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Parabolic Dune Behavior under Effective Storm Wind Conditions

João José Bigarella
Fundação João José Bigarella para Estudos e Conservação da Natureza
Rua Dep. Joaquim José Pedrosa, 618 - Cabral, Curitiba, Paraná, Brasil
CEP: 80.035 – 120

ABSTRACT

The present paper is the result of 32 years of field observations in the coastal plain dunes of Santa Catarina, Brazil. The Lagoa dune field has been surveyed since 1963. In 1972 a parabolic dune was selected for a systematic study of the primary sedimentary structures and its internal organization. The displacements and morphological changes were accompanied with a sequence of measurements from 1975 on. In 20 years the parabolic dune nose advanced 49.7 meters northward, at an average rate of 2.49 meters per year. The dune's volume above the arbitrary three meters contour line was mantained around 22,500 cubic meters during the period 1975-1995, increasing to 33,7257.13 cubic meters in 1995. The dune behaviour through the time is shown in the several illustrations presented in the text, allowing a better understanding of the parabolic dune inside a reverse dune field, where the storm winds play an effective role in the eolian sand transport.

Keywords: Parabolic dune, primary sedimentary structures, dune movement, dune morphological changes

RESUMO

O presente trabalho apresenta o resultado parcial de 32 anos de pesquisas de campo realizadas nas dunas de Santa Catarina durante o período compreendido entre os anos de 1963 a 1995. O campo de dunas da Lagoa, Ilha de Santa Catarina foi objeto de pesquisas desde 1963. Em 1972 foi selecionada uma duna parabólica para um estudo sistemático de suas estruturas primárias. Em 1975 iniciou-se o acompanhamento do movimento da duna e de suas mudanças morphológicas. Em 20 anos o nariz da duna parabólica deslocou-se 49,7 metros para o norte numa velocidade média de 2,49 metros por ano. Seu volume acima da curva de nível arbitrária de 3m manteve-se em torno de 22.500m^3 durante o período 1975 a 1988, aumentando para 37.257,13m^3 em 1995. O comportamento da duna através dos anos é apresentado nas várias ilustrações, as quais permitem uma melhor compreensão das tendências evolutivas da duna parabólica num campo de dunas reversas, onde a ação dos ventos de tempestade é bastante efetiva.

Palavras chave: duna parabólica, estruturas sedimentares primárias, movimento de duna, mudanças morfológicas em duna

Foreword

During a research work programme granted by the John Simon Guggenheim Memorial Foundation in 1952-1953 related with the interpretation of sedimentary rocks in Southwestern United States with the advise of Edwin D. McKee, we defined the general lines for approaching the paleogeographic interpretation of the environmental conditions prevailing both in the sedimentary basins and in the source areas.

The rock sequences well exposed in the Colorado Plateau, and specially those of the eolian sandstones, allow us to visualize a correlation programme to be established between South America and Africa concerning the Gondwana formations, in order to obtain paleogeographic data for the study of continental drift problems.

This project started by surveing the Botucatu, the Sambaiba and the Independencia formation sandstones in South America (Brasil, Uruguay and Paraguay), and the Cave and Etjo sandstones, respectively in South Africa and Namibia (Bigarella and Salamuni, 1961; Bigarella, 1973).

Several geologists questioned the validity of the methodology used to determine the paleowind directions. To confirm it, a new project of measurements was undertaten in 1963 in order to compare the present day wind pattern with the resultant vector obtained from the measurements of cross-strata dip directions of recent dunes along the south-american coast between the Amazon River mouth and the vicinities west from Punta de Leste, in Uruguay.

The methodology used prooved to be valid for achieving paleogeographic informations, like the position both of the paleoequator and the weel-round latitude, the location of high pressure cells and the atmospheric circulation pattern, among others.

1. Introduction

The study of the brazilian coastal dune primary sedimentary structures started in 1963 after the Paleoclimate Conference held in New Castle upon Tyne (January 7-12, 1963) in Great Britain in order to confirm the methodology used for determination of palèowind patterns from eolian sandstones.

Cross-bedding measurements made in the coastal dunes of Santa Catarina and Rio Grande do Sul indicate the dominance of northeasterly- to easterly-winds ("return" trade winds).

On the Santa Catarina Island, attitudes of cross-strata were measured in four localities (Praia dos Ingleses, Praia do Santinho, Lagoa, and Praia do Pântano do Sul). Results are not in agreement with the general circulation pattern. In the first two localities (122 cros-bedding measurements), the main sand movement is toward NNW because the dune field is protected from prevailing winds by local relief [consistency ratios: 0.72 and 0.83] (Bigarella, 1972).

At Lagoa and Praia do Pântano do Sul dune fields also are largely affected by local relief. At Lagoa the resultant vector (158 cross-bedding measurements) indicates wind blowing from east-northeast (prevailing wind quadrant), but the consistency ratio is very low (0.12) and the rose diagram shows dips all around the quadrant. Nevertheless, dune morphology indicates that occasional strong southerly winds result from advances of polar air masses over the region. Short-term observations in the field (not accurate determinations) indicate that the prevailing winds are deflected by the topography, changing to northerly winds. This situation favours the development of an environment of reversing dunes.

The influence of the topography is clearly indicated in cross-bedding measurements (resultant vector and consistency ratio). At the Lagoa dune field both are not in agreement with the prevailing wind pattern. As this locality is protected from prevailing winds, the resultant vector and the consistency ratio indicate the result of occasional strong southerly storm winds. Elsewhere, in other dune fields along the southern brazilian coast, the cross-bedding measurements and rose diagrams show no effective influence of the occasional southerly storm winds, indicating in this way the predominance of the prevailing winds which blow over the region. The data furnish excellent evidence of the importance of prevailing winds in accumulating sand and the ephemeral nature of the short-term strong winds (Bigarella, 1972).

During the field work study of the coastal dunes in Brazil and Uruguay, two localities were selected for detailed surveying: Jardim São Pedro, Praia de Leste (PR) and the Lagoa dune field in the Santa Catarina Island, near Florianópolis (SC).

The present contribution tries to add more informations about the behaviour of parabolic dunes along the time in a reversing dune field, by studying internal structures and morphological changes.

2. Lagoa Dune Field

The Lagoa da Conceição dune field located between the homoninous lagoon and the Joaquina Beach, constitutes an area of excepcional value for the study of eolian deposits, both from the transversal-reversing dunes and from the parabolic dunes, as well as for the study of the dissipation deposits derived from the dissipation of the captation (climbing and hanging) dunes located eastwards on the granitic hill slopes.

The Lagoa dune field is located in the east-central part of Ilha de Santa Catarina (State of Santa Catarina, Brazil). The dune field is bounded on the eastern side by crystalline hills (mostly granite), on the south by the Joaquina and Campeche beaches, on the north by the Lagoa da Conceição lagoon, and on the west by the same lagoon and by crystalline hills.

3. Prevailing Winds

The prevailing winds at the coastal area of Santa Catarina blow from the northeast, but short term storm winds come from the south. The influence of the prevailing winds on the Lagoa dune field decreases considerably by the granitic relief located upwind. The prevailing winds become deflected by the mountain situated westward from the lagoon and from the dune field area, reaching the later as northerly winds.

Due to the location of the dune field in a shadow area protected from the northeasterly prevailing winds, the deflected northerly winds are not able to counteract the action of sand transport resulting from the southern short-term storm winds.

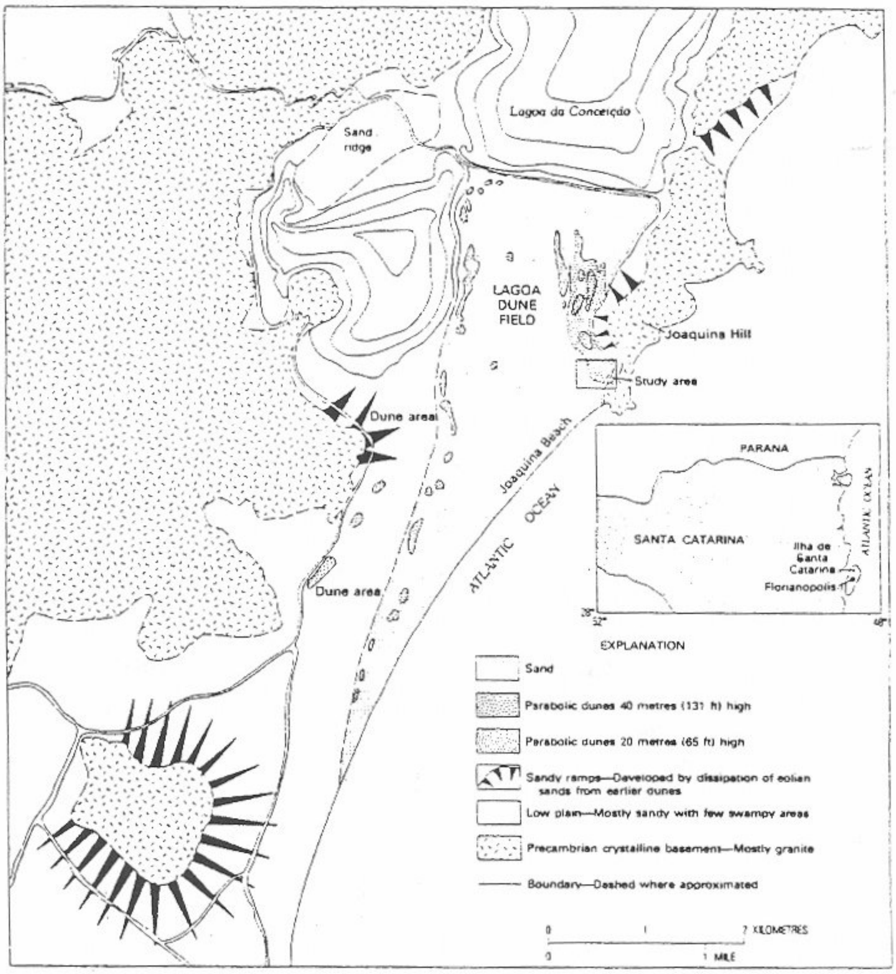


Figure 1: Location of Lagoa dune field, Santa Catarina Island, State of Santa Catarina, Brazil (Bigarella, 1975b, 1979).

Thus, the main eolian sand shift movement is to the north (Bigarella, 1972, 1975b, 1979).

4. Reversing Dunes

By reversal dune field it is understood an area of dunes where the prevailing wind is not responsible for the main eolian sand shifting, but the storm winds. The reversal dunes were formed in areas where the action of the prevailing winds was locally strongly disturbed by physical barriers, like hills or mountain ranges, which cause wind deflection weakenig its capacity of sand transport.

Hedin (1896) mentioned in central Asia the existence of dunes formed as a result of reversing winds. Reversing wind dunes referred by Cornish (1897) indicate the development of steep slipfaces on opposite sides of a sand hill with a re-forming of the dune top during the wind reversal. Other references to reversing dunes have been made by Bagnold (1941) for North Africa, Merk (1960) for the Great Sand Dunes National Monument in southern California, Sharp (1966) for the Kelso dunes in the Mohave Desert of California, and by McKee and Bigarella (1972) and Bigarella (1975b) for the Lagoa dune field, Santa Catarina Brazil.

For the reversing dunes at Great Sand Dune National Monument, Merk (1960), mentions that the base and lower parts of the large dunes indicate deposition by the prevailing southwesterly winds, whereas the upper parts indicate the influence of easterly storm winds. In both situations the slipfaces were steep, originating two groups of steeply dipping foresets, facing nearly opposite directions.

In the Kelso dunes the most frequent winds come from the west, however winds from other quadrants have higher velocity being nearly equal in sand moving capacity (Sharp, 1966). As a result, the dune ridges moved northeast at a very slow rate of about 30cm per year with a continuous back and forth shifting of the dune crest.

The majority of the sand dune fields have developed under prevailing wind conditions, i. e. the

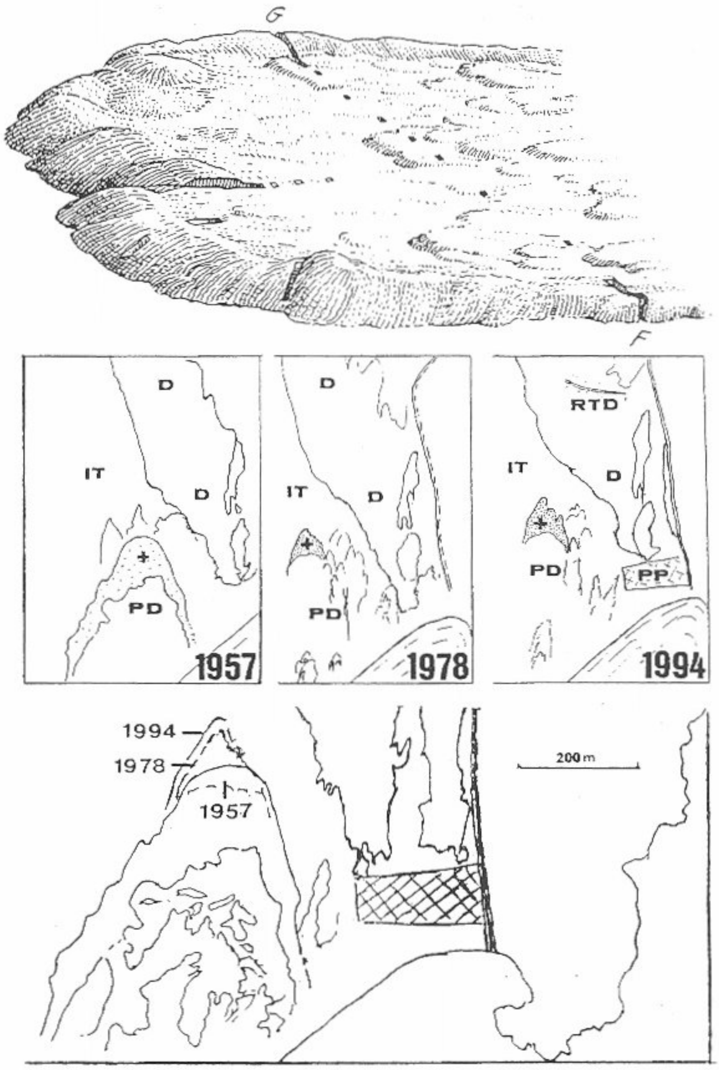


Figure 2: Diagram of the surveyed parabolic dune indicating the location of the trenches and pits (Bigarella, 1975b). Position of the parabolic dune from aerial photographs (1975, 1978, and 1994). D = dune; IT = interdune area; RTD = reversal transversal dune; PD parabolic dune area; PP = parking place.

sand movement follows closely its path. This condition could be defined as the normal one. All cross-bedding measurements in such a dune field will indicate a vector closely parallel to the prevailing wind direction.

Besides the predominant wind, there are other strong winds (storm winds) shifting the dune sands. Their direction and importance are related to the dune fields geographical position. The storm winds are responsible for changes in the dune shape, as well as in its internal structure. In this case, the cross-strata measurement resultant vector may or may not be closely parallel to the prevailing wind direction, but the corr-strata consintency ratio is lower than the one from the dunes where the storm winds were less effective.

Where the dunes were mostly developed by unidirectional winds, some preserved cross-strata sets may have been formed as result from reversal wind direction.

The reversing dunes are characterized by the predominance of cross-strata sets formed under reversal wind conditions (storm winds). The effectiveness of the prevailing wind has been considerably reduced by the physical barrier. Even than, the different wind directions have shifted the sands forth and back with a predominant positive sand budget for the storm winds.

5. Source of the Eolian Sands

The development of a dune field and of a dune type depends on an adequate sand source, as well as on sufficiently strong wind of enough duration to transport and deposit the eolian sands.

The Joaquina Beach constitutes the main souce area of eolian sands for the Lagoa dune field. However, the amount of dry sand available for eolian transport on the beach is too small to counteract the deflation by the strength of the southern storm winds in the southern part of the dune field. Therefore, great number of blowout features, including parabolic dunes were formed. In the northern part of the dune field, a series of reversing transversal dunes have been developed from the interaction of opposing winds. They are slowly moving northward (Bigarella, 1972, 1979).

6. Parabolic Dune

In the Lagoa dune field one parabolic dune was selected for a long term observation programme. The present study concerns a compound parabolic dune located in the southern part of the dune field about 480m from the beach. At the begining, a survey was made inorder to determine the internal organization of the primary sedimentary structures. Most of the internal structures to be recorded and analysed were exposed by digging a series of trenches and pits, and by cleaning the erosion scarps cut by deflation near the dune nose (figure 3). Trenches C, D, I and H have been dug in the most active part o the compound parabolic dune, trench I on the slipface, trench H on the windward side behind the crest, and trenches C and D oriented oblique to the wind direction. Trench E and pits E_1, E_2 and E_3, were aligned roughly parallel to the wind direction and constitute a southern continuation of scarp B extending down the windward slope into the interdune area. Trenches F and G, and pits 1-7 were oriented normal both to the dune' s arms and to the dominant storm wind direction. These pits were located in the interdune area and dissected some of the small satellite parabolic dunes as well as low dome-shaped hummocky features (figures 3 and 4).

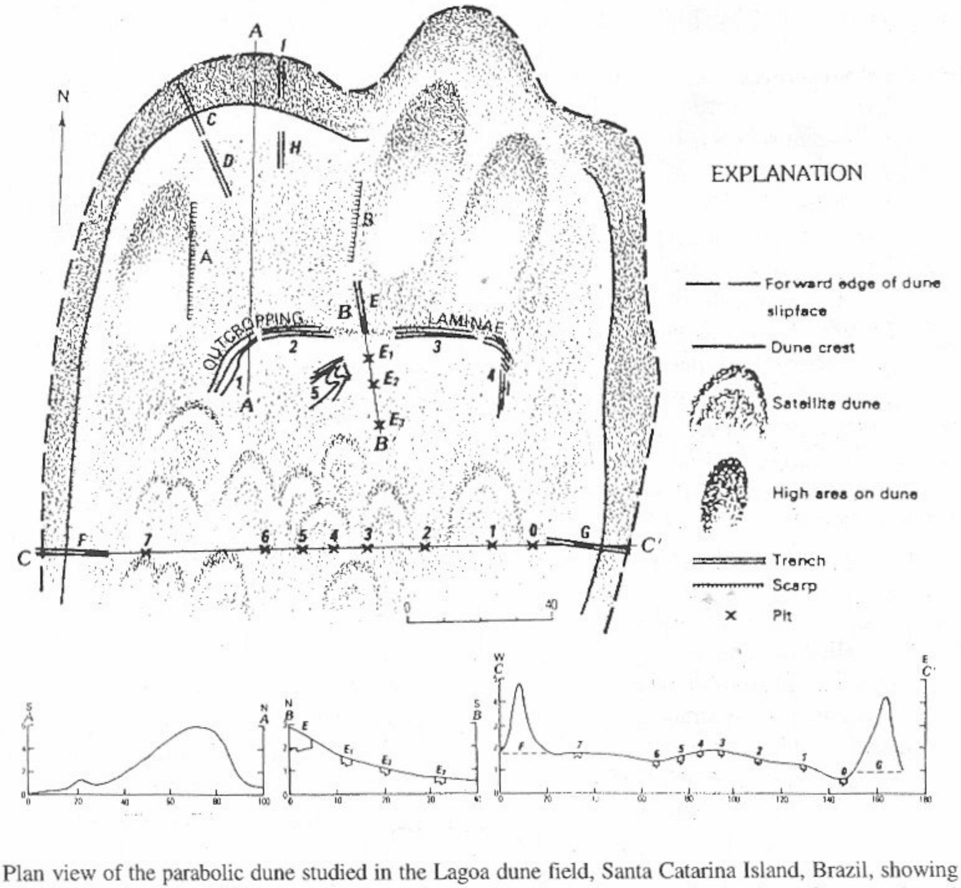


Figure 3: Plan view of the parabolic dune studied in the Lagoa dune field, Santa Catarina Island, Brazil, showing scarps, trenches and pits. Group of lines numbered 1-5 are approximate locations of outcropping laminae. Cross sections A-A', B-B', and C-C' show surface profiles across dune and interdune areas with locations of pits and trenches. Scale in meters (modified from Bigarella, 1979).

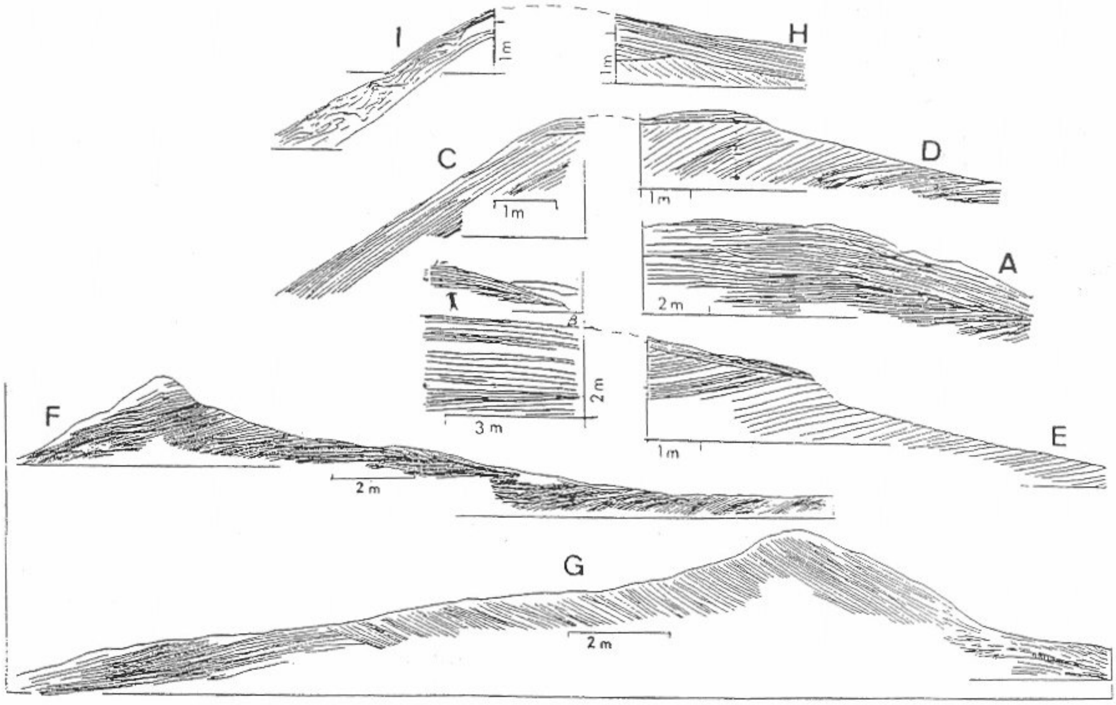


Figure 4: Cross sections of the parabolic dune studied in the Lagoa dune field, Santa Catarina Island, Brazil. The profiles are related to the primary structures shown in the scarps A and B, and in trenches C, D, E, F, G, H, and I dug across the dune and the interdune areas (modified from Bigarella, 1975b).

7. Sedimentary Structures

Most frequent sedimentary structures in the dunes consist of sets of medium- to large-scale foresets that dip downwind and are separated by bounding surfaces that are horizontal or inclined at low-angles (McKee, 1979). Exceptions to this pattern develops: a) - where the available sand load exceeds the amount of sand that the wind can move up a dune slope, causing the deposition of low-angle strata dipping to windward side; b) - when the wind is unusually strong or changes direction causing partial erosion of earlier deposits to form either trough or beveled surfaces, that become subsequently buried (McKee, 1979).

Sets of medium- to large-scale cross-strata dipping at high angles, and sets of tabular-planar cross-strata with bounding surfaces mostly horizontal, or sligthly dipping downwind, are common features to most types of dunes.

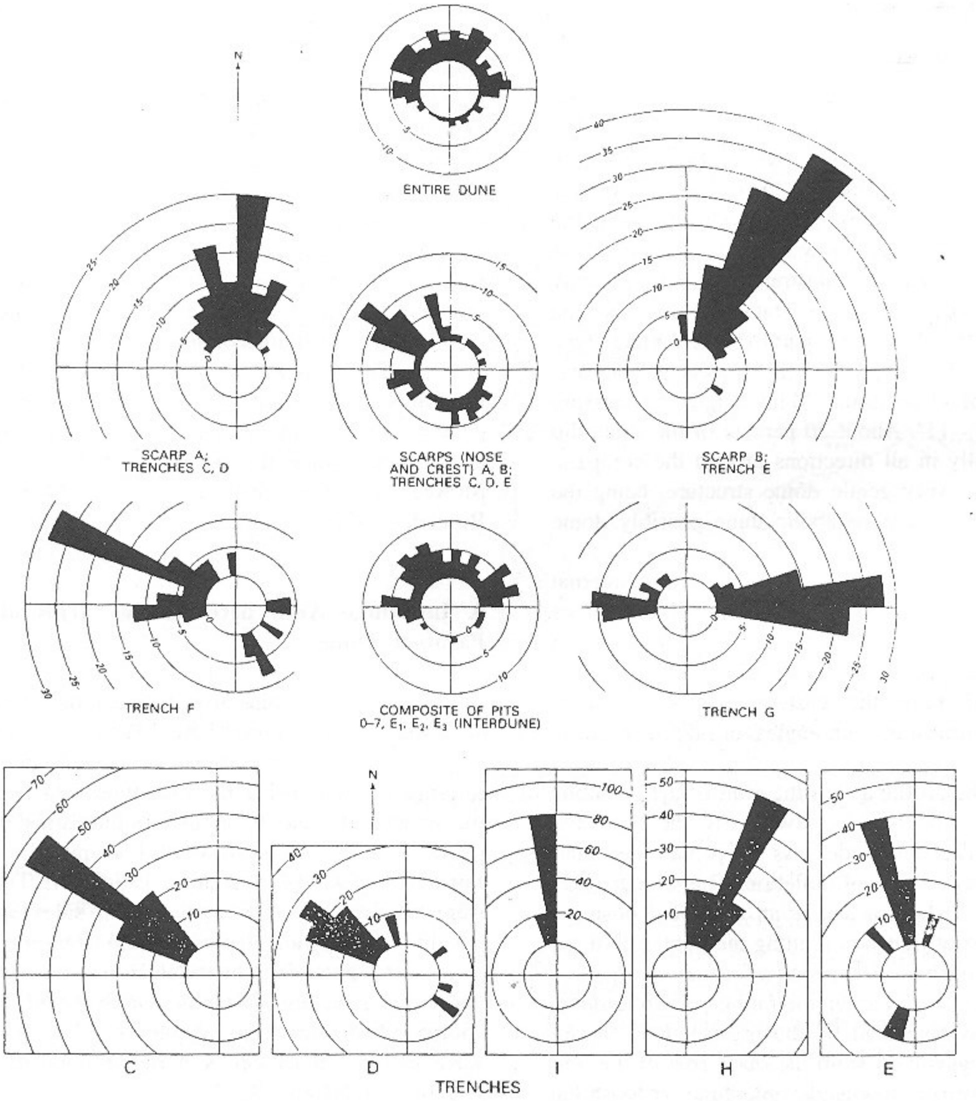
Most common cross-strata in the parabolic dune are medium scale in the crest area but large scale in the nose and the arms. Many laminae dip at high angles (29° - 34°) in the nose and also in the arms. In the nose the laminae are convex upwards dipping around the slipface; in the arms they are roughly parallel to the dune axis dipping away from the arm crests. Both along the crest and in some parts of the arms, the bounding surfaces between sets of cross-strata are nearly horizontal. Elsewhere, as in the nose and parts of the arms, they dip at angles ranging from low to high. Individual sets of cross-strata tend to be thinner and the laminae flatter near the top than at the bottom of the dune, as has been verified for other dune types (McKee, 1966; Bigarella, Becker and Duarte, 1969).

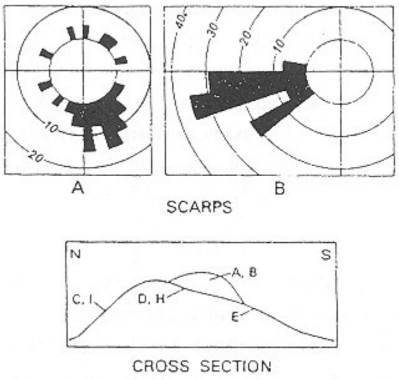
At the time of recording and drawing the structures, cross-bedding measurements were made in the trenches, scap walls and pits. From the rose diagrams of figure 5 it can be seen that every section of the dune is influenced by the local dune morphology.

In the nose area, high angle foresets are characteristic features in the walls of trenches C and I oriented oblique and parallel, respectively, to the southern storm winds (figures 3 and 4).

The rose diagram of figure 5 illustrate cross-strata dip directions from various trenches dug in the slipface and crest areas. The slipface and the crest just behind have a similar cross-strata attitude, but differ in the average of the cross-strata dip angles, which are 10° - 13° less in the crest beds.

In the crest area, surveyed in 1972, trenches D and H constituted southward continuations of trenches C and I in the slipface area (figure 3). In trenches D and H, internal structures consist of





Number of measurements (nm), dip direction (dd), consistency ratio (cr), and average dip (ad) data for trenches and scarps

			nm	dd	cr	ad (degrees)
Trench	C	——	9	N. 55° W.	0.99	32.6
	D	——	23	N. 46° W.	.66	19.8
	I	——	5	N. 07° W.	1.00	29.8
	H	——	6	N. 22° E.	.99	19.5
	E	——	10	N. 22° W.	.61	12.9
Scarp	A	——	28	S. 25° E.	.57	12.8
	B	——	14	S. 74° W.	.98	8.4

Figure 5: Rose diagrams of cross-strata dip directions recorded for scarps, trenches and pits representing the main parts of the parabolic dune and of the interdune area (modified from Bigarella, 1975b).

two main parts: (1) a thick set of cross-strata with high-angle foresets, deposited as the nose of this parabolic dune at an earlier stage, and (2) thinner cross-strata sets with low- to moderate-angle dips deposited on the crest (figure 4).

Structures representing an earlier position of the crest were exposed in the scarps A and B. The former crest was cut in half by deflation and a new crest was built downwind. From the cross-strata pattern, the whole crest seems to result from the coalescence of several low mounds of sand. Rose diagrams in figure 5 illustrate the peripherically dipping attitudes of cross-strata deposited in the windward and downwind parts of the former dune crest. High-angle dips (15° -30°) occur among lee-side sets of cross-strata. Many angles of dip are between 3° - 11°. About 20 percent of the strata dip peripherically in all directions around the compass, suggesting a very gentle dome structure, being the former crest of the parabolic dune possibly dome shaped (Bigarella, 1979).

Trenches F and G illustrate the internal structures in the parabolic dune arms. The trenches were dug normal to the direction of the southern storm winds (figures 3 and 4). The cross-strata sets dip toward both the eastern and the western quadrants, almost at rigth angles, or oblique to those on the dune nose.

The profile across the arms of the parabolic dune may be devided into two parts: the inner and the outer. The inner side, less steep than the outer, commonly is an area of deflation. The steeper outer profile has a slipface and is an area of deposition. The left part of trench G (cutting the right arm of the parabolic dune) may represent a former outer part of the left arm of an earlier migrating parabolic dune, subsequently truncated by the present dune (figure 4). High-angle strata from the outer part of the arm seem to overlie low-angle interdune cross-strata, enriched with humate compounds. In some places, an incipient paleosoil A horizon is found.

The internal structure of trench F is far more complex than that of trench G. The right side of trench F (figure 4) is composed in the lower part of truncated cross-strata dipping westward at moderate angles (18° - 25°). They represent deposits of a former parabolic dune which migrated across the area. Between this sequence and the one forming the crest of the arm, are nearly flat lying strata (3° - 5°) which probably represent interdune deposits. Above the interdune strata, the structure of the arm can be traced across a series of erosion surfaces, each series truncating slipface strata, up to the present position of the crest.

The opposing attitudes of cross-strata in trenches F and G are illustrated in a rose diagram (figure 5).

8. Deformational Structures

Penecontemporaneous deformation, caused by slumping of steep foresets, is common in most coastal dune structures (figures 6 and 7). This gravity slumping occurs during or soon after deposition. Deformational structures also occur in moderately to gently dipping strata. Deformed laminae may occur between undeformed beds or may affect adjoining sets of strata. The structures produced by deformation seem to be chaotic: folds, faults, and breccias which consist of brocken, rolled, and crinkled masses of sand. Some contorted structures result from the activities of organisms.

The response to stresses and the type of structures developed during deformation, are controlled largely by the amount of moisture present in the sand (Bigarella, Becker and Duarte, 1969; McKee, Douglas and Rittenhouse, 1979; McKee and Bigarella, 1972).

9. Interdune Area between the Arms of the Parabolic Dune

In an interdune area, between the arms of a surveyed parabolic dune (figure 3) two lines of pits were dug. The east-west line (pits 1-7) provided information concerning the interdune area between the trenches G and F on the trailing arms of the parabolic dune. The north-south line (pits $E_{1,\ 2\ \mathrm{and}\ 3}$) forms a southward continuation of trench E. The pits were irregular in cross section with sides aproximately 1-2m long and depths of 1-2m (figure8).

Characteristic of the interdune area are the apparently structureless sands, enriched with humic compounds derived from incipient soil formation. In some places , paleosoil A horizons alternate with stratified sand (figure 8).

The interdune area frequently becomes wet, sometimes swampy. In the lower parts, after rains, small pounds may be formed where the phreatic water level rises above the surface. A typical vegetation cover of grasses and small shrubs grows in the interdune environment when the sand is wet, and many small plants specially Gramineae and Cyperaceae germinate there. Humic compounds that originate from the decay of the organic material stain the sandy substratum and are responsible for the brown color of both ground water and surface water.

The burried upper surface of the brown structureless sand is irregular. Above this surface are sequences of cross-stratified eolian sand deposited either by migration of the main parabolic dune or by growth of small satellite parabolic dunes, and dome-shaped features. The cross-bedding pattern from the interdune area documents the migration or movem-

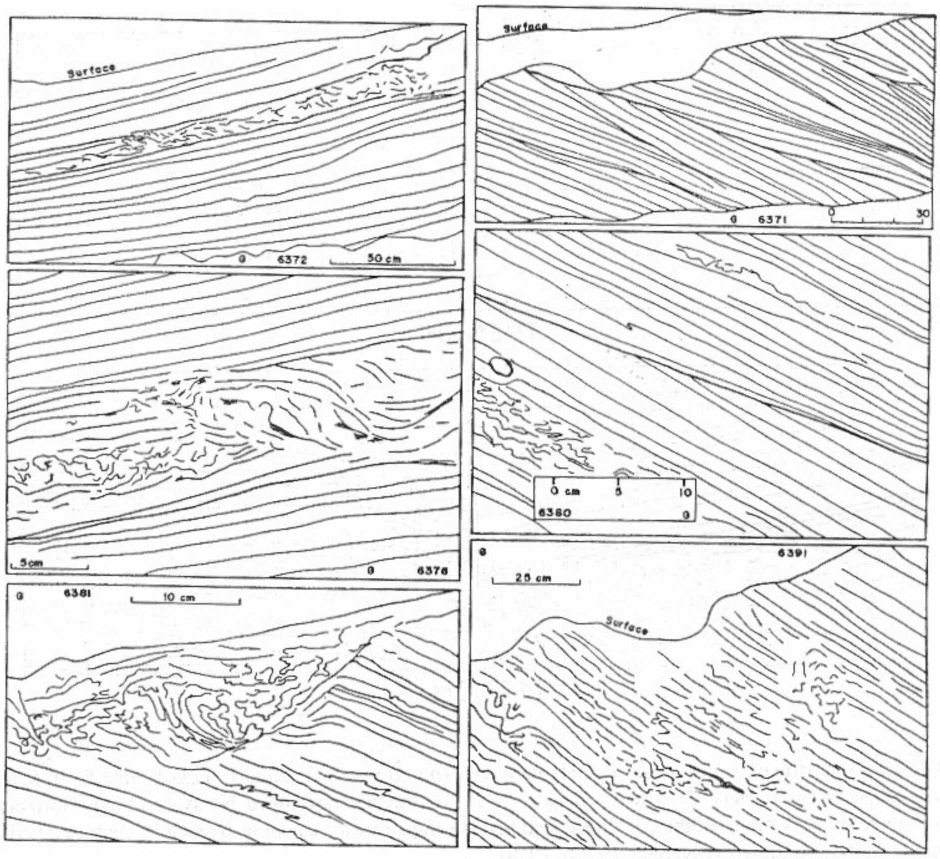


Figure 6: Deformational structures observed in parabolic dune exposed in trench G, Lagoa dune field, Brazil. Scale in centimeters (modified from Bigarella, 1975b, 1979).

ent of former dune bodies across this area. The trace of several parabolic dunes, both nose and arms can be recognized (figure 8). A rose diagram (figure 5) shows most strata in this area dipping toward the northern quadrants, with an average dip direction of N 5° W parallel to the southerly storm winds recorded for the whole parabolic dune, coinciding with the dune axis (Bigarella, 1975b, 1979).

10. Environmental Changes

During the Quaternary the Lagoa dune field underwent substantial changes on dune morphology. By the action of concentrated rainfall the original sand body dissipated, i. e. the eolian sands spread all around as a blanket decreasing in thickness downwater.

The present day humid climate with somewhat even rainfall distribution favours the development of a vegetation cover. Under these conditions the dune tends to be stabilized or active depending on its position in the dune field.

Remnants of eolian sand dissipation ramps, as well as of colluviu-alluvium ramps indicate that in the past the climatic conditions were not the same as today. Climate in the past provided conditions for extensive dune development alternating episodes of dune dissipation. Previously deposited eolian sands became mixed with colluvium material decreasing the sorting degree of the sandy sediment.

At the Lagoa dune field region periodical and recurrent episodes of semiaridity or phases of dryer climate changed the rainfall regimen, concentrating yearly precipitation in few months. The worsening of the climatic conditions caused forest retaction exposing soils to erosion. The weathered mantle from the hills mixed with large amounts of eolian sands and moved downslope forming a sandy ramp, referred by Bigarella (1975a) as dissipation ramp.

The dune submitted to heavy rainfall became soaked with water which caused wet sliding, sandflow, rainwash and gullying with formation of many alluvial fans coalescing into dissipation ramps. Many faults in the sand body were developed by sliding. The sandflow and the rainwash deposits are usually wavy or lense-shaped and frequently imbricated or contorted. Some deposits are mostly derived from dissipation of the dunes, while others

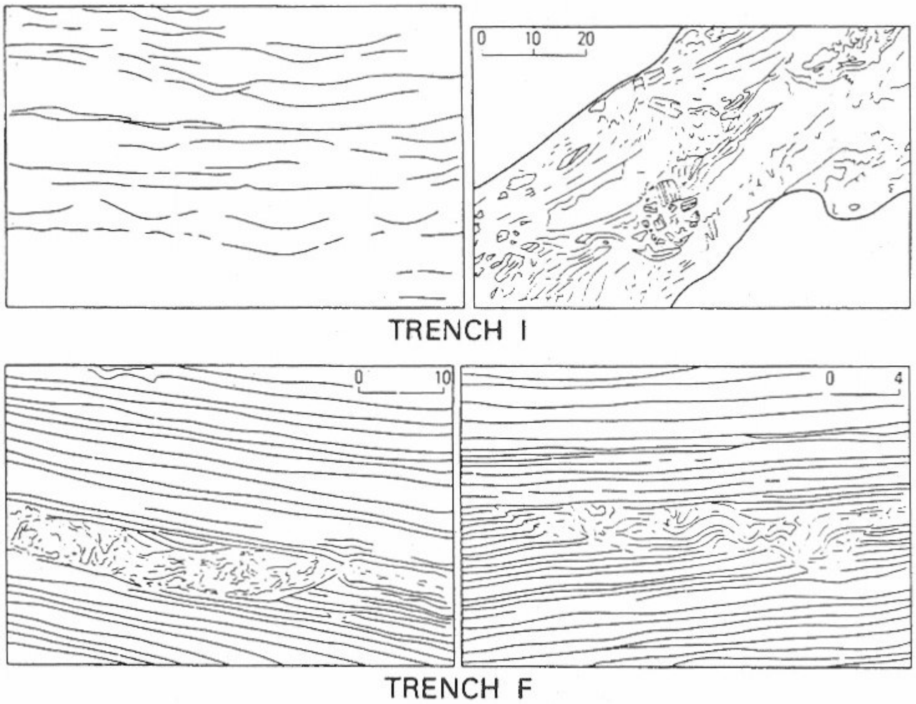


Figure 7: Deformational structures observed in parabolic dune exposed in trench I and F, Lagoa dune field, Santa Catarina Island, Brazil. Scale in centimeters. Trench I, left side: scallope structure developed by avalanching. Horizontal surface exposing high-angle foresets strata. Right side: brecciated bed developed by avalanching. Trench F: contorted beds and faults between slightly dipping strata sets (Bigarella, 1975b, 1979).

are mixtures of colluvium and dissipated eolian sands. In some places clay was deposited in ephemeral interdune ponds. Phases of soil formation alternated with deposits originated under more rough conditions. In the same way dissipation deposits are intercalated with regular dune cross-strata sets.

The dissipation structures were interpreted and considered by most pedologists as typical of a podzol or of a podzolic soil developed by pedogenetic processes. However, according to sedimentological and stratigraphical evidences, these structures originated by geogenetic processes and not by pedogenesis. Changes due to pedogenesis are subsequent and they usually destroy the original primary sedimentary structures developed by the dissipation of the dunes.

Under normal conditions the coastal dunes from Lagoa dune field are formed primarily by the accumulation of sand that avalanche in the slip face of the dune. The most common structures that result from avalanching, besides cross-stratification, are shearing planes, thrusts, high-angle asymmmetrical folds, overturned folds, breccias, normal faults, fadeout laminae and intertonging sand lenses (McKee & Bigarella, 1972).

Under dissipation conditions, the amount of water increases considerably. In the dunes may occur mass-movements like "wet avalanches" which originate faults connected with a system of shearing planes, brecciated sands and folds. The downward movement, saturated with water differs from the normal avalanching process being associated with sandflow and rainwash deposits. In a more advanced stage the action of sandflow and rainwash predominate over the whole sand body producing its dissipation characterized by strutures with a wavy and lenticular pattern.

The avalanching of sands on the lee side of a dune produces shearing planes, on which heavy minerals concentrate by migrating down through the voids between grains. The avalanching movement may start in wet sand by undercutting the base of the deposit. The avalanches in wet sand resemble mass movement in which may develop more than one shearing plane (faults) parallel or subparallel to the main movement. A secondary system of shearing planes is developed roughly perpendicular to the main faults (Bigarella, 1975b).

Normal faults and breccia are characteristic of avalanching in wet sand (McKee and Bigarella, 1972). Faulting due avalanching, is related to heavy rainfall, which soaked the dune with water. Associated sediments indicate the presence between the dunes of small ephemeral streams, which could undercut the base of the dune slope promoting conditions for sand to slide.

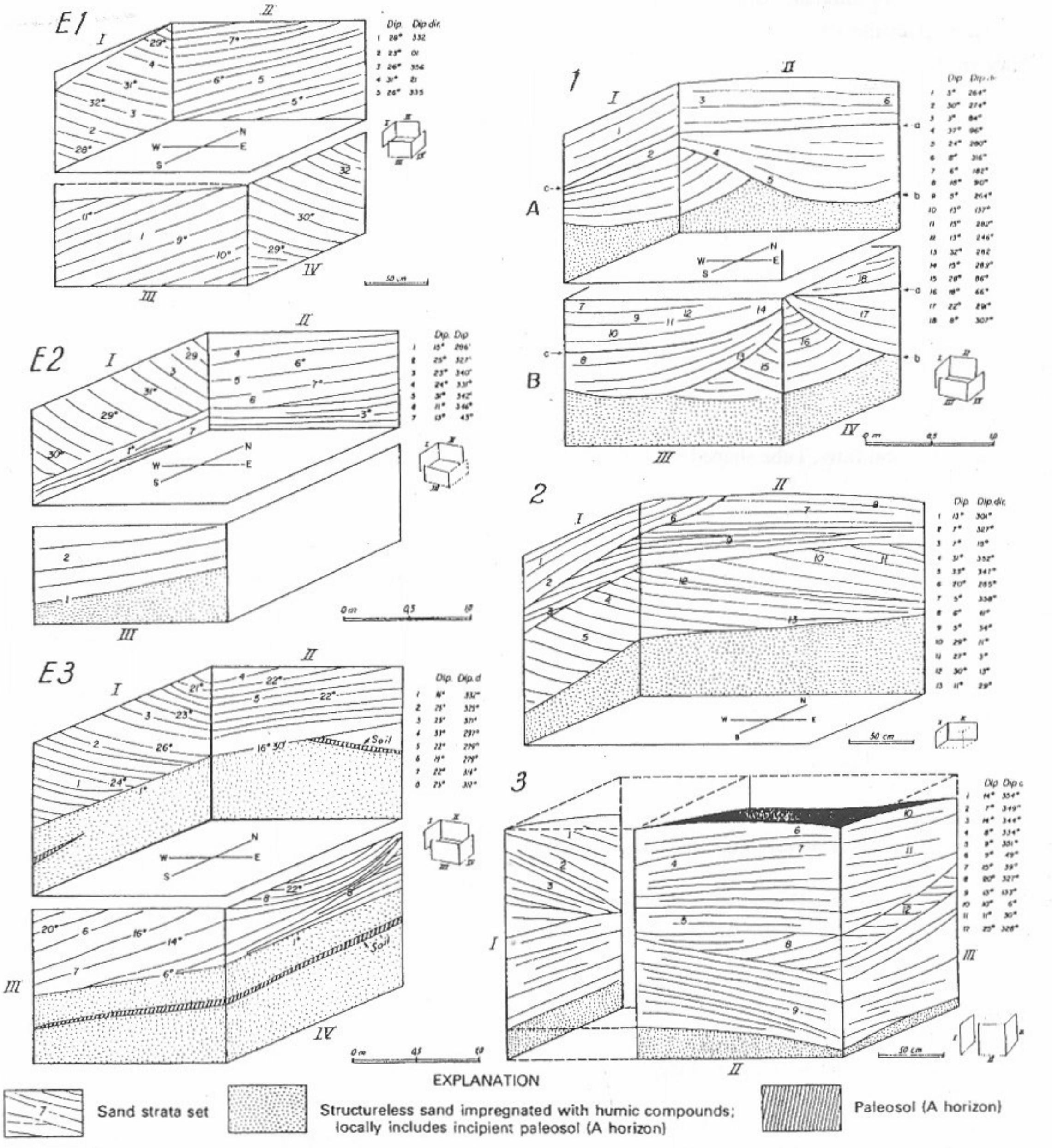


Figure 8: Stratification in pits 1, 2, 3, E_1, E_2, and E_3 in the interdune area betwee the arms of a parabolic dune in the Lagoa dune field, Santa Catarina Island, Brazil. Dip and strike are given for each numbered cross-strata set whitin a pit. Pit locations are shown in figure 3. (modified from Bigarella, 1975b).

Scour-and-fill structures may form as part of a single process in which the through are scoured by flowing waters with small load of sediments and subsequently filled with sand transported by water overcharged with sediments. Scouring and filling are related to rainfall regimen and the relative amount of sediment charge in the small ephemeral stream flowing in the interdune area during the action of the dissipation processes.

The reworking by dissipation destroys original dune structures, and concentrates colloidal materials in a wavy irregular pattern as dissipation structures.

In an area within the Lagoaa dune field dissipation structures in parabolic dunes were studied (Bigarella, 1975a). Flash flooding in this area forms the large sandy ramps and the small scale structures that interrupt dune beddig patterns. The processes seem to have been cyclic and developed under certain environmental conditions; accordingly, dissipation layers alternate with dune bedding and are recurrent in the stratigraphic section. The older dunes in the field have lost their original shape by dissipation. Some still show either hummocky morphology or a rounded topography. Others have been changed to tongue-shaped layers that are not intercalated among other dune deposits.

The new structures produced by the reworking of the eolian sands are not as easily visible as those from the previous dunes. Nevertheless, they constitute actually new primary sedimentary structures. Most of them suggest contorted bedding produced by heavy density flow (load structures). Some may resemble cut-and-fill, others follow shearing planes and small intraformational faults originated by sand flow. Tube shaped features can be related either to root growing or burrowing animals like crabs. Small, either circular or irregular patches would suggest the influence of root growing activity.

11. Dune Movement

Eolian topography, comprising deflation plains and concentration of large sand bodies (dunes) is widely distributed not only in dry regions, but also in humid regions. Eolian topography develops where a sufficient sand supply is available and where winds are strong enough to shift the sands, even in areas where the rainfall is relatively high, as along coastal areas.

In the coastal regions, the landward transport of beach sands by the wind is an important process in the development of the coastal morphology. During the Quaternary, a considerable amount of eolian sand was deposited on the coastal plains. Active dune areas were much larger than at present, and today these former dune fields are largely stabilized by vegetation.

The rate of movement of the parabolic dune from Lagoa dune field was determined by the analysis of three sets of aerial photographs (1957, 1978, and 1994), and by topographic measurements made durig a period of 20 years (1975, 1984, 1988, and 1995). In the literature concerning other dunes there are many references on the rate of dune movement. The photographs provided greater periods of time, while the measurements made in the field correspond to shorter periods of time.

The relative movement of barchan dunes in southern Peru was determined from two sets of aerial photographs taken three years apart (Finkel, 1959). The speed of movement of the barchan was greater for the smaller dunes and lesser for the larger ones. The average annual movement was of 15.4m. The forward movement affects the entire barchan without changing the size of the dune. It is developed mostly by sliding on the slipfaces, caused by sand which is blown directly up the windward slope and over the crest. The sand leaves the dune between the horns, crossing the bare stretches between barchans and accumulates in the next dune which obstructs its path. The rate of sand loss from any dune is roughly compensated by sand coming from the upwind barchan (Finkel, 1959).

In the coastal dunes of Lake Michigan the following figures for movement have been determined by Cressey (1928): 1.5m in 4 months, 3m in 6 months, and 0.9m in 11 months.

At Guerrero Negro dune field, Mexico the rate of movement in the winter has been determined to be 2.1cm/day, whereas in the summer it is 8.4cm/day (Inman, Ewing and Corliss, 1966).

Parabolic dunes in Denmark are at present stabilized: however, they had a total movement of 350-750 meters during a period of about 90 years between 1795-1886, as can be demonstrated by the analysis of old maps (Hansen, 1959).

The rate of dune movement is not uniform. Barchan dunes of the Salton Sea area had average movement of 15m per year during the period 1941-1956, and 25.5m per year during the years 1956-1963 (Long and Sharp, 1964). The difference in the average movement was attributed to an increased sand supply.

At White Sand National Monument, New Mexico, the dunes close to the source area showed considerable greater movement than those downwind. Parabolic dunes farthest downwind not only moved less, but actually retreated on their windward sides because of accumulating sand (McKee, 1966).

In spite of many references concerning the movement of the dunes, apparently no single dune has received in available literature a systematic study with observations and measurements during a long period of time, following its behaviour, displacement, and morphological changes. These have been the main purposes of the present contribution.

12. Parabolic Dune Displacement and Morphological Changes

From the selected sets of aerial photographs (figures 2 and 9), the 1994 airphotos have the best quality, showing morphological contrast in the dune not shown in the aerial photographs of 1957 and 1978.

The airphoto made in 1957 shows the parabolic dune area in white without any contrast for the identification of the morphological features. The area covered with grass vegetation is rather small

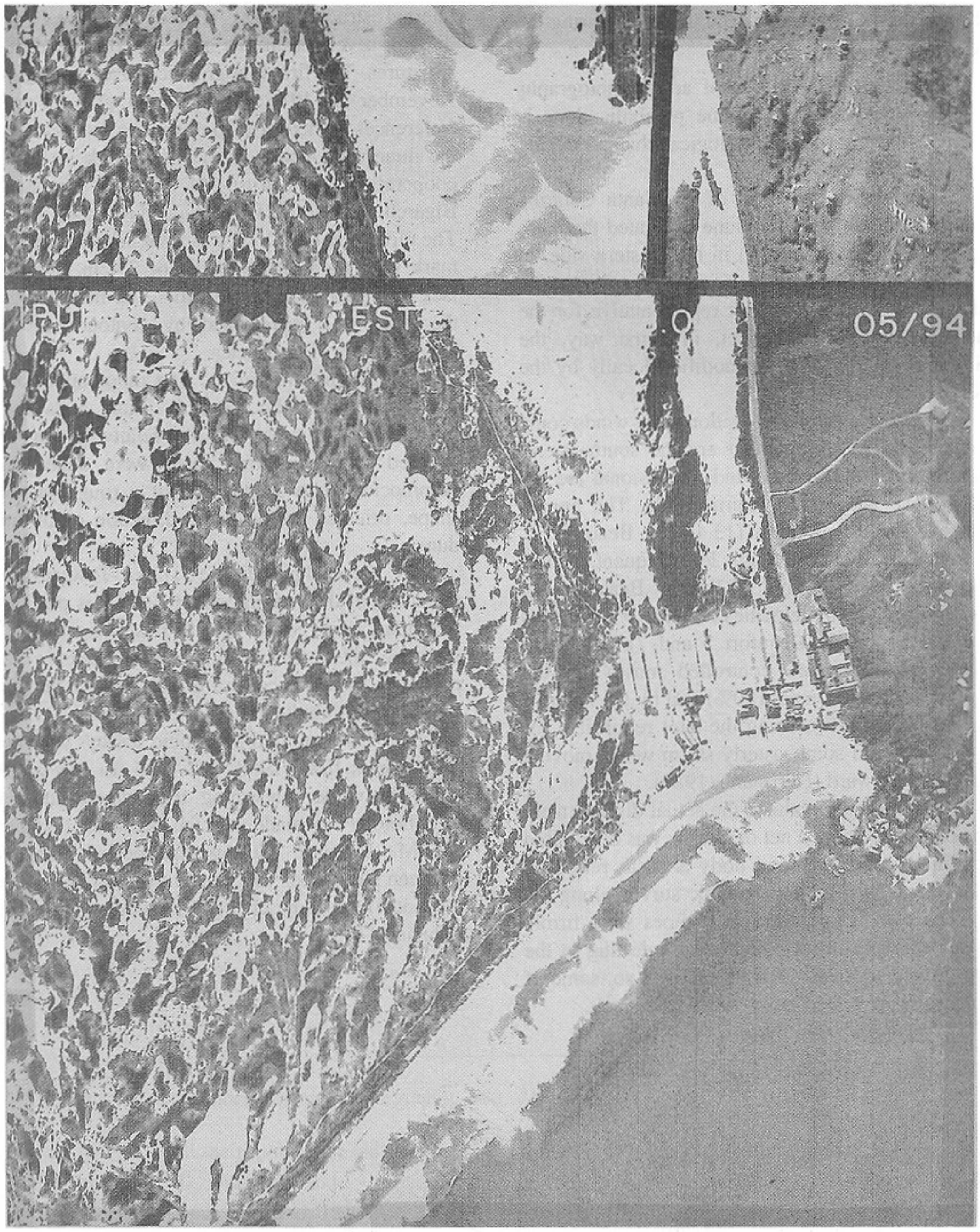


Figure 9: Aerial photograph taken in 1994 showing the Joaquina Beach and the southern part of the Lagoa dune field. The studied parabolic dune is located in the central area of the photograph.

when compared with those on photographs from 1978 and 1994.

In 1957 the sand exposed area for eolian transport was roughly one third bigger than 21 years later in 1978. In spite of a high precipitation during the year 1957 (2,019.8mm/year) the preceeding 6 years [1951-1956] were in average less humid (1,045.6mm/year). From 1971 to 1978 the amount of rainfall increased (in average: 1,644.7mm/year). The same happened during the period 1983-1995, in which the average precipitation was even higher (1,714mm/year). The highest rainfall recorded (2,598mm/year and 2,023.4mm/year) ocurred, respectively in 1983 and 1995. Rainfall data are from São José, near Florianópolis (Herrmann, 1998).

The rainfall distribution may explain to some extend the difference on the grass cover inside the dune field. However, more meteorological data are required specially those on winds for a better understanding of the parabolic dune dynamics, including local wind measurements, as well as measures on the amount of sand transport during the episodes of strong winds.

From the three sets of aerial photographs the northward movement of the parabolic dune is evident, as well as the morphological changes during a period of 38 years.

At the eastern part of the Santa Catarina Island, where the parabolic dune is located there are no data on winds. However, in the western side, at the airport meteorological station informations are available. Although being not representative for the dune field, they may reflect, in some way, the regional circulation pattern modified locally by the relief.

At the airport, the predominant winds come from the north; less frequent are the southeastern, southern and northeastern winds; occasional are the northwestern and southwestern winds. The annual average velocity is 3.65m/s (13.4km/h; Beaufort 3). The southerly wind, although less frequent, attains high speed over 20m/s (72km/h; Beaufort 9), blowing usually with velocities between 9 and 17m/s (32.4 and 61.2km/h; Beaufort 5 and 7). The local climatic conditions are controlled mostly by the Atlantic Tropical air mass (80%) and by the Atlantic Polar air mass (20%), being the later reponsible for the southerly and southeasterly storm winds moving the dunes northward (Herrmann, 1989).

In order to evaluate the actual displacement of the parabolic dune, a net of pickets was distributed around and inside the sand body area, as reference marks (points) for the topographic survey along the time. The two inches galvanized pipes were firmly set with concrete inside a cylindric hole dug in the sandy ground to avoid vandalism. Even so, some of the pickets were pulled away with a truck jack.

The systematic study of the parabolic dune internal structures was started in February 1972 digging several trenches and pits for recording the structures. The first topographic survey was made in November of 1975 for setting a grid of pickets (references marks) to accompany the displacement of the dune sand body. In the field work we had the cooperation of Gerusa M. Duarte, Nicolau C. Bigarella, Laertes P. Bigarella and Reinaldo A. Petta. The pipe picket no. VIII was established as reference mark with an arbitrary quota of 2.42m, due to the lack of a geodetic point nearby. The morphology of the dune was represented by contour lines with equidistances of one meter.

At the time of the first topographic survey (1975), between the parabolic dune arms behind from the nose crest, in the relatively flat grass covered interdune area there were small sandy hummocks, many of them with a rough parabolic shape, oriented in the same direction of the main dune.

Several pits (figure 3, pits 1-7) were dug for the study of the internal structure of this part of the interdune area. Some of the pits indicated by its structure the presence of convex dipping strata related to the advance of a former nose or an arm of a previous parabolic dune.

Three more topographic surveys were made in the years 1984, 1988, and 1995. In July of 1984 the field work concerning the contour lines and morphology was made with the assistance of Antonia M. M. Ferreira. During the period comprised between November 1975 and July 1984 (8 years and 7 months) the dune changed its shape (figures 10a, 10b, and 11).

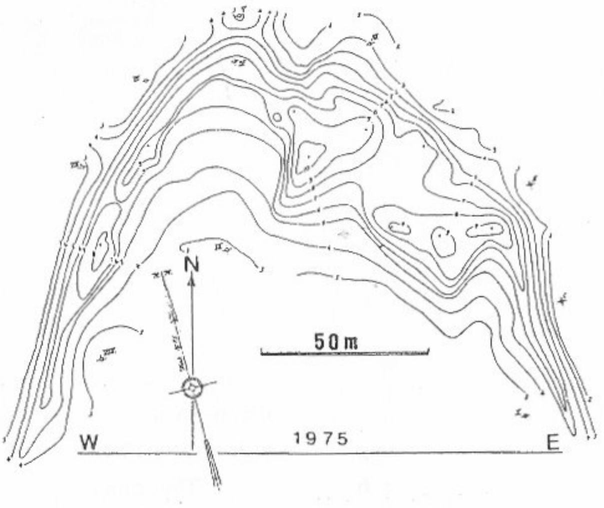


Figure 10a: Parabolic dune topography surveyed in November 1975.

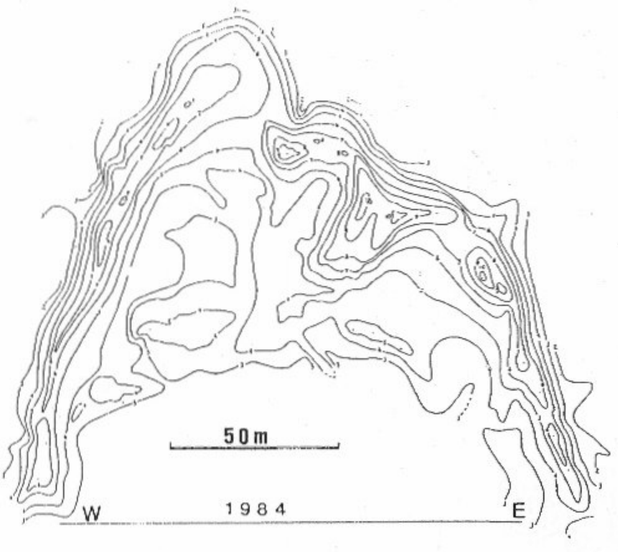


Figure 10b: Parabolic dune topography surveyed in July 1984.

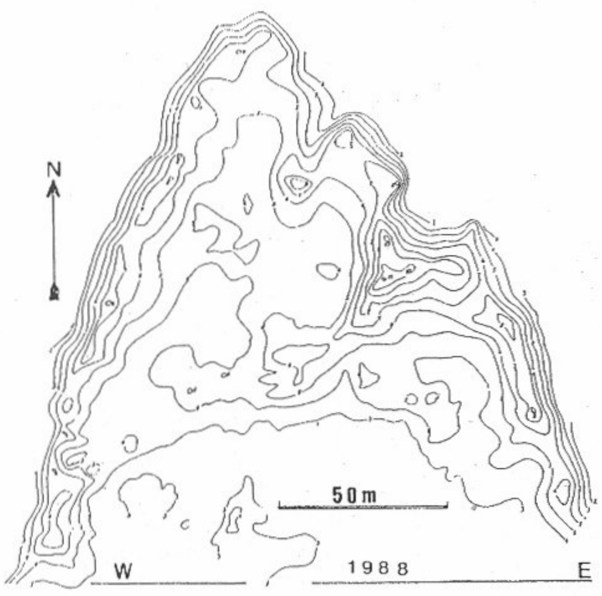


Figure 10c: Parabolic dune topography surveyed in August 1988.

In August 1988 the topographic survey was made by Ana Maria B. Franzoni and by Cláudio César Zimmermann (figs. 10c and 11). The next topographic field work was done in October 1995 by João Luiz Godinho (figs. 10d and 11). At different occasions we had the field assistence of Edmar de Lima e Silva Hoerhan, Magaly Mendonça, Maria Lúcia de Paula Herrmann, Gilberto F. dos Santos and Maurício Camargo Filho.

Two sets of profiles, being one parallel or subparallel to the parabolic dune axis, and another normal to it, in a west-east direction, show the morphological changes at different sections of the sand body (fig. 12)

In the profile A-A' (figure 13) the displacement (1975-1984) of the nose front in the 3m contour line was 26m at a rate of 3m/year. In the period 1984-1988 the nose of the parabolic dune advance 14m to the north at a rate of 3.5m/year. Between 1988-1995 the dune increased in size and the displacement decreased to 9.7m at a rate of 1.4m/year.

From 1975 to 1988 the volume of the parabolic dune above the 3m contour line was about 22,191m^3 [1975], 22,980m^3 [1984], and 22,523m^3 [1988]. The dune sand volume changed considerably in 1995, being of 37,257m^3. These values were determined from the contour line maps by Arnaldo Nicolack (Marco Engenharia de Agrimensura e Serviços de Precisão Ltda).

In 1975,behind the nose crest backward slop,there was no sand deposit above the 3m contour

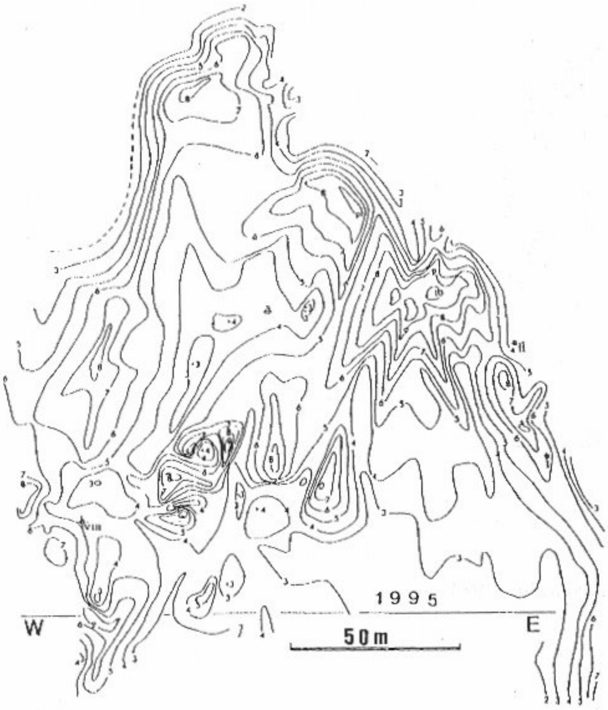


Figure 10d: Parabolic dune topography surveyed in October 1995.

line. In 1984 a small sand dome mound about one meter high was there. In 1988 the size of this mound has increased, and another was developed southward. In a field survey made in 1995 these mounds have changed considerably in size originating a compound parabolic dune with two main noses, one inset in the other. Figure 13 shows the development of the profile changes at four stages along the time.

The profile B-B' oblique to the dune axis (figure 14) shows the movement in a secondary nose protuberance to the right of the main one. During the period 1975-1984, in the 3m contour line this protuberance advanced 6m northward at a rate of about 0.7m/year. From 1984 to 1988 the displacement increased to 11.6m with a rate of 2.9m/year. In the period 1988-1995 the nose protuberance retreated 1.1m at a rate of 0.16m/year.

From 1988 on in the back side of the dune (profile B-B'), started the development of sand dome features, which changed in time to small irregular parabolic dune satellites with a progressive increase in size.

The internal structures of these small scale satellite features were studied by digging several trenches following their development through the time changing from dome- to parabolic-shaped sandy bodies (figure 15).

At the begining stage, they present convex strata ("shield-shaped") dipping all around (dome or foredune stage). Later on, start the formation of the slipface strata with higher dipping angles.

The sands were shifted both from the parabolic dune crest by deflected weakened prevailing winds, and from the south by the short-term storm winds. The greatest amount of sand deposited mounds in the backslope of the dune came from the northerly eolian transport.

In the early stages, in the upper part of the dome-shaped satellite dune is frequent the presence of almost horizontal to low dipping strata (figure 15). In many places there are lee-side strata dipping both to the northern and southern quadrants reaching up to 31°, in average 21°, considering only the dips greater than 10°. In the trenches dug in the satellite dune features 38 cross-bedding measurements were taken, being the resultant vector N 32° W and the consistency ratio 0.21.

For the Lagoa dune field were made 524 cross-bedding measurements, being 158 for the whole area (Bigarella, 1972) and 366 for the studied parabolic dune (Bigarella, 1975b). The results are presented in table 1, including those of the satellite dunes inside the parabolic dune.

The parabolic dune cross-bedding resultant vector N 05° W (Bigarella, 1975b) coincides with the direction of the southerly storm winds, being the consistency ratio 0.42. For the whole Lagoa dune field and for the satellite dunes, the consistency ratio is very low and the resultant vector is not significative for indicating neither the prevailing northerly winds nor the southerly storm winds.

At the 4m contour line, in the profiles C-C' and D-D' (figures 12 and 14) located in another fro-

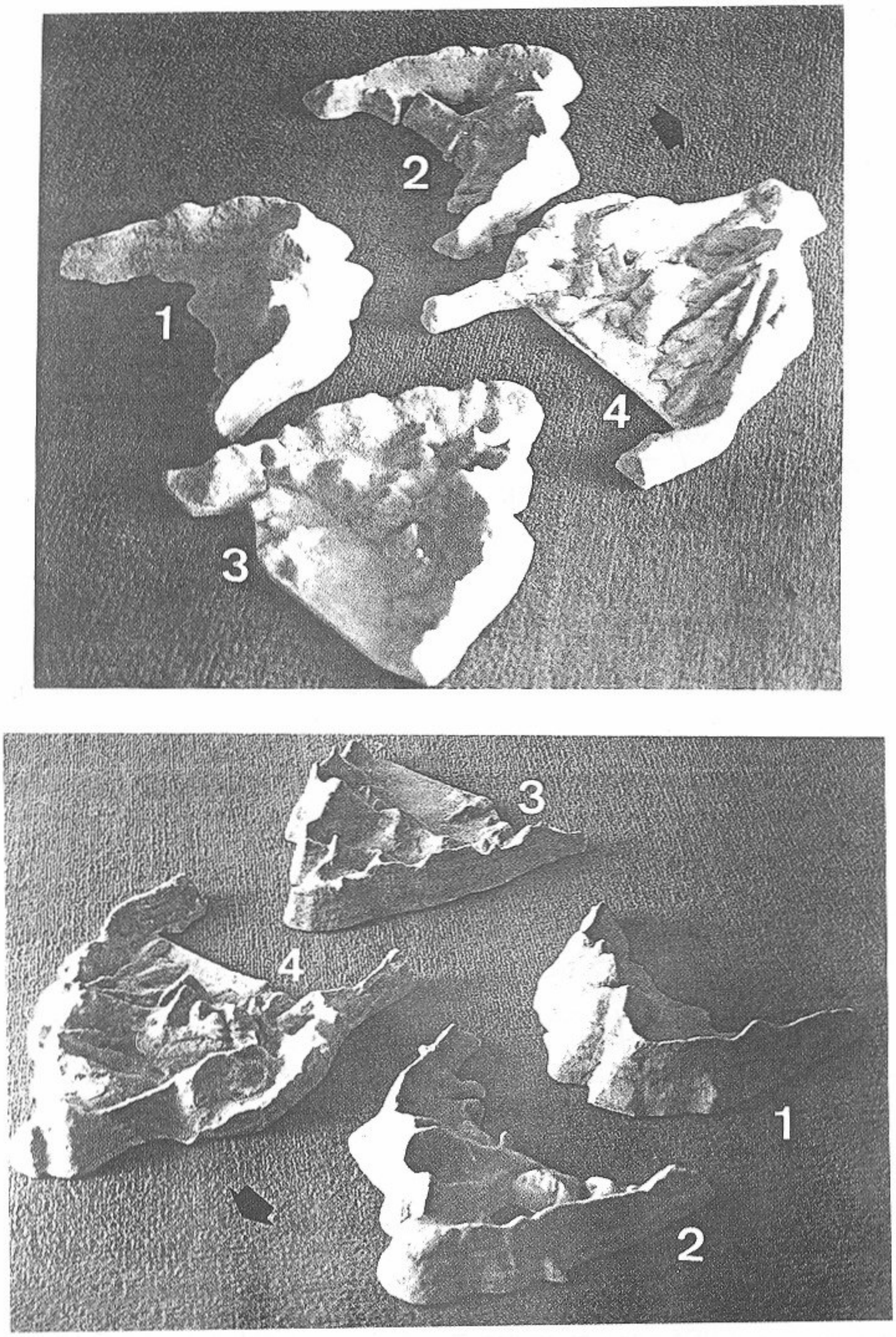


Figure 11: Scale models based in topographic plans, prepared by Maria Lúcia de Paula Herrmann. The arrows indicate the direction of the southerly storm winds. 1 - 1975; 2 - 1984; 3 - 1988; 4 - 1995 (photo: J. J. Bigarella).

ntal small nose protuberance connected with the parabolic dune right arm. The dune during the period 1975-1984 migrated in the profile C-C' 7.7m at a rate of 0.9m/year, and in the profile D-D' 11m at a rate of 1.3m/year. During the period 1984-1988 the displacement for both profiles was respectively 6.2m [1.6m/year] and 6m [1.5m/year]. In the period 1988-1995 the frontal part of both profiles became stationary. In the profile C-C' there was in the crest an increase in height of about two meters, and in the profile D-D' less than half meter. In this period a back dune was developed reaching in height the 6m contour line.

The transversal profile M-M' cuts the nose of the parabolic dune. In 1975 the dune front was 23m behind this line (figures 12 and 16). In 1984, the lower part of the nose appears in the profile above the 3m contour line. From there on, the amount of sand in the profile increased both in 1988 and 1995 by the northward advance of the dune. From 1988 to 1995 the nose shifted as well 8m in the profile to the left at a rate of about 1.1 m / year

Table 1: Cross-bedding measurements, Lagoa dune field. N.m. = number of measurements; A.d.d. = average dip; M.d. = maximum dip; A.d. = average dip; C.r. = consistency ratio.

Area	N.m.	A.d.d.	M.d.	A.d.	C.r.
Whole dune field	158	S 65• W	32•	17.7•	0.12
Studied parabolic dune	366	N 05• W	37•	19.6•	0.42
Satellite dunes (this paper)	38	N 32• W	31•	21•	0.21
General	562	N 31• W	37•	19.2•	0.28

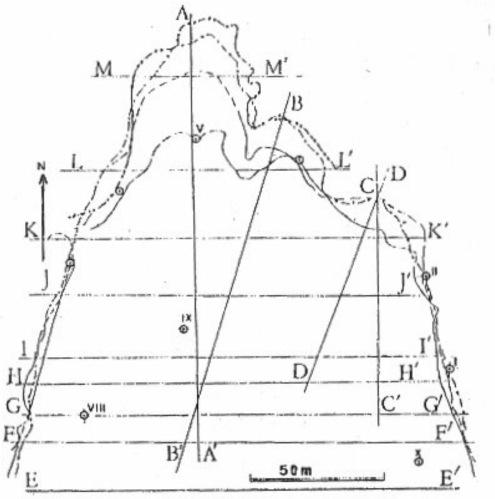


Figure 12: Location of the longitudinal and transversal profiles in a plan showing the progressive northward advance of the parabolic dune. The roman numbers indicate the position of the reference marks (pipe pickets). The several irregular lines represent the 3m contour lines relatively to the dune position in 1975, 1984, 1988, and 1995.

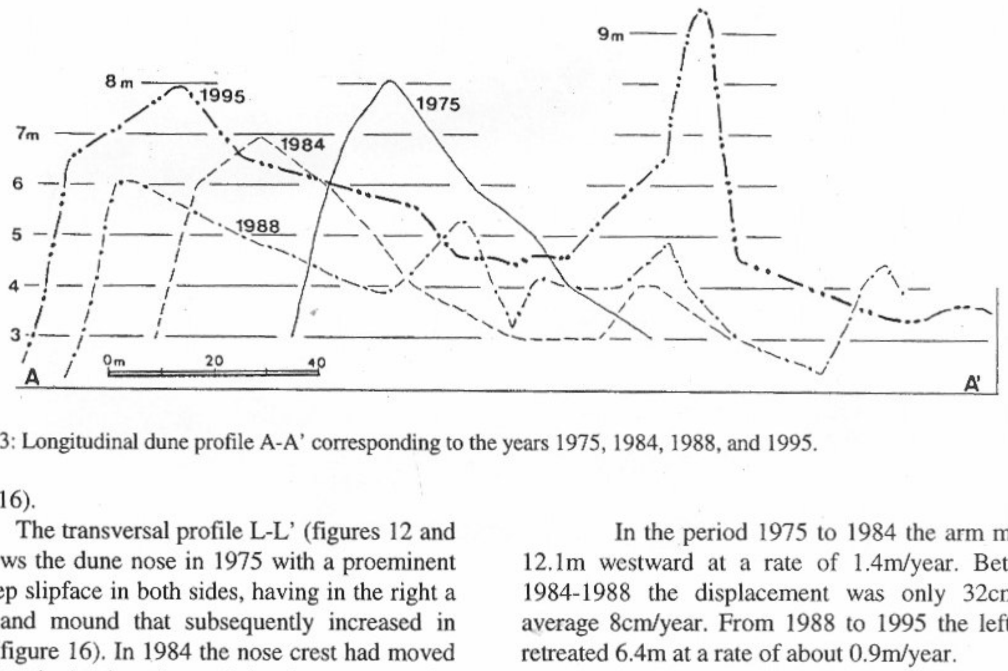


Figure 13: Longitudinal dune profile A-A' corresponding to the years 1975, 1984, 1988, and 1995.

(figure 16).

The transversal profile L-L' (figures 12 and 16) shows the dune nose in 1975 with a proeminent and steep slipface in both sides, having in the right a small sand mound that subsequently increased in height (figure 16). In 1984 the nose crest had moved to the north; in the place of the former crest the profile shows a corridor having in both sides higher dune walls with slipfaces dipping to the western and southern quadrants. From 1984 on the height of the arms that was above 8m started to decrease, becoming slightly over 6m in 1995.

In the period 1975 to 1984 the arm moved 12.1m westward at a rate of 1.4m/year. Between 1984-1988 the displacement was only 32cm, in average 8cm/year. From 1988 to 1995 the left arm retreated 6.4m at a rate of about 0.9m/year.

The transversal dune profile K-K' shows a considerable displacement (20.3m) of the sand body to the east at a rate of 1m/year. From 1975 to 1995

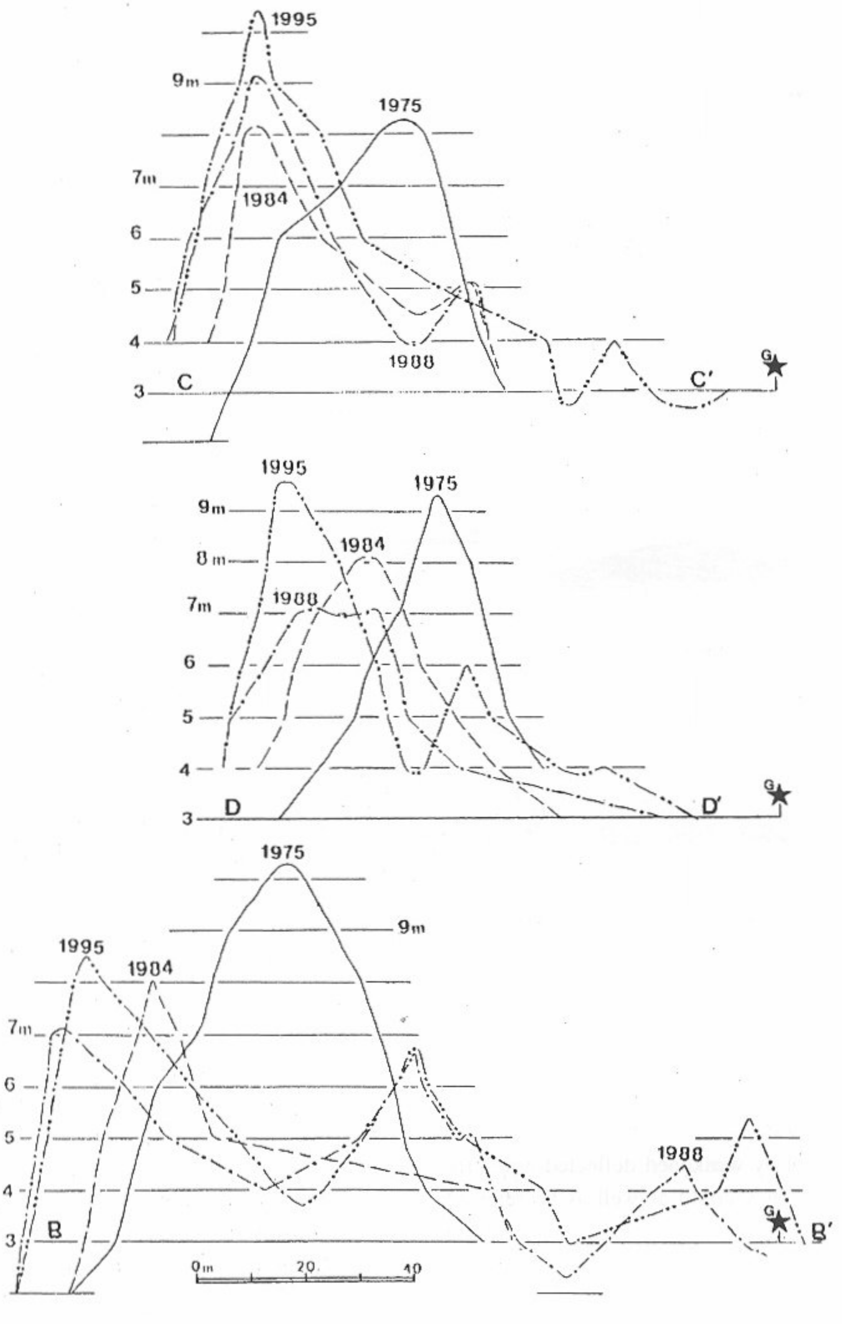
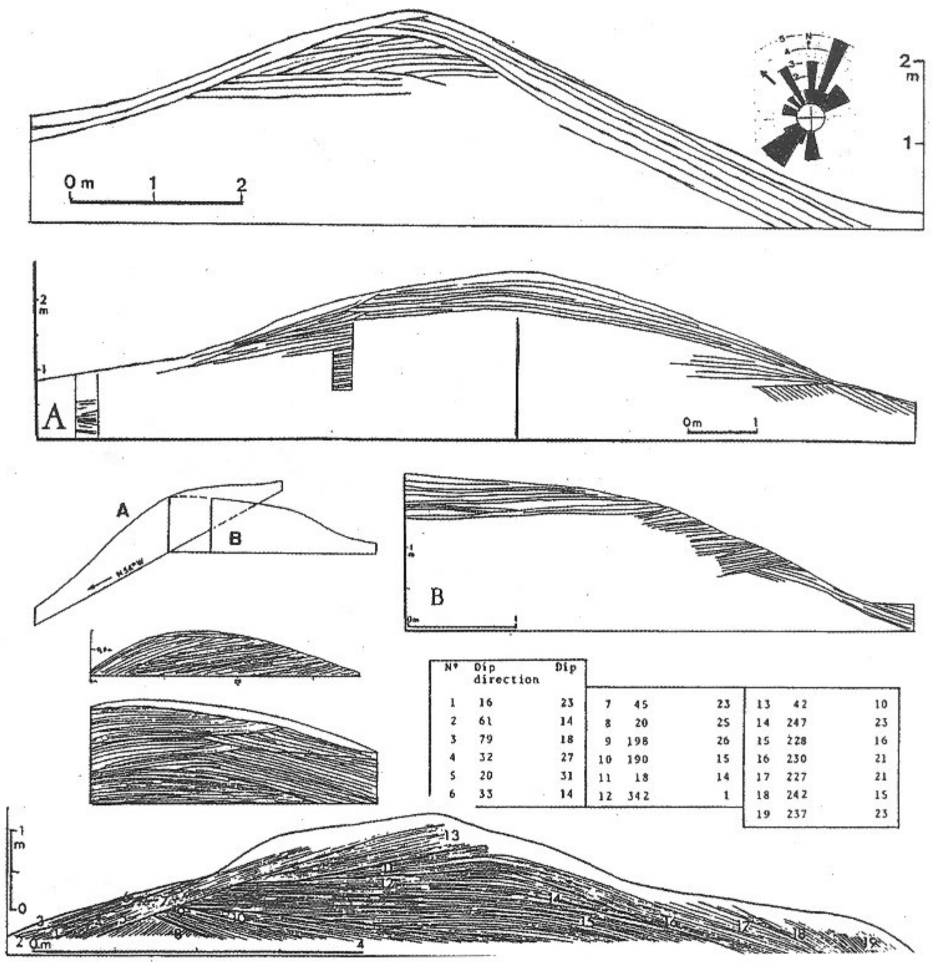


Figure 14: Longitudinal dune profiles C-C', D-D', and B-B' corresponding to the years 1975, 1984, 1988, and 1995. The black star indicate the point where the transverse line G-G' cuts the longitudinal profile lines.

the left arm decreased in height and moved 6.4m westward at a rate of 32cm/year (figure 16). From 1975 to 1995 the central corridor lost a large amount of sand; subsequently were formed small hummocks that loosed height after 1988.

In the transversal profile J-J' (figures 12 and 17) the left arm of the parabolic dune increased in height with small displacements throughout the time. In the eastern part of the profile the changes were bigger. The 1975 sand body moved to the right increasing its height in 1984 from around 8m to about 9.5m; from there on the height decreased to 7m in 1995. At this time the right part of the profile gained sand which has formed three new forms about 7m high.



Nº	Dip direction	Dip
1	16	23
2	61	14
3	79	18
4	32	27
5	20	31
6	33	14
7	45	23
8	20	25
9	198	26
10	190	15
11	18	14
12	342	1
13	42	10
14	247	23
15	228	16
16	230	21
17	227	21
18	242	15
19	237	23

Figure 15: Internal structures of the satellite dunes (dome- or gugh parabolic-shaped; hummocky features) in the back part of the parabolic dune. These features were inicially developed in the interdune area between the arms. Cross-bedding measurements from these features are represented in the rose diagram.

In the transversal profile I-I', from 1975 on started the deposition of small incipient dome dunes as "back dune" features in relation to the nose and to the crest of the parabolic dune. These features were probably deposited by weakened deflected northerly prevailing winds. They could as well as be referred as "foredunes or produnes" in relation to the strong storm southerly winds which dominate the eolian sand transport (figures 12 and 17).

With the time, these small mounds changed their form becoming small parabolic features originating the satellite dunes shown in figure 3. In 1984, one of them became higher reaching the 4m contour line. In 1988 this feature disappeared. From 1988 to 1995 a great amount of sand was deposited in this part of the profile reaching height over 9m (figure 17).

In 1975 in the eastern side of the profile I-I' the right arm of the parabolic dune was above the 7m contour line. The same was true for the left arm. Twenty years later both arms shifted eastward.

Similar features described for the profile I-I' are present in some way in the transverse profiles H-H' (figure 17) and G-G' (figure 18), being less representative in the profiles F-F' and E-E' (figure 18).

The displacement of the contour lines from 3m up to 9m are shown in figures 19a to 19g. The 3m, 4m, 5m and 6m contour lines (figures 19a, 19b, 19c, and 19d) clearly indicate both a northward movement of the dune, as well as deposition of sand in the back side of the parabolic dune in the interdune area between the arms. This deposition seems to be influenced both by the weakened deflectened northerly prevailing winds and by the southerly storm winds. For a better understanding of the problem, sand shifting measurements are required in further work. The contour lines 7m, 8m and 9m (figures 19e, 19f, and 19g) indicate, besides the northward and southward movement of the sands, the existence of an eastward displacement of the sediments.

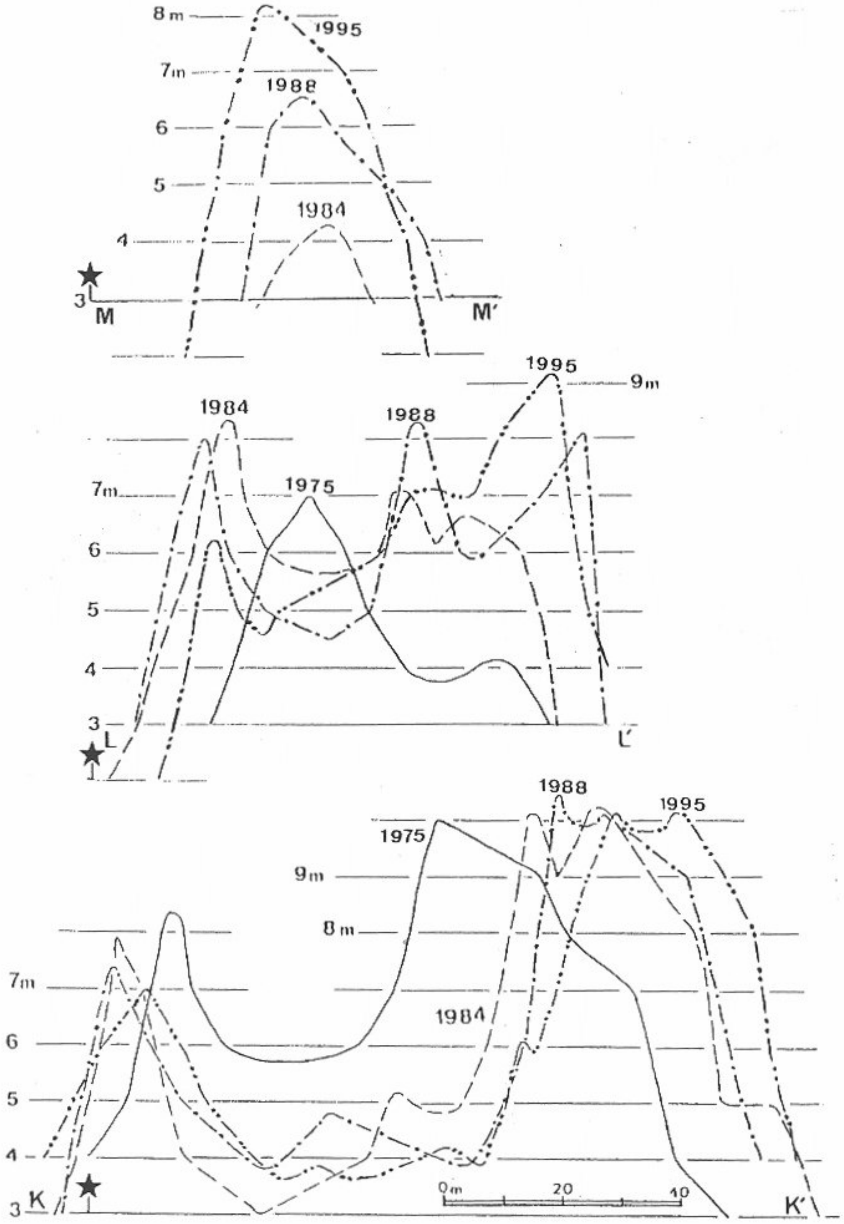


Figure 16: Transversal dune profiles M-M', L-L', and K-K' corresponding to the years 1975, 1984, 1988, and 1995. The black star indicates the intersection point of the transversal line with the northern projection of the reference mark no. VIII situated on the line G-G'.

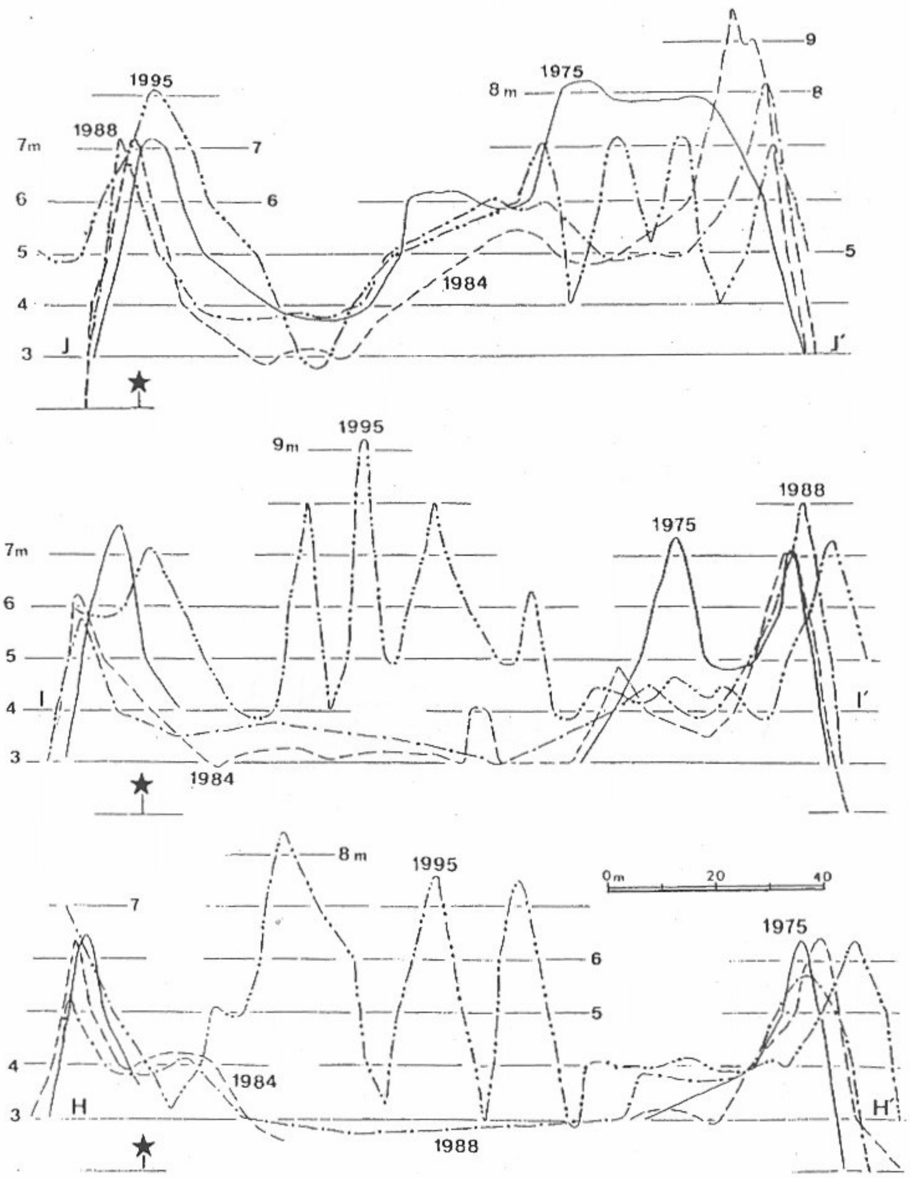


Figure 17: Transversal dune profiles J-J', I-I', and H-H' corresponding to the years 1975, 1984, 1988, and 1995. The black star indicates the intersection point of the transversal line with the northern projection of the reference mark no. VIII situated on the line G-G'.

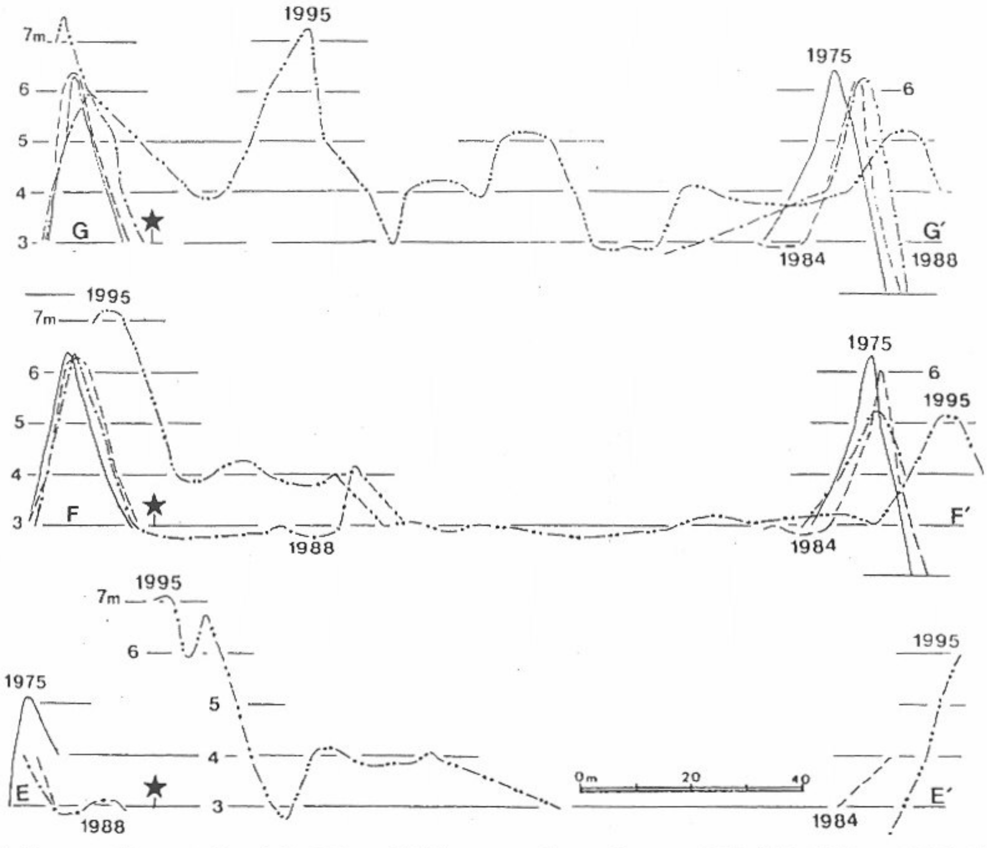


Figure 18: Transversal dune profiles G-G', F-F', and E-E' corresponding to the years 1975, 1984, 1988, and 1995. The black star indicates the intersection point of the transversal line with the northern projection of the reference mark no. VIII situated on the line G-G'.

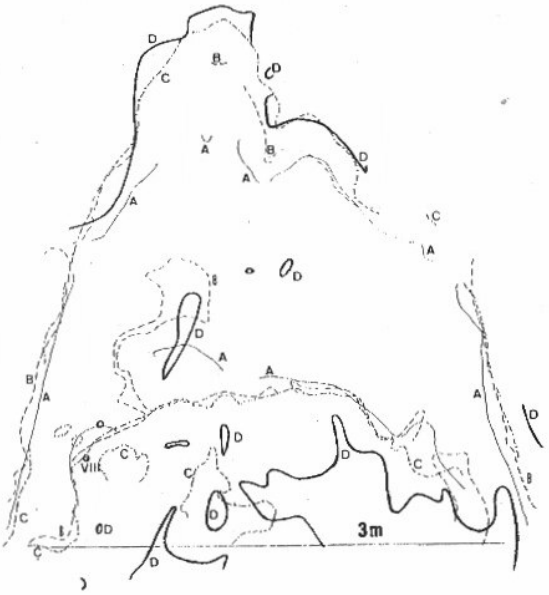


Figure 19a: Displacement of the 3m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

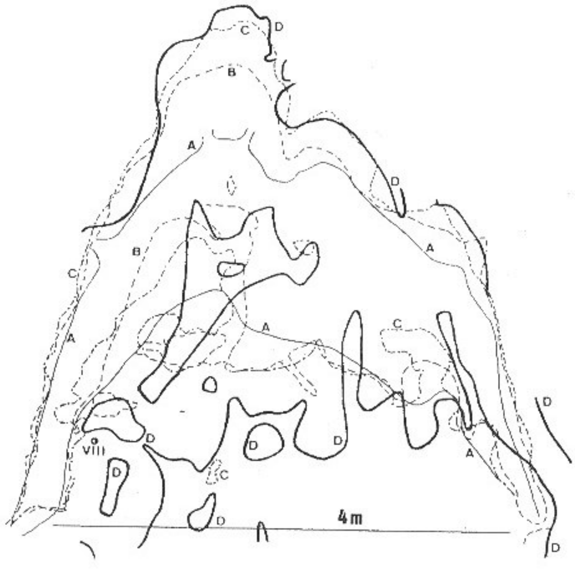


Figure 19b: Displacement of the 4m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

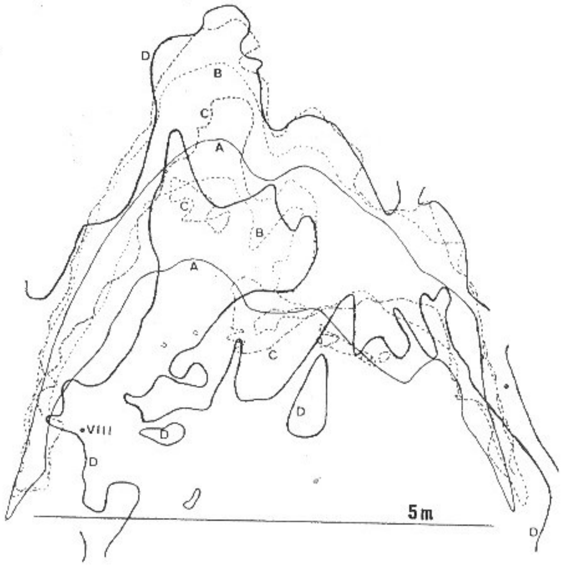


Figure 19c: Displacement of the 5m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

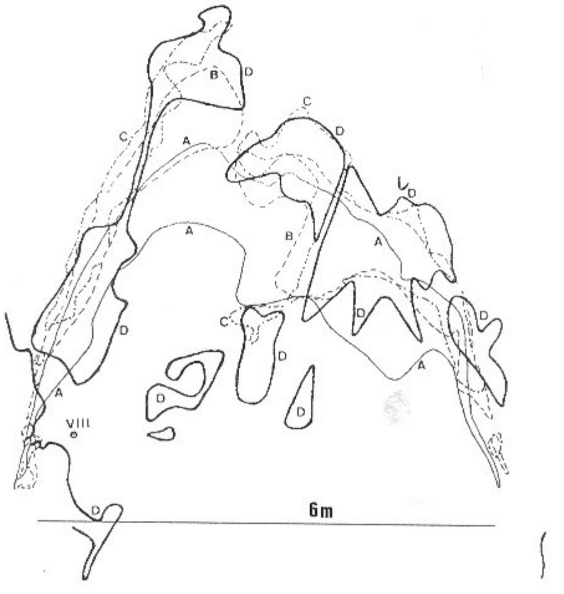


Figure 19d: Displacement of the 6m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

Figure 19e: Displacement of the 7m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

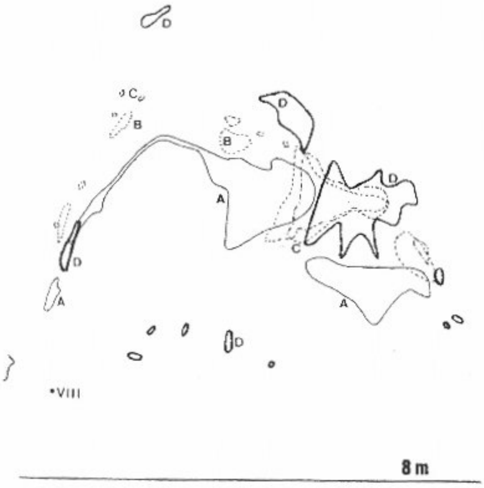


Figure 19f: Displacement of the 8m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

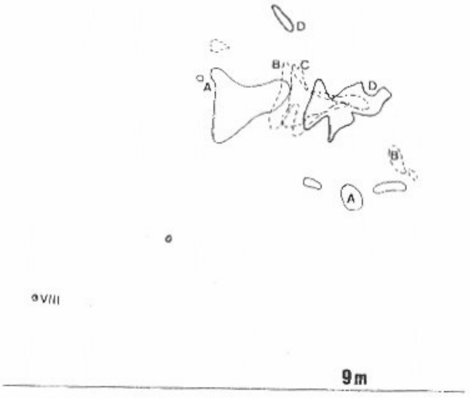


Figure 19g: Displacement of the 9m contour lines thoughout the time. A - 1975; B - 1984; C - 1988; D - 1995. The horizontal line is 150m long. See as well as the figures 10a to 10d.

13. Final words

By Federal Law the dune areas in Brazil are supposed to be protected, being therefore prohibited to be occupied by any means. However, large areas have been damaged not only by individuals, but as well as by the municipalities allowing invasions and by setting facilities, like water, electriciy and precarious urbanization.

After the occupation of the dune field area, the authorities complain about the increasing eolian activity shifting the sands over houses and streets of the town causing great expenses to the county and private property.

In order to restrict the use of the dune field area, the participants of the International Symposium on the Quaternary (Southern Brazil, July 15 - 31, 1975) sponsored by the Brazilian Academy of Sciences and other associated institutions proposed the permanent protection of the Lagoa dune field recommending the organization of a County Park in order to mantain the natural ecologic conditions related to the typical local flora and fauna. The recommendations included as well the establishement of a research programme for the study of pluvial and eolian activities, besides other projects.

The park was created, but later on the county allowed the interference in the dune field, in an area upwind of the storm winds, authorizing the building of a parking place cutting the sand supply from the Joaquina Beach. As a result of this interference increased the northward movement of a large transversal reversing dune over the road accessing the Joaquina Beach.

The present paper tries to demonstrate the need for more studies concerning the displacement of the dunes and for other projects devoted to environmental protection.

14. References

Bagnold, R. A. (1941) The physics of blown sand and desert dunes. Methuen & Co. Ltd., 265p.

Bigarella, J. J. (1972) Eolian environments - their characteristics, recognition and importance. In Rigby, J. K. and Hamblin, W. K. (eds.) Recognition of ancient sedimentary environments. Soc. Econ. Paleontologists and Mineralogists, Spec. Publication, 16:12-62.

Bigarella, J. J. (1973) Paleocurrents and the problem of continental drift. *Geologische Rundschau*. Stuttgart, 62(2):447-477.

Bigarella, J. J. (1975a) Structures developed by dissipation of dune and beach ridge deposits. *Catena*. Giessen, 2(1-2):107-152.

Bigarella, J. J. (1975b) Lagoa dune field, State of Santa Catarina, Brazil - A model of eolian and pluvial activity. *Bol. Paranaense de Geociências*. Curitiba, 33:133-167.

Bigarella, J. J. (1979) The Lagoa dune field. In McKee E. D. A study of global sand seas. *Geological Survey Professional Paper 1052*. United States Government Printing Office, Washington, 1^{rst} ed.:114-134.

Bigarella, J. J.; Becker, R. D. and Duarte, G. M. (1969) Coastal dune structures from Paraná (Brazil). *Marine Geology*. Amsterdam, 7:5-55.

Bigarella, J. J. and Salamuni, R. (1961) Early Mesozoic wind patters as suggested by dune bedding in the Botucatu sandstone of Brazil and Uruguay. *Geological Society America Bull.* New York, 72:1089-1106.

Cornish, V. (1897) On the formation of sand dunes. *Geogr. Jour.*, 9:278-309.

Cressey, G. B. (1928) Ihe Indiana sand dunes and shorelines of the Lake Michigan Basin. *The Geogr. Soc. of Chicago Bull.* no. 8, 20p. (Univ. Chicago Press).

Finkel, H. J. (1959) The barchans of southern Peru. *Journal of Geology*. 67(6):614-647.

Hansen, V. (1959) Sandflugten i Thyog dens indflydelse pa Kulturlandskabet. *Meddelersser fra Skalling Laboratoriet*. København, 6:69-91.

Hedin, S. (1896) A journey through the Takla-Makan Desert, Chinese Turkistan. *Geogr. Jour.* 8:264-178.

Herrmann, M. L. de P. (1989) Aspectos ambientais da porção central da Ilha de Santa Catarina. Florianópolis:UFSC / Curso de Mestrado em Geografia. 229p. Dissertação de Mestrado.

Herrmann, M. L. de P. (1998) Problemas geoambientais na faixa central do litoral catarinense. São Paulo, Depto. de Geografia, Univ. São Paulo, 307p. Tese de Doutorado.

Inman, D. L.; Ewing, G. C. e Corliss, J. B. (1966) Coastal sand dunes of Guerrero Negro, Baja California, Mexico. *Geol. Soc. Amer. Bull.* 77:787-802.

Long, J. T. and Sharp, R. P. (1964) Barchan dune movement in Imperial Valley, California. *Geol. Soc. Amer. Bull., 75:149-156.*

McKee, E. D. (1966) Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). *Sedimentology*. Amsterdam, 7(1):3-69, Spec. issue.

McKee, E. D. and Bigarella, J. J. (1972) Deformational structures in Brazilian coastal dunes. *Jour. Sedimentary Petrology*. 42(3):670-681.

McKee, E. D.; Douglas, J. R. & Rittenhouse, S. (1971) Deformation of lee-side laminae in eolian dunes. *Geological Society America Bull.* New York, 82(2):359-378.

Merk, G. A. F. (1960) Great sand dunes of Colorado: Guide to the Geology of Colorado. *Rocky Mt. Assoc. Geologist*. p. 127-129.

Sharp, R. P. (1966) Kelso dunes, Mohave Desert, California. *Geological Society America Bull.* New York, 77:1045-1073.