

SEDIMENTOLOGY AND QUATERNARY GEOMORPHOLOGY OF SOUTH TEXAS

Supplementary to Field Trip Manual "SEDIMENTOLOGY OF SOUTH TEXAS" Corpus Christi Geological Society Spring Field Trip 1958

W. Armstrong Price*

INTRODUCTION

Problems of Southwest Texas

The sedimentology and Quaternary geomorphology and stratigraphy of southwestern Texas have not received the same amount of detailed study as has been devoted to them in the Mississippi delta region. However, the investigations so far carried out indicate that southwestern Texas has at least as much to contribute to fundamental geology as the Mississippi delta has already given it.

The present study is designed to outline some of the mainly unpublished results of the writer's intermittent field studies in the region and to show how the information from the topics treated may integrate when more fully investigated.

Some additional topics, not treated directly here, but on which work done has given positive results or shows that such results can be obtained are: (a) the origin of the barrier chain; (b) the relation of the heights and frequencies of marine floods of a region to the heights and degrees of development of beaches, beach ridges, storm benches, tidal marshes and wind-tide flats; (c) the influence of the standing wave or seiche on the shorelines of the inner bays and lagoons; (d) enlargement of the list of varieties of strand plains and strand terraces, (e) the patterns of strandline geomorphology and deposition.

The present contribution is intended as a supplement to the Corpus Christi Geological Society's 1958 Field Trip volume, "Sedimentology of South Texas".

Pleistocene Formations

Doering's (1935, 1956, 1958) studies of the deltaic plains of the Gulf Coast and his discussion of the correlations of the Louisiana geologists (Fisk 1944 and Varvaro 1957), show the complexities of the problem. The mapping requires detailed contouring of the restored deltaic surfaces. Doering's latest mapping is an improvement on previous mappings, although he did not treat the coast southwest of Corpus Christi in the same detail as he did that further northeast.

Extension of the eolian sand sheet of southwestern Texas to the entrenched valley of Rio Grande probably invalidates the surface gradient method of formation-mapping there because there is no assurance that the gradients of the sheet follow those of the underlying deltaic formations sufficiently closely. Doering's recognition of Pleistocene formations older than Lissie and Willis complicates the problem, especially under the sand sheet of the Rio Grande delta region.

*Consulting Geologist and Oceanographer
Corpus Christi, Texas

Doering's (1958, fig. 4) profile across the barrier-and-lagoon terraces of South Carolina notes the two low terraces commonly disregarded in American mapping before 1950 but that are well preserved in southeastern Virginia, the Silver Bluff (3-10 feet) and Princess Anne (15 feet). Topographic maps were not adequate for the mapping of these terraces when the state geological reports were made in the Carolinas, Georgia and Florida. F. S. MacNeil's (1950) later mapping shows the Silver Bluff in parts of Florida and Georgia.

The writer, assisted by V. J. Henry (1956) searched for evidences of the Silver Bluff and Princess Anne on the Texas coast but concluded that the downwarping at and toward the Gulf has been of the order of 15 feet west and southwest of Galveston Bay.

Where the Silver Bluff would be expected in Texas, if it were of Recent age as many have supposed, but without positive proof, only a storm terrace (4 to 6 feet above mean sealevel) with washover faunal assemblages was found. The storm bench is partly erosional and partly depositional, with beach ridges and spits. It is likely that the Angelita terrace of Nueces River (Price 1933b, fig. 17), which disappears gulfward under the Nueces floodplain marshes at Calallen, may be of Silver Bluff age and the Corpus Christi terrace (25 feet at Corpus Christi) may be of Princess Anne age.

Gulf-facing benches at 12 to 15 feet in Texas are the result of the reopening of deltaic river channels by small drainage courses, the bench being formed when only one natural levee is eroded away.

Terminology of "Beaumont" in Corpus Christi Area

In this paper, the writer returns to Doering's names used in the writer's article: "Quaternary deltaic plains and strand terraces" in the Corpus Christi Geological Society's Field Trip book for 1956, pp. 1 to 3. In the book for 1958, Fisk's terms were used. The correlations in this area are:

Quaternary	Doering 1956	Fisk 1944
	Recent	Recent
(Beaumont)	{ Eunice Oberlin Lissie Citronelle	Prairie Montgomery
Pliocene	Goliad	

The writer made this last change in his usage after Doering again discussed the Louisiana correlations in his paper of 1958.

Erosional Scarp Marking Transgression of Pre-Ingleside Pleistocene Sea

Doering (1956) maps the older Oberlin and younger

Eunice as formations replacing the Beaumont in Texas. They are not exactly equivalent to the writer's discarded "old and young Beaumont" (Price 1947 b, fig. 1). The Ingleside barrier (Price 1933) and its lagoon plain have been correlated with a portion of the Eunice delta. This barrier was not its final deltaic shoreline in Chambers County and at the mouth of San Antonio Bay. The final Eunice shoreline has not been preserved in southwest Texas unless it is part of the barrier there.

East of Galveston Bay, the Eunice distributaries broke through the Ingleside barrier and the delta then grew at least 10 miles gulfward. This growth placed about 10 feet of alluvium over the horizon of the shoreline of the Ingleside lagoon (V. J. Henry 1956).

At Corpus Christi, there is neither an early nor a late Eunice delta and the Ingleside lagoon plain abuts against an erosional scarp 10 to 15 feet high (contact between Oberlin and Ingleside, pl. 8. Field Trip 1958) along the front of the Oberlin delta. The latter has lost its barrier chain by erosion.

Instead of a younger Eunice delta being present, the Ingleside barrier is beveled toward the modern lagoon by a modern storm bench at 4 to 6 feet elevation. The bench is upwards of one mile wide in places, as west of Texas City.

If we follow the pre-Ingleside scarp to the southwest, we find that, at Baffin Bay and along its Grullo Arroyo, the Montgomery is either gone or only narrowly preserved.

There seems to be a Eunice delta in Cameron County, where the Ingleside has been slightly down warped and removed by erosion along the front of the Rio Grande delta. South of this delta, the Ingleside terrace again cuts out the Montgomery and finally the entire older Pleistocene. Approaching the Soto la Marina River (24° N. Lat.) from the north, the Ingleside terrace lies against an erosional scarp cut in Miocene and Oligocene beds (Geologic Map of Mexico, XX Int. Geol. Congr. 1956) with dips as high as 8°.

The Ingleside barrier with its lagoon, thus, forms a strand terrace which borders an erosional scarp southwest of Galveston Bay except on parts of the larger deltas.

On the Atlantic coast, similar erosional scarps in the Pleistocene indicate chiefly episodes of straightening of deltaic shorelines. But, approaching the tilted and warped Cretaceous coastal plain of Mexico, where it comes to the Gulf, the pre-Ingleside scarp is continuous and prominent, transgressing the older Pleistocene and younger Tertiary to the volcanic coast of Vera Cruz. Tracing of the Ingleside terrace to the Soto la Marina and to Tampico is tentative. A prominent barrier chain of Pleistocene age is preserved there with a similar relation to the scarp as the Ingleside has in Texas.

INTEGRATION OF QUATERNARY RIVER SYSTEMS OF THE SOUTHWEST DOMINANTLY IN RESPONSE TO CLIMATIC FACTORS

Late Integration into Drainage Systems

Geomorphologists have long recognized that the scenery of the continents is primarily a development of the Quaternary. Erosion and the development of drainage systems by progressive stream piracy developed much of the inland scenery, while mountain-flank and plains alluviation and coastal progradation built the Quaternary lowlands. Crustal deformation and climatic variations also played prominent parts.

F. B. Plummer (1933, fig. 51) discussed some of the episodes of stream capture in the headwaters of the Brazos and Colorado rivers. The Pecos beheaded the Brazos at Fort Sumner, New Mexico, and captured the drainage of the southeastern flank of the Southern Rockies which used to reach the Gulf via the Brazos, Fig. 1. Heavy minerals of Rocky Mountain type reported on the beach at Galveston need not have come from the Rio Grande, but probably came from sands of Pleistocene deltaic stream channels exposed in the bluffs of Galveston Bay. The beheaded Clovis-Portales valley (of Blackwater Draw and other intermittent streams of the Brazos drainage on the Llano Estacado) has Pleistocene elephant bones in its gravels and extinct bison in its lake beds (Sellards 1940 a). This valley is in a hanging position on the east side of the Pecos river at Fort Sumner. The Colorado River of Texas was also beheaded by the Pecos.

Plummer's (1933, p. 771) suggestion that distance to the Gulf favored the southward flowing streams because they had shorter courses and therefore steeper gradients needs elaboration because it is approximately 800 miles along the modern Pecos-Rio Grande, and only 700 miles along the Clovis-Portales Valley and Brazos River from Fort Sumner to the Gulf.

Because of the southeast diagonal course of the mountain systems, including the Eastern Sierra Madre and the Sacramento and other mountains of New Mexico and Texas, the rivers crossing the Plio-Pleistocene plains at the south originally had much shorter courses to base level than had the Canadian, Brazos and Colorado.

Therefore, the short streams draining the front of the high Sierra Madre in the Monterrey-Laredo region had the advantage in gradient steepness over rivers draining the Rockies and Sacramento mountains west of Midland, Lubbock and Amarillo. The southern streams cut down through obstructions much more rapidly than the more northerly streams could do.

One of the early Laredo-Monterrey streams captured and integrated the drainage of that area to become the ancestral Rio Grande. It had a short steep course to the Gulf from high rain-condensing mountains that furnished enough precipitation during the pluvial-glacial events of the Quaternary to develop a vast, mountain flank stream system. The headwater branches of this system captured the mountain front drainage to the northwest, and so on, step by step, as long as the initial advantage of distance and gradient favored the more southerly of adjacent streams. This process, so far as is evident from the regional maps, may have reached its limit at Fort Sumner with the capture of the headwaters of the Brazos. The mountain front drainage basin of the Brazos furnished an insignificant volume of runoff in comparison with that of an integrated mountain front system 1,300 miles long along the Pecos-Rio Grande.

The Rio Grande and Pecos picked their routes around uprising or resistant residual mountains and through subsiding structural troughs, also profiting from solution channels in limestone and gypsiferous beds. But the subhumid to humid climates of the mountain summits and flanks (C. W. Thornthwaite 1931, 1948), evidenced by their pines and other forest trees, gave the advantage to the Rio Grande-Pecos over the rivers that had to cross the arid to semiarid plains without renewals of drainage from mountain chains along the way. It is also likely that proximity of their mountain hinterland to the storm tracks of cy-

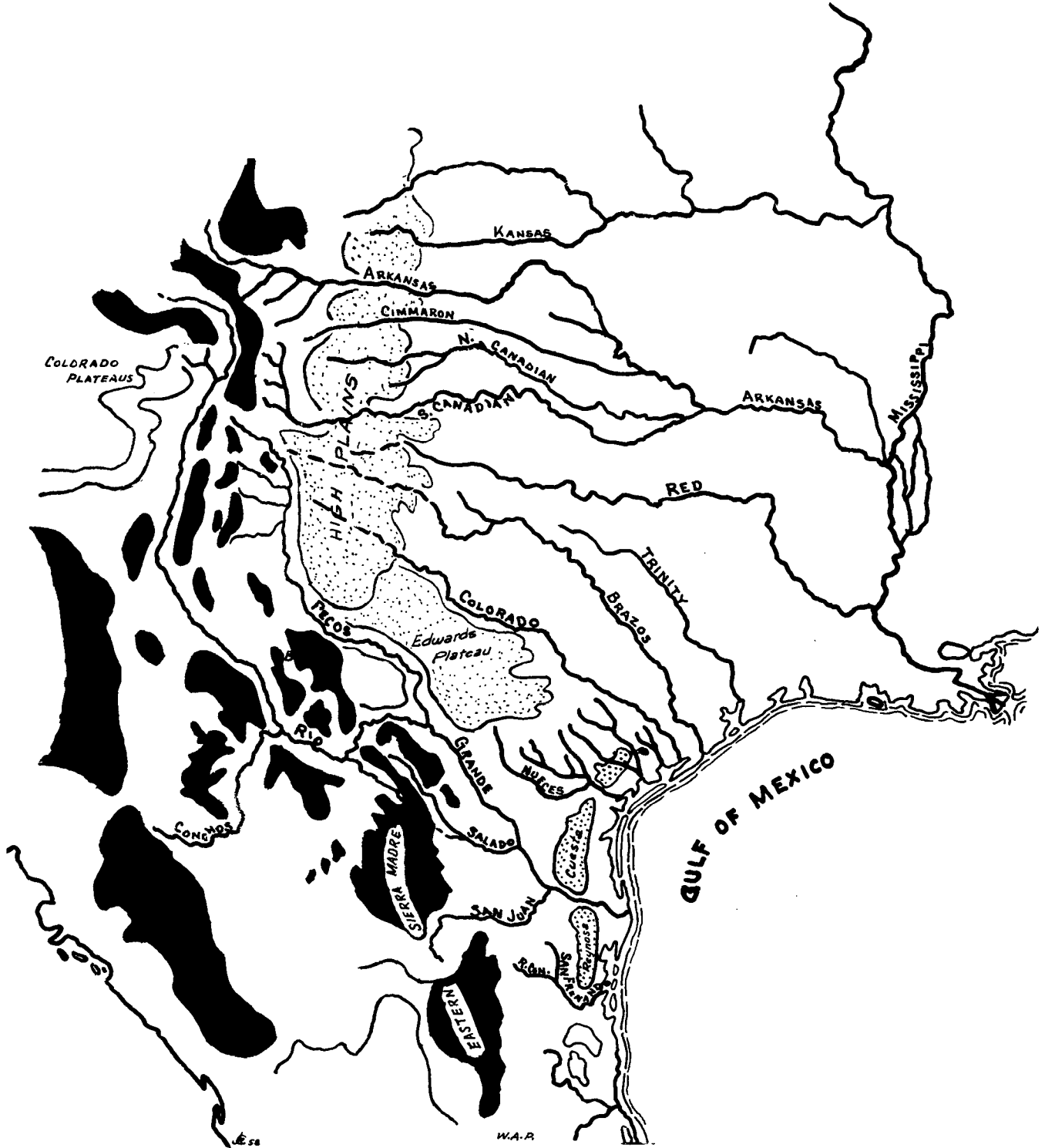


Figure 1

CLIMATIC FACTOR IN DEVELOPMENT OF RIO GRANDE-PECOS RIVER SYSTEM

Mountains (solid black) are rain-condensers, plains dry. Plateaus (stippled) represent initial surfaces of drainage cycle. Broken lines show underfit, beheaded valleys of Brazos and Colorado rivers on Llano Estacado section of High Plains.

clonic Gulf storms gave the southern rivers some advantage.

As an example of down-stream renewal of flow in the Rio Grande from incoming mountain front streams, its waters dwindle by evaporation and the lowering of the wa-

ter table through the desert valleys of New Mexico and the Big Bend country, becoming mineralized. But, the San Juan River of the Monterrey region brings in a new supply, providing the main source for the delta and freshening the

Rio Grande water. The Falcon dam is located to receive and regulate the flow of the San Juan at the Rio Grande.

PLEISTOCENE VERTEBRATE FAUNA IN POND BEDS OF INGLESIDE BARRIER CHAIN
Surface Features of the Barrier

The writer discussed this Pleistocene barrier in 1933, and assigned different names to different segments of it and the associated lagoon. It is, however, simpler to apply the name Ingleside to the entire barrier and lagoon strand terrace.

Northeast of the junction of Copano and Aransas bays (Pl. 3, Field Trip 1958) the barrier is a beach plain at least as far as the Neches River. The individual parallel beach ridges are separated by shallow marshy and pond-dotted swales. Some of the ponds have been slightly enlarged to the northwest, cutting through a beach ridge. Some are rounded but many are oval.

Southeast of the Copano-Aransas bay junction, the Ingleside barrier is surfaced by stabilized eolian sand, the dune forms being much downweathered and probably indefinite as to type. This section is scored by elongated parallel

NW-SE pond swales, eroded into the eolian plain by the on-shore winds.

Pond Fillings

The elongated pond swales of the eolian plain of the barrier have black lake deposits in their shallower parts. Some of these ponds and some of those of the beach plain to the northeast are known to have fillings of marly sand with, in some cases, a shallow-lying bed of nearly pure marl. The observed pond fillings are mostly only about 10 to 12 feet thick. At least two of these ponds have yielded bones of the horse-elephant fauna of the Pleistocene.

The marl beds have become lithified where they are exposed or have internal drainage. One of the cemented marls—at the Harbor City locality east of Ingleside and south of the town of Aransas Pass—has a well developed mud crack pattern on its upper surface.

Vertebrate Fossil Collections from Barrier

The writer and L. C. Benedict of Corpus Christi obtained a molar of *Mastodon americanus* and a collection of pea-sized gravel believed to have been gastroliths (stomach stones) of grain eating birds from a marly pond filling in the low bluff of

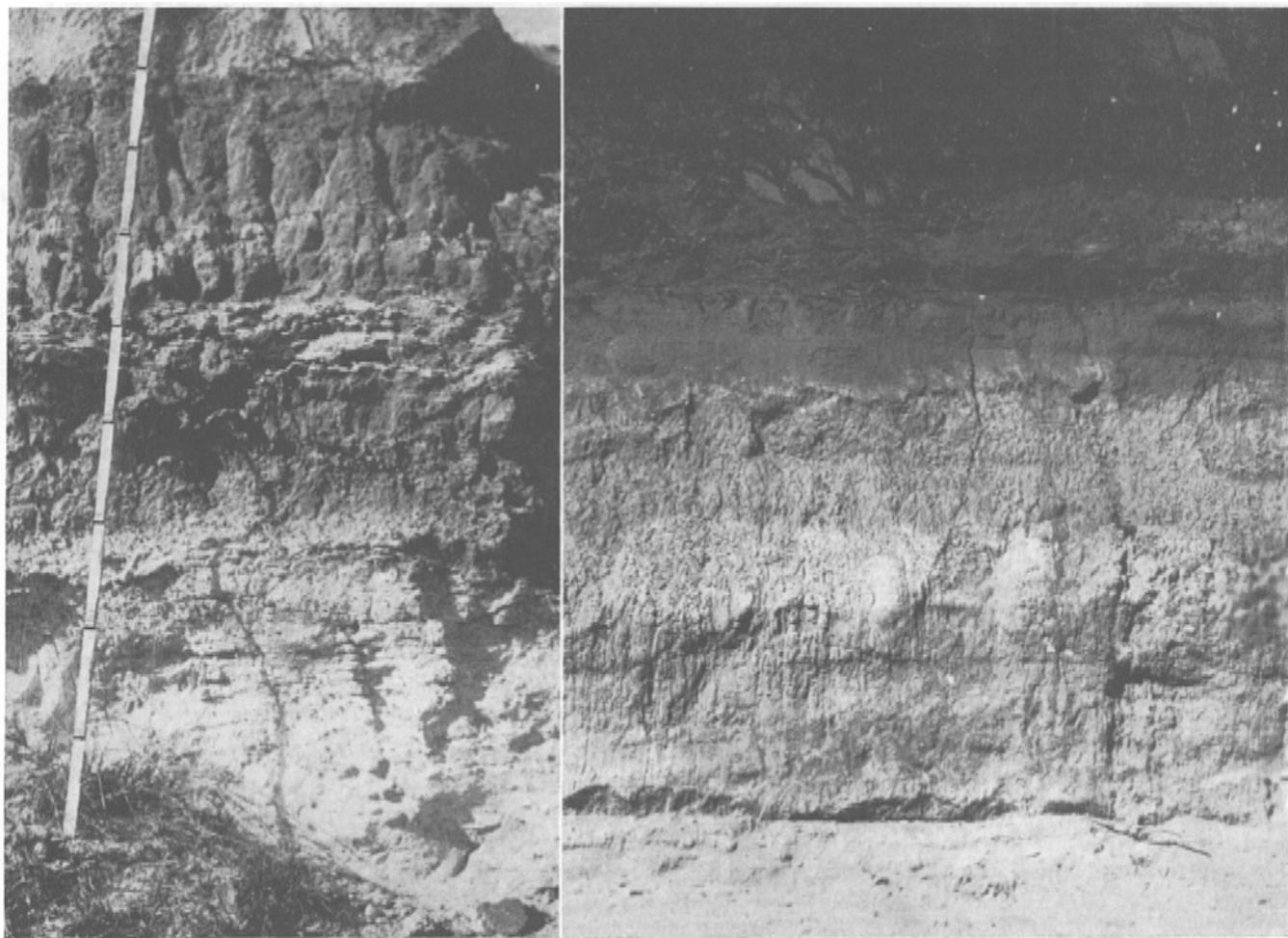


Fig. 2. Pond deposit, Ingleside barrier chain, Nueces Bay bluff, Flour Bluff. Price, photo. 1940. Weathered face, east end of pond deposit, undisturbed by roots. Sand below, strongly marly. Sand above, with 2 zones of thin marl forming "crusts." Upper dark sand has prismatic soil structure. Lagoonal clay concealed at base. See Table III.

Fig. 3. Pond deposit, Ingleside barrier chain, Tedford quarry, north wall, west center. See Table II. Marly sand at base to 4.5 feet above lowest foot-marker. Marl, 4.5 to 7.0. Dark brown soil above to 9 ft with spoil material above. Price, photo.

Corpus Christi Bay. The deposit, Table I, formerly lay near the center of the north shore of Flour Bluff at the present location of the Corpus Christi Naval Air Station (fig. 2). There were fragments of bones of birds, wolves and other mammals. The site has been graded and a seawall built along the outcrop of the pond filling, so that the deposit is no longer exposed.

Two thin zones of purer marl formed projecting "crusts." Traced west in the deposit, these were reworked into "caliche" stalactites, or root-channel cylinders, and into large quadratic masses measuring about 1.5 feet on each edge. The reworking of the caliche was plainly accomplished by plant roots and water following root channels.

TABLE I—SECTION OF POND DEPOSITS AT FLOUR BLUFF Nueces County, Texas

(Lower 5.5 feet from augur hole)			
	FEET		
	Beds	Depth, Base	Elevation Base of Bed MSL
	Thickness		
Dune sand, 15 to 20 feet. Dunes back from bluff.	0.0	14.0
Sandy soil, dark brown, prismatic, Land snails. Soil lime begins 0.5 ft. below top, disseminated and as "caliche stalactites" in root channels. Root channels also contain organic soil materials and charcoal.	4.8	4.8	9.2
Sand, yellow, marly; abundant tiny fresh water mollusca. Bog manganese, quartz gastrolith pebbles, vertebrate bone fragments. Tooth of <i>Mastodon Americanus</i> . Turkey bones. Other bone fragments.	9.2	14.0	0.0
Clay streaks, plastic, bright green in sand.	1.6	15.6	-1.6

Winter fresh water level in beach at 1 foot above sea in augur hole. High wet weather fresh watertable at top of soil under dunes. Caliche "stalactites" in zone of watertable fluctuation.

The Bureau of Economic Geology of the University of Texas under E. H. Sellards (1940b), with a Works Projects Administration grant, collected over 2,000 specimens of Pleistocene vertebrate bones from the Tedford Quarry. G. L. Evans and A. H. Witte were engaged in the work. Besides the bones, there were pond mollusca with some underlying lagoonal foraminifera and beach shell species. The pit was a road material quarry in a pond deposit on the eastern edge of the town of Ingleside (Sellards 1940b; Field Trip 1958, pl. 8, locality x). The excavation is now a pond at a private residence.

The northwestern portion of the pond deposit, west of a N-S road, has not been excavated. The collection is in Austin, specimens having been mounted for display in the Texas Memorial Museum. A single flint javelin point was taken from one of the trucks that came from the pit, but as the truck had previously been hauling gravel elsewhere, the flint point was not known to have come from the pit, or if so, to have been buried. The addition of Pleistocene man to the fauna is, therefore, not warranted here.

A section of the deposits in the quarry (Fig. 3) is given in Table II and the published incomplete list of genera and species is given in Table III.

TABLE II—SECTION IN TEDFORD QUARRY, INGLESIDE, TEXAS, IN CENTER OF PLEISTOCENE BARRIER CHAIN

A Characteristic Section of North Wall, West Center, of Pit, East Half of Pond-Basin Filling (Measurements in Feet) Elevations from mean Sealevel (MSL)

Surface & Bed No.	Description of Beds	Thickness of Bed	Depth of Base	Elev. of Base MSL
a	Ground surface at 50 ft. N. of pit wall.	19.75
b	Glade surface before excavation.	16.00
1	Soil, sandy, dark brown, prismatic, from dune sand. Land snails throughout (<i>Bulimulus</i> , <i>Helicina</i>).	3.0	3.0	14.25
POND DEPOSITS, INGLESIDE (To Post-Ingleside?)				
2	Sand, yellowish, fine; calcareous nodules where exposed. Bones; a few pea-sized quartz pebble gastroliths. Base of elephant bone at 13.75 msl. Pond shells near base (<i>Gyraulus Helisoma</i> , <i>Physia</i>) with land snails.	1.75	4.75	12.50
3	Marl, sandy, friable, structureless, cemented in places, especially on exposure. Pond shells 1 ft. below top. Bones.	1.50	6.25	11.00
4	Sand, marly, yellowish; bog manganese nodules and aggregates; pond shells; a few pea-sized gastroliths; bones. A few lenses of white sand. Base of pond deposit.	6.00	12.25	5.00
LAGOONAL CLAY, INGLESIDE				
5	Clay, plastic, marly, greenish, with some sand. Foraminifera. Marine mollusca: <i>Chione</i> , <i>Arca</i> , <i>Donax</i> . Some bones in upper part.	7.00	19.25	-2.00

TABLE III—FAUNA OF TEDFORD QUARRY, INGLESIDE BARRIER CHAIN, INGLESIDE, SAN PATRICIO COUNTY, TEXAS

Lists from sources shown. Complete listing not yet published.

SELLARDS (1940b)	Common names
<i>Parelephas columbi</i>	Columbian elephant
<i>Mastodon americanus</i>	Mastodon
<i>Equus complicatus</i>	Ass, extinct
(<i>Onager</i> c. of Quinn 1957)	
(<i>Onager fraternus</i> of Quinn)	
<i>Camelops</i> sp.	Large camel
<i>Tanupolama</i>	Small camel
<i>Bison antiquus</i>	Large extinct bison (modern bison is absent)
<i>Odocoileus virginianus</i> *	American deer
<i>Aenocyon ayersi</i>	Wolf
M <i>Holmesina septentrionalis</i>	Armadillo
M <i>Glyptodon petaliferus</i>	Armadillo, giant form
M <i>Mylodon harlani</i>	Sloth
<i>Sylvilagus</i> sp.**	Pigmy swamp rabbit or cottontail
* Living.	M, warm, moist habitat
** Not known to be extinct.	D, considerably drier habitat
STOVALL & McANULTY (1950)	
D <i>Cervus</i>	Elk, old-world deer
D <i>Capromeryx</i>	Antelope
<i>Canis</i>	Dog, coyote or wolf
<i>Smilodon</i>	Sabre-toothed tiger
<i>Felis</i>	Cat
<i>Ursus</i>	Bear
D <i>Cynomys</i>	Prairie-dog
<i>Geomys</i>	Pocket gopher
D <i>Lepus</i>	Hare, jackrabbit
<i>Reithodontomys</i>	Harvest mouse
M <i>Mylodon</i>	Sloth
M <i>Nothotherium</i>	Ground sloth
M <i>Dasyus</i>	Armadillo
M <i>Boreostracon</i>	Glyptodont, giant armadillo
M <i>Testudo</i>	Tortoise (land turtle)
<i>Cistudo</i>	Box turtle
<i>Trionyx</i>	Soft-shelled turtle
M <i>Amphisbina</i>	Lizard, limbless
M <i>Alligator</i>	Alligator
<i>Lepisosteus</i>	Gar fish
<i>Amiurus</i>	Cat fish

The following tentative identifications were made in the field by A. H. Witte, collector for Sellards and Evans. It is possible that some of these tentative identifications were not confirmed, and that some are listed above.

Tapir	Beach shells, including those identified by H. G. Richards, were recorded in Price's field notes as being only in the lagoonal clay below the pond beds. They were collected from the upper 2 or 3 feet of that clay. As these notes were discussed in 1939 with Sellards and Evans, it is likely that all of the large marine shells were from below the pond beds.
Peccary	
Snakes	
Birds, several species	
Dire wolf (giant)	
Horse, a very large form	
Turtle, (a large marine form, very abundant)	
Hackberry seeds	

LIST OF INVERTEBRATES, TEDFORD QUARRY Pond Deposit

(Reported by H. G. Richards from preliminary studies)

Gyraulus parvus Say. Freshwater shell of wide distribution.

Helisoma trivolvis Say. As above.

Physia integra Haldeman. Freshwater species, Texas today.

Bulimulus dealbatus Say. Land gastropod; common in Texas.

Helicina orbiculata tropica 'Jan' Pfeiffer. As above.

The Underlying Marine Layer—Upper 2 or 3 Feet*

Chione cancellata Say.

Arca transversa Say.

Arca ponderosa

Donax tumidus Philippi.

* Previously reported from the Pleistocene of Texas (Richards 1939).

Environment of the Pond Fauna

The calcareous nature of the sediments and the occurrence of a fairly pure marl bed suggest that algae were present in the water at times. The algae would have provided basic food for a minor cycle of aquatic life in the pond, represented by the fish and turtles. The large accumulation of vertebrates, in the presence of the predators, indicates a typical waterhole situation, water having been the chief thing that brought most of them together, with vegetation also a factor. Jackrabbits and pocket gophers that did not drink water, would have been present because of the vegetation.

Clarence Cottam, biologist formerly with the U. S. Fish and Wildlife Service and now director of the Rob and Bessie Welder Wildlife Foundation, Sinton, Texas, says that the modern representatives of the forms marked M, in Table II, live chiefly in moist, tropical areas where there is some forest nearby. Those marked D, are related chiefly to forms of somewhat drier areas. He says also that nearly all the forms present live in fresh water areas.

Dr. Cottam agrees with the writer that these relationships depict the barrier much as it is today, in a subhumid to semiarid climate with forest, glade and prairie and with dry plains nearby. Barrier chains, because of the high porosity of their sands and because they have a slight elevation above sea, accumulate large supplies of fresh ground water. The salty water of the beach does not mix with that of the barrier back of the beach because of the difference in density, the fresh water riding on any salt water present. Hence, with a climate as described, the vegetation of a barrier back of the foredune is not zerophytic. The ponds probably filled rapidly with sediment. They seem to be too small and shallow to have remained open long enough for a change in climate to have produced a change in the fauna.

The fauna of the Padre Island section of the modern barrier of Texas before 1870 (Price and G. Gunter 1943, p. 144) conspicuously contained cottontail rabbits and spotted skunks. After 1880, the rabbits and skunks largely disap-

peared and coyotes and jackrabbits have become conspicuous.

Because the Ingleside bone locality is at the northern margin of the present semiarid climate, and because the barrier has a cover of eolian sand, it seems unlikely that these shallow ponds remained open long. There seems to be nothing in the environmental make-up of the vertebrate fauna that would require a change of climate during the period of their entombment. The Ingleside locality is at the point where the barrier was in contact with the delta of Nueces River, permitting free access to the barrier. The river and its valley—shallow in interglacial periods and deeply entrenched in glacial periods—provided another area of forest and brush and abundant water nearby.

Stomach Stones in Pond Deposit

Gravel is swallowed by grain eating birds to chew their food. Cottam reports that gravel is retained in some way by the birds for long periods where gravel is scarce. Ducks migrate for great distances and wild turkeys, present in the pond deposit at Flour Bluff, may range from 10 to 50 miles, though usually not more than a few miles in a day.

The gravel-bearing Lissie formation now has numerous exposures within 50 miles and other gravel-bearing strata occur along the Reynosa Scarp, not over 75 miles from the coast. Gravel bars would have been present in the river valley at and not far down stream from the outcrops of the gravel-bearing formations. Such bars are now only 25 miles inland from Ingleside. The gravel-bearing strata would outcrop much nearer the coast in the entrenched glacial-time valleys than in the alluviated interglacial valleys. The birds could then have obtained the gravel when the valleys were shallow or when they were deep.

The gravel in the pond deposits is not stratified or sorted and its range of coarseness is small, being about that of the stomach stones of the turkeys. The gravel is pea-sized to a little larger. The gravel occurred in small aggregations usually not dispersed through more than about a double handfull of sand each. About 80 percent of the gravel was shiny and likely to attract the eye. The barrier sands do not otherwise contain gravel, there being only shell fragments in the range between the flour-fine beach sand and the relatively rare cobbly fragments of beach rock and indurated Pleistocene sandstones. The latter are, at times, strewn on the beaches by heavy storms that cause a retreat of the offshore bottom profile.

Worn Shells in Pond Deposit

Quinn (1957a, 1957b) attempting to reconstruct the environment of the Ingleside pit from the notes and rather inadequate literature available when he wrote, thought of the worn beach shells as having been washed into the pond from the beach. However, the writer's notes show that these shells were in the upper part of the lagoonal clays below the pond deposits. As the fossil collections by the W. P. A. party were obtained in part from disturbed (loose) material, specimens of beach shells might have been mixed with bone-bearing materials by the grader. The writer saw no beach shells in the pond deposits.

The foraminifera also were from the greenish clayey sand just below the pond deposits, recording a retreat of the upper part of the barrier over some of its lagoon sediments. This is a characteristic relationship along the inner borders of barrier chains (Field Trip 1958, pl. 4).

The beach-shell and foraminiferal faunas of the Texas Pleistocene have not been zoned by age and no correlation

can be made by them within the Pleistocene, as Quinn implies.

Quinn considers his Ingleside horse species to indicate Sangamon or "Third" Interglacial age. Because the later Pleistocene formations are downwarped here and their faunas are unknown, such age assignments must as yet be considered tentative.

ORIGIN OF CALICHE AND CALICHE CAP ROCKS Three Modes of Caliche Formation

After half a century of the study of caliche by geologists in the Gulf Coast,* it seems that 3 separate and distinct methods may be established, with intergradations. The types are (1) soil carbonate caliche, (2) outcrop induration caliche and (3) the caprock caliche type developed on plateau and cuesta surfaces forming contemporaneously with accumulating calcareous loess in a dry climate.

Soil Carbonate

The accumulation of soil carbonates in the zone of clay-accumulation (B zone) and in the upper part of the weathering parent materials (C zone) is well known, but does not now seem to lead to the formation of thick marls of caprock type from normal soils. A soft marly clay or sand with disseminated carbonate nodules, the latter developing from exposure or soil desiccation, is the characteristic type of accumulation in soils that are not initially highly calcareous. Such soil carbonates are found generally in the clayey, and some sandy, surface materials in the dry climates where they are not too rapidly eroded.

"Case Hardening" and Outcrop Induration

A second common type of surficial or shallow-lying carbonate accumulation in the form of caliche is the surface induration or "case hardening" of highly calcareous materials. This takes place by solution from rain or dew and redeposition under evaporation. The process can be observed in an initial stage on the surface of calcareous shales which are being eroded, as for example, along hillside exposures of fossiliferous Cretaceous or Eocene shales which become slick after each rain, but where the thin layer of redeposited calcite does not have time to accumulate to form a permanent crust before it is eroded. Similarly, caliche placed on a roadbed that is being traveled and wetted will acquire a slick surface which, on exposure, develops a thin, impermanent crust. Case hardening is, however, responsible for the fine lamination of the exposed older surfaces of caprock caliche.

An outcrop surface or "wall" of lithified caliche a foot or more thick develops from the exposure of a bedded marl on steep slopes. An example is seen at the marly clay dune on the northwestern side of the playa terrace 3 miles south of Armstrong, Kenedy County (Stop IV, second day, Field Trip 1958, p. 12, pl. 15). The marl presents a lithified surface ("wall") but is still soft a foot back under cover. This lake marl is not conspicuously laminated in its indurations.

Lissie marls outcropping between Refugio and Kleberg counties have developed Reynosa-like "walls" and "reefs" of caliche. For example, the west bank of Blanco Creek on the Goliad highway 3 miles west of Refugio, has a heavily indurated Reynosa-like caliche outcrop wall in a curve of the creek at the bridge. Nearby, to the south, the marl is soft where it has been undercut by the creek and the indurated surface removed. The same marl in a friable, unindurated condition, is seen in the blowout craters at the

northern end of the Refugio field on the Goliad highway.

A long outcrop "reef" of Reynosa-like caliche occurred about 2 miles east of the Kingsville-to-Sarita highway west of Ricardo, Kleberg County (Stop 1, second day, Field Trip 1958, p. 10, pl. 10). The dense caliche has now been quarried out and the bedded shaly marl is exposed. This caliche had the internal brecciation, recementation, rebrecciation and eventual pisolitic structure once described as of "algal reef" origin (Price, Elias and Frye 1946). The marl of this horizon outcrops on Escondido Creek along the highway just south of Kingsville. Its outcrop has many small caliche nodules.

An exposure of the calichified Lissie marl on a northward flowing branch of Olmos Creek on the McGill Ranch a few miles west of Sarita has a lens of porcellaneous caliche about 15 feet thick which is heavily impregnated on fracture surfaces by black manganese oxide or wad. This lens suggests lake marl origin. It contains vertebrate bones including horse teeth. The bones are so heavily incrustated that most are unrecognizable.

Loessic Cap Rock Caliche of Quaternary Desert Margins

The loessic caprock type of caliche is the most widely known. Its origin as a contemporaneous calichification of accumulating loess was first proposed in America by C. N. Brown (1956). The map of the eolian deposits of the United States (U. S. Eolian Map 1952) shows that a broad band of loess accumulated on the Great Plains south of South Dakota, and on the High Plains and Llano Estacado. The loess is a sandy, calcareous windblown silt or clay which develops loamy soils. Under the loess, in the warm-to-hot dry climatic regions from northern Oklahoma to Mexico, there slowly develops a bed of caprock caliche commonly about 10 feet thick, but thicker under shallow playa lake beds and toward shallow creek valleys. Along the eastern side of the High Plains and Llano Estacado, there are several of these caliches in the Ogallala section, but only the upper one or its upper part seems to be indurated to rock hardness. The caliche caprock lies to the east of the desert areas of the Pecos River depression and the retreating scarp of the Llano and Southern High Plains.

Similar caprock caliches, the hammadás, occur in an identical relation to great desert areas along the northern border of the Sahara Desert and on the borders of deserts of Asia and South America.

On the Llano Estacado, the west winds have been dominant at various times during the Quaternary, as has been shown by Melton's (1940) study of the trends of stabilized dunes of the Llano and the writer's study of the orientation of playa lake basins (Price 1944). There is an eastward to northward gradient of increasing fineness in the windblown mantle on the caprock of the Llano Estacado from its southwestern portion (Fig. 4). The Ogallala sandstone of the plateau contributed coarse sand to the loess.

The Pleistocene mantle has been stripped from the caprock in Lea County, New Mexico, and has accumulated as a reddish sand along the Texas state line at the east side of Lea County. From there, the mantle becomes progressively finer to the east, and north. Along the longitude of Midland, Lubbock and Amarillo, the mantle is fine grained and marly (Fig. 4 and U. S. Eolian Map, 1952). Here, in many places, the caprock lies under as much as 50 to 75 feet of loessic cover.

* Probably Pleistocene in upper part.

*Beginning with A. Deussen's field work before 1914 (Deussen 1924).

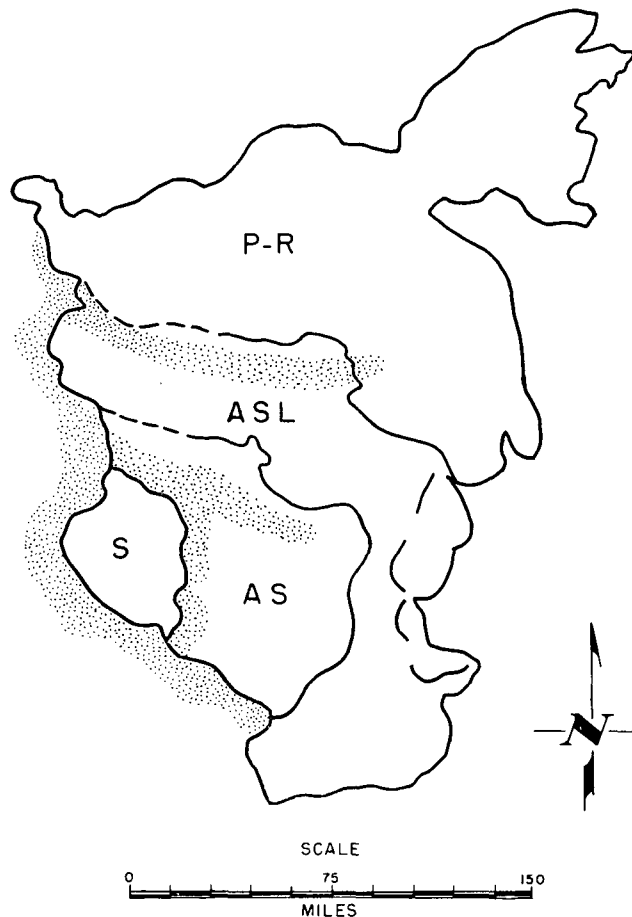


Fig. 4. Sandy and loessic soils of Pleistocene mantle on Ogallala caprock caliche, Llano Estacado. S, stripped eolian plain or scabland, with caprock exposed, Lovington area, New Mexico. Stippled areas, sand dunes, partly stabilized, reddish (Mescalero and Judkins sands). AS, Amarillo sand soil group. ASL, Amarillo sandy loam group. P-R, Pullman-Richfield clay loam group. Soils after W. T. Carter (1930) and Harper and Smith (1932), some boundaries inferred in New Mexico, see U. S. Eolian Map (1952).

The testimony of the cap rock caliches of the desert margins indicates that desert conditions have existed, with some periods of less aridity, since the initial entrenchment by Pleistocene drainage of the Pliocene alluvial aprons of the flanks of such mountain systems as the southern Rockies, the Eastern Sierra Madre of Mexico, and some of the mountains of the Sahara desert.

Reynosa Caliche as a Loessic Cap Rock

The writer suggests that the Reynosa caprock caliche of the Goliad formation is a member of this worldwide desert-margin caprock series, and that offshore winds brought the loess to the top of the Reynosa scarp as this escarpment retreated under post-Pliocene erosion.

The former soil-carbonate hypothesis (Price 1933a, Weeks 1933) of caprock origin and the lacustrine origin (Trowbridge 1923, 1932) are placed in subordinate positions under the loess theory. The basic process emphasized under the 1933 hypotheses of solution by rain, dew and other surface waters with redeposition during evaporation is applicable also to the development of caliche from accumulating

calcareous loess. The original Blake (1902) hypothesis the calcium carbonate being derived from uprising deep seated groundwater has long since been proved untenable as there is no widespread source of shallow waters on the plains involved.*

The Blake hypothesis probably originated in linking capillary soil moisture of the internal dew type, seen in the upper parts of sand dunes and in some soils, with a deep seated source. Such a linkage is erroneous.

Field studies in the Rio Grande delta region—the Reynosa cuesta—and its sheet of eolian materials have not been carried out to test the hypothesis that the material was derived from the west. In general, relatively undisturbed sands in the western part of the Reynosa cuesta are reddish, like those at the west on the Llano Estacado. Some soils on the eolian sheet to the east, as in southeastern Fidalgo County and adjacent parts of Cameron County, may have developed from a considerably finer grained and less oxidized material than the western red sands. There seems to be no data in hand opposing a gradient from coarse to fine in an easterly direction in the delta area. The presence of a delta complicates the situation.

QUATERNARY DELTAIC PLAINS OF RIO GRANDE DELTA

Figure 5, shows a tentative mapping of the Rio Grande delta in Texas. Doering (1956) has a somewhat different arrangement. Trowbridge's (1923, 1932) mapping is still different. Figure 5R shows the recent delta and floodplain which are fully exposed. The floodplain has a branch valley from Mercedes to Raymondville now graded with floodplain deposits and containing the prominent Llano Grande distributary.

The Eunice delta surface is mostly exposed, but has no eolian cover. It has well developed distributaries, with series east of Rio Hondo having meanders with unusual large loops and a wide channel. This delta slopes about 4 feet per mile.

Surfaces O and L (fig. 5) are plains that slope about 4 and 4 feet per mile, respectively. They may represent the Oberlin and Lissie plains, although their eolian mantle prevents their being mapped with confidence.

West and north of plain L, the caliche-and-eolian surface shown as "Pre-L" has not been mapped in detail.

The Mercedes-Raymondville floodplain probably does not lie in an entrenched valley, but many have been a short-lived distributary formed when an independent consequent delta stream like the Arroyo Colorado captured the river for a time.

ERG (EOLIAN SAND SHEET) OF RIO GRANDE DELTA AREA

The Sheet, Erg or Matle

The usual mapping of this sand sheet (Field Trip 195 pl. 1) follows Loughridge (1884) who outlined approximately the looser, non-arable part of an extensive erg that stretches in Texas from the drainage of Baffin Bay to the Rio Grande (fig. 6) and from there to the southern border.

*Traced to its original source, this hypothesis was a development of land-sales promotion in the "dry farming" areas of the West in the latter part of the last century at the first part of this. It was written into geological literature at a convention as a committee assignment by a mining engineer whose published correspondence repudiates any specialized knowledge of caliche.

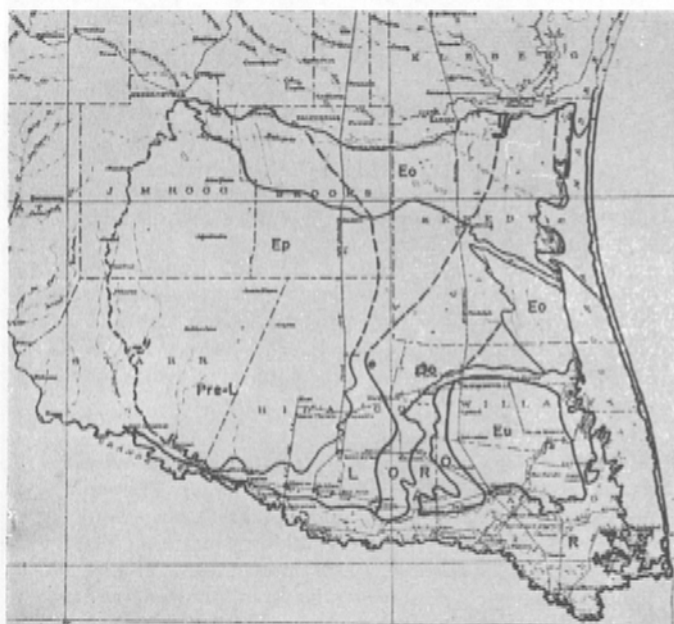


Fig. 5. Quaternary formation plains of Rio Grande delta in Texas. Tentative identification of plains older than Eunice. R, Recent delta and floodplain with northward Mercedes-Raymondville branch. O, Oberlin delta bisected by the branch floodplain. L, Lissie. Pre-L, plain of caliche caprock with eolian sand cover, not differentiated. Ep, baselevelled eolian plain covering, in part, the Pre-L formations. Eo, eolian sand, lightly stabilized and with bare dune fields here and there. Broken line at west, Borda or Reynosa scarp. Central Mud Flats of Laguna Madre lies east of Eo in central and northern Kenedy County.



Fig. 6. Erg (eolian sand sheet) of Rio Grande delta area. A, B, Fs, S, Armstrong, Bruni, Falfurrias and Starr base-levelled eolian plains (Starr not mapped in detail except in small isolated eastern area). En, N, Sa, lightly stabilized sand lobes with banner-complex pattern and fields. E, Edinburg stabilized longitudinal dune field cut across by Mercedes-Raymondville abandoned valley floodplain. F, Faysville train of stabilized banners. H, R, Hargill and Rachal fields of stabilized conical dunes. K, scattered stabilized dunes (conical?) in Kleberg County. M, Mogotes area of stabilized sand west of Reynosa scarp and below level of erg. T, T, remnants of river terraces (Eunice?) with 10 feet of eolian sand covering the alluvium.

of the delta in Mexico. It has not been mapped in detail in Mexico (Geologic Map, XX Int. Geol. Congr. 1956). The U. S. Eolian Map (1952) omits only the Edinburg longitudinal dune field lobe (E, fig. 6).

The erg lies on and mostly covers the Reynosa caprock caliche of the Pliocene Goliad formation. It also covers the Pleistocene delta plains (fig. 5) with the exception of the Eunice and Recent deltas, although there are some dunes on the Eunice.

An erg is a term applied to any isolated region covered largely or entirely by eolian sand with dune fields. In the Sahara, where the term originated, it is commonly applied to much larger sheets.

The Rio Grande delta erg is roughly triangular in shape. It extends about 96 miles from Punta Peñascal, at the mouth of Baffin Bay, to Oilton (Torrecillas), and 175 miles from Oilton to the southern end of the delta. The erg covers most of the Reynosa cuesta, the higher part of the depositional plains of Doering's (1935) analysis of the division of the coastal plain into an interior erosional plain and a coastward depositional plain.

Origin of the Sand of the Erg

The erg is believed to represent the sand and sandy loessic accumulation from which the Reynosa cap rock was developed with later loess and probably with various additions of eolian sand. The loess that blew up the Reynosa scarp was very sandy because of the outcrop along the scarp of the Oakville sandstone and the Catahoula ash. An

addition of sand from the Ingleside barrier at the north-eastern margin of the erg was added to the sheet and it is possible that it has received other accessions of sand from other vanished barrier chains. The present (modern) barrier is joined to the land by the Recent delta at the south and separated from land by the Laguna Madre north of it.

Before the long drought of 1950-56, sand from the barrier had reached the mainland of Laguna Madre only in small amounts, so far as there is any direct evidence. This conclusion rests on (1) the protective beach ridges of northern Kenedy County (potrero ridges) and (2) the 10 feet or more of clay filling of the western part of the Central Mud Flats which seems to represent a century and a half of filling. This fill had only one thin tongue of sand derived from the barrier. For sand to be blown inland in quantity from a lagoon shore, the shore must have a well-developed sandy beach, a feature that is foreign to coastal lagoons in general and to the coastal lagoon of Texas, the wave action on that shore being too light to develop a longshore sediment drift capable of carrying large amounts of sand.

The Central Mud Flats of Laguna Madre shows a drowning of sand dune topography of the mainland by the invading clay sheet from the lagoon (plate I, figs. 1-3). This sand dune topography seems to extend in places below sea-level within the lagoon clay. If this is true, the sand of the stabilized dunes along the lagoon shore may have been blown inland from former areas of the erg now lying offshore. The writer cannot see how any large amount of sand

could cross the protective lagoon as long as a barrier has existed on this coast. There seems to be no reason for a barrier to have been absent at any time unless the climate were arid and eolian sand filled the lagoon.

Sand may have reached the delta from entrenched valley sides during glacial times. Recession of the valley wall and dessication of upland soils by drainage at the valley wall furnish some sand to the sheet, as in the Faysville dune train (fig. 6).

If the erg is contemporaneous with that of the Llano Escacado, it is likely that its growth has alternated in place or in time, or both, with climatic changes and with the spread of deltaic fans. It is possible that sheets of eolian sand may lie along the intraformational unconformities of the Pleistocene.

Baseleveled Plain of the Erg

The Rio Grande delta erg is primarily a baseleveled eolian plain (A, B, Fs, S, fig. 6) with a flat to slightly rolling surface and with scattered areas of dunes (E, En, F, H, N, Sa, fig. 6).

The water table is the base level of eolian erosion. Here and there shallow drainage courses run into basins where they disappear through absorption and evaporation. Playa lakes abundantly dot large parts of the erg. The playa-in-playa locality (on A, fig. 6) at Armstrong, Kenedy County (Stop IV, second day, Field Trip, 1958) shows how local lowerings of the surface accompany fluctuations of the water table. Lake terraces and inactive lee dune groups result from abandonment of one level for a lower one. The baseleveled plain was called the Armstrong old dune plain by Barton (1936).

The plain is covered by grassy vegetation with a development of (zonal) loamy to sandy soil in some areas. The soils have been described for Cameron, Hidalgo and Willacy counties (Hawker and Simmons 1926, Hawker, Beck and Devereux 1925, Beck and Hendrickson 1923).

The western part of the plain in Starr and Jim Hogg counties has not been studied in detail by the writer and there are no published detailed soil maps for it. The underlying caliche caprock is exposed here and there. Red-brown sandy soils are associated with the caliche outcrops and with the numerous oval playa basins which rest on or penetrate the caprock.

Dune Fields of the Erg

The map (fig. 6) shows six distinct dune fields in each of which the sand is thicker and less stable than in the baseleveled plains and each of which is characterized by a single type of dune or dune complex (See also U. S. Eolian Map 1952). These dune fields and their dune types are listed in Table IV.

TABLE IV—DUNE FIELDS AND TYPES

Dune Type	Field	County
Banner Complex	Encino-Sarita Lobes Faysville Train	Brooks, Kenedy Hidalgo, Starr Jim Hogg.
Conical	Norias Lobe Hargill Field	Kenedy Hidalgo, Starr, Willacy.
Longitudinal Parabolic	Rachal Lobe Edinburg Areas in Tamaulipas	Brooks Cameron, Hidalgo

In an area in southwestern Kleberg County, the sand sheet seems to be thin in places and the dunes are well stabilized with rounded to oval shapes the forms of which have not been analyzed. In addition, there are fields of parabolic dunes in Mexico the outlines of which have not been mapped.

The Banner Complex

Figure 7 shows a diagram of a dune complex which may be called a banner (U. S. Eolian Map 1952). Examples are seen in pl. I, figs. 1 and 2 and the Field Trip book 1958 pl. 14. Figure 8 shows the coastal wind pattern.

The banner consists of (a) a spot blowout (fig. 4, pl. I) which develops into a triangular areal blowout and (b) a fan of bare sand widening downwind, with marginal ridges on each side of the fan diverging from the blowout a ragged terminal line or zone of shrub-coppice mounds with fingers of sand and a field of bare, migrating transverse dunes on the bare fan. In Kenedy County the apex angle is 30° to 40°, but may be less in other regions. A common length in Kenedy County is 1.4 by 0.6 mile. The central axis of the fans in Kenedy County trends from 145° W to N 55° W.

The associated forms of the banner develop at the same time under the same wind and with the same type of sand. The different forms are the result of various combination of the factors: vegetation, soil, sand supply, soil moisture and water table position. There are three types of eolian blowouts: spot, linear and areal. The spot blowout is a basin-shaped excavation which stops at the water table and may be lengthened to form a linear blowout. The linear ridges are narrow and straight and develop along the margins of the moving sand sheet where the vegetation store enough sand to form a ridge but without being itself entirely overwhelmed and killed. The angle of divergence of the ridges is that of the spread of the fan as controlled by the angular shift in the sand-moving wind and the volume of the sand supply.

Bare transverse dunes form where there is an abundant supply of sand. The bases of the dunes still rest on sand and are not limited by a resistant rocky or wet base. Thus:

*Sand held by a group or clump of plants.

PLATE I—CENTRAL MUD FLATS OF LAGUNA MADRE

Drowning of banner-complex dune-topography of erg by marine clay sheet. Sheet, 2.5 feet msl along former axis of lagoon, 5.5 feet at grassline margins.

Figs. 1, 2, 3, 5, views of flats and dune topography with grassed stepped-back eolian ridged-plain belts (potreros) along lagoonward margin of erg. Fig. 1, Mesquite Rincon islands with line of clay dunes from SE point to land at west. Fig. 2, Potrero Farias and parts of adjoining potreros. Fig. 3, Padre Island on horizon; El Toro island in far distance; potrero Lopeño at left and Calabaza at right in distance.

Fig. 4, spot blowout in Norias banner lobe.

Figs. 6-10, building of new eolian "beach" ridge against Potrero Lopeño in 1948.

Fig. 9, ridge from the air.

Fig. 10, lowest old ridge of Lopeño. Figs. 7 and 8, sand storing in growth of 2-inch cedar grass (Fig. 7) and 44-inch sunflowers (Fig. 8). Fig. 6, detail of sand accumulation of Fig. 8. Figs. 1 and 2 by Edgar Tobin Aerial Surveys; 3-10 by R. E. George and W. A. Price.

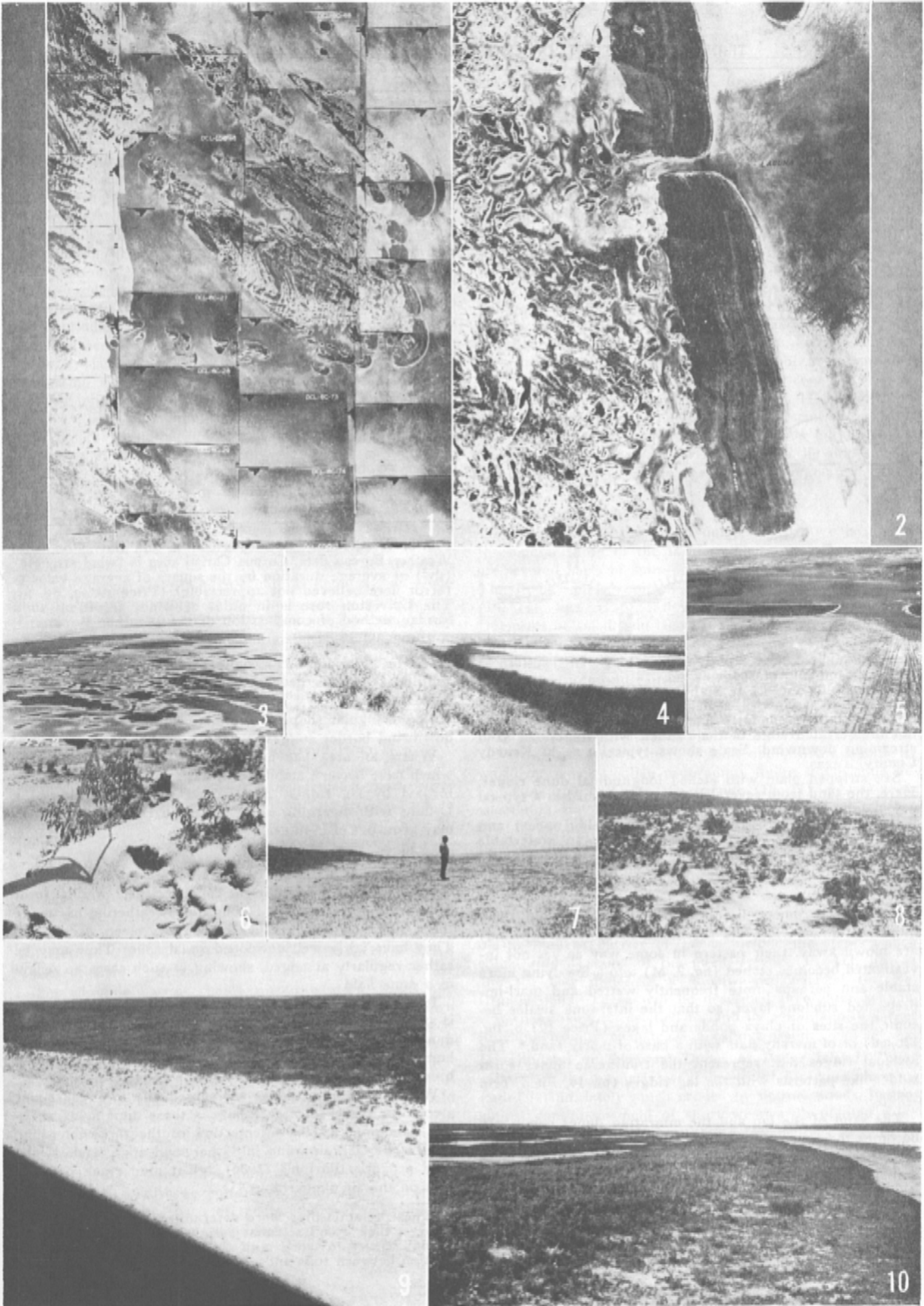


Plate I



Fig. 7. Banner dune complex, with etching of its pattern as its bare sand migrates downwind.

S, spot blowout. L, L, stabilized lag ridges enclosing a bare fan of sand with a field (D) of transverse dunes. Shrub-coppice mounds (bunch-vegetation holding sand) dot the serrated edge of the banner, with fingers of sand streaming downwind. Scale shows typical size in Kenedy County, Texas.

SP, stripped plain with etched longitudinal dune ridges. Here, the sand from several banners has joined in a typical association.

Below, profile across transverse dune field (upper) and (lower) the same, after eolian stripping to watertable (WT). Vegetation stabilizes the remnant ridges (R, R) and marl (M, M) has formed in etched swale ponds.

the transverse dunes disappear behind as the sand sheet moves on down wind. As the dunes to the rear (upwind) are blown away, their pattern in some way as yet not investigated becomes etched (fig. 7, M) into a low-lying more stable and perhaps more frequently wetted and marl-impregnated subdune layer, so that the interdune swales become the sites of playa ponds and lakes (Price 1933b, fig. 12b,c,d) or of marshy flats with a base of marly sand.* The residual ridges that represent the transverse dunes form ladder-like patterns with the lag ridges (pi. 14, Field Trip 1958).

The sand of the fan and the migrating dunes commonly becomes the source of additional blowouts, so that the fan of one banner may give rise to a new banner. Thus, a train or belt of banners moves down wind across the stabilized

*Any of the ponds of the erg may develop a bed of plastic white marl a foot or more thick. The marl is probably of algal origin, algae being the only observed probable source of marl-manufacture present.

Fig. 8. Wind roses for Corpus Christi and Galveston from Weather Bureau data. Corpus Christi rose is "wind strength (dv^2) or average duration by the square of average velocity (error here believed not appreciable) (Price 1933b, fig. 9). The Galveston rose is in miles of wind, according to former method of computation of the Weather Bureau.

sand sheet (see fig. 6, Fa3'sville Train), in the Sarita lobe additional banners develop often on the north flank of preceding one.

The triangular shape of the dune complex and its ragged downwind border suggest the term banner.

Where an area has had many banners all or most of which have become stabilized, it has a mosaic of Vs and Ws formed by lag ridges. The banner may be considered a U-dune with diverging sides. On the barrier chain banners may grow out of U-dunes.

Conical Dunes

The fields of stabilized conical to oval-conical dunes have not been analyzed in sufficient detail for their original form to have been determined. Strong downweathering has made them oval, and haystack-like, with fairly steep, even sides. They have fairly well developed zonal soils. They may be rather regularly arranged, showing in such cases an original form in a dune field.

In the central part of the Hargill conical dune field, there is an area with a band of reddish soil in the B-zone of the dunes which suggests that it was developed under a more humid climate. The red band is now being changed to brown soil more typical of the region today.*

Where the conical dunes are sub-equally arranged about a common point, as often occurs in these dune fields, there is a rain pond at the intersection of the three interdune swales and a drain runs into the pond from each swale. This produces Barton's (1936) "giant mud crack pattern" seen on the air photographs.

*These relationships were determined in 1940 by Sutton Meyers, then a soil scientist assigned by the Soil Conservation Service to work with the writer in a study of the relation between soils and geomorphic forms in the delta.

The stabilized dunes of Kleberg County can be placed in the category of conical dunes until they are studied in more detail. Some are more elongated than the Hargill dunes.

Faysville Banner Dune Train

This belt of banner dunes gives an extreme illustration of one banner or group of banners starting others down wind almost indefinitely. The Faysville train is a narrow, almost entirely stabilized belt commonly 4 to 6 miles wide, about 80 miles long and bearing N 40° W from the edge of the river valley between Mercedes and La Feria to the eroded margin of the Reynosa Scarp, near Randado.

Longitudinal Dunes on the Mainland

Longitudinal dunes are elongated with the direction of the long-period resultant of the sand-moving winds. They grow by lateral additions from the lesser winds and by elongation with the resultant.

They form with a minimum of sand on a shallow, resistant base with a minimum of vegetation. For this reason they are the commonest dunes of all large deserts (Price 1950). Other forms develop in deep sand with an abundant supply.

Recent information shows that longitudinal dunes also occur in the edges of desert areas and even in the semi-arid zones, as in the Bad Lands of southwestern South Dakota and on the Navajo Plateau in Arizona.

The Edinburg field is cut into two parts at Mercedes by the Mercedes-Raymondville natural floodway, an abandoned Recent erosional-depositional course of the Rio Grande. The longitudinal dunes of the Edinburg Field (Price 1947b, fig. 1b) are inactive and well stabilized, their soils being zonal and closely related to the type of soils on the younger parts of the Pleistocene delta which have no sandy mantle. The eolian sheet here may have been finer grained and more loessic than further west toward the Reynosa Scarp.

The ridges of the Edinburg field trend from N 37° W to N 55° W, with N 40° W being the mode. They are seldom over 10 feet high with the northeast flank lower because of the slope of the plain, along the strike of which they run in places. They reach lengths of about 5 to 10 miles.

Each of the towns along the E-W highway from Mission to La Feria is located on a longitudinal dune. The citrus orchards of the upland surface are all on stabilized dunes.

BARRIER CHAINS OF SOUTHWESTERN TEXAS

Types of Barrier Terrain

The 245-mile barrier chain of southwestern Texas and remnants of the Ingleside Pleistocene barrier are shown on figure 9. This barrier will be discussed in later pages.

The surface of a barrier chain may show any one or more of three types of terrain besides the beach: (1) a beach plain, composed of parallel, even-topped beach ridges evidencing forward gulfward growth (prograding) (Field Trip 1958, pl. 3), parts of which may be composed of eolian sand; (2) an eolian plain with dune fields, consisting of (a) the foredune (Pl. II, figs. 1-3) built along the youngest beach ridge, being more hummocky and higher than a normal more or less even-topped beach ridge, and (b) fields of bare dunes back of the foredune (Pl. II, figs. 2, 4), always subject to stabilization by plants under the less violently eolian conditions; (3) washover fans with diverg-

ing overwash channels (Pl. II, fig. 2) (Field Trip 1958, Pl. 3). The tidal delta of the transecting tidal inlets (Price 1952, figs. 1-3, Field Trip 1958, Pl. 8) has a low marshy fan in the lagoon and a convexity of the beach plain or foredune on the oceanic side.

Washovers

Washover fans are formed by marine floods that break through or over either a dune field or a beach plain (Price 1947a, pp. 1653-1654, fig. 4a; plate 3, Field Trip 1958). Because a marine flood raises the level of the inner waters, there is a reverse flow across the barrier as the flood subsides in the gulf. Hence, the pattern of the washover fan becomes doubly streamlined and complex. There are usually cross-channels connecting the radial ones.

Washarounds

Residual areas of beach plain or stabilized eolian plain left between the channels of the washovers or between adjacent washover fans (Pl. II, fig. 4; Pl. III, fig. 6) may be called *washarounds*. These at times resemble vegetated islands in a sea of sand. The washarounds may even acquire encircling low beach ridges formed by flood or by windblown sand stored in the marginal vegetation of the "island."

Captive Flying-Spit Islands

Very similar to the washarounds are captive islands of the lagoon shore of the barrier. The commonest of these are severed parts of spits—called flying "bars" by Johnson. The flying spits become encircled by small beach ridges (Pl. III, figs. 1, 4). They commonly contain abundant fragments of small, thin lagoonal shells, and also organic flotsam—trash—from the marshes and shoreline plains. The combination of the porous ridge, the calcareous sediments and the organic admixture usually produces a rank growth of vegetation on each of the encircling small beach ridges. Bird Islands in Laguna Madre at 27° 30' off the Kleberg County shoreline are flying spit islands (Pl. III, fig. 1).

As the lagoonward shore is built out into the lagoon by washover fans or eolian prograding, flying spit islands become incorporated into the barrier (Pl. III, fig. 4) their vegetation and beach ridge encirclement making them distinct from the adjacent terrain unless fan growth or retreat of the gulf shore of the barrier toward the mainland occurs so that captured islands and washarounds approach each other.

Other Types of Captive Islands

Other captive island types of the Padre Island section of the modern barrier of Texas include the stepped-back eolian ridged plains of the gavilan type (Pl. III, fig. 3) and the clay dunes of a downwarped part of the Rio Grande delta. These will be described in a later section.

A rocky islet or reef tied to land by a tombolo or larger foreland, usually cusped, is a captive island.

Longitudinal or Diagonal Dunes of Padre Island, Texas

Back of the formerly well developed foredune chain of Padre Island, lately much eroded by marine floods, lies an almost continuous field of short westwardly-pointed dune ridges that trend E-W or within a few degrees to N or S. Each of these dunes originates as an asymmetrical barchan and grows to a rather uniform length of 0.75 mile. They are bluntly rounded at the gulfward end, which has a stubby NE horn (Pl. II, figs. 2, 4). Slip faces occur on the north slope in summer and may have a lesser development on the south side in winter droughts.

The initial small sand accumulation for one of these dunes is a symmetrical barchan which, in a few hours or days becomes asymmetrical. It seems that successive small barchans migrate to the initial one and lose their form, their sands being added to the initial one.

No other dune form is definitely known on either Padre or Mustang island except the foredunes, these pointed dunes and the banner complex.

In the better stabilized areas of Mustang Island and the northern end of Padre Island (the two now joined), shallow blowouts along the foredune develop banner complexes, each with a field of bare dunes on the fan. Close study is necessary to determine the trend of the fans and the type of the bare dunes. The fans seem to trend dominantly NW and the dunes on it to be diagonal to the long-period resultant sand-moving wind of the mainland. There is, however, some doubt as to the resultant of the dune making winds of the barrier having the same trend as that on the mainland. A diagonal type of dune has lately been described by Cooper (1958) for dunes of the Washington and Oregon coast. The Padre Island dunes may be diagonal.

Eolian Beach Ridges of Barriers

Where barrier islands are made solely of gravel and coarse sand as in some European barriers, the ridges of beach plains may have no eolian additions. On the coast of Texas, the fineness of the beach and barrier sands (commonly 0.25 to 0.10 mm) subjects them to much eolian transport, so that the upper part of probably all barrier beach ridges acquires an eolian addition, making them eolian beach ridges in part. The very small degree of size differentiation in the barrier sands of Texas, makes it difficult to distinguish between beach sands and the same sands built into eolian beach ridges.

Waterlaid ridges when composed of fine sand weather down rapidly. On the Texas coast, it is only when they contain beach shell that there is a conspicuous marker—a shell pavement—for the unconformity between waterlaid and eolian materials in the ridge. These pavements commonly remain intact until they reach the gradient plain of the bottoms of the gulleys that cut the beach between cusp ridges. If sand is blown too rapidly to the ridge, a pavement can not develop.

The beach ridges of the Texas barriers vary irregularly in height from about 5 to 12 feet above mean sea level and fit into no scheme of changing sealevel. Their heights seem to be related to the amount of eolian sand stored in them, to the heights of the original storm tides that formed them, and to later ones that may have modified them.

Prograding of Barrier Islands

The modern barrier of Texas (Fig. 9) extends about 245 miles between the deltas of the Rio Grande and Colorado-Brazos river confluence. Considerable lengths of barriers at and near the deltas are narrow and simple, recording the late retreat of the delta flanks and the reworking or re-making of the retreating barrier.

Other simple narrow sections lie immediately to the northeast of the tidal inlets, each of which is known to have migrated to the southwest. The migrating inlet plows up the barrier in its path, leaving the remade, up-current barrier segment new, narrow and simple (Price 1952, figs. 1-3).

Between these simple segments of the inlets and delta margins, the modern barrier is broad and compound, consisting of a beach plain north of the center of St. Joseph Island and of a foredune with an eolian plain behind it south of that point (Field Trip 1958, Pl. 3). Both beach plains and eolian plains have many washover fans.

Although the beach ridges may be largely eolian in composition and origin in their upper parts, it is believed that their bases are generally waterlaid, as were those few seen in excavations by the writer. Even if the beach ridges were wholly eolian in origin, their multiplicity would record prograding.

Shepard's (1956) borings seem to have been too few to establish his tentative thesis that the modern barrier of Texas has not prograded. The regressions and transgressions of the Quaternary are too complex and poorly known for us to assume a simple sedimentary pattern or stratigraphy below the barriers of today.

SOURCE-BORDERING LEE RIDGES AND DUNES Source-Bordering Eolian Ridges

There seems to be no definite dividing line between a high, even-topped lee dune of sand and an eolian beach ridge if both occur on the shore of a body of water. Eolian beach ridges of some of the large Llano Estacado playa basins are 100 feet high without being hummocky and dune-like. How much of the sand is deposited by waves and how much by wind is not clear.

Melton (1940) described a class of source-bordering lee dunes. In the same way, the very high, even-topped, lee eolian ridges which are source-bordering but not hummocky, and hence not dunes in the usual concept, may be called *source-bordering eolian ridges*.

Hummocky ridges of the last type belong with the foredunes.

Stepped-Back Eolian Ridge Plains (Potrero Ridges and Gavilan Mesas)

The foregoing discussion shows why it is not entirely clear to term the class of ridges to be described beach ridges. They are built by wind when a lagoon to windward is a dry flat and no ridges are built by waves. They form on the lee sides of wide lagoonal flats bared by a combination of a seasonal low tide and occasional strong and persistent onshore winds (Pl. I).

The daily range of tide in the western Gulf is low, ranging from nearly zero in some lagoons to a maximum of 2 to 3 feet in the open Gulf.

The midsummer low seasonal tide in the western Gulf occurs between May and November, being at its low point

PLATE II—SOME SURFACE FEATURES OF PADRE ISLAND SECTOR OF MODERN BARRIER CHAIN.

Fig. 1, Gulf surf on 4 longshore bars.

Figs. 1-3, show eroded foredune.

Fig. 2, overwash channel through foredune with grassed washaround. Field of bare dune ridges in foreground under plane. Dark area has shrub coppice mounds, and vegetation on low areas. Gulf in distance. R. E. George, photo., Figs. 1, 2.

Fig. 3, foredune bluffed when shoreface was regraded by tide of distant hurricane of Oct. 3-4, 1949. Price, photo.

Fig. 4, washaround of dune field. Tiny barchans at upper left. Edgar Tobin Aerial Surveys, photo, 1947.

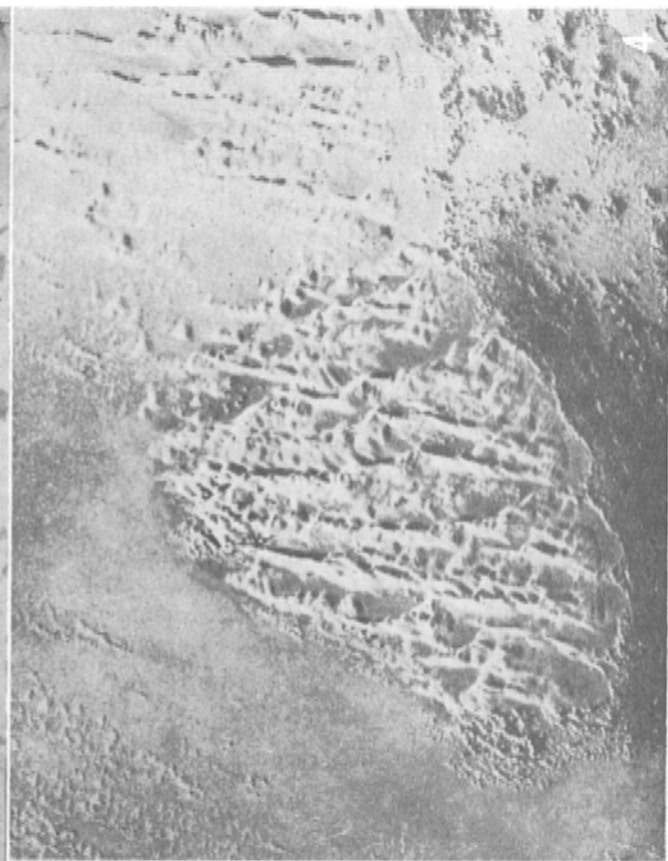
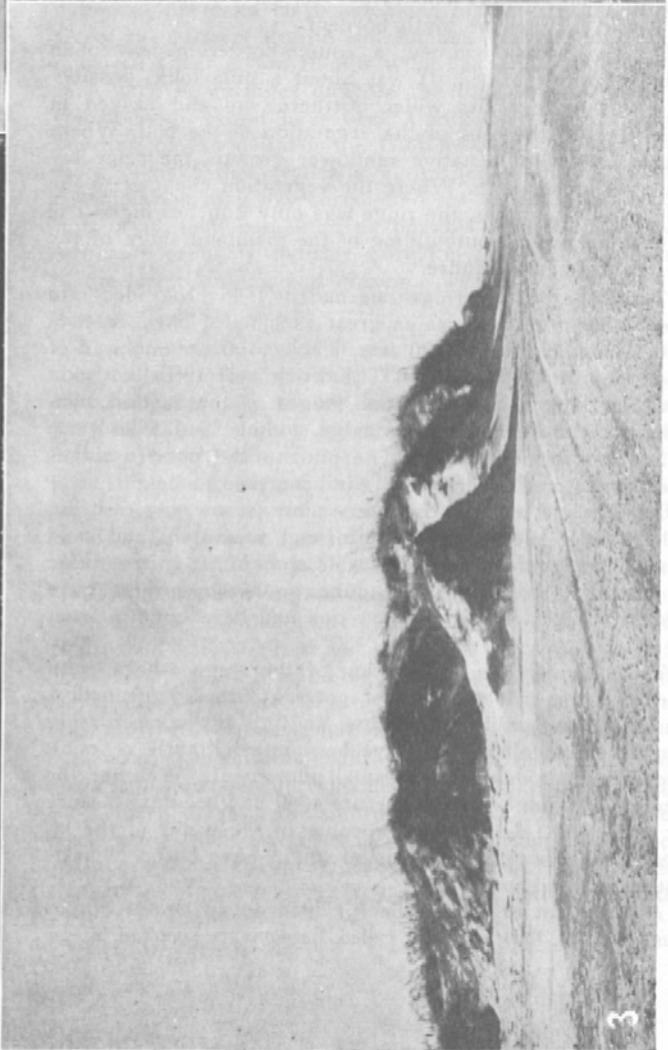
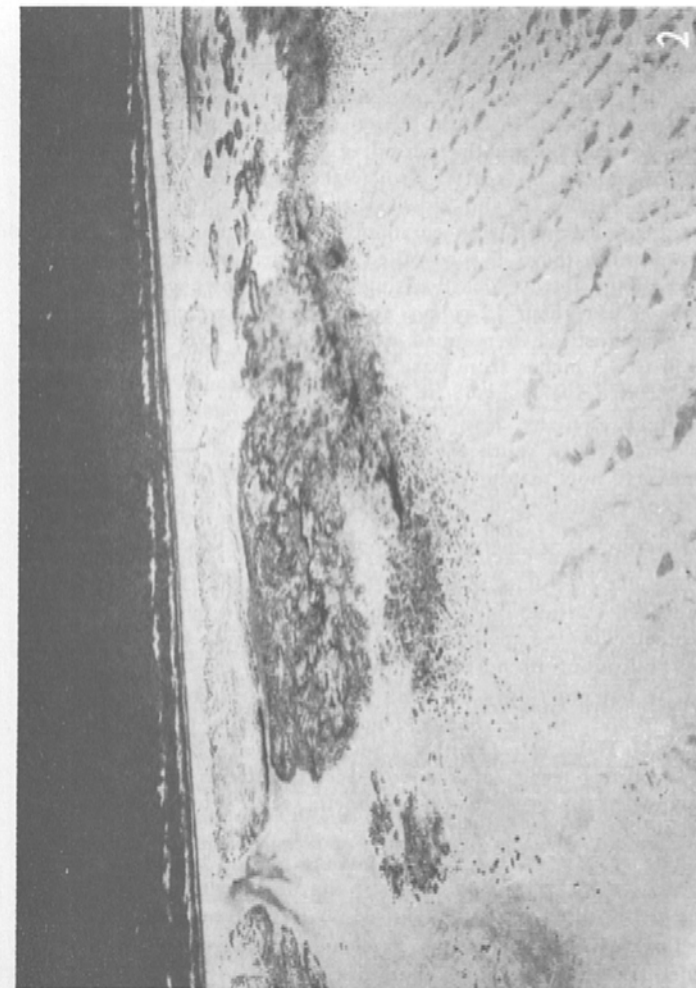
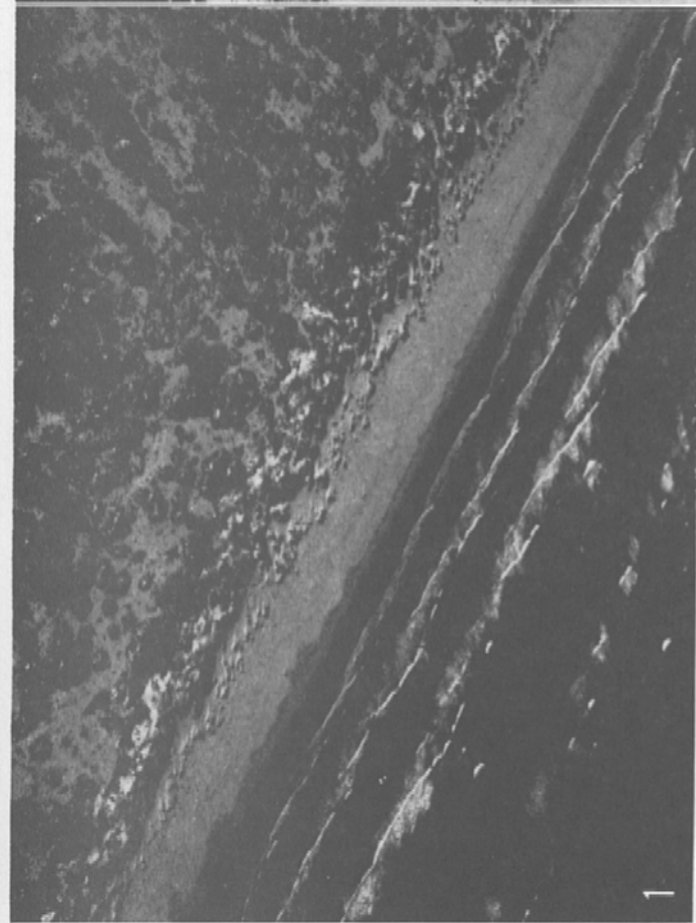


Plate II

of 0.6 to 0.8 foot below the following high seasonal tide in July and August. The total range in the seasonal tide is about 0.9 foot. Another low seasonal tide is at its lowest level in February (H. L. Marmar, 1951, fig. 27; 1954, fig. 32).

The low seasonal tides at Galveston and Port Isabel occur during the periods of maximum strengths of the monsoonal winds as determined at Corpus Christi (Price 1933b, fig. 5). The winter wind maximum is the result of the strong northerly winds of the year. The summer maximum results from the still stronger southerly winds, with the southeast wind much the strongest.

This relation between the seasonal low tide and the seasonal winds results in lagoonal shallows being bare for periods of days and weeks during which time their surfaces, especially in summer, may remain dry for long periods.

The writer observed sand being blown across 4 miles of bare, dry flats of the Central Laguna Madre during 6 weeks of dry droughty winds in the summer of 1948 (Pl. I). The sand accumulated in a belt of low vegetation along the winter shoreline of the mainland of the lagoon against a section of the 20-mile line of the long, high, stepped-back ridged eolian plain bodies of the northeastern coast of Kenedy County known locally as *potrero ridges*. *Potrero* means pasture, the sandy ridges supporting a luxuriant growth of tall pasture grasses. The *potrero* ridges stretch from just south of the mouth of Baffin Bay for 20 miles to the area of maximum inland spread of the clay sheet of the Central Flats (Field Trip 1958, pl. 14, east shoreline to within 0.2 inch of south border).

On the occasion noted, a source-bordering lee eolian ridge of sand formed. It was about a mile long, possibly 30 yards wide at its wider northern end and ranged in height up to the tops of the vegetation of the belt. Where this consisted of a native sunflower growth, the ridge became 44 inches high. Where the vegetation changed to the north to cedar grass, the ridge was only 2 inches high. The new ridge was an outbuilding of the mainland shore of the northern Laguna Madre.

Thus, the *potrero* ridge line had in 1948 prograded into the lagoon for distances as great as a mile. They reached heights of about 15 to 20 feet. Their total volume was of the order of 30,000 cu. yds. The drought of 1950-1956 soon reworked the individual eolian ridges of the eastern two-thirds of the *Potrero Farias* ridge, adding sand, killing the grass and forming dunes. The undisturbed *potrero* ridges are parallel and well grassed, and increase in height, step-by-step inland without the intervening narrow swales being filled. Thus, the ridges were formed separately and sand can not have moved in appreciable amounts from one ridge to another without forming dunes, nor can a ridge have grown appreciably after a new one had been built in front of it.

The only feasible explanation of the stepped-back form seems to be that the line of *potrero* ridges represents a period during which moderate and gradually decreasing quantities of eolian sand have been intermittently crossing the bared lagoonal flats in small increments. Whether the decrease in ridge-building before 1949 had a climatic cause or was due to a gradual deepening of the water of the lagoon by erosion, which in itself might have had a climatic cause, is not known.

A lesser set of stepped-back ridged eolian bodies of Laguna Madre that may be called *gavilans* or *gavilan mesas*

(Pl. III, figs. 3 and 5) may not have been individually contemporaneous in origin. They may, however, as a group have formed during the period of *potrero* formation. The *gavilan* mesas are scattered over the southern part of the Laguna Madre in and close to the barrier. The *gavilans* are oval, ridged plains commonly isolated and about 1.5 to 2.5 miles long. The so-called Mesa de Gavilan lies just west of the Boca Chica tidal inlet on the Brownsville highway. It has about 15 ridges, the highest of which reached 9 to 10 feet when mapped in 1929 (Field Trip 1958, pl. 18, 4 to 4.5 inches from base and 0.2 inches west of shoreline; Price 1947b, fig. 5 at 26° and 97° 10').

Other *gavilans*, less completely preserved, form Clark Island 2 miles southeast of Port Isabel and several low "mesas," now captured islands of the barrier chain on Brazos Santiago and southern Padre Islands. A part of the town of Port Isabel lies on a *gavilan* (Price 1933b, fig. 10). Clark and Gavilan "mesas" still have their intermittently dry tidal flats to the southeast, although Clark Island had been considerably eroded by wave action before it was protected by the spoil bank of the Brownsville Ship Channel built along its northern side.

The *potrero* ridges are built against high and low stabilized dunes of the Sarita Dune Field lobe of the Rio Grande Delta erg (Pl. I). The *gavilans* are built against low natural levees of abandoned distributaries of the Rio Grande in the present active subdelta, the Port Isabel delta (Field Trip 1958, pl. 18).

The capture of the *gavilan* islands by the barrier chain records a local wasting away of the northeastern front of the delta, after the river shifted to its present position.

The involvement of the *gavilans* in the growth of the Port Isabel delta shows that they belong to the late part of prehistoric Recent time. The *potrero* ridges may be no older than the older captured *gavilans*.

CLAY DUNES AND SALINE LOESS OF THE RIO GRANDE DELTA FRONT

Jackass Prairie

Consolidation of the clays of the front of the delta between the arms of the active Port Isabel subdelta and north of it has caused subsidence of the delta, converting a large part into a grassy and treeless plain with many playas, lagoons and clay dunes (Field Trip 1958, pl. 18; Price 1933b, fig. 10; Price 1947a, fig. 5). The plain is about 18 miles wide between Olmito and the Gulf. Northward it narrows but borders the mainland of Cameron and Wilbacy counties to the edge of the sheet of the erg. This plain has locally been known as the Jackass Prairie because, due to its supposed barrenness, it was once given over to herds of wild jackasses (or burros). It furnished the jackasses for Democratic parades in the political campaigns of William Jennings Bryan in the early part of the century.

The soil of the Jackass prairie is strongly salty except for aprons of alluvial clay on the flanks of the natural levees of the arms of the river in the present Port Isabel subdelta. This plain had been abandoned by the river for a long period, evidently many centuries, while the river built at least three main subdeltas in Mexico.

The Jackass Prairie has its counterpart in Mexico just south of the river within other arms of the Port Isabel delta.

The salty soil rises up the slopes of the old, pre-Port Isabel distributary ridges. These ridges enclose the saline plain on all sides except toward Laguna Madre and the Gulf. This soil reaches a maximum elevation of 22 feet at Olmito. Its upper limit slopes downward to the shore of Laguna Madre more steeply than the slope of the delta. The saltiness is not, therefore, a relict condition of a Recent invasion of the Gulf and does not mark the outlines of a former bay, as was once supposed.

Salty Loess From Saline Flats

The evidence is strong that the saltiness of the surface of the Jackass Prairie is due primarily to the formation over it of a sheet of salty loess and secondarily to the rise of capillary salt water, which latter is limited to lagoon flats, playa lake beds and their low-lying margins.

The topographic and soils maps of eastern Cameron and Willacy counties show that clay dunes by the hundreds are dotted over the eastern part of the saline plain. A rough comparison of the volume of a large crescentic clay dune near Port Isabel with the estimated volume of the playa basin from which the clay was blown shows that only about a fourth of the clay was retained in the dune, three fourths passing over as dust, the saline loess.

The landward border of the area of abundant clay-dune occurrence east of Olmito is 8 to 10 miles from the inner border of the saline soil, as shown on the county soil map. The loess supports only salt-tolerant vegetation, producing the only semiarid-looking area in the oasis of the delta.

The loess also covers the extension of the Jackass Prairie in Mexico south of the levees of the present main river course.

Clay Dunes of the Jackass Prairie

In many places, the old abandoned distributary ridges of the saline plain which the Port Isabel subdelta has invaded have long, high clay dunes along the flanks of their levees to the east, southeast and south. Many have been bluffed and rounded by lagoon waves (Price 1933b, fig. 10; Price 1947b, fig. 5, west half). The dunes reach a general maximum height of 30 feet above their bases, which lie either below sealevel, on a low plain a foot or two above sea, or on the lee sides of inland playas at various elevations above sea.

All but a very few of the dunes were inactive during a period of continuous observation from about 1905 to 1949. A. E. Anderson, Brownsville land surveyor began studying the dunes in 1905 and the writer about 1935. The drought of 1950-56 caused many of the clay dunes to become rejuvenated and covered by a fresh layer of clay dune pellets and loess.

The inactivity of the dunes in 1905 seems to have been due to the flat having reached a low point in its consolidation and sinking and to the invasion of many of the source flats of the dunes by salt water or alluvium and fresh water from the Rio Grande. There is the possibility that there was a general slight downwarp of the area of the Port Isabel subdelta due to its increasing volume or to some warp of the Rio Grande delta as a whole, but the subsidence cannot have been more than very slight.

Clay Dune Islands of Southern Laguna Madre

The most striking group of clay dunes along the coast of the Rio Grande delta forms long peninsulas and islands along the mainland coast of northeastern Cameron County. Some of the islands reach the eastern part of the lagoon,

one being 1.5 miles west of Padre Island east of the mouth of the Arroyo Colorado. Green Island (Pl. III, fig. 2), Three Islands and Horse Island are names assigned to some of the larger of these clay dune islands. Alan Löhse reports* that one small clay dune has been captured by Padre Island. These island dunes are inactive, their former saline accumulation flats having been drowned by the lagoon. However, as noted, some have been rejuvenated.

Thus, the saline plain has been drowned for a width of 8 miles in northeastern Cameron County. With this subsidence has gone erosion of the old and new subdeltas so that the mainland shoreline of the lagoon in southern Cameron County has been smoothed, rounded and recessed.

The clay dunes of eastern Willacy County in general are smaller and lower than those of Cameron County. They represent a lesser subsidence of an abandoned delta front. Many of them lie in the lee of southward projecting sand spits of the shore of the Laguna. These spits are probably late incidents of the erosion of the sand of the erg just north of the clay dunes.

Gulfward Warp Indicated By Clay Dune Islands and Off-shore Bottom Profile

It has previously been noted (Price 1954, p. 93, fig. 9) that the profile off the delta in the Gulf has been beveled so as to suggest that the Gulf shoreline has retreated about 25 miles under wave attack. To this may be added the 8 to 10 miles of drowning of the Recent delta by Laguna Madre. The sinking in Laguna Madre shows that consolidation of the delta clays aided the marine erosion. If the tilt of the Jackass Prairie and Laguna Madre floor was as much as 2 feet in the 18-mile width, as would seem necessary, then in 25 miles offshore the total lowering due to consolidation might have been 4 to 5 feet. The indicated beveling of the delta in the Gulf may not have been by more than 25 feet vertically at its deepest point, so that consolidation may have accounted for an appreciable fraction of it, here estimated as possibly one fourth. These estimates probably indicate only the order of magnitude of the latest sinking and erosion.

Age of Clay Dunes

Three estimates assist in dating the clay dunes of the southwestern coast of Texas. These are (1) the upper foot of consolidated clay of the dunes on the Oso Creek, Corpus Christi, in 1946 was barren of Indian artifacts or camp debris. The coastal tribe, the Karankawas, that inhabited the clay dune zone, generally abandoned the coast for life in the missions early in the last century, or by about 1850 to 1875. This barren upper foot may represent a growth of about 0.75 to 1.0 foot per century.

(2) The upper 4 feet of clay below the barren top zone on the Oso contains pottery, "bird points" or tiny flint points used with the bow and arrow and European materials (glass, copper and iron). This 4 feet represents at least the period 1523 to 1850 or 1875, or 325 to 350 years. This 4 feet may represent a longer, but not a much longer period.

(3) Buried at the midheight of a 14-foot dune on a saline playa of the Ingleside lagoonal flat just north of Baffin Bay, there were two highly developed stone artifacts representing trade materials from Mexico, along with local points of the "Archaic" or pre-pottery period. One of these artifacts (a figurine in the L. E. Rawalt collection in the

*Field trip discussion.

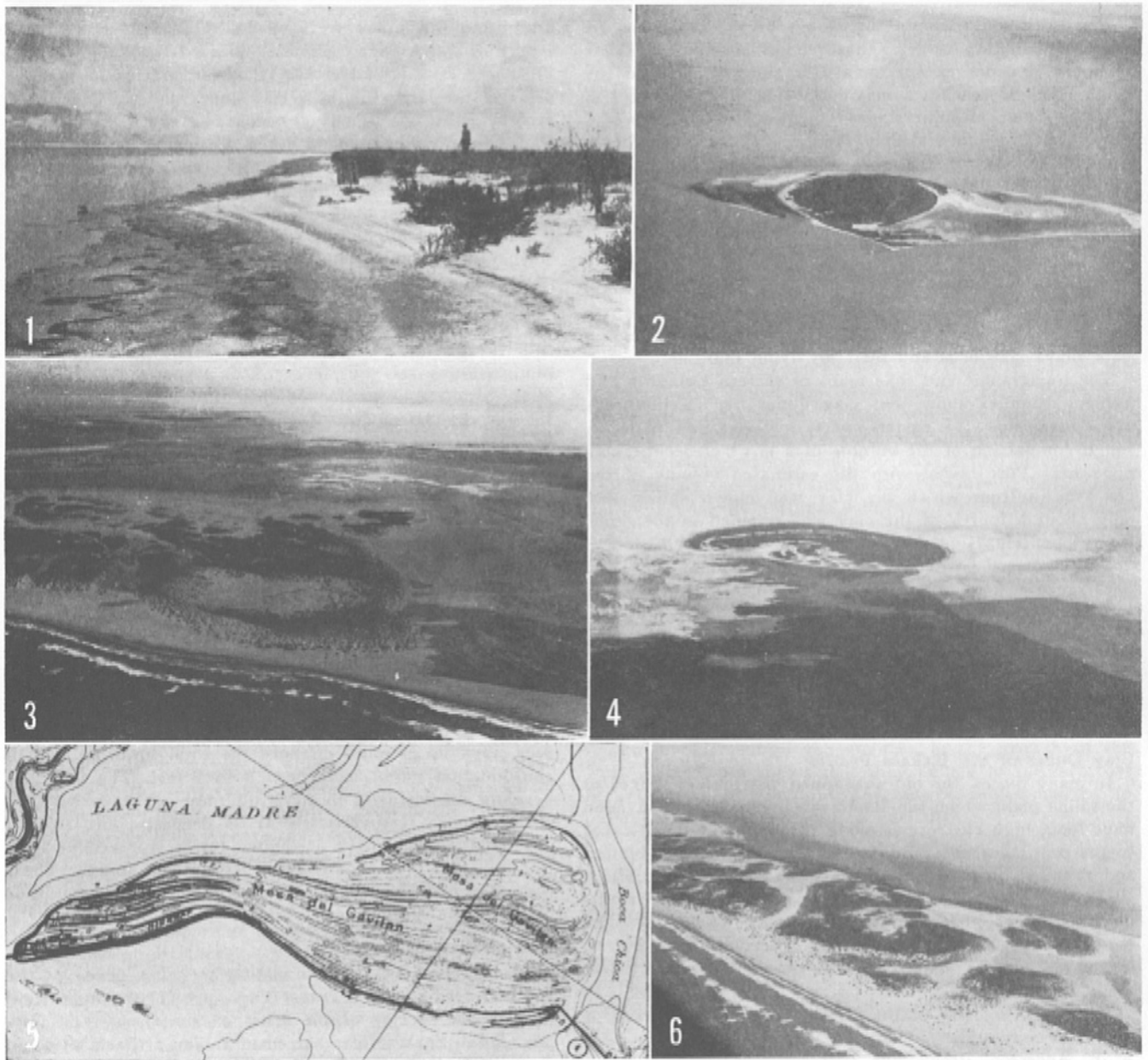


PLATE III. SMALL ISLANDS AND ISLAND-LIKE BODIES OF PADRE ISLAND AND LAGUNA MADRE.

Fig. 1. Shelly beach ridge of North Bird Island flying spit, 26° 30' N. L. Price, photo.

Fig. 2. Green Island clay dune remnant, 20 to 30 feet high. Island seems to have beach plain development on streamlined spit ends.

Fig. 3. A gavilan type of stepped-back eolian plain, developed on lee side of a lagoon flat, now a captured island at Gulf beach of Padre Island barrier.

Fig. 4. Deer Island, a flying spit made oval by a beach plain growth and now captured by eolian plain of Padre Island. Algae make bottom of Laguna Madre dark, outlining a tidal invasion of marginal flats. Looking east.

Fig. 5. Mesa de Gavilan stepped-back ridged eolian plain. Ridges rise from 3 feet toward flat (below) to 9 feet at Laguna Madre (at north) along nearly buried distributary ridge. Dimensions 1.0 by 2.6 miles.

Fig. 6. Washarounds of southern Padre Island where it is one-half mile wide. Gulf under plane, Laguna Madre beyond barrier. Figs. 2, 3, 4, 6, R. E. George, photo.

Corpus Christi Junior Museum) has been identified by Mexican and University of Texas archeologists as belonging to the La Venta horizon of middle or late "Archaic" age or from the period from the time of Christ to 200 or 300 A. D.* This dune probably grew more slowly than those facing a lagoon flat and may not have begun to grow as early as those of Oso Creek and the Rio Grande delta. It is estimated that the mid-dune position of the figurine may be equivalent to a level above the mid-height in a 30-foot Rio Grande delta dune. This would be equivalent to less than 15 feet. Thus, something less than 15 feet of clay accumulated in 1700 years or a little less time.

The rate of growth for compact dune clay has probably averaged something less than 1.00 foot per century and probably at least 0.75 foot per century. During active growth, a loose deposit a foot or more thick may form on top of a clay dune in a season or a few seasons.

Clay dunes subjected to continued additions of saline clay have only rudimentary soils. Clay dunes cut off for centuries from salt water inundation by an apron of late Recent alluvium, as at points close to the main channel of the Rio Grande in Cameron County, and some in filled and marshy playas of the Ingleside lagoon flat in Kleberg County, have developed soils with a reddish or orange red color. This suggests that these soils have been leached during episodes of somewhat more moist climates than that of today. These soils are the only ones known to be of Recent age in southwestern Texas which show a zone of oxidation, except in some of the sand dunes of the Hargill area (Fig. 5).

Application of a knowledge of clay dune growth to settlement and land use shows that a house built on or to leeward of a clay dune will be subject to the settling on and in it of salty dust, sand-sized clay particles and some sand. West and north of the Oso clay dunes at Corpus Christi salty dust and sand have damaged paint and shrubbery for many city blocks. Because the salt flats accumulate algae, the odor of hydrogen sulphide may accompany the dust. It has also been found that house foundations settle on clay dunes and the clay does not hold water if used to make dams.

CENTRAL MUD FLATS OF LAGUNA MADRE*

In the latter part of the last century, the coastal lagoon behind the southern part of the modern barrier chain of southwestern Texas seems to have been fairly open, although locally shallow, from Corpus Christi Bay to Port Isabel. Historical records are few and vague, but seem to support this conclusion.

Because of the gradual but regular westwardly reentrant curvature of the lagoon, the longshore currents and longshore sediment drift of the northerly winds are diagonally opposed south of Latitude 27° by the eastward curve of the inner shore, while the same is true for the currents of the southerly winds north of this meridian. The area of maximum resistance has become filled to elevations above mean sealevel with plastic, saline clay finely laminated with fine sand and shell fragments (Fig. 5; pl. IV, and

Field Trip 1958, pl. 24). The surficial layer of clay with the upper few laminae are held together as a leathery mat by a growth of green algae. The death of the algae forms hydrogen sulphide gas. Wetting of the algal mat after it has been dried by exposure (probably not gas) causes the mat to swell and elevates the clay mat into knobs, domes, ridges and winding root-like forms which change pattern with the coming and going of wind tides.* This clay plain is commonly called the Central Mud Flats of Laguna Madre. It is much like the Buena Vista Flats described by Lohse (Field Trip 1958, pp. 45, 46, pls. 26, 27).

The flats has been built up to a minimum elevation along its north-south axis of 2.5 feet above mean sealevel. Toward the mainland it slopes up at 1 foot per mile—with local depressions—to marginal elevations as high as 5.5 feet where it invades the ridged topography of the banners of the Sarita and Norias lobes of the erg (Pl. I, figs. 1, 2, 3, 5) (Price 1933b, figs. 12 E, 14). Remnants of the dunes stand on the flats as islands in the mud and have been partly surrounded by crescentic beach plains of low sandy ridges of the potrero type. The landward limits of the bare flat—the grass line—have been shown on official maps (as Fig. 9) as the shoreline, no detailed sealevel boundary based on systematic tidal observations having been surveyed. The Flats has no vegetation other than the algal cover.

The clay deposit seems to be at least 10 feet thick, although Fisk's detailed coring has yielded a more accurate figure.

The eastern half of the part of the Flats which is axial to the former lagoon—the eastern 2 miles of the Flats—was, before 1950, colored reddish yellow by eolian sand from the island. Laminae and lenses of dune sand occur in the clay in the eastern half of the fill. One of these lenses was found to cross under the clay surface to the western side, probably representing a drought. Gypsum crystals occur in places in the sand near the barrier shore at depths beginning about 2 feet below surface.

The Flats widens to a total of 8 miles in its central part, having invaded a low area between higher sand dune masses. A line of shortened potrero ridges, the Stepping Stones, runs westward along the north side of this indentation. These potrerros have much the same form as crescentic sand keys.

In the southern part of this indentation, there is a line of large clay dunes running west from Mesquite Rincon Island,* the clay having blown up from the flats.

The entire aspect of the flats as it was in 1949, showed that very little dune sand had been crossing it. The potrero ridges had caught most of what came and are mainly at the north, showing that the crossing sand took mainly a north-westerly course. Clay dunes dominated the southern part of the western indentation, showing relative freedom from dune sand there.

In 1949, the Intracoastal canal was cut through the flats from north to south exposing a cross section of the clay deposit. It is reported that a buried layer with marsh plants was found several feet below the surface.

The Central Mud Flats is not a tidal flat in the usual sense of the word, as there are no regular daily tides and

*Letter of Alex Krieger, February 6, 1951.

*A voluminous report on the sediments of this flat by H. N. Fisk has not been published. The writer collaborated in the field work on this flat, studying mainly the geomorphic aspects.

*See observations by L. S. Kornicker, this volume.

*See topographic sheets for names of the islands of the flats.

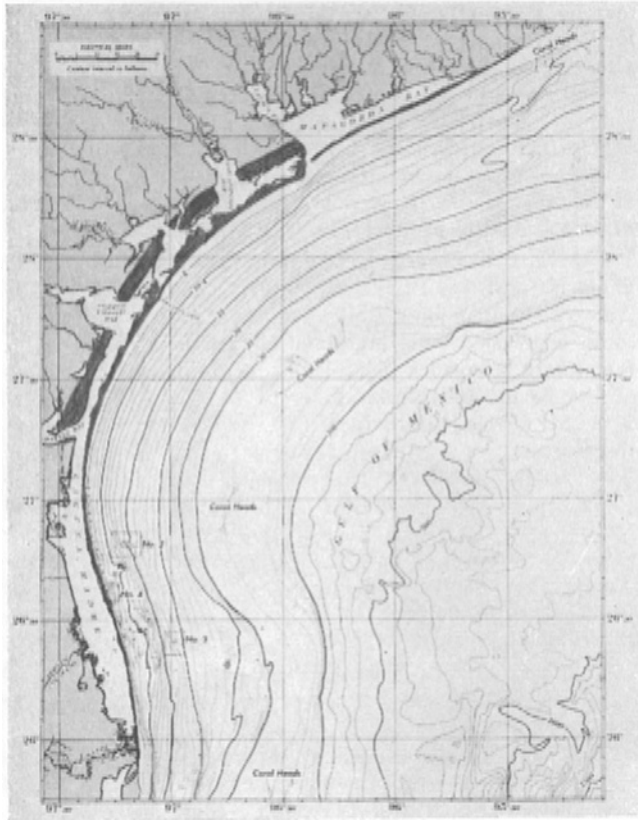


Fig. 9. Barrier chains of southwestern Texas. The modern barrier chain between Colorado-Brazos and Rio Grande delta fronts, and remnants of Ingleside barrier on the mainland, both solid black. (Base map from *Journal of Coast and Geodetic Survey*).

no sensible astronomical tides of any kind in this part of the lagoon, or there were none before the canal was cut. Sheets of wind blown water, however, frequently climb up its eastern and western slopes when strong winds blow steadily across it from northerly or southerly quadrants. The flats might, then, be called a wind-tide accumulation flat.

The upbuilding of the flat, after it reached mean sea-level, has depended entirely on the windiness of the climate. The semi-arid climate is notably windy, but the windiness varies widely from one group of years to another.

The sedimentation on the flats seems to be due to a combination of the settling of clay particles (1) by gravity, (2) by evaporation of the thin edges of the sheets of water and of the water left behind in depressions, (3) incorporation

of fine sand grains from the barrier and broken shells from the lagoon, (4) algal growth and decay with accumulation of partly oxidized organic remains in depressions and particularly in the western lee of the islands of the flats, (5) possible addition of organic material from the fish trapped in the evaporating waters and killed, (6) chemical combination of iron from the water with sulphur and organic materials of the dead algae, (7) deposition of evaporites and other minerals in the laminated clay and sand. The small run off from the porous erg seemed to make no alluvial fans or deltas and is probably insignificant.

The drought of 1950-56 saw the blowing on and across the flats of large amounts ofolian sand, the formation of dunes reported to contain barchans or barchan-like forms, and the movement of much of this sand to the mainland shore. These changes are shown in part by the topographic sheets made in the period between 1950 and 1956 when compared with older maps and photographs.

Samples from the highly organic areas of the Central Flats yielded minute amounts of petroliferous compounds on analysis (Smith 1952a,b). These were developed in place.

FAULTING IN HISTORIC AND LATE RECENT TIME

Low-Grade Diastrophism of Gulf Coast Post-Cretaceous Plains

Sheets (1947) cooperated with the writer in a study of Quaternary deformation of the coastal plain, requested by Monroe G. Cheney, then President of the American Association of Petroleum Geologists. Sheets discussed the known earthquakes of the Tertiary and Quaternary plains of the Gulf Coast from Louisiana to Texas. The quakes have all been of a low energy type but numerous enough to show that faulting of a minor nature is characteristic of the region. We may, then, conclude that the faults that have topographic scarps may be considered to be geologically alive.

The shocks accompanying the faulting have, so far, been of such low-grade energy that the quakes were not recorded on the seismographs of North America except when they occurred in close proximity to a fixed recording station at New Orleans.

As an example of the low grade type of faulting, a quake in Lee County in the 1930s was well known in the county but no account of it seems to have been carried by an out-of-county newspaper. The active faults of Lee County are noted by Weeks (1945).

Current Faulting Near Galveston and Texas City

Lately, several geologists have studied the faulting that has been going on in the past decade in two areas adjacent to Galveston Bay (E. V. Gray 1958; V. J. Henry 1956).

PLATE IV—CENTRAL MUD FLATS OF LAGUNA MADRE, SURFACE DETAIL.

Figs. 1-3, normal conditions before 1948.

Figs. 4-10, with sand and salt depositing during strong droughty winds.

Fig. 1, mud-cracked algal mat, dark clay beneath algal sheet, with laminated sand below.

Fig. 2, mud cracks near shore beyond algal mat. H. O. Wyneken, photo.

Fig. 3, large polygon held by Lewis E. Rawalt, Padre Island naturalist.

Fig. 6, snake-like and root-like welts raised on mat by hydrogen sulphide gas from decay of algae.

Figs. 5, 7, ballooning of mat by gas.

Figs. 4, 7, 8, 9, sand drifting on flats from barrier chain, with salt from sheets of wind blown water.

Fig. 10, stiff foam from wave activity in lagoon water which has been evaporated to brine.

Fig. 4, drowning of clay dune by clay sheet, south of Mesquite Rincon. Dune in distance at left has windward slope toward land. Bluffs of dunes at right are 12 feet high. Photos (except Fig. 2) by R. E. George and W. A. Price.

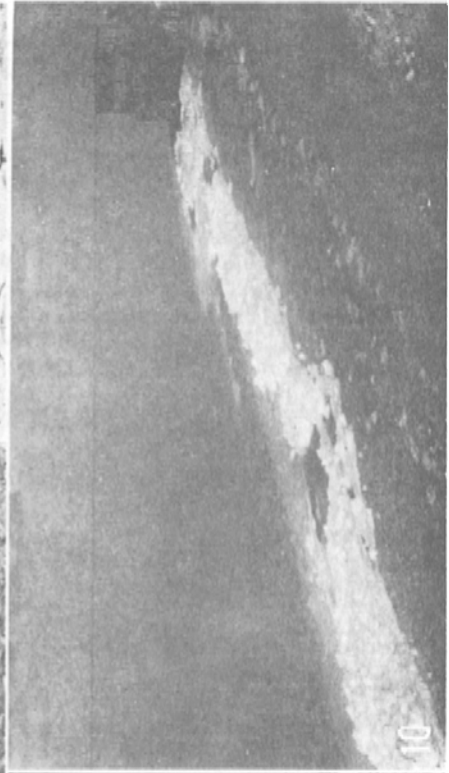
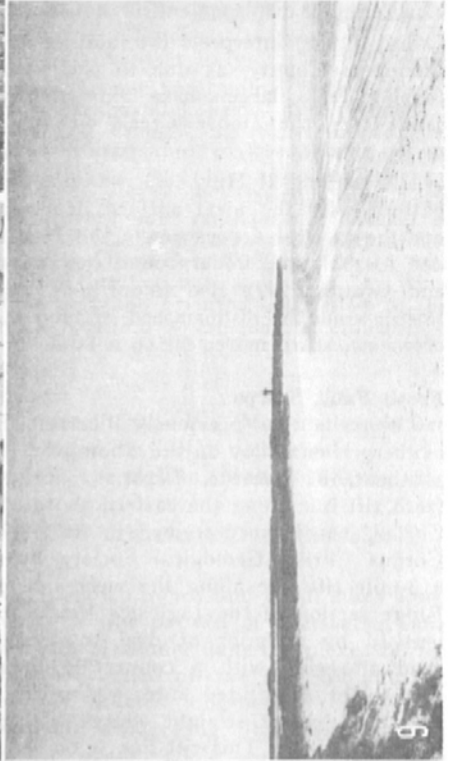
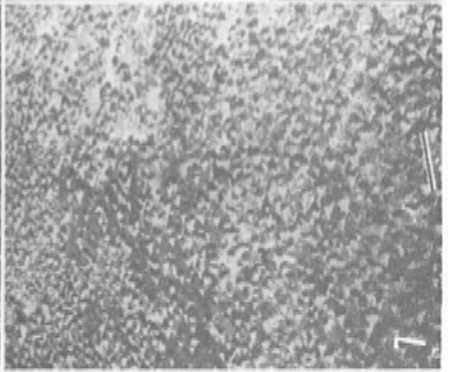
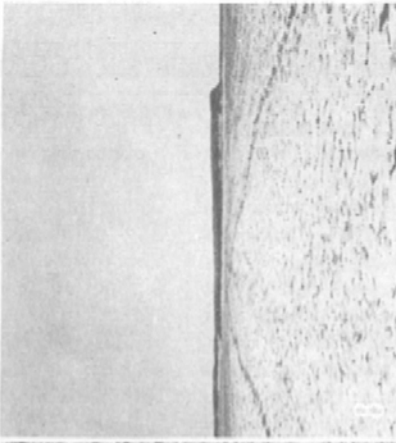
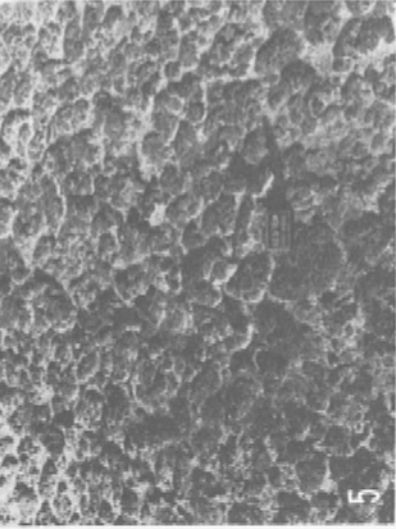
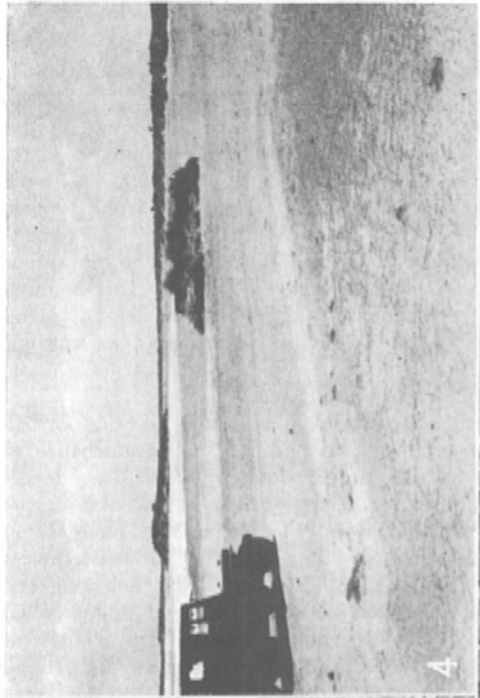
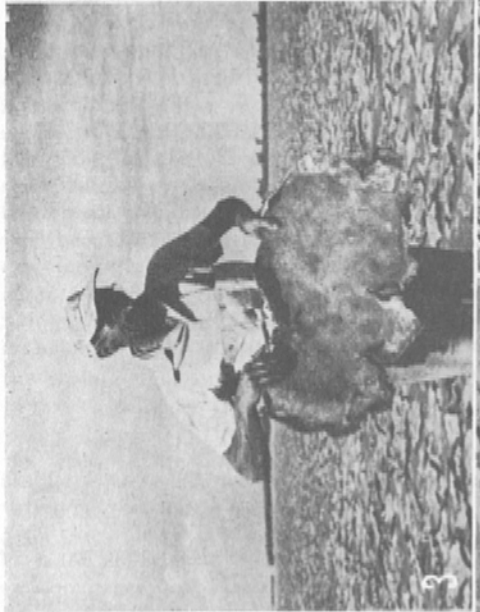
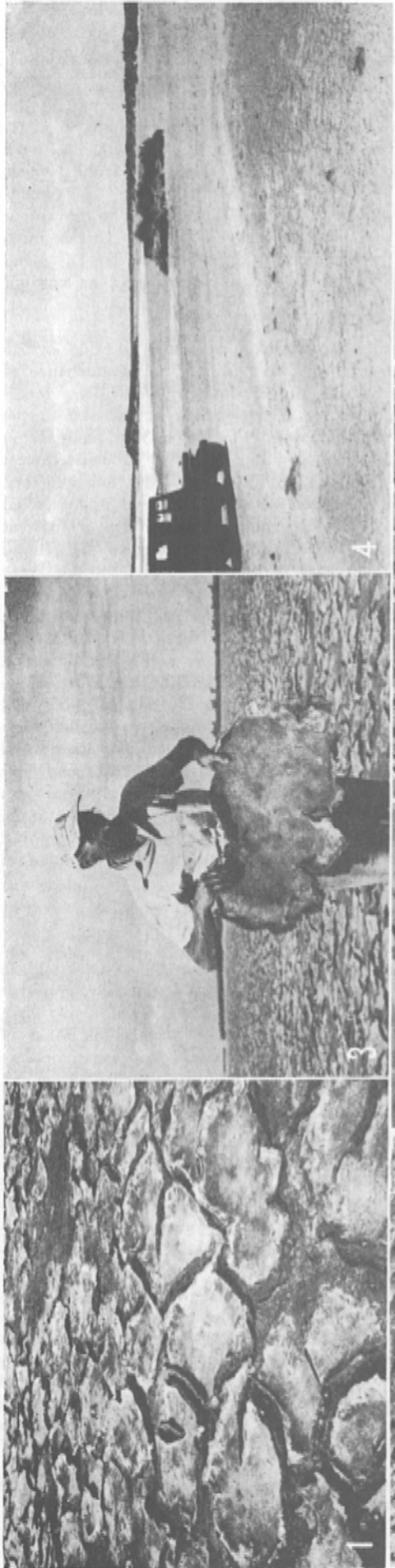


Plate IV

Henry and the writer measured a 1.5 to 2.5-foot increment of post-1928 displacement along an east-west fault that runs through Hitchcock and Texas City. The late movement may not have reached Texas City but formed a new scarp for several miles to the west. This fault cuts across a Pleistocene deltaic distributary ridge and river channel with a previous vertical displacement of at least 3.0 feet. This fault caused a depth of 2.5 feet of tidal water to invade a former tidal marsh just north of Swan Lake, south of Texas City. The fault has cracked roadways and school walls within the present decade. Paul Weaver reports that its growth is intermittent and the place of movement horizontally shifting.

The northern shore of Galveston Island for several miles west of the City seems to have a drowned washover delta topography, indicating tilt toward the coastal lagoon. This topography is weak and the drowned channels cut in loose sands, so that the feature may be quite young.

The problem of rapid rates of sealevel rise in the Gulf of Mexico, as seems to be indicated by the tide records, has not been solved. For a while, the Galveston record seemed to show an anomalously rapid rate of rise, but other tide-gauge stations of the Gulf now show similar rates of rise. Whether the Galveston gauge has suffered a local crustal displacement is not determined.

Gray (1958) interprets the faulting in the Baytown area, Chambers County, as due to shallow subsidence accompanying rapid large-volume extraction of water, oil and sand from the Goose Creek oil field and the shallow water sands used by industrial plants.

The faulting at Hitchcock was not associated in time or pattern with the local surface depression at Texas City nor the general depression in the Houston-Galveston area due to the rapid underground extraction of fluids. Gilluly and Grant (1949) also found that local extraction subsidence could be distinguished in time and pattern from an occasional sharp movement on a fault.

Fresh Fault Scarps

The writer has previously illustrated the striking faults of the graben valley on the Thompson Ranch, twelve miles southeast of Beeville, Texas. (Price 1933 b, fig. 1.) A fresh rift line along the eastern shore of Oso Bay, Corpus Christi, has been described in field trip manuals of the Corpus Christi Geological Society by the writer.* It is a 3-mile rift line along the west side of the Flour Bluff Ridge section of the Ingleside barrier chain. The fault is marked by a series of oval to bowl shaped basins in sand and clay with a connecting linear depression, the whole not integrated into a through flowing drainage course. Adjacent straight shoreline lengths seem also to reflect the fault. This rift line is on the upward projection of one of the faults of the Flour Bluff oil field structure. The writer has inquired without success among local historians, including those of the Catholic missionaries, for any record of a disturbance which might have been caused by movement on this fault.

Current Regrowth on Clarkwood-Viola Fault, Saxet Field

This fault was illustrated by the writer in a paper on topography and diastrophism of the Corpus Christi area

*Also shown in fig 8, Price 1933b, as a former creek valley.

(Price 1933b, fig. 5, 15, 17). The scarp as shown on the topographic map for 1923 is about 15 feet high.

In the past few years, conspicuous regrowth has been taking place along the length of this fault from Nueces Bay bluffs to about 0.7 mile south of the Clarkwood-Robstown highway just west of Clarkwood. The movement is reported to have been in progress possibly for as much as 15 years. A slight amount of movement has occurred in the last two years. The fault is revealed as curving slightly to the south away from the general northeast-southwest alignment of the old scarp.

Besides (1) the abrupt drop on the east side of 2.5 feet, other features along the fault are, (2) disturbance of the direction of surface runoff along plow furrows, necessitating a realignment of the direction of furrows in the area southwest of Clarkwood in 1957, (3) an increase in the area of rainwater ponding about 1 mile northwest of Clarkwood at the Rand Morgan farm headquarters, (4) the breaking of highway surfaces along all roads crossing the fault line, (5) the arched nature of the plain west of the fault and the ridged and wavy nature of the ground for about 1,000 feet east of the fault scarp in the areas where the displacement is greatest, and, finally, (6) a contrast in soil color and mineralogy along the fault. The high side of the fault presents the grayish to whitish C soil zone with decrease in black soil coloration and abundant calcium carbonate nodules. The low side of the fault has the deep black color of the normal A-B soil zone of the area,* with the grayish-black to whitish zone of carbonate accumulation lying supposedly at its normal depth of some 2.5 feet. The writer saw no evidence here of carbonate addition from fault plane waters or any evidence of the issuance of groundwaters along the fault. There is a report from the Morgan office of a slight but definite jar felt and heard one day by a man seated in a spring-based chair.

ORIENTED LAKES

Oriented Lakes

Oriented lakes are lakes that occur in groups with a common direction of elongation. They are usually smoothly oval, but some roughly oval lakes and even some long, narrow lakes and ponds have group orientation. Most of the groups of strikingly oriented lakes are present in large numbers because they occur in multiple parallel alignment.

Aligned Lakes

Groups of lakes, whether oriented or not, that occur in series along the same, or parallel, straight to smoothly curved lines may be called **aligned**. The oxbow lakes of river meander belts occur in an irregular group alignment but not individually aligned, because their long axes are either curved or their orientations are random within the group.

Oriented Aligned Lakes

Most of the more striking oriented lake groups, as the Carolina "Bays," owe their pictorial pattern and symmetrical appearance to being not only smoothly oval and regularly oriented (D. W. Johnson 1942) but also to a considerable degree of common alignment on either their long or short axes.

*The soil zonation into A, B, and C zones is not typical here in the chernozem soils of the Oberlin deltaic plain.

Preexisting Ridged Topography of Oriented and Aligned Lakes

The aligned oriented lake occurrences owe their parallel alignment, and any common original orientation of their individual axes, to their development along the swales between parallel ridges. Most of the groups of oriented lakes which have come to the writer's notice occur in the swales of ridged sandy land or in tundra having a network of ice veins in which there is a dominant parallel vein series. Seasonal melting along these veins and wave action give rise to ponds which are enlarged into oval lakes (Black and Barksdale 1949).

Primary and Secondary Orientation

Lakes may be oriented along the swales of the ridged topography in which they originate (**primary orientation**). If the elongation of the ridges is not that of the resultant of the wave forming and sand moving winds, or if there is a shift in the wind pattern, the lakes will tend to become elongated after a time with the wind pattern (**secondary orientation**).

When beach ridge lakes or lakes of transverse dune fields are enlarged by the wind system which produces the ridges, the orientation becomes secondary without a change in wind pattern.

FORMER LONGITUDINAL DUNE FIELDS OF THE LLANO ESTACADO, TEXAS AND NEW MEXICO

The former longitudinal dune fields of the Llano Estacado (Price 1944) are outlined, at least in part, by the topographic grain (fig. 10) of etched swales, remnant ridges, swale drainage and deeply sunk (deflated) swale ponds and lakes, the latter being oriented along the swales. The eastern direction of accumulation of sand blown off the stripped eolian plain of Lea County, New Mexico, (Fig. 11) (Harper and Smith 1932) and the ESE position of lee dunes of the oriented lakes show the direction of migration of the dunes, there being no evidence of a reversal by 180°.

The Lea County scabland preserves the swales with loessic loam soils in them. Drainage develops along the swales in Curry County, New Mexico (Fig. 12), and the oriented ponds and lakes are of moderate sizes. More deeply incised drainage, fewer remnants of the swales but larger and deeper oriented swale lakes appear in Parmer County, Texas, (Fig. 13), adjoining Curry at the east.

Finally, still farther east, in the Amarillo-Canyon area of Randall and Potter counties, Texas (Fig. 14), the swales are all but gone, the lakes are large and well oriented and the drainage still more deeply incised.

The oriented lakes considered above do not penetrate the Ogalalla caprock caliche, their maximum depth being about 50 feet. Many round, unoriented lakes of this depth occur in the counties adjacent to the former dune fields outlined in the preceding discussion. They are solution deflation lakes which had no ridged terrain to orient them.

OCCURRENCES OF ORIENTED LAKES IN TEXAS Llano Estacado Dune-Field Lakes

The Llano Estacado dune-field lakes have primary orientation, on ESE-WNW axes with the lee beach ridges and

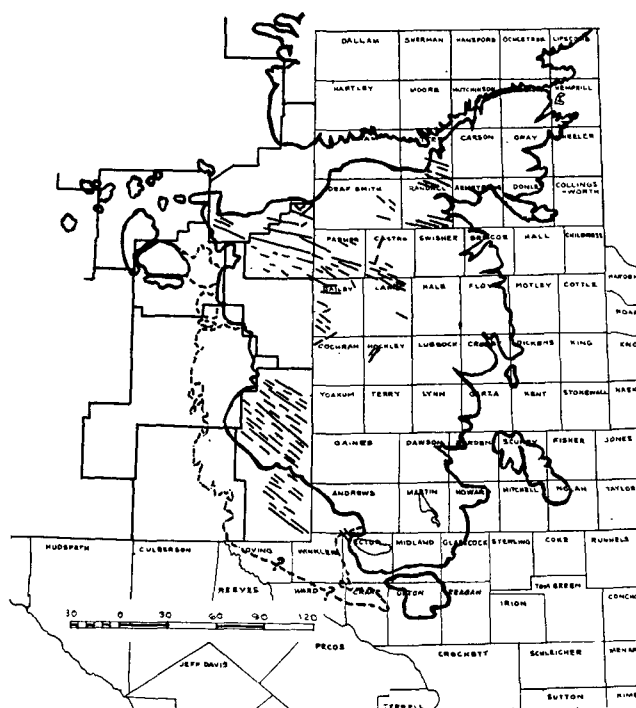


Fig. 10. Lineaments of former longitudinal dune fields of Llano Estacado, New Mexico and Texas. Lineaments are (a) etched swales in Lea County, SE New Mexico, (b) etched swales, swale drainage and lake orientations in Curry County, New Mexico, and the adjoining Parmer County, Texas, (c) strong lake orientations with some swale drainage and a very few remnants of swales in Randall and Potter counties, Texas. Scattered parts of the northern field are seen in Quay County, New Mexico, and Bailey, Lamb and Deaf Smith counties, Texas. The wind resultants of the dune field and oriented lakes blew to the SE, as is shown by the position of lee dune accumulations.

dunes on the eastern end (Fig. 15). Modern winds are dominantly directed toward the NNW on the east side and NNE on the west side of the plateau (Melton 1940, fig. 29).

Oriented Ponds of Etched Transverse Dune Fields of Banners

The small groups of aligned ponds and small lakes associated with the etching of the pattern of transverse dune fields (Fig. 7), of the fans of banner dune complexes (Price 1933b, figs. 12 b-d) are oriented on the NE-SW axes, at right angles to the NW-directed long-period resultant of the on shore sand-moving winds (Fig. 8). They are fairly numerous as rainwater ponds, while some groups have been deepened by deflation, to become playas.

Aligned and Secondarily Oriented Lakes of Ingleside Barrier Northeast of Copano Bay

This portion of the Ingleside barrier (Field Book 1958, pl. 3) has a beach plain. In the swales are numerous black-floored ponds. A few of these have been elongated sufficiently to the northwest by the onshore winds to cut through a beach ridge. The primary direction of alignment and some elongation of individual ponds was NE-SW.

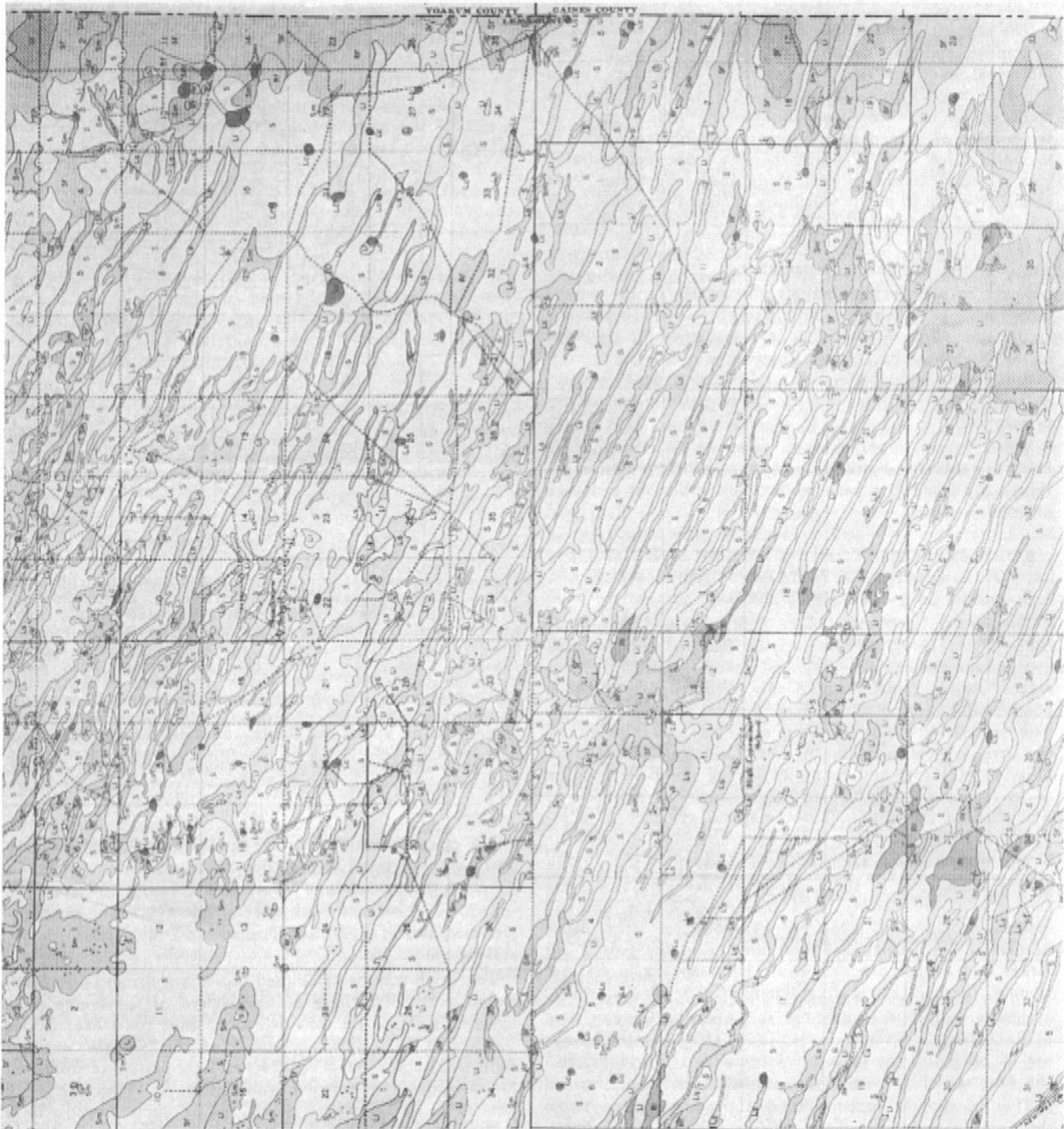


Fig. 11. Scabland (stripped eolian plain) of Lea County, New Mexico. From soil map (Harper and Smith 1932). Narrow, parallel dark bands are etched swales of a former longitudinal dune field outlined by loam soils. Rounded spots are shallow playa ponds. Larger dark areas are lee accumulations of sandy loess and sand along eastern border of county and state. Change in swale orientation along an irregular NE-SW band of loessic accumulation (NW border of figure) was probably caused by a reworking of dune pattern. Wedge-shaped groupings of swales to the NW (out of this figure) suggest former banners. North is to the left.

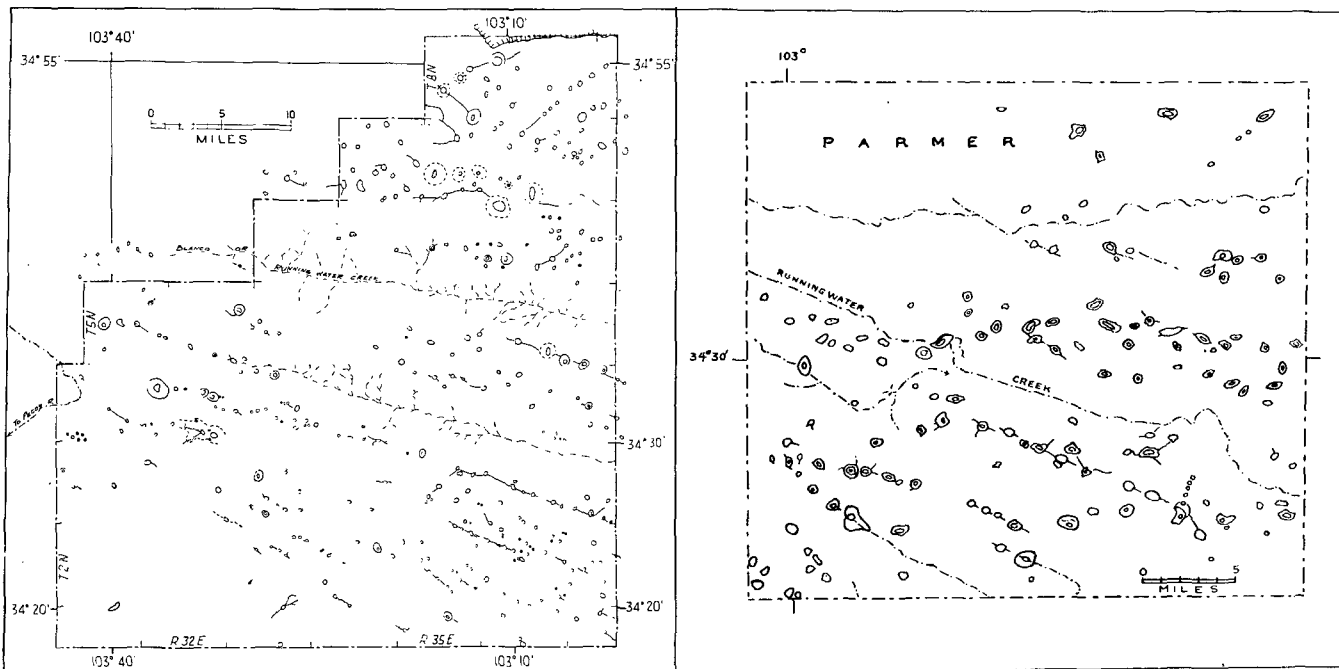


Fig. 12. Swale drainage and oriented lakes of Curry County, New Mexico. From data of State Engineer. Playa basins are larger and deeper than in Lea County, some central ponds showing NNE reorientation by modern winds. Note capture by Pecos of swale drainage at west.

Fig. 13. Oriented lakes and swale drainage of Parmer County, Texas. From field work of Price. Playas somewhat more concentrated than in Curry County, with swales less well preserved and fewer drainage lines. Incision of Runningwater (Blanco) Creek in 2 areas has destroyed the swale lineament there.

Oriented (But Not Aligned) Lakes of Drainage Courses of the Erg

Depressions in the sand of the shallow southeastwardly flowing drainage courses of the Rio Grande delta erg have formed shallow playa lakes and these have been irregularly segmented by marshy and sandy clay dunes (Fig. 16). The dunes are long and aligned roughly E-W, crossing the drainage courses diagonally. The resulting lanceolate lakes are irregularly disposed along the valleys but have a modal E-W orientation.

Oriented (Partly Aligned) Lakes of Ingleside Barrier South of Copano-Aransas Bays Junction

Where the Ingleside barrier segments have a cover of eolian sand, as on Live Oak and Flour Bluff Ridges, they are cut here and there by elongated eolian blowout swales—linear blowouts—in which there are playa lakes and grassy lake glades (fig. 17). These blowout swales are oriented and some are aligned. They are not known to be related to initial inter-dune swales, the dune pattern of these unsurveyed ridges not being readily apparent because of strong down-weathering. The glade of the Tedford lake at Ingleside has a NW-SE axis but this axis may be secondary. The trend of the original basin is not known.

Oriented (But Not Aligned) Lakes of Tidal Marsh

Tidal marsh along some shores of the coastal lagoon and the inner bays, here and there, have groups of rimmed ponds. The rims are low, narrow beach ridges of sand and shell material. They are the result of strong windblown currents, some of the groups having common directions of long diameters where there has been overwash of a partly

protecting levee, spit or tidal delta. Such lakes can be analyzed in vertical air photographs but not well from the ground or in oblique view.

Clam-Shaped and Heart-Shaped Lakes of Texas Coast

D. C. Barton called the attention of D. W. Johnson (1942, pp. 321-323, fig. 46) to this class of lakes which they also called the Vidauri lakes. Johnson commented on it in his study of the Carolina Bays, but without reaching a conclusion as to their origin.

A prominent group of these lakes lies on the Lissie plain northwest of the town of Refugio in the Vidauri area (fig. 18). Others are scattered here and there in Kleberg County. They all presumably lie in sandy materials but without sand dunes having affected their shapes.

If the writer's wind strength diagram (fig. 8) (Price 1933 b, fig. 9) is used, it will be seen that the wind pattern of southwestern Texas is monsoonal; that is, the combined summer southerlies (E, SE, S) and the combined winter northerlies (NW, N, NE) are both competent to modify shorelines, while there is virtually no wind from the west or southwest.

The outline of the clam-shaped and heart-shaped lakes (fig. 18) consists of two intersecting, broadly curved and shallowly reentrant arcs, each being roughly perpendicular to the resultant of one of the monsoonal wind groups. The arcs come together at the west but diverge at the east. The eastern shoreline between the two arcs is either straight with a northerly course, or is convex. Some of the associated lakes are irregular.

The interpretation of the form of the eastern shore is that, because of the absence of any strong winds from the

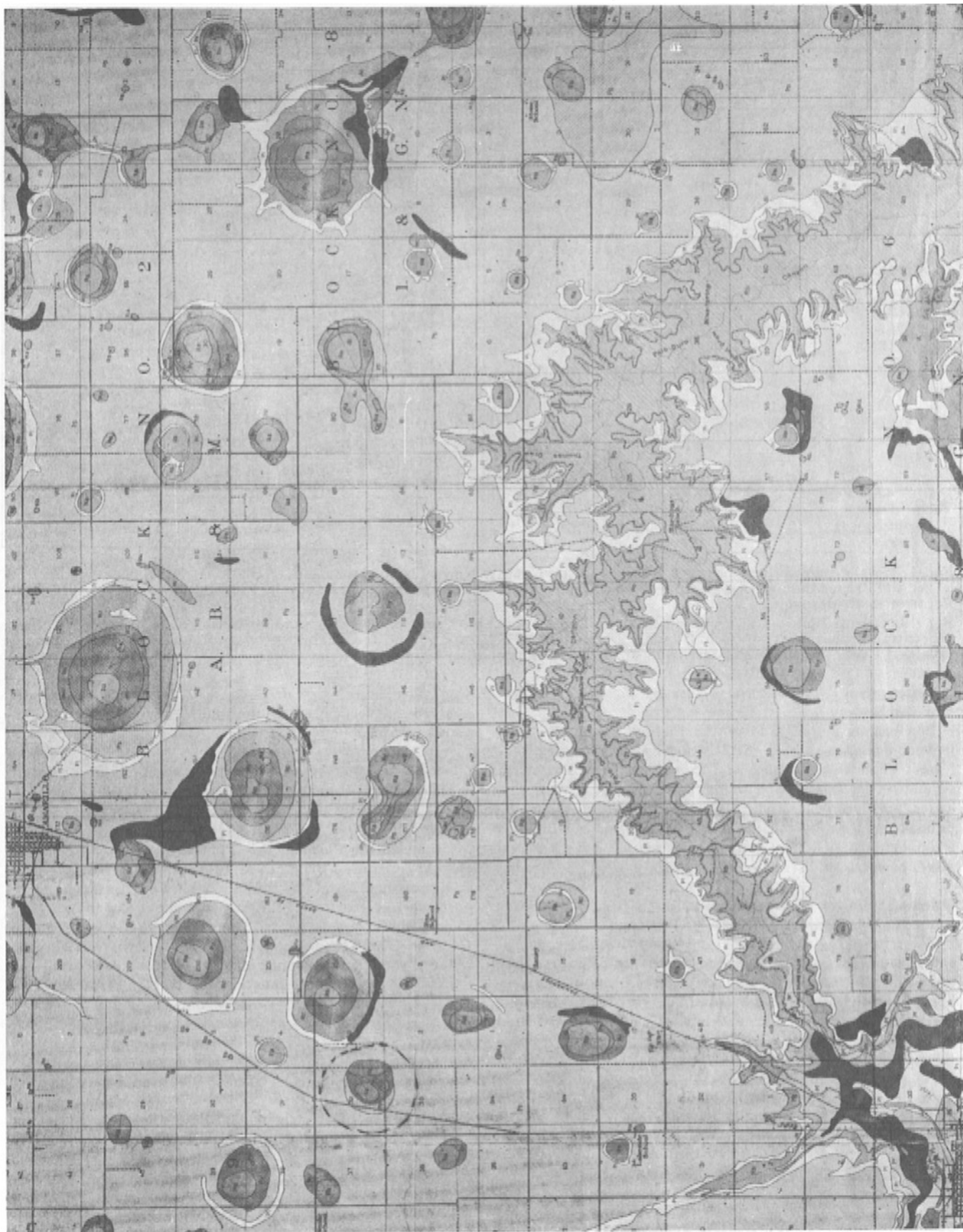
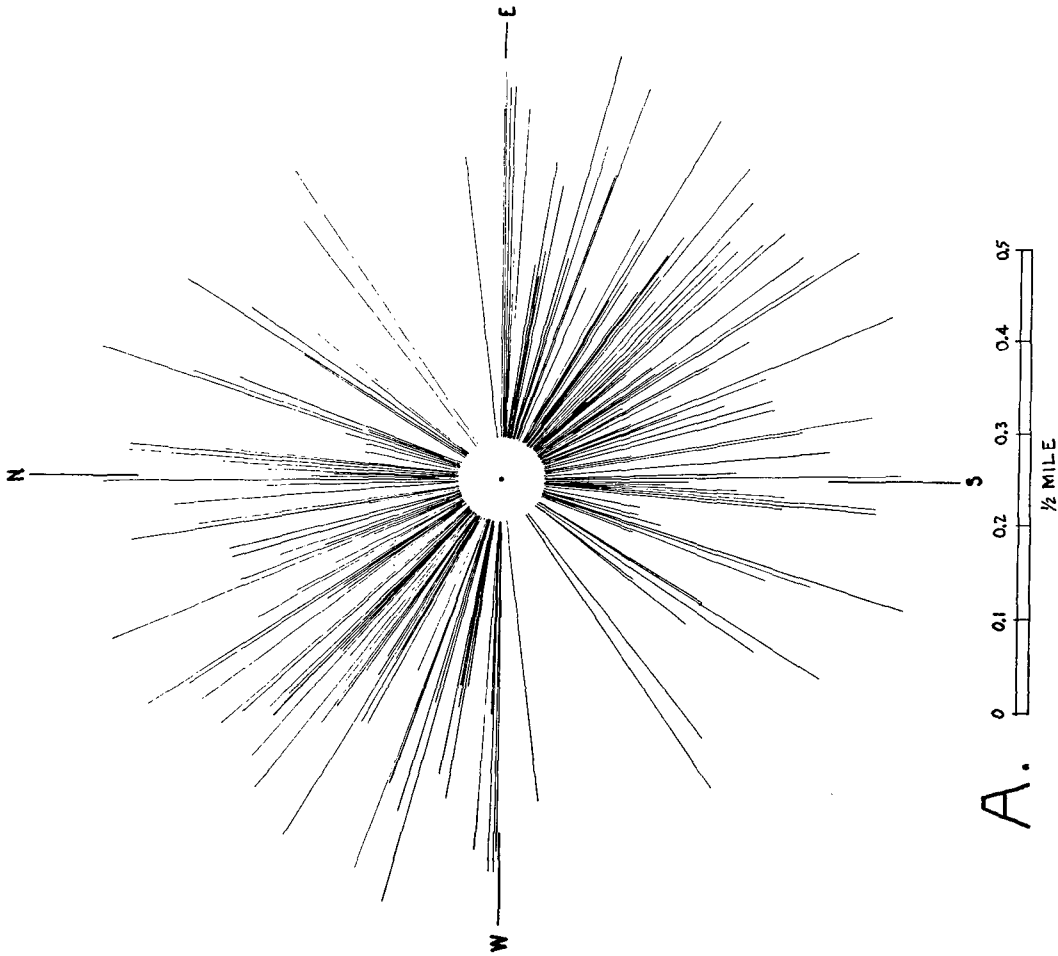
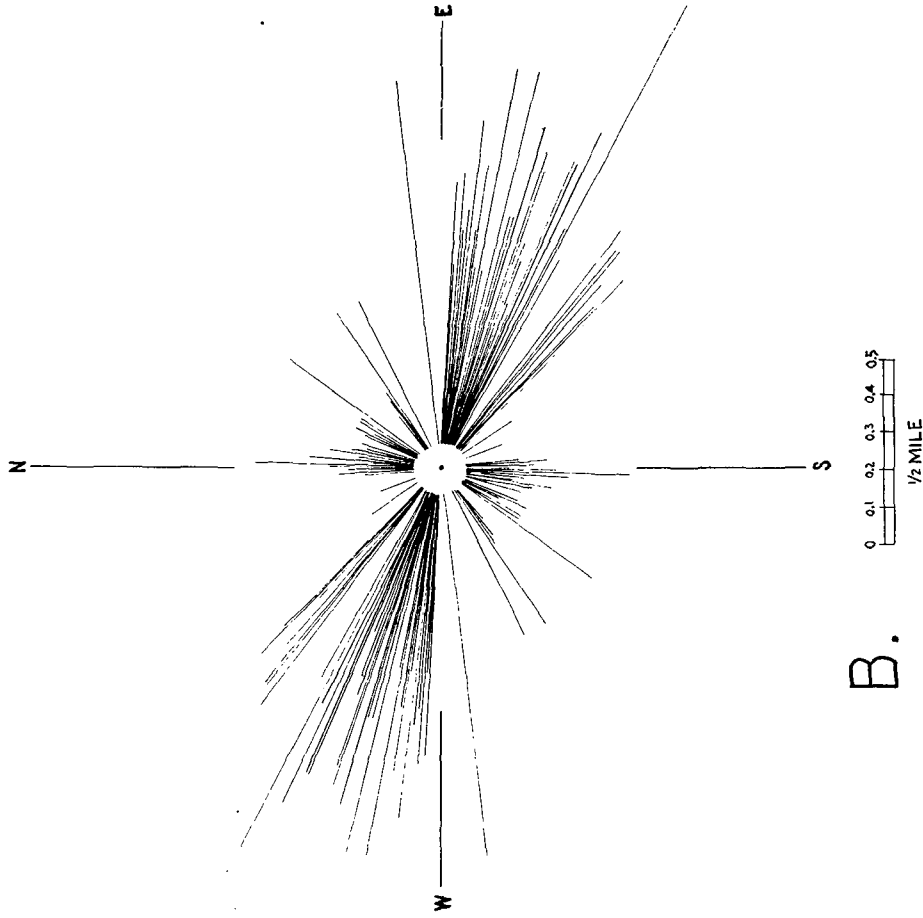


Fig. 14. Oriented lakes of northeastern Randall County, Texas, in Amarillo-Canyon area. From soil map (Templin and Reich 1930). The largest group of oriented lakes in Texas. Would be like Carolina "Bays" if filled with lake deposits. The inner pond ovals show some NNE reorientation by modern winds. Only small basins are found close to the Palo Duro canyon. North is to the left.



A. 83 SOLUTION BASINS 9/10 MILE & LESS



B. 21 PONDS 0.25-0.7 MILE
35 SOLUTION BASINS 0.95-3.10 MILES

Fig. 15. Axial directions of the 50-foot deep playa basins of Randall and Potter counties, Texas. The long basins show strong primary orientation on dune swales. Tiny central ponds show NNE reorientation by modern wind. Basins of intermediate size show only slight oval elongation but with some orientations in both series.

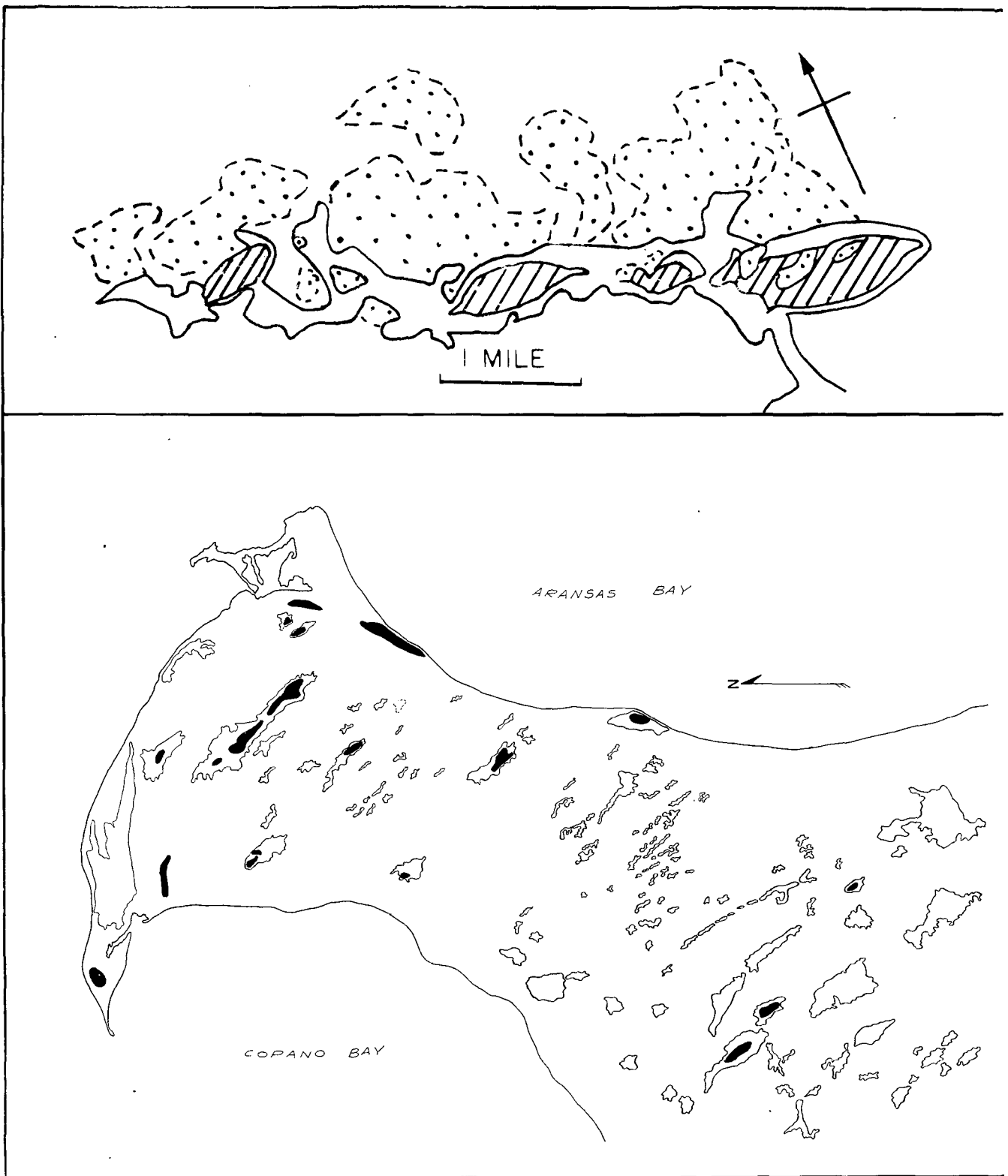


Fig. 16. Playa lakes slightly reoriented from stream channel elongations by lee dune accumulations. Shallow intermittent stream course of the eolian sand sheet (erg) in east-central Kenedy County, Texas.

Fig. 17. Lakes and ponds with primary orientation in swales of eolian erosion, Live Oak Peninsula, Aransas County, Texas.

"Slash" (Recent?) lakes in stabilized, downweathered eolian sand of a sector of the Pleistocene Ingleside barrier chain. Pattern of the downweathered ancient dunes not evident.

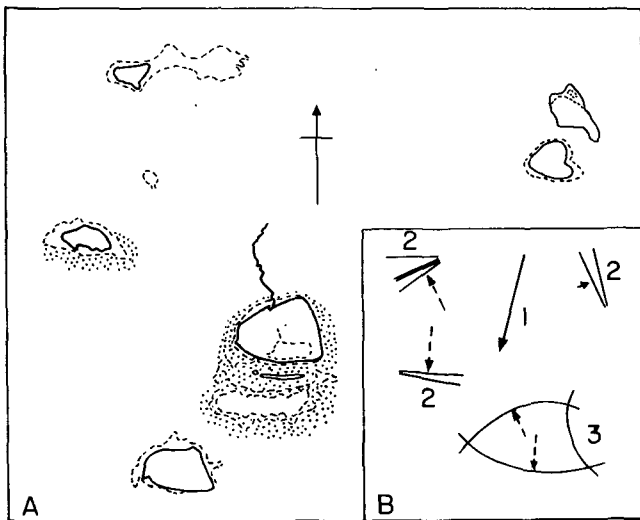


Fig. 18. Clam-shaped and heart-shaped lakes of Texas. Willow Lakes on Lissie Plain north of Refugio and west of Vidauri, Refugio County, Texas.

A, Willow Lakes from air photographs. Stipple, light colored sandy soil, including 10-foot beach ridges forming south shore of largest lake.

B, analysis of shaping of lakes under wind rose of southwest Texas. 1, axis of depression holding the largest lake and resultant of wind that drove waves that formed the beach ridges. 2, directions of NW, E and S shorelines with resultants of winds which caused their recession.

west, this shoreline has receded slowly, while the north-western and southern shores have retreated more rapidly under wave erosion, developing smoothly curved reentrants.

Sharp's, the more prominent of the Vidauri lakes (fig. 18A) (Johnson 1942, fig. 46) is about twice as long as its N-S diameter, the southern belt of beach ridges being 10 feet high. The southern end of the basin is marshy when the water table is high. Overall, the N-S basin axis is the longer.

The N-S depression of the Vidauri lake basin and the heavy development of its south end-beach ridges provides the only observed topographic lineament on this coast of a N-S Pleistocene wind resultant which, as will be seen, should be expected to have dominated the surface winds at one or more times. Later erosion and eolian activity may have destroyed these lineaments.

The Vidauri lakes have not commonly been filled with water in recent decades. W. S. Fitzpatrick, archaeologist, has found a series of flint points dating from the Angostura culture 6,000 to 8,000 or more years old down to the time of the modern Indians. These finds were in the large lake of fig. 16 which has the long N-S basin axis.

CONTINENTAL WHEELROUND OF DUNE- MAKING AND WAVE-FORMING WINDS OF GLACIAL TIMES

Ancient Wind Systems

In all the numerous areas where lakes of extensive sandy plains remote from mountains give geomorphic evidence of a former wind pattern diverging as much as 90° from the present pattern, the forms give evidence of considerable age. This age seems sufficient for the ancient lineaments to have been developed during glacial times, when the climate was sufficiently different from that of

today for such a shift to have affected the surface wind (Melton 1940, Black and Barksdale 1949, Hunt and others 1953).

The evidence of an ancient WNW-ESE wind system 90° different from that of today was noted by Melton (1940) in stabilized dunes of the borders of the Llano Estacado and by the writer (Price 1944) in the topographic grain of the vanished longitudinal dune fields of the upper surface of the Llano Estacado and the associated oriented lakes (fig. 10). Black and Barksdale (1949) show that the long-axis orientation of the lakes of the patterned ground of the Arctic plain of North America is at 90° to the present wind pattern. Hunt and others (1953) found evidence for a shift of the wind since the Wisconsin at Lake Bonneville, Utah.

Johnson shows the orientation directions of the Carolina Bays (1942, figs. 27-28), with their ESE beach ridges, to be at 90° to the present sand-moving winds (1942, table 5, pp. 297-302). These winds have very slightly recessed the eastern shores of some lakes and moved some of the sand of the ancient beach ridges.

The NW-SE topographic grain of the entrenched dune field swales of the northeastern Great Plains from Wyoming to Nebraska (Russell 1929) has a SE direction, formed under NW winds. The present sand-moving winds seem to be chiefly from the SE and S.

The strong sand-moving activity of the present onshore winds of the semiarid and adjacent dry subhumid zones on the Texas coast southwest of central St. Joseph Island seems to have obliterated nearly all the topographic evidences of a former glacial wind system or systems. The clam-shaped Sharp's lake studied on large scale photographs and on the ground has a N-S depression axis and a beach plain south of its center.

However, as previously discussed, if the Reynosa caprock caliche and the older sand and loess of the Rio Grande delta erg were developed from a loess sheet deposited by winds that blew across the retreating Reynosa or Bordas scarp from the interior, after the hypothesis of Brown (1956), we would expect the dominant wind to have been from the west or southwest. The desert areas lie to the west of the present erg. A westerly wind might have blown at 90° from the resultant of the northerlies and at 90° to 135° from the resultant of the southerlies of today.

The periods during which the ancient dunes of the Southwest were formed must either have been dry or the climate had a strongly dry season. It is not clear how this fits into the concept of pluvial climate occurring in the middle latitudes while the arctic climate was glacial. The matter needs much more study. The present climatic regime of the Texas coast includes a winter drought with northerly winds. When these are strong enough, they move sand and temporarily reverse the patterns of the dunes. It requires only a strengthening of the winter winds for them to become the dominant sand-moving winds, as they are said to be now at Vera Cruz, where the northers have a much longer fetch across the Gulf than they have on the Texas coast. The Vera Cruz coastal dunes reach heights of 300 feet while those of Texas are mostly not over 25 feet, rarely 75. The cold air of winter gives the north wind more strength per mile of velocity than the light, warm air of the southerly summer winds develops.

Desert Wheelround

The continental patterns of the present dominant winds of northern desert Africa, of the interior desert of Australia,

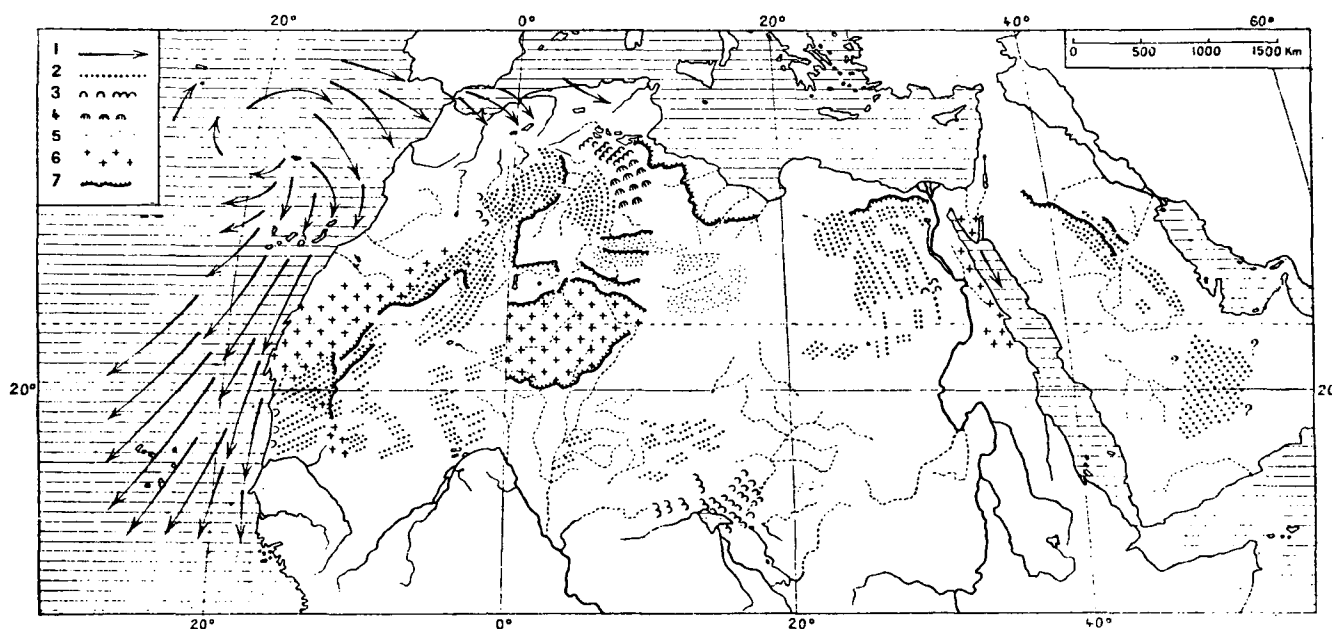


Fig. 19. Clockwise modern North African wheelround (Aufrère 1931).

1. Azores anticyclone. 2. Dune chains (longitudinal dunes, with clockwise migration directions). 3. Transverse dunes. 4. Rhourds and couchets, large eolian forms of the Sahara. 5. Ergs with unknown dune types. 6. "Saharidien" regions, including the Tanezrouft district.

and probably of Arabia, form what Madigan (1936) called a *wheelround* of concentric dune elongations and wind paths. L. Aufrère (1931) mapped the Saharan wheelround (fig. 19) and it has been elaborated by the work of Bagnold and others.

The latest mapping of the Saharan and Australian (fig. 20) wheelrounds (Madigan 1946, Crocker and Wood 1947) does not show the wind systems involved as following circular paths, but the concentric patterns are composed of long straight elements which change somewhat abruptly to other directions instead of always changing by curved paths. As mapped, the paths are concentric, but polygonal on some sectors, curved on others.

The concentric paths and modern winds have a counter-clockwise direction in the southern hemisphere and a clockwise direction in the northern hemisphere. The resultants of the upper winds above 19,000 feet (Stevens 1937) in summer (fig. 21) have a clockwise circulation over the United States, as we might expect a desert ground circulation to be for the sand-moving winds. While the upper winds do not now control the surface winds, this map shows that such a wheelround is not a meteorological impossibility for North America.

Meteorologists have not attempted to analyze the desert-dune and surface-wind wheelround, pointing out that the data on the climate of the great continental deserts are incomplete. However, the geological evidence shows that there is such a surface phenomenon. The direction of circulation in each hemisphere conforms to that of the Coriolis effect caused by the deflection of currents by the rotation of the earth.

Wheelround of Ancient Wind Vectors in the United States

The sand-moving and wave-producing wind directions associated with the development of the regional patterns

of ancient, stabilized dune ridges and large oriented lake systems so far studied by the writer in the field or from detailed studies of others fall into a clockwise continental wheelround pattern (fig. 22). The pattern has not been filled out by examples in all parts of the "wheel." The lineaments used may have been produced initially under hot or cold desert conditions, although the lake axes used show that wave erosion has continued in most cases to elongate them along the initial swales of an eolian ridged pattern. That is, the oriented lakes have primary orientation where they are associated with dune patterns. The change in wind systems, where this has occurred, has usually not yet accomplished any marked lake reorientation (fig. 15).

The SW wind of the longitudinal dune field pattern of the stabilized dunes of the Navajo Plateau in Arizona (Hack 1941) and adjoining states is parallel with the existing wind pattern.

The west wind of the dune tongue of the Red Desert of Wyoming (Lat. 42°, Long. 109°) seems also to be that of the modern wind. The writer has seen no detailed account of the ancient dunes of this region. The long, narrow outline of the eolian materials as mapped on the U. S. Eolian Map suggests that, if this sand tongue had a Pleistocene existence, the lineament may have been that of today.

East of the 107th Meridian, the lineaments used show a SE direction with shifts which seem to indicate curvature from more easterly directions at the northeast to more southerly directions at the southeast. There is a definite shift of this kind in the axes of the Carolina Bays (Johnson 1942, figs. 27, 28) which is emphasized by the lineaments added from Maryland and Virginia. The "Bays" are discussed on the following pages.

The questionable southerly lineament represented by the largest of the Vidauri clam-shaped lakes studied falls into the wheelround, but is not as yet supported by other ex-

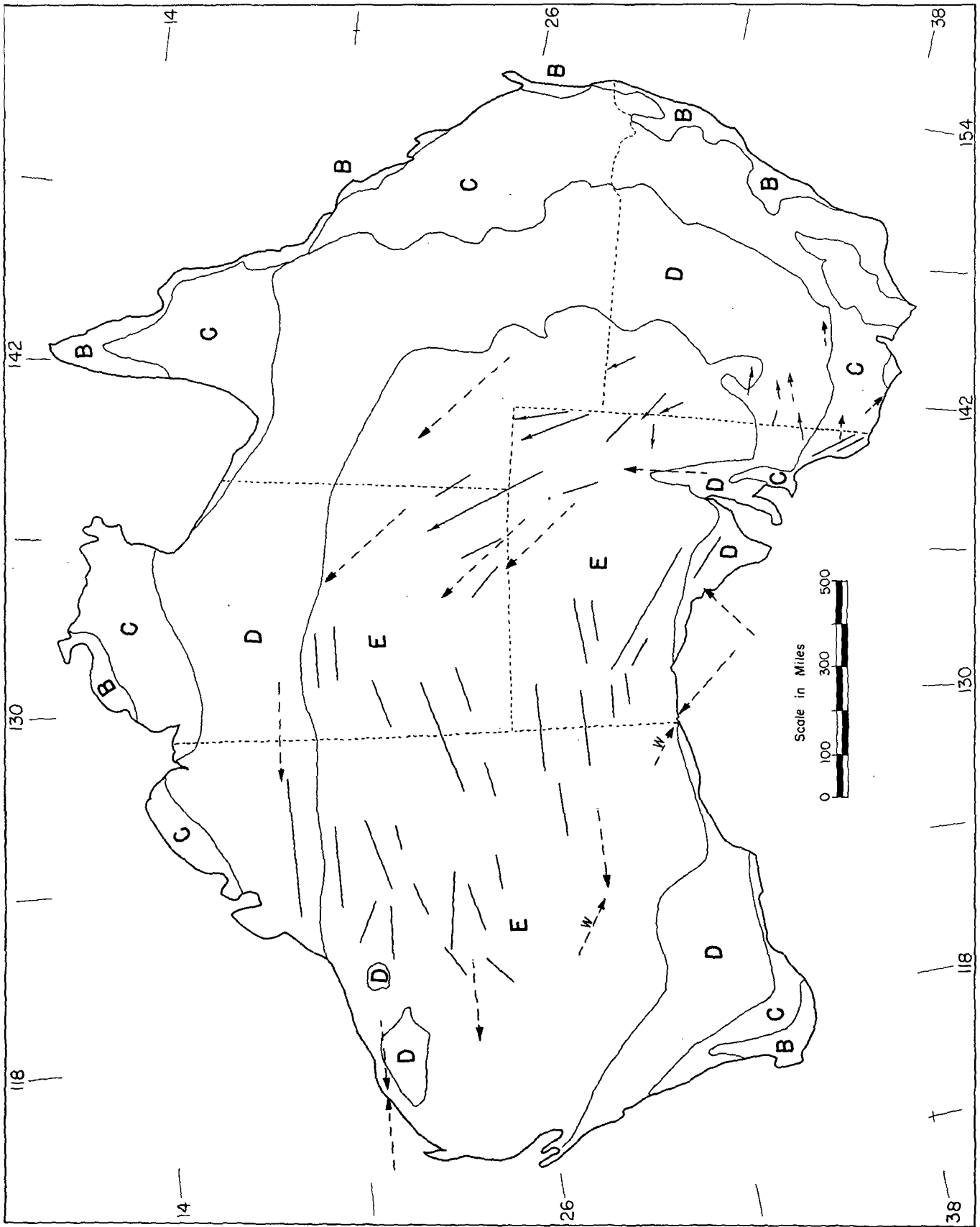


Fig. 20. Counterclockwise Australian desert wheelaround of modern longitudinal dune ridges and wind vectors (frequencies). After Madigan and others. Climate after Thornthwaite (1933) and Gentilli (1946); E, arid; D, semi-arid; C, dry subhumid; B, moist subhumid. Winds (broken arrows), measured at stations located at points, are dominant summer winds, except those marked W for winter. Dune ridges (solid lines) show migration directions where observed in field. Short wind arrows in Victoria (SE lobe of continent) are inferred by Price from clay-dune mapping.

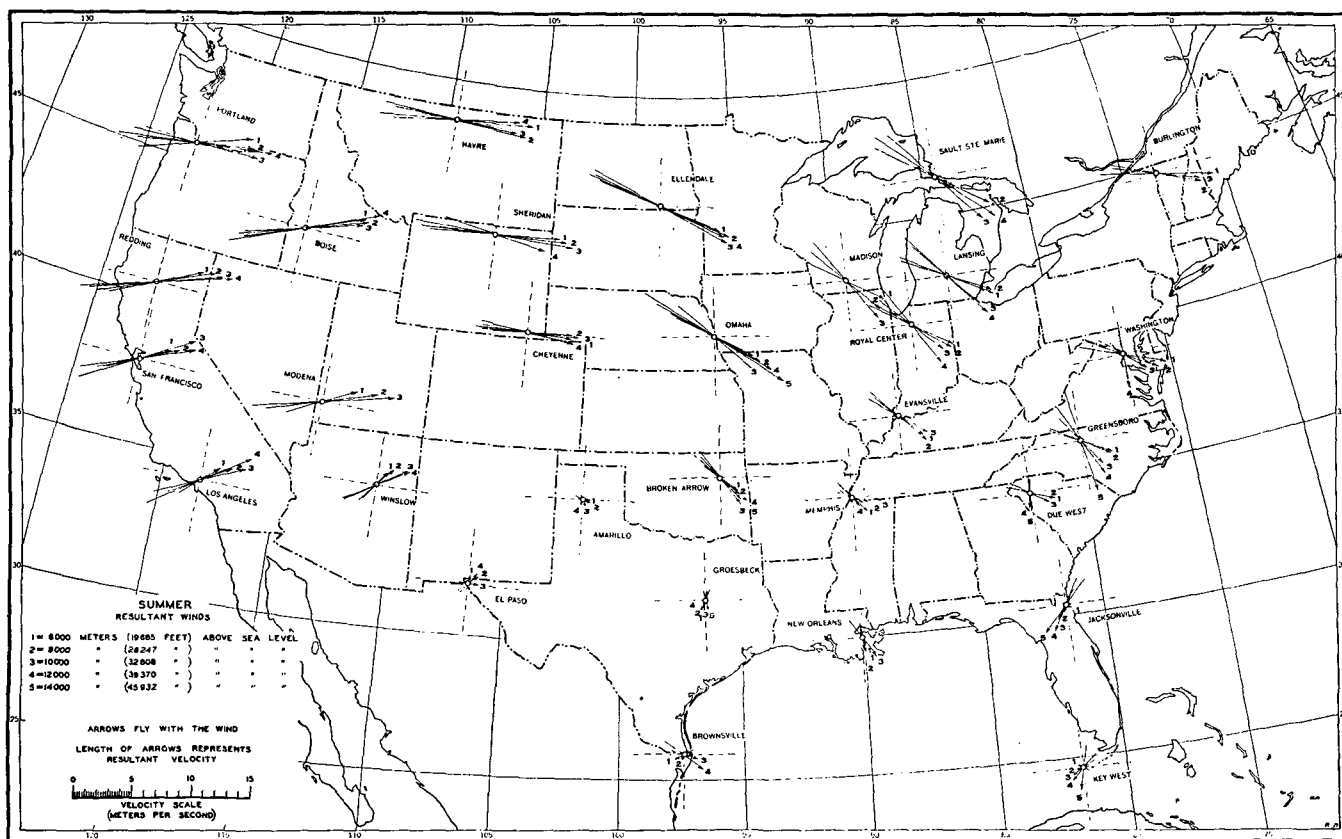


Fig. 21. Summer resultant winds of upper air circulation (Stevens 1937).

Winds above 19,000 feet. Scale for velocities, 15 meters per second.

This clockwise circulation does not control the surface winds but shows that such a circulation can exist (in an interglacial period) although the surface sand-moving winds do not now conform to it.

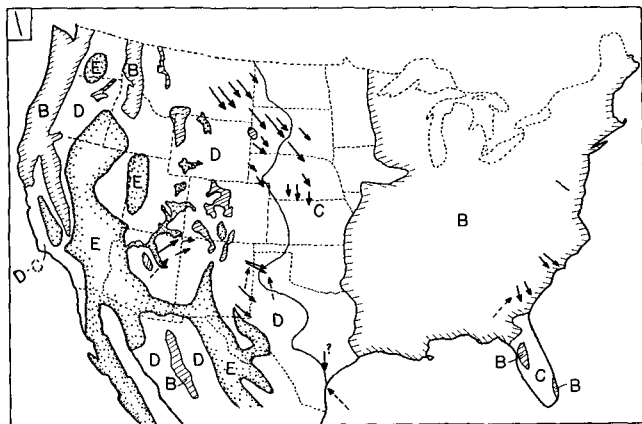


Fig. 22. Clockwise wheelround of ancient dune lineaments for United States. Broken arrows show modern sand-moving winds. Climatic regions after Thornthwaite (1931, 1948) as in Fig. 20. Arizona, Hack (1941). Wyoming Red Desert (U. S. Eolian Map 1952). Great Plains, Russell (1929). Llano Estacado, Price (1944), dune and oriented lake lineaments. Texas coast, one arrow of doubtful significance for Willow Lakes. Carolina "Bays," Johnson (1942). Massachusetts coastal lakes, Raisz (1934), direction not clear.

amples. A southerly wind in Refugio County would not be too much out of phase with southeasterly winds along the Reynosa Scarp to conform to the general wheelround pattern. The strong on-shore wind influence in the Rio Grande delta erg is a coastal effect which may often have been dominant. But the shoreline moved far offshore during glacial events.

Although a wheelround of ancient wind systems of the United States is far from being established by the data of figure 20, which are incomplete and for which synchronicity cannot be claimed at present, yet the data found do not in any case seem to be opposed to a clockwise Pleistocene glacial circulation for the more desert-like times.

Carolina "Bays" as Oriented Lakes

The evidence for the "Bays" or "pocosons" (lakes and lake glades) being oriented lakes and not meteorite scars is now so strong that the meteoric hypothesis can be discarded along with the fish-nest, and gyroscopic eddy hypotheses and other hypotheses invoked before oriented lakes were widely recognized. Johnson's (1942) elaborate study gave results in the main in harmony with an oriented lake origin, although his groundwater-flow factor is probably not quantitatively important.

If Cooke's (1954) hypothetical gyroscopic eddy is an actual phenomenon, it needs to be supported by the answers

to two questions: (1) what is the strength of the eddy in relation to winds? (2) are there oriented lakes on the Pacific coast with a NW-SE axis and direction of growth parallel with the "Bays" elongation and the supposed eddy axis? The writer's U. S. wheelround (fig. 21) would predict NE-SW axes there.

The magnetometer surveys of "bays" cover small isolated areas (McCarthy 1936, 1937; Prouty 1952). In the widespread use of the magnetometer for the mapping of oil-bearing structures, with which there was a considerable degree of success before more accurate geophysical methods were developed, it was recognized that the meaning of local magnetic gradient anomalies could not be determined, if at all, (1) until large areas comprising from one to several counties of average size had been surveyed, or (2) where a known magnetic stratum could be mapped at shallow depths. There are large regional gradient patterns which must first emerge before primary, secondary and doubtful anomalies can be recognized in either type of survey. The published magnetometer surveys of the "bays" area do not fulfil these requirements, the research funds appropriated for the surveys having been small and the results conflicting.

As several observers have recognized, while the orientation of the bays in any one area is uniform within a small angular variation, there are two basic types of bays: (1) a coastal series of bays associated and laterally aligned with the ridges of a beach plain but elongated across them (Johnson 1942, figs. 3, 7, 12-14), and (2) oriented bays lying interior to the beach plains where no transverse ridge pattern is present (Johnson 1942, figs. 6, 29). Neither (1) the good longitudinal alignment of the second group nor (2) the similar linear orientation of the associated secondary drainage seem to have been commented on or used in the interpretation of these "bays."

The coastal bays are on barrier chains, or the cusped forelands of mainland cusped deltas, both of which types have well developed beach plains. Where the beach ridges curve, the common orientation of the bays causes a progressive change in the angle between the axes of lake elongation and the trend of the initial swales. The angular change reverses as the apex of the cusped delta is passed. The lakes are aligned laterally along their short axes with the original swales in which they had their primary orientation.

The inner bays (Johnson 1942, fig. 29), not associated with beach ridges, are however associated with a striking parallel linearity of the secondary upland drainage. This linearity is the same as that of the lake elongation, the lakes having a primary elongation. It can be seen that many of the lakes also fall along the same lines, so that there is a strong degree of NW-SE alignment. This group exhibits primary alignment and orientation. Their relationship with the parallel rectilinear drainage needs to be examined in the light of dune-field geomorphology.

Thus, Madigan (1936) long ago called attention to the capture of desert drainage by the swales of longitudinal dune fields. The resulting linearity is characteristic of all large stabilized longitudinal dune fields, including those of the Navajo Plateau (Hack 1941) and the Llano Estacado (figs. 9-11, 17). The fact that in these areas the slope of the plain happens to be that of the inter-dune swales is immaterial, because short examples can be found of the re-

versal of swale drainage, where the swales lie near up-slope plateau scarps.

The interior group of mutually aligned and oriented lakes of the Carolina "Bays" region evidently descended from the swale ponds of fields of longitudinal dunes of one or more Pleistocene ages. The terrain is sandy (U. S. Eolian Map 1952) and remnants of longitudinal dunes are preserved (Johnson 1943, fig. 29).

Johnson's photograph shows a wind-eroded sand ridge (gray) trending northwest across the area from the north shore of White Lake bay, and passing five miles northeast of Elizabethtown, North Carolina. This is one of the many northwest-southeast sandy ridges shown on the Bladen County soil map.

There are examples of oriented bays with the southeastern part of the basin cut squarely off by the building of a coastward beach plain across its coastward half in Brunswick County, North Carolina. The barrier involved is probably older than Wisconsin. These bays show that the inner series was enlarged before the formation of the oldest preserved barrier chain of the local areas.

Cooke found (1954, pls. 41-43) partly submerged "bays" along the lagoonal coast of the Eastern Shore of Maryland. Unlike Cooke, the writer interprets the occurrence as the drowning of subaerially formed "bays," but not their development as lagoonal features. The phenomenon is exceedingly rare as a modern shoreline feature.

Desert Expansion

The writer previously postulated (Price 1944) that the longitudinal dune fields of the Llano Estacado, Navajo Plateau and Edinburg dune field indicated a former expansion of American deserts to the north and east by some 200 or more miles. He also suggested that it might have occurred in the Recent, assuming that the climatic optimum (hypsihermal) period might have been warm enough to bring it about.

There seems now, however, to be no evidence that these dune fields, including those of the Carolina "Bays" region, were younger than Wisconsin time. The bays cut off by barriers in the Carolinas seem to include examples older than Wisconsin, though no specific study of their age has been made.

The longitudinal dune is probably not exclusively a product of full aridity, as has been debated in the past. It can be developed in semiarid regions if there is sufficient sand in motion and the plant resistance is sufficiently weak—as on Padre Island and in the South Dakota badlands—yet extensive fields of long longitudinal dunes can probably be developed only under fully arid conditions or along the margins of arid deserts. Whether they are ever made of sandy loess is not known to the writer.

Sand will be moved by wind if the wind is strong enough to overcome the resistance of whatever sand binder is present. Sand binders include cement, a clayey matrix, vegetation and moisture. Winter or cold region vegetation may be weak, and winter or cold region droughts may depress the water table and reduce the amount of soil moisture. Hence, if cold winds are strong enough, dry enough and persistent enough, dune fields can be developed under cold climates, as is reported from some Arctic regions today. Storm winds may even move wet sand.

The longitudinal dune fields indicated by the regional topographic lineaments of the Great Plains and the Carolinas and adjoining states might have been produced under

the activity of seasonally dry winds of a glacial period. The longitudinal dune fields of the Llano Estacado and the Edinburg field of the Texas coast may have developed in sand blown from the west in the transition zone between the arid and semiarid regions. The scarps of both elevated plains have thick beds of sand. The scarp of the Llano Estacado now has a large field of climbing dunes along it, the Mescalero dune field.

The subject of the vanished dune fields and the continental wheelround should, if comprehensively investigated in detail, contribute to Pleistocene geology, both in the history of climates and in the dating of fossil remains.

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