Circular 164 1979

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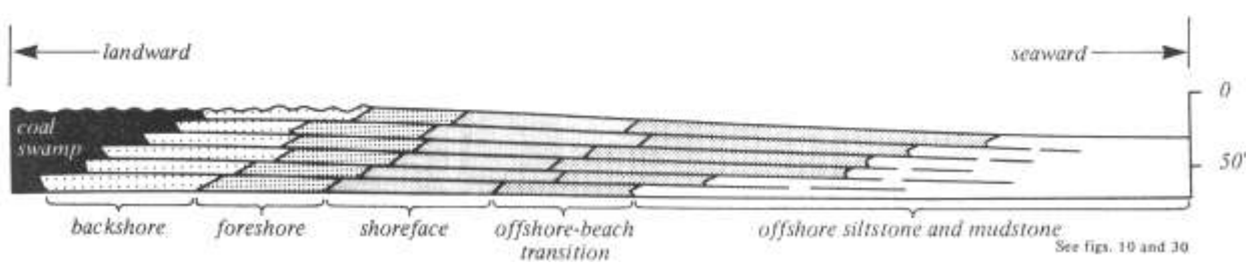
by C.V. Campbell



New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

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Preface

Surface exposures of the Upper Cretaceous Pictured Cliffs, Mesaverde, and Gallup sandstones around the San Juan Basin in northwestern New Mexico provide a natural geological laboratory for the study of ancient shorelines marked by beach deposits. These deposits are reservoirs for gas and some oil. At the end of 1975, the Pictured Cliffs and Mesaverde sandstones had produced 6.5 trillion cu ft of gas and still contained 9 trillion cu ft of proved reserves (Parker and others, 1977); the Gallup Sandstone had produced 132 million barrels of oil and still contained an additional 20 million barrels of proved reserves (Reese, 1977). Consequently, these outcrops are useful for locating hydrocarbon-producing trends and for understanding internal characteristics of the hydrocarbon reservoirs. Further, because those sandstones are aquifers, determining their distribution and continuity is important in evaluating water resources of this area. Also, coal deposits are mined from the landward equivalents of the beach deposits.

All of the Upper Cretaceous beach sandstones consist of similar facies, but the Gallup Sandstone was selected for study because of its easier access, lack of structural deformation, and greater extent of exposure perpendicular to the ancient shoreline. Principles developed from the Gallup study apply to the other Upper Cretaceous beach deposits in the San Juan Basin as well as to ancient beach shorelines elsewhere.

This circular provides a description of the Gallup beach shoreline and an interpretation based upon comparisons with modern beach deposits. These results were summarized in my 1971 and 1973 papers without the documentation herewith released for the first time. Included here are previously unpublished illustrations, discussions updated in response to literature through early 1977, and an extended discussion of concepts and terminology (appendix 1). Some figures are reprinted from the 1971 and 1973 papers. A geologic road log to Gallup Sandstone localities near Ship Rock is presented in appendix 2. These localities were inspected in May 1976 during a field conference sponsored by the New Mexico Bureau of Mines and Mineral Resources.

ACKNOWLEDGMENTS—The writer expresses his appreciation to the many people who aided this study in various ways. R. N. Van Horn first guided the writer through the study area. D. P. Philips and B. Biswas served ably as field assistants. Biswas initiated the microfossil study, and J. H. Beard completed identification of the microfossils. Adolf Seilacher visited a part of the area where he identified most of the trace fossils. J. **D.** Howard made the grain-size analyses. L. J. Eicher and W. E. Murrah accompanied the writer in the field on various occasions and critically discussed the observations and concepts developed in this study. Sam Thompson **III** checked and revised the road log in appendix 2. Kate Hadley and P. R. Vail of Exxon Production Research and W. J. Stone and Sam Thompson **III** of the New Mexico Bureau of Mines and Mineral Resources reviewed the manuscript and made suggestions that resulted in a better book. I thank the *Journal of Sedimentary Petrology* and the Society of Economic Paleontologists and Mineralogists for permission to reprint figures used in my 1971 papers.

Charles V. Campbell
Research Associate
Exxon Production Research Company

Houston, Texas
October 20, 1978

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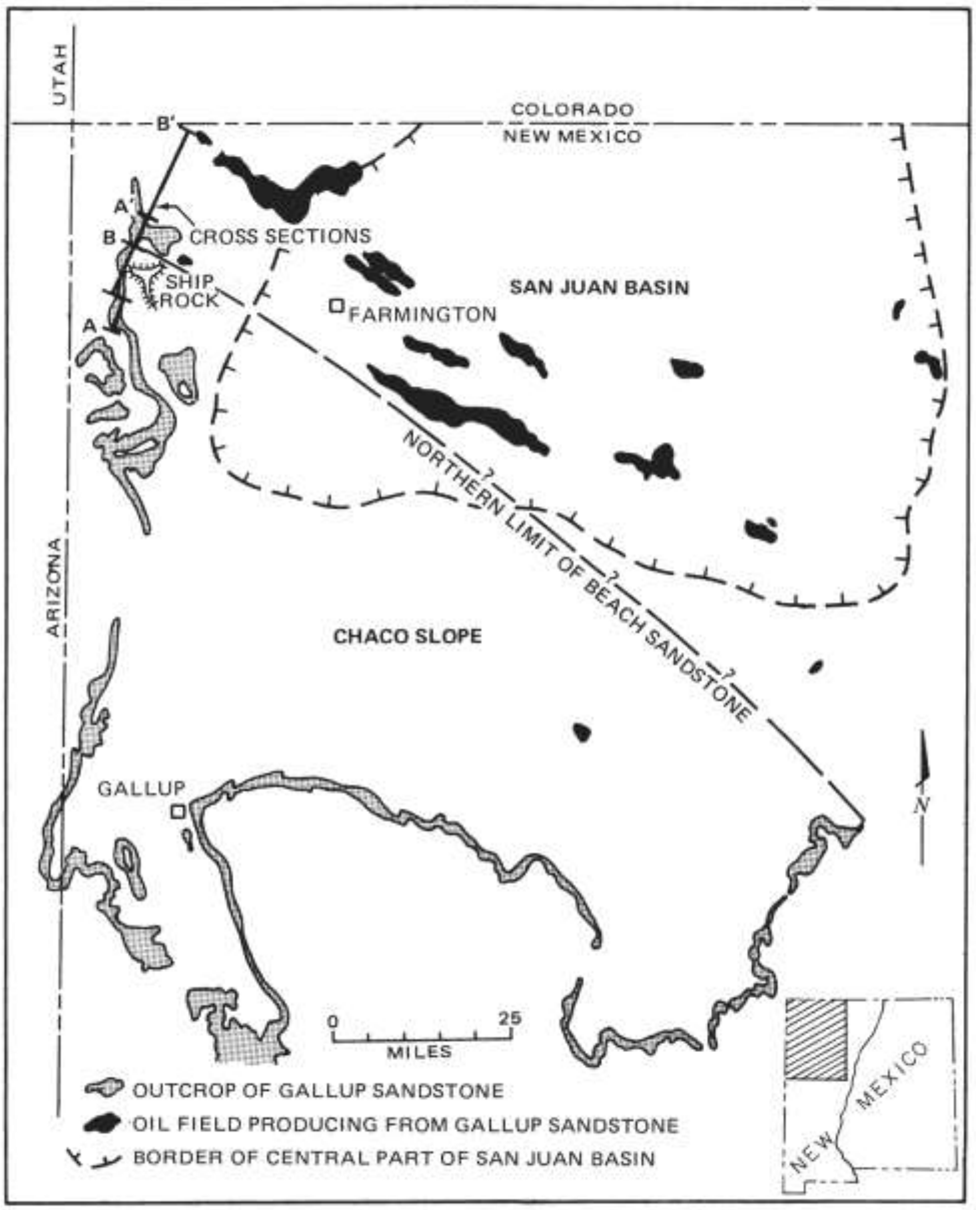


FIGURE 1—LOCATION MAP. Overlap of cross sections *A-A'* and *B-B'* is also shown in fig. 5 (data from Exxon Company sources; adapted from Campbell, 1971).

Abstract

A model stratigraphic cross section for beach deposits in the Gallup Sandstone (Upper Cretaceous) in the Ship Rock area of northwestern New Mexico was contructed for comparison with other ancient deposits as well as with modern beaches. The model shows a lower regressive beach sandstone overlain unconformably by an upper transgressive offshore-bar sandstone. Landward, the beach sandstone interfingers with coal-swamp deposits or is truncated and overlain by dune sandstone. Seaward, the beach sandstone grades through shoreface sandstone into a transition zone that gives way to offshore siltstone and mudstone. Offshore siltstone and mudstone overlie and, in part, grade laterally into offshore-bar sandstone, which has no contiguous landward equivalents and transgresses all beach and related facies. Beach and offshore-bar sandstones, as well as their related facies, are identified by sedimentary structures within a particular stratigraphic framework; lithologic and paleontologic data support the interpretation. Both the beaches and the offshore bars consist of imbricate patterns of parallel beds. In the backshore of the beach, cross laminae dip either in diverse directions or landward; in the foreshore, cross laminae dip uniformly seaward at low angles. Shoreface sandstone is either churned by burrowing organisms or composed of large-scale, truncated wave-ripple laminae. Offshore-bar sandstone is generally churned but may show high-angle cross laminae that dip parallel with the length of the bar. This model provides a basis for predicting the location of petroleum reservoirs, evaluating source and seal relationships, determining volumes of both the reservoir and the aquifer providing the water drive, and predicting flow patterns within the reservoir.

Introduction

Sandstone bodies interpreted as regressive beaches and transgressive offshore bars are well exposed in the Gallup Sandstone (Upper Cretaceous) near Ship Rock in northwestern New Mexico (fig. 1). These outcrops trend perpendicular to the depositional strike and, along with information from core holes, provide data for constructing a model cross section of sandstone bodies across a beach shoreline. The model shows the distribution of beaches and their component facies as well as enclosing and associated facies. Both the model and its facies characteristics are presented as an example of an ancient shoreline that may be compared with other ancient and recent shorelines.

Both surface and subsurface procedures were used to compile the model (fig. 2). Outcrops of the Gallup Sandstone were correlated by walking selected bedding surfaces between measured sections. Subsurface correlations connect similar configurations on electric logs. In addition, as the bedding surfaces were walked, facies changes between them were mapped. On well logs, facies were identified by comparing log responses to cores and well samples and then interpreting facies in the framework established in the study of outcrops. Finally, the correlation and facies patterns were drawn on various datums; setting the landward tops of the offshore-bar sandstones as horizontal datums provides the most realistic reconstruction of the stratigraphic and facies relationships shown on fig. 2.

In the field, facies characteristics were recorded according to the principles of layering described by Campbell (1967). Diagnostic characteristics include stratigraphic relationships, external geometry, internal bedding pattern, sedimentary structures, texture and composition, and fossil content (including trace fossils).

In the laboratory, 315 samples from 34 measured sections were slabbed and then examined with a binocular microscope. Variations in texture, composition, and sedimentary structures were further studied in thin sections of 70 samples selected as typical of the different facies. Also, combined sieve and pipette analyses of 35 samples representative of the different facies were run. In addition, 64 of the 126 samples that were examined for foraminifers, spores, and pollen contained fossils.

Across the Gallup shoreline, facies were identified and named by comparing them with facies in present nearshore environments. These environments and their facies responses are discussed in appendix 1. Similarities and differences between Gallup and facies are discussed here following a description of the geologic setting, the cross-sectional model, and the facies. Finally, applications to exploration and development of hydrocarbon reserves is discussed.

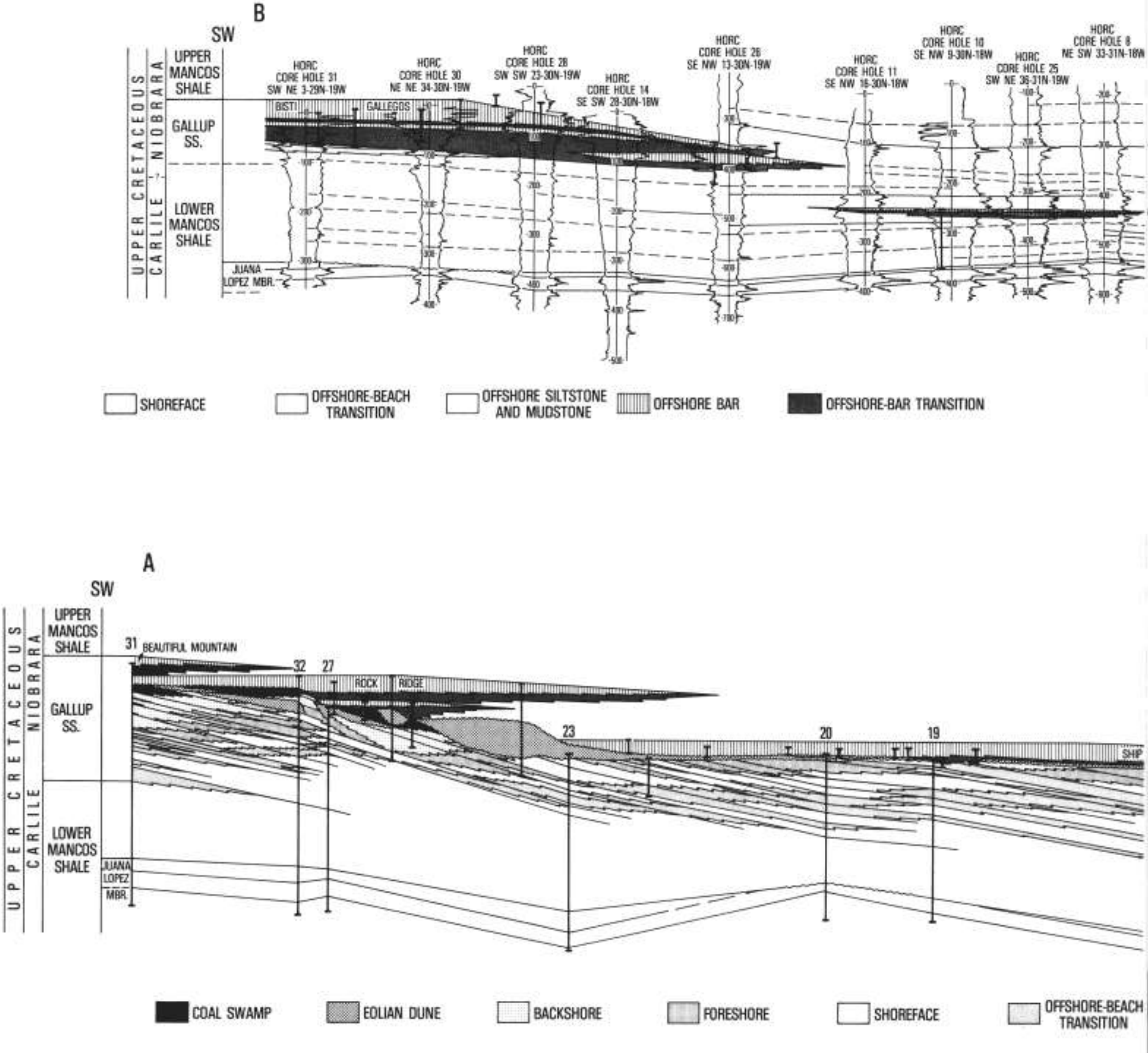
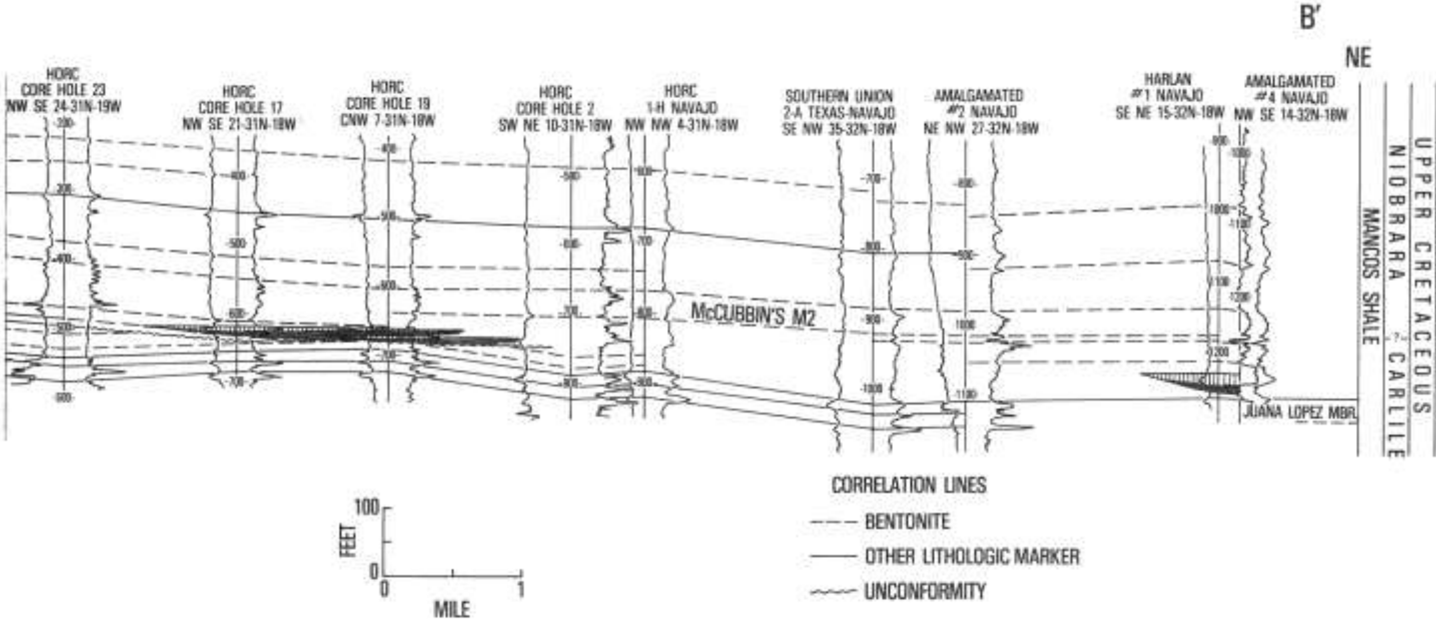
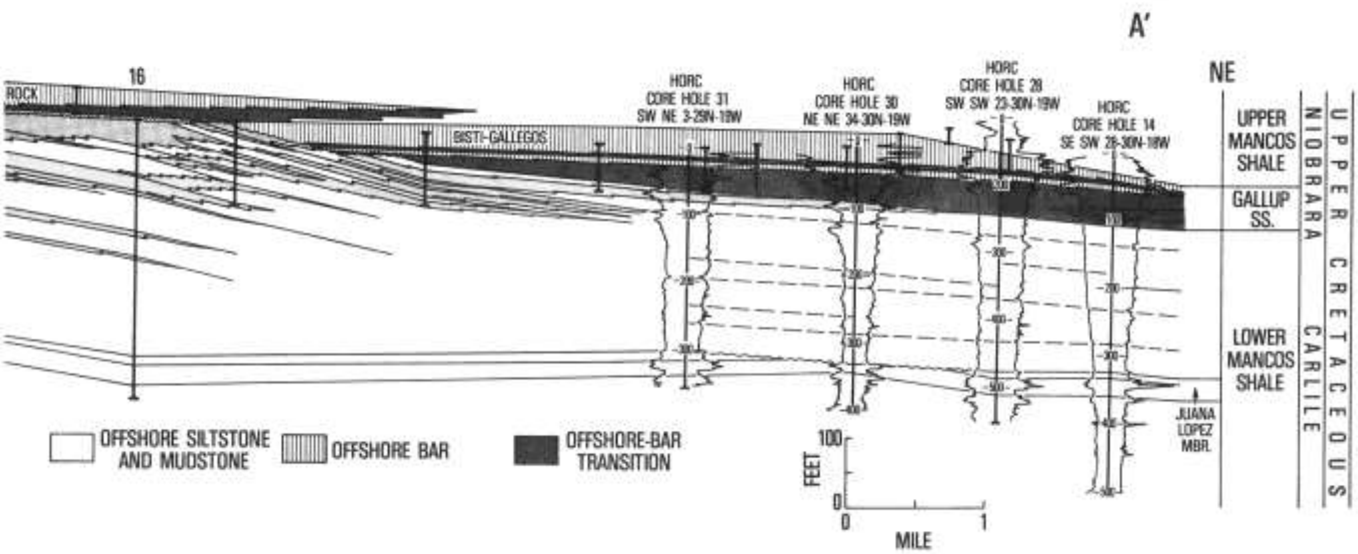


FIGURE 2—Model stratigraphic cross section for Upper Cretaceous Gallup beach shoreline. *A-A'*, the southern part, overlaps *B-B'*, the northern





part. Location of sections shown in figs. 1 and 5. Principal measured sections are numbered as are core holes (adapted from Campbell, 1973).

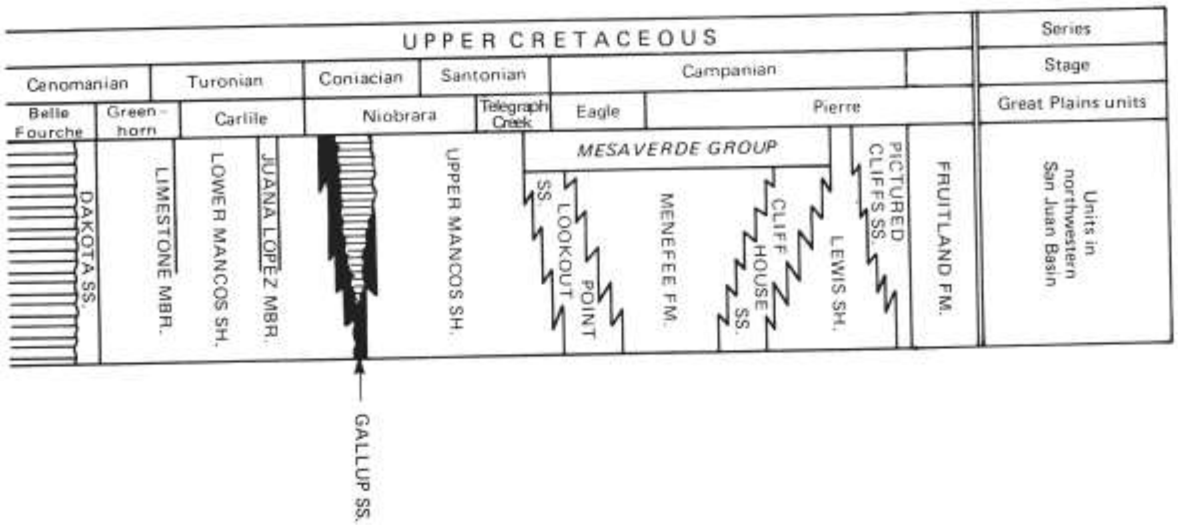


FIGURE 3—STRATIGRAPHIC COLUMN. Sequence of Upper Cretaceous stratigraphic units in northwestern San Juan Basin (tabulated from Exxon Company sources; adapted from Campbell, 1971).

FIGURE 4—PANORAMA SHOWING IMBRICATE STRUCTURE OF GALLUP BEACH COMPLEX. Parallel beds descend from near top of cliff at right to base at left. These imbricate beds comprise a succession of beach cycles as illustrated by measured section 27 on *A-A'* (fig. 2). The beach cycles are truncated and capped by a veneer of eolian dune sandstone. Offshore bar sandstone caps the hill at left. This panorama is at Stop 7 on road log; view is to northeast at approximately secs. 2 and 12, T. 27 N., R. 20 W. See Molenaar (1973, fig. 6) for a closeup of part of this exposure.

Geologic setting

The Gallup model shows nearshore and offshore deposits that accumulated in a small area of the late Cretaceous seaway. This seaway extended from the Gulf of Mexico northwest through the central part of North America to the Arctic Ocean. A portion of this seaway was downfolded during early Tertiary to form the present structural San Juan Basin.

In the San Juan Basin, Upper Cretaceous rocks (fig. 3) consist of a southward-pointing wedge of marine Mancos and Lewis Shales bounded by the continental Dakota Sandstone below and the continental Fruitland Formation above. Two principal regressive-to-transgressive sandstone units appear within the shale wedge; the upper one is the combined Point Lookout and Cliff House Sandstones, and the lower is the Gallup Sandstone.

Recent publications note that the Gallup consists of upper and lower parts separated by a regional unconformity. Dane (1960) first postulated the unconformity, and subsequent workers (Penttilla, 1964; Lamb, 1968, 1973; McCubbin, 1969; Sabins, 1972; Thompson, 1972; Molenaar, 1973, 1974, 1977) accept the concept of the unconformity. It presumably separates rocks of Niobrara and Carlile ages and descends as much as 400 ft from the Gallup through the lower Mancos to the Juana Lopez Member. The offshore bars discussed in this paper would overlie the unconformity. However the well correlations, based on bentonite markers and faunal data subsequently presented, deny the possiblity of a regional unconformity descending through the lower Mancos Shale.

Differing environmental interpretations for the Gallup suggest deposition in a variety of shoreline settings. Most workers identify a lower regressive unit and an upper transgressive one. For the lower Gallup, some of the more recent nonspecific interpretations are littoral (Dane, 1960), shoreline and nearshore marine (McCubbin, 1969), and coastal barrier or delta front (Molenaar, 1973); a more specific recent interpretation is beach with lateral equivalents (Sabins, 1963; Campbell, 1971). For the upper Gallup, nearly all workers recognize nearshore or offshore marine conditions and deposition on the seaward side of a break in slope, but reasons for and the position of this break in slope differ. Early workers such as Sabins (1963) compared the bars to those found in the surf zone off present beaches. McCubbin (1969) interpreted the bars as "strike-valley sandstones" (see Busch, 1959) formed some miles from shore. Campbell describes the bars as offshore terrace (1971) or simply as offshore (1973) and believes they formed many miles offshore—an interpretation that is documented in the present paper.

Description of model

The model section of Upper Cretaceous rocks extends 32 mi across the Gallup shoreline and is divided into two overlapping parts (fig. 2). The southern part, *A-A '* , is based mostly on studies of surface outcrops, and the northern part, *B-B '* , derives mostly from subsurface data. The cross sections show three distinct depositional episodes separated by unconformities. From base to top, they are: the Juana Lopez Member of the lower Mancos Shale, the lower Gallup regressive beach complex, and the upper Gallup transgressive offshore bars.

The *Juana Lopez is* a distinctive lithologic and electric-log marker averaging 40 ft thick over at least the southern half of the San Juan Basin. In the subsurface, this marker usually consists of three resistive siltstone and sandstone intervals separated by less-resistive mudstone and siltstone units. In outcrops the same sequence is present. However, the uppermost of these units has been eroded locally.

The sandstone, siltstone, and mudstone occur in thin wavy beds. Both the siltstone and sandstone show current-ripple and truncated wave-ripple laminae, but their surfaces are often covered by interference types of wave-ripple patterns. *Inoceramus,* oyster fragments, and sharks teeth are common in the siltstone and sandstone. Shallow-water types of foraminifera are abundant in the mudstone.

All of the above features suggest slow deposition on a stable shelf. Siltstone and sandstone were spread over the depositional site by unidirectional currents; waves planed the bottom to a nearly uniform depth. This slightly wavy bottom formed the surface for accumulation of the Gallup regressive-beach complex. This surface is probably synchronous as first stated by Dane (1960), although Lamb (1968) and Thompson (1972) indicate that this surface becomes younger toward the northern edge of the San Juan Basin.

The *Gallup beach complex* consists of a shingled system of individual beach sandstone bodies (fig. 4) representing separate cycles or episodes of beach building. The overall relationship between bodies is regressive; each younger beach lies slightly seaward of the underlying one, although occasional cycles transgress over older ones. Also, each beach rests upon the seaward-sloping face of the underlying one. This imbricate arrangement forms a complex of beach sandstone bodies that extends for more than 100 mi perpendicular to the average shoreline trend and at least 200 mi along depositional strike.

Each beach episode consists of the following seaward succession of facies (figs. 2 and 10): 1) coal swamp, 2) beach sandstone, including backshore, foreshore, and shoreface sandstones, 3) offshore-beach transition, and 4) offshore siltstone and mudstone. However, facies in the overlying cycle are usually displaced seaward from the underlying one. Consequently, the common vertical sequence through a beach complex corresponds to a succession of repeated, partially complete, lateral sequences of beach and associated facies.

Of the facies of a beach episode, the three most landward may be overlain unconformably by eolian dune sandstone *(A-A')*. Both the dune sandstone and all of the beach cycle may be unconformably overlain by Gallup offshore bars and associated facies.

In outcrops *upper Gallup offshore bars* transgress over older bars and onlap progressively landward upon older rocks of the beach complex and then upon eolian dune and coal swamp deposits. However, in the subsurface ***(B-B ')*** some thin offshore bars correlate as equivalent to landward beaches. This equivalence is indicated by the position of the bars within the pattern of converging and parallel correlation lines (parallel in the sense of never intersecting rather than of being everywhere equidistant). Most of the correlation lines mark bentonites identified in cores. Some bentonites continue at least to the southern end of cross section ***B-B '***, where they occur below the most northerly beach sandstone; others project landward into offshore bars (McCubbin's M2) or extend landward from the tops of offshore bars (southward from core hole 19); and still others appear to onlap the seaward slope of the beach complex *(A-A'* between core hole 31 and measured section 16). McCubbin's M2 bentonite marker (McCubbin, 1969, fig. 4) ties this regular pattern of correlation lines to his regional subsurface cross section that trends at approximately right angles to the cross sections in fig. 2.

The regular pattern of correlation lines in ***B-B'*** is interrupted only by local unconformities below offshore bars and on top of the Juana Lopez. The unconformity between the offshore bars and the beach complex in *A-A'* must then pass northward of ***B-B'*** (figs. 2 and 5) at the top of the beach complex into an unidentified bedding surface beyond core hole 30; the bedding surface must conform with the correlation pattern of the bentonites. These correlations counter the idea that a single regional unconformity descends through the lower Mancos Shale and separates the lower Gallup beach complex from the upper Gallup offshore-bar complex.

The unconformity between the offshore bars and the beach complex marks a succession of three terraces that are progressively younger and lower seaward *(A-A')*. From older to younger these terraces are: the Rock Ridge terrace between measured sections 31 and 32, the Ship Rock terrace between measured sections 23 and 19, and the Bisti-Gallegos terrace to the left of center between measured section 16 and core hole 31. Another minor terrace under the Rock Ridge bar is indicated at measured section 27. The Beautiful Mountain offshore bar suggests the presence of yet another terrace; others are probably present south of the area covered by fig. 2. Each terrace level is an erosional feature resulting from episodic lowering of sea level. At each successively lower level, a new beach complex was deposited; then a new terrace level was eroded. Next eolian dune sandstone was spread over the terrace (except for the Bisti-Gallegos terrace). The eolian dune sandstone rests unconformably upon truncated edges of beach sandstone and suggests subaerial erosion.

After the terraced surface of the unconformity had formed, sea level began to rise also in episodic pulses; the shoreline presumably moved southward with each pulse. Each pulse of sea level rise was followed by a period of nondeposition. During that time burrowing marine organisms churned the upper 2-3 ft of sediment on the terrace surfaces, irrespective of whether the original deposit was continental or marine. After the period of churning, an offshore bar began to form at a landward terrace edge and spread over the adjacent lower terrace *(A-A')*. Thus, the Bisti-Gallegos offshore bar was deposited upon the youngest terrace and at the edge of the next older one. Later, the Ship Rock bar was deposited upon the next older terrace and at the edge of

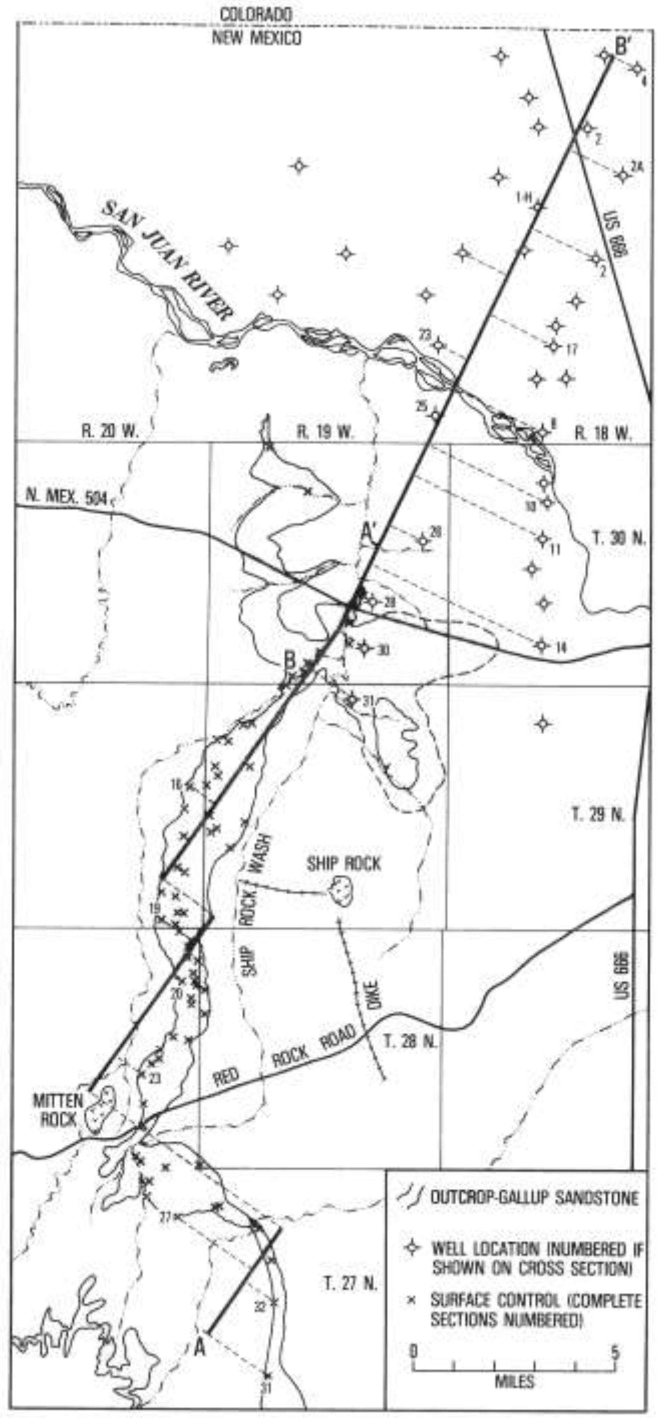


FIGURE 5—LOCATION OF MODEL RELATIVE TO CONTROL POINTS. Note overlap of *A-A'* and *B-B'*. Principal control points and their projection to the line of cross section are shown.

a still older one. This depositional cycle was repeated with the Rock Ridge bar and probably many more times as the sea transgressed southward.

Offshore bars consists of offshore-bar sandstone. The sandstone grades through a transition (offshore-bar transition) into offshore siltstone and mudstone enclosing the bars except where they onlap the beach complex. The bars wedge out landward and have no contiguous landward equivalent; seaward they interfinger with and grade into offshore siltstone and mudstone.

Description of Gallup Sandstone facies

Facies of the Gallup Sandstone are divided into three associations: 1) eolian dune sandstone; 2) facies of the beach cycle, including coal-swamp deposits (characterized by the presence of coal beds and not further discussed), backshore, foreshore, shoreface, and offshore-beach transition; and 3) offshore facies, including offshore siltstone and mudstone and offshore-bar sandstone and its transition. Each association has a discrete external geometric form and distinct internal bedding pattern. Each facies is characterized by diagnostic sedimentary structures. Texture and composition may be similar in adjacent facies; fossils may overlap facies boundaries.

Eolian dune sandstone

External geometry

Eolian dune sandstone in the Gallup Sandstone forms either pods or sheets. The pods rest upon and uncommonly are enclosed in facies of the beach cycle, and the sheets veneer facies of the beach cycle. Both geometric forms may be overlain by offshore facies.

Internal bedding pattern

Dunes consist of a complex of trough-shaped beds or beds bounded by curved nonparallel bedding surfaces. Bed thicknesses range from 6 inches to 5 feet.

Sedimentary structures

Cross laminae compose the trough-shaped beds of dune sandstone, and this structure is commonly termed "festoon cross bedding." Laminae in adjacent beds form a crisscross pattern in exposures perpendicular to the wind direction (figs. 6 and 7) and dip in one direction between nearly parallel bedding surfaces in exposures parallel with the wind direction (figs. 6 and 8). Occasional structures include contorted laminae, root casts, and rare burrows, tracks, and trails. Moreover, where dunes are transgressed by offshore facies, as much as 3 ft of sandstone at the top of the dune may be churned by burrowing marine organisms.

Texture, composition, and fossils

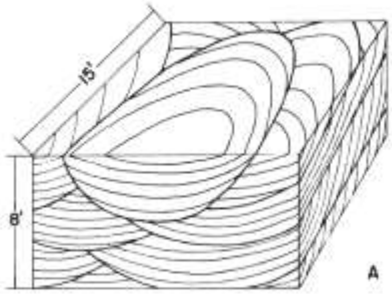
Gallup dune sandstone is well sorted but contains somewhat more fines than the associated beach sandstone (fig. 9). The dune sandstone consists of quartz grains with minor feldspar grains. Dolomite and collophane grains are very rare. No fossils were found in dune sandstone.

The eolian dunes of this paper have been interpreted as distributary channel sandstones by Molenaar (1973, fig. 6). However, the writer rules out a fluvial interpretation due to: 1) lack of the vertical sequence of sedimentary textures and structures typical of fluvial deposits (Campbell, 1976, fig. 6), 2) veneering sheet geometry of many of the sandstone bodies, and 3) stratigraphic association with the beach sandstones. Excellent examples of a variety of fluvial sandstone bodies are present immediately south of the present study area in the coal-swamp facies.

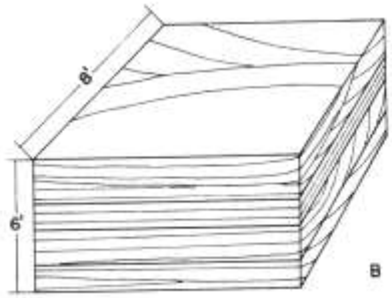
Facies of beach cycle

External geometry

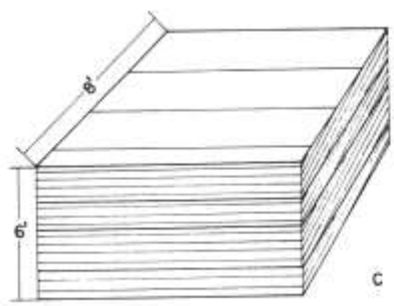
Each beach episode forms an elongated prism that ranges 3-20 ft thick and 1-3 mi wide (fig. 2). The length parallel with the shoreline cannot be measured from the outcrops studied, but may compare with some modern beach shorelines that extend uninterrupted for more than 100 mi. Further, the seaward sloping top of each cycle generally parallels its base, although examples of both seaward and landward convergence are found on fig. 2. Finally, a succession of these beach cycles, each younger one building on the seaward face of the underlying cycle, forms an extensive seaward-imbricated system of sandstone bodies having the general geometric form of a sheet sandstone.



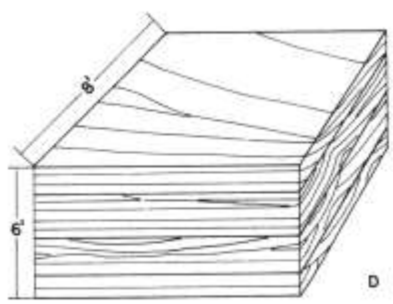
A. Dune structure—In exposures perpendicular to wind direction, dune sandstone shows a crisscross pattern of laminae that compose the trough-shaped beds. In exposures parallel with wind direction, dune sandstone consists of sets of cross laminae that dip in a single direction and are contained between nearly parallel bedding surfaces. Downwind is toward viewer.



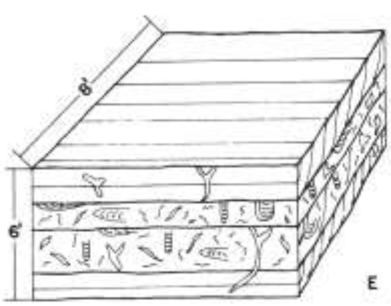
B. Backshore structure—Cross laminae dip in diverse directions between parallel bedding surfaces or are parallel with the bedding surfaces. Seaward is toward viewer.



C. Foreshore structure—Cross laminae dip uniformly seaward between parallel bedding surfaces. Seaward is toward viewer.



D. Shoreface structure—Large-scale truncated wave-ripple laminae form laminasets between parallel bedding surfaces. However, churning by burrowing organisms commonly destroys all evidence of original laminations in shoreface sandstone. Seaward is toward viewer.



E. Offshore-bar structure—Cross laminae in offshore-bar sandstone dip uniformly in a single direction and at a high angle between wavy-parallel bedding surfaces. Cross laminae may be partly to completely destroyed by the churning of burrowing organisms. Downcurrent is toward viewer; seaward is to right.

FIGURE 6—DIAGRAMS COMPARING BEDDING AND LAMINATION PATTERNS (from Campbell, 1971).

FIGURE 7—Dune sandstone bedding nearly perpendicular to wind direction. Axes of troughs and laminae are dipping away from the viewer in this veneer of dune sandstone. View is to northeast at approximately center sec. 25, T. 29 N., R. 20 W.

FIGURE 8—Dune sandstone bedding parallel with wind direction. Bedding surfaces appear parallel and planar; cross laminae dip generally to right. Photograph taken in the area of Stop 7 in road log; west bank of Shiprock Wash, approximately NE¼SW¼ sec. 35, T. 28 N., R. 20 W.

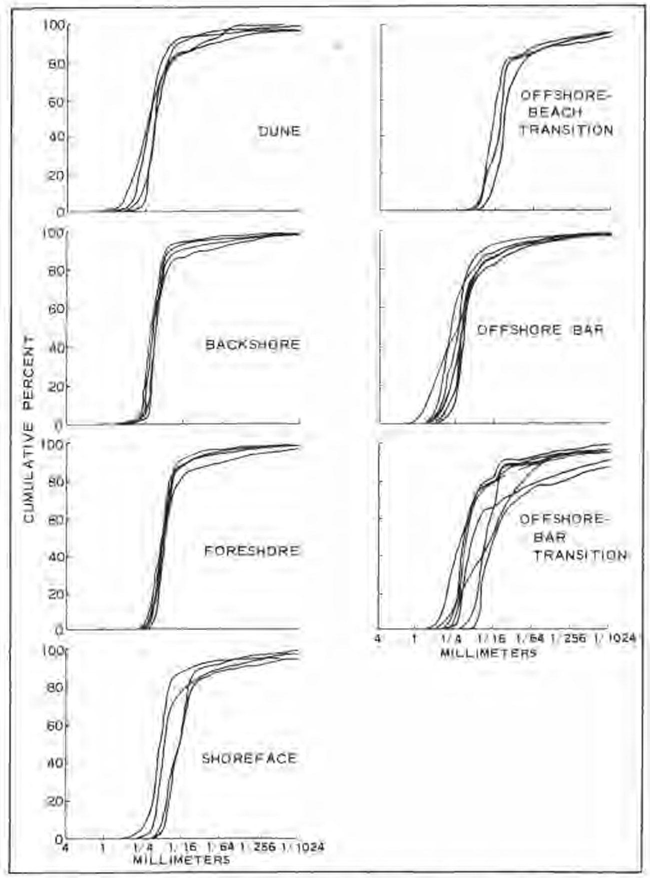


FIGURE 9—Grain-size comparisons. Samples from different Gallup facies are compared (analyses by J. D. Howard).

Internal bedding pattern

Beds composing a beach cycle are bounded by even, parallel bedding surfaces. These surfaces parallel the uppermost seaward-sloping surface of the particular beach episode and continue from coal-swamp deposits through backshore, foreshore, shoreface, and offshore-beach transition into offshore siltstone and mudstone (fig. 10). Occasionally, the bedding surfaces converge or diverge seaward where the beach cycle thins or thickens. Beds range in thickness from 4 inches to 2 ft.

Each younger bed in the vertical sequence of a beach cycle lies slightly seaward from the underlying bed. The youngest bed extends farthest seaward; the oldest, farthest landward. Also the facies changes in each successively younger bed usually are shifted slightly seaward from those in the underlying bed. Because of this imbrication and the pattern of facies changes, beach sandstone bodies commonly are drawn with flat bases and convex-upward tops, even though such interpretations ignore the internal layered structure and facies changes.

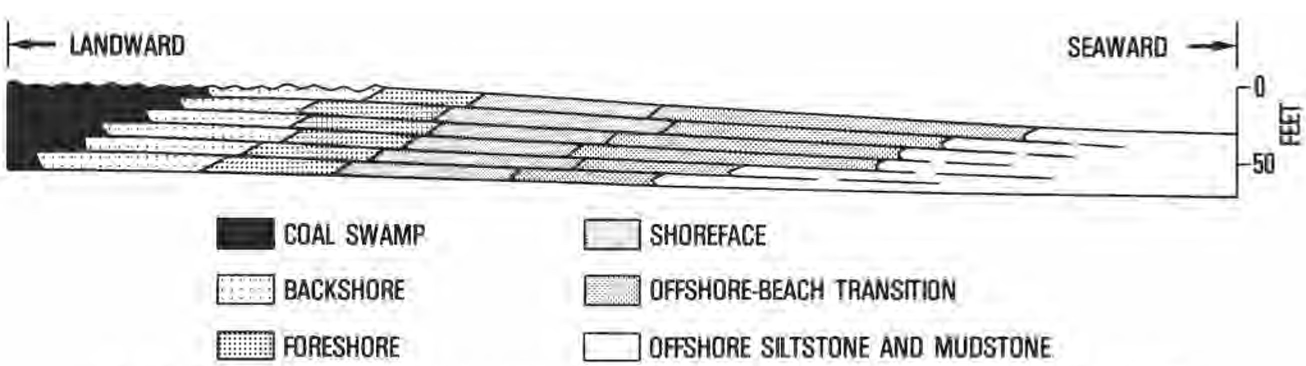


FIGURE 10—Cross-sectional geometry, bedding pattern, and facies of a beach cycle. Note continuity of bedding surfaces through a beach cycle and the bed-by-bed changes in facies.

FIGURE 11—BACKSHORE SANDSTONE. Outcrop is approximately perpendicular to shoreline. Between parallel bedding surfaces most sets of laminae dip to the right or landward, but some sets parallel bedding surfaces and others dip seaward. This exposure is at Stop 7 in the road log. East bank of Shiprock Wash, approximately center S½ sec. 35, T. 28 N., R. 20 W.

FIGURE 12—FORESHORE SANDSTONE. This photograph shows the pattern of cross laminae on bedding surface. Cross laminae dip away from the viewer and have straight traces on a bedding surface, although some traces in this photograph appear curved due to differential erosion into the exposed bed. This photograph was taken at Stop 5 on the road log. View is to southeast, approximately NW ¼ sec. 18, T. 29 N., R. 19 W.

Backshore sandstone

The even, parallel beds of backshore sandstone (figs. 6 and 11) consist of a complex of laminasets that are partially preserved swale fillings. The swales trend generally parallel with the shoreline; laminae may dip from both sides into the swales, but many swales are filled with cross laminae that dip landward. Occasional sets of backshore laminae in the Gallup dip landward with inclination of about 25 degrees but most dips are less than 20 degrees. Laminae in some beds parallel the bedding surfaces. Other uncommon sedimentary structures in backshore sandstone include ripple marks, ripple laminae, rib-and-furrow structure, air-heave structure, and locally profuse burrows.

Foreshore sandstone

Cross laminae in the even, parallel beds of foreshore sandstone dip uniformly in a seaward direction (figs. 6 and 12). Thus, the strike of the cross laminae is parallel with the shoreline. The cross laminae usually dip less than 6 degrees, although dips as great as 20 degrees are found where the beaches were built across tidal inlets. Additional uncommon sedimentary structures in foreshore sandstone include both wave- and current-ripple laminae, parting lineation, swash and rill marks, and vertical burrows.

Shoreface sandstone

Either one or the other of two intergradational structures compose the even, parallel beds of shoreface sandstone. The first is churned or bioturbated structure, where burrowing organisms have churned the sandstone and destroyed the original laminae (fig. 13). Where differences in composition of the sandstone are slight, the churning structure is described as mottled or homogeneous (structureless). The second structure is termed truncated wave-ripple laminae (Campbell, 1966) consisting of truncated sets of wave-ripple laminae that form laminasets (figs. 6 and 14). Crest-to-crest distances (wave lengths) of wave ripples in the Gallup shoreface beds commonly range from 5-15 ft, but lesser wave lengths are found. Heights of the wave ripples average 10 inches. Although crests of individual wave ripples show diverging orientations, their overall trend is parallel with the shoreline. Other sedimentary structures in the shoreface are wave-ripple marks, burrows, and contorted (convolute) laminae.

Offshore-beach transition

In the transition from shoreface to offshore siltstone and mudstone, the shoreface sandstone gradually grades bed by bed into siltstone; the siltstone may grade

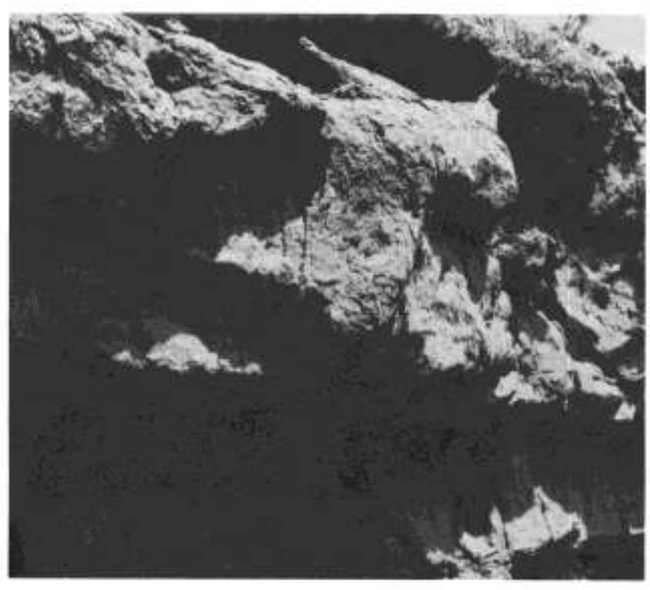


FIGURE 13—CHURNED STRUCTURE IN SHOREFACE SANDSTONE. This sandstone has been homogenized by burrowing organisms; distinct burrows are uncommon. Churned sandstone commonly weathers with rounded, exfoliating surfaces. View to east, approximately S½ sec. 13, T. 29 N., R. 20 W.

FIGURE 14—TRUNCATED WAVE-RIPPLE LAMINAE IN SHOREFACE SANDSTONE. Exposure is perpendicular to shoreline; ledge in the center shows curved parallel laminae extending from a wave crest on the left through a trough onto another crest on the right. These ripples have heights of about 8 inches and a wave length of approximately 13 ft. Elsewhere, laminations dip more steeply into troughs; only small parts of the original forms are usually preserved. View is to east, approximately NE¼SW¼ sec. 24, T 29 N., R. 20 W. (from Campbell, 1966, Fig. 1).

into mudstone. Along with this textural change, truncated wave-ripple structures decrease in wave lengths to less than 1 ft and in wave height to less than 3 inches. Burrowing organisms may obliterate this structure and mix sandstone and siltstone as well as siltstone and mudstone into churned structures. Other structures observed are isolated burrows, wave-ripple marks, and rare current-ripple and contorted laminae.

Texture

Combined sieve and pipette analyses of sandstones from the beach cycles show a gradual seaward decrease in grain size from backshore to offshore-beach transition (fig. 9). Backshore and foreshore sandstones are slightly better sorted than shoreface sandstones; statistical-moment measures (sorting, skewness, and kurtosis) do not clearly distinguish these facies.

Composition

Sandstones within the beach episodes vary little in composition. All consist predominantly of quartz. Feldspar, although minor, is the second most abundant mineral, except in some shoreface sandstones and offshore-beach transition where rock fragments predominate over feldspar. Dolomite, glauconite, and collophane grains are most common in thin sections from the shoreface and offshore-beach transition. Grains of carbon exceed 10 percent of the total volume in some offshore-beach transitions, but are sparse in all other

and mudstones were not analyzed.

Fossils

Megafossils are rare in the beach facies, although *Inoceramus* prisms and fragments along with oyster fragments are present. Plant-fragment imprints are especially abundant in some offshore-beach transitions. However, trace-fossil associations combine with foraminiferal faunas to provide a continuous sequence of

TABLE 1—SEQUENCE OF DIAGNOSTIC TRACE FOSSILS[1] AND FORAMINIFERS ACROSS THE GALLUP SHORELINE (modified from Campbell, 1971).

	Beach		Shoreface	Offshore-Beach Transition and Offshore Siltstone and Mudstone		
	Backshore	Foreshore				
Trace Fossils Associations	*Ophiomorpha*		*Ophiomorpha* Sigmoidal *Teichichnus*	Shallow-marine association — *Ophiomorpha* Sigmoidal *Teichichnus* *Gyrochorte* Arthropod tracks	*Curvolithus* *Rhizocorallium* *Asterosoma* *Rosselia*	*Chondrites* *Phycosiphon* *Scolicia* *Taenidium* *Skolithos*
				Arenaceous[2] Benthonic	Calcareous[2] Benthonic	Planktonic[2]
Foraminiferal Assemblage	None		None	*Ammobaculites* *Haplophragmoides* *Spiroplectammina* *Reophax* *Trochammina* *Anomalina*	*Dentalina* *Marginulina* *Lenticulina* *Anomalina* *Gaudryina* *Frondicularia* *Heterohelix* *Globigerina* *Epistoma* *Trochammina* *Haplophragmoides* *Spiroplectammina* *Globotruncana*	*Heterohelix* *Anomalina* *Globotruncana* *Neobulimina* *Globigerina* *Dentalina* *Lenticulina* *Gyroidina* *Epistoma* *Frondicularia* *Marginulina* *Gavelinella* *Cibicides*

[1] Trace fossils are described by Walter Häntzschel in Teichert, Curt, ed., 1975, Treatise on Invertebrate Paleontology, Part W, Miscellanea, Supplement 1, Trace Fossils and Problematica (2nd ed.): Geol. Soc. America, Boulder, 269 p.

[2] Foraminifers are listed in order of abundance in each assemblage.

diagnostic fossils across the Gallup shoreline (table 1). The backshore and foreshore contain *Ophiomorpha;* the shoreface contains *Ophiomorpha* and sigmoidal *Teichichnus.* The offshore-beach transition as well as offshore siltstone and mudstone contain the shallow-marine association of trace fossils. The offshore-beach transition also contains arenaceous benthonic foraminifera that give way seaward first to calcareous benthoic and then to planktonic foraminifera in the offshore siltstone and mudstone. Spores and pollen are most abundant along with the planktonic foraminifera.

Offshore facies

External geometry

Offshore siltstone and mudstone, the dominant offshore facies, form sheet deposits covering much of the area of the Late Cretaceous shelf seas of interior North America. This dominant facies locally encloses elongated lenses of offshore-bar sandstone and its transition into offshore siltstone and mudstone. An average offshore bar is less than 20 ft thick by 2 mi wide by 4-40 mi long. Where two or more lenses are superposed in regressive order, widths and thicknesses of the composite sandstone body are multiples of the above dimensions. In addition, offshore bars (fig. 15) have a flat landward

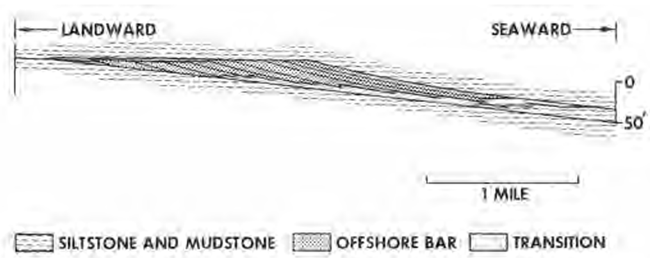


FIGURE 15—CROSS-SECTIONAL GEOMETRY, BEDDING PATTERN, AND FACIES OF AN OFFSHORE BAR. The bar is enclosed in offshore siltstone and mudstone. Landward top is flat; seaward top slopes offshore. Internal pattern of curved parallel lines represents bedding surfaces that parallel the sloping seaward top (from Campbell, 1973).

FIGURE 16—OFFSHORE SILTSTONE AND MUDSTONE. This example is dominantly a mudstone in which laminations parallel bedding surfaces. Ripple-laminated siltstones shown in thin ledge at butt of hammer handle occur locally. View is to west, roadcut along highway between Shiprock, New Mexico, and Cortez, Colorado.

top that diverges seaward from the sloping base and a sloping seaward top that converges with but never intersects the base. Thus, offshore bars wedge out landward and have no adjacent temporal equivalents, but grade seaward through a transition zone into contemporaneous offshore siltstone and mudstone.

Internal bedding pattern

Offshore siltstone and mudstone consists of even and wavy, parallel (sometimes nonparallel) beds that range in thickness from a fraction of an inch to 4 inches (fig. 16). These beds may parallel the top of the deposit, form clinoform patterns, or diverge and then converge to enclose offshore bars.

Beds composing offshore bars are bounded by wavy, parallel bedding surfaces (fig. 17). These surfaces parallel the sloping seaward top of the bar and terminate at the flat landward top but extend seaward across the facies change through the offshore-bar transition (fig. 18) into offshore siltstone and mudstone. Specific bedding surfaces may become obscure in the areas of these facies changes. Furthermore, the beds form a seaward-

FIGURE 17—BEDDING IN OFFSHORE BAR AND ITS TRANSITION. The cross-laminated ledge on which geologist is standing is basal bed of offshore-bar sandstone above the offshore-bar transition. The wavy, parallel bedding characterizes both the bar sandstone and its transition. Location is Stop 3 in road log. East side of Shiprock Wash, approximately S½ sec. 27, T. 30 N., R. 19 W.

imbricated pattern as the oldest beds terminate farthest landward and the youngest extend farthest seaward. Moreover, the beds of offshore-bar sandstone are imbricated parallel with the length of the bar, but the angle of initial dip in this longshore direction is less than in the seaward direction. Beds in both the offshore-bar sandstone and its seaward transition range in thickness from 2 inches to 2 ft.

Offshore siltstone and mudstone

Siltstone beds in the offshore siltstone and mudstone show truncated wave-ripple or current-ripple laminae, along with wave-ripple-marked surfaces. However, both the siltstone and mudstone beds may consist of even, parallel laminae that are concordant with bedding surfaces (fig. 16), and both may be reworked and mixed by burrowing organisms that produce churned and mottled structures. Less important sedimentary structures in offshore siltstone and mudstone include burrows, trails, and minute scour-and-fill structures.

Offshore-bar sandstone

Wavy, parallel beds of offshore-bar sandstone are commonly churned by burrowing organisms (fig. 19), but some consist of preserved planar cross laminae (figs.

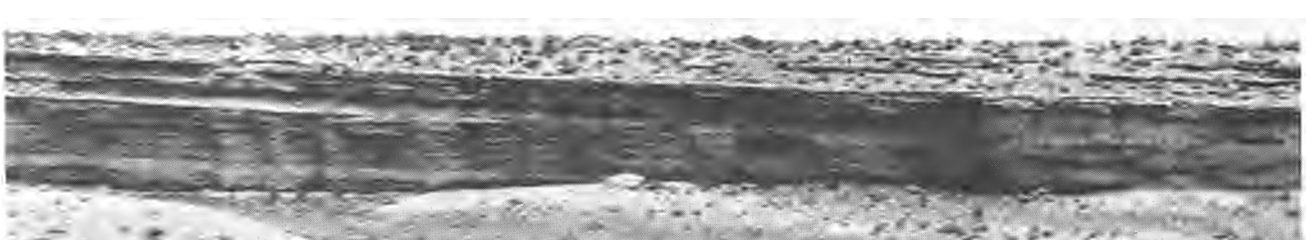


FIGURE 18—SEAWARD FACIES CHANGE OF OFFSHORE-BAR SANDSTONE. Resistant beds of clean bar sandstone at upper left grade into muddy sandstone transition beds forming the sheer face at right. The cliff face is about 15 ft high. Exposure is at Stop 1 in road log. North side of wash, approximately N½ sec. 9, T. 30 N., R. 19 W. (from Campbell, 1973).

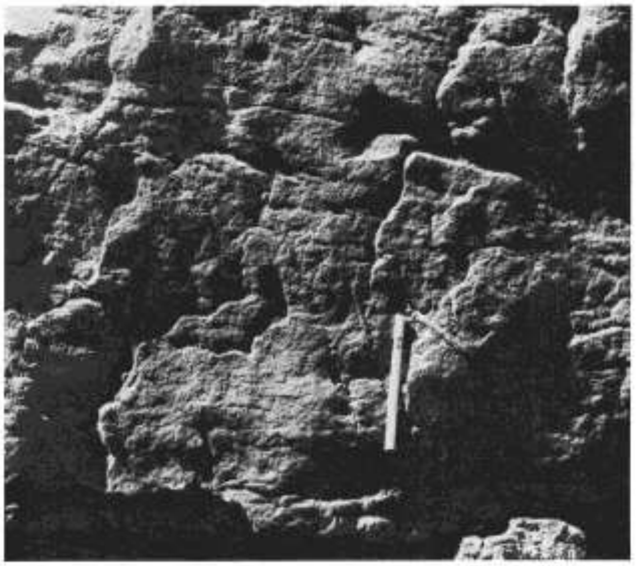


FIGURE 19—CHURNED STRUCTURE IN OFFSHORE-BAR SANDSTONE. The lower bed is churned with two distinct *Ophiomorpha* burrows; the upper bed still shows traces of cross laminae. The bedding surface between the two beds is marked by the horizontal line above the burrow to left of pen. Exposure is at Stop 3 in road log. East bank of Shiprock Wash, approximately S½ sec. 27, T. 30 N., R. 19 W.

FIGURE 20—PLANAR CROSS LAMINAE IN OFFSHORE-BAR SANDSTONE. Cross laminae composing the ledge-forming bed become tangential with the plane base of the bed. Exposure is at Stop 3 in road log. East bank of Shiprock Wash, approximately S½ sec. 27, T. 30 N., R. 19 W. (from Campbell, 1973).

6 and 20). The cross laminae usually dip 20-25 degrees, are convex downward, and become tangent to the plane base of the bed. Cross laminae in superposed beds dip uniformly in one direction (figs. 21 and 22) nearly parallel with the length of the bar (fig. 23). McCubbin (1969) and Lamb (1968) also note this pattern of cross laminae. Additional sedimentary structures in offshore-bar sandstone are burrows and trails, wave-ripple marks, truncated wave-ripple laminae, and contorted laminae.

Offshore-bar transition

Wavy, parallel beds of the offshore-bar transition are characteristically churned by burrowing organisms (fig. 24). Distinct burrows and trails are uncommon. Likewise, original laminae are rarely preserved, although high-angle cross laminae (as in offshore-bar sandstone) and wave-ripple laminae may be present.

FIGURE 21—AIRVIEW OF OFFSHORE-BAR SANDSTONE AT STOP 1 IN ROAD LOG. Traces of sets of cross laminae on bedding surfaces are shown. The traces strike in a generally uniform direction; curves are due largely to differential erosion of the four or more beds exposed. Cross laminae dip to the right, the direction of elongation of the bar. The distance from bottom to top of photo is about two miles. View to northeast, secs. 8 and 9, T. 30 N., R. 19 W. (from Campbell, 1971).

FIGURE 22—CLOSE-UP VIEW OF OFFSHORE-BAR SANDSTONE. Traces of sets of cross laminae shown in fig. 21 are illustrated. Cross laminae dip to right. Exposure is at Stop 1 on the road log; view is to northeast.

Texture

The offshore siltstone and mudstone facies is either an alternation or any gradation between the two lithologies in the facies name. Usually mudstone predominates but siltstone may be more abundant where this facies approaches the transition into beaches or offshore bars. Thin lenses of sandstone, sandy skeletal limestone, or skeletal limestone may be present; grains of carbonaceous material are locally abundant.

The offshore-bar sandstone is coarser and less well sorted than any of the beach or dune sandstones (fig. 9). Sorting also decreases into the offshore-bar transition, which contains 15 percent or more mudstone matrix. Both of these facies may contain up to 7 percent pebbles.

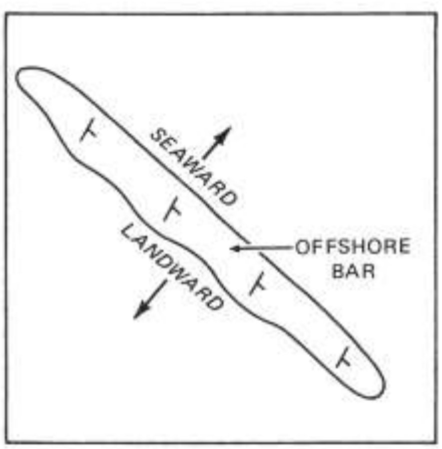


FIGURE 23—DIP OF CROSS LAMINAE COMPARED WITH ELONGATION OF OFFSHORE BAR. Cross laminae dip parallel with the elongation of the bar; the bar is elongated nearly parallel with a distant shoreline (from Campbell, 1971).

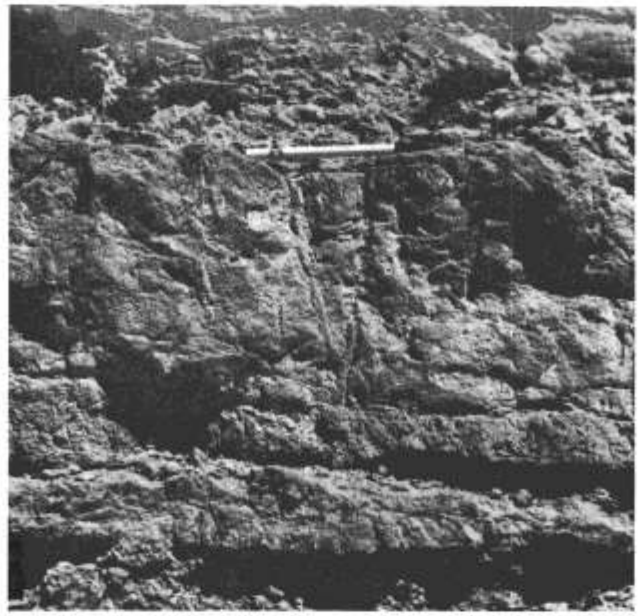


FIGURE 24—CHURNED STRUCTURE IN OFFSHORE-BAR TRANSITION. Burrowing organisms have completely reworked this sand; the distinct vertical burrows are *Ophiomorpha*. Northwest bank of Shiprock Wash, approximately center sec. 33, T. 30 N., R. 19 W. (from Campbell, 1973).

Composition

Both the offshore-bar and the transition sandstone consist predominantly of quartz grains; feldspar grains (although minor) are the second most abundant mineral. Disseminated glauconite is especially abundant in the offshore-bar; dolomite and collophane are more common in the transition than in the bar. Also, rock fragments are present in both facies. The small pebbles are mostly chert but may be of other compositions. Grains of carbon are locally abundant in the transition and are present in the bar sandstone.

Fossils

Megafossils are common in the offshore environment. Molds of ammonites and thin-shelled mollusks are present in offshore siltstone and mudstone. *Inoceramus* fragments are locally abundant in offshore-bar sandstone and occur, along with prisms, in the offshore-bar transition and offshore siltstone and mudstone. Imprints of plant fragments are locally abundant in silty and muddy lithologies and are present in the offshore-bar sandstone.

Foraminiferal assemblages in the offshore siltstone and mudstone change seaward from predominantly arenaceous benthos close to shore to calcareous benthos and then to planktonic forms. The calcareous benthonic assemblage is present in offshore bars and their transitions. In addition, the shallow-marine association of trace fossils is found in offshore bars as well as in offshore siltstone and mudstone.

Comparison of Gallup and Recent nearshore facies

The depositional environment of an ancient deposit is usually interpreted by comparison with a present-day counterpart. However, problems arise in making such comparisons. For example, ancient rocks clearly show bedding patterns and large-scale sedimentary structures that can be exposed only in extensive trenches in modern sediments. But such extensive trenches, except in eolian dune and in the backshore and foreshore of beaches, cannot be excavated in present counterparts of Gallup environments due to covering nearshore waters. Consequently, our knowledge of the subaqueous counterpart of Gallup environments derives from punch and box cores in which the sample may be too small to satisfactorily identify bedding patterns. Preservation of bedding is another problem. Processes responsible for differing bed forms have been studied extensively, but these forms commonly are not preserved in ancient nearshore sediments due to subsequent destruction, apparently by storm currents. Further, some bed forms are erosional and do not conform with the internal depositional sedimentary structures composing the bed form. In spite of these problems, judicious comparisons of ancient rocks with modern sediments results in the best interpretation for the ancient environment.

Stratigraphic and facies relationships

An approximate modern counterpart of the lower Gallup beach complex is the succession of Holocene regressive beaches on the Costa de Nayarit, Mexico (Curray and Moore, 1964; Curray and others, 1969). Cross sections of the Costa de Nayarit show similar relationships to those in the Gallup, except that the basal transgressive sand in the modern example is absent in the ancient. These cross sections are based on surface morphology, lithology and fauna from cores, and geophysical data, but this information does not allow the refinement of facies possible with the Gallup. Thus these cross sections show only the following gross lithologic facies: 1) alluvium and marsh, corresponding to the Gallup coal-swamp facies; 2) littoral sands, equivalent to the Gallup backshore, foreshore, and shore-face; and 3) shelf muds, equivalent to the Gallup offshore siltstone and mudstone.

The regressive depositional patterns and grossly similar facies in the Nayarit and Gallup complexes suggest similar origins. In both examples a number of small rivers have supplied the sand to the shoreline. The sand was worked by waves and longshore currents and formed a strand plain consisting of a seaward-building succession of younger and younger beaches. As the beaches built seaward, alluvial deposits advanced over the landward margins of the strand plain. A difference is eolian dunes spread over much of the Gallup strand plain. Such dunes are inconspicuous on the Costa de Nayarit, apparently due to tropical vegetation and the high level of the ground water.

Eolian dune sandstone

As in the Gallup, present coastal dunes along the south Texas coast consist of a complex of trough-shaped beds. In trench faces perpendicular to wind direction, beds are bounded by curved, nonparallel bedding surfaces; and the cross laminae composing adjacent beds form a crisscross pattern (fig. 25). Further, in faces parallel with the wind direction, the cross laminae dip in one direction often steeper than 25 degrees between nearly parallel bedding surfaces. Milling and Behrens (1966, fig. 8) and McBride and Hayes (1962, fig. 2) have illustrated bedding aspects of these Texas coastal dunes.

Elsewhere coastal dunes have been studied in Brazil by Bigarella (1972) and Bigarella and others (1969, 1970/71). Although these investigators state that tabular planar sets of cross laminae predominate, this writer suggests that trough beds may be much more abundant than they recognized. For example, in their 1969 paper, profile IV in their fig. 9 suggests beds bounded by curved nonparallel bedding surfaces in a trench face perpendicular to the wind direction. In addition, profile I, also in their fig. 9, suggests beds bounded by nearly parallel bedding surfaces with cross laminae dipping generally in one direction. This latter profile is somewhat divergent from the wind direction showing some wedging of bedding surfaces.

Many of the structures observed in modern eolian dunes are not commonly preserved in Gallup dunes,

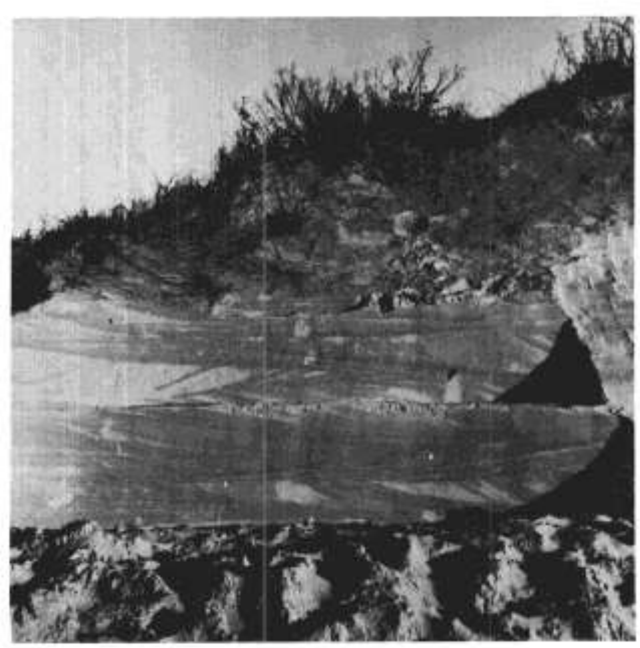


FIGURE 25—Eolian dune bedding. Trench face is perpendicular to wind direction. Observe the crisscross pattern of cross laminae that composed the trough beds (beds bounded by curved, non-parallel surfaces). View is to southeast; Mustang Island, Texas.

where only the foreset or slipface beds and cross laminae are commonly found. Among the uncommonly preserved structures are:

1) Windward-dipping beds and laminae (Bigarella and others, 1969, fig. 8, and 1970/1971, fig. 1; Coastal Research Group, 1969, fig. 1 1 b-1; Land, 1964, fig. 2; McBride and Hayes, 1962, fig. 3; McKee and Tibbitts, 1964, fig. 6; McKee, 1957, plate 3A-B)
2) Various types of slumps and contorted structures (Bigarella and others, 1969, figs. 16-18 and 21-28, and 1970/71, figs. 11-15; McKee, 1957, fig. 4A, and 1966, plates 4B and 5E; McKee and others, 1971)
3) Ripple marks shown on many closeup photographs of dune surfaces (for example, McKee, 1966, plate 2D)
4) Root casts, burrows of rodents and insects, and tracks and trails of animals (commonly observed by the writer).

The process of dune formation and preservation explains why only slipface beds and laminae are usually preserved in ancient dune deposits. As a dune migrates downwind, sand from the windward side is eroded and then redeposited on the slipface. Thus a dune that has migrated beyond its initial position will consist almost entirely of slipface deposits in its lower part. Moreover, only the lower part of the dune will usually be preserved because erosion, both on the windward side of dunes and from the top of a coalescing field of dunes, will be controlled by the surface of the water table within the dunes (Stokes, 1968).

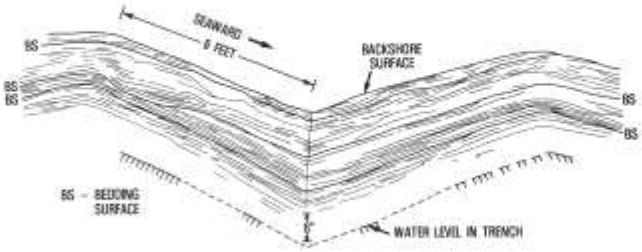


FIGURE 27—Bedding and lamination pattern in modern backshore. Note continuity of bedding surfaces (labelled BS), the patterns of swale-filling laminae in face perpendicular to shoreline and the parallelism of laminae to bedding surfaces in the face parallel with the shoreline. Traced from photograph at northern Padre Island, Texas.

Backshore, foreshore, and shoreface

The continuity of bedding surfaces between the backshore and the foreshore, as commonly observed in the Gallup, is evident in trenches dug across berms on beaches (fig. 26; see also Andrews and van der Lingen 1969, figs. 2 and 3; van Straaten, 1959, fig. 19; Coastal Research Group, 1969, figs. 19-11). However, the continuity of bedding surfaces between the foreshore and shoreface and further into the shallow marine shelf deposits can be observed only in ancient beach deposits; digging extensive trenches in the surf off beaches is presently impractical.

A modern *backshore* swale filling on the low-tide beach of Padre Island, Texas, is shown in fig. 27. Observe laminations dipping into a swale filling as well as the parallel bedding surfaces. Other examples of backshore sedimentary structures have been illustrated by Milling and Behrens (1966, fig. 5), Soliman (1964, figs. 4 and 5), and Moiola and Spencer (1973, plate II-B). Another example (Deery and Howard, 1977, plate 1, fig. 1) from a washover fan shows "subhorizontal stratification" that resembles the even, parallel laminae concordant with bedding surfaces in some Gallup backshore outcrops. Cross laminae dipping landward at steep angles into swales appears to be a feature of the backshore on high-tide beaches such as those described by Hayes and others (1969) rather than on low-tide beaches as along the Texas Gulf Coast.

Figure 28 from the *foreshore* on Padre Island, Texas, illustrates cross laminae that dip seaward at a low angle between parallel bedding surfaces. The dip of the cross laminae is often less than 6 degrees relative to the lower bedding surface. In trenches less than 6 ft long, laminae usually appear parallel with bedding surfaces. Other photographs of foreshore bedding and cross laminae have been published by Andrews and van der Lingen (1969, figs. 2 and 3) and Clifton and others (1971, fig. 8).

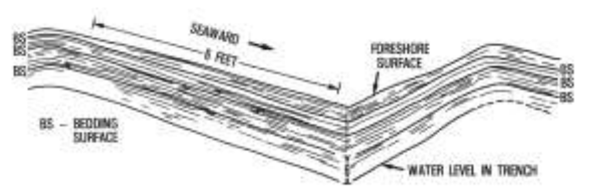


FIGURE 28—Bedding and lamination pattern in modern foreshore. Note relationship of laminae to bedding surfaces (labelled BS). In the face perpendicular to the shoreline, laminae dip seaward at a slightly steeper angle than the bedding surfaces. An exposure about six feet long is needed to determine that the laminae intersect the lower bedding surface. In the face parallel with the shoreline, laminae are parallel with the bedding surfaces. Traced from a photograph, northern Padre Island, Texas.

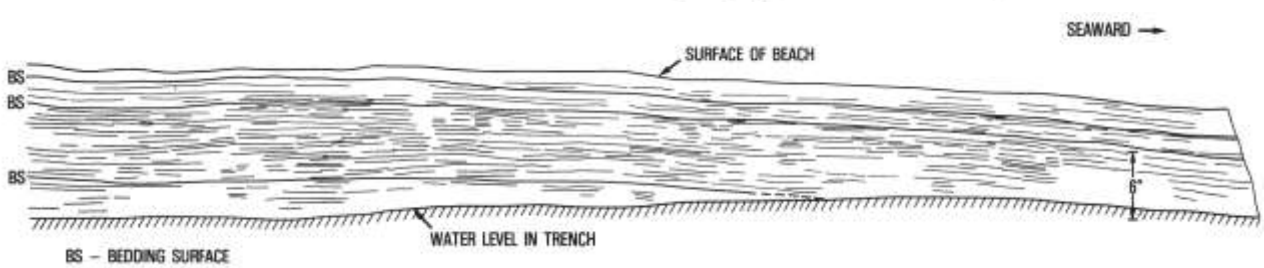


FIGURE 26—Modern deposits across a berm. The berm crest moved successively landward (left) and is located where traces of laminae change from a seaward to a landward or flat altitude. Note parallelism and continuity of bedding surfaces (labelled BS) across this 9-ft-long exposure. Traced from series of photographs at Mustang Island, Texas.

Sedimentary structures from present *shoreface* sands are known principally from punch, box, or can cores. Most of these samples show the churned structure that characterizes one type of Gallup shoreface (for example, Bernard and others, 1962, fig. 10; Howard and Reineck, 1972, fig. 4; Hunter and others 1972, fig. 7; Hill and Hunter, 1976, fig. 2). However, in box cores from the shoreface of Nordernay Island, North Sea, Reineck (1976, plate 1) has identified truncated wave-ripple laminae like those found in the second type of Gallup shoreface. Varying aspects of truncated wave-ripple laminae (Campbell, 1966, fig. 1) have been illustrated from box cores by others including DavidsonArnott and Greenwood (1974, 1976), Clifton and others, (1971, figs. 10b and 18), Hill and Hunter (1976, figs. 6, 7, and 8), Hunter and others (1972, fig. 6), and Howard and Reineck (1972). Most of these cores show sets of laminae that resemble the laminasets consisting of truncated wave-ripple laminae observed in outcrops; the laminasets are components of a still larger layer, the principal layer or bed (Campbell, 1967).

The process of formation of backshore, foreshore, and shoreface structures, except for the parallel bedding, can be observed on many beaches. Backshore laminasets form in swales as waves wash sand and water over the berm crest, and water drains from the swales. Foreshore laminae are deposited by the backrush of the swash from breaking waves. Shoreface large-scale wave-ripple laminae apparently form as waves break in their advance across the surf zone. For explanations of these processes, basic references are Davis and Ethington (1976) and Komar (1976).

The mechanics of forming the parallel bedding surfaces that continue through the backshore, foreshore, and shoreface have not been observed. Presumably, such bedding surfaces form during storms when waves with maximum energy erode the beach to some critical depth. This maximum energy of the waves would tend to have a constant value because fetch, a critical factor in wave development, is controlled by the constant size and configuration of the body of water on which a specified beach is located. A further control seems to be that the body of water must be subjected to tidal fluctuations, for bedding surfaces through beaches bordering nontidal bodies of water are not continuous (Panin, 1967, figs. 5 and 6; Logvinenko and Remizov, 1964, figs. 5, 6, and 7). Consequently, when the sand supplied to the beaches from a tidal sea exceeds the amount removed by storms, a succession of parallel bedding surfaces continuing through shoreface, foreshore, and backshore could be preserved. Such cyclic removal and addition of sand to beaches has been recorded by many students of beaches (Hayes and Boothroyd, 1969; Hayes, 1972).

Offshore facies

Offshore siltstone and mudstone

Textures and sedimentary structures like those in the Gallup offshore siltstone and mudstone are illustrated from modern shelf sediment cores by many workers (for example, Curray 1960, fig. 15; Howard and Reineck, 1972, fig. 4). Foraminiferal faunas are especially useful in identifying this facies because silts and muds showing similar textures and structures may occur in other environments such as lagoons and bays. Also the gradual change in composition of the foraminiferal population may indicate the approximate depth of water and distance from the shoreline during deposition.

Offshore bars

As modern counterparts of offshore bars are not known to the writer, interpretation of their origins is open to question; such interpretations must be based upon observable attributes. Further, Gallup offshore bars are not unique. Among the sandstone bodies with the same characteristics observed by the writer in other Upper Cretaceous outcrops are: basal Mesaverde sandstone on the North Platte River, Rawlins Uplift, Wyoming; basal Blair sandstone, Rock Springs Uplift, Wyoming; and some Ferron Sandstone bodies near Price, Utah (see also Cotter, 1975).

Subsurface examples identified by the writer include some Lower Cretaceous Viking and Upper Cretaceous Cardium sandstone bodies in Alberta, Canada. Furthermore, Evans (1970) described an imbricated complex of probable offshore bars from the Viking in Saskatchewan, Canada. Spearing (1976) identified offshore bars in the outcrops of the Upper Cretaceous Shannon Sandstone in Wyoming. Probable examples of oil-producing offshore bars have also been identified by several workers in Wyoming (Davis, 1976; Lange, 1976; and Crews and others, 1976).

Attributes of the Gallup offshore bars previously described suggest that the following combination of conditions prevailed during their formation:

1. Offshore bars form on a shallow-marine shelf that may be more than 100 mi wide. The marine fauna as well as the geologic setting indicate a depositional site on a shelf.

2. Offshore bars form 11 mi (or more) seaward from contemporaneous shoreline (beach) deposits. This minimum distance is determined by projecting intervals containing offshore bars shoreward in accordance with the pattern of correlation lines shown on fig. 2. The Bisti-Gallegos, Ship Rock, Rock Ridge, and Beautiful Mountain bars transgress the beach complex and presumably have shoreline equivalents many miles south of the study area.

3. The source of sand for a particular offshore bar was a shoreline deposit as much as 200 mi northwest of the depositional site. The direction to the source is indicated by the persistent southeastward dip of cross laminae in all bars; the distance is indicated by the absence of any possible source along the path of transport to the most southeasterly bars in the San Juan Basin. Also the supply of sand was limited because sand does not form a continuous deposit across the shelf from source to depositional site. Finally, the texture of the closest beach deposits is so different from the bar sandstone that a possible beach source is precluded.

4. A temporary stillstand of sea level during deposition is indicated by the absence of landward contemporaneous deposits contiguous to each offshore bar. If subsidence had accompanied deposition, contemporaneous deposits should be present landward of the bars.

If uplift of as much as 20 ft took place, the bar would have been destroyed. In addition, both the external geometry and internal layering patterns of the offshore bars suggest deposition during a period of constant water depth.

5. Bottom currents, indicated by the persistent dip direction of cross laminae within the bars, flowed nearly parallel with the distant shoreline and parallel with the length of the bar. These currents maintained velocities great enough to transport pebbles. Although the origin of these currents is unknown, some type of tidal current could have been the transporting agent.

6. A seaward steepening in slope (a terrace edge) localized deposition of sand. The slope probably increased in dip less than 1 degree; the trend of this break in slope diverged downcurrent only slightly from the distant shoreline. Judging from their external geometry, internal bedding pattern, and stratigraphic reconstruction, offshore bars never formed ridges on the sea floor.

7. The water depth at the break in slope was at some critical depth. Above this depth sand was in transit; below this depth sand was deposited. Stratigraphic reconstruction along with paleobathymetry based on foraminifers suggest that the critical depth for the break in slope was near 200 ft. Further, both a critical depth for the break in slope and its presence are dictated by the absence of a contiguous landward equivalent, the external geometry, and the internal layering pattern of the offshore bars.

Figure 29 outlines the inferred process for the deposition of an offshore bar. A sand-transporting current, sweeping across the break in slope at a slight angle to the trend of the break, dropped sand immediately below the break and thus began forming the first bed of an offshore bar. A minor bend in the break could localize initial deposition (A). With continuing deposition, each bed grew by advancing downcurrent along a front that commonly extended for as much as 2 mi **(B).** This front trended approximately perpendicular to the break in slope and to the ultimate long dimension of the growing bar.

Each bed formed as sand spilled over the break in slope and formed cross laminae upon cross laminae. Thus, sand composing each successive cross laminae was swept across the edges of previously deposited laminae. This process is self-truncating and would maintain a nearly plane scoured surface. Furthermore, as the laminae composing the bed extended into deeper and deeper water, more and more fine sediments were deposited with the sand. Hence, the bed then grades seaward into siltstone and mudstone through a transition composed of mixed sand and mud.

Next, a temporary interruption in the supply of sediment or some other change terminated the formation of the bed. Then burrowing organisms destroyed most of the original laminae before the process of forming a new bed began again. Accordingly, the landward edge of each successive bed lies somewhat seaward from the underlying one; the bed also extends somewhat farther seaward than the underlying one. Bar formation eventually terminated with subsidence (or sea-level rise) and deposition of silt and mud across the top of the bar (C).

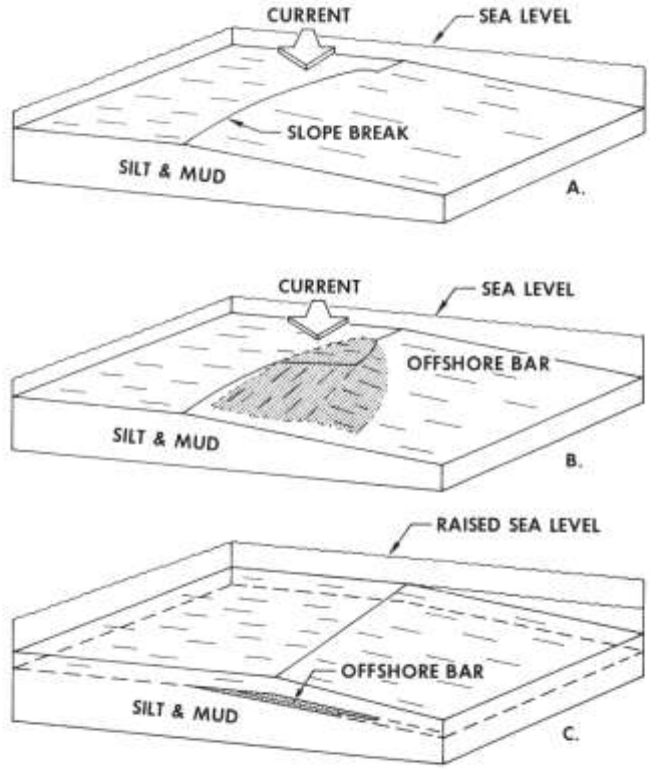


FIGURE 29—Stages in evolution of offshore bars (from Campbell, 1973).

A. Initial conditions include a break in slope at a critical water depth on an open shelf, where currents flow approximately parallel with the break in slope.

B. The bar builds downcurrent as sand is deposited immediately below the downcurrent-advancing break in slope. As the current moves sand across the edges of previously deposited beds, these edges are maintained as a near plane. Maintenance of this level surface requires a critical depth of water at the break in slope. Above this depth sand is in transport; below this depth sand is deposited. A stillstand of sea level is also required to maintain the transport-to-sediment relation at a constant value.

C. Subsidence (or sea-level rise) terminates offshore bar deposition, and the bar is then buried by shelf silts and muds. These stratigraphic relations could result simply from cessation of the sand supply and continuous deposition of shelf silt and mud; or uplift could terminate offshore bar deposition, but the bar might not be preserved below silts and muds.

Application of model to petroleum exploration

In the exploration for oil and gas, depositional models are used to predict both the location and the quality of reservoir rock in a prospect. Further, once hydrocarbons are found, the depositional model aids in developing the reservoir.

An excellent example of the use of a beach-shoreline depositional model in exploring for gas in the San Juan Basin has been described by Hollenshead and Pritchard (1961). These investigators studied the beach sandstone complexes in the Point Lookout and Cliff House Formations of the Mesaverde Group (Upper Cretaceous) and conclude ". . . the sandstone zones of the Mesaverde group, within the San Juan basin, possess a definable geometric pattern of distribution. By establishing this pattern it is possible to project with a reasonable degree of accuracy known producing sandstone benches into relatively unexplored areas. This pattern of distribution, the varying lithologic characteristics of the sand benches, the degree of fracturing, and possibly certain hydrodynamic factors, control gas accumulation and production."

The definable geometric pattern is also well illustrated by the distribution of gas pools in the regressive beach-shoreline Pictured Cliffs Formation, an Upper Cretaceous formation above the Mesaverde Group (Brown, 1973).

In addition to the gross geometric and lithologic aspects emphasized by Hollenshead and Pritchard, the present Gallup model provides the following types of information useful in prospecting for oil and gas in beach deposits. First, knowledge of the stratigraphic relationships between the beach sandstone and capping and laterally equivalent rocks enables better prediction of the nature of the reservoir seal and of the migration paths from the hydrocarbon source to the reservoir. Second, stratigraphic relationships along with the distribution of facies within the beach sandstone body provide a basis for evaluating volumes both of the reservoir and of the aquifer providing the water drive. Third, differing porosity and permeability characteristics of the internal facies allows better prediction of the patterns of fluid movement within the reservoir.

The model for offshore bars may also be applied to exploration for offshore-bar reservoirs. Such bars are usually anomalous lenses enclosed in marine shale. The lenses are thin, narrow, and elongated; they occur in extensive linear trends that nearly parallel distant shorelines (fig. 1; see also Crews and others, 1976; Spearing, 1976).

References

Andrews, P. B., and van der Lingen, G. J., 1969, Environmentally significant sedimentologic characteristics of beach sands: New Zealand Journal of Geology and Geophysics, v. 12, p. 119-137

Bernard, H. A., LeBlanc, R. J., and Major, C. F., 1962, Recent and Pleistocene geology of southeast Texas, *in* Geology of the Gulf Coast and central Texas, Guidebook of excursion, E. H. Rainwater and R. P. Zingula, eds.: Houston Geological Society, p. 175-224

Bigarella, J. J., 1972, Eolian environments: their characteristics, recognition, and importance, *in* Recognition of ancient sedimentary environments, J. K. Rigby and W. K. Hamblin, eds.: Society of Economic Paleontologists and Mineralogists, Spec. Pub. No. 16, p. 12-62

Bigarella, J. J., Becker, R. D., and Duarte, G. M., 1969, Coastal dune structures from Parana (Brazil): Marine Geology, v. 7, p. 5-55

Bigarella, J. J., Duarte, G. M., and Becker, R. D., 1970-1971, Structural characteristics of the dune, foredune, interdune, beach, beach-dune ridge and sandridge deposits: Boletin de Paranaense de Geociencias, n. 28-29, p. 9-72

Brown, C. F., 1973, A history of the development of the Pictured Cliffs Sandstone in the San Juan Basin of northwestern New Mexico, *in* Cretaceous and Tertiary Rocks of the Southern Colorado Plateau, J. E. Fasset, ed.: Four Corners Geological Society, Mem., p. 178-184

Busch, D. A., 1959, Prospecting for stratigraphic traps: American Association of Petroleum Geologists, Bull., v. 43, p. 2829-2843

Campbell, C. V., 1966, Truncated wave-ripple laminae: Journal of Sedimentary Petrology, v. 36, p. 825-828

, 1967, Lamina, laminaset, bed, and bedset: Sedimentology, v. 8, p. 7-26

, 1971, Depositional model—Upper Cretaceous Gallup beach shoreline, Ship Rock area, northwestern New Mexico: Journal of Sedimentary Petrology, v. 41, p. 395-401

_____________, 1973, Offshore equivalents of Upper Cretaceous Gallup beach sandstone, northwestern New Mexico, *in* Cretaceous and Tertiary Rocks of the southern Colorado Plateau, J. E. Fasset, ed.: Four Corners Geological Society, Mem., p. 78-84

1976, Reservoir geometry of a fluvial sheet sandstone: American Association of Petroleum Geologists, Bull., v. 60, p. 1009-1020

Clifton, H. E., Hunter, R. E., and Phillips, R. L., 1971, Depositional structures and processes in the non-barred high-energy nearshore: Journal of Sedimentary Petrology, v. 41, p. 651-670

Coastal Research Group, University of Massachusetts, 1969, Coastal environments of northeastern Massachusetts and New Hampshire: Department of Geology, University of Massachusetts, Field trip guidebook, 462 p.

Cotter, Edward, 1975, Late Cretaceous sedimentation in a low-energy coastal zone: the Ferron Sandstone of Utah: Journal of Sedimentary Petrology, v. 45, p. 669-685

Crews, G. C., Barlow, J. A., Jr., and Haun, J. D., 1976, Upper Cretaceous Gammon, Shannon, and Sussex Sandstones, central Powder River Basin, Wyoming: Wyoming Geological Association, Guidebook 28th annual field conference, p. 9-20

Curray, J. R., 1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico, *in* Recent sediments, northwest Gulf of Mexico, F. P. Shepard, F. B. Phleger, and T. H. van Andel, eds.: American Association of Petroleum Geologists, p. 221-266

Curray, J. R., Emmel, F. J., and Crampton, P. J. S., 1969, Holocene history of a strand plain, lagoonal coast, Nayarit, Mexico, *in* Coastal lagoons, a symposium, A. A. Castanares and F. B. Phleger, eds.: Universidad Nacional Autonomade Mexico-United Nations Educational, Scientific, and Cultural Organization, Mexico D. F., p.63-100

Curray, J. R., and Moore, D. G., 1964, Holocene regressive littoral sand, Costa de Nayarit, Mexico, *in* Deltaic and shallow marine deposits, L. M. J. U. van Straaten, ed.: Amsterdam, Elsevier Publishing Company, p. 76-82

Dane, C. H., 1960, The boundary between rocks of Carlile and Niobrara age in San Juan Basin, New Mexico and Colorado: American Journal of Science (Bradley volume), v. 258-A, p. 46-56

Davidson-Arnott, R. G. D., and Greenwood, Brian, 1974, Bedforms and structures associated with bar topography in the shallow-water wave environment, Kouchibouguac Bay, New Brunswick, Canada: Journal of Sedimentary Petrology, v. 44, p. 698-704

, 1976, Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick, Canada, *in* Beach and nearshore sedimentation, R. A. Davis and R. L. Ethington, eds.: Society of Economic Paleontologists and Mineralogists, Spec. Pub. No. 24, p. 149-168

Davis, M. J. T., 1976, An environmental interpretation of the Upper Cretaceous Shannon Sandstone, Heldt Draw Field, Wyoming: Wyoming Geological Association, Guidebook 28th annual field conference, p. 125-138

Davis, R. A., and Ethington, R. L., 1976, Beach and nearshore sedimentation: Society of Economic Paleontologists and Mineralogists, Spec. Pub. No. 24,187 p.

Deery, J. R., and Howard, J. D., 1977, Origin and character of washover fans on the Georgia coast, U.S.A.: Gulf Coast Association of Geological Societies, Transactions, v. 27, p. 259-271

Evans, W. E., 1970, Imbricate linear sandstone bodies of Viking Formation in Dodsland-Hoosier area of southwestern Saskatchewan, Canada: American Association of Petroleum Geologists, Bull., v. 54, p. 469-486

Hayes, M. 0., 1972, Forms of sediment accumulation in the beach zone: *in* Waves on beaches and resulting sediment transport, R. E. Meyer, ed.: New York, Academic Press, p. 297-356

Hayes, M. 0., Anan, F. S., and Bozeman, R. N., 1969, Sediment dispersal trends in the littoral zone: a problem in paleogeographic reconstruction, *in* Coastal Environments of Northeastern Massachusetts and New Hampshire: University of Massachusetts Coastal Research Group, Field trip guidebook, Contr. No. 1-CRG, p. 290-315

Hayes, M. 0., and Boothroyd, J. C., 1969, Storms as modifying agents in the coastal environment, *in* Coastal environments of northeastern Massachusetts and New Hampshire: University of Massachusetts Coastal Research Group, Field trip guidebook, Contr. No. 1-CRG, p. 245-265

Hill, G. W., and Hunter, R. E., 1976, Interaction of biological and geological processes in the beach and nearshore environments, northern Padre Island, Texas, *in* Beach and nearshore sedimentation, R. A. Davis and R. L. Ethington, eds.: Society of Economic Paleontologists and Mineralogists, Spec. Pub. No. 24, p. 169-187

Hollenshead, C. T., and Pritchard, R. L., 1961, Geometry of producing Mesaverde sandstones, San Juan Basin, *in* Geometry of sandstone bodies, J. A. Peterson and J. C. Osmond, eds.: Tulsa, American Association of Petroleum Geologists, p. 98-118

Howard, J. D., and Reineck, Hans-Erich, 1972, Georgia coastal region, Sapelo Island, U.S.A.: Sedimentology and biology. IV. Physical and biogenic sedimentary structures of the nearshore shelf: Senckenbergiana Maritima, v. 4, p. 81-123

Hunter, R. E., Watson, R. L., Hill, G. W., and Dickinson, K. A., 1972, Modern depositional environments and processes, northern and central Padre Island, Texas, *in* Padre Island National Seashore field guide: New Orleans, Gulf Coast Association of Geological Societies, p. 1-27

Komar, P. D., 1976, Beach processes and sedimentation: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 429 p.

Lamb, G. M., 1968, Stratigraphy of the lower Mancos Shale in the San Juan Basin: Geological Society of America, Bull., v. 79, p. 827-854

, 1973, The lower Mancos Shale in the northern San Juan Basin, *in* Cretaceous and Tertiary rocks of the southern Colorado Plateau, J. E. Fasset, ed.: Four Corners Geological Society, Mem., p. 72-77

Land, L. S., 1964, Eolian cross-bedding in the beach dune environment, Sapelo Island, Georgia: Journal of Sedimentary Petrology, v. 34, p. 389-394

Lange, A. U., 1976, Trabing field: Wyoming Geological Association, Guidebook 28th annual field conference, p. 179-186

Logvinenko, N. V., and Remizov, I. N., 1964, Sedimentology of beaches on the north coast of the Sea of Azov; *in* Deltaic and shallow marine deposits, L. M. J. U. van Straaten, ed.: Amsterdam, Elsevier Publishing Company, p. 245-252

McBride, E. F., and Hayes, M. 0., 1962, Dune cross-bedding on Mustang Island, Texas: American Association of Petroleum Geologists, Bull., v. 46, p. 546-551

McCubbin, D. G., 1969, Cretaceous strike-valley sandstone reservoirs, northwestern New Mexico: American Association of Petroleum Geologists, Bull., v. 46, p. 546-551

McKee, E. D., 1957, Primary structures in some Recent sediments: American Association of Petroleum Geologists, Bull., v. 41, p. 1704-1747

, 1966, Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas): Sedimentology, v. 7, p. 1-69

McKee, E. D., Douglass, J. R., and Rittenhouse, S., 1971, Deformation of lee-side laminae in eolian dunes: Geological Society of America, Bull., v. 82, p. 359-378

McKee, E. D., and Tibbitts, G. C., 1964, Primary structures of a seif dune and associated deposits in Libya: Journal of Sedimentary Petrology, v. 34, p. 5-17

Milling, M. E., and Behrens, E. W., 1966, Sedimentary structures of beach and dune deposits, Mustang Island, Texas: University of Texas, Publications of Institute of Marine Science, v. 11, p. 135-148

Moiola, R. J., and Spencer, A. B., 1973, Sedimentary structures and grain-size distribution, Mustang Island, Texas: Gulf Coast Association of Geological Societies, Transactions, v. 23, p. 324-332

Molenaar, C. M., 1973, Sedimentary facies and correlation of the Gallup Sandstone and associated formations, northwestern New Mexico: *in* Cretaceous rocks of the southern Colorado Plateau, J. E. Fasset, ed.: Four Corners Geological Society, Mem., p. 85-110

, 1974, Correlation of the Gallup Sandstone and associated formations, Upper Cretaceous, eastern San Juan and Acoma Basins, New Mexico: New Mexico Geological Society, Guidebook 25th field conference, p. 251-258

, 1977, Stratigraphy and depositional history of Upper Cretaceous rocks of the San Juan Basin area, New Mexico and Colorado, with a note on economic resources: New Mexico Geological Society, Guidebook 28th field conference, p. 159-166

Panin, N., 1967, Structures des depots de plage sur cote de la Mer Noire: Marine Geology, v. 5, p. 207-219

Parker, J. M., Riggs, E. A., and Fisher, W. L., 1977, Oil and gas potential of the San Juan Basin: New Mexico Geological Society, Guidebook 28th field conference, p. 227-234

Penttilla, W. C., 1964, Evidence for the pre-Niobrara unconformity in the northwestern part of the San Juan Basin: The Mountain Geologist, v. 1, p. 3-14

Reese, V. R., 1977, Oil and gas potential of the Gallup Formation-a fourth stratigraphic producing interval of the inner San Juan Basin: New Mexico Geological Society, Guidebook 28th field conference, Supplement, p. 23-29

Reineck, Hans-Erich, 1976, Primargefuge, Bioturbation and Makrofauna als Indikatoren des Sandversatzes im Seegebiet vor Norderney (Nordsee): Senkenbergiana Maritima, v. 8, no. 4/6, p. 155-169

Sabins, F. F., Jr., 1963, Anatomy of stratigraphic trap, Bisti field, New Mexico: American Association of Petroleum Geologists, Bull., v. 47, p. 193-228

, 1972, Comparison of Bisti and Horseshoe Canyon stratigraphic traps, San Juan Basin, New Mexico: American Association of Petroleum Geologists, Mem. 16, p. 610-622

Soliman, S. M., 1964, Primary structures in a part of the Nile delta sand beach: *in* Deltaic and shallow marine deposits, L. M. J. U. van Straaten, ed.: Amsterdam, Elsevier Publishing Company, p. 379-387

Spearing, D. R., 1976, Upper Cretaceous Shannon Sandstone: an offshore, shallow-marine sandbody: Wyoming Geological Association, Guidebook 28th annual field conference, p. 65-72

Stokes, W. L., 1968, Multiple parallel-truncation bedding planes-a feature of wind-deposited sandstone formations: Journal of Sedimentary Petrology, v. 38, p. 510-515

Thompson, G. G., 1972, Palynologic correlation and environmental analysis within the marine Mancos Shale of southwestern Colorado: Journal of Sedimentary Petrology, v. 42, p. 287-300

van Straaten, L. M. J. U., 1959, Minor structures of some Recent littoral and neritic sediments: Geologie en Mijnbouw, v. 21, p. 197-216

Walther, Johannes, 1894, Einleitung in die Geologie als historische Wissenschaft: Gustav Fischer, Jena, 1055 p.

Appendix 1

Discussion of depositional zones, depositional environments, and sedimentary facies

The terms used in this report are defined and discussed in this appendix. Figure 30, a hypothetical profile across a regressive beach shoreline, shows depositional zones and environments represented by the sedimentary facies identified in the Gallup Sandstone in northwestern New Mexico. Other profiles would illustrate different environments within these zones.

Depositional zones, depositional environments, and sedimentary facies are all interrelated. Depositional zones are both geomorphic and geographic: the nearshore zone is along the margin of the sea; the coastal zone includes the adjacent land; and the offshore zone includes the water-covered adjacent shelf. Each zone contains a variety of depositional environments; and each environment is identified by a set of complex physical, chemical, and biological conditions. These conditions are recorded in the rocks by specific combinations of structures, textures, and fauna that identify different sedimentary facies. Sedimentary facies are "the distinguishing features of simultaneously formed rocks" (Gressly's definition as quoted by Walther, 1894). Thus coal-swamp, beach, and offshore deposits formed contemporaneously are facies. In general, facies are designated by the environmental name modifying a lithologic type or deposit—for example, beach sandstone and coal-swamp deposit. Some environments are divided into subfacies; for example, backshore, foreshore, and shoreface sandstones are subfacies of beach sandstone.

Depositional zones

The hypothetical profile across a regressive shoreline consists of three depositional zones: coastal, nearshore, and offshore.

Coastal zone

The coastal zone lies landward from the usual upper limit of storm tides. Catastrophic storm tides, such as hurricanes, may flood low-lying portions of this coastal zone. The seaward boundary of the coastal zone coincides with the seaward limit of a dune marginal to a coal swamp. This zone extends inland to the first major change in topography or the line where sediments transported in streams begin to aggrade the coastal plain.

Of the wide variety of environments and corresponding facies that may be found in the coastal zone, only eolian dune and coal swamp are discussed here. Other environments that may be present are marshes, lakes, and a wide variety of fluvial channels and associated natural levees and floodplains.

Nearshore zone

For a beach shoreline, the nearshore zone extends from the usual upper limit of storm tides to the seaward limit of sand deposition. The seaward limit off beaches along many modern coasts is in 20-30 ft of water. In this zone, which may be a few hundred feet to several miles wide, deposits form under conditions ranging from subaerial and brackish to shallow marine.

The nearshore zone is usually best developed along shore from a source of clastic sediments; usually this zone is least well defined along the seaward margin of a growing delta. However, a wide zone fitting this description may form during destructive phases of a delta's history. Then, delta margin islands, separated from the coast by bays, may form near the original seaward extent of the initial subaerial delta.

The nearshore zone may or may not consist of a complex of environments. The simplest examples are land-attached beaches or tidal flats. The example in fig. 30 includes a land-attached beach along the seaward side of a coal swamp, a lagoon that eventually became a coal swamp, and a barrier beach that became land attached as the swamp replaced the lagoon. The beaches are topped by eolian dunes. Other marine environments include estuary and bay or sound. Freshwater environments on barrier beaches include marsh, swamp, and lake.

Offshore zone

The offshore zone extends seaward from the nearshore zone to the edge of the continental shelf. This zone is a nearly flat surface compared to the somewhat steeper surface of the nearshore zone. The width of the offshore zone varies with the width of the continental shelf; water depths over the shelf increase gradually seaward to about 400 ft.

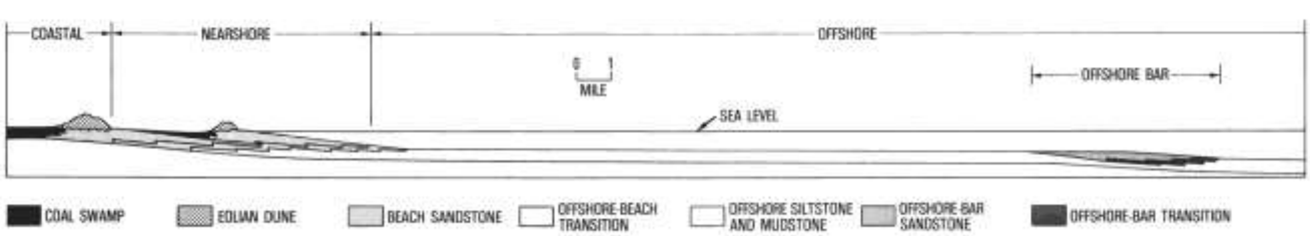


FIGURE 30—HYPOTHETICAL PROFILE ACROSS A REGRESSIVE BEACH SHORELINE. Positions of the coastal, nearshore, and offshore depositional zones are shown as well as the distribution of facies (the rock records of the different depositional environments).

Because the facies of the offshore zone is usually recorded in siltstone and mudstone, the several depositional environments within the zone are difficult to distinguish. However, offshore bars and their transitions interrupt the monotony of the siltstone and shale in the Gallup offshore zone. Elsewhere the zone may include biogenic carbonate bodies.

Depositional environments and facies

Only the depositional environments and their corresponding facies identified across the Gallup beach shoreline are discussed here. Other types of shorelines that have counterparts in the geologic record are deltaic, tidal-flat, and marsh or swamp. This latter is marked by the merging of swamp or marsh muds and similar appearing shelf muds and therefore is especially difficult to identify in the geologic column.

Eolian

The eolian environment is dominated by wind. Conditions in this environment include a surface source of sand, a climate allowing the sand to dry out, and a prevailing wind velocity sufficient to drive the sand into mounds or ridges. Eolian dunes are mounds or ridges composed of wind-deposited sand or gravel. Along shorelines dunes derive their sand from adjacent beaches; the sand is deposited by unidirectional or occasionally fluctuating air currents. The facies product of the eolian environment is *eolian dune sandstone.*

Coal swamp

The coal-swamp environment favors prolific growth of plants that appear in the geologic record as coal beds. The swamps were commonly freshwater but also were brackish when associated with marine shorelines. Swamps may extend for tens of miles inland. *Coal-swamp deposits,* the facies designation for this environment, are characterized by the presence of coal beds; but usually the predominant lithologies are carbonaceous siltstone and mudstone. Channel-filling sandstone is a minor rock type.

Beach and shoreface

The beach and shoreface environments are dominated by wave impact. Beach is commonly defined as the sandy or gravelly zone along the margin of a body of water. Along a sea this zone lies between the highest and lowest normal tide levels. However, this definition is unsatisfactory because it applies equally well to tidal flats. Consequently, beach is redefined as a zone along a body of water that consists of the transient clastic material that is worked and deposited by wave action and lies in dynamic repose between the lowest tide level and the highest noncatastrophic storm-tide level. Being in dynamic repose, beaches are subject to rapid changes in width and thickness by normal wave action; and catastrophic storms, such as hurricanes, may completely destroy the beach.

Beaches conform to a characteristic profile (fig. 31) that includes backshore and foreshore subenvironments; the foreshore gives way seaward to the shoreface environment. The *backshore,* consisting of one or more berms (terraces) situated between the levels of noncatastrophic storm tides and normal high tides, is subject

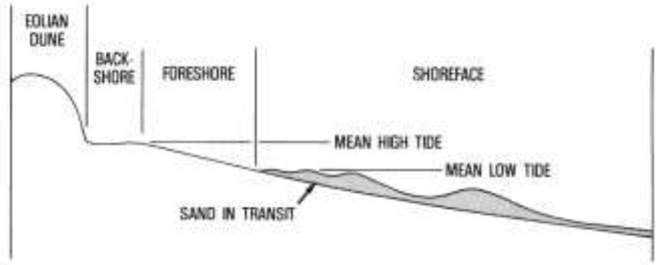


FIGURE 31—BEACH PROFILE. The beach as defined includes only the backshore and foreshore but the shoreface is part of the same wave-fashioned system. The bedding pattern is continuous across the beach into the shoreface; the composition and texture of the beach and shoreface sandstones are similar.

to wave action only during storms. The seaward edge of the berm is the berm crest.

The *foreshore* (beach face) lies between the levels of normal high tide and normal low tide. This seaward-sloping face is formed by the uprush and withdrawal of water that follows each breaking wave. Its slope is related to the size of the material composing the foreshore—the coarser the grain size, the greater the slope.

The *shoreface* lies below low-tide level and is the seaward continuation of the foreshore slope with interruptions into water 20-30 ft deep. Where the tidal range is high compared with wave height, a low-tide terrace builds on the landward part of the shoreface. However, no low-tide terrace builds on fine sand beaches where wave height equals or exceeds the tidal range. In addition, sand ridges and troughs (breaker point or long-shore bars) form still farther seaward approximately at the plunge point of breakers. Both the terrace and the bars move landward during periods of low summer waves and seaward during winter storms. Seaward from the breaker point bars, the shoreface slopes smoothly to the seaward limit of sand deposition.

Deposits in the backshore, foreshore, and shoreface consist of clean, well-sorted sandstone with a continuous bedding pattern. Consequently, these deposits are included under the single facies term *beach sandstone* which includes three subfacies: *backshore, foreshore,* and *shoreface* sandstones (fig. 31).

Offshore-beach transition

The environment of the offshore-beach transition environment lies between the shoreface environment and offshore environments (fig. 30). It is marked by the change from the seaward slope of the shoreface to the nearly horizontal surface of the offshore deposits, and the change occurs in approximately 30 ft of water. Weak bottom currents prevail in this shallow-marine environment. The distinctive facies in the offshore-beach transition consist of interfingering and intergrading beds of shoreface sandstone and of offshore siltstone and mudstone; the facies name is *offshore-beach transition.*

Offshore

The offshore environment includes the submerged shelf seaward from the beach and its transition; it is covered with marine waters 20-400 ft deep and may be several to hundreds of miles wide and tens to thousands of miles long. Over an area this extensive, the marine waters vary in temperature, salinity, and content of nutrients and dissolved gases. Also, over most of the area currents and waves disturb the bottom at irregular intervals, and burrowing organisms flourish on or near the surface of the sediments. Other types of organisms are also abundant at the sediment-to-water interface and in the overlying water.

The facies of most of the offshore environment is designated *offshore siltstone and mudstone* because these two lithologies compose the facies.

A distinct subenvironment in the offshore is the *offshore-bar environment*, where linear sandstone bodies termed offshore bars are deposited. The depositional conditions in the *offshore-bar environment* are inferred from stratigraphic relations, external geometry, internal bedding pattern, sedimentary structures, textures, and fauna; recent counterparts of this type of sandstone body are not known.

Inferred conditions for the formation of offshore bars, based on the Gallup as well as on other examples in the Upper Cretaceous in Wyoming and Alberta, follow.

1) Offshore bars form on a shallow-marine shelf that may be as wide as 100 mi.
2) They form at least 11 mi seaward from contemporaneous shoreline deposits.
3) The source of sand was a shoreline deposit as much as 200 mi from the depositional site, and the supply of sand was too small to blanket the shelf.
4) Deposition occurred during a temporary stillstand of sea level.
5) Depositing currents flowed nearly parallel with the distant shoreline and the length of the bar.
6) Deposition was localized at a slight steepening of slope (a terrace edge).
7) The water depth at the break in slope was at some critical depth above which sand was in transit and below which sand was deposited.

Facies representing the offshore-bar environment are *offshore-bar sandstone* and *offshore-bar transition*, which is the interfingering and intergrading of offshore-bar sandstone and offshore siltstone and mudstone.

Appendix 2 follows

Appendix 2

Geologic road log to Gallup Sandstone near Ship Rock, New Mexico

by Charles V. Campbell and Samuel Thompson III

This 2-day road log is a guide to readily accessible outcrops where the Gallup Sandstone may be observed. Figure numbers refer to maps, sections, and photos in preceding part of the book.

Accommodations are available near the starting point in Shiprock, New Mexico, but better accommodations may be found in Farmington (30 mi east on US-550) or in Cortez, Colorado (40 mi north on US-666).

Although most of the roads are accessible in a passenger car, a four-wheel drive vehicle is preferable; some routes should not be followed in wet weather. The length of 1st day trip is 35.6 mi; 2nd day 23.6 mi. En route to each stop, the map (fig. 32) should be consulted because mileages and junctions given in the road log at this time may change later. Both trips are entirely within the Navajo Indian Reservation.

1st day road log—stops 1-5

Miles

0.0 **STARTING POINT** at junction of NM-504 and US-666 on southwest side of **Shiprock, New Mexico.** *Proceed* west on NM-504.

1.2 Mancos Shale in roadcut to left. Road climbs east flank of the Rattlesnake anticline.

2.9 Gallup Sandstone crops out in ditches and gullies on both sides of road.

0.7 Junction with graveled road left to Rattlesnake oil field; *continue ahead* on NM-504. Ship Rock is to the left (south) with the Chuska Mountains beyond on the skyline. Through the low break to the right of Ship Rock are the Lukachukai Mountains. The Carrizo Mountains lie straight ahead, and the Ute Mountains include the high peaks on the skyline to the right (north).

0.5 Approximate crest of Rattlesnake anticline.

2.6 Bridge across Shiprock Wash. Approximate axis of syncline west of the Rattlesnake anticline. The wash is cut into Gallup Sandstone.

1.6 Culvert across wash cut into Gallup Sandstone.

1.5 Crest of ridge; *turn right* (north) on dirt road.

1.0 **STOP 1.** *Walk* northeast down dry wash

(12.0 mi) (past earthen dam) to see the seaward imbricate structure of offshore-bars as well as the facies change from offshore-bar sandstone into offshore bar transition (fig. 18). Both churned and crosslaminated beds of offshore-bar sandstone are exposed in vertical sections on the north bank of the wash. On the flat area above and south of the wash, bedding surfaces of offshore-bar sandstone are exposed (figs. 21 and 22). Trace fossils appear in the bottom of the wash in the western part of this stop area. *Return to car and retrace route* to NM-504.

1.0 *Turn left* (east) on NM-504.

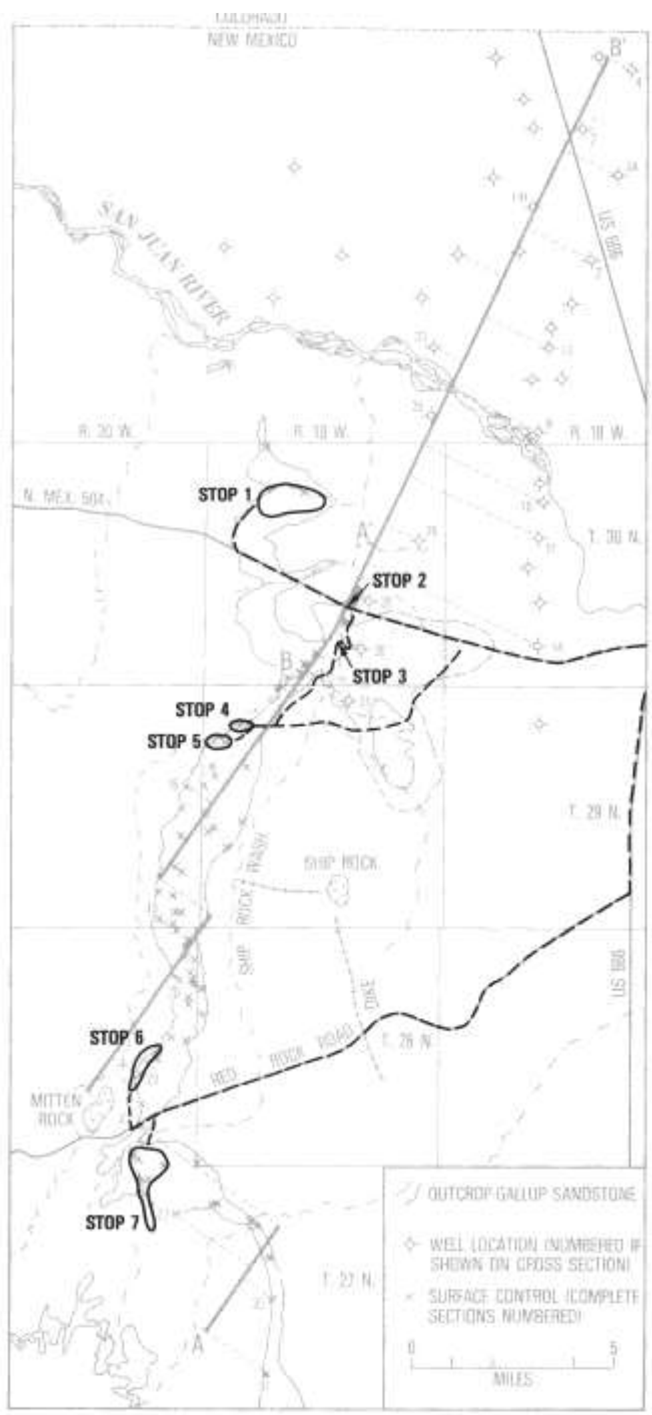


FIGURE 32—MAP OF FIELD TRIP ROUTE IN SHIP ROCK AREA.

1.5 Culvert. Good exposures of cross-laminae in beds of offshore-bar sandstones in Gallup.

1.6 Bridge across Shiprock Wash. *Proceed slowly.*

0.2 *Turn right* (south) onto dirt road and park.

(16.3 mi) STOP **2.** *Walk back* to road cut. Observe the characteristics of the Mancos Shale and the sharp contact with the underlying Gallup offshore bar. *Return to car and go south* on dirt road (most easterly of four); *follow* main road toward Ship Rock.

0.8 Casing of abandoned oil well on right; production was from offshore-bar transition deposits at a depth of approximately 100 ft. A windmill was used to pump oil.

0.2 Road curves right (southwest).

0.3 Road begins descent northwestward into Shiprock Wash.

0.2 STOP 3. East side of wash. *Walk northeast*

(17.8 mi) toward cliff. This cliff face shows the bedding pattern of the offshore-bar sandstone and its transition (fig. 17). Both the churned offshore-bar sandstone (fig. 19) and the crosslaminated sandstone (fig. 20) may be studied here. Also, the bedding and internal structures of the offshore-bar transition are well exposed. Observe the dead oil stain in the offshore-bar transition at the base of the cliff. *Return to car and proceed westward.*

0.1 *Cross* Shiprock Wash, curving left (south); *stay* on main (lower) road.

0.1 *Cross* Little Shiprock Wash; then *keep left* (south) toward Ship Rock.

0.1 Cottonwood tree on left, windmill on right. *Continue* south.

0.1 "Y"; *continue straight* (south).

0.2 Road climbs ledge of Gallup Sandstone.

0.1 Road curves right (west).

0.5 "Y"; *continue straight* (southwest).

0.3 Hogan on left. *Continue* (southwest) on main road.

0.4 "Y"; *go left* (south-southwest) on main road (toward Beautiful Mountain).

0.6 Gate in fence; *continue straight* (south-southwest).

0.3 Intersection; *turn right* (west) on road following old seismic line.

0.7 "Y"; *continue straight* (west).

0.3 STOP **4.** *Park* near edge of bluff. *Walk*

(21.6 mi) southwest downhill to first 3-ft ledge-an offshore-bar sandstone that has been highly bioturbated (burrows are rarely seen). *Continue* southwest through 7 ft of generally covered, offshore-bar transition deposits. Next below is 2-3 ft ledge-a beach-shoreface sandstone with truncated wave-ripple laminae (low wave heights and long wave lengths); some parts are bioturbated. *Go west* and down section about 5 ft to another ledge (weathered reddish sandstone)-also a beach-shoreface deposit.

Look southwest along ridge of Gallup Sandstone to outlier. Below is lower Mancos Shale and Juana Lopez Sandstone (ledge near Little Shiprock Wash).

This ridge of Gallup beach-shoreface sandstone may be walked and traced to Stop 5; otherwise *return to car (go south-southeast).*

0.1 *Join road* following along and near crest of dip slope (going south-southwest toward Mitten Rock); breached hogan on left.

0.3 Road curves right (southwest).

0.1 *Go straight* (southwest) on secondary road (main road curves left).

0.4 Wide outcrop of Gallup Sandstone on right; earthen dam.

0.1 *Go right* (southwest) downhill (other road curves left).

0.1 STOP 5. On left (southeast) side of road are

(22.7 mi) 6 ft of offshore-bar sandstone ledges, which unconformably overlie beach sandstone at road level. Note finer grain of beach sandstones; this upper 3 ft of the beach unit (from road to cliff) has been highly bioturbated by marine burrowers prior to deposition of the offshore unit.

Walk southwest to reentrant in cliff and *go* down section about 15 ft to base of ledges. These beach deposits are backshore (filling broad swales) and foreshore.

Continue southwest around reentrant to terrace with good exposures of the tops of foreshore laminae dipping gently to the southwest (at lower angle than inclination of present surface). See fig. 12. Overlying ledges to southeast are eolian dune deposits.

In good exposures, changes from one beach subfacies to another may be observed. *Return to car, turn around,* and *retrace route* (to northeast).

1.1 Breached hogan near Stop 4.

0.1 *Curve right* (east).

0.9 Intersection. *Turn left* (northeast) to retrace same route back to NM-504. This log continues east to Rattlesnake for a shortcut back to Shiprock.

0.5 Cattle guard on earthen dam across Shiprock Wash.

0.3 Junction on top of hill, *go left* (southeast).

1.1 *Curve left* (east-northeast).

1.1 Rattlesnake oil field; abandoned separators and tank.

0.2 Cattle guard, *continue straight* (east).

0.4 Junction; *turn left* (north) on main road past Rattlesnake camp.

2.5 Junction with NM-504; *go right* (east).

4.7 Junction with US-666 at Shiprock, N.M.

(35.6 mi) END OF 1ST DAY.

2nd Day road log-stops 6 and 7

0.0 **STARTING POINT** at junction of NM-504 and US-666. *Proceed south* on US-666 past uranium-processing plant on left and helium-processing plant on right.

3.1 Tanks on right store oil from the West Shiprock field (shallow Gallup production).

2.9 Road on left to Shiprock Airport. View ahead: Upper Cretaceous Mesaverde Group forms hogback to left (east); Table Mesa lies directly ahead; sharp peaks east of Table Mesa are Tertiary plugs.

0.3 Junction; *turn right* (southwest) on highway to Red Rock. Ship Rock plug ahead to right (west).

7.5 *Pass through* breach in dike extending south from Ship Rock.

2.1 Intersection with side roads. Panoramic view. To left (southwest) is Gallup Sandstone dip slope on northeast flank of Beautiful Mountain anticline. Beautiful Mountain and the Lukachukai Mountains (on skyline to right) are capped by Chuska Sandstone (Tertiary) with extrusions of Tertiary basalts. Ahead (west-southwest) is Mitten Rock, a volcanic neck of Tertiary basalt. In the foreground is the Gallup hogback, which continues to right (northwest). On skyline to right (northwest) are the Carrizo Mountains, a Tertiary laccolith of diorite porphyry. Road is on upper Mancos Shale.

3.9 Junction with road to left (southwest) to Red Rock; *continue straight.*

0.1 Breach in Gallup hogback.

0.4 Intersection with side roads; *turn right* (northwest) and *go across* cattle guard and down hill, then *follow* strike valley (northeast) in lower Mancos Shale; Mitten Rock to northwest.

0.7 Junction with road from left.

0.5 Junction on top of low ridge; *turn right* (east-southeast) and follow road along ridge.

0.2 *Go left* (northeast) over dam around waterhole.

0.2 **STOP 6. East side of dam near top of Juana**
(21.9 mi) **Lopez** (very poorly exposed). *Walk northeastward* along the top of the Juana Lopez scarp for approximately 1 mi. At the base of the Gallup Sandstone cliff on your right, notice how muddy and silty intervals grade into sandstone. *Climb* to the base of the cliff, and *walk southwestward* along the base of the cliff observing the facies change from offshore siltstone and mudstone into shoreface sandstone. *Return to highway.*

1.6 *Continue straight* (southeast) across highway; *go across* cattle guard. Slightly to right (south-southeast) are bluffs of Gallup Sandstone that may be studied along Shiprock Wash at Stop 7.

0.3 Roadcut in Gallup Sandstone.

0.1 **STOP 7.** *Park* on **north bank of Shiprock**
(23.0 mi) **Wash in Red Rock.** *Walk* up wash (southwest) and then left (south) up main wash to see excellent exposures of Gallup beach facies. The complete walking tour takes about four hours.

At north end of main wash on the west side are good exposures of eolian dune sandstone (fig. 8). These sandstones overlie the beach deposits and form knobby outcrops on the dip slope to the east. There both beach and dune characteristics are commonly obscured by churning of burrowing marine organisms prior to the deposition of the offshore-bar complex.

Continue upstream (south) along wash. Backshore sandstone is exposed on the east bank (fig. 11). Farther upstream the backshore rests upon shoreface. Still farther, shoreface changes to foreshore and then foreshore to backshore as the beach beds rise to the top of the cliff.

Continue upstream (southwest) around a left bend (to southwest) in the outcrop to a spring and a trail ascending a break in the cliff. *Walk southwestward* from the spring for a panoramic view of the Gallup Sandstone (shown in fig. 4).

Climb trail to the top of the cliff. Probable eolian sandstone is exposed at the top of the cliff. The eolian sandstone is overlain in turn by offshore-bar transition deposits and then offshore-bar sandstone. *Walk east and north* along the contact between the offshore-bar transition and dune sandstone deposits; observe carbonaceous mudstones and associated fluvial channel deposits that appear between the dune and offshore deposits.

Next, *walk northeast* down the dip slope across the eolian dune sandstones toward the low scarp of offshore-bar sandstone. There, backshore sandstone interfingers with swamp or lagoonal mudstones.

Walk northwestward along the scarp formed by the offshore-bar sandstone. *Return to car. Go left* (east- northeast).

0.1 Junction; *go left* (north) on good road.

0.5 Junction with highway; *go right* (23.6 mi) (east-northeast) to return to Shiprock. END OF 2ND DAY. END OF LOG.

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