the less felspar will be found in it and the more dominant is the quartz over the other minerals. As a rule, all the sand grains, however, exhibit more or less the rounded appearance due to attrition and weathering.

Besides the sand, the wind carries all kinds of light plant remains, thin shells, dry crabs, dead and living insects, and similar particles. All these temporary constituents of the dune are, however, insignificant in comparison with the sand, and are usually so rapidly decayed that they are seldom found in the deeper parts of the dune. The separate grains are mostly covered with a fine mold, in part due to the decomposition of the above organic remains, on which depends the fertility of the sand. The drift sand, though varied with a sprinkling of somewhat rare grains of darker colored substances, is generally a mass of a light color.

The stratification of dunes is usually very mixed, and in the same

dune strata, cut in all the four directions of the compass, can be seen. Successive layers dip in various directions, and are abruptly cut short, showing that the growing dune hill was partly cut down by storms and was again and again built up by such disasters. The consolidation of sand is best observed in ripples and rarely well shown in dunes, because the latter are the result of changing winds, and the time involved in their formation is too great for observation.

The fundamental forms of sand dunes include the *transverse* and the *longitudinal*. The former, which is the most common on sea coasts, especially where the wind is of moderate strength or the sand strip comparatively narrow, is that placed at right angles to the prevailing wind; the latter, formed where the wind is so strong as to prevent free lateral growth, is that following the direction of the wind; between these two there is an *intermediate form*; when varying winds act upon this latter form, *conical* dunes are produced. They are, as a rule, *stationary*, while the longitudinal form represents the most rapidly *traveling* dune.

The dunes which are placed parallel to the direction of the prevailing winds have originated quite differently from those which are placed at right angles to the wind. As we have seen, the usual mode of development of a dune is that the sand forms a ridge transverse to the direction of the wind. The sand is blown up on the lower slope on the front, and when it reaches the top it falls down along the lee slope; the ridge growing until it has reached considerable height. The parallel longitudinal dunes are, however, formed through the central part of the dune, being blown further and further forward, while the ends are kept back by various forces. The rule is that such a horseshoe-shaped or *parabolic* dune on the seashore *moves with the convex side in the direction of the prevailing wind*.

Apparently diverse, even opposing effect is produced in sandy deserts, if the observations of *Rolland* and many other travellers regarding the dunes called *Barchanes* are correct. In *Traité de Géologie* of *Lapparent*, 3 Ed., 1893, p. 140, we find the following opinion expressed about these wandering dunes: "Enfin la forme de dunes en marche doit être généralement celle d'un croissant tournant sa convexité vers le vent; par les particules sableuses, ayant moins de hauteur à franchir sur les bords de la dune qu'en son centre, cheminant plus vite à droite et à gauche. La crête doit donc se courber en projetant deux pointes vers l'intérieur. Cette forme *en croissant* a été bien constatée par tous les voyageurs qui ont parcouru le Sahara et les déserts américains."

Now the question arises: How is this phenomenon to be explained? *Cornish*¹⁾ refers to the development of barchanes in the following words: "They form here and there upon the desert floor where the wind will let them. It appears that they neither occur in localities where the sheet of wind has everywhere a complete mastery over the sand, nor where the burden of all the flying sand is everywhere too great for the carrying power of the wind; they dot the desert plain in localities where the sheet of wind has, for the most part, the mastery of the sand, but drops its burden here and there at certain points or more probably along certain strips."

"The *horns* or *cusps* of the barchanes, pointing to leeward, are readily explained, for the lowest parts of the dune travel quickest. A form as of the moon in her first quarter (i. e. that is to say with the cusps pointing in the direction of motion) is the form of front proper to a traveling sand-wave as viewed in plan. In this case gravity does not operate, so that the incoherence of sand does not hinder the formation of the cusp as it does in the profile of dunes."

This explanation seems negatived by the fact that the cusps generally are very insignificant as compared with the body of the dune, and in most cases a difference in size of the cusps can be recognized. Thus *Lessár*²⁾ observed in the Kara-Kum desert in Central Asia that the southwesterly cusp always was longer. This seems to indicate that the cusps are formed in a way similar to that of the low ridges which have often been noticed on the lee side of both stationary and wandering dunes on sea coasts. These lee ridges are usually placed at right angles to the length of the dune and are formed by the combined action of the eddy in the lee and the current sweeping around the side of the dune. If we accept this explanation for the formation of cusps in lee of the barchanes, the original form of which tends to the oval, according to *Sokoloff*³⁾, we will find a satisfactory solution of the action of wind in the development of the barchane without having to theorize about the lower cusps of the dune moving more rapidly than the higher, which cannot be correct, as we know that the force of the wind is considerably greater on the higher parts of the dune hill than on the lower, and that consequently the central and highest part travels quicker. *Steensrup*⁴⁾ has also shown that a parabolic dune never can move with the

1) On the formation of sand dunes, p. 290.

2) *P. M. Lessár*: Die Wüste Kara-Kum. "Izvestija" Russ. Geogr. Soc. 20: p. 115. 1884.

3) *Die Dünen*. 1894. p. 164.

4) *Om Klitternes vandring*. 1894. p. 14.

closed side toward the wind, and I must subscribe to his opinion, as I have not, on any of the dunes visited by me, been able to observe a phenomenon of that kind.

Summing up the foregoing discussion on dune forms, we would say that:

1. Dunes are formed in lines transverse to wind in unobstructed places.
2. Dunes are formed in lines parallel with wind in places where some kind of obstruction is in the path of the wind.
3. Wandering dunes have their convexity in the direction of the prevailing wind.

POLYGENETIC ORIGIN OF A DUNE COMPLEX.

The fundamental principles of dune formation established in the previous section must be recognized at the outset of this discussion in order to facilitate an understanding of the conditions which cause the origin and development of a dune complex. With this term, dune complex or dune tract, as distinguished from a solitary dune or a dune massiv, we signify a collection of secondary dune hills interspersed with deep gullies.

The dune complex is formed behind the chain of primary dunes, when the rate of travel of the sand is locally diminished without a corresponding decrease in the supply of sand. The formation takes place either through older dunes having been broken up into rough hummocks by the wind, or through secondary embryonic dunes being started by the piling up of drifting sand around some obstacle, in most cases a congregation of plants.

One of the most important factors determining the development of a dune complex is the presence of ground moisture. Without this factor we would not be able to explain the apparent irregularity of formation of a group of small dunes, where the quality of sand ought to have called for a regular dune massiv. The action of wind alone is insufficient for this modelling of the surface, but in connection with the greater coherence of the sand particles caused by the ground moisture the phenomenon is easily explicable.

It is the irregularity in action of wind, caused by the breaking up of the regular even surface of a dune or a sand field into small elevations

and depressions, that governs the development of such embryonic sand hills into a dune complex. In almost every case the latter formation has had such origin from a number of nuclei, while a dune mass is formed from a single embryonic dune.

If the plants should not influence the development of dunes the ridges would, like large waves, roll over the land until they were stopped either by water or by high mountains. In most cases it is the plants which have caused the broken forms of the sea coast dunes. Inland dunes have, as a rule, a more regular shape.

There is no other geological formation of the present time which is the result of such a combination of factors from the organic and inorganic nature. Dunes are developed wherever the winds can play over the loose sands, and as soon as the sand begins to drift, the ordinary vegetation is destroyed and plants which thrive in drifting sand immigrate, and thus begins the co-operation between the drift sand and the dune plants, the result of which is the dune. Although there is a struggle for power between the moving sand and the plants, it is remarkable with this strife that they both thrive best where they are almost of equal strength. If the plants have gained a victory they will soon be replaced by other plants, and then it can happen that the wind again breaks open the soil and the sand starts to drift afresh.

SAND FIELDS NEAR THE COAST.

As long as an obstruction has caused the formation of a dune, one of these will act as a recipient for the sand, and in this way dunes after dunes are formed until finally a whole sea of sand covered with dunes is formed.

The encroachment of dunes is due not only to the travel of the dunes themselves, but also to the formation of new dunes to the leeward from material supplied by the sand shower.

In some cases, however, when the dunes have not been fixed by a vegetation, the sand skims along the surface like snow drifting before a stiff breeze and accumulates rapidly, covering the plains without forming any hills. Further, the fine material which has been lifted to a certain height in the air, is deposited behind the dune region, and is quickly covered with vegetation, as it offers better condition for plant life on account of its greater coherence and capacity of retaining moisture than the coarser dune sand. These sand fields sometimes cover con-

siderable areas, and it seems often almost inexplicable that no rippling or dune formation takes place. The explanation of their non-formation is to be sought in the fact that the sand-sized particles are too small in proportion to the mass of material, and further, the deposition of dust takes place so rapidly that the wind is not able to carry it away, leaving the coarser particles to accumulate.

CONDITIONS FOR PLANT LIFE.

There is a great variation in the conditions for plant life on different sand formations. The climate has something to do with this result as well as the quality of the soil. Sea air and saline constituents of the soil destructive to some plants may be beneficial to others. The mobility of a drifting sand dune on the coast may be a condition of life to one plant, while dry atmosphere and the stability of an inland sand field may be essential to the growth of another. Even *Pinus maritima*, which has produced such wonderful results on the Landes of Gascony, does not grow everywhere even on sand formations in France. It is therefore necessary to study in every case the natural conditions of the locality before the problems of ecological relationship can be solved.

Some of the conditions of sand formations are, however, everywhere the same and these will here be briefly considered. One of the most important points in this connection is the relation to moisture. The rain-water sinks easily into the sand, the better the coarser the grains are. Generally speaking, the power of retention of water is very small and of all soils sand ranges lowest in this respect. The sandy soil has also a very low power of absorption, and is able to condense only a small portion of the atmospheric moisture. This is especially the case with quartz sand.

Further, sandy soil dries easily, and it is therefore heated quickly by the sun; but it also cools very soon at night. The difference between day and night temperature can be as high as 40-50° C. In consequence of this, sand is subjected to a considerable bedewing at night, a factor which is important for its capability of carrying a vegetation cover. The great variation of temperatures of the soil is disadvantageous to the plants in one respect, they being more liable to injury by frost, than if growing on any other soil. Sand floras, on the other hand, are always developed earlier, because of the greater heat capacity of the soil.

The nutritive value of the sand is very different according to the chemical character of the grains. The commonest form, or quartz sand, is the most barren on account of the insolubility of the quartz grains, and also because of their resistance to decomposing agencies, as already mentioned. Sand consisting of mica, felspar, limestone, and other minerals, disintegrate, however, and have by reason of this a higher nutritive value.

Formation of mould takes place only to a small degree in dry sandy soil, because the organic constituents are so easily decomposed through the admittance of air, and the particles are further quickly distributed and carried out of reach of the plants by sinking with the water through the loose soil. The proportion between organic and inorganic constituents in this soil is too great, the quantity of the former being too small to establish a sufficient supply for the demand of a more luxuriant growth of plants.

This scarcity of plant food results in a more or less open vegetation consisting of low growing plants, which do not give each other the mutual assistance against mechanical influence of wind and other factors, that is evident in the arrangement of plants on most other soils. The injurious effect of the intense light, both direct and reflected from the surface of the sand, has to be guarded against. The transpiration of open sand vegetation, especially on the seacoasts, is always considerable because of the constantly changing atmosphere, resulting from the almost continuous winds. The plants have to develop some means of reducing this excessive transpiration.

Summing up, we may say that the competition for food is more intense, the water supply less, the light stronger, the temperature higher, the transpiration greater, the foothold more uncertain and difficult, the conditions for plant life generally more adverse, than on any other soil.

Bibliography.

- Ackermann, Carl—Beiträge zur physischen Geographie der Ostsee. pp. IX—399.—Hamburg, 1883.
- Andersson, Joh. Gunnar—Mellan haf och dyner. (Gotska Sandön).—Särtryck ur Sv. Turistf. årsskr. 1895. 16 p.
- Andouard, A.—Les sables du désert de la Basse-Egypte.—Compt. Rend. Ac. Sci. 117: 258—. 1893.
- Andresen, C. C.—Om Klitformationen og Klittens Behandling og Bestyrelse.—Kjöbenhavn. 1861.
- Andrews, E. W.—Pebbles and Drifting Sand.—Trans. N. Z. Inst. 26: 397—.
- Benbow, C. A.—Interior Land Changes. 6 p.—Agr. Gaz. N. S. W. XII. 1901.
- Berendt, G.—Geologie des Kurischen Haffes und seiner Umgebung.—Königsberg, 1896.
- Berghaus, A.—Das Dünengebiet langs der Ostsee im Stettiner Regierungsbezirk.—Das Ausland, 1880. No. 35.
- Bezenberger, Adalbert—Die Kurische Nehrung und ihre Bewohner.—Forsch. D. Landesk. vol. iii, pt. 4: 169—. 1889.
- Blanford, W. T.—On the Physical Geography of the Great Indian Desert; with Special Reference to the former existence of the sea in the Indus Valley; and on the origin and mode of Formation of the Sand Hills.—Jour. R. Soc. Bengal. XLV, pt. II: 86—103. 1876.
- Blijdenstein, A. J. & Brants, L. R.—Onderzoek naar de duinbeplantingen in Jutland en langs de Oostzee.—Nederlandsche Heide-Maatschappij Tijdschrift, ii: 103—155. 1890.
- Blijdenstein, A. J. & Brants, L. R.—Rapport van het Bestuur der Nederlandsche Heidemaatschappij aan de Regeering over het beplanten van de Nederlandsche Zeeduinen met bosch.—Nederlandsche Heide-Maatschappij Tijdschrift, 1892. 4: 41—147.
- Bolton, X. C.—Denudation.—Trans. New York Ac. Sci. ix: 110—126. 1889—90.
- Branner, J. C.—The aeolian sandstones of Fernando de Noronha.—Amer. J. Sci. 39: 247—257. 1890.
- Branner, J. C.—The Origin of Beach-cusps.—Journ. Geol. viii: No. 6: 481—484. 1900.
- Briart, A.—Sur la stratification entrecroisée.—Bull. Soc. geol. France. vol. 3: 587—. 1880.
- Briggs, Lyman J.—The Mechanics of Soil Moisture.—Bull. Div. of Soils, U. S. Dept. Agr. 24 p. Washington, 1897.
- Salts as Influencing the Rate of Evaporation of Water from Soils.—U. S. Dept. Agric. Rep. 64: 184. 1900.
- Buffault, Pierre—Étude sur la côte et les dunes du Médoc. Littoral ancien, littoral actuel.—Souvigny, 1897.

- Candolle, C. de—Rides formées à la surface du sable déposé au fond de l'eau et autres phénomènes analogues.—Arch. Soc. phys. et nat. [3] 9: 241—278. 1883.
- Chambrelent—Mémoire sur l'assainissement et la mise en valeur des Landes de Gascogne.—Annales des ponts et chaussées, 5, xvi. 2: 157. Paris, 1878.
- La stabilité des dunes du golfe de Gascogne et les dangers dont elles sont menacées.—Compt. Rend. Ac. Sci. 114: 883—889. 1892.
- Chelius, C.—Flugsand auf Rheinalluvium und sur Jetztzeit.—N. Jahrbuch f. Mineralogie und Geologie. I: 224—226. 1892.
- Cholnoky, I.—Die Bewegungsgesetze des Flugsandes.—Földt. Közl., Budapest. 32: 6—38. 1902.
- Conrad, F. W.—Over duinen en stranden.—In Verspreide bijdragen, Amsterdam, 1849, p. 57—112.
- Cornish, Vaughan—Ripple Mark.—Rep. Br. A. A. S. 1896: 794—795.
- Sand Dunes.—Rep. Br. A. A. S. 1896, p. 857.
- On the Formation of Sand dunes.—Geogr. Journ. ix: 278—302. 1897.
- On Sea Beaches and Sandbanks.—Geogr. Journ. xi: 628—647. 1898.
- On Photographs of Wave Phenomena.—Rep. Br. A. A. S. 1899. p. 748—749.
- On Sand-dunes Bordering the Delta of the Nile.—Rep. Br. A. A. S. 1899, p. 812—813.
- On Desert Sand-dunes Bordering the Nile Delta.—Geogr. Journ. Jan. XV: 1—30. 1900.—Abridged in Nature, 61: 403—404. 1900.
- On Tidal Sand Ripples above Low-water Mark.—Rep. Br. A. A. S. 1900, p. 733—734.
- On Sand-waves in Tidal Currents.—Geogr. Journ. XVIII: 170—202. 1901.
- On the Formation of Wave Surfaces in Sand.—Scot. Geogr. Mag. 17: 1—11, Jan. 1901.—Abridged in Nature, 63: 623—625. 1901.
- Courbis, E.—Les dunes et les eaux sauterraines du Sahara.—Compt. Rend. Soc. Geogr. Paris. 1890: 114—119, 259—.
- Credner, G. Rudolf—Die Deltas, ihre Morphologie, geographische Verbreitung und Entstehungsbedingungen.—Pet. geogr. Mitt. Ergänzt. bd. xii. 1878.
- Rügen, Eine Inselstudie.—Stuttgart, 1893.
- Czerny, Franz—Die Wirkung der Winde auf die Gestaltung der Erde.—Pet. geogr. Mitt. Ergzh. 48. 1876.
- Darwin, G. H.—On Ripple Mark.—Proc. R. S. L. vol. 36, 1883.
- On the Horizontal Thrust of a Mass of Sand.—Min. Proc. Inst. C. E. v. 51: 350—378. 1883.
- DeGeer, Gerard—Om vindnötta stenar.—Geol. för förh. Bd. VIII. H. 7, No. 105. 15 p.
- Doss, Bruno—Ueber Dünen der Umgegend von Riga.—Korr.-bl. Natf. Ver. Riga, 39: 31—40. 1896.
- Engler, Arnold—Aus den Dünen und Landes der Gascogne.—Natw. Wochenschr. 17: 277—282, 292—295. 1902.
- Fabre, L. A.—Les plateaux des Hautes.—Pyrénées et les dunes de Gascogne. Se Congrès géologique intern. Paris. 1900. 2: 785—798. 1901.
- Fischer, Theobald—Küstenstudien aus Nordafrika.—Pet. geogr. Mitt. 33, p. i, 1887.

- Forchhammer, G.—Geognostische Studien am Meeres-Ufer.—N. Jahrb. f. Miner. 1841, 23.
- Klitterne paa Vestsiden af den jydsk Halvö. Almenfattelige Afhandlinger og Foredrag, udgivne af Johnstrup.—Kjöbenhavn, 1869.
- Girardin, Paul—Les Dunes de France.—Ann. Géogr. Paris. 10: 267—272. 1901.
- Giraud, Jules—Sur la formation des surfaces ondulées dans le sable, d'après Mr Vaughan Cornish.—Géographie, Paris. 3: 345—347. 1901.
- Boursand—Les Landes et les dunes de Gascogne.—Revue des Eaux et Forêts. 1870—1880.
- Grandjean, C.—La dune littorale.—Revue des Eaux et Forêts. 1886.
- Les Landes et les dunes de Gascogne.—Bull. Soc. Géogr. Com. de Bordeaux, March, 1896.
- Gras, Scipion—Formation des dunes, ensablement et envasement du côté de la France. 18°. 1866.
- Gulliver, F. P.—Cuspate forelands.—Bull. Geol. Soc. Amer. 7: 399—422. 1896.
- Gunther, Siegmund—Akustisch-geographische Probleme. Gaea, Leipzig, 37: 394—406. 1901. — Sitz. ber. Ak. Wiss. München, 1901: 15—33, 211—263.
- Hall, C. W. & Sardeson, F. W.—Eolian Deposits of Eastern Minnesota.—Bull. Geol. Soc. Amer. x: 349—360. 1899.
- Hall, H. H. van—Zandgronden en zandstuivingen in Nederland.—Album der Natuur, 1863: 22—32.
- Hall, T. S.—Incrustations on wood in dune sand.—Vict. Nat. Melbourne. 18: 47—52. 1901.
- Houtreaux—Étude sur les sables et vases de la Gironde.—Bordeaux. 1887.
- Hult, Ragnar—Flygsand i det inre af Finland.—Geogr. Förr. Tidskr. 1891: 133—140.
- Hunt, Arthur R.—On the Formation of Ripple Mark.—Proc. R. S. L. 34: 1—18. 1883.
- Jordan—Physische Geographie und Meteorologie der libyschen Wüste.—Casel, 1876.
- Keller—Studien über die Gestaltung der Sandküsten.—Zs. f. Bauwesen, XXXI: 190—. 1881.
- Kerr, Walter C.—The Geology of Hatteras and the Neighboring Coast.—Bull. Phil. Soc. Wash. 6: 28—30. 1884.
- Labat—Les dunes maritimes et les sables littoraux.—Bull. Soc. géol. France. (3) xviii: 259—273. 1889—90.
- Lamb, Frank Haines—The Sand dunes of the Pacific Coast.—Forester, 3: 94. 1897.
- Langley, S. P.—The Internal Work of the Wind.—Am. Journ. Sci. ser. 3. 47: 41—63. 1894.
- Lorié, J.—Binnenduinen en bodenbewegingen.—Tijdschr. aandr. genootsch. 1893: p. 753.
- Lyell, Sir Charles—Principles of Geology. New York, 1892.
- Maak—Die Dünen Jutlands.—Zeitschr. f. allg. Erdk. 19: 198—. 1865.
- Mackie, William—On the Laws that Govern the Rounding of Particles of Sand.—Trans. Edin. Geol. Soc. VII: 298—311. 1897.
- Wind-worn Pebbles.—Rep. Br. A. A. S. 1901: 650.

- Maiden, J. H.—Some Remarks on the Sand Drift Problem.—N. S. W. Dept. of Agr. Misc. Publ. No. 351, 7 p. Sydney, 1900.
- McNaughton, C. B.—The Sand-dunes of Gascogne.—Agr. Journ. Capetown, Feb. 7, 1895.
- Manby, Charles & Forrest, James—On Reclaiming Land from Seas and Estuaries.—London, 1864.
- Merrill, G. P.—Wind as a factor in geology.—Engin. Mag. ii: 596—607. 1896.
- Middendorff, A. von—Einblicke in das Ferghanathal.—Mém. Ac. Sci. Petersburg. (7), 29: No. 1. 1883.
- Mitchell, Henry—The Coast of Egypt and the Suez Canal.—North American Review. 1869: 36 pp.
- Morès—Note sur la constitution générale du Sahara au sud de la province d'Oran.—Bull. Soc. Geol. France. (2) 14: 524—. 1857.
- Nalivkin—Investigations of the Sand of the Province Ferganah.—New Margelan, 1887: 228—. (Russian.)
- Nesbit, D. M.—The Tide Marshes of the United States.—U. S. Dept. Agr. Misc. Spec. Rep. No. 7, 1884.
- Oldham, Richard Dixon—Physical geography and its evolution (of the Snow Valley).—Mem. Geol. Surv. Ind. Calcutta, 31, I: 36—57. 1901.
- Parrau—Observations sur les dunes littorales en Algérie et en Tunisie.—Bull. Soc. Géol. France. (3) xviii: 245—251. 1889—90.
- Partiot—Sur les sables de la Loire.—Ann. ponts et Chauss. (5), I. 1871. Mémoires p. 233.
- Passarge, S.—Ueber Winderosion.—Natw. Wochenschr. Berlin. 16: 369—373. 1901.
- Penck, Albrecht—Dünen in der oberrheinischen Tiefebene.—Das Ausland, 1893: 350—.
- Morphologie der Erdoberfläche.—Stuttgart, 1894.
(Dunes described especially in I: 247—259, 360—362; II: 38—50.)
- Radde, Gustav—Talsch, das Nordwestende des Alburs und sein Tiefland.—Pet. geogr. Mitt. 1885. No. 7.
- Rankine, Macquorn—On the exact form of the waves.—Phil. Trans. R. S. Lond. vol. 153. 1863.
- Раунеръ, Ст.—Дюны, ихъ укрѣпленіе и облѣсненіе.—Ст. Петербургъ, 1884.
- Reade, T. Mellard—Sand-blast of the shore and its erosive effect upon wood.—Geol. Mag. Lond. (ser. 2), VIII: 193—194. 1901.
- Reclus, Elisé—Étude sur les dunes.—Bull. Soc. géog. France. (5), ix: 193—. 1865.—Also in La Terre II. 4 ed. 1881. p. 239.
- Reynolds, Osborne—Certain laws relating to the regime of rivers and estuaries and on the possibilities of experiments on a small scale.—Rep. Br. A. A. S. 1887: 555—562.
- Rice, William North—The Geology of the Bermudas.—Bull. U. S. Nat. Mus. No. 25, 7. 1884.
- Richthofen, Ferdinand Freiherr von—China. Ergebnisse eigener Reisen und darauf gegründeter Studien. I, II. Berlin, 1877.
- Führer für Forschungsreisende.—Berlin, 1886. (Dunes, pp. 345—352, 476—477, 504—507.)

- Riston, Victor—Les Dunes Mouavantes D'Ain-Séfra (Sub-Oranais) dangers d'envahissement du Kéar plantations et essais de fixation des sables.—Paris, 1890.
- Robertson, A. J.—On the theory of waves.—London, 1854.
- Rolland, G.—Sur les grandes dunes de sable du Sahara.—Bull. Soc. géol. France, (3). 10: 30—. 1882.
- Rosberg, Johan Evert—Nägot om Karlö.—Geogr. För. Tidskr. 1893: 201—211.
- Bottenvikens finska deltan.—Medd. Geogr. För. Finl. II: 103—375. 1895.
- Några dynbildningar på Bottniska vikens ostkust.—Medd. Geogr. För. Finl. II: 78—96. 1895.
- Dynerna på Tavvonsaari.—Medd. Geogr. För. Finl. iv. 3 p. 1897—98.
- Sabban, Paul—Die Dünen der südwestlichen Heide Mecklenburgs und über die mineralogische Zusammensetzung diluvialer und alluvialer Sande. Diss.—Rostock, 1897.
- Sauer, A. & Siegert, Th.—Ueber Ablagerung recenten Lösses durch den Wind.—Zs. D. geol. Ges. xi: 575—. 1888.
- Sauvage—Dünen der Normandie.—Bull. Soc. géol. France. 3. 8: 601—. 1880.
- Schroeder, van der Kolk—Bydrage tot de Karteering onzer zandgronden.—Amsterdam, 1895, 1897.
- Sieger, R.—Seenschwankungen und Strandverschiebungen in Skandinavien.—Zs. Ges. Erdk. Berlin, 1893: 1—106, 393—488.
- Simonds, Frederic W.—Floating Sand: an unusual mode of river transportation.—Amer. geol. xvii: 29—37, 1896.
- Smith, Walter A.—Treatment of drift-sand as applied to the Bondi sand dunes.—Read before the Sydney University Engineering Society, Oct. 27th, 1902. p. 15—20.
- Sokoloff, N. A.—Die Westküste des kaspischen Meeres von der Festung Petrowsk bis zum Flusse Ssamur.—Ermans Archiv, vii. 1848.
- Die Dünen. Bildung, Entwicklung und innerer Bau. German trans. by Andreas Arzruni.—Berlin, 1894.
- Die Dünen der Finnischen Meerbusens.—Trav. Soc. Nat. St. Petersburg. 1882.
- Ueber die Entstehung der Limanen Südrusslands.—Mém. com. geol. X, No. 4. St. Petersburg, 1895.
- Staring, W. C. H.—Windvormingen (d. i. zandheuvels in onze heivelden, met afbeeldingen).—Alb. d. natuur, 1861: 7.
- Steenstrup, K. J. V.—Om Klitternes Vandring.—Nath. Medd. Kjöbenhavn. 1894.
- Tarr, R. S.—Wave-formed cusped forelands.—Amer. Geol. XXII: 1—12. 1898.
- Themak—Die südungarische Sandwüste.—Földt. Közl. XVII: 275—. 1887.
- Thesleff, Arthur—Dynbildningar i östra Finland.—Medd. Geogr. För. Finl. II: 36—77. 1895.
- Thuret, Gustave—Expériences sur les graines de diverses espèces plongées dans de l'eau de Mer.—Archives des sciences de la bibliothèque universelle. 1873: 177—194.

- Trouessart, E. L.—Au bord de la mer. Géologie, faune et flore des côtes de France de Dunkerque à Biarritz.—Paris, 1893.
- Udden, J. A.—Erosion, transportation, and sedimentation performed by the atmosphere.—*Journ. geol.* II: 318—332, 1894.
- Dust and sandstorms in the West.—*Pop. Sci. Mo.* 1896: 655—664.
- Loess as a land deposit.—*Bull. Geol. Soc. Amer.* ix: 6—9, 1897.
- The Mechanical Composition of Wind Deposits.—*Augustana Library Publications*, No. 1, Rock Island, Ill. 1898.
- Vasselot, de Régné de—La dune littorale.—*Revue des eaux et forêts.* 1875.
- Vauthier, L. L.—Mémoire sur l'entraînement et le transport par les eaux courantes des vases, sables et graviers. *Compt. rend. par M. Durand-claye, A.*—*Ann. d. ponts.* T. 2, 1885.
- Venukoff—Sur les résultats recueillis par M. Sokoloff, concernant la formation des dunes.—*Compt. Rend. Ac. Sci.* 100: 472—474. 1886.
- Vernon, Harcourt—On the means of improving harbours established on low and sandy coasts.—London, 1880.
- Vries, G. de—De Rijndijk in de duinen te Petten.—*Versl. K. Ak. Wet.* 3 sér. pt. 3. 35 p. Amsterdam, 1886.
- Wahnschaffe, F.—Die lössartigen Bildungen am Rande des Norddeutschen Flachlandes.—*Zs. D. geol. Ges.* 1886.
- Walther, Johannes—Das Gesetz der Wüstenbildung in Gegenwart und Vorzeit.—Berlin, 1900.
- Die Denudation in der Wüste und ihre geologische Bedeutung. Untersuchungen über die Bildung der Sedimente in der ägyptischen Wüsten.—*Abh. K. Sächs. Ges. Wiss.* 1891. math. Phys. Cl. xvi. No. 3: 570.
- Ueber die geologische Thätigkeit des Windes.—*Natw. Wochenschr.* Berlin, 16: 431—432. 1901.
- Weber, Ernst Heinrich & Wilhelm—Wellenlehre.—Leipzig, 1825.
- Wessely, Josef—Der Europäische Flugsand und seine Kultur.—Wien. 1873.
- Weule, Karl—Beiträge zur Morphologie der Flachküsten.—*Zs. Wiss. Geogr.* v. 8. 1891.
- Wheeler, W. H.—The Action of Waves and Tides on the Movement of Material on the Sea Coast.—*Rep. Br. A. A. S.* 1898. 883—884.
- The Sea Coast: 1. Destruction. 2. Littoral Drift. 3. Protection.—London, 1902.
- Winkler, T. C.—Zand en duinen.—Dokkum, 1865.
- On the maritime dunes of low countries.—*Report of the International Congress of Geologists.* 1878: pp. 181—.
- Sur l'origine des Dunes maritimes des Pays-Bas.—*Arch. Néerl.* xiii: 417—427. 1878.
- Considérations géologiques sur l'origine du zand-diluvium, du sable campinien et des dunes maritimes des Pays-Bas.—*Teyler. Arch.* vol. V. 1880.
- Woodworth, J. B.—Post-Glacial Action in Southern New England.—*Am. Journ. Sci.* ser. 3. 47: 63—71. 1894.
- Zobrist—Les dunes. Réfutation des théories de M. Bouthillier de Beaumont.—*Bull. Soc. neuchât. géogr.* IV: 1—17, 1888.

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