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MODELS OF SAND AND SANDSTONE DEPOSITS: A METHODOLOGY FOR DETERMINING SAND GENESIS AND TREND

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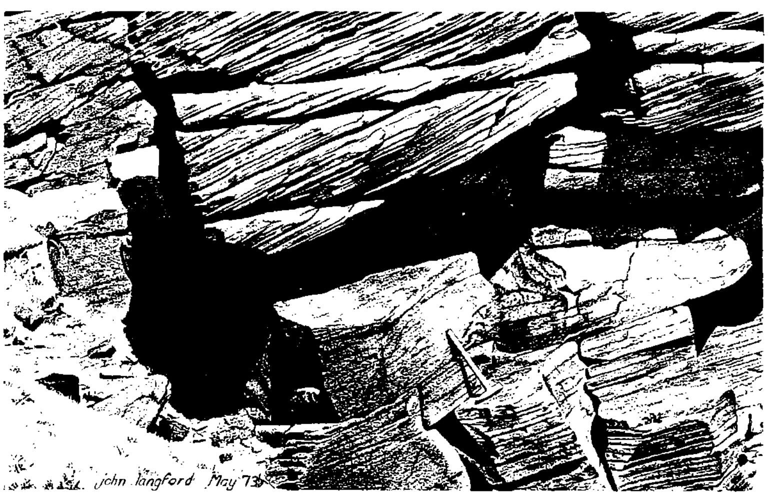

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Title Page Illustration

Pencil drawing by John O. Langford III from photograph of Rough Rock Sandstone (Upper Carboniferous), Lancashire, England. (Plate 31 of *Atlas and Glossary of Primary Sedimentary Structures* by F. J. Pettijohn and Paul Edwin Potter; Springer-Verlag, 1964. Original reference: plate 8 of "Cross-Strata of the Rough Rock [Millstone Grit Series] in the Pennines" by J. S. Shackleton; *Liverpool Manchester Geological Journal,* 1962.)

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MODELS OF SAND AND SANDSTONE DEPOSITS: A METHODOLOGY FOR DETERMINING SAND GENESIS AND TREND

John W. Shelton[1]

Abstract—Both geometric and internal features of sand and sandstone deposits are significant in estimating depositional environments. Use of depositional models is thought to represent the most reliable method for determining the genesis of sand deposits. In this method of study significant features of the deposit are compared to those of an actual or idealized unit for which the depositional environment is well known. A systematic description of geometry (trend, length, relative location, width, thickness, and boundaries) and internal features (sedimentary structures, texture, and constituents) permits a meaningful comparison and insures a more reliable estimate of depositional environment. As a part of this study, criteria for recognizing sand and sandstone deposits from 20 different environments have been tabulated.

Twenty-four well-documented deposits, which are regarded as depositional models, are described systematically according to geometry and internal features. They range in genesis from alluvial valley to deep marine. Models of Quaternary sand deposits are included along with studies from six other systems. Represented in the compilation are deposits from both North American cratonic and geosynclinal areas, and models are presented of both genetic sand units and multistoried units. Because the models in this compilation represent a wide range of depositional and stratigraphic-tectonic conditions, it is thought that they may be used for comparative purposes in the study of many sandstone deposits with a reasonable level of confidence.

PART I

INTRODUCTION

The object of this work is to record uniformly and systematically the results of selected studies of sands and sandstones. These studies present accurate estimates or determinations of the genesis and geometry of sand bodies from the major physical depositional environments.

The value of knowing the genesis and geometry of a sand body precisely is at least twofold: that segment of geologic history and paleogeography represented by the sand is rather clearly known, and the exploration or exploitation of natural resources in the sand may then be conducted on a sound technological basis involving less economic risk.

In estimating most depositional conditions, significant features need to be determined and recognized and then compared to those of well-documented Holocene sand deposits. Significant features are related to both the geometry and the internal characteristics of a sand body, and a more accurate determination of genesis is possible wher both are studied. In most cases the combination c these features and their vertical and later sequences are of more genetic significance tha any one characteristic.

The environment for sand deposition may als be inferred from a knowledge of sedimentar processes—primarily depositional currents—or froı a study of small-scale laboratory models o those processes. These methods generally giv information concerning the internal characteristics of a sand body, but few geometric data.

As the number of studies of depositional environments has increased, emphasis has also been placed on the trend of the sand deposit. Trend is that element of sand-body geometry that defines sand length in geographic terms. The trend can be determined directly where unusual opportunities are afforded on outcrop, such as in the Colorado Plateau where Jurassic stream deposits have been exhumed (Stokes, 1961, p. 167), or in subsurface where exploitation of hydrocarbon accumulations, coal, or uranium deposits has resulted in dense control. However, in most studies the trend must be estimated indirectly by relating

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it to paleocurrent indicators or to a paleogeographic framework.

If this compilation is to be meaningful, it seems necessary first to defend the proposition that the results of several sand studies may be of considerable assistance in solution of many sand-deposit problems. Furthermore, some explanation should be given of the style used in reporting the results of each study and of the selection of studies.

Concepts

MODELS

The number of processes, agents, and reactions which are responsible for forming all the characteristics of a sand or sandstone deposit is large indeed, and the number of possible combinations of values of these variants is even larger. Commonly, however, it is not an impossible task to determine that segment of geologic history corresponding to the deposition of a sand body. It would seem that the significant variants are relatively few in number and that each varies within a small range. This is the obvious reason why it is valid to compare an ancient sand body to a modern counterpart. The modern sand deposit serves as a useful model or analog, although undoubtedly its depositional environment is not precisely identical to that of the ancient sand.

It is thought that the *general* types of sand bodies, classified according to depositional framework, or genesis, are not innumerable. It is held further that determination of sand genesis can most realistically be achieved by using well-documented studies such as models, analogs, or prototypes. The most suitable model is representative of rather generalized conditions. For a meaningful estimate of a generalized depositional environment for any sand, probably less than 20 good models would be required. A precise estimate requires that some modification be made, according to differences observed between features of the Holocene model and those of the sandstone being investigated. Proper modifications are made by discreet use of the worker's experience, insight, and intuition. Many of the most useful models are understandably from Holocene sand deposits where depositional conditions can be observed directly. However, in submerged depositional environments, such as offshore or deep-water marine, the best models at present are from Tertiary sediments; paleoecologic inferences from them involve the least risk. Danger does exist in using Holocene surface-sand deposits as models. Emphasis is too easily placed on ephemeral surficial features which are not preserved during burial. Also, in many Holocene studies sand geometry is not accurately determined. The ideal model is probably a Holocene sand in the initial stage of burial and readily accessible for direct observation. Its genesis is known quite well, and sand geometry, where preserved, may be readily determined.

GENETIC SAND UNITS

A genetic sand unit is a sequence deposited by one process (or a group of processes operating at the depositional site concurrently) while the spatial positions of that process and of the depositional interface, or surface, are essentially fixed. For example, the sand deposits in the meander belt of the present Mississippi River in its valley represent one genetic unit; those of the Holocene Mississippi alluvial plain contain as many units as there were courses of the river. The sand of Galveston Island, excluding the eolian deposits, is essentially one genetic unit. The desirability of studying and mapping each genetic unit separately is obvious. The recognition of individual genetic units in the geologic column depends upon the ease of stratigraphic correlation, which is commonly related to (1) the size of the study area, (2) the rate of subsidence, and (3) the depositional framework itself. Units that are essentially genetic can be delineated over significant parts of tectonically stable areas such as the Eastern Interior basin during the late Paleozoic and the Western Interior basin during part of the Cretaceous. Multilateral units (Fisher and McGowen, 1969, p. 36) are developed by lateral migration of the depositional process in stable areas. In typical geosynclinal conditions, mapping genetic units can only be achieved locally.

The Tertiary of the western Gulf Coast and of the basins along the Pacific Coast contains thick sand sequences, each of which is composed of a number of genetic units. Where the rate of subsidence equaled the rate of deposition, a sandstone sequence consisting of a number of units of the same genesis is termed "multistoried" (Pettijohn and others, 1965, p. 134). This relation is present in some of the Frio sands of south Texas, where genetic units are stacked vertically. Most commonly the rates of subsidence and deposition were not equal, and a sand sequence is composed of several genetic units.

Reliable correlation over a sizable area is largely dependent upon the presence of marine beds or fallout units. In general, where marine units are completely absent, genetic units can only be mapped locally. Bentonites from volcanic fallouts and units deposited during radioactive fallouts are ideal markers for correlation. Their continuity for regional mapping is not, however, independent of depositional environment. They are most readily recognized and correlated in a sequence of marine sediments for which the rate of deposition was slow.

TRANSGRESSIVE-REGRESSIVE COUPLETS

Subdivision of a terrigenous clastic sequence for sedimentologic-stratigraphic purposes is achieved most reliably by recognition of units deposited during marine transgressions. On outcrop these units are commonly thin and widespread but inconspicuously exposed. Lithologically, transgressive units are characteristically sand or sandy conglomerate, poorly sorted, fossiliferous, and with authigenic constituents such as glauconite and collophanite. In subsurface most reliable markers on geophysical logs and many paleontological markers (tops) are in thin transgressive units. These units were apparently deposited slowly after the site of a depocenter shifted, as a eustatic rise in sea level occurred, or as the subsidence rate increased.

Isolating sediments between successive transgressions divides a sequence into sedimentologic entities—into transgressive-regressive couplets, which in a number of cases corresponds to formats, as defined by Forgotson (1957, p. 2108), or to genetic increments of strata, as defined by Busch (1971, p. 1138). A couplet contains the sand or sands deposited during one regression and preserved during the succeeding marine transgression. Recognition of genetic sand units is made most readily within a layer or interval that is a transgressive-regressive couplet.

Thick transgressive sands undoubtedly occur. However, sand deposited during an overall transgression may be regressive in nature. The *Marginulina* sands of the Frio-Anahuac (Tertiary) of the western Gulf Coast were deposited during the transgression that was culminated by deposition of part of the Anahuac Formation. Yet the sands were deposited during the minor regressions that interrupted transgressive conditions. Similar relationships apparently existed in the Colorado-Utah area during the Late Cretaceous, the Rocky Mountain area during the Middle and Late Cambrian, and the western Gulf Coast area during the Early Cretaceous (Lozo and Stricklin, 1956, p. 68).

Scope

NATURE OF MODEL

The most meaningful characterizations of sand and sandstone deposits are those that permit, or result in, accurate determinations of depositional environment and geographic distribution. Accordingly, sand deposits from various major environments have been categorized and summarized by various workers, including Potter and Pettijohn (1963), Pettijohn and others (1965), Visher (1965), Potter (1967), Shelton (1967), Bernard and others (1970), Allen (1970), and Selley (1970). To a sizable degree these investigations and compilations are expressions of the influence of the pioneering and classic work of Fisk (1944, 1947, 1952) with the Mississippi River Commission.

In the present study significant features of each sand model are summarized and used in the analysis without defining them or establishing their validity as criteria. The characteristics are summarized in the following categories:

- Geometry
  - Geographic location and trend
  - Vertical position
  - Length
  - Width
  - Thickness
  - Boundaries
- Internal features
  - Sedimentary structures
  - Texture and mass-derived properties
  - Constituents

Geometric characteristics of sand deposits from the various environments have not been summarized as systematically as the internal features. However, geometry has been noted in some detail by Potter and Pettijohn (1963), Potter (1967), Shelton (1967), and Selley (1970). Geographic location and trend define the sand body on a map, whereas vertical position defines its location relative to the earth's surface. Geographic location is probably the most important feature an industrial geologist must estimate. Considered a part of geographic location is the position relative to associated facies. Vertical position is not of environmental consequence but is important in exploratory strategy and in determining the type and quality of data available for environmental study. In some cases ratios involving combinations of length, width, and thickness are important in estimating sand genesis as well as generating reservoir data. Boundary conditions include the nature of the contact of the sand with the underlying and overlying beds as well as with laterally equivalent beds. Sedimentary structures have been cataloged by Pettijohn and Potter (1964) and by Conybeare and Crook (1968). The significance of textures and composition in determining depositional environments has once again become a subject of interest to a number of sedimentologists. Friedman (1961), Moiola and Weiser (1968), and Visher (1969) are of the opinion that subtleties in grain-size distributions are indicative of particular environments, whereas Ferm (1962) and Davies and others (1971) have attempted to relate relative percentages of major detrital constituents, especially quartz, to specific depositional conditions.

In this compilation the combination of internal features, rather than isolated characteristics, is thought to be most meaningful in environmental analysis. The sedimentary structures are generated at the depositional site; the vertical and lateral sequences of grain size and sorting reflect energy levels of the depositional process; the biota offers the potential for paleoecological interpretation; and certain syngenetic and authigenic minerals reflect geochemical conditions which can be related to major physical environments. Megascopic paleocurrent directions are considered with the sedimentary structures. Porosity and permeability are the most common features considered as mass-derived properties. Grain-orientation data are included with the more conventional textural features of grain size and sorting. Significant constituents, especially fossils and autochthonous minerals, are summarized, but no attempt is necessarily made toward a complete study of composition.

In any study of ancient sand deposits the depositional framework is best estimated after the data requiring little interpretation have been cataloged. Such a procedure is followed in presenting the sand-deposit studies in this compilation. As background material, each study is prefaced with a summary of the structural and stratigraphic framework for the sand body.

TYPES OF MODELS

In selecting studies for models, consideration was given to the structural framework, geologic age of the sand or sandstone, areal extent of the study area, and the number of genetic sand units in the sequence (table 1). However, the studies of sand and sandstone deposits used as models are classified primarily according to depositional environment or framework. The environmental range represented in this compilation is from alluvial valley to deep marine. Studies are included from both North American cratonic and geosynclinal areas. Models of Holocene sand deposits are given along with those from various systems from the geologic column. Both local and subregional or regional studies are summarized in this compilation. Some of the local studies are of oil or gas fields, whereas others are surface or near-surface investigations in which outcrop continuity or borings permit an accurate determination of genesis and geometry of the sand deposit. Models of one genetic unit are presented; yet on the other hand, some are of sand sequences that are composed of a number of genetic units.

Miscellaneous Methods and Techniques

In the study of sand and sandstone deposits probably no method or technique known is universally applicable. However, two ideas are considered to be of general value in determining geometry.

The first, a basic premise, is that the areal distribution of sand (or sandstone) in the stratigraphic unit under investigation is of prime importance. Consequently, in each study the lateral boundaries of sand should be mapped. The determination of what constitutes a sand edge depends on the needs of each case. In some cases the effective boundary may be 30 feet of net sand in a stratigraphic unit (e.g., where depth to a reservoir is 12,000 feet), or in other cases it may be less than 1 foot. The effect of such a procedure is to downgrade the importance of conventional lithofacies and thickness maps.

The second suggestion involves preparation of a network of correlation cross sections of the stratigraphic interval under investigation. Sections aid in delineating individual sands or sand groups within the interval and in determining the position and nature of sand boundaries. Geophysical logs of wells and/or graphic logs of grain size and resistance to weathering of outcrop sections should be plotted in such a manner that the entire interval can be readily observed visually. In studies of thick sand-bearing sections, such as the upper Frio of southeast Texas or the lower Pliocene of the Los Angeles basin, the most appropriate vertical scale may be 1 inch = 200 feet or even 1 inch = 500 feet. It is suggested that logs from adjacent wells be plotted as close to each other as possible, even

Table 1.—Geologic and Geographic Distribution of Models Studied in This Report

	Depositional Environment of Model					
Age of model	Alluvial valley	Alluvial plain	Deltaic	Interdeltaic barrier bar	Shallow marine	Deep marine
Quaternary	1		1	2		
Tertiary		1	3	1	1	2
Cretaceous		1	2	1	1	
Pennsylvanian	2	1	1			
Silurian		1				
Ordovician						1
Cambrian					1	
Location of model (province)						
Appalachian Mountains		1				1
Eastern Interior	1	1				
Great Lakes					1	
Midcontinent	1	1	1			
Western Interior-Rockies			2	1	1	
Gulf Coast	1	1	4	3		1
Pacific Coast					1	1

if this necessitates lateral cutoff of curves (fig. 1). Also, each vertical section should be plotted on a correlation section, the most useful of which is generally oriented normal to the trend or length of the sand deposit. These suggestions for preparation of correlation sections are techniques which geophysicists have employed successfully in preparing seismic cross sections. Where the stratigraphic interval is thin, logs may be plotted according to location; the resulting log map is very useful in delineating sand trends (fig. 1).

The distribution of individual lenticular sand bodies with abrupt changes near lateral boundaries is probably shown better by edge lines than by thickness values. In regional studies of thick sand-bearing sections, the sand edges, sand thicknesses, and sand percentages all should be mapped.

It is important to calibrate well logs to rock parameters in order that some understanding of depositional environment can be achieved early in each study. The estimate of environment influences the estimate of sand distribution where data permit considerable latitude in interpretation. Also influencing the interpretation of sand distribution are the paleocurrent indicators, which commonly are closely related to sand trends.

Acknowledgments

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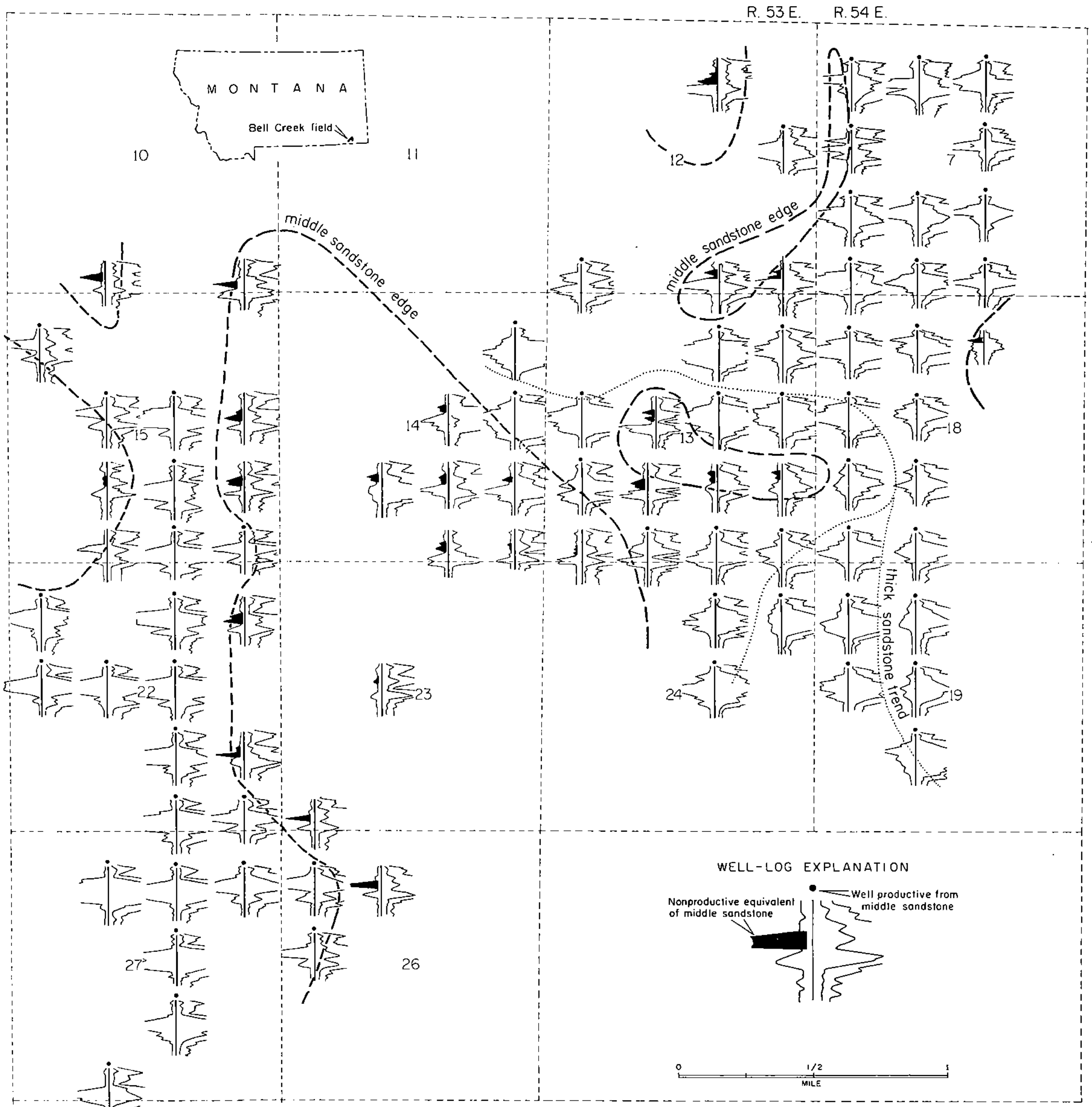

Figure 1. Log map of a part of Bell Creek field, Montana, illustrating the value of small-scale, compressed log sections in determining sandstone trends.

provided personnel to assist in preparation of the compilation. Roy D. Davis, Oklahoma Geological Survey, prepared many of the illustrations in final form. R. D. Helton and R. K. Oines were instrumental in obtaining photographs from the National Aeronautics and Space Administration; the courtesy extended by NASA is greatly appreciated. Figure 6 is included with the kind permission of John Wiley and Sons and The Geological Society of America; figure 7, with the permission of The Geological Society of America.

If the compilation is of value, much of the credit must go to former colleagues who have been instrumental in the continuing education of the writer. Included in this group are R. H. Nanz, R. J. LeBlanc, H. A. Bernard, B. W. Wilson, K. J. Hsu, W. F. Roux, G. Rittenhouse, R. L. Heacock, W. C. Gibson, and A. O. Beall. To them, and to scores of others, sincere appreciation is expressed for invaluable aid in improving the compiler's understanding of sand and sandstone deposits.

Specific acknowledgments and references re-

lated to compilation of the sand and sandstone models are given at the end of each study.

SAND GENESIS: DEPOSITIONAL ENVIRONMENT

Definition

Depositional environment, or sedimentary environment, is, in the broad sense, that system involving physical, chemical, and biological elements where sediments are deposited or formed. Scruton (1960, p. 82) aptly stated that the three factors that determine the initial characteristics of sediments and that therefore define a depositional environment are (1) sediment sources, which determine material available to the environment; (2) the processes that act in the environment, and their intensities; and (3) rate of deposition, which determines the period of time the processes act before the sediments are buried beneath the depositing interface. These three undoubtedly reflect the more fundamental factors of tectonism and climate. In the present work, emphasis is given primarily to the physical depositional framework, that is, the system in which physical processes deposit sand, sand and clay, or sand and gravel. For sand deposits the chemical and biological processes are considered to be modifiers of the more fundamental physical setting or framework.

Basis for Classification of Sand Deposits

Most classifications of depositional environments where sand is deposited include consideration of one or more of the following: (1) nature of the depositional medium, (2) the depositional process, and (3) the physiography and bathymetry. Each category is discussed briefly here only as it is related to classification.

NATURE OF DEPOSITIONAL MEDIUM

The most common and useful gross classification of sand deposits is based, to a large extent, on the salinity of water at the depositional site. Accordingly, the gross or primary environments are the familiar continental (or nonmarine), marine, and transitional (paralic or coastal). Continental deposits are those formed on the continent where fresh water or air is the depositional medium. Saline lakes do exist on continents, and proper classification of ancient deposits formed under saline-lacustrine conditions generally requires an accurate reconstruction of paleogeography. Marine deposits are formed in bodies of water that are a part of the open ocean or are closely related to it. Most marine sand bodies have formed on the continental margin or upon the continent itself. Transitional, paralic, or coastal deposits are those deposited along or very near the shoreline. The area along the Atlantic and Gulf Coasts is a modern regional model for coastal conditions. The water under coastal conditions is generally brackish, but in some places it may be supersaline.

DEPOSITIONAL PROCESS

For secondary classification of sand deposits according to genesis, it is common practice to utilize the depositional process or agent. For example, alluvial, or fluvial, and eolian deposits were formed by continental depositional agents, and turbidity-current deposits, or turbidites, by a marine agent.

PHYSIOGRAPHY AND BATHYMETRY

Another means of classifying continental sand deposits genetically is according to the landform present or forming at the depositional site. A similar basis for classification of marine deposits is bathymetry or water depth. These features are used generally in secondary or tertiary classifications. For example, alluvial valley and plain are tertiary environments. Nearly all the coastal or transitional deposits are subdivided according to physiography. On the other hand, most marine deposits are categorized according to bathymetry.

Foraminiferal paleoecology is presently the most important tool in determining bathymetry of Tertiary deposits, and it is useful in delineation of paralic or coastal deposits. The term "transitional" has been used extensively by paleontologists in referring to those environments characterized by brackish-water foraminifers.

Classification

Many attempts have been made to classify sand deposits according to depositional environment; the classifications by Potter (1967) and Selley (1970) are particularly worthy of note. For this compilation the sand deposits are categorized according to the classification given in table 2. Most of the environmental terms in table 2 are self-explanatory, but some may require a statement of definition.

It is obvious that dunes form the eolian sand deposits (fig. 2). No attempt is made to divide the deposits according to the common dune types, such as barchan, transverse, seif, and longitudinal.

Alluvial sand and gravel deposits are con-

Table 2.—Classification of Sand Deposits According to Genesis

Primary classification
- *Secondary classification*
  - *Tertiary classification*

- Continental (nonmarine)
  - Alluvial
    - Piedmont
    - Valley
    - Plain
  - Lacustrine
  - Eolian
- Coastal-paralic-transitional
  - Estuary (alluvial-estuarine)
  - Deltaic
    - Delta front and margin
    - Distributary
  - Interdeltaic
    - Barrier island, bar, beach
    - Tidal pass
    - Tidal flat
- Marine
  - Shelf (shallow)
    - Nearshore
    - Offshore
  - Deep
    - Turbidity current
    - Normal bottom current

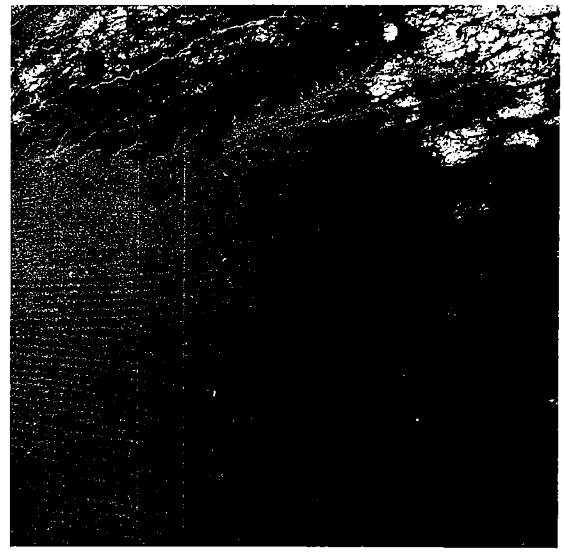

Figure 2. Framework for eolian deposition. Area shown is Empty Quarter of southeastern Saudi Arabia and southern Yemen, looking southeast. Longitudinal sand dunes are in foreground and center. Photograph courtesy of NASA (S-65-32802).

Figure 3. Framework for alluvial-piedmont deposition in Basin and Range province. Area shown is Gila River valley between Yuma and Phoenix, Arizona, looking north-northeast. Mohawk and Growler Mountains are in right foreground, and Gila Bend Mountains are at upper right in bend of river. Illustrated are fault-block mountains and sediment-filled valleys including bajadas and fans. Photograph courtesy of NASA (S-65-45384).

sidered piedmont deposits where steep stream gradients and proximity to elevated source areas may be inferred from internal rock characteristics of the deposit (fig. 3). Valley deposits are those which formed after the stream had eroded significantly older beds (fig. 4). Alluvial-plain deposition (fig. 4) occurs downstream from the valley environment and upstream from the deltaic complex; as defined in this compilation, alluvial-plain deposits include beds of the deltaic plain of numerous workers. No marine units are present in the sequence, and beds that alluvial-plain streams erode are of essentially the same age as those that are subsequently deposited. Numerous workers, in classifying alluvial sands, have emphasized channel types and have distinguished braided alluvial, or fluvial, deposits from meandering-stream deposits (e.g., Ore, 1964; Allen, 1965, 1970; Williams and Rust, 1969; Smith, 1970; and Selley, 1970). By utilizing the type of load, channels have been classified as bed load, mixed load, and suspended load (Schumm, 1968, p. 1579; McGowen and Garner, 1970, p. 80). It is recommended, however, that determination of the physiographic framework for an ancient alluvial deposit should precede an estimate of channel type or nature of stream load. Deposits of braided streams are probably preserved only under special aggradational conditions. On alluvial fans braided-stream deposits are preserved because of subsidence and also because stream shifts are not restricted by valley edges. Within late Paleozoic and Pleistocene valley systems, changes in sea level were instrumental in preservation of braided-stream deposits. Because channel migration is restricted in a valley, features of a braided stream under stable conditions do not represent the bulk of the deposit, which forms during recession of flood waters when the stream is not braided.

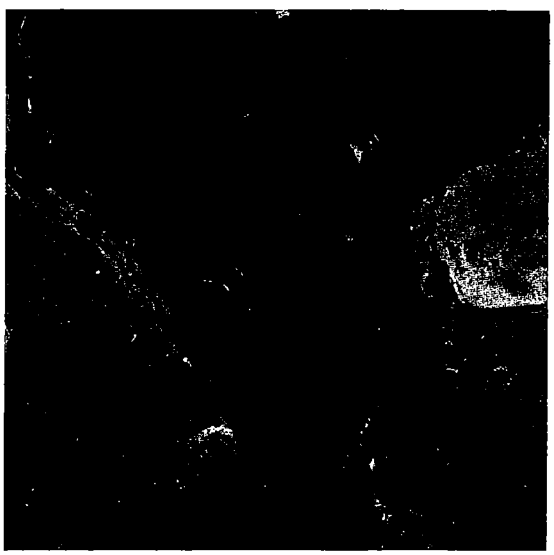

Figure 4. Framework for alluvial-valley and alluvial-plain deposition. Area shown is Nile River valley and upper part of Nile delta (alluvial plain) in United Arab Republic, looking north. Branching off north of Cairo (lower center) are Rosetta Nile (left) and Damietta Nile (center). Photograph courtesy of NASA (S-65-45413).

Lacustrine deposits may be subdivided into a number of types, such as deltaic, shoreface and beach, and offshore. However, because lacustrine units form a very small percentage of sand deposits in the geologic column, the classification used in this work is a gross one.

Alluvial-estuarine sand deposits are not particularly well documented. The sediment is deposited at the head of the funnel-shaped area of an estuary, and the inflowing river is commonly the primary depositional agent. In the lower part of an estuary, sediment is either tide or wave controlled, and corresponding ancient sediments should be categorized as tidal channel or shallow marine, respectively.

Deltaic deposits merge not only with alluvial-plain deposits but also with marine and coastal interdeltaic units (fig. 5). The landward area of interfingering is the upper deltaic plain; the seaward zone is characterized by prodeltaic silts and clays; the coastal gradational area is the marginal deltaic, or strandline, plain. Delta-front and delta-margin sand units, commonly referred to as delta-fringe sands, may form unique bodies such as bar fingers and distributary-mouth bars. On the other hand, delta-fringe sands may be expressed by physiographic features, such as barrier islands and tidal flats, which may be developed in any part of the coastal belt. Deltaic distributary deposits are the stream-formed beds. Typically, little sand is deposited in the interdistributary areas. Because deltaic sands are complex and diverse in orientation and origin, less precision in classification is commonly the result.

Figure 5. Framework for coastal deltaic and interdeltaic deposits, showing Rio Grande deltaic plain; Gulf of Mexico is at right. The Rio Grande delta is arcuate, with a relatively simple, convex shape and regular shoreline composed of bars and lagoons. Just north of the Rio Grande delta is the interdeltaic Padre Island. City of Corpus Christi is at very top center. Photograph courtesy of NASA (S-66-45807).

Interdeltaic sand deposits are more closely related to the regional depositional strike, and reasonable precision can be expected in their classification. Bars that are close to a mainland beach or an offshore island are considered part of a barrier-bar-beach complex (fig. 5). They are to be distinguished from marine sand buildups, which are essentially independent of sand deposits along the strandline. Most tidal-pass deposits are intimately associated with the barrier-bar-beach complex. Sand of significant thickness on the tidal flat is deposited in channels, creeks, or gullies.

Marine beds are classified secondarily according to a qualitative depth at the site of deposition (fig. 6). Shallow-marine beds are those deposited on the continental shelf in the inner, middle, and outer neritic environments of the paleontologists. Where precision is possible, offshore beds are distinguished from nearshore. The former commonly consist of silt and clay, but sand apparently was deposited great distances offshore in some of the epeiric seas. Turbidity-current sand deposits (fig. 7) contrast sharply with the deep-marine pelagic muds, which are deposited by normal marine processes.

Criteria for Recognition

Data tabulated in table 3 (in pocket) summarize a number of features of sand deposits that are considered to be of significance in estimating or recognizing depositional conditions. The criteria,

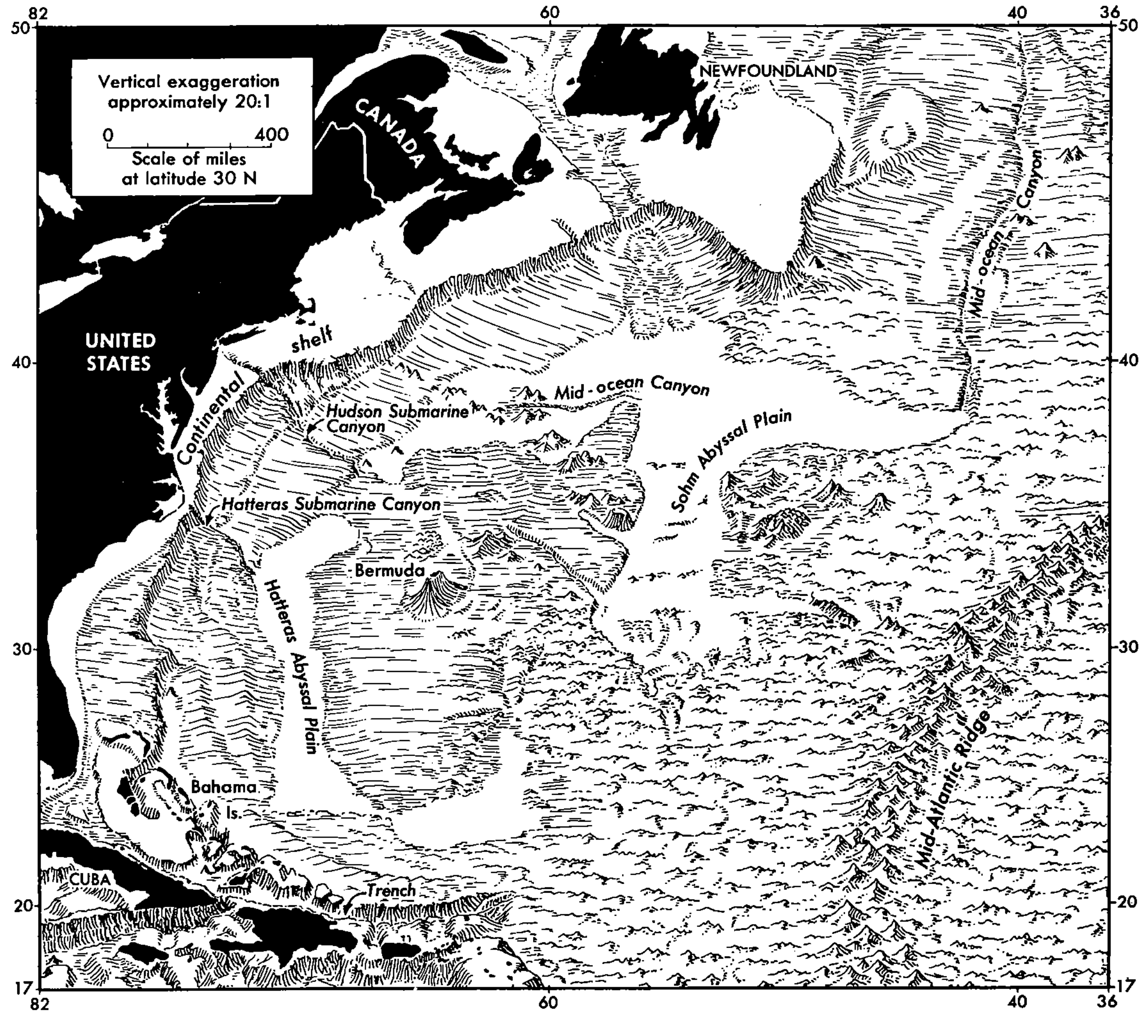

Figure 6. Framework for marine deposition. Shallow-marine deposition may occur in nearshore areas fringing the coastal environment, offshore in the Newfoundland-New England area, and on the Bahamian platform. Deep-marine deposition, or erosion, occurs elsewhere. *From* Longwell and Flint (1962); *after* Heezen and others (1959, pl. 1).

which are listed according to geometry and internal rock features, are not defined nor defended. Undoubtedly exceptions exist to almost every characteristic listed. Therefore, the reliability of the criteria for estimating depositional environment improves as the number of criteria utilized increases. It should also be understood that the reliability is dependent upon the writer's ability to interpret properly the wide variety of sand and sandstone studies. In determining the significant characteristics of eolian sands, considerable reliance is placed on the work of McKee (1966) and Glennie (1970). The work of Bull (1968, 1969) is particularly diagnostic for delineating alluvial-fan, or piedmont, deposits which form in arid regions. Characteristics of other alluvial environments are summarized by Allen (1965) and McGowen and Garner (1970). The compilations of Gagliano and others (1969), Fisher and others (1969), and Morgan (1970) are especially noteworthy for students of deltaic sedimentation.

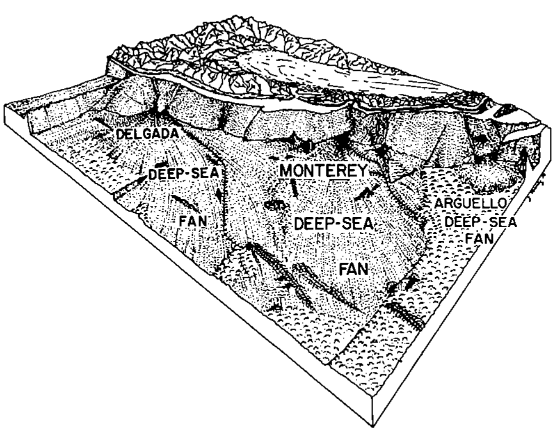

Figure 7. Diagram of sea floor and coast off central California, illustrating an environment for turbidity-current deposition. Deep-sea fans spread out from the mouths of several canyons. *From* Menard (1960, fig. 1).

Salient features of interdeltaic coastal deposits have been summarized by Allen (1970) and Selley (1970). In addition, a useful reference for estuarine and tidal-flat deposits is the volume edited by Lauff (1967). Allen (1970) and Selley (1970) have also summarized characteristics of several types of shallow-marine sand units which correspond generally to nearshore-marine bodies of this compilation. An abundance of literature is available on the features of turbidites; the volume edited by Bouma and Brouwer (1964) and the work of Dżuliński and Walton (1965) and of Enos (1969) represent comprehensive studies. In this publication the physiographic terms "channel" and "fan" correspond to the "proximal facies" of many workers, and "basin floor" to "distal turbidites."

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PART II

MODELS

Continental Environments

ALLUVIAL-VALLEY ENVIRONMENTS

Mississippi River Sand, Holocene, East-Central Louisiana (1)

Physiography and History

The Old River locksite, near Simmesport, Louisiana, is a segment of the downstream arm of the Mississippi River Turnbull Island meander, which was isolated by the Shreves Cutoff in 1831 (fig. 1-1). Features in that local area of the lower Mississippi alluvial valley have been shaped to a large extent by migration of this meander. In 1765, when Lieutenant Ross surveyed the river, a bend of the downstream arm was nearly a mile south of the locksite (fig. 1-1). Northeastward migration of the bend was accompanied by accretionary development of a broad point bar.

By 1830, migration of the opposing bends of the Turnbull Island meander had reduced the intervening land to a narrow neck. When Shreves Cutoff was made through this neck the following year to form Turnbull Island, the downstream arm of the meander silted rapidly; the lower end of the abandoned channel was completely sealed by 1854. A channel constructed across the sealing bar to connect the Mississippi and Atchafalaya Rivers resulted in the formation of the Old River (lower Red River) (figs. 1-1, 1-2). Its course became established along the thalweg position of the abandoned Mississippi channel. Progressively greater diversion of Mississippi water into the Atchafalaya system has resulted in gradual enlargement and migration of the Old River channel.

Major topographic features of the Mississippi system are the oxbow depression and the enclosed point-bar area of Turnbull Island (fig. 1-1). Ridge-and-swale features, formed by bar accretion, characterized the island and also part of the area south of the Old River near the cutoff (fig. 1-1).

The locksite excavation, which was completed in 1960 by the U.S. Army Corps of Engineers, measured 2,000 by 500 by 75 feet (fig. 1-2). The base of the excavation was 35 feet below sea level. Relative to the sediment-filled abandoned Mississippi River meander, the locksite was constructed within the 1831 channel of the downstream arm close to the midpoint of the bendway. The southeast orientation of the excavation parallels abandoned channel alignment, direction of flow in the downstream area, and trend of the point bar (figs. 1-1, 1-2). In the study of the sand by Frazier and Osanik (1961), data from the excavation were supported by those from numerous borings.

Geometry

Geographic location and trend.—Meander belts of the Mississippi River in its valley are characterized by sand, with a myriad of interruptions by loose silt and clay deposits in abandoned meanders and stretches. With respect to the river system, sand in the area of study represents an insignificant volume of alluvial sand. The trend of Mississippi River sand at Old River locksite near Simmesport is controlled by the downstream area of the Turnbull Island meander. The overall orientation of the arm is approximately S. 60° E., whereas the local trend of the bend and the sand at the locksite is S. 50° E. (fig. 1-2).

Vertical position.—Sand in the immediate area of the locksite lies about 20 to 85 feet below the surface. The topstratum of silty clays, clayey silts, and sandy silts blankets the sand. South of the locksite, where ridges and swales are present and the topstratum is thin, sand forms the uppermost part of the point-bar sequence. Elsewhere it forms the fill of the abandoned channel. In the locksite excavation, the topstratum is some 35 to 55 feet thick (fig. 1-2). The topstratum-sand contact slopes northeastward at a rate of 2°.

Length.—The sand extends well beyond the excavation, which is 2,000 feet long. The bend of the southeast-trending downstream arm is 2-3 miles long, whereas the entire arm of the meander is some 5-6 miles long (fig. 1-2). The length of uninterrupted sand is not known with certainty, but the 5 to 6 miles also represents the distance along sand trend between the Mississippi and Atchafalaya Rivers.

Width.—The width of sand in the area also is not known. In the bend area of the downstream arm, sand extends an undetermined distance beyond the mile of point-bar accretion between 1765 and 1831.

Thickness.—The Mississippi River sand in the locksite area varies from 0 to 100 feet in thickness (fig. 1-2). It is present as a north-thinning wedge. It is thickest where the point-bar sequence is fully developed, and it is absent in what was the deepest part of the channel before abandonment.

Old River has enlarged itself within the thick

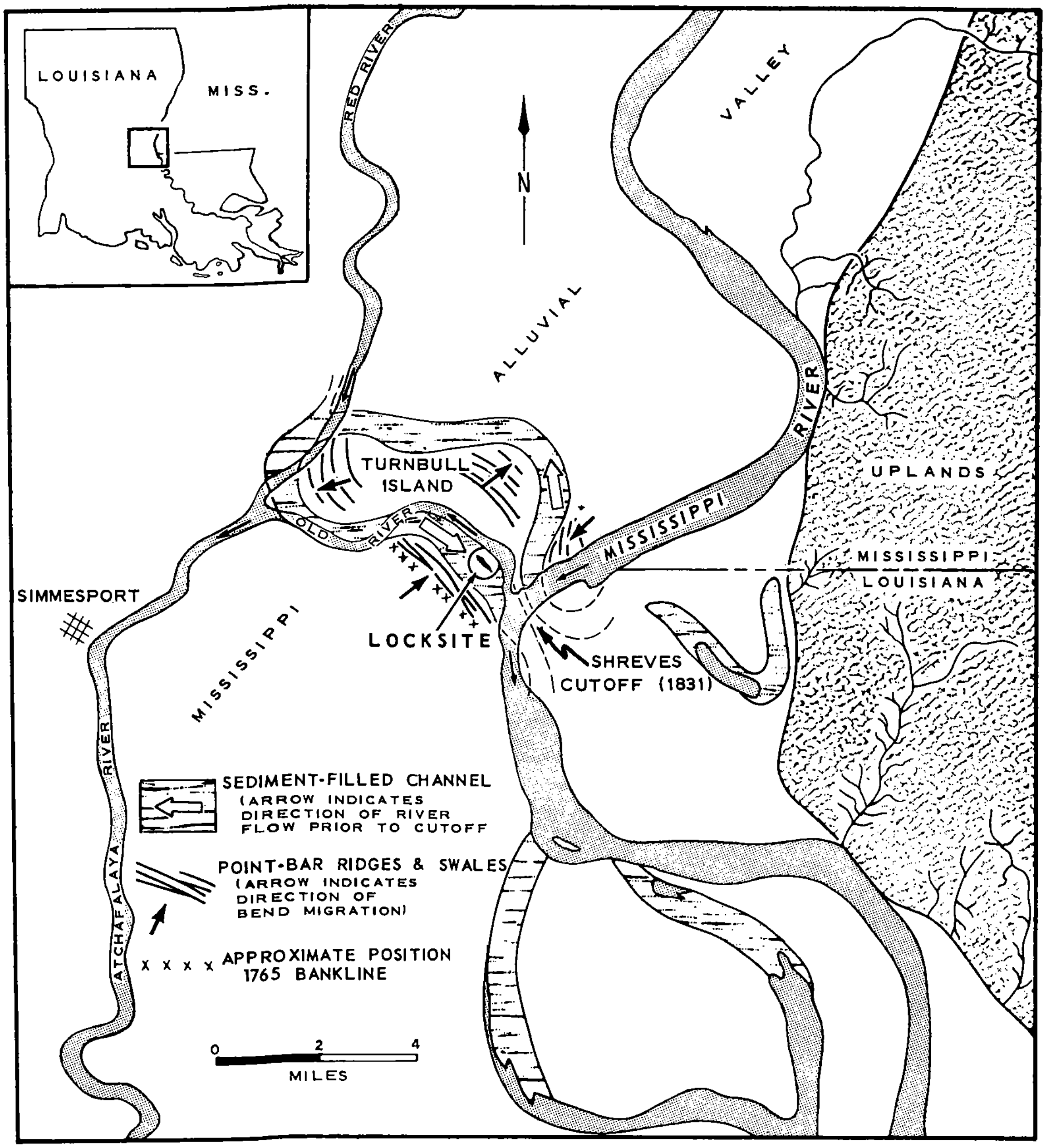

Figure 1-1. Area of Old River locksite, showing development of Turnbull Island meander. *From* Frazier and Osanik (1961, fig. 1).

channel fill of the topstratum. It has deposited sands within migrating bends of an enlarging channel and upon eroded topstratum or Mississippi River sand. Old River sand reaches a maximum thickness of 50 feet (fig. 1-2).

Boundaries.—The upper contact of sand with the channel fill is sharp and is relatively sharp with the point-bar topstratum. The basal contact is sharp with gravel-bearing Mississippi River deposits of the rising-sea-level stage during early Holocene time. The sand, deposited during historic time, rests on the beds of graveliferous medium- to coarse-grained sand at an elevation of approximately 75 feet below sea level. This elevation corresponds to that of the base of the channel fill and to that of the thalweg of comparable present-day Mississippi River bendways. Together the two

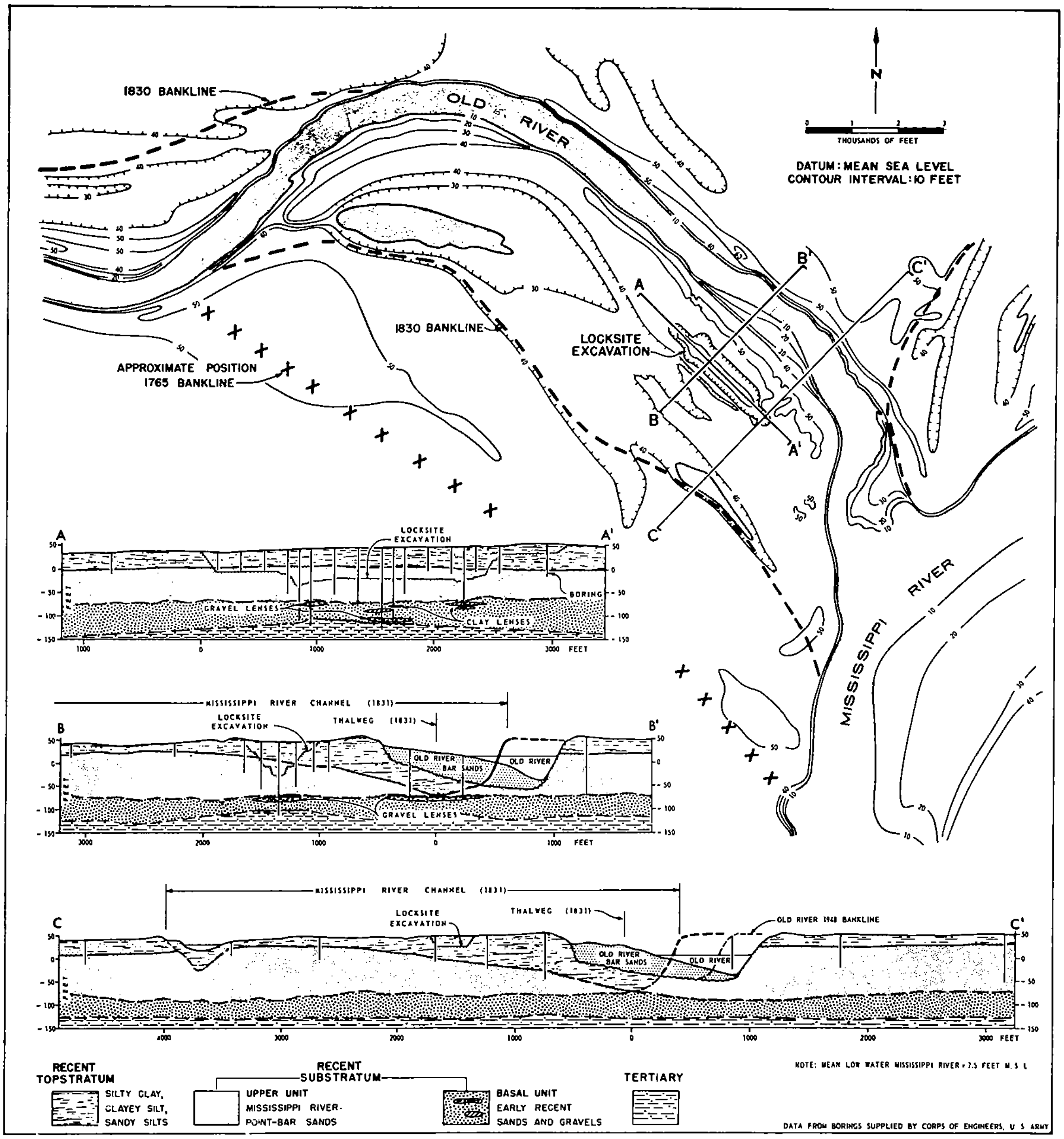

Figure 1-2. Topographic map of Old River locksite area and cross sections showing stratigraphic relationships of Holocene alluvial deposits. Point-bar sands abruptly overlie gravel-bearing sand; channel fill forms sharp upper and lateral boundaries for sand at locksite. *From* Frazier and Osanik (1961, fig. 2).

coarse-grained sequences represent a multistoried sand unit. The northeast lateral contact is sharp because the channel fill there lies at the same stratigraphic position as the point-bar sand. The nature of the other lateral contact is not known.

Internal Features

Sedimentary structures.—Medium-scale, festoon crossbedding characterizes the entire exposure of point-bar sands in the locksite excavation (fig. 1-3). Individual units are less than 4 feet thick. Festoon width is from less than 3 feet to more than 50 feet; the greatest length is more than 90 feet. Maximum observed dip of the crossbeds is 34°; most dips are between 20° and 30°. The average dip direction is S. 40° E. (fig. 1-4).

Convolute bedding is locally developed in the crossbeds. Horizontal bedding, associated with festoon crossbedding, is present in the upper part of the point-bar sequence which formed during high-water stage. Small-scale crossbedding characterizes the sandy silts of the point-bar topstratum. The channel fill contains thin laminations and, locally, small-scale crossbedding. The counterparts of 25-foot sand waves observed in the Mississippi River channel, if present, would be preserved below the level of the excavation.

Texture.—Sand composes 97 percent of the point-bar deposits exposed in the excavation. Pebbles and a minor amount of silt are the other textural classes present. The sands are fine to medium grained and well sorted. An overall upward decrease in grain size is shown in a vertical section of point-bar deposits which formed in historic time. However, in the excavation no consistent vertical change was observed. The upper 18 feet does show a general upward decrease in grain size. The lowermost sample of that sequence is coarse-grained, poorly sorted sand. Porosity ranges from 42 to 48 percent. Photometric measurement of grain orientation indicates an average trend of N. 26° W.-S. 26° E. (fig. 1-4).

Constituents.—The sand is a feldspathic litharenite, with an average of 56 percent quartz, 30 percent rock fragments, and 12 percent feldspar. Also present are wood fragments, macerated plant material, mudballs, and reworked pulmonate gastropods.

Depositional Framework

Sand deposited during historic time in the lower alluvial valley of the Mississippi River at Old River is characterized by sharp boundaries and

Figure 1-3. Dip section of festoon, medium-scale crossbedding. *From* Frazier and Osanik (1961, fig. 6).

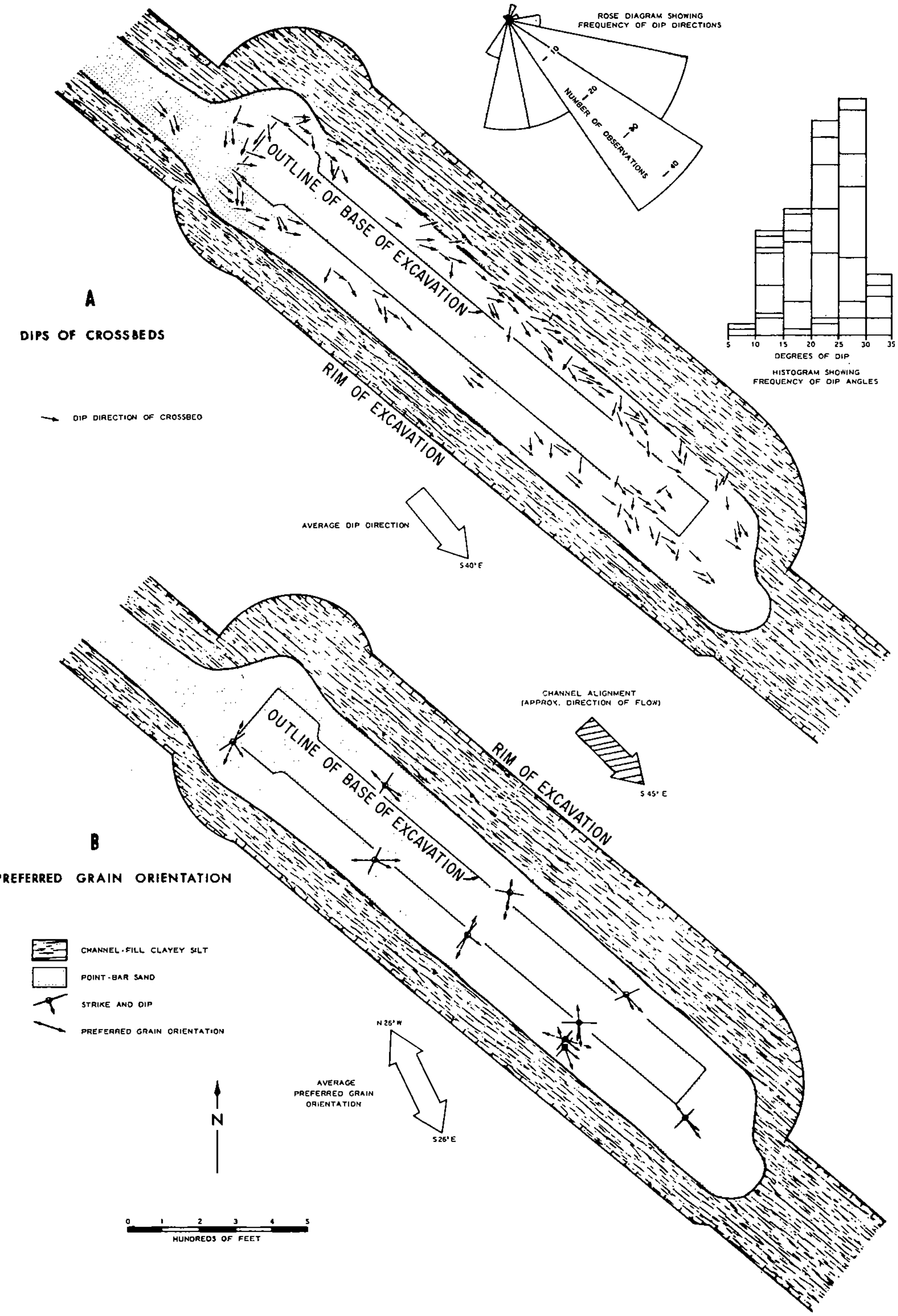

Figure 1-4. Paleocurrents in Mississippi River sand. Crossbedding averages S. 40° E. and grain orientation N. 26° W. *From* Frazier and Osanik (1961, fig. 11).

medium-scale crossbedding which parallels local current direction and sand trend. The alluvial deposit also shows an overall upward decrease in grain size from sand to silt. The relatively coarser beds in the upper 18 feet of the point-bar sands may represent deposits of a secondary channel which commonly forms across bends during high-water stage.

The Mississippi River sand in the locksite area illustrates two conditions which may not be recognized in the deeper subsurface. First, the total sand-bearing Quaternary section is multistoried in being composed of two genetic units, the upper of which is described herein. Second, the thick portion of fine-grained channel fill, which is less than 2,000 feet wide, limits sand width and is as effective a barrier to fluid migration as a wide body of silt and clay. A genetic sand unit for the Mississippi River at this stream position is approximately 100 feet thick. This value apparently is greater than that for most ancient genetic sand units formed in alluvial valleys.

The section at the study site is similar to that of the Brazos River point bar near Houston, Texas (Bernard and others, 1970), and that of the Red River near Shreveport, Louisiana (Harms and others, 1963). For each river the textural sequence shows an upward fining; the best development is at the Brazos, probably because of its position near the lower limit of the valley. Festoon crossbedding, which is a dominant feature of each sand, shows a preferred orientation parallel to local stream-flow direction. Small-scale crossbedding is present at the top of each sequence, and horizontal bedding is present on the upper part of the point bars. The sand unit at the Mississippi River site is twice as thick as that of the Brazos, and the meander-belt width of approximately 6 miles is 4 times that of the Brazos and 2 times that of the Red River.

The Amite River of Louisiana and the Colorado River near Columbus, Texas, are characterized by a somewhat different sequence, which is expressed by uniform grain size, large-scale, lunate crossbeds of chute bars and fine-grained chute deposits on the upper point bar, and coarse-grained flood-plain deposits (McGowen and Garner, 1970). The differences may represent a higher percentage of bed load, steeper gradient, and shorter periods of high discharge.

Acknowledgment

Illustrations are from Frazier and Osanik (1961) and are used with the kind permission of the Gulf Coast Association of Geological Societies.

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Kisinger Sandstone, Pennsylvanian, North-Central Texas (2)

Structural Framework

Surface beds strike northeast and dip toward the northwest at an angle of approximately 1° to 2°. The attitude of beds in the shallow subsurface is consistent with that at the surface, whereas deeper units dip gently eastward. Tectonically the area is on the Bend arch.

Stratigraphic Framework

The Kisinger Sandstone is the basal unit of the Virgilian Series of Pennsylvanian age, which is characterized by cyclic sequences of sandstones, thin limestones, and shales. The lowermost Virgilian limestone, the Salem School, is a widespread marker in north-central Texas. The underlying Missourian Series, in contrast to the Virgilian, is composed of massive limestones, with shale and some sandstone. Alternation of rock types gives rise to a "staircase" topography, with prominent escarpments formed by the limestones. The two limestones in the upper 200 feet of the Missourian are the Ranger, 50 feet thick, and the Home Creek, 30 feet thick. The latter is the youngest unit of the Missourian Series, and where the

Kisinger is absent the Home Creek lies 5 to 15 feet below the Salem School Limestone.

The Kisinger Sandstone is present locally at the stratigraphic position of the Home Creek Limestone and underlying Colony Creek Shale. The sandstone contains a number of genetic units.

Geometry

Geographic location and trend.—The Kisinger Sandstone is present in a curved west- to southwest-trending belt along or near the Brazos River in southeastern Young County (fig. 2-1). It crops out directly northwest of the more prominent Pennsylvanian limestone escarpments. In the area of study, the trend changes from west in the eastern part to southwest in the western part, beyond which the sandstone body is thought to extend again toward the west.

Vertical position.—Distribution of the Kisinger Sandstone has been mapped from surface exposures. From the study of drill samples, the sandstone trend has been extended 5 miles to the west into the shallow subsurface.

Length.—In the area of study the Kisinger Sandstone is recognized on outcrop for a distance of 7 miles (fig. 2-1). Present erosion is responsible for the eastern outcrop edge, whereas to the southwest the sandstone body extends beyond the study area but is concealed by younger beds.

Width.—The sandstone body is approximately 1 to 2 miles wide (fig. 2-1). It is wider in the eastern part than in the southwestern part of development, where sandstone width is only half a mile as it enters the subsurface.

Thickness.—The thickness ranges from 0 to 150 feet (figs. 2-2, 2-3). The sandstone thickens at the expense of lower stratigraphic units. For example, where the Kisinger is more than 30 feet thick the Home Creek Limestone is completely absent. Vertical repetition in textural parameters and the geometry of a lenticular carbonaceous shale in the upper part of the sandstone body suggest a thickness for genetic units of some 20 to 30 feet (figs. 2-3, 2-4).

Boundaries.—The lower and lateral contacts are sharp (figs. 2-2, 2-3). The lower contact, noted at several localities before construction of Possum Kingdom Reservoir, is abrupt, with sandstone disconformably overlying the Ranger Limestone or Colony Creek Shale. The lateral contacts are also erosional, with development of the Kisinger at the expense of the persistent Home Creek Limestone and Colony Creek Shale. The upper contact of the sandstone body is gradational. Fine-grained sandstone grades upward into a thin shale, which is overlain directly by a fossiliferous conglomerate bed below the Salem School Limestone.

Internal Features

Sedimentary structures.—Observed most commonly in the lower 120 feet of the sandstone body are massive bedding, medium-scale crossbedding, horizontal bedding, parting lineation, and convolute bedding (figs. 2-4 through 2-8). The bases of genetic units are characterized by cutouts or channels. The upper part of the sandstone contains horizontal bedding, interbedding, small-scale crossbedding and associated rib and furrow, parallel and cuspate ripple marks (fig. 2-9), and burrows. Dip directions of medium-scale crossbedding vary from north-northwest to southwest (fig. 2-1). The average paleocurrent direction is consistent with the sandstone trend.

Texture.—A number of textural sequences, characterized by an upward decrease in grain size, are present in the lower 120 feet of the sandstone body. Each sequence consists of conglomerate, conglomeratic sandstone, and medium-grained sandstone, in ascending order, and is commonly 20 to 30 feet thick (fig. 2-4). Generally, the conglomerate is massively bedded; thin lenses of sandstone in the conglomeratic intervals reflect sharp vertical changes in grain size. The conglomeratic sandstone is crossbedded (medium scale), and the sandstone is horizontally bedded or contorted. Locally the sandstone is crossbedded. Conglomerates include chert pebbles, most commonly 25 mm or less in diameter, limestone cobbles and boulders, and siltstone and claystone pebbles and cobbles (North Texas Geological Society, 1958, p. 17). Fine- and very fine-grained sandstone and interbeds of shale compose the upper 30 feet.

Constituents.—The characteristic constituent of the Kisinger Sandstone is chert, most commonly white or gray but with some black, banded, or green. Locally derived particles of limestone, siltstone, and claystone are also present. Carbonized plant material, casts and molds of plant fragments, and associated iron oxide minerals are present in the conglomeratic sequences (fig. 2-10). Concretions of sideritic claystone with plant remains are present in the fine-grained sandstone and overlying carbonaceous shale.

Depositional Environment and Geologic History

The Kisinger Sandstone was deposited in a deep and narrow valley by a westward-flowing river. The abundance of conglomerate, thin lenses of sandstone in the conglomeratic units, and the absence of fine clastics suggest that the stream was

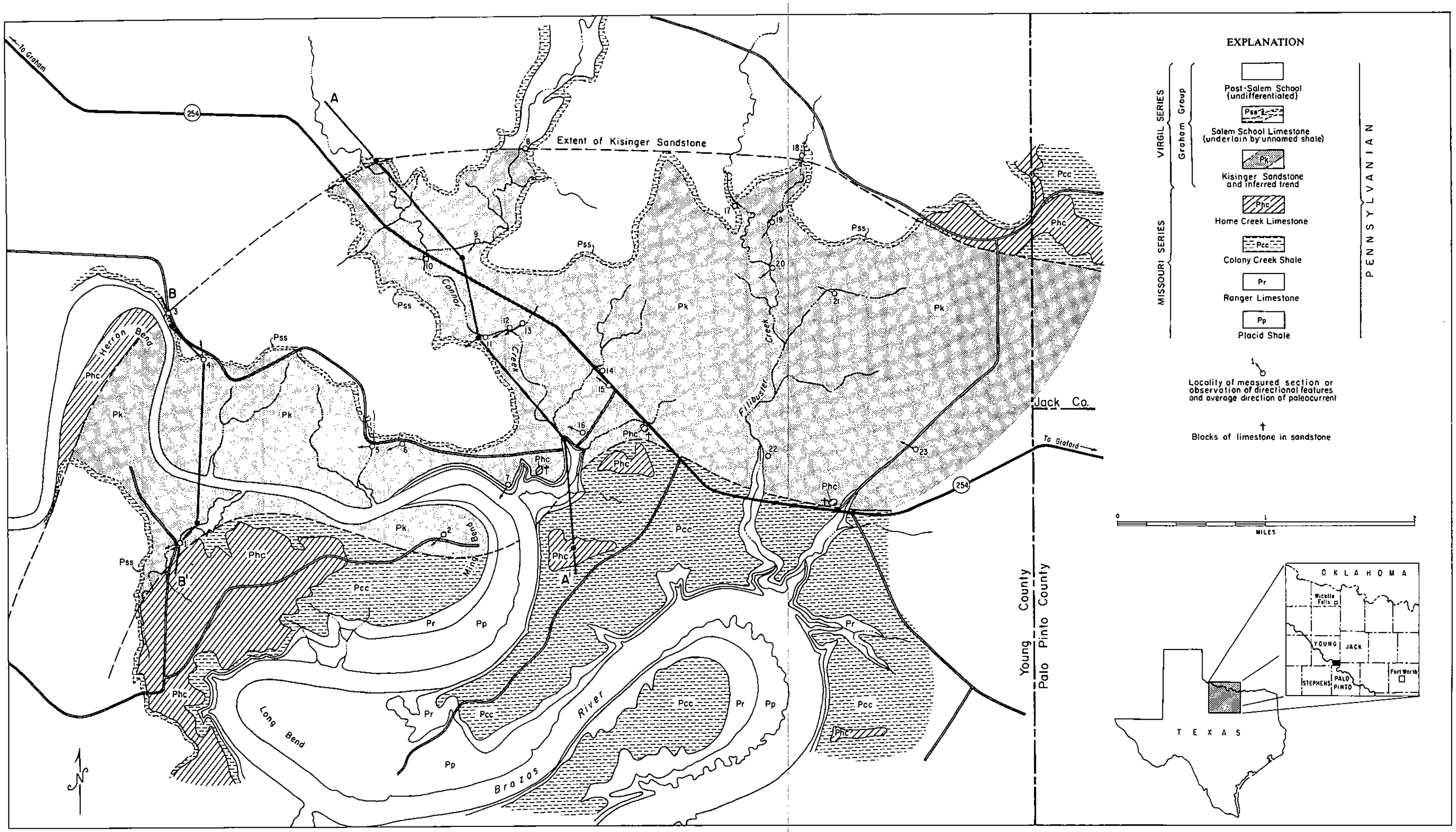

Figure 2-1. Geologic map of a part of north-central Texas, showing trend, length, width, and paleocurrents of Kisinger Sandstone.

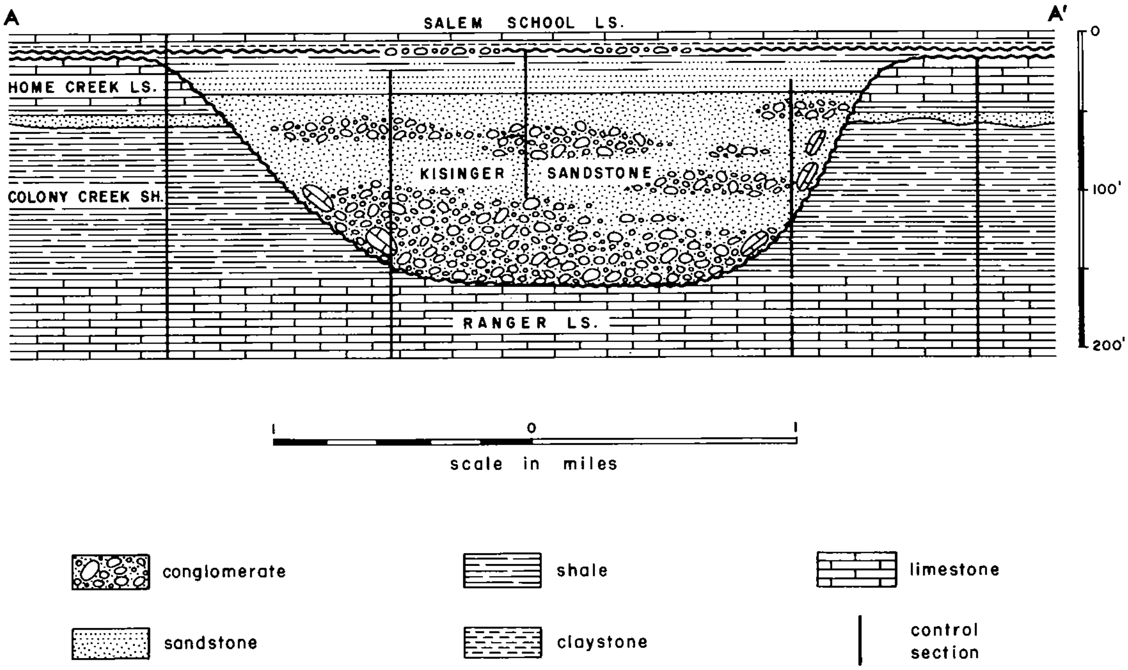

Figure 2-2. Cross section *A-A'* of Kisinger Sandstone, illustrating thickness, width, and boundary conditions. Line of section shown in figure 2-1. *Modified from* Lee and others (1938, pl. 1).

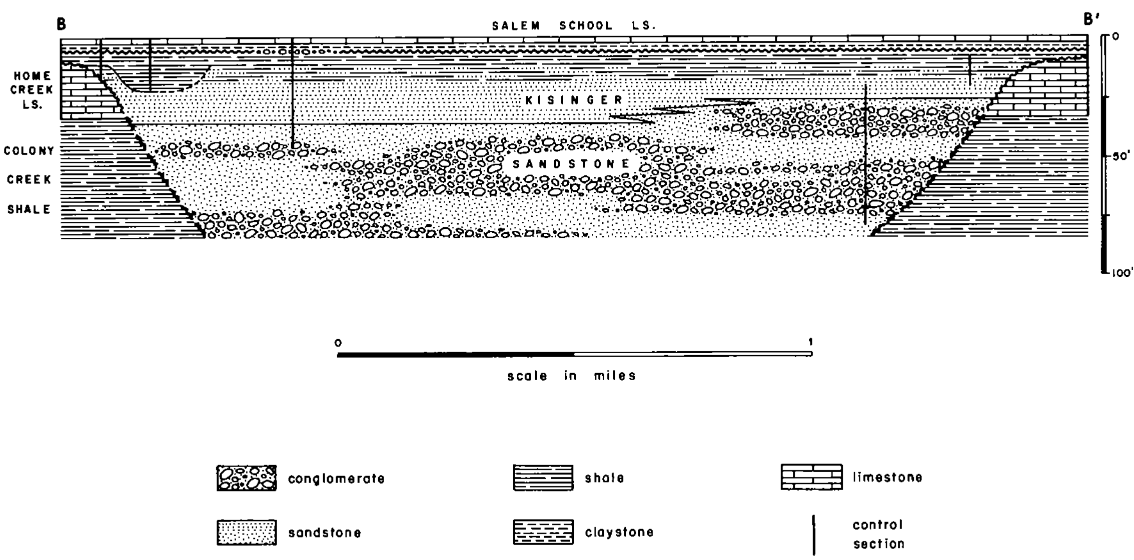

Figure 2-3. Cross section *B-B'* of part of Kisinger Sandstone, showing width, boundaries, and lateral lithologic variations within sandstone body. Note apparent abandoned channel filled with clay. Line of section shown in figure 2-1.

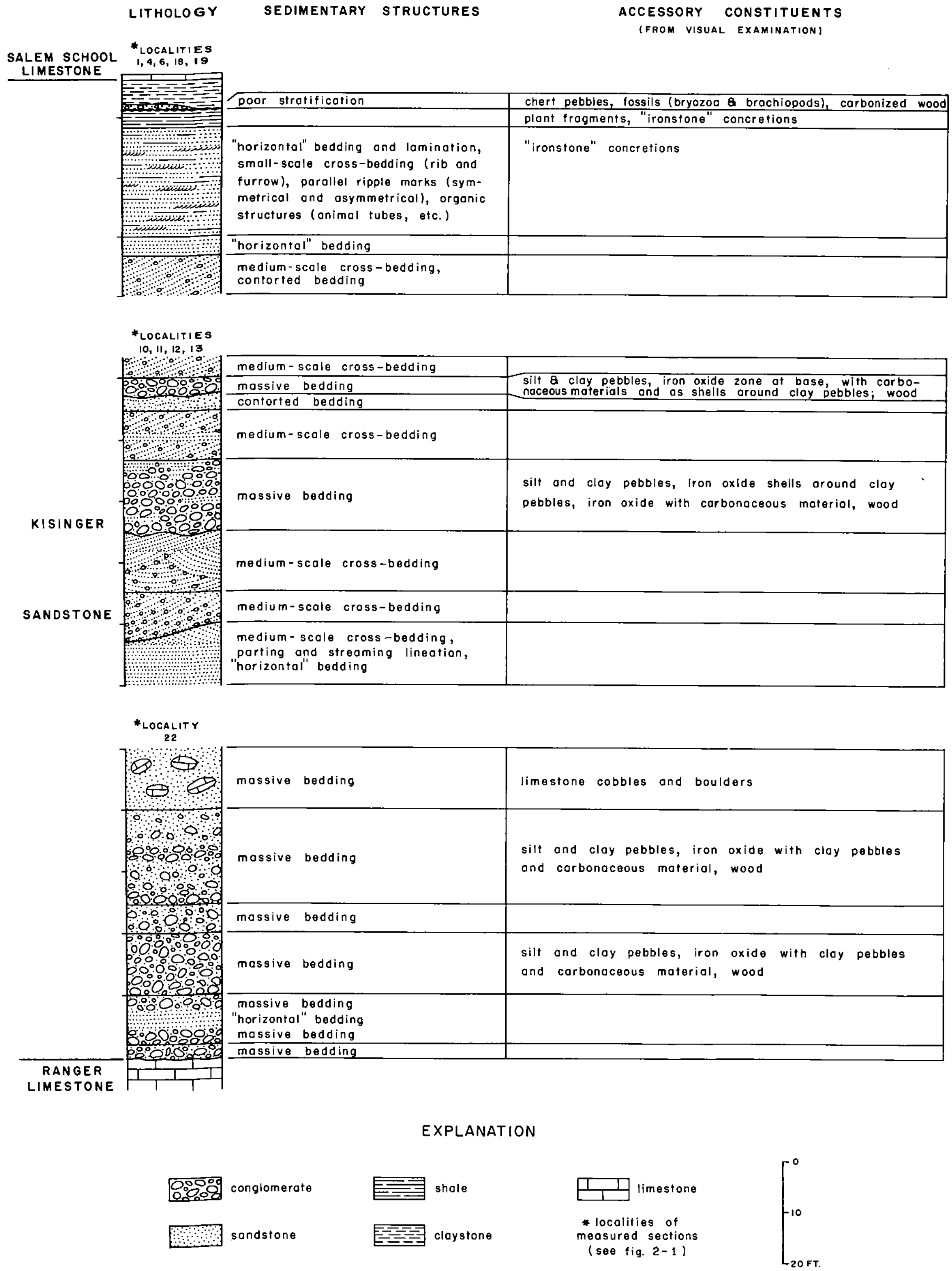

Figure 2-4. Composite measured section of Kisinger Sandstone, showing best development of vertical textural sequences in middle part.

Figure 2-5. Massively bedded Kisinger conglomerate below, with crossbedded conglomeratic sandstone above.

Figure 2-6. Medium-scale crossbedding in conglomeratic sandstone of the Kisinger.

Figure 2-7. Horizontal bedding and medium-scale crossbedding in medium-grained sandstone of the Kisinger (in upper part of textural sequence), overlain by conglomeratic sandstone. Contact rises to right.

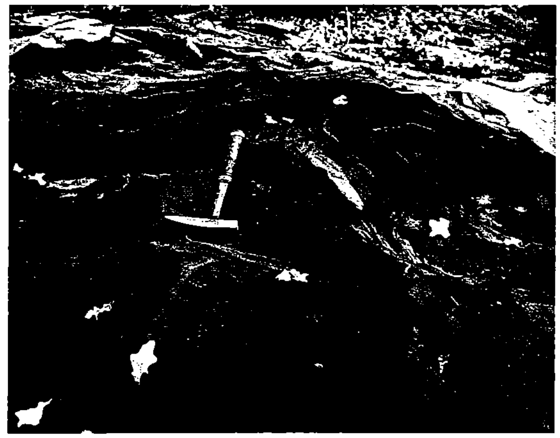

Figure 2-8. Contorted bedding in medium-grained sandstone of the Kisinger.

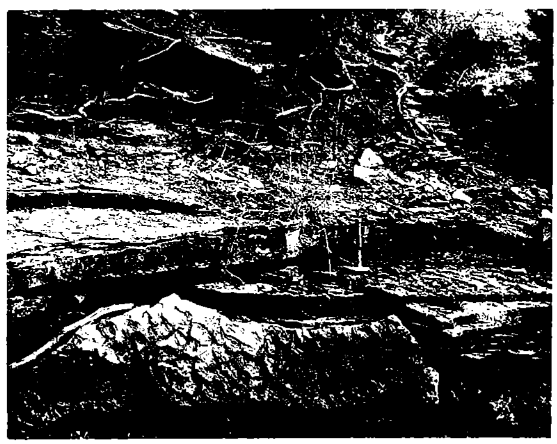

Figure 2-9. Cuspate ripple marks in sequence of interbedded sandstone and shale from upper 30 feet of Kisinger Sandstone.

Figure 2-10. External mold of log in Kisinger conglomerate, marked by rim of iron oxide.

braided during much of Kisinger deposition. Each of the textural sequences is thought to be a genetic unit formed at one position of the river in the valley. Based on the thickness of the sequence, the river may have been 200 to 300 feet wide. The lenticular carbonaceous shale, considered to be an abandoned channel deposit, suggests a stream width of 1,000 feet during deposition of the upper part. Headwaters were in the Ouachita Mountain system, some 90 to 100 miles to the east and southeast, where Paleozoic chert beds were exposed.

After deposition of the Home Creek Limestone, sea level was apparently lowered and the Kisinger valley cut into the upper 150 feet of Missourian strata. Although some of the Kisinger Sandstone may represent preservation of beds deposited during an overall degradation, it is thought that deposition in the valley was initiated as the stream regimen changed in response to a rise in sea level. The upper 30 feet of the sandstone body probably represents deposition by a less competent coastal stream either as sea level continued to rise or as a result of stream diversion. Finally, the area was transgressed by marine waters, which first deposited the fossiliferous conglomerate and later, the Salem School Limestone.

Acknowledgment

Appreciation is expressed to Shell Development Company for permission to use unpublished data and illustrations.

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Anvil Rock Sandstone, Pennsylvanian, Illinois Basin (3)

Structural Framework

The area of study includes some 10,000 square miles in an L-shaped area of west-central and southern Illinois. The western part lies on the stable west shelf area of the Illinois basin, whereas the southern part lies in the deep part of the basin (fig. 3-1). Structural dip is gentle toward the axis of the basin. Anticlinal belts, parallel to the basinal axis, were apparently active during a part of the Pennsylvanian Period. Along the southern edge of the deeper part of the Illinois basin are east-southeast-trending fault zones, which are in or near the outcrop part of the area of study.

Stratigraphic Framework

The Anvil Rock Sandstone is part of the Carbondale Formation of the Kewanee Group of Middle Pennsylvanian age. In terms of the standard Midcontinent section, the sandstone lies near the middle of the Marmaton Group of the Desmoinesian Series. Formerly, when stratigraphic boundaries were drawn at the base of the lowermost sandstone of a cyclothem, the Anvil Rock was considered the basal unit of the McLeansboro Group in Illinois and the Lisman Formation in Kentucky. A striking feature of Carbondale and/or McLeansboro sediments is the lateral persistence of certain coals, underclays, and limestones.

Although some doubt exists concerning the stratigraphic position of the top of the sandstone at the type locality along the Ohio River in Union County, Kentucky, the Anvil Rock is generally considered to lie below the Bankston Fork Limestone (fig. 3-2). Normally the Jamestown coal (Kentucky No. 12 coal) underlies the sandstone in the southern part of the area. The coal is not developed in the western part, where the Brereton (Herrin) Limestone is the youngest recognizable unit below the Anvil Rock (fig. 3-2). The limestone overlies the widespread Herrin (No. 6) coal (Kentucky No. 11 coal). On outcrop in western Illinois, the Copperas Creek Sandstone is thought to be the correlative of the Anvil Rock. In west-central Illinois the persistent Piasa Limestone, above the Bankston Fork Limestone and the Danville (No. 7) coal, is a good marker for stratigraphic mapping.

Determination of sandstone distribution of the Anvil Rock was made by Hopkins (1958, fig. 4, pl. 1) and Potter and Simon (1961, fig. 4) from examination of the southern outcrop and of more than 3,700 subsurface control points. In the western part of the study area, sandstone is developed at the expense of the older stratigraphic units. A normal stratigraphic sequence is present in the southern part, where the sandstone is no thicker than 20 feet. However, additional thick-

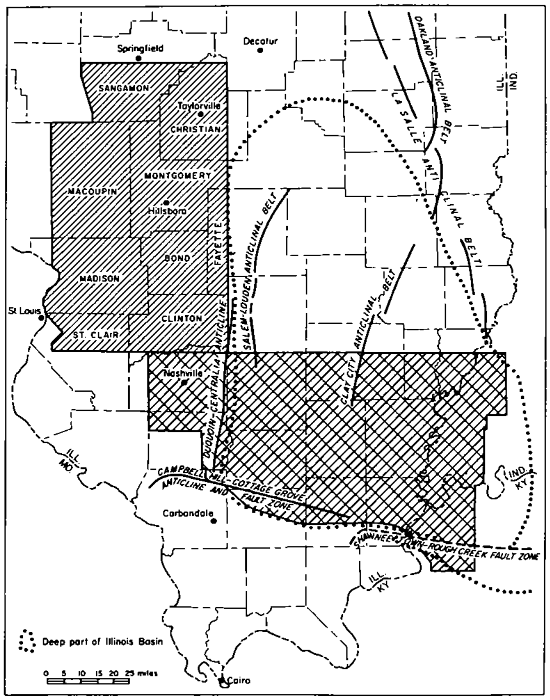

Figure 3-1. Index map showing area of study and structural features of Illinois basin. *Modified from* Potter and Simon (1961, fig. 1).

ness is achieved by erosion of older beds. The widespread, relatively thin sandstone of the Anvil Rock, which has been termed the sheet phase by Hopkins (1958, p. 7), is present in the deeper part of the Illinois basin (fig. 3-3). It is absent in the western shelf area, west of the Duquoin-Centralia anticline. Also, it is absent in substantial areas along the Illinois-Indiana boundary, where positive structural elements are present. The sheet phase is regarded as a regressive marine or coastal deposit and as being older than that part of the Anvil Rock Sandstone which is not widespread but thick. In other words, two types of sandstone bodies are present at the same stratigraphic position but are of different age. The lenticular type of sandstone is described herein; it is composed of a number of sandstone bodies, each of which may include more than one genetic unit.

Geometry

The thick, lenticular bodies of Anvil Rock Sandstone are widely distributed in southern Illinois and adjacent parts of Indiana and Kentucky but are less widely distributed in west-central Illinois (fig. 3-3). The resulting overall pattern includes dendritic and anastomosing networks of long, sinuous bodies. Sandstone bodies are divided into major and minor units on the basis of thickness, continuity, and presence or absence of the No. 6 coal.

Geographic location and trend.—The most extensive unit is an S-shaped body that extends through both parts of the area (figs. 3-3, 3-4). It has two branches, one extending southward in the southwestern part of the area and the other extending southwestward from Indiana. The other major body trends west-southwest in the area near the outcrop in Union County, Kentucky. In several parts of the area, some correlation apparently exists between structure and sandstone-body trend. The major unit in the southwest parallels the Duquoin-Centralia anticline (figs. 3-1, 3-4). It most commonly lies on the basinal side of the structure but does cross over to the stable shelf. The branch from Indiana parallels the Wabash River fault zone. Also, where the S-shaped body trends east-west it lies over structurally controlled oil fields.

Minor sandstone bodies are commonly a complex system of anastomosing units, but some are branches of the major ones. Others show an overall trend parallel to the southwestern segment of the S-shaped body in southern Illinois or parallel to the south-trending branch.

Vertical position.—The Anvil Rock Sandstone is present at the surface along the southern edge of the study area. The greatest subsurface depths, 1,000 to 1,200 feet, occur in the north-central part of the southern area.

Length.—The S-shaped body has been recognized for approximately 300 miles along its sinuous course (fig. 3-4). The branch in the southwest has been mapped for 50 miles along its circuitous trend of development, and the Indiana body extends some 40 miles northeastward from its junction with the 300-mile unit.

Minor bodies joining major units are from 3 to more than 40 miles in length. One body parallels the S-shaped trend for almost 50 miles in the southwestern part of the area.

Width.—Major sandstone bodies average about 2 miles in width. Where they are relatively straight for a considerable distance the width is approximately 1 mile; at junctions and bends the width increases to as much as 5 miles.

The width of minor bodies varies from about 1/3 to 3 miles. Their most common width is 1/2 to 1 mile.

Thickness.—Intimately associated with the sandstone is siltstone, which is considered a part of the sandstone deposit. The thickest sections of the lenticular Anvil Rock are in Washington County, Illinois, where at one place the deposit is 216 feet, including 110 feet of siltstone. At another Washington County locality, sandstone 210 feet thick composes the entire deposit. Average thickness for major units is approximately 120 feet, with 70 feet of sandstone and 50 feet of siltstone.

Along the minor trends siltstone is not well developed, and sandstone composes the bulk of the deposit. Average thickness of the minor bodies is 40 feet; maximum thickness is 100 feet.

Boundaries.—The lower contact is represented by a sharp lithologic break and correspondingly sharp deflection on electric logs (figs. 3-5, 3-6). The lateral contacts, noted in underground and strip mines, and established from closely spaced well logs (fig. 3-6), are also sharp. Flat-lying beds have been truncated at angles as high as 35°. The upper contact is gradational, as sandstone changes upward into siltstone and shale. This change is also reflected by the gradual deflection of electric-log curves.

Internal Features

Sedimentary structures.—The most characteristic structure of the Anvil Rock Sandstone is medium-scale crossbedding. Other features are ripple marks, contemporaneous slump features and load casts, streak lineation, and cut and fill. Crossbeds vary from northwest to south-southeast

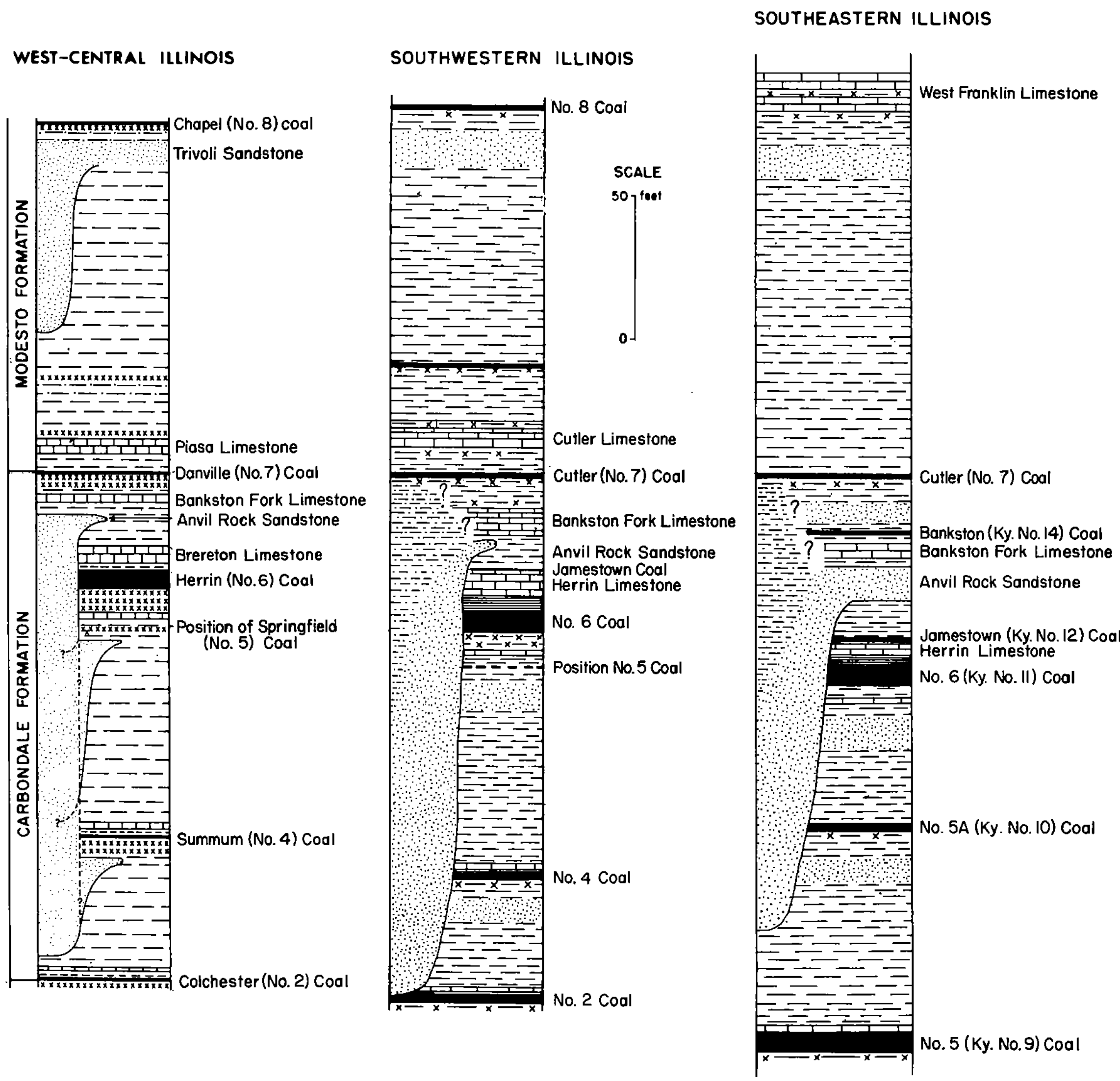

Figure 3-2. Generalized stratigraphic sections showing position of Anvil Rock Sandstone. *Modified from* Hopkins (1958, fig. 3) and Potter and Simon (1961, fig. 3).

in dip direction; the average dip is southwest. The most noticeable structures of the sheet phase of the Anvil Rock Sandstone are parallel bedding, interbedding, and sporadic ripple marks.

Texture.—The textural rock types are sandstone and siltstone, with lesser amounts of shale and basal conglomerate. Locally derived pebbles of shale, coal, clay-ironstone, and limestone are present in a sandstone matrix. The average diameter for sandstone is 0.24 mm, as determined from thin-section analysis, and 0.29 mm, from sieve analysis. Grain size decreases in an upward direction. The sandstones are well sorted, with an average sorting coefficient of 1.35.

The older sheet phase is finer grained than the model sandstone, averaging 0.19 mm in diameter (from thin section) or 0.15 mm (from sieve analysis). Also, the finer grained sandstone is only moderately sorted on the average, with a sorting coefficient of 1.78.

Constituents.—The Anvil Rock Sandstone is argillaceous, micaceous, and sparingly feldspathic.

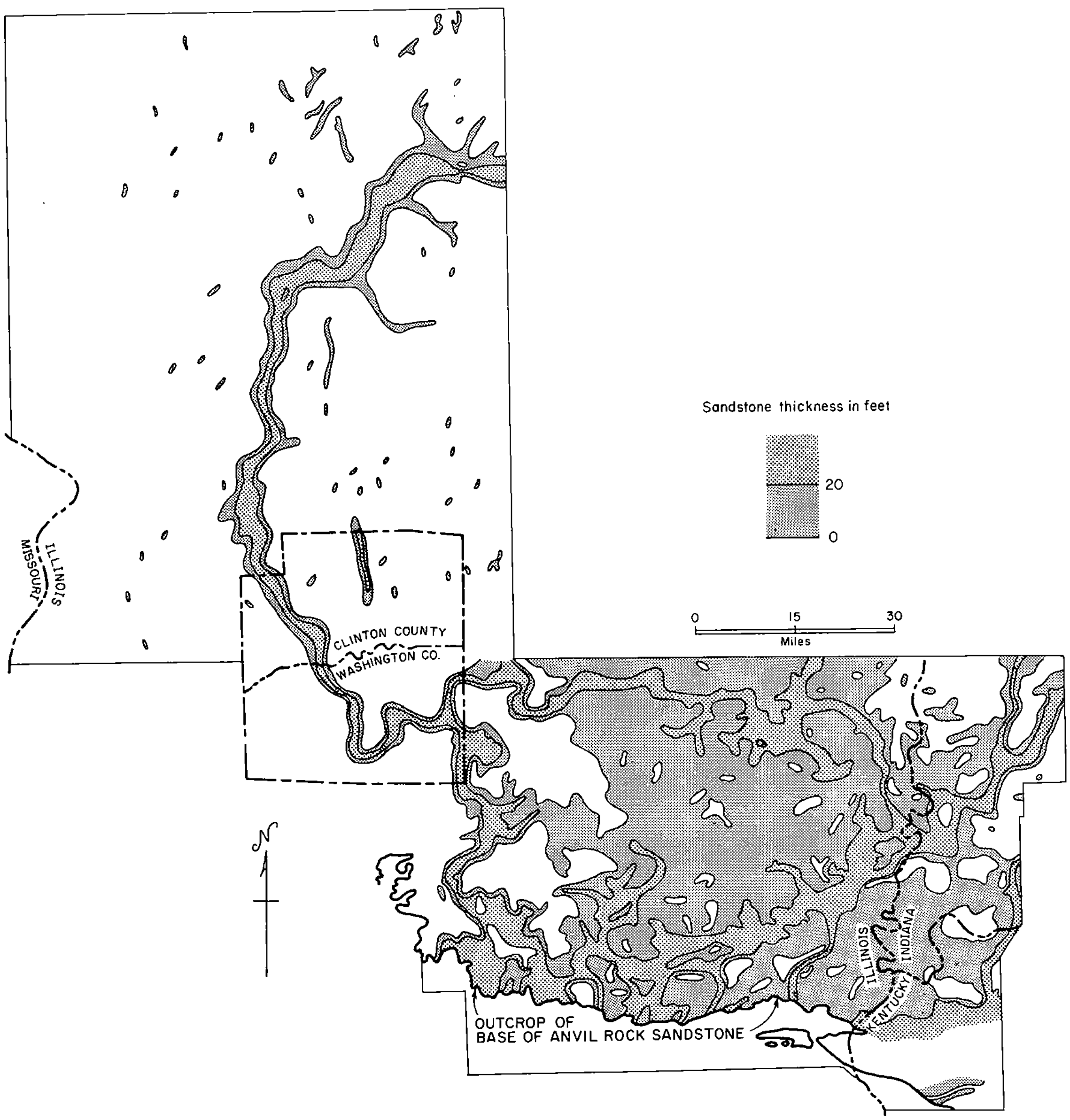

Figure 3-3. Thickness and distribution map of Anvil Rock Sandstone in area of study. *Modified from* Hopkins (1968, fig. 4, pl. 1) and Potter and Simon (1961, fig. 4).

Based on textural and mineralogical attributes, it is a subgraywacke. On the average, the Anvil Rock is 70 percent quartz, quartzite, and chert; 19 percent clay; 5 percent carbonate; 3 percent feldspar; 1.5 percent rock fragments; and 1.5 percent mica. The sandstone is classified as a quartzarenite according to the composition of framework grains, which are 92 percent quartz, 4 percent feldspar, and 4 percent rock fragments. Calcite and clay are present as interstitial materials. Siderite is present as cement and as sand-sized spherulites. Accessory constituents include detrital glauconite and various stable heavy minerals. Clay minerals in the fine fraction of sandstone average 40 percent kaolinite, 29 percent illite, 8 percent mixed lattice, and 23 percent chlorite. Shale interbeds are 24 percent kaolinite, 40 percent illite, 14 percent mixed lattice, and 22 percent chlorite. The differences are thought to reflect changes during diagenesis by ground water. Petrographic homogeneity exists

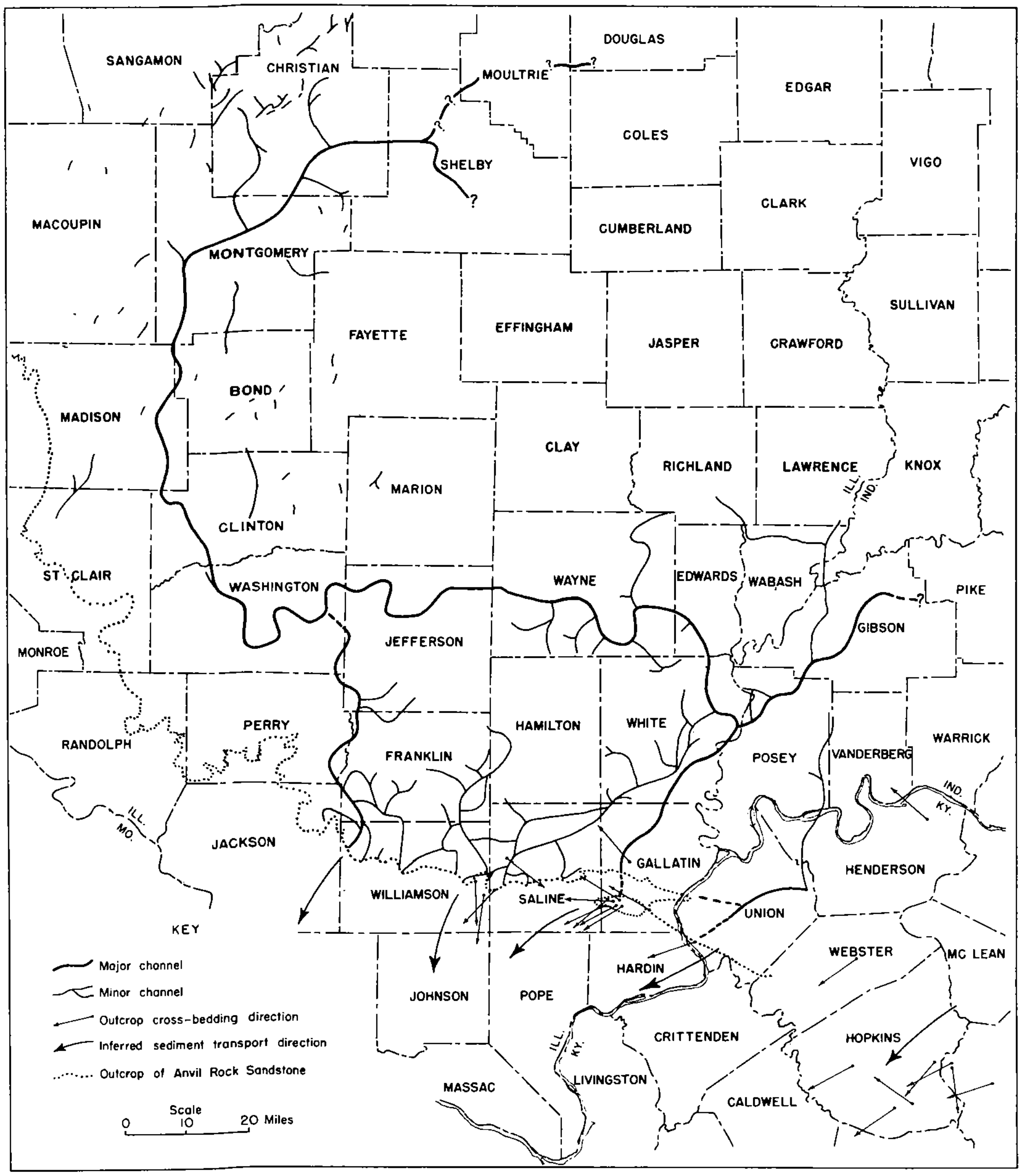

Figure 3-4. Generalized map of known lenticular bodies in Anvil Rock Sandstone in Illinois, showing stream courses and paleocurrents. *From* Simon and Potter (1961, fig. 2).

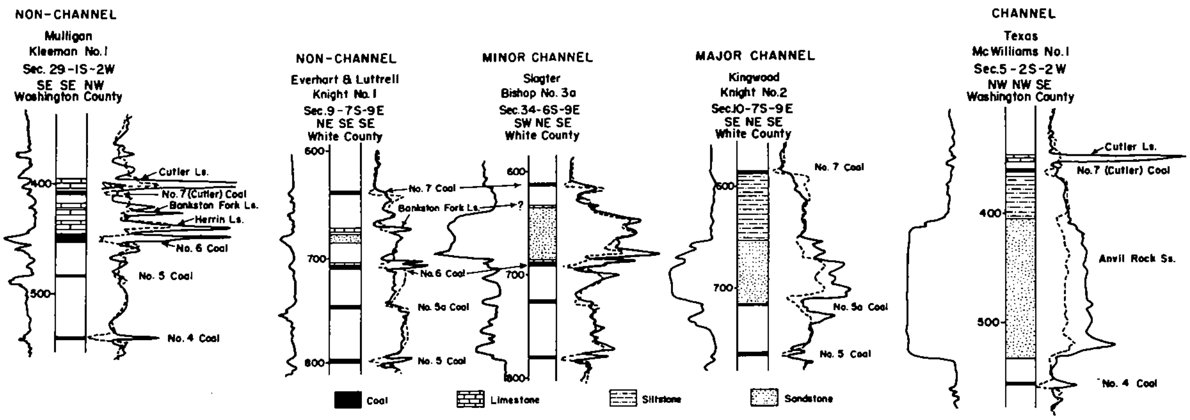

Figure 3-5. Representative electric logs of section which includes Anvil Rock Sandstone. Logs show no sandstone, sheet phase, minor lenticular sandstone bodies, and major bodies. *Modified from* Hopkins (1958, figs. 7, 9).

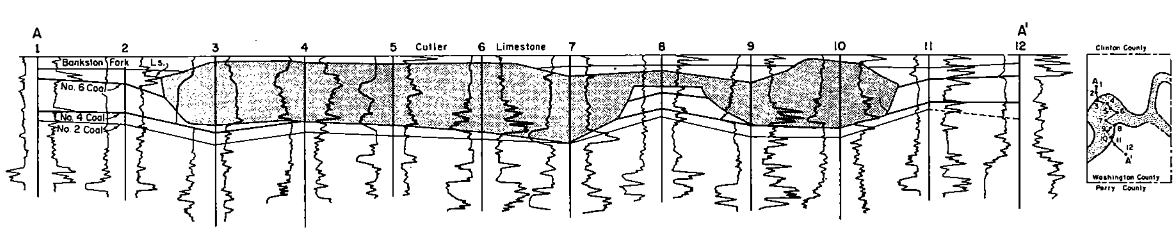

Figure 3-6. Correlation section of Anvil Rock Sandstone across a major lenticular body, showing boundaries and distribution of lithologies. *Modified from* Hopkins (1958, pl. 2).

between the lenticular bodies and the older sheet phase.

Depositional Environment

Lenticular bodies of the Anvil Rock Sandstone are thought to represent alluvial deposits in relatively narrow valleys cut on a coastal plain. A eustatic lowering of sea level was the probable cause for downcutting after deposition of the sheet phase, and a subsequent eustatic rise resulted in deposition of the valley fill. The dominant direction of transport was toward the southwest, although streamflow in the major channel was easterly for about 65 miles. A change in the longest stream course by piracy is suggested by the branch in the southwest.

Evidence of stream deposition includes (1) sharp basal and lateral boundaries, (2) characteristic width-thickness and width-length ratios, (3) dendritic and anastomosing patterns for sandstone bodies, (4) medium-scale crossbedding with average dip directions paralleling paleoslope, and (5) siderite spherulites. Siltstone units suggest deposition in abandoned channels or in estuaries which formed as sea level rose faster than the rate of deposition. Estuarine or marine deposition of silt in the uppermost part of the channel fill may explain the absence of the overlying Bankston Fork Limestone in most of the channel areas.

The ultimate sediment source is thought to have been the highlands of New England and the southern portion of the Canadian shield. Sandstone deposits in minor channels that drained local areas were probably derived from erosion of the earlier deposited sheet phase of the Anvil Rock.

The two successively younger Pennsylvanian sandstones, the Trivoli and the Ingleside, have similar geographic distributions and paleocurrent directions (Andresen, 1961). This relationship suggests that the axis of the Illinois basin exercised a weak but distinct influence on the trend of Middle Pennsylvanian valley systems.

Acknowledgments

The Illinois State Geological Survey has kindly permitted use of illustrations from its publications. Appreciation is expressed to M. E. Hopkins for his helpful suggestions.

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ALLUVIAL-PLAIN ENVIRONMENTS

Zone 19b, Frio Group, Oligocene, Seeligson Field, South Texas (4)

Structural Framework

The area of study, Seeligson field, lies in the central part of the Rio Grande embayment of south Texas, in the Frio-Vicksburg trend of oil fields. The field was discovered in 1943 by testing a structural anomaly on the downthrown side of a fault. At the level of zone 19b, the anticlinal feature, which is composed of three gentle domal structures (fig. 4-1), is on the downthrown (east) side of a major contemporaneous normal fault, the Sam Fordyce-Vanderbilt zone. Several minor faults are present in the field area.

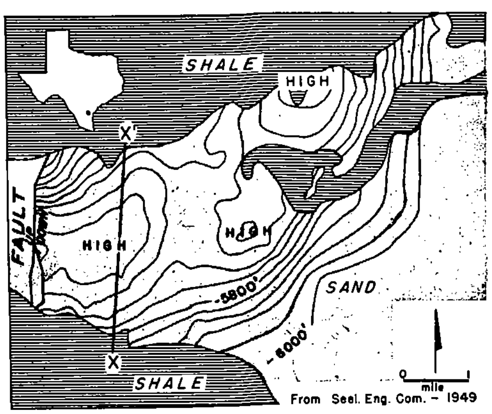

Figure 4-1. Structural-contour map of Seeligson field area, South Texas, on top of zone 19b; elevations shown in feet. *From* Nanz (1954, fig. 2).

Stratigraphic Framework

At Seeligson field more than 40 sands, all of which are irregularly developed, have combined with the structural pattern to account for more than 140 individual reservoirs. These sand units are present in a 1,500-foot section of Oligocene (or Miocene) Frio strata, which are considered non-marine in origin.

Zone 19b is an irregularly developed belt of sand representing approximately 1/9 cubic mile of sediment. It lies 300 to 400 feet above the base of the Frio at Seeligson. Zone 19b was delineated for study by utilizing two shale markers above the zone (fig. 4-2). These markers were established by careful correlation of more than 500 electric logs by Nanz (1954, p. 101). After 6 years of production this zone had accounted for one-eighth the total production of the field.

Geometry

Geographic location and trend.—Sand of zone 19b is present in most of the field area. The belt of development forms an easterly trend, which is essentially at right angles to the regional depositional strike during the Cenozoic (figs. 4-1, 4-3).

Vertical position.—At Seeligson the sand lies between 5,500 and 6,000 feet below the surface. Undoubtedly the sand is present along trend both at shallower depths west of the field and downdip to the east.

Length.—Sand of zone 19b was mapped for a distance of some 7 miles. Along the east-trending length it extends beyond the field in both directions.

Width.—The average width of the sand belt is approximately 4 miles. The belt is narrowest in the westernmost part of the field area, west of the fault, where it is less than 2 miles wide. It widens progressively eastward, and at the eastern edge of the area it is more than 5 miles wide. Consequently, the shape of the sand body is somewhat deltoid or fanlike.

Thickness.—The sand body ranges in thickness from 0 to between 60 and 80 feet (fig. 4-3) and has an average thickness of 40 feet. In addition to the area outside the east-trending sand belt, sand is not developed in two areas within the belt (fig. 4-3).

Boundaries.—The upper and basal contacts are irregular in position, and electric-log characteristics indicate that they are generally sharp (fig. 4-2). The sharpness of the lower contact is indicated

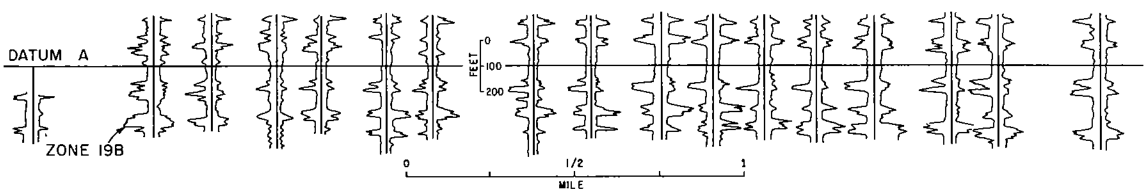

Figure 4-2. Typical electric-log characteristics and correlation section of zone 19b. *Modified from* Nanz (1954, fig. 4).

also by the configuration of the base of the sand, as determined by a thickness map of the interval from a marker overlying the sand to the base (fig. 4-4). Based on a sand-thickness map (fig. 4-3) and correlation sections (fig. 4-2), the lateral contact is sharp. The most abrupt change laterally is along the southern sand edge, especially in a local area within the southwestern part.

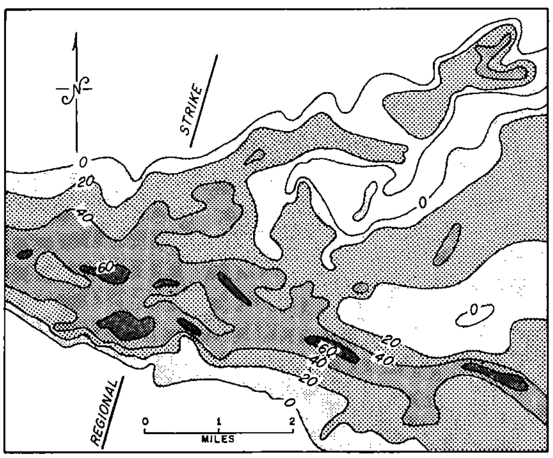

Figure 4-3. Total-sand-thickness map of zone 19b; thicknesses shown in feet. *Modified from* Nanz (1954, fig. 6).

Internal Features

Sedimentary structures.—Medium-scale cross-bedding is a common structure in sand of zone 19b. Mud fragments in the sand are thought to have resulted from limited transportation of desiccated and disrupted clay drapes.

Texture.—Four textural groups are present in zone 19b: conglomeratic sand, sand, shaly sand, and silty shale. Locally derived mud fragments are the gravel-sized particles in the conglomeratic sand. The average grain size varies from very fine to fine, and the maximum size, excluding the mud fragments, varies from medium to coarse. Most samples are well-sorted sand, with 5 to 20 percent interstitial silt and clay.

Both the average and the maximum size are coarsest at the base and exhibit an upward decrease (fig. 4-5). On the basis of maximum size, sand of zone 19b contains three vertical textural zones, the coarsest zone occupying only the lower part of the sand (fig. 4-5). No significant lateral variation is recognized in grain size within the sand body.

Constituents.—Sand of zone 19b is classified as a lithic sand (litharenite) and has an average composition as follows:

Minerals	Percent
Quartz	30
Chert	15
Potash feldspar	5
Plagioclase feldspar	5
Micas and opaques	1
Rock fragments	
Rhyolite or trachyte	8
Limestone and fossils	6
Shale	3
Quartzite	1
Volcanic glass	1
Interstitial or secondary constituents	
Calcite	19
Clay	6

Glauconite is included in the micas, and authigenic pyrite in the opaques. Illite is the predominant clay mineral in the fine fraction of the sand. Montmorillonite is also common.

Compositionally, sand of zone 19b is quite similar to Holocene alluvial- or deltaic-plain sand of the Rio Grande embayment and dissimilar to beach and dune sands of the same area (fig. 4-6).

Depositional Environment

Sand of zone 19b represents channel and bank-slope deposits of an ancestral Rio Grande meandering on an alluvial plain (fig. 4-7). Supporting this interpretation are the following features which are similar to those of alluvial-plain deposits

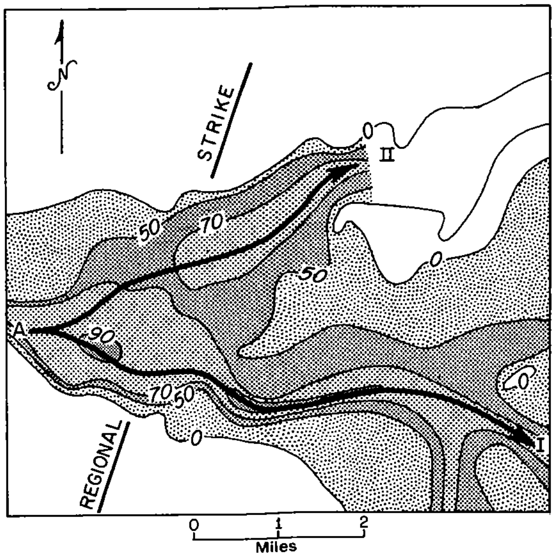

Figure 4-4. Thickness map showing configuration of base of zone 19b sand and postulated positions of channels; thickness of interval from shale marker above sand to base of sand shown in feet. *Modified from* Nanz (1954, fig. 8).

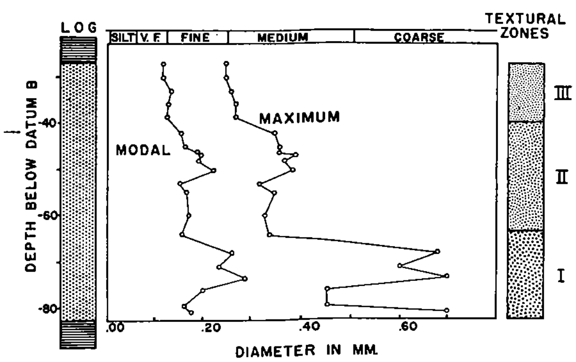

Figure 4-5. Vertical variation of grain size in sand of zone 19b in a single well. *From* Nanz (1954, fig. 14).

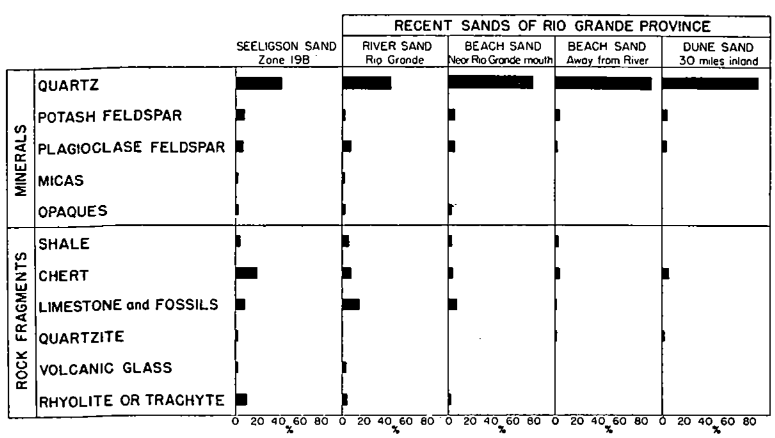

Figure 4-6. Comparison of composition of zone 19b sand with Holocene sands of same region. *From* Nanz (1954, fig. 19).

of the Holocene Rio Grande (Corpus Christi Geological Society, 1958, p. 54): easterly trend normal to depositional strike, sharp boundaries, upward-decreasing grain size, and lithic sand with sedimentary- and volcanic-rock fragments. In addition, shale in the sand interval, which is brown and/or green, and shale above the sand, which is green, are barren of fossils.

The regional depositional framework for the Frio was also quite similar to that which exists today (fig. 5). The ancestral Rio Grande alluvial-plain and deltaic complex lay south of a major interdeltaic coastal area with major barrier-bar development (*see* discussion of the Frio sand complex, model 17) and associated lagoonal and shelf deposits.

Acknowledgment

The figures are included with the kind permission of The American Association of Petroleum Geologists.

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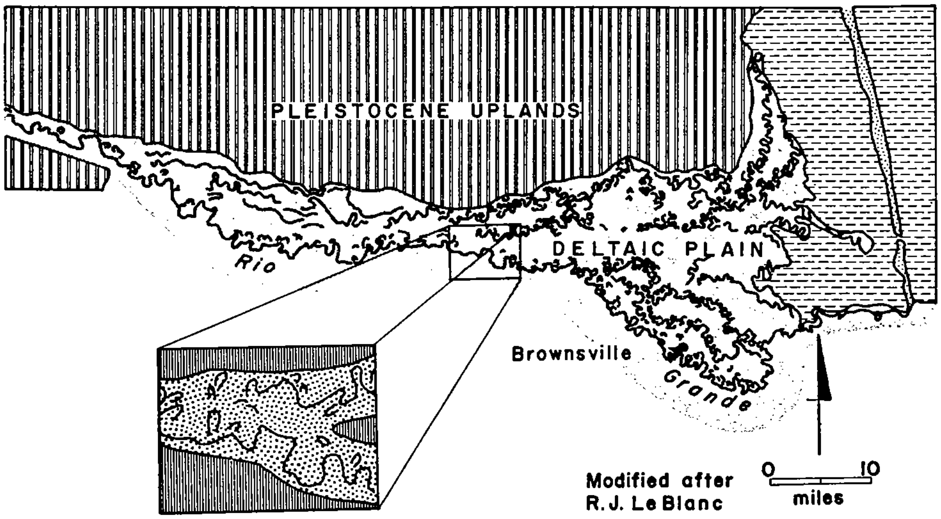

Figure 4-7. Distribution of Holocene alluvial- and deltaic-plain deposits of Rio Grande. *From* Nanz (1954, fig. 7).

Rocktown Sandstone Member, Dakota Formation, Cretaceous, Kansas (5)

Structural Framework

Surface beds in western and central Kansas dip generally northward, and in Russell County the dip is north-northeastward at an average rate of 7 feet per mile. In the northern part of the county the dip is approximately 12 feet per mile, whereas it is 5 feet per mile in the southern part. However, numerous structural anomalies are present locally. Most of the area is in the Salina basin, as reflected by subsurface Paleozoic rocks. The southwesternmost and southernmost parts of the county lie on the Central Kansas uplift.

Stratigraphic Framework

The Dakota Formation in west-central Kansas is a heterogeneous sequence of claystone, mudstone, siltstone, and sandstone, with lignitic beds near the top. A common rock type of the Dakota is light-gray to greenish-gray kaolinitic mudrock, mottled with red patches. Pellets of spherulitic siderite are a common constituent of the variegated mudrock. Sandstone generally composes less than 40 percent of the formation, which is approximately 300 feet thick.

For purposes of studying clay resources, the Dakota is separable into the Terra Cotta Clay and Janssen Clay Members. Red-mottled mudrock most commonly typifies the former, which composes the lower two-thirds of the formation. Gray mudrock and lignite are confined mainly to the Janssen Clay Member. The contact between the two members is not a distinctive stratigraphic horizon, and precise subdivision of the formation is not possible over any significant area (Franks, 1966, p. 203). Sandstone in both members is quartzarenite. Crossbedding indicates that the average paleocurrent direction for the Terra Cotta Clay Member was approximately S. 65° W. Crossbed dips in the Janssen Clay Member show considerable variation in direction: the average direction of dip is approximately S. 70° W.

The Dakota Formation of Kansas is noted for its fossil leaves. Vertebrate fossils are also present, along with some marine and brackish-water mollusks in the upper part of the Janssen Clay Member.

In Russell County, the upper 160 feet of the Dakota is exposed at the surface and includes locally thick sandstone bodies in a sequence composed of four lithologic units. These units are, in descending order:

1. Upper sandstone unit, very fine- to fine-grained, regularly bedded to massive, with some lenticular beds. It is 0 to 20 feet thick and contains ferruginous layers and carbonized wood. It is thought to represent a coastal deposit, preceding the transgression associated with the overlying Graneros Shale.
2. Lignitic beds, composed largely of carbon-

ized wood fragments, 1 to 2 feet thick. The lignite probably represents a coastal-marsh deposit.

3. Clay-shale beds: light-gray, fissile shale with very thin, ferruginous, sandy beds; 15 to 40 feet thick. Layers of dark carbonaceous claystone are interbedded with the variegated mudrock. Thin, lenticular sandstone beds are present throughout the unit.

4. Variegated mudstone unit: hard, massive gray-green shale with varying amounts of maroon, lavender, and brown. Layers of dark carbonaceous claystone are interbedded with the variegated mudrock. Thin, lenticular sandstone beds are present throughout the unit, which extends downward at least to the base of exposed Dakota. It is considered a flood-basin deposit.

The lenticular sandstone bodies of the Dakota were designated inclusively by Rubey and Bass (1925) as the "Rocktown Channel sandstone member." In the present description, the term "Rocktown" is retained to refer to the uncommon development of sandstone in the upper part of the Terra Cotta Clay and in the Janssen Clay Members. The irregularly developed but prominent sandstone lenses may be present at almost any position from the top of the Dakota Formation down to 125 feet below the top. The Rocktown is, of course, composed of a number of genetic units. Rubey and Bass (1925, p. 61) were ingenious in distinguishing relative age, trend, and width of extrapolated sandstone bodies. Age (or correlation) was based on position below the top of the Dakota; trend and width were based on direction of crossbeds and sandstone thickness.

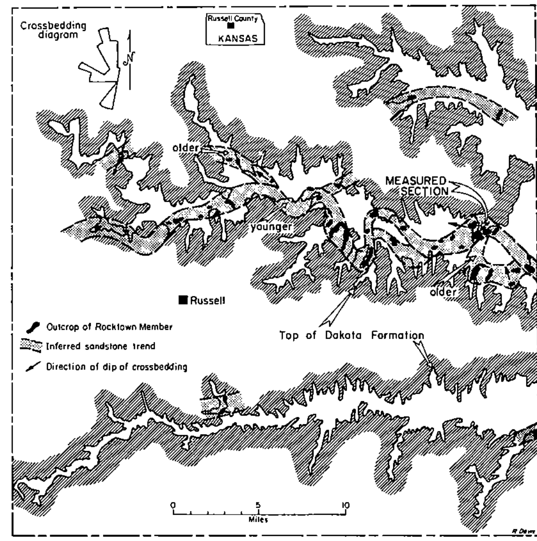

Figure 5-1. Area of Dakota Formation outcrop in Russell County, Kansas, showing interpretive distribution of sandstone bodies identified as the Rocktown and generalized paleocurrents in the Rocktown. *Modified from* Rubey and Bass (1925, pl. 3).

Geometry

Geographic location and trend.—The Rocktown Sandstone Member is present in several rather narrow, west-trending belts in Russell County, Kansas (fig. 5-1). The most prominent belt or outcrop extends across the central part of the county. The various sandstone bodies and trends suggest a slight westward divergence.

Vertical position.—Sandstone bodies recognized as the Rocktown lie at the surface. Extrapolation of sandstone trends has been projected into the shallow subsurface.

Thickness.—The Rocktown Member ranges from 0 to 100 feet in thickness. One sandstone body, thought to be a genetic unit, ranges from 15 to somewhat more than 25 feet in thickness.

Length.—From the eastern county line, the sandstone has been mapped for some 27 miles along its most prominent trend. The Rocktown interval is in the subsurface in the westernmost part of the county and has not been recognized.

Width.—The average width of a sandstone body is somewhat less than 1 mile; the range in width is from 0.4 to 1.5 miles. Along the length of the best documented sandstone body a meandering pattern is shown within a belt about 3 or 4 miles wide. Where sandstone bodies have been recognized at different stratigraphic positions the belt is almost the width of a township.

Boundaries.—The lateral and lower contacts are sharp and abrupt. Laterally it is not uncommon for a well-developed sandstone more than 25 feet thick to pinch out in the distance across a narrow valley. The basal boundary likewise is abrupt and is undulatory. At places the base of the sandstone cuts more than 25 feet into the underlying mudstone.

Internal Features

Sedimentary structures.—The most characteristic feature of sandstone of the Rocktown is medium-scale crossbedding (fig. 5-2). The average crossbed is 6 inches to 3 feet in thickness. However, the range in size of the crossbeds is 1 inch to 8 feet, which corresponds to small scale and large scale, respectively. Although the dip direction is variable, southwest, west, and northwest are the most common directions. In any vertical section, multiple sets of crossbeds have the same direction of dip. Crossbeds may be present in successive sets, or horizontally bedded sandstone may separate sets.

Horizontal bedding is most commonly present as interbeds. Not uncommonly, however, interbeds are characterized by initial, or depositional, dip with inclination either at right angles to, or in an opposite direction to, that of the crossbeds. Cutouts, or washouts, are present at the base of the sandstone body.

In west-central Kansas, medium-scale cross-bedding in the Dakota is of both festoon and planar types. Rib-and-furrow and parting lineation are other structures present in the Dakota.

Figure 5-2. Typical outcrop of Rocktown Sandstone Member of the Dakota Formation. Some 20 feet is exposed, showing medium-scale crossbedding and horizontal bedding. Location is sec. 3, T. 13 S., R. 14 W., north of Russell, Kansas. Photograph by C. T. Siemers.

Texture.—Excluding infraformational fragments, the range in grain size is 0.06 to 0.5 mm, or very fine to coarse. The average diameter is approximately 0.25 mm. Clay pebbles are as coarse as 10 mm in diameter. Grain size is finer along the edges of the sandstone body. The sandstone is generally well sorted, with many samples being very well sorted.

Constituents.—The Rocktown Member is a quartzose sand, with colorless and pink quartz and scattered black, opaque grains and pebbles of clay. The finer grained sandstone also contains some muscovite.

Depositional Environment

The Rocktown Sandstone Member was formed by stream deposition, largely in the channels and/or on the banks within meander belts of an alluvial plain (Siemers, 1971). The sinuous thread of sandstone within the most prominent meander belt indicates that migration of the westward-flowing stream was somewhat limited. Changes in the stream course did occur by abandonment of meanders and stretches (fig. 5-1). A thickness of 15 to 30 feet for a genetic unit suggests that the stream width was some 200 feet. Streams flowed westward toward the Western Interior sea, and the source of sediments may have been as far to the east as the Appalachian Mountains.

A lenticular sandstone body, with characteristics of the Rocktown, and developed at the top of the Dakota, may have formed in a deltaic distributary. Siemers (1971) noted that the meandering sandstone body changes within 30 miles to a tabular-wedge-shaped, delta-front sandstone containing brackish-water fossils and trace fossils.

Acknowledgments

Appreciation is expressed to N. W. Bass for furnishing written description of a measured section. P. C. Franks made helpful suggestions concerning the correlation of units within the Dakota. The photograph of sedimentary structures is included through the courtesy of C. T. Siemers. The availability of the photograph and of Franks' work became known to me because of the interest expressed by G. F. Stewart. The Kansas Geological Survey has kindly permitted use of the map in this compilation.

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Robinson Sandstone, Pennsylvanian, Southeastern Illinois (6)

Structural Framework

The area of study lies in the La Salle anticlinal belt on the east flank of the Illinois basin (fig. 6-1). The anticlinal structure is expressed subtly in Upper Pennsylvanian rocks below surficial glacial deposits, and dip is very gentle at the level of the Robinson sandstone (Middle Pennsylvanian).

Stratigraphic Framework

Pennsylvanian rocks in the general area are characterized by their classical cyclic nature, with coals, shales, sandstones, and limestones occurring repetitiously in vertical sections. The Robinson sandstone is part of the Spoon Formation of the Kewanee Group (fig. 6-2). The Spoon, which is as much as 350 feet thick, is the lowermost formation of the Desmoinesian Series. It is overlain by the Carbondale Formation, with the No. 2 coal at its base, and is underlain by the Abbott Formation.

The term "Robinson" designates an informal oil and gas zone in Illinois. In the general area of interest (Crawford County) Robinson sandstones include a number of irregularly developed sandstones in a 250-foot interval. The sandstones are oil bearing on most structurally high features on the La Salle anticline. The sandstone herein summarized from the description of Hewitt and Morgan (1965) is approximately 225 feet below the top of the Spoon Formation (fig. 6-2).

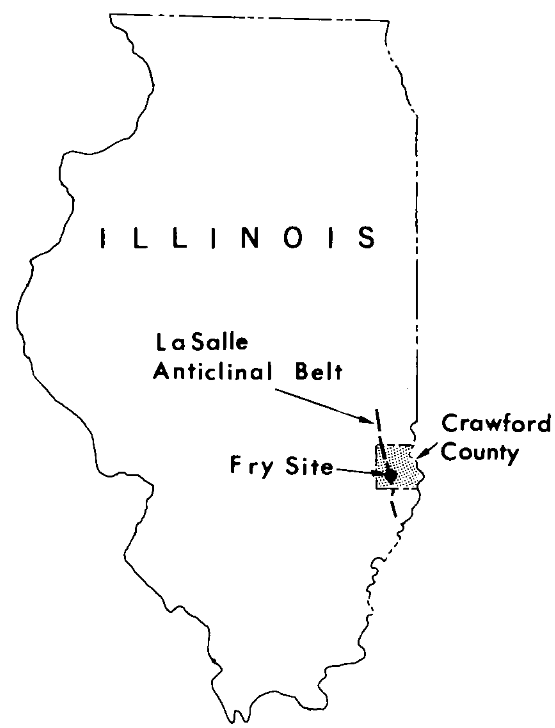

Figure 6-1. Index map of Illinois showing location of study area. *After* Hewitt and Morgan (1965, fig. 1).

Geometry

Geographic location and trend.—The Robinson sandstone is developed southwest of the city of Robinson in Crawford County, Illinois. The overall trend is east-northeast (N. 70° E.) through the southeastern part of T. 6 N., R. 13 W. (fig. 6-3).

Vertical position.—The sandstone is known entirely from the shallow subsurface, and its top ranges in depth from approximately 880 to 940 feet.

Length.—Along trend the Robinson sandstone is thought to extend beyond the area of study, which is approximately 2½ miles long. For engineering purposes, the reservoir is considered to be approximately 12,000 feet long (fig. 6-3).

Width.—The sandstone body is less than 1 mile wide. The belt of net sandstone thickness exceeding 10 feet is as much as 3,500 feet wide and averages half a mile (fig. 6-3).

Thickness.—The sandstone varies in thickness from 0 to more than 50 feet (fig. 6-4). For the purpose of calculating reservoir volume, net sandstone has been determined to be as thick as 40 to 50 feet in 3 separate areas (fig. 6-3). At one locality within the sandstone belt net sandstone is less than 10 feet thick. Two areas of local thickening are present along the southern edge of development.

Boundaries.—Based on electric-log characteristics, lithologic changes, and variation in sandstone thickness, the basal and lateral contacts are sharp (fig. 6-4). Although the upper contact is fairly sharp on electric logs, it is gradational lithologically. The transition from sandstone to shale occurs over a vertical distance of 2 to 6 feet.

Internal Features

Sedimentary structures.—The Robinson sandstone is divisible into three types or zones, each characterized by a particular sedimentary structure. Small-scale crossbedding and associated climbing ripples distinguish the upper zone (fig. 6-5), about 5 to 10 feet thick. The middle zone is characterized by sets of medium-scale crossbedding with thin interbeds of small-scale crossbedding (fig. 6-6). This unit is commonly 20-30 feet thick. Crossbeds in three wells show an

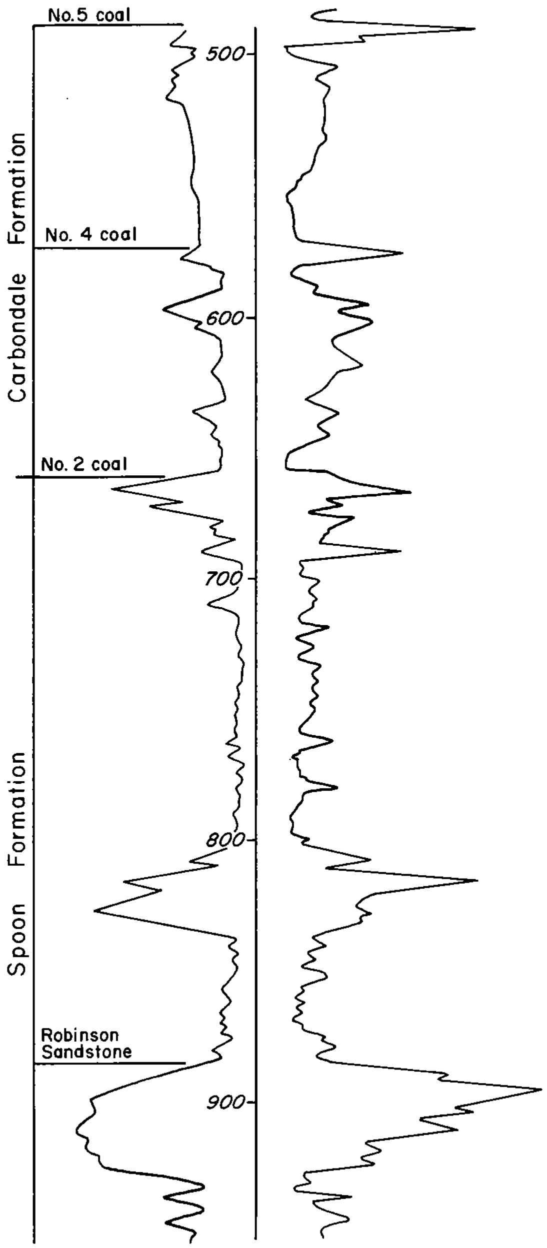

Figure 6-2. Electric-log section of interval containing Robinson sandstone.

average current direction of S. 78° W., which varies approximately 10° from the sand-body trend (fig. 6-3). The lower zone is a mixed lithology of sandstone with thin interbeds of shale (fig. 6-7). The shale, commonly with mud-crack features, may mantle ripple marks. Sporadic medium-scale crossbeds occur in the interval, which is as thick as 20-25 feet.

Texture.—The sandstone shows an overall upward decrease in grain size (fig. 6-8). The upper zone is very fine to fine grained. The middle zone with medium-scale crossbedding is generally fine grained and is somewhat finer in the upper part. Also, in detail the grain size is finer in the interbeds of small-scale crossbedding. A conglomerate of intraformational pebbles is present at the base of the unit; these pebbles occur isolated or in clusters along crossbeds. Within the lower zone grain size decreases upward within the fine-grained class. Permeability (and porosity to a lesser extent) decreases upward in a manner corresponding to grain-size change (fig. 6-8). The lower zone has an average porosity of 20 percent and a permeability of 425 millidarcys. Average porosity in the middle zone is 19 percent, and permeability averages 300 millidarcys. The upper zone averages 18 percent in porosity and 50 millidarcys in permeability. Maximum porosity is 25 percent, and permeability exceeds 1,000 millidarcys. In the more uniform middle zone, vertical permeability is 75 to 95 percent of the horizontal. The three zones are effectively isolated reservoirs; the conglomerate separates the middle and lower zones, and vertical permeability in the upper zone is essentially zero because of clay films on crossbed surfaces. In general, the direction of maximum permeability tends to parallel the sandstone trend, especially in the upper two zones.

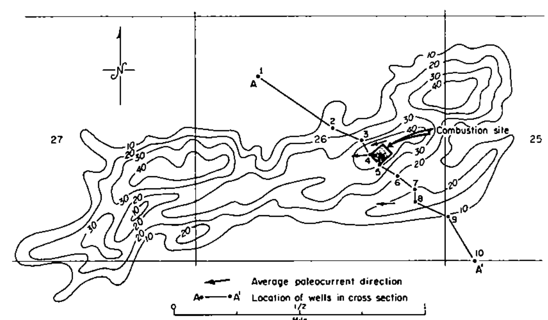

Figure 6-3. Net-sandstone-thickness map (shown in feet) of potentially oil-productive Robinson sandstone. Average paleocurrents subparallel sandstone trend. *After* Hewitt and Morgan (1965, fig. 8).

Constituents.—The major constituents are grains of quartz, feldspar, and muscovite. The matrix includes the clay minerals illite and kaolinite. Calcite, siderite, and pyrite are present as cement or replacement minerals. Carbonized fragments are common on bedding surfaces. Clay pebbles have been replaced to a varying extent by siderite.

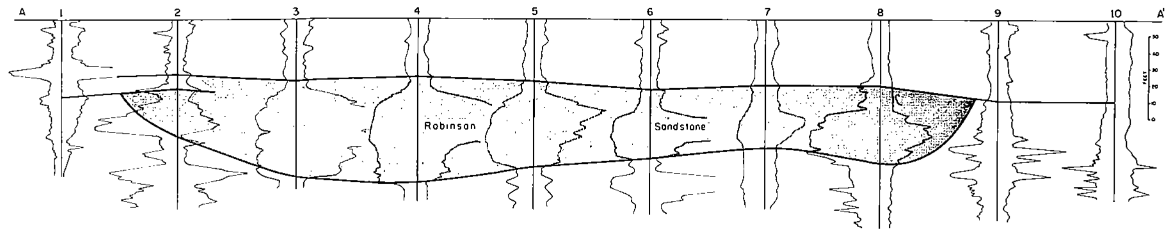

Figure 6-4. Correlation section (*A-A'*) of Robinson sandstone, showing sharp basal and lateral contacts. Line of section shown in figure 6-3.

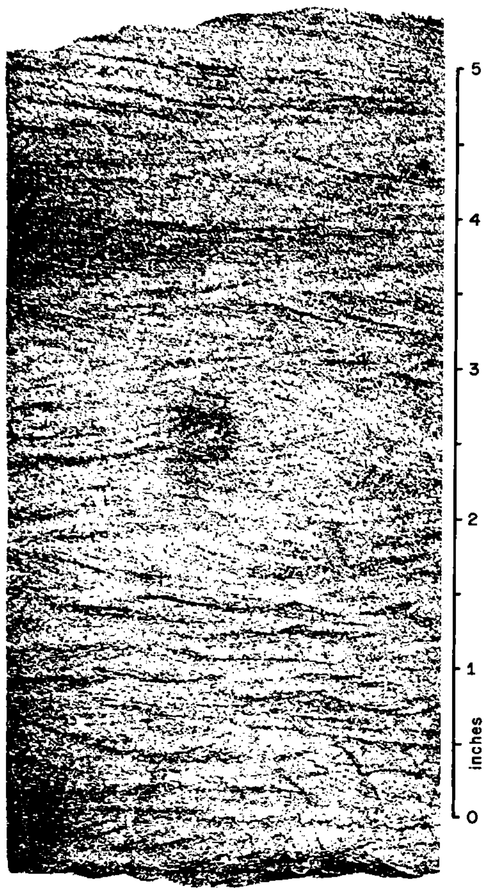

Figure 6-5. Small-scale crossbedding in upper zone of Robinson sandstone. Upper part of slabbed section, which parallels dip, is associated with climbing ripples; lower part shows trough-shaped crossbeds. *From* Hewitt and Morgan (1965, fig. 3).

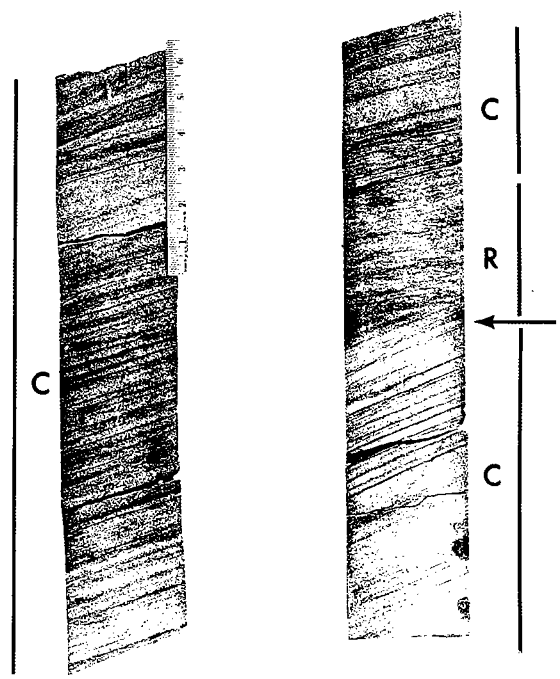

Figure 6-6. Typical sequence of medium-scale crossbedding with interbed of small-scale crossbedding in middle zone. Arrow marks contact separating sets of crossbedding. *From* Hewitt and Morgan (1965, fig. 5).

Depositional Environment

The Robinson sandstone is thought to have been deposited on the banks and/or in the channel of a river flowing to the west-southwest on an alluvial plain. The sedimentary structural sequence of unidirectional medium-scale and small-scale crossbedding, upward decrease in grain size, and sharp basal and lateral contacts indicates meandering-stream deposition. The presence of the Robinson in a complex of lenticular sandstones and the absence of allochthonous pebbles suggest plain rather than valley deposition. The absence of marine indicators suggests alluvial rather than deltaic conditions.

In detail, the area of thin sand within the trend probably represents a deposit of an abandoned meander. The width of 1/2 to 3/4 mile for a 50-foot deposit suggests only limited lateral shift of the stream.

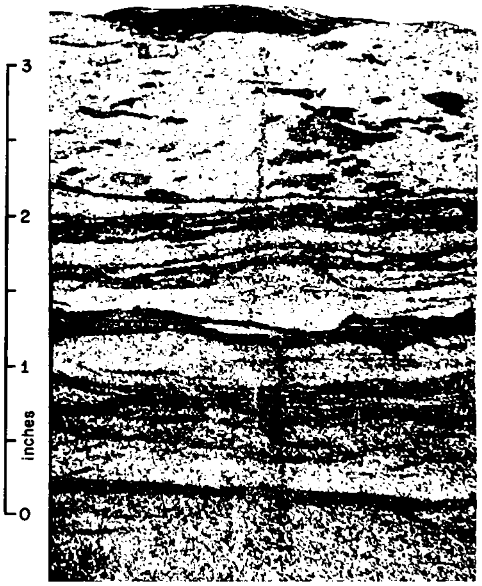

Figure 6-7. Sandstone with clay pebbles and interbeds of shale in lower zone. *From* Hewitt and Morgan (1965, fig. 6).

Acknowledgments

C. H. Hewitt, Marathon Oil Company, kindly furnished prints of photographs of cores, and M. E. Hopkins, Illinois State Geological Survey, arranged for use of electric logs for correlation, stratigraphic sections, and stratigraphic orientation. Illustrations are used with the permission of AIME, Society of Petroleum Engineers.

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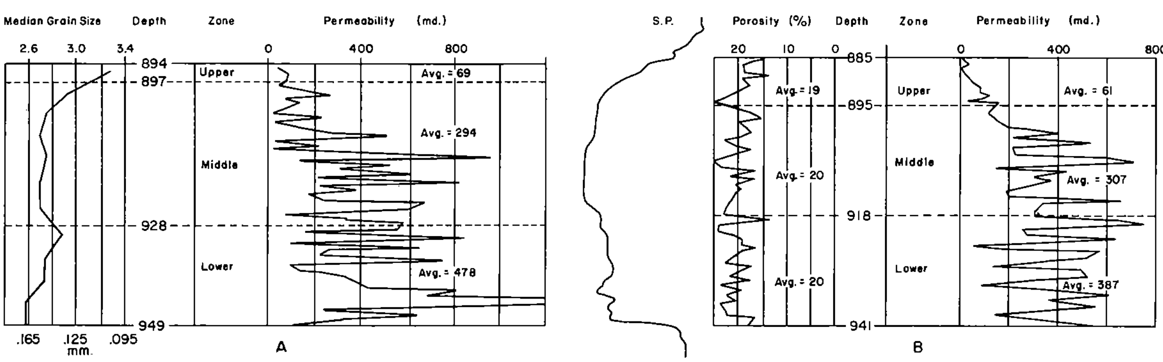

Figure 6-8. Textural and associated features of Robinson sandstone from analysis of two cores. Average grain size and permeability show significant decrease in upward direction, and porosity shows a slight decrease. Well A is at north corner of combustion site; well B is at west corner (fig. 6-3). *Modified from* Hewitt and Morgan (1965, figs. 7, 10).

Tuscarora Sandstone, Silurian, Central Appalachians (7)

Structural Framework

The area of study is in the Valley and Ridge province between New Jersey and Virginia, where the Tuscarora Sandstone forms many of the major mountains between the Allegheny Front and the Piedmont (fig. 7-1). The sandstone crops out as linear ridges on the flanks of gently plunging synclines and anticlines. Deposition was in the Appalachian basin.

Stratigraphic Framework

The Tuscarora Sandstone is classified as Lower Silurian (Albion Series) and is continuous with the Shawangunk Conglomerate on outcrop in southeastern New York and eastern Pennsylvania. The underlying units are the Juniata and Bald Eagle Formations, which the Tuscarora overlaps in an eastward direction. The Bald Eagle overlies the Martinsburg Formation (or Reedsville of central

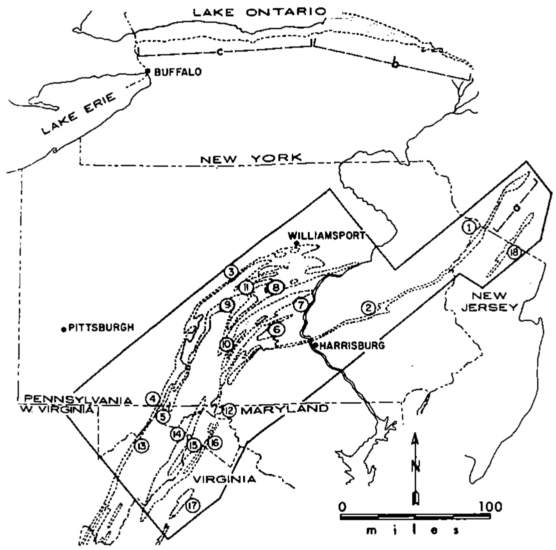

Figure 7-1. Index map of central Appalachian region, showing Silurian outcrops. *From* Yeakel (1962, fig. 1).

Pennsylvania). From central Pennsylvania to northeastern Tennessee the Tuscarora is overlain by the Castanea Sandstone, which in turn is overlain by the Clinton Group of the Niagaran Series.

The interval selected by Yeakel (1962) for regional mapping is the outcropping Tuscarora plus the Castanea in the study area and Albion rocks in adjacent areas. The Oneida Conglomerate, the Shawangunk Conglomerate, and the Thorold Sandstone are well-known units included in regional mapping of thickness and lithofacies. In Yeakel's (1962) study, definition of lower and upper contacts was based on physical breaks which are not considered precise for regional mapping but which are more accurate than the poorly defined time boundaries.

Regionally, sandstone and conglomerate dominate the Tuscarora interval in the east. Sand-shale ratios decrease uniformly westward into Ohio, southwestward into West Virginia and Kentucky, and northwestward into New York and Ontario. In the outcrop area the ratio is generally greater than 8:1. Ratios of less than 1:1 show a consistent distribution in western West Virginia and eastern Ohio.

The Tuscarora Sandstone in the area of study includes an abundance of undefined sandstone bodies (it is both a multistoried and a multilateral unit). Consequently, any meaningful subdivision is local in nature.

Geometry

Geographic location and trend.—The Tuscarora and equivalent sandstone units extend beyond the area of study to the southwest, west, and northwest. In southern New York the northeastern edge is apparently defined by unconformity. The southeastern edge is erosional; the Tuscarora originally may have extended as far as Chesapeake Bay and Richmond, Virginia. Sandstone in the Tuscarora is best developed in the areas of eastern Pennsylvania-northern New Jersey and northeastern West Virginia-Virginia (fig. 7-2). These two centers show an irregularly arcuate configuration, convex to the northwest. The centers of best development are probably responsible for the complex fanlike distribution. It is possible that the widespread distribution of the Tuscarora reflects coalescence of deposits from the centers. Between these two areas, local thickness maps indicate a northeast-southwest linear pattern.

Vertical position.—In the area of study the Tuscarora is exposed at the surface along linear trends and is present in the subsurface between outcrop bands. The Tuscarora is also concealed beneath younger sediments in the Allegheny Plateau to the west.

Length.—Along the southeastern erosional edge the Tuscarora Sandstone and equivalents extend a minimum distance of 575 miles (fig. 7-2). The southwestern edge is not defined. The northwestern center of good sandstone development is thought to extend toward the northwest as a prominent trend for a distance of 75 miles.

Width.—The Tuscarora and equivalents extend northwestward well beyond the area of study, which itself is some 60 miles wide in Pennsylvania. Regionally, sandstone is present in a belt more than 250 miles wide and which is limited on the southeast by the erosional edge of the Tuscarora (fig. 7-2).

Thickness.—The Tuscarora Sandstone increases in thickness eastward and southeastward to the two centers of maximum thickness (depocenters) in Pennsylvania and Virginia, where overall thicknesses are as much as 1,800 and 800 feet, respectively (fig. 7-2). Along the southeastern erosional edge, minimum thicknesses are present in the northeasternmost and southwestern segments. In the former area a thickness of only 10 feet represents the Tuscarora (fig. 7-2). In the southeastern West Virginia-Virginia area the thickness is 60 feet. Sandstone thicknesses in the east and southeast are of the same order of magnitude as overall thicknesses, for sand-shale ratios there are greater than 8:1.

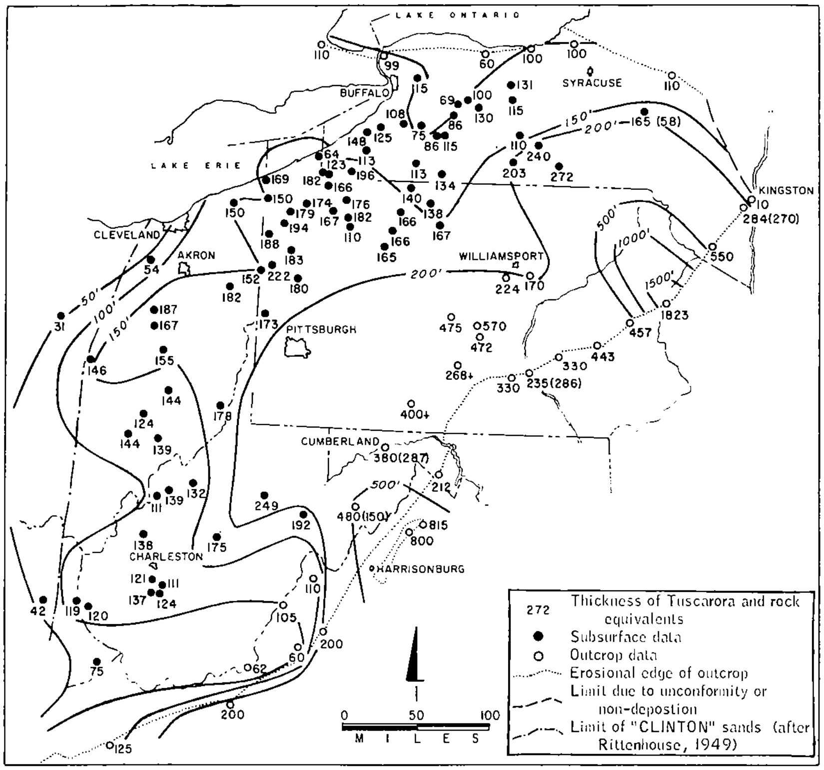

Figure 7-2. Regional thickness map of Tuscarora Sandstone and equivalents, showing a gently arcuate pattern and two centers of development (depocenters). *From* Yeakel (1962, fig. 4).

Boundaries.—The basal formational contact is generally gradational where the sequence is normal—namely, where the Tuscarora is underlain by the Juniata. Locally, however, basal Tuscarora conglomerates overlie thin-bedded Juniata sandstones. The basal contact is abrupt where the Martinsburg Formation is the underlying unit. The top of the Tuscarora-Castanea is gradational, as shale content increases upward into the overlying Clinton. The top of the Tuscarora is distinct in central Pennsylvania, owing to the red color of the overlying Castanea Sandstone.

Based on thickness and lithofacies maps, the northwestern, western, and southwestern boundaries of gross sandstone development are gradational. The most abrupt change is at the northeasternmost edge of the Tuscarora, because of an unconformity. The nature of the southeastern contact, which is now an erosional feature, is not known. However, the eastern depositional edge of the Appalachian basin may have been sharp, with maximum sandstone development adjacent to bounding contemporaneous faults. The nature of the boundaries was not determined for individual sandstone units within the formation.

Internal Features

Sedimentary structures.—The most prominent structure is medium-scale crossbedding. Other features include massive and horizontal bedding, interstratification (especially in the uppermost part), parting lineation, small-scale crossbedding, ripple marks, mud cracks, current crescents, flute casts, horizontal burrows (*Arthophycus*), and vertical tubes (*Scolithus*).

The festoon type of crossbedding is predominant, with an average curvature of 50° to 55°. The angle of inclination varies from less than 12° to more than 30° and averages 23°. The thickness of crossbeds ranges up to 50 inches, with 6 inches the average. Orientation of dip directions varies insignificantly vertically. The mean dip direction for 6,753 measurements is N. 38° W. The average standard deviation for localities with 40 or more measurements is 60°. Approximately 75 percent of the azimuths (vector means) at 122 localities

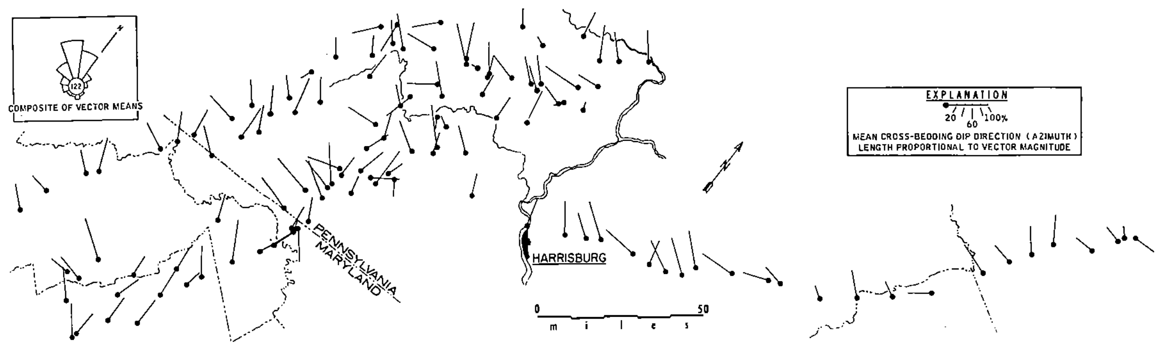

Figure 7-3. Tuscarora Sandstone crossbedding vector means, showing predominant northwesterly direction. *From* Yeakel (1962, fig. 7).

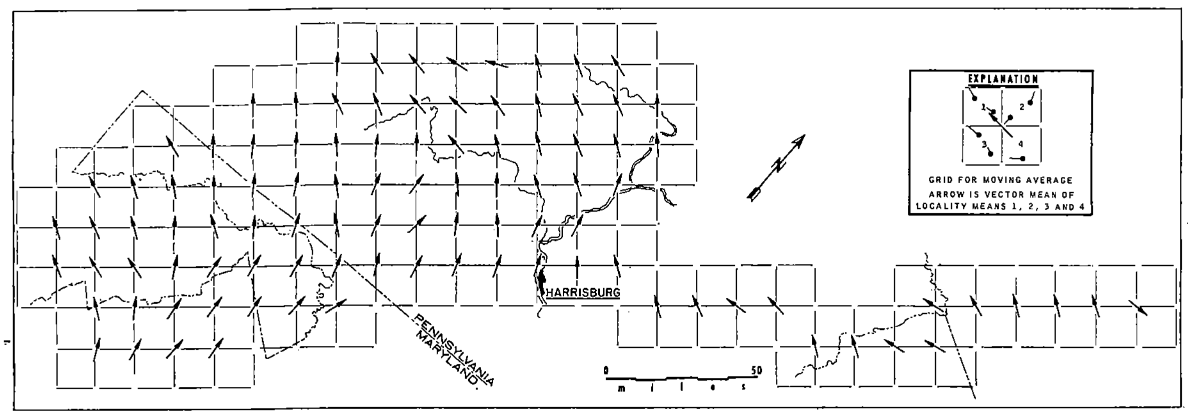

Figure 7-4. Moving average of Tuscarora Sandstone crossbedding vector means, which generally show transport to northwest. Fan-shaped arrangement of currents is centered in depocenter in the Virginias. *From* Yeakel (1962, fig. 8).

are in the northwest quadrant (figs. 7-3, 7-4). Easterly and southeasterly azimuths are rare. The only major deviation from the regional northwesterly trend is the fan-shaped arrangement of dip directions centered in the area of maximum development in the Virginias (fig. 7-4). Some divergence is shown in the other area of maximum development in Pennsylvania. Dip directions for crossbeds of the older Juniata and Bald Eagle are very similar to those of the Tuscarora. The Juniata shows two centers of diverging dip directions, one in the Virginias and the other in south-central Pennsylvania.

Texture.—Analyses of 12 sandstone samples indicate that the Tuscarora is characterized by medium-grained, very well-sorted sand. Conglomerate is present locally, and pebbles more than 16 mm in diameter are not uncommon. Maximum grain size of vein-quartz particles, which is in the lower part of the 64-128 mm class, occurs along the northern half of the eroded southeastern edge (fig. 7-5). Grain size diminishes toward the west and northwest. Two centers of maximum size correspond to the Virginia and Pennsylvania areas of good sandstone development, respectively (fig. 7-5).

The development of local conglomerates at the base and the increase of shale interbeds in the uppermost part indicate that the overall grain size decreases in an upward direction within the Tuscarora.

Constituents.—The Tuscarora ranges from subgraywacke to protoquartzite. Eastern outcrops have feldspathic subgraywacke beds that decrease in abundance upward. The widespread typical white sandstone is a protoquartzite. Potassic feldspar never exceeds 9 percent and is generally less than 1 percent in a framework that ranges from 74 to 86 percent.

Authigenic quartz is the most common cement. Siderite and hematite are minor cements. Opaque heavy minerals are largely hematite,

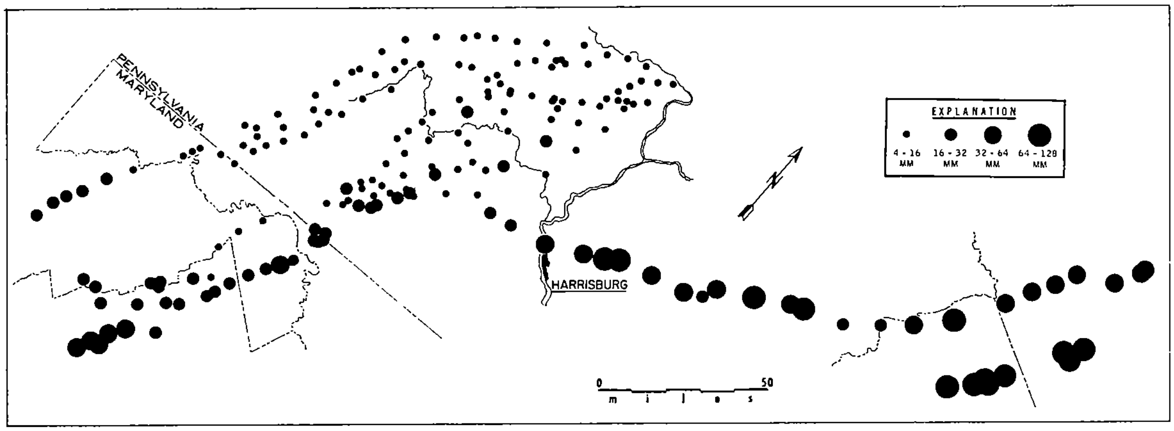

Figure 7-5. Average maximum diameter of Tuscarora vein-quartz pebbles, illustrating northwestward decrease in grain size. *From* Yeakel (1962, fig. 14).

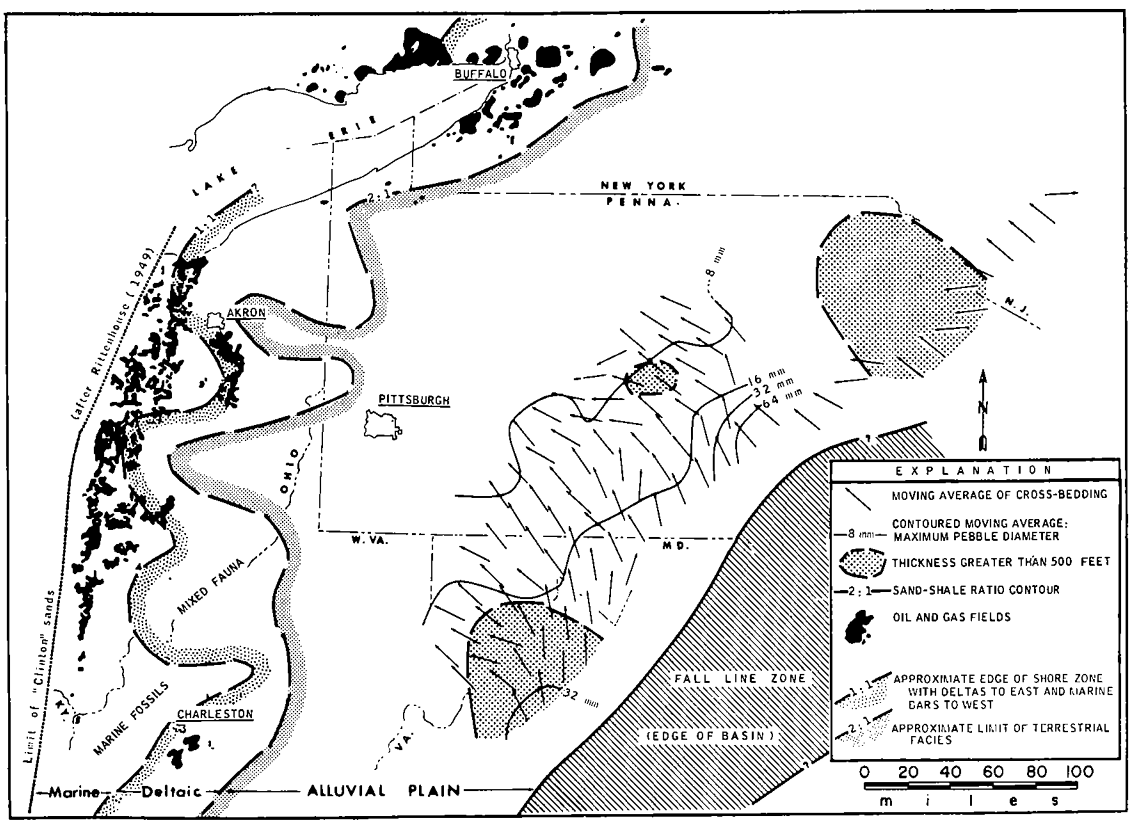

Figure 7-6. Tuscarora Sandstone depositional framework. *Modified from* Yeakel (1962, fig. 17).

limonite, and leucoxene. Zircon and tourmaline are the most common nonopaque accessories. Others are rutile, garnet, and, rarely, amphibole.

Depositional Environment and Paleogeography

In the area of study the Tuscarora Sandstone is a thick complex of alluvial deposits. With its correlatives it forms a large fan-shaped wedge of clastic rocks derived principally from two centers of accumulation (depocenters) to the southeast (fig. 7-6). Clastics were apparently transported radially from these loci and merged toward the northwest. The overall formational configuration, crossbedding dip directions, and grain-size variations suggest that most of the deposits formed on an alluvial plain by a series of stream systems. Whereas Yeakel (1962, p. 1534) considers the Tuscarora to have been deposited by highly meandering streams, Smith (1970, p. 3005) is of the opinion that it was deposited by braided streams which formed by dissection of transverse bars. The Tuscarora is finer grained than the upslope Shawangunk and is characterized by smaller crossbeds. The Shawangunk, which shows evidence of rapidly changing flow conditions, is thought by Smith (1970, p. 3007) to have been deposited as longitudinal bars in braided streams. In the easternmost parts of the depocenters the maximum grain size is suggestive of an alluvial-piedmont environment. Apparently those conditions were predominant in the area of Tuscarora development, which has since been eroded. Paleocurrent and depositional conditions were essentially unchanged during deposition of a maximum thickness of 3,000 feet in the Bald Eagle-Juniata-Tuscarora sequence. A northwestward paleoslope was maintained, although subsidence was greatest in the near source areas. Northwest of the outcrop areas, where the sand-shale ratio is less than 2:1, coastal deltaic and marine conditions apparently prevailed (fig. 7-6). Constituents of the Tuscarora indicate that it was derived principally from earlier sandstones. Smaller contributions may have come from carbonates, low-grade metamorphic rocks, and feldspathic gneisses.

The depositional framework apparently was similar to that for the Mississippian Pocono and Pennsylvanian Pottsville of the central Appalachians (Meckel, 1970). Each sequence apparently represents part of the molasse stage in a geosynclinal cycle (Hsu, 1958, p. 321-322).

Acknowledgment

Illustrations are from Yeakel (1962) and are used with the permission of The Geological Society of America.

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Coastal Environments

DELTAIC ENVIRONMENTS

"New" Brazos Delta Sand, Holocene, Southeast Texas (8)

History and Sedimentologic Framework

In 1929 the U.S. Army Corps of Engineers diverted the entry of the Brazos River into the Gulf of Mexico by dredging a 5-mile channel west and southwest of the old channel, which was closed to the river's discharge (fig. 8-1). The channel was dredged to a depth of about 14 feet below sea level, with a bottom width of 300 feet. Since that time a new delta has formed and a portion of the old delta has been destroyed by marine processes as the shoreline there has undergone transgression (fig. 8-2).

The arcuate "new" Brazos delta is approximately 20 miles southwest of the southwestern end of Galveston Island (fig. 8-1). It is the third delta the Brazos River has constructed in the immediate area during stillstand of the Gulf. The oldest delta formed when the river occupied the Oyster Creek course for some 3,000 years. Approximately 1,000 years ago the Oyster Creek course was abandoned about 85 miles inland from the coast in favor of the present course. The Brazos then developed the "old" Brazos delta, which existed until the man-made diversion. Because of marine transgression the Oyster Creek delta is not expressed by the shoreline or by bathymetry, and even during the 40 years after initiation of the "new" delta the "old" delta has been modified so that the shoreline is now rather

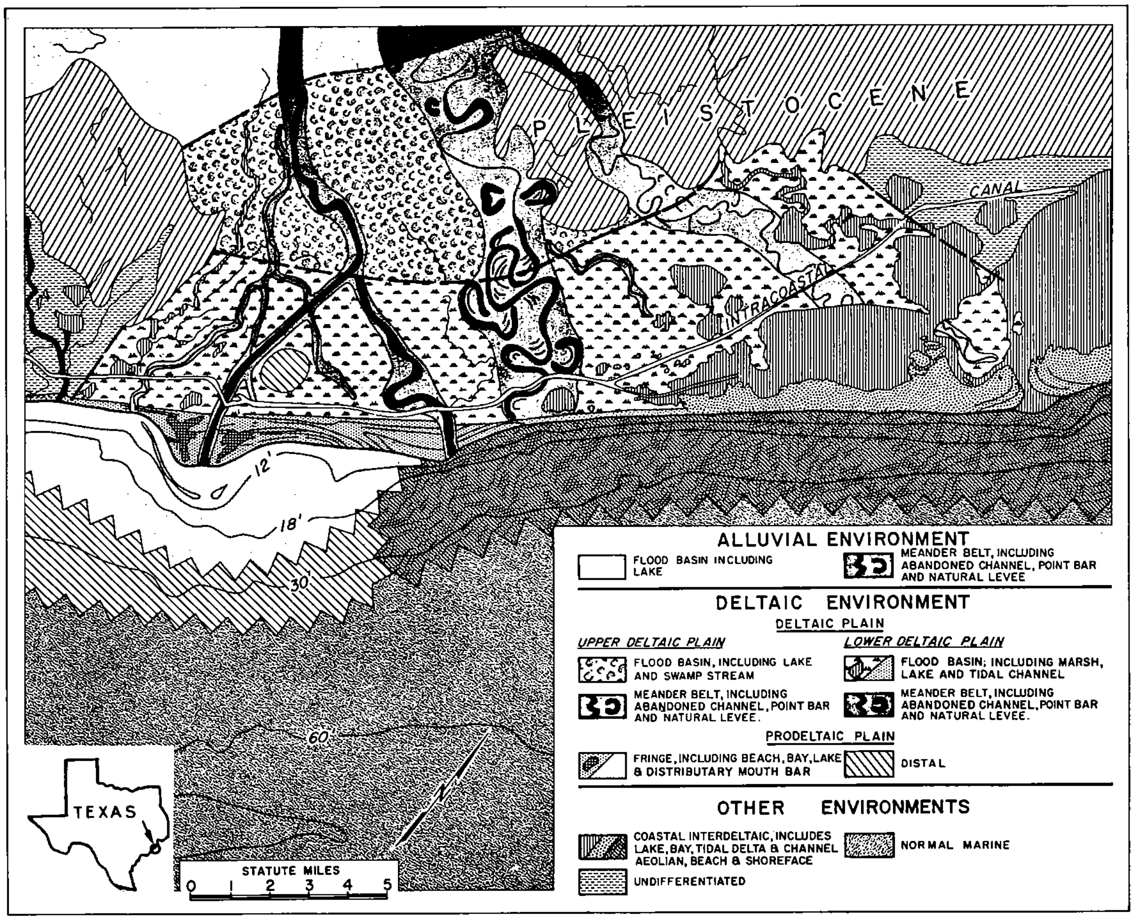

Figure 8-1. Environments of deposition of Brazos delta and adjacent coastal interdeltaic and marine area. Truncated Oyster Creek delta and "old" Brazos delta are northeast of "new" delta. Sand of "new" delta is present in subaerial part (lower deltaic plain) of "new" delta and subaqueous delta fringe. *From* Bernard and others (1970, fig. 30).

straight and the shoreface linear (figs. 8-1, 8-2).

The marine input in the delta area is essentially the same as that for the Galveston area, as described in the model for the Galveston Island sand (15). The normal tidal range is 1 to 2½ feet; however, 15-foot tides accompany hurricanes, and abnormally low tides occur during strong northerly winds. The dominant direction of longshore drift is toward the southwest, and both the natural and man-made diversions of the Brazos have been in that direction. Consequently, the abandoned deltas have been relatively starved from riverine sediment, and marine transgression has been enhanced. It is estimated that the average annual discharge of the river is 5 million acre-feet. The riverine input modestly exceeds marine input and consists annually of some 3 million tons of sand, 10.5 million tons of silt, and 16.5 million tons of clay.

The present small delta, which has formed in water depths of less than 30 feet, represents an excellent laboratory for study of deltaic processes and sediments. It not only represents a model for thin deltaic deposits that form under stable tectonic conditions but also an approximate scale model for deposits of major rivers. Bernard and others (1970) have studied the Brazos delta in considerable detail, and the following description of sand deposits of the "new" delta is largely from their account.

Geometry

Geographic location and trend.—Sand of the "new" delta is present as an arcuate bulge of the coastline 40 miles southwest of the city of Galveston (figs. 8-1 through 8-3). Within the delta area, several sand-rich physiographic features are present. For example, beach ridges converge in both directions away from the river, which itself has sand oriented approximately normal to the coastline. The river-mouth (or distributary-mouth) bar is arcuate, paralleling the shoreline. The bulge of sand merges gulfward with prodeltaic clays and landward with flood-basin deposits of previous Brazos deltas (fig. 8-1). Along the coast to the northeast, "new" delta-sand units merge with those of the "old" delta and with those of the Colorado-Brazos delta complex to the southwest.

Vertical position.—Outside the channel, sand extends from the surface to depths as great as 25 to 30 feet (fig. 8-3). The elevation of the deltaic plain is generally less than 5 feet above sea level, but some dunes and beach ridges are between 5 and 10 feet in elevation. Offshore, the greatest depth of sand deposition is approximately 25 feet. Sand is present on the channel floor, which shallows progressively gulfward through the "new" delta.

Length and width.—The subaerial sand bulge has a radius of about 2 miles (figs. 8-1 through 8-3). The subaqueous part, with delta-fringe sand, extends northeastward along the coast for 5 miles

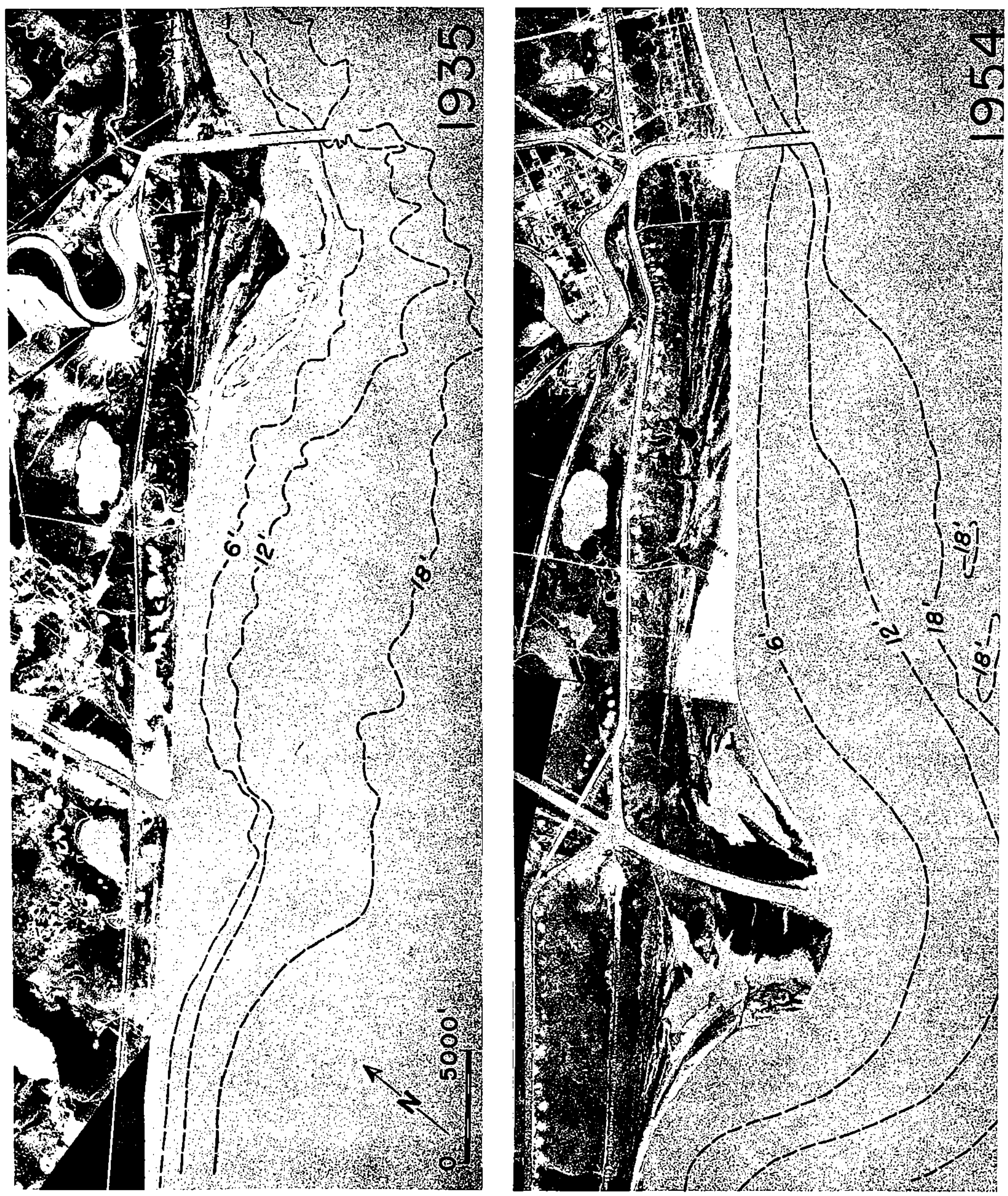

Figure 8-2. Aerial photographs recording development of "new" Brazos delta. *From* Bernard and others (1970, fig. 35).

to a point near the mouth of the "old" delta and southwestward for a greater distance, beyond the area mapped (fig. 8-1). From the line of progradation, sand extends gulfward for a maximum distance of 4 miles.

Thickness.—Net sand thickness on the subaerial part of the delta shows an overall gulfward thickening and is known to vary from 7 to 23 feet (fig. 8-3). Although only 6 feet of sand is present in the 25-30 feet of fill of an abandoned channel of the Oyster Creek delta, thickness of channel sand may approach the depth of an active channel. It is thought that a thickness greater than 25 feet is present along the crest of the river-mouth bar.

Boundaries.—Lateral and basal contacts are gradational in cores from the deltaic plain (Bernard and others, 1970, figs. 38, 39) (figs. 8-4, 8-5). The basal contact, as well as the lateral contacts, of channel sand with delta-fringe sand is expected to be sharp.

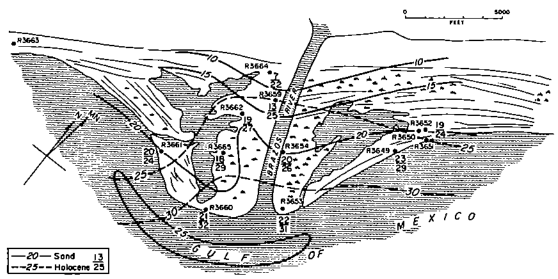

Figure 8-3. Thickness map of Holocene sediments and net-sand-thickness map, in feet, showing a gradual gulfward increase in thickness of sediments and a more marked increase in sand thickness. Data and base map *modified from* Bernard and others (1970, figs. 37, 41).

Internal Features

Sedimentary structures.—Delta-fringe deposits are characterized by interstratification with alternation of beds and laminae of sand and clay (fig. 8-4). Sand layers increase in abundance and thickness in an upward direction. Horizontal beds are generally present, but small-scale crossbeds along with sporadic medium-scale crossbeds are also present. Other structures are mottling, or bioturbation, and convolute bedding.

Texture.—With allowances for interstratification, the vertical sequence shows an overall upward increase in grain size (fig. 8-5). The coarsest median grain size is approximately 0.18 mm, or fine. The interstratification and upward coarsening are reflected on the self-potential curve by a serrated funnel shape (fig. 8-5).

Constituents.—According to Hsu (1960, fig. 6) the common terrigenous clastics are quartz, quartzite, and chert (89 percent) and feldspar (9 percent). Feldspar is dominantly of the alkali types. By comparison, the Brazos River 50 miles inland contains 85 percent quartz types and 11 percent feldspar. In the delta sand, garnet is twice as abundant as staurolite and kyanite together.

Sand deposits also contain significant numbers of Cretaceous foraminifers and finely divided organic matter (coffee grounds). Holocene foraminifers, which are present in greatest abundance in clay interbeds, are characterized by the bay-shallow-marine genera *Rotalia* and *Elphidium,* especially *R. beccarii* and *E. gunteri*. Ostracodes, gastropods, pelecypods, and echinoid spines have also been noted in the delta-fringe deposits by Bernard and others (1970, fig. 42).

Depositional Sequence

Sand units in the "new" Brazos delta are part of an offlap, progradational sequence that overlies marine clays deposited on the Gulf floor before delta formation (fig. 8-6). The basic sequence is as follows:

Beach: laminated sand or organic-rich clays of subaerial part of the delta

River-mouth bar:
- bar back: interbedded silty clay and sand
- bar crest: laminated or crossbedded sand
- bar front: interbedded silty clay and sand

Prodelta (or distal): laminated clay

The sequence from the subaerial part of the delta is, of course, repeated laterally in a gulfward direction (fig. 8-6). Inland from the "new" delta the alluvial plain, or deltaic plain of many workers, is characterized by sand and organic-rich clay. The former was deposited on point bars and in channels within the meander belt. The flood-basin clays overlie interlaminated clay and silt of the distal delta fringe. Near the ends of the deltaic arc, Gulf currents and waves deposit delta-margin and delta-front sands, which are derived from the river-mouth bar.

The arcuate, lobate shape of the "new" delta is similar to those of shallow-water Holocene deltas of the Mississippi (Frazier, 1967; Fisher and others, 1969) and to that of the Rio Grande delta. Delta-fringe sand is relatively widespread in deltas of this shape because of the dominant riverine input. The Brazos delta is dissimilar in configuration to the modern Mississippi delta, where sand is largely restricted to fingers of the delta. A

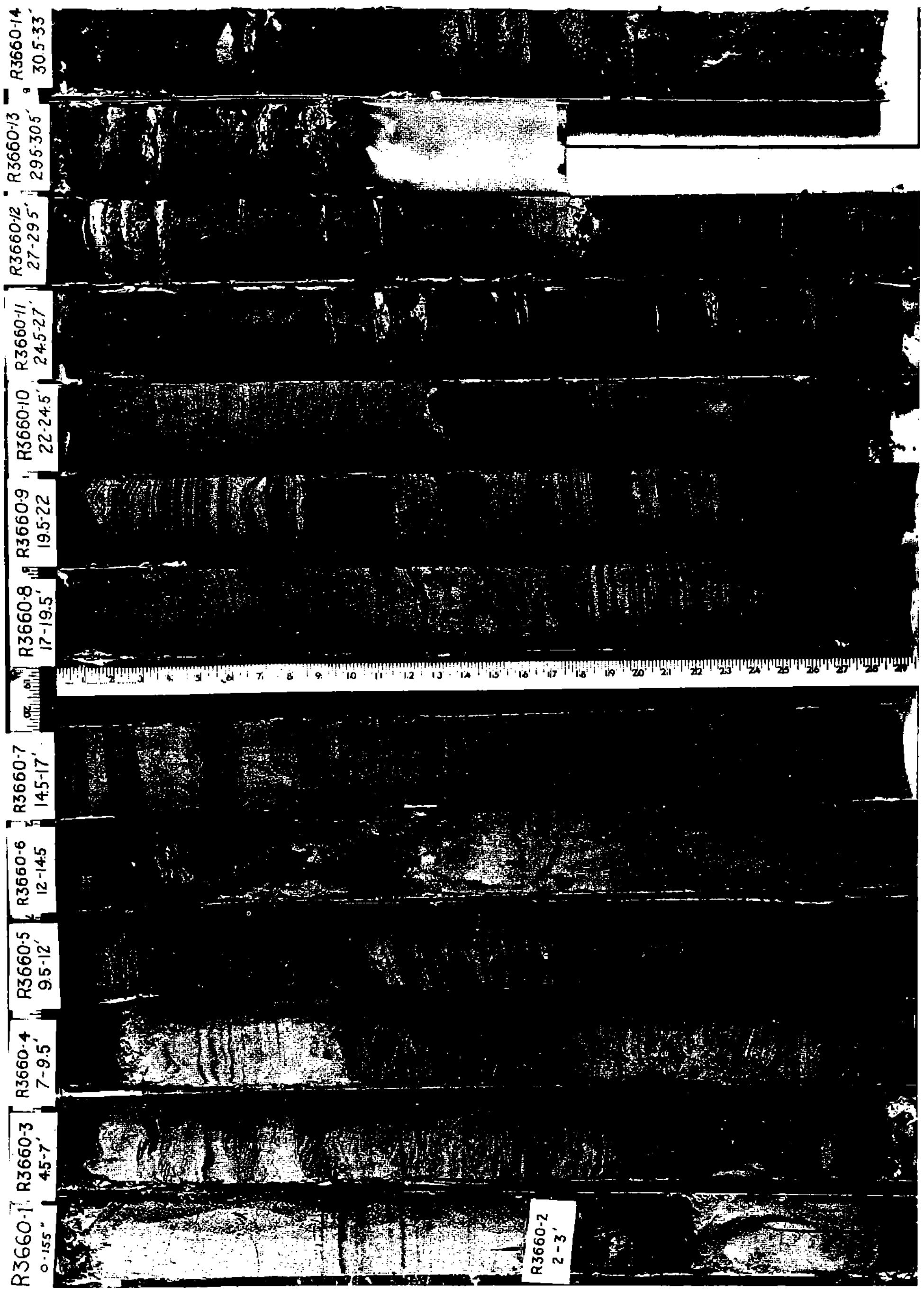

Figure 8-4. Vertical sequence of deltaic deposits resulting from gulfward progradation of "new" Brazos delta: 0-2 feet, beach sand; 2-13 feet, bar-back sand and clay; 13-23 feet, bar-crest sand; 23-32.5 feet, interbedded bar-front deposits, distal clay, and marine sand and clay; 32.5-33 feet, Pleistocene sandy clay. Location for core R3660 is shown in figure 8-3. Log of core is shown in figure 8-5. *From* Bernard and others (1970, fig. 39).

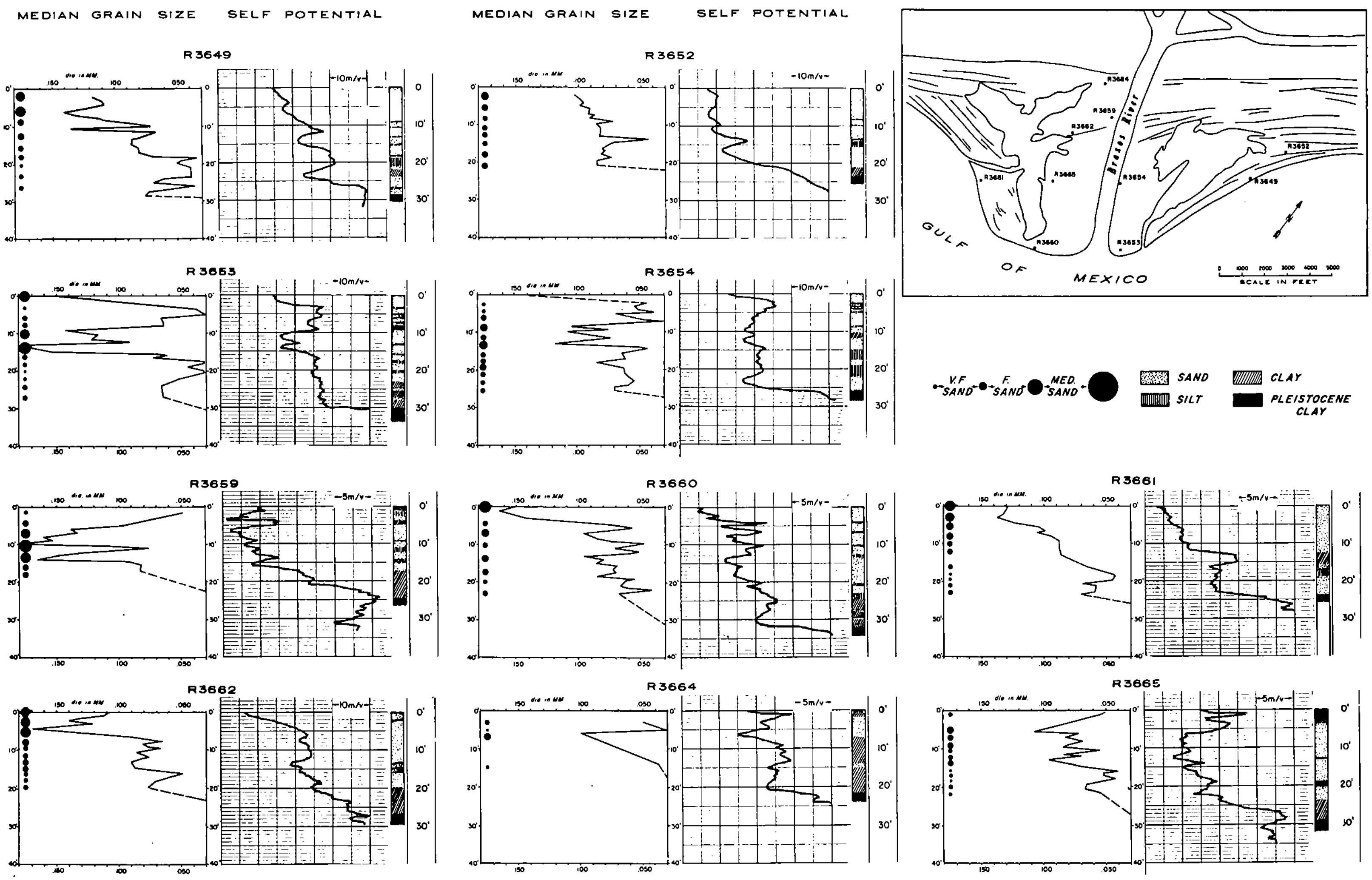

Figure 8-5. Relationships between grain-size changes and self-potential character of delta-fringe deposits of "new" Brazos delta. Dominant serrated funnel shape reflects upward coarsening of grain size. Cored section for station R3660 is shown in figure 8-4. *From* Bernard and others (1970, fig. 41).

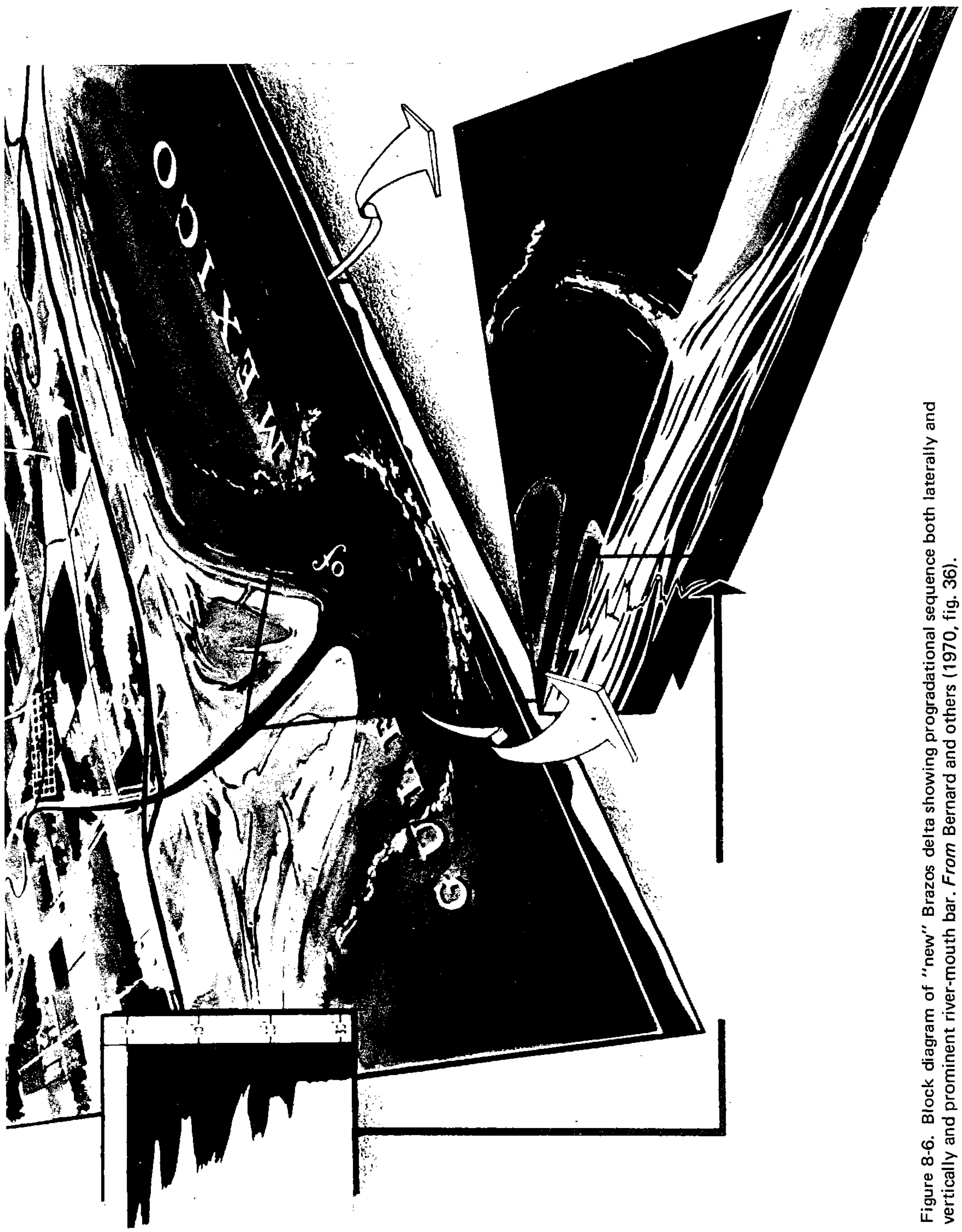

Figure 8-6. Block diagram of "new" Brazos delta showing progradational sequence both laterally and vertically and prominent river-mouth bar. *From* Bernard and others (1970, fig. 36).

combination of high tide and wave energy is largely responsible for development of the arcuate Niger delta (Allen, 1965, p. 553-554; van Andel, 1967, p. 308). The Rhone delta, with two lobes, is wave dominated (van Andel, 1967, p. 308; Fisher and others, 1969, p. 24). Dominant sand wedges of the Niger and Rhone deltas, reflecting high energy of marine agents, contrast sharply with the interstratification of the Brazos delta deposits forming in the low-energy environment of the Gulf of Mexico.

Acknowledgments

All the figures except figure 8-3 are from the paper by Bernard and others (1970) and are used with the permission of The University of Texas Bureau of Economic Geology, W. L. Fisher, Director. Original plates were kindly furnished by R. J. LeBlanc, Sr., and J. S. Bush, Shell Development Company, and by W. L. Fisher. Data concerning the riverine input were supplied by I. D. Yost, U.S. Geological Survey, and D. T. Graham, U.S. Army Corps of Engineers.

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Rockdale Delta System, Wilcox Group, Eocene, Texas (9)

Structural Framework

The Wilcox Group (early Eocene) is best known from the updip portions of the Gulf Coast paraliageosyncline and the East Texas basin. In much of the area of study dip is gently gulfward. Dips are locally variable because of salt intrusion and growth faults. The stratigraphic section thickens abruptly across regional contemporaneous fault zones.

Stratigraphic Framework

The Wilcox is a thick sequence of predominantly terrigenous clastics. It provides oil, gas, and fresh-water reservoirs as well as deposits of lignite, ceramic clay, and industrial sand.

The lower and upper parts of the group are major regressive wedges involving gulfward pinch-out of sand. The middle part contains a significant marine section, which terminated the earlier regression and preceded the later Wilcox regression. The Wilcox is underlain by marine mudrock of the Midway Group of Paleocene age and is overlain by the Carrizo Formation of Eocene age.

Seven major depositional systems, each of which displays extensive vertical and lateral stacking of many genetic units, are recognized in the lower part of the Wilcox Group of Texas (Fisher and McGowen, 1969, p. 31) (fig. 9-1). The large Rockdale delta system, present principally in the subsurface, is dominant. It is composed of lobate wedges of sandstone, mudstone, and lignite; its maximum thickness is 5,000 feet. It grades in a northerly direction, up the depositional slope, into the thinner Mount Pleasant fluvial system of sandstone bodies and mudstone, which originally extended northward beyond the present outcrop in the East Texas basin (figs. 9-1, 9-2). Three elements recognized in the Mount Pleasant system are the northern tributary-channel facies, the central slightly meandering channel facies, and the southern highly meandering channel facies.

Because longshore transport of sand was southwestward, the dominant mudstone facies of the Pendleton lagoon-bay system developed east of the delta system, whereas the San Marcos strandplain-bay system developed to the southwest (fig. 9-1). The latter is composed of interbedded shale and

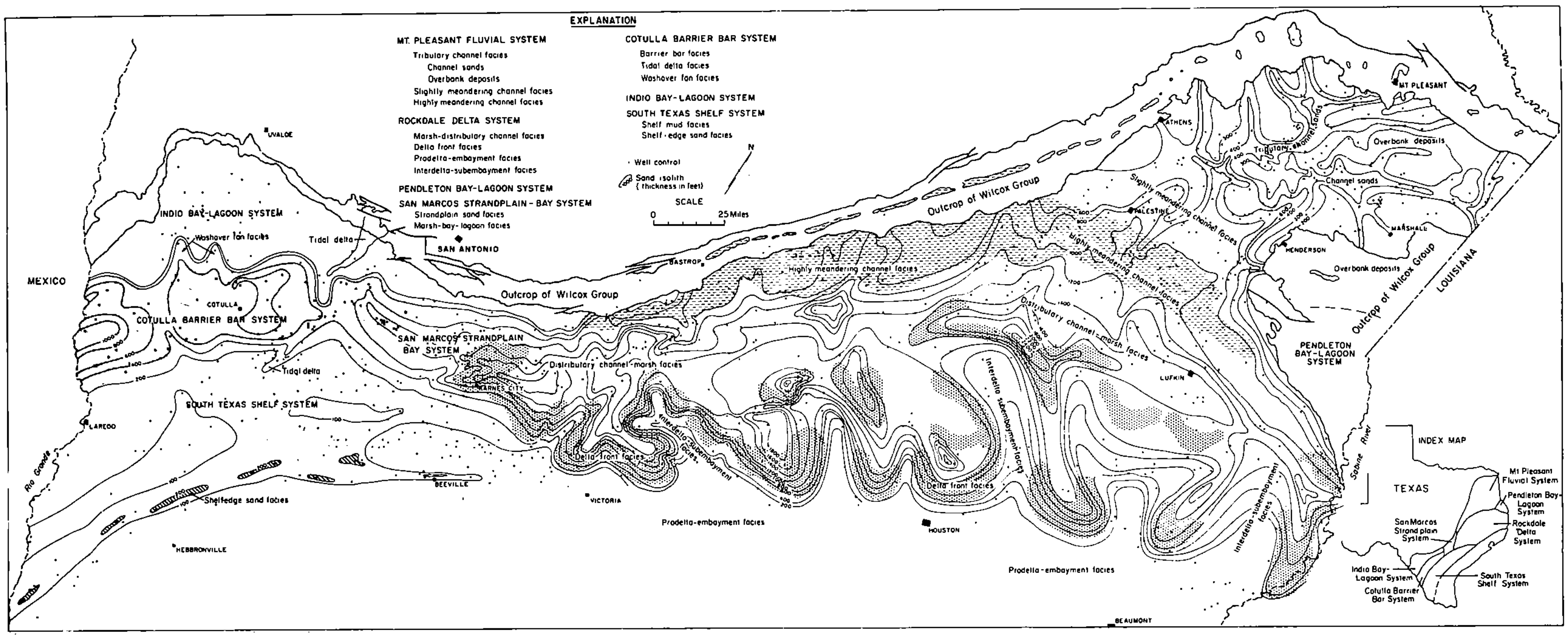


Figure 9-1. Major depositional systems in lower part of Wilcox Group of Texas, as shown by sandstone trends. The dominant Rockdale delta, which composes more than half the area of study, is characterized by southeast- and south-trending lobes of sandstone. *From* Fisher and McGowen (1969, fig. 1).

sandstone bodies that are either sheetlike or elongated parallel to depositional strike. Farther to the southwest the Cotulla barrier-bar and complementary Indio lagoon-bay systems are developed. The Cotulla system is composed of elongated sandstone bodies arranged parallel to depositional strike in individual units as much as 100 feet thick. The predominantly mudstone facies of the Indio system is updip from the northeasterly trending Cotulla system. Gulfward from the barrier-bar complex and partly lateral to the delta system is the South Texas shelf system, composed chiefly of shale with minor amounts of sandstone.

The Rockdale delta system makes up approximately 60 percent, areally, and 80 percent, volumetrically, of the known deposits of the lower Wilcox Group. It ranges in thickness from 1,000 to 5,000 feet. Not only was it the final depositional site of most sediments, it was also the principal source of sediments redistributed and deposited in the associated systems noted previously.

The system is particularly characterized by extensive vertical stacking of individual elements, which are grouped into three principal facies: alternating units of sandstone and mudstone-lignite in the updip part of the system, thick sequences of sandstone, and thick mudstone generally in the farthest downdip sections of the lower Wilcox (figs. 9-1, 9-2). Because interfingering characterizes the downdip changes, and because three different episodes of regression, or progradation, are recognized, the general characteristics of sandstone in the system are grouped in the summary that follows.

Geometry

Geographic location and trend.—The Rockdale delta system is located in southeast Texas, extending from the Sabine River on the east to Karnes City on the southwest (fig. 9-1). The downdip limit is not known from present well data; the updip limit coincides with the southern extent of the Mount Pleasant fluvial system. The overall trend of the system is northeast—only because of the general coalescence of southeasterly and southerly trending individual lobate deltas.

Vertical position.—The Rockdale system is known from subsurface data. At present the downdip limit has not been penetrated by deep drilling to depths below 15,000 feet.

Length and width.—Sandstone in the system is

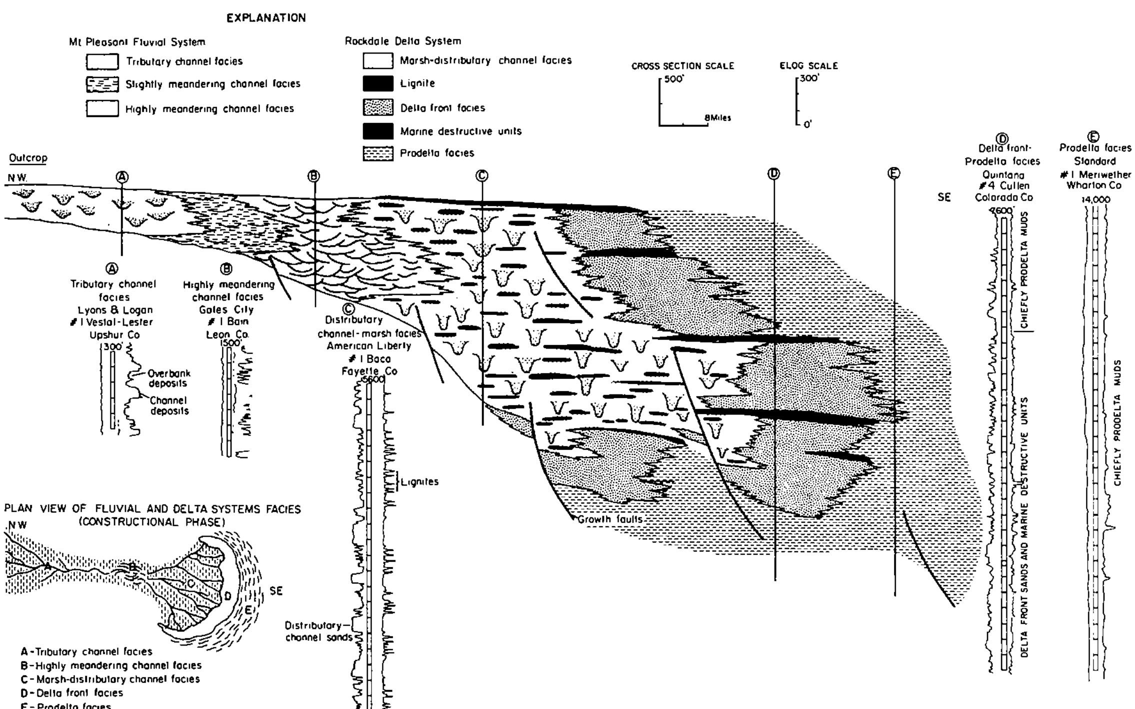


Figure 9-2. Diagrammatic stratigraphic dip section of Mount Pleasant fluvial system and Rockdale delta system, showing relation and character of component facies. *From* Fisher and McGowen (1969, fig. 3).

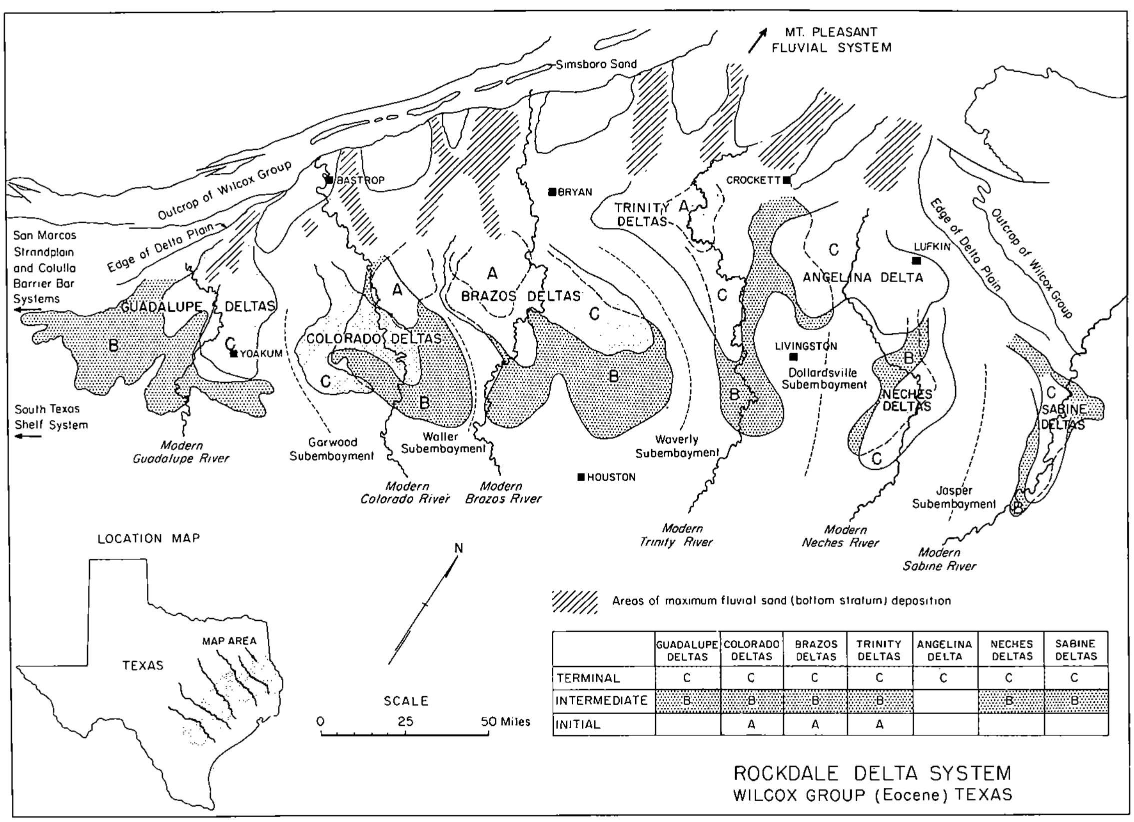
recognized for approximately 300 miles in a northeasterly direction, which is approximately parallel to structural and depositional strike (fig. 9-1). The northeastern limit is marked by a change from sandstone to shale of the Pendleton bay-lagoon system. The deltaic sandstone units are differentiated from those of the San Marcos strandplain on the southwest by their greater thickness and southeasterly trends.

The known extent of the deltaic sandstone in a downdip direction is approximately 60 miles in the southwestern part of the area and 100 miles along an individual trend north and east of Houston. In both cases sand is present at the farthest downdip control points.

Thickness.—In the area of study, net sandstone thickness varies from less than 100 feet at the southwestern edge of the system near Victoria to more than 2,400 feet in 3 local areas, 2 of which are north of Houston (fig. 9-1). At the northeastern edge of the system only 200 feet of sand is present. Along the updip edge of the system, where it grades into the Mount Pleasant fluvial system, the thickness ranges from 600 feet in the southwest to 1,200 feet in the northeast near the trend of maximum development of the fluvial system (fig. 9-1).

Thick lobate or thick elongate trends do not completely coalesce, and areas of thin sandstone (less than 200 feet thick) are present between a number of the lobes. By utilizing thin marine transgressive units, 16 principal deltas representing 3 phases of deltation have been recognized within the lower Wilcox (fig. 9-3). The oldest deltas range in area from 200 to 350 square miles and in thickness from 300 to 500 feet. The largest deltas formed during the intermediate period, and they are as much as 2,000 square miles in area and 1,500 feet in thickness. Although the youngest deltas are comparable in thickness to the underlying deltas, they do not extend as far downdip.

Boundaries.—The gross system is characterized by gradational boundaries. The sharpest changes in sandstone thickness generally occur in downdip areas where lobate patterns of thickness are developed. Although individual units have not been delineated for mapping purposes, electric-log characteristics suggest that their lateral and basal



	GUADALUPE DELTAS	COLORADO DELTAS	BRAZOS DELTAS	TRINITY DELTAS	ANGELINA DELTA	NECHES DELTAS	SABINE DELTAS
TERMINAL	C	C	C	C	C	C	C
INTERMEDIATE	B	B	B	B		B	B
INITIAL		A	A	A			

Figure 9-3. Distribution of major deltas of Rockdale system. Sixteen lobes, recognized during 3 periods of deltation and grouped in 7 different areas, show coincidence with modern streams. *From* Fisher and McGowen (1969, fig. 5).

contacts are gradational in downdip areas (fig. 9-2). Many basal and lateral contacts are sharp in other areas of the system, especially where sandstone, in association with mudstone and lignite, composes only 40 percent of the section (fig. 9-2).

Internal Features

Sedimentary structures.—The sand-rich facies of the system is characterized by multidirectional small-scale crossbedding and ripple marks. Sandstone in the updip area grades into the fluvial

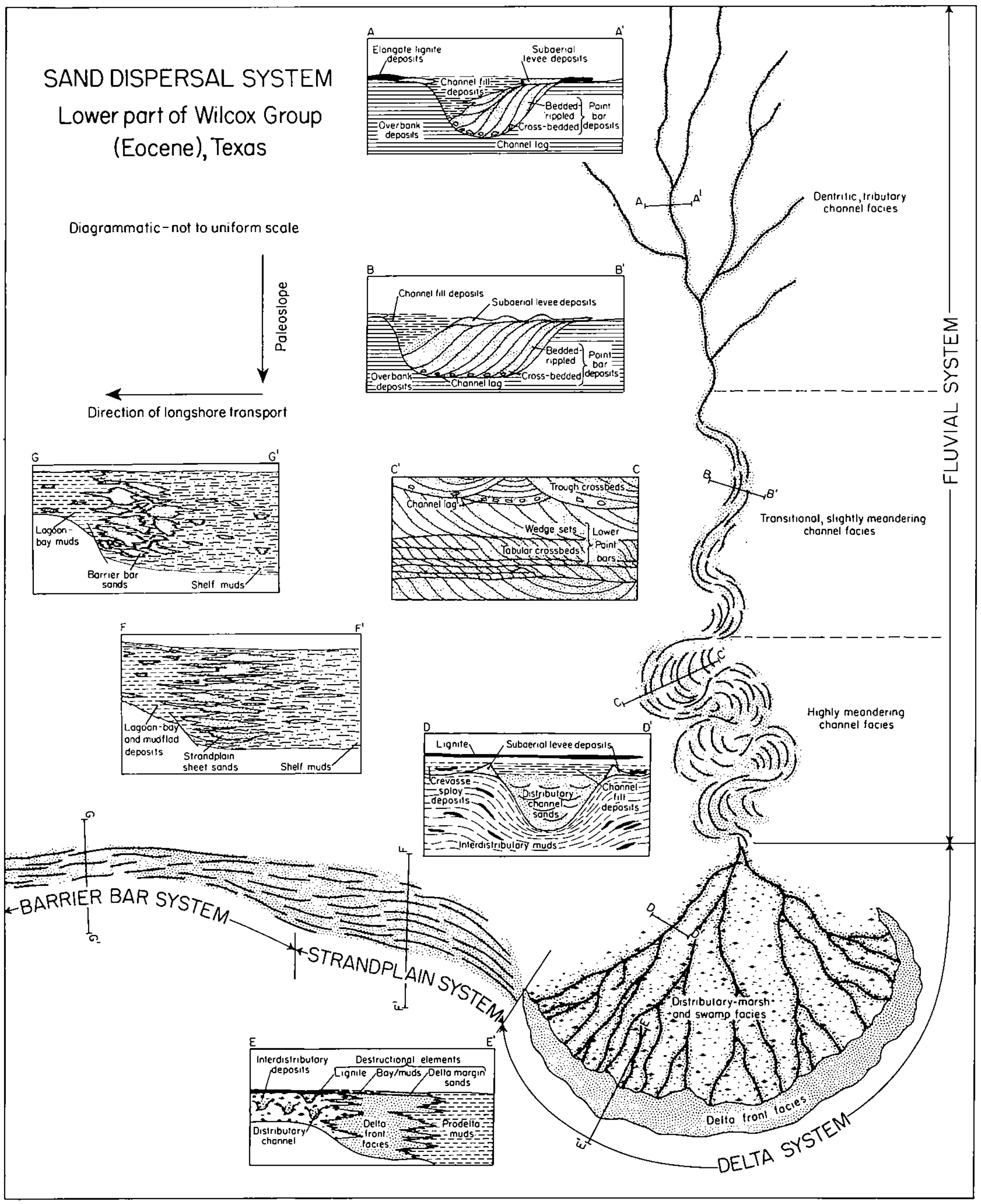


Figure 9-4. Diagrammatic sand-dispersal system in various depositional systems of lower Wilcox. *From* Fisher and McGowen (1969, fig. 10).

system, which is characterized by a basal, locally conglomeratic zone with festoon, medium-scale crossbedding and an overlying zone of planar and wedge-set crossbedding. Thin sandstones are burrowed in the areas of mudstone between lobate sand trends.

Texture.—The sandstone of the lobate apron is fine grained and better sorted than the updip sandstones, which grade into sandstones of the fluvial system, averaging 0.22 mm in diameter. Within the mudstone section between lobes are thin units of siltstone and very fine-grained sandstone.

Constituents.—The sand-rich facies is characterized by low mudstone content and significant plant fragments. The updip section, which contains as much as 60 percent mudstone, possesses two types of lignites. One is tabular in shape but only local in extent; it contains high percentages of woody material. The other type is much more extensive and is of higher specific gravity and grade; it contains relatively low percentages of woody material. Farthest downdip, the thick sequences of dark mudstone facies contain moderately large amounts of very finely comminuted and disseminated organic matter and a marine fauna which is low in number of species and in species diversity. In the embayments between the lobate sand aprons, thin sandstone units in the mudstone section contain glauconite.

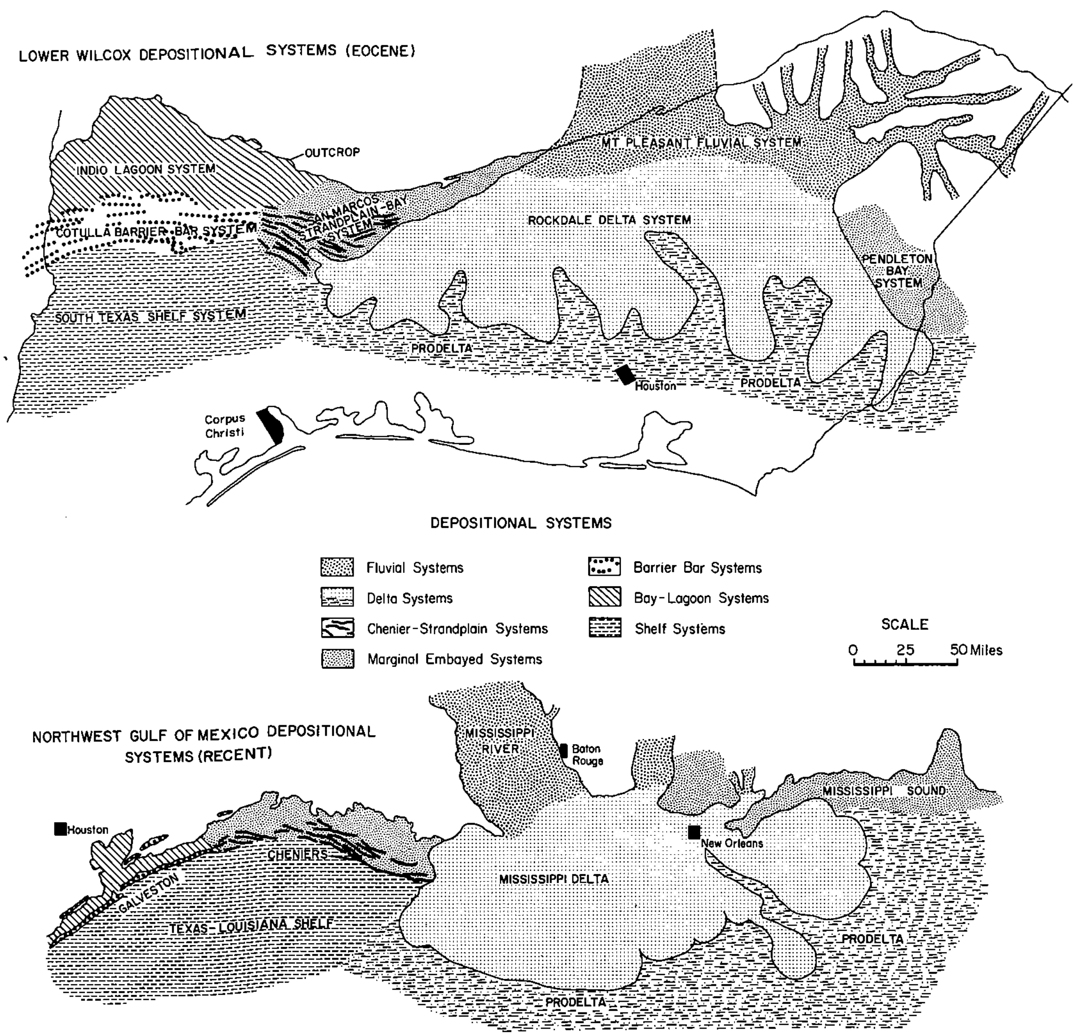


Figure 9-5. Comparison of lower Wilcox depositional systems with those of the Holocene in northwestern Gulf of Mexico basin. *From* Fisher and McGowen (1969, fig. 12).

Depositional Environment

The 16 lobes which have been recognized within 3 periods of deltation (fig. 9-3) are thought to be analogous to deltas of the Mississippi River system of Holocene age. They are similar in progradational development, shape, and development of transgressive marine units. The Wilcox shows a greater amount of vertical stacking, or persistent aggradation, a feature that reflects more subsidence owing to contemporaneous faulting and sediment load. Striking are the persistence of the embayments between lobes and the coincidence of the lobes with modern coastal-plain streams (fig. 9-3). Some lobes have the elongated, narrow shape of the modern birdfoot delta, whereas others are more rounded in shape, similar to premodern abandoned deltas of the Mississippi. Using the Holocene model, elongated Wilcox deltas may have prograded into deeper water over thick mudstone. The rounded deltas suggest construction as shoal-water deltas analogous to those of the premodern Mississippi.

The sandstone associated with mudstone and lignite represents distributary-channel deposition (figs. 9-2, 9-4). The narrow, elongate sandstones, which are symmetrical in cross section, show distributary areal patterns. Compactional subsidence into mudstone resulted in relatively thick sandstone units, which are probably analogous to top-splayed sands described by Gagliano and others (1969). The mudstone and lignite of local extent represent interdistributary deposition in lakes, swamps, and flood basins. The more extensive lignite units represent the landward facies of delta abandonment and concomitant marine transgression.

The sand-rich facies is the sequence of deposition which formed on the delta front as distributary-mouth bars and distal bars (figs. 9-2, 9-4). It is bounded landward by the distributary-flood-basin facies and seaward by the prodelta-mudstone facies.

The entire lower Wilcox of Texas is similar to the depositional systems and sand dispersal of the Holocene in the northwestern Gulf of Mexico basin both in distribution and in component facies of those systems (figs. 9-4, 9-5). In addition to the similarities of the deltaic facies, the Pendleton bay-lagoon system represents the marginal basin, which corresponds to the Lake Pontchartrain area of the modern Mississippi (fig. 9-5). Also, the San Marcos strandplain composes the marginal-deltaic plain, analogous to the Holocene chenier plain; the Cotulla system is comparable to the Texas barrier complex; and the shelf system is similar to the Holocene continental shelf off the coast of Texas and western Louisiana (fig. 9-5).

The development of the fluvial system along the axis of the East Texas basin, or structural embayment, strongly suggests structural influence on transportation and deposition of sediments. The influence of the structural embayment is reflected not only in positioning the stream system but also in the downdip dispersal of sand in the Rockdale delta system. Subtle topographic expression of the Sabine uplift is suggested by the sand-poor facies of the Pendleton bay-lagoon facies. Contemporaneous faulting apparently was not significant in modifying distribution of sediment types.

Acknowledgments

This account is essentially a summary of Fisher and McGowen (1969). The illustrations are used with the permission of the writers, who kindly furnished the originals, and of The American Association of Petroleum Geologists.

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Davis Sand, Yegua Formation, Eocene, Hardin Field, Texas Gulf Coast (10)

Structural Framework

Hardin field is a low-relief dome in southeast Texas (fig. 10-1), with 500 feet of closure at the top of the Yegua Formation, which lies 7,000 to 7,500 feet below sea level. Uplift is due to a deeply buried salt intrusion. The discovery well tested a gravity anomaly which reflects the salt mass. Oil accumulation is on the downthrown, or south, side of a major fault that strikes N. 60° E.

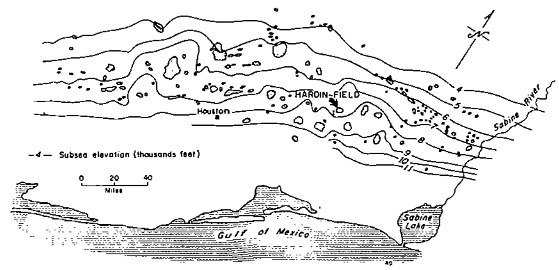

Figure 10-1. Map of southeast Texas showing location of Hardin field and other fields producing from Yegua Formation. Structural contours show top of Yegua.

Stratigraphic Framework

In the Hardin field area, the Yegua Formation of middle Eocene age, a major regressive tongue in southeast Texas, is 700 feet thick and contains 10 sands, 9 of which are productive (fig. 10-2). The sand-bearing portions of the Yegua are distinguished by foraminiferal and electric-log characteristics.

The Davis sand, one of the productive sands, was encountered unexpectedly during early development drilling of the field and has been described by Casey and Cantrell (1941). The Davis lies 300 to 350 feet below the top of the Yegua and is the uppermost sand of the *Eponides yeguaensis* zone (fig. 10-2). It is overlain by the McMurtry sand and underlain by the Frazier sand, the main producing zone of the field. The McMurtry sand is generally poorly developed where the Davis sand is well developed. The Davis sand is developed only where the McMurtry-Frazier interval is greater than 66 feet. Changes in the interval suggest that the shale and siltstone section equivalent to the Davis has compacted to one-half or one-third of its original thickness.

Geometry

Geographic location and trend.—The Davis sand is developed in 12 wells in the southwestern and south-central parts of the field (fig. 10-3). The sand trends approximately N. 60°E.

Vertical position.—The depth to the Davis sand is approximately 7,500 feet in the northeast to 7,600 feet at the southwestern edge of the study area.

Length.—The Davis sand has been recognized in the field for a length of some 11,000 feet (fig. 10-3). However, neither the southwestern nor the northeastern edge of sand development has been mapped.

Width.—The sand body averages 1,250 feet in width (fig. 10-3). The minimum known width is

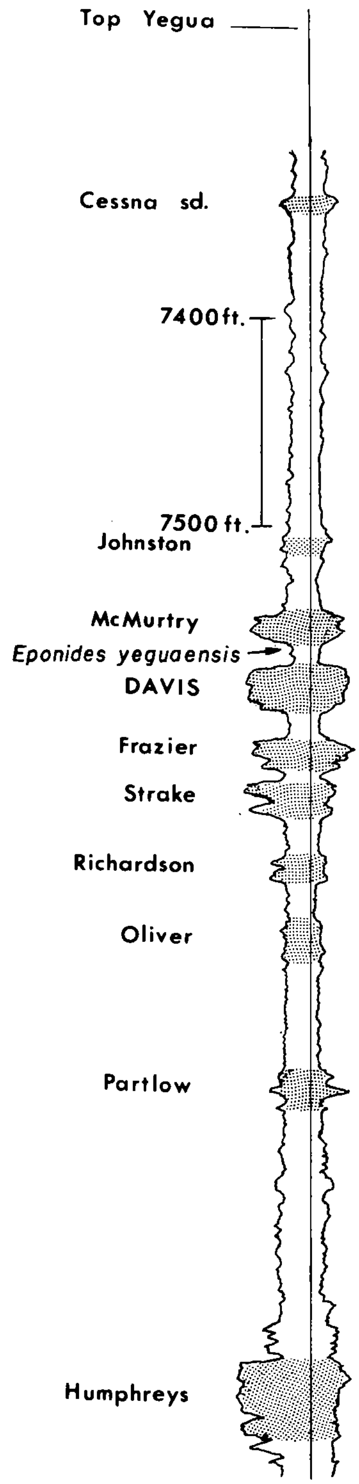

Figure 10-2. Electric log of sand-bearing Yegua Formation at Hardin field, illustrating stratigraphic position, thickness, and log characteristics of the Davis and other Yegua sands. *Modified from* Casey and Cantrell (1941, fig. 2).

900 feet in the southwest, and the maximum, 1,800 feet in the northeast.

Thickness.—The known range in thickness is 0 to 43 feet (fig. 10-3). Along the midline of development the sand is most commonly 40 feet thick.

Boundaries.—Abrupt changes in thickness, illustrated by the thickness map (fig. 10-3) and electric-log correlation sections (fig. 10-4), indicate sharp lateral contacts. Sharp electric-log deflections correspond to an abrupt basal contact. The upper boundary is also rather sharp but not so abrupt as the lower.

Internal Features

Sedimentary structures.—Limited data indicate that the Davis sand is massively bedded with some horizontal bedding and crossbedding. The equivalent section is characterized by interstratification of coarse silt or sand 1 inch to 3 feet in thickness and shale. The silt-sand units contain small-scale crossbedding.

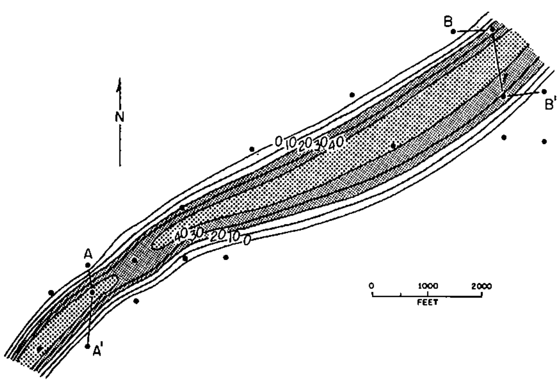

Figure 10-3. Thickness map of Davis sand, showing trend of N. 60° E., length of at least 11,000 feet, and average width of 1,250 feet. *Modified from* Casey and Cantrell (1941, fig. 10).

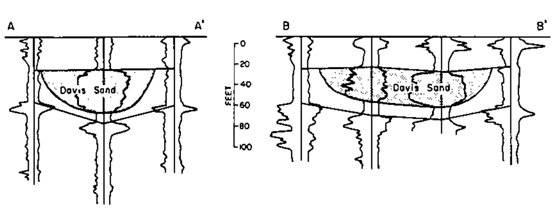

Figure 10-4. Correlation sections *A-A'* and *B-B'* across Davis sand, showing narrow width of sand body and abrupt lateral and basal contacts. Lines of sections shown in figure 10-3. *Modified from* Casey and Cantrell (1941, figs. 5, 8).

Texture.—The Davis sand is medium grained, with a median diameter of 0.33 mm. The silt and clay compose 9.5 percent of the sand. The framework of the sample analyzed is extremely well sorted (1.07). The porosity is 27 percent, and the permeability is 2,260 millidarcys. For comparative purposes, the framework of the Frazier sand has a median diameter of 0.20 mm, a sorting coefficient of 1.19, a porosity of 27 percent, and a permeability of 615 millidarcys.

Constituents.—The principal constituent is quartz; chert is of secondary importance. Both potassium feldspar and plagioclase are prominent, constituting as much as 20 percent of some sample fractions. Accessories include lignite and muscovite plus a number of heavy minerals.

The equivalent interstratified section contains lignitic material, siderite, arenaceous and calcareous foraminifers, ostracodes, and pyrite (some of which replaces foraminifers).

Depositional Environment

Although Casey and Cantrell (1941, p. 595) considered the Davis sand to represent a barrier-bar sand, I believe it was deposited in a deltaic distributary. A width-thickness ratio of approximately 30:1, abrupt lower and lateral contacts, and interstratification and fauna of the equivalent section are suggestive of deposition near the mouth. The narrow width of some 1,250 feet suggests further that the sand represents a genetic unit, with insignificant lateral migration. The sand width is comparable to that of a Holocene Mississippi River distributary of La Fourche delta, whereas the thickness is two-thirds that of La Fourche sand and half the thickness of sand and sandy silts together (Fisk, 1952, pl. 35b).

Acknowledgments

Figures 10-2 through 10-4 are modified after those of Casey and Cantrell (1941) and are utilized with the permission of The American Association of Petroleum Geologists.

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Casey, S. R., Jr., and Cantrell, R. B., 1941, Davis sand lens, Hardin field, Liberty County, Texas, *in* Levorsen, A. I. (ed.), Stratigraphic type oil fields: Am. Assoc. Petroleum Geologists, p. 564-599.

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Fisk, H. N., 1952, Geological investigation of the Atchafalaya Basin and the problem of Mississippi River diversion: U.S. Army Corps Engineers, Waterways Expt. Sta., v. 1, 145 p.

Bolivina perca Sand, Oligocene-Miocene, Thornwell Field, Louisiana Gulf Coast (11)

Structural Framework

Thornwell field, mostly in Jefferson Davis Parish, Louisiana, is a domal structure with a complex fault pattern (fig. 11-1). The faults were contemporaneous with late Oligocene deposition. A large northeast-trending fault enters the field from the southwest and splits into a system of smaller radial faults as it crosses the dome. The northwestern block is highest structurally, and each block becomes lower in a clockwise manner.

Development of the *Bolivina perca* sand took place between two major faults recognized on the east side of the structure. Two smaller faults are present in the area of study. At the level of the *Bolivina perca* zone, dip is generally eastward at 2° to 6°. A small structure is developed on the downthrown side of the northernmost fault in the area.

Stratigraphic Framework

The *Bolivina perca* foraminiferal zone is present in the middle of the Anahuac Shale, which overlies the Frio Formation and underlies lower Miocene beds (fig. 11-2). The Anahuac represents an overall transgressive unit between two regressive sequences, although detailed study reveals that a number of regressions interrupted the overall transgression. The Anahuac is subdivided into three major biostratigraphic units, which, in ascending order, are characterized by the foraminiferal genera *Marginulina, Heterostegina,* and *Discorbis. Bolivina perca* is a characteristic form of the lower part of the *Heterostegina* unit, which is representative of the climax of the Anahuac transgression in most of the Gulf Coast.

In the Thornwell field area, a fairly consistent stratigraphic section is present from the surface

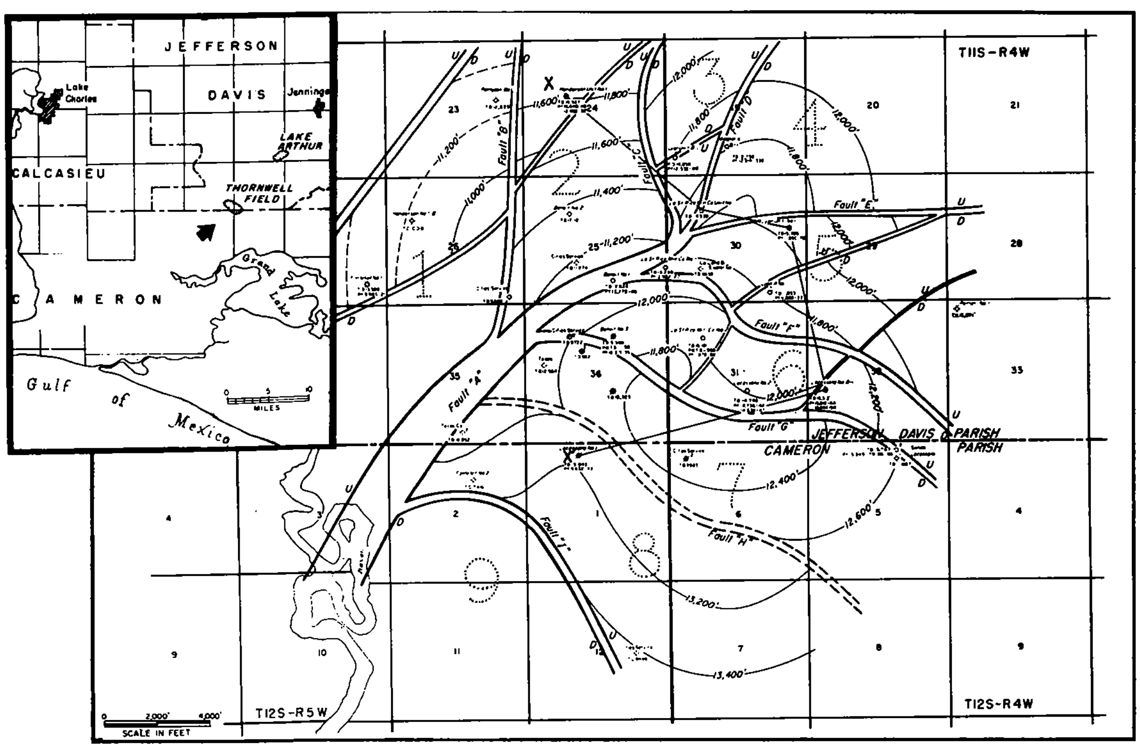

Figure 11-1. Index map and structural-contour map of Thornwell field, Louisiana. Complex fault pattern is present at level of reference surface, a *Marginulina* sand below *Bolivina perca* sand. *After* Hardin (1959, fig. 3).

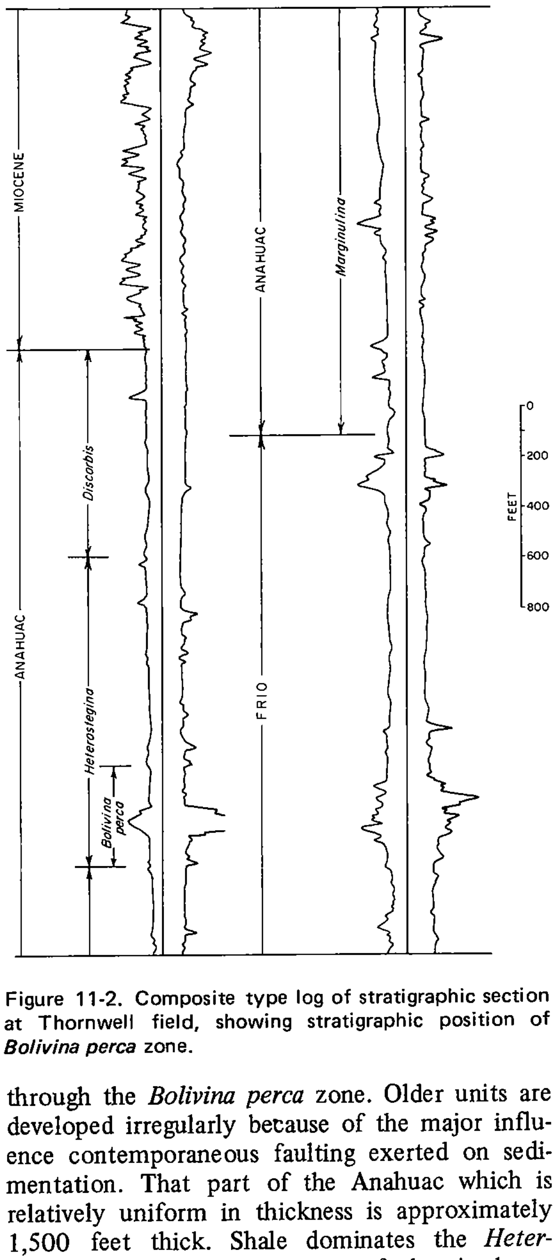

Figure 11-2. Composite type log of stratigraphic section at Thornwell field, showing stratigraphic position of *Bolivina perca* zone.

through the *Bolivina perca* zone. Older units are developed irregularly because of the major influence contemporaneous faulting exerted on sedimentation. That part of the Anahuac which is relatively uniform in thickness is approximately 1,500 feet thick. Shale dominates the *Heterostegina* and *Discorbis* zones of the Anahuac; major sand development is present in the lower two *Marginulina* subzones.

In the Thornwell field area, where the *Bolivina perca* zone was studied by the Lafayette Geological Society Study Group (1963, p. 37-38), it is some 300-400 feet thick. Where present, the sand is developed in the lower half but above the lowermost part of the zone. It is composed of two distinct sand sequences separated by a thin shale. The sand-bearing interval probably contains at least two genetic sand units, and perhaps as many as four.

Geometry

Geographic position and trend.—The *Bolivina perca* sand is developed along a narrow, northerly to north-northwesterly trend in the eastern part of Thornwell field (fig. 11-3). It is best developed in secs. 17 and 20, T. 11 S., R. 4 W.

Vertical position.—The sand and equivalent section lie below the surface at a depth which in the study area ranges from approximately 11,300 to 12,000 feet.

Length.—Development of the *Bolivina perca* sand in the Thornwell field area is known for a distance of 3 to 4 miles, although it undoubtedly extends well beyond the study area (fig. 11-3).

Width.—In an east-west direction, the sand is approximately 1 mile wide. It is widest (1¼ miles) in the area of best development, in secs. 19, 20, and 21 (fig. 11-3).

Thickness.—Net sand ranges from 0 to 100 feet in thickness (figs. 11-3, 11-4). The gross sand interval is as thick as 120 feet. A lower sand sequence in the northern part of the study area is 40 feet thick, and an upper sand is 70 feet thick (fig. 11-4).

Boundaries.—All contacts are sharp (fig. 11-4). The upper boundary is less abrupt than the basal and lateral contacts. The basal contacts of each sand sequence in the *Bolivina perca* interval are sharp. The upper boundary of the lower sand is equally sharp.

Internal Features

Texture.—The *Bolivina perca* sand is a fine-grained, well-sorted sand (fig. 11-5). In the area of Thornwell field, average grain size is 0.15 to 0.20 mm; maximum size ranges from 0.30 to 0.43 mm. A shale interbed is poorly sorted with sand-size grains and shale fragments. The marker above the sand (fig. 11-4) is a poorly sorted shale containing silt and sand.

Constituents.—Included in the framework fraction of the sand are feldspar, chert, and a planktonic foraminifer. Shales above and below contain abundant benthonic and some planktonic forms. Muscovite, pyrite, and siderite are other constituents of the *Bolivina perca* zone above and below the sand.

Depositional Environment

The *Bolivina perca* sand represents at least two depositional sequences of a deltaic distributary. The sharp boundaries and relatively small width-thickness ratio characterize distributary deposits. Limited lateral migration of the distributary is suggested by apparent width-thickness ratios of

75:1 for the upper sand body and 100:1 for the lower.

Acknowledgments

Chevron Oil Company, and W. E. Crain in particular, kindly furnished descriptions of sidewall cores by A. A. Meyerhoff and the photomicrograph (fig. 11-5). Appreciation is expressed to Pan American Petroleum Corporation, now Amoco, and W. W. Tyrrell in particular, for lending an electric log and samples from a well along the sand trend. The interest, comments, and suggestions of R. C. Weissmann, D. M. Curtis, and E. Picou, Shell Oil Company, are gratefully acknowledged. Figures 11-1, 11-3, and 11-4 are used with the permission of the Gulf Coast Association of Geological Societies.

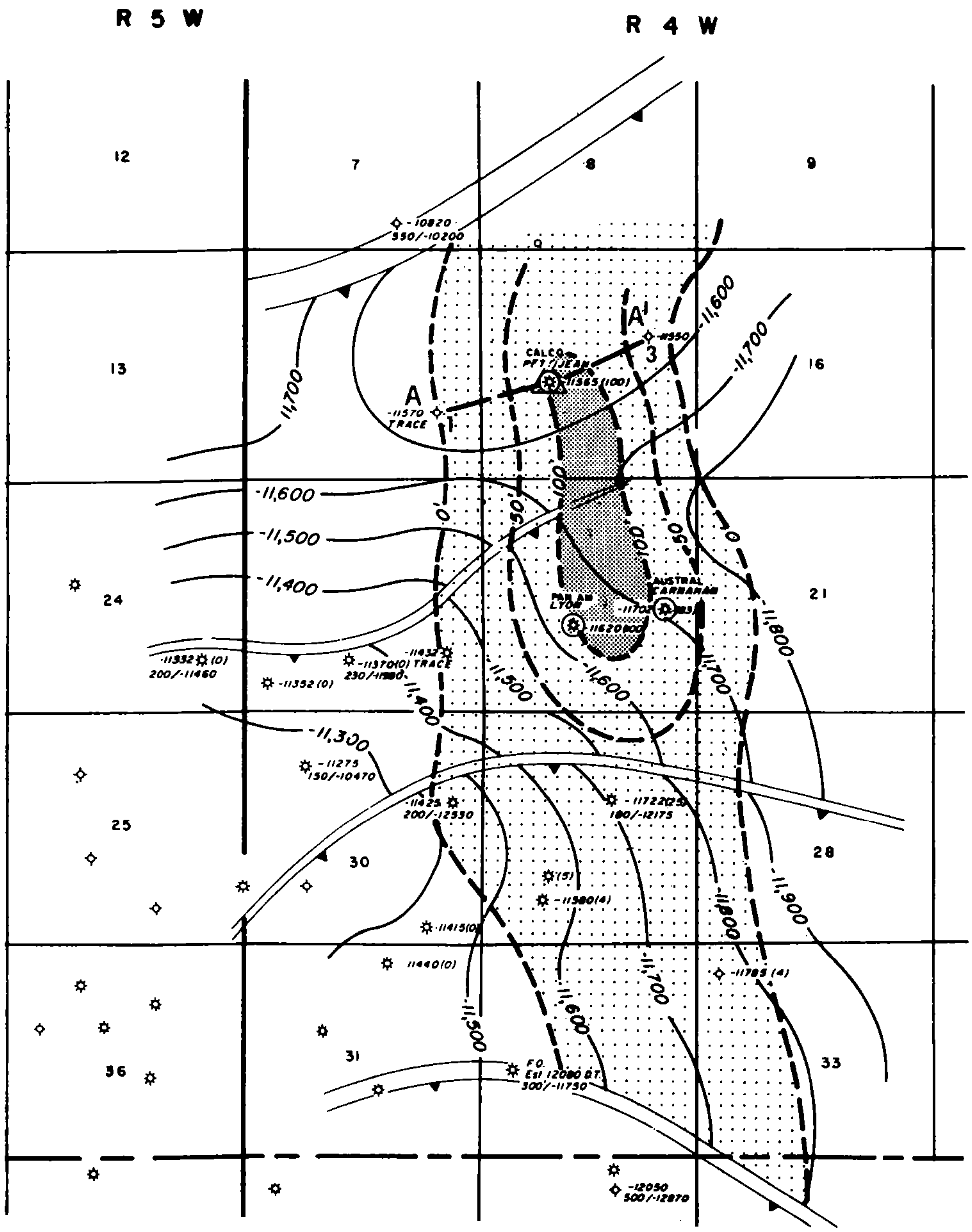

Figure 11-3. Thickness map of *Bolivina perca* sand (heavy dashed lines), illustrating narrow belt of development, and structural-contour map in area of sandstone development. Reference surface is marker below sand. *After* Lafayette Geological Society Study Group (1963, p. 37).

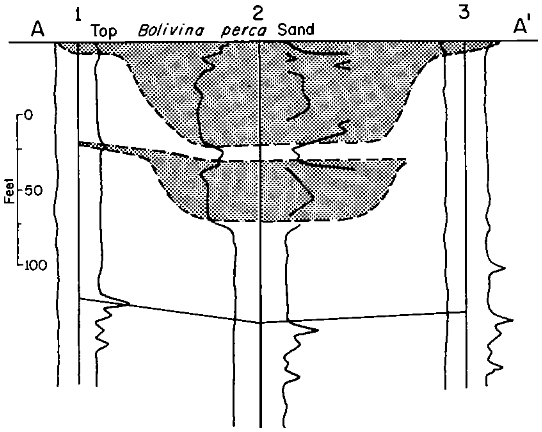

Figure 11-4. Correlation section of *Bolivina perca* sand, illustrating two separate units characterized by sharp boundaries. Line of section shown in figure 11-3. *Modified from* Lafayette Geological Society Study Group (1963, p. 38).

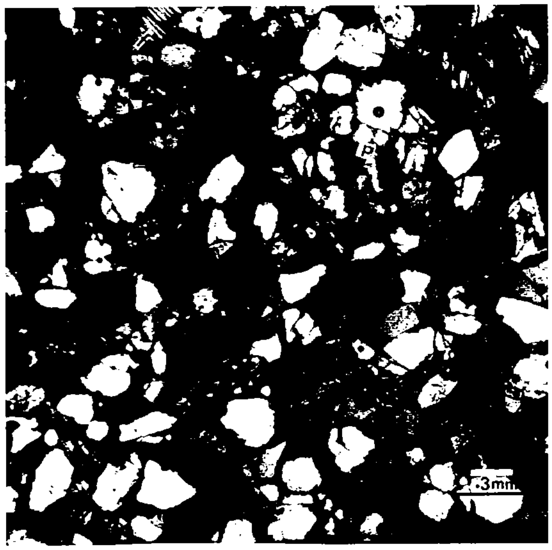

Figure 11-5. *Bolivina perca* sand, from well 2 of figure 11-4. Sand is fine grained and well sorted. Constituents include feldspar (f) and planktonic foraminifer (p). Fracturing of grains due to sidewall-coring technique. Photomicrograph by A. A. Meyerhoff, courtesy of Chevron Oil Company.

Primary Reference

Lafayette Geological Society Study Group, 1963, Stratigraphic factors in southwest Louisiana oil prospecting: Gulf Coast Assoc. Geol. Socs. Trans., v. 13, p. 9-47.

Selected Reference

Hardin, F. R., 1959, Thornwell Field, Jefferson Davis and Cameron Parishes, Louisiana: Gulf Coast Assoc. Geol. Socs. Trans., v. 9, p. 105-110.

Bluejacket (Bartlesville) Sandstone, Pennsylvanian, Northeastern Oklahoma (12)

Structural Framework

The area of study includes two structural provinces, the Northeastern Oklahoma platform and the Arkoma basin (fig. 12-1). Most of the area lies in the former province, which is west-southwest of the Ozark uplift. West of the area is the north-trending Nemaha ridge.

In the Arkoma basin, which was actively subsiding during Middle Pennsylvanian time, local structures consist of folds in front of the Ouachita deformational belt. They may be superimposed upon faults that developed contemporaneous with Atokan deposition. Structures of the Northeastern Oklahoma platform are normal faults, some of which are part of *en-echelon* patterns and upthrusts, with associated drape folds.

Stratigraphic Framework

In the Arkoma basin and on the eastern part of the Northeastern Oklahoma platform, Pennsylvanian rocks apparently overlie Mississippian rocks conformably. In a considerable part of the platform, however, Middle Pennsylvanian (Desmoinesian) rocks unconformably overlie older units.

The Desmoinesian Series includes the Krebs, Cabaniss, and Marmaton Groups, in ascending order. The older two groups, commonly referred to as the Cherokee Group, are characterized by lenticular sandstones, shales, coal beds, and thin but persistent limestones. The Marmaton is characterized by shale, limestone, and minor amounts of sandstone. The depositional sequences

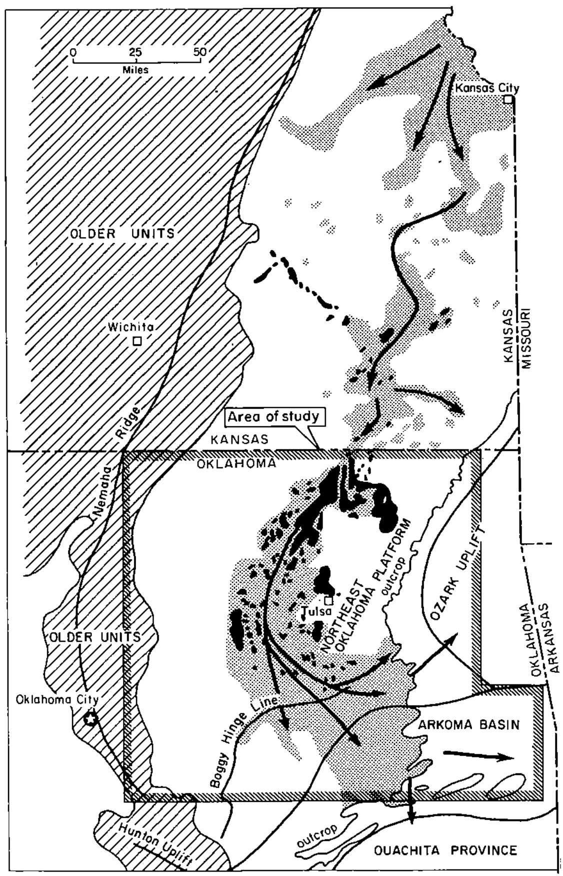

Figure 12-1. Index map showing area of study, oil and gas fields producing from Bluejacket (Bartlesville) Sandstone (black), outcrop limit of Bluejacket (Bartlesville), contemporaneous tectonic features including area of exposed older rocks, gross distribution of coarse clastics in Bluejacket (Bartlesville) complex (stippled pattern), and general system for sediment dispersal (arrows). *Modified from* Visher (1968, fig. 1).

are imperfectly cyclical.

The Bluejacket Sandstone on outcrop and the equivalent Bartlesville in subsurface constitute the basal member of the Boggy Formation, the uppermost formation of the Krebs Group.

The Bluejacket Sandstone on outcrop is underlain by shale and siltstone of the upper part of the Savanna Formation and is overlain by a variable section of unnamed Boggy units. Most commonly the sandstone is a ridge former, and as such it is readily mappable. Its subsurface equivalent, the Bartlesville, makes up the major part of a sequence between two thin but persistent limestones, the Inola above and the "Brown lime" below (fig. 12-2). The studies of Visher (1968) and Visher and others (1971), combining subsurface and surface data, are the basis for much of this summary.

The Bluejacket (Bartlesville) is composed of a large number of genetic sandstone units formed in several specific depositional environments. Significant lateral shifting of depositional processes and limited vertical stacking have given rise to multilateral and multistoried units.

Geometry

Geographic location and trend.—The Bluejacket (Bartlesville) Sandstone in northeastern Oklahoma forms an outcrop belt which is arcuate around the Ozark uplift and convex to the west-southwest. The sandstone extends north-northeastward into Kansas and Missouri, where it is known from both the surface and subsurface. It is limited on the west in a general way by the Nemaha ridge and associated features, which extend north-northwestward from the Arbuckle Mountains-Hunton arch area through Oklahoma City and thence north-northeastward through Kansas.

Sandstone is developed in two general areas (fig. 12-3). Within the larger area in the east, sandstone is locally absent at the stratigraphic position of the Bluejacket (Bartlesville). Sandstone is not developed at numerous localities in the smaller area, which adjoins the Nemaha ridge.

In the northern part of the larger area, the overall sandstone trend for the many genetic units is north-northeast. The trend in the southern part is southeast, with an easterly trend in the southeasternmost part.

Vertical position.—The Bluejacket Sandstone at the surface forms the eastern edge of the study area. In the Arkoma basin it crops out on flanks of folds in a rather wide zone which converges westward and southwestward. The subsurface Bartlesville is encountered at depths ranging to approximately 4,000 feet.

Length.—The Bluejacket extends northward beyond the study area, and the limit of sandstone is a modern erosional edge in the southernmost part, where, however, very fine-grained sandstone with interbedded shale on outcrop suggests proximity to the depositional edge of sand. Elsewhere in the south sandstone is thin or is not developed. In Oklahoma, sandstone has been recognized in the larger eastern area of development for a distance of 180 miles along its arcuate trend of maximum sandstone (fig. 12-3).

Width.—The eastern area of sandstone is presently 50-60 miles wide in the north and 110 miles wide along the southern edge (fig. 12-3). The eastern edge is the Bluejacket outcrop, and consequently the original width cannot be determined.

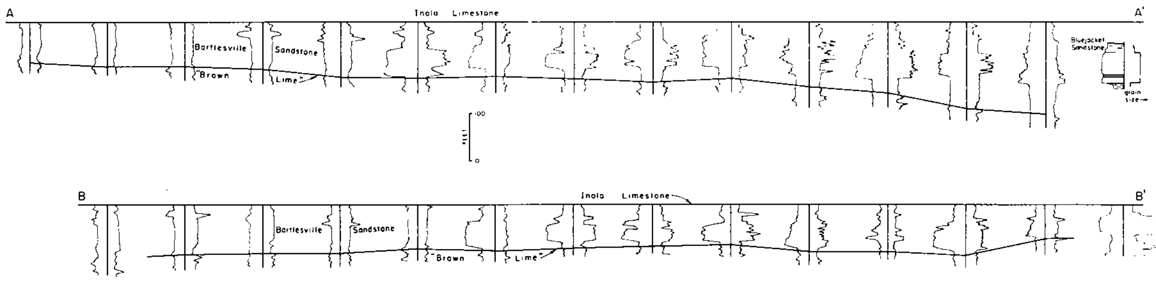

Figure 12-2. Correlation sections showing stratigraphic position of Bluejacket (Bartlesville) Sandstone and lateral and vertical variations in lithology. Lines of sections shown in figure 12-3. *Modified from* Visher (1968, fig. 3).

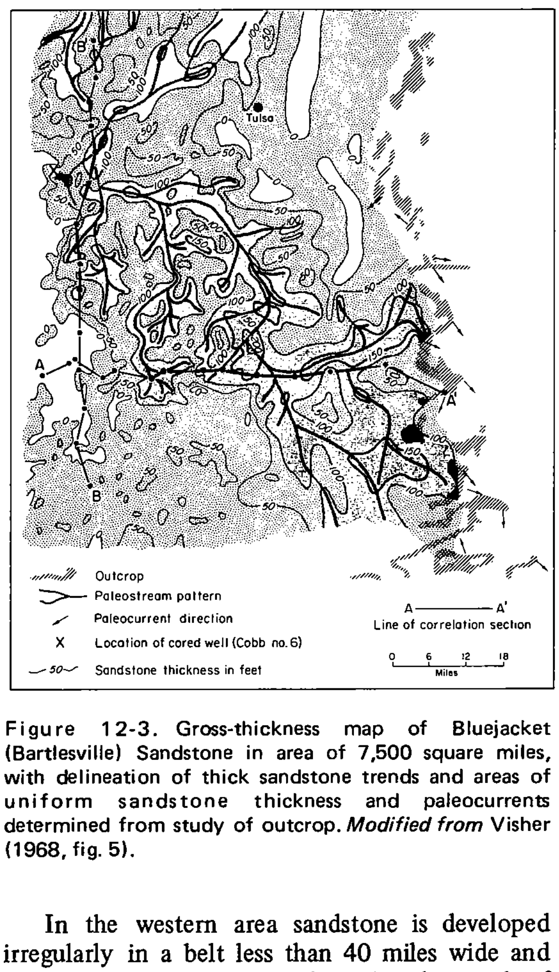

Figure 12-3. Gross-thickness map of Bluejacket (Bartlesville) Sandstone in area of 7,500 square miles, with delineation of thick sandstone trends and areas of uniform sandstone thickness and paleocurrents determined from study of outcrop. *Modified from* Visher (1968, fig. 5).

In the western area sandstone is developed irregularly in a belt less than 40 miles wide and which extends approximately 100 miles south of the Oklahoma-Kansas line.

Thickness.—The sandstone-bearing interval (gross sandstone) ranges in thickness from 0 to more than 200 feet (fig. 12-3). The thickest section occurs in a branching pattern in an area south of Tulsa. The thick trends are narrower than the intervening areas of rather uniform sandstone thickness, which average approximately 50 feet.

Boundaries.—Along thick sandstone trends the basal contact is generally sharp, whereas the upper contact may be either gradational or sharp (figs. 12-2, 12-4). Away from thick trends the base most commonly is gradational. Lateral boundaries of the Bluejacket (Bartlesville) complex are gradational, except where thick trends are present near the sandstone edge. Within the sandstone mass, contacts are sharp between the thick trends and the more uniformly developed sand.

Internal Features

Sedimentary structures.—Medium-scale crossbedding, along with scour surfaces, is a common feature of sandstone in the thick trends. Other features include horizontal bedding, massive bedding with irregularly distributed carbonized filaments or clay pebbles, parting lineation, current ripple marks, and small-scale crossbedding (fig. 12-5).

Considerable variation exists in local paleocurrent direction on outcrop, but the average of S. 30°–35° E. corresponds quite well to the average of thick sandstone trends.

The more uniform sandstone contains parting lineation, rib-and-furrow structures, current- and wave-generated ripples, burrows, and interstratification (fig. 12-6). Thin sandstone beds may be characterized by soft-sediment slippage and flowage.

Texture.—The thick, well-developed sandstone is commonly coarsest at the base. Pebbles and cobbles of intraformational fragments may be present at several levels in this type of sandstone. Average sand size is fine, and the sandstones are well sorted (fig. 12-4).

In one well, porosity in the thicker type of sandstone varies from about 11 to 25 percent and averages 20 percent. Corresponding permeabilities vary from 8 to 1,740 millidarcys, and the average is approximately 500 millidarcys.

The uniform sandstone units between thick trends, above or below well-developed sandstone, in the southeastern part of the area, are very fine grained, moderately sorted, and commonly show an upward increase in grain size.

In the well previously noted, porosity in this

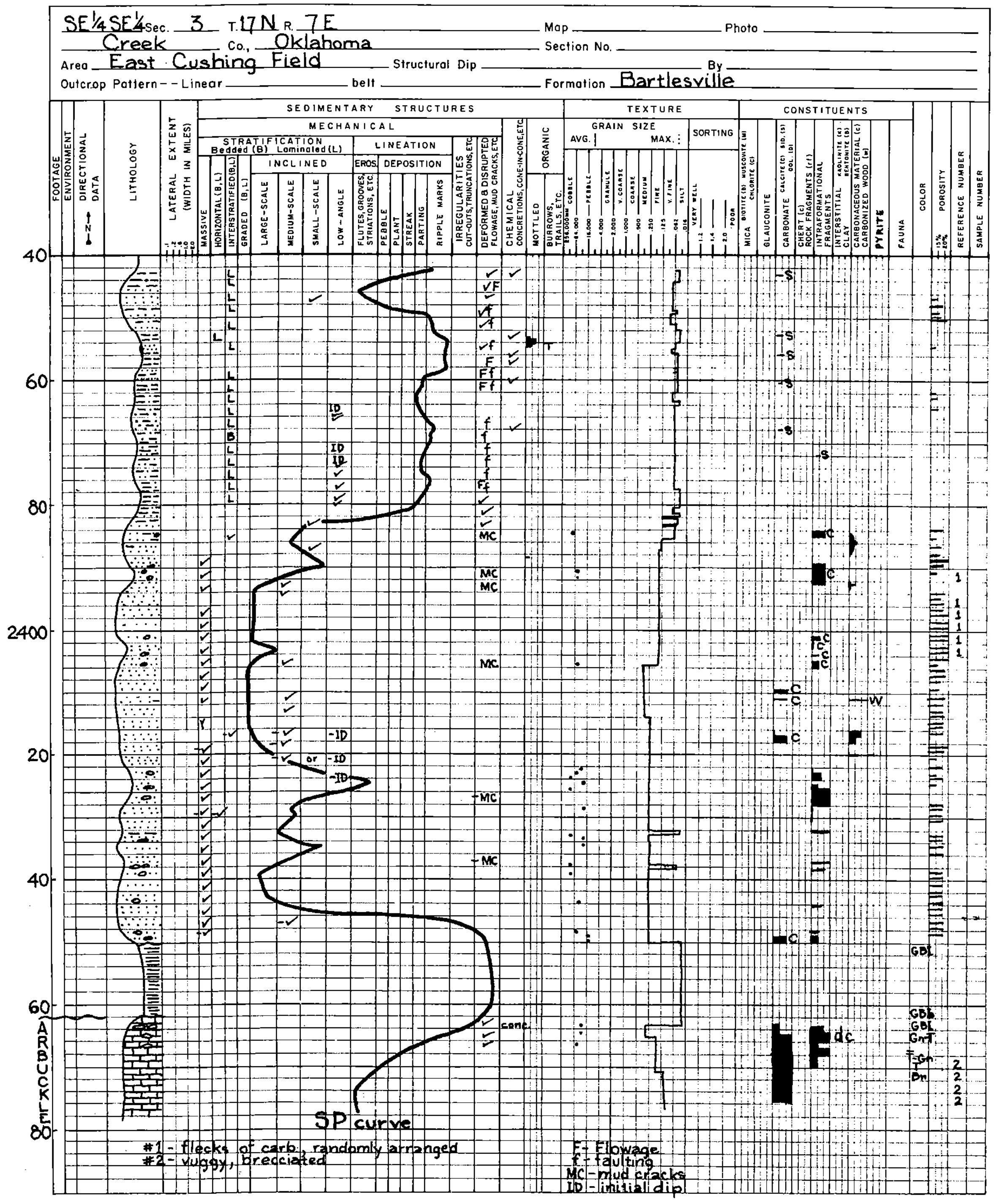

Figure 12-4. Core description of Bluejacket (Bartlesville) Sandstone, East Cushing field, Creek County, Oklahoma, and electric log of interval. Location of well shown in figure 12-3.

sandstone type ranges from 7 to 21 percent, with an average of 12 percent; permeability ranges from less than 1 millidarcy to 110 millidarcys and averages 16 millidarcys.

Constituents.—In addition to intraformational clay fragments, accessory materials in the coarser grained sandstone include carbonaceous material and carbonized wood, pyrite (in cores), and calcite cement. In the finer grained sandstone and interbedded shale, concretionary siderite is rather common.

Depositional Environment

The Bluejacket (Bartlesville) Sandstone is thought to represent various units of a deltaic complex (fig. 12-7). The thick sandstone trends are thought, for the most part, to be deposits of deltaic distributaries. The thinner, more widespread sandstone units are considered to be delta-fringe and/or interdistributary deposits. The former includes delta-front, distributary-mouth, and marginal-deltaic-plain deposits.

The positioning of deltaic advance may have been determined by the Ozark uplift and the Nemaha ridge. Southern progradation is expressed both vertically and laterally. In a vertical section, distributary sands overlie or occupy channels cut into delta-fringe sandstones. The interbedded sandstone and shale in the southeastern part represent distal-delta-front, or fringe, deposits bordering prodelta clays. A sand-starved marginal basin or coast may have lain to the north or northeast of the southeasterly bulge of sandstone while westerly marine currents deposited the relatively thin sandstone units west of the bulge as part of a marginal deltaic plain. Upstream, greater width of distributary sandstone resulted from lateral shifting of the stream; depositional conditions in the northern part of the study area became indistinguishable from those of an alluvial plain.

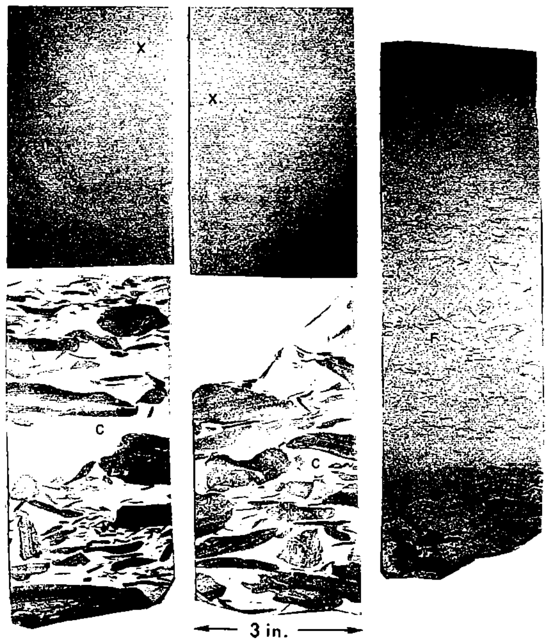

Figure 12-5. Sedimentary structures in well-developed Bluejacket (Bartlesville) Sandstone, East Cushing field. Medium-scale crossbedding (X), clay-pebble conglomerate (C), massive bedding with randomly oriented carbonized filaments (F).

Slow subsidence during deposition and eustatic rise of sea level are probable causes of vertical

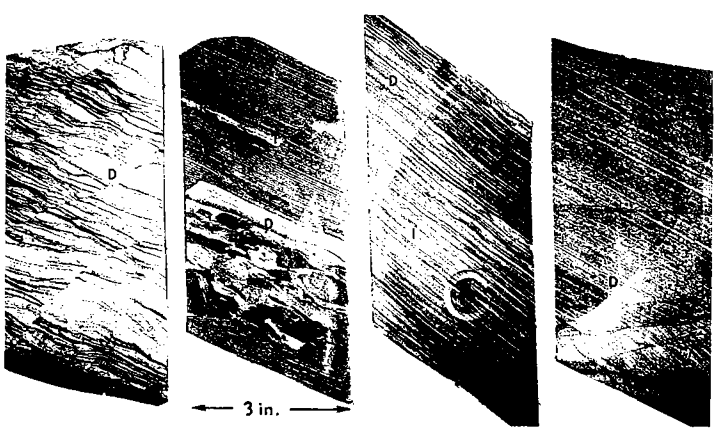

Figure 12-6. Sedimentary structures in thin sandstone unit, East Cushing field. Contemporaneous faulting and flowage and associated steep dips (D), burrows (B), and interstratification (I).

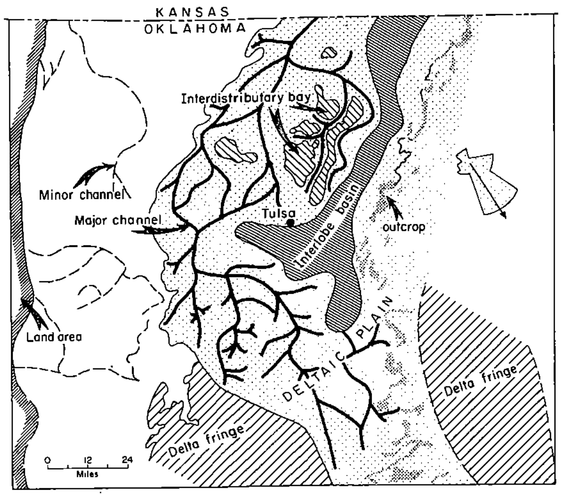

Figure 12-7. Paleogeographic map of Bluejacket (Bartlesville) Sandstone complex. *Modified from* Visher (1968, fig. 5).

stacking. A genetic distributary sandstone for the Bluejacket (Bartlesville) is thought to be less than 70 feet thick. A sandstone body 200 feet thick probably represents a minimum of 3 genetic units. Such a depositing stream would have been slightly larger than the Brazos River near Houston, Texas (Bernard and others, 1970, fig. 6), but smaller than the lower Mississippi at Old River (model 1). The drainage basin extended for a considerable distance beyond the northern edge of the study area.

Acknowledgments

Maps and cross sections are modified from illustrations in papers published in Visher (1968); appreciation is expressed to the Oklahoma City Geological Society for their use. Photographs and the core description were furnished through the courtesy of Getty Oil Company, particularly B. Mobley.

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Frazier, D. E., and Osanik, A., 1961, Point-bar deposits, Old River Locksite, Louisiana: Gulf Coast Assoc. Geol. Socs. Trans., v. 11, p. 121-137.

Dakota "J_3" Sandstone, Cretaceous, Western Nebraska (13)

Structural Framework

The study area is in Morrill and Cheyenne Counties, Nebraska, on the northeast flank of the Denver basin (fig. 13-1). Regional structural dip is west-southwest at 25-35 feet per mile. In detail, the area is characterized by northwest-plunging, long but low-relief folds or noses, with structural closure uncommon (fig. 13-2).

Stratigraphic Framework

The Cretaceous rocks of the Dakota Group of the Denver basin include the familiar "D" and "J" sandstones, the Skull Creek Shale, the Fall River Formation, and the Lakota Sandstone (fig. 13-3). The "J" sandstone is equivalent to the Muddy or Newcastle Sandstone of Wyoming, and the "D" sandstone represents the stratigraphic equivalent of part of the Graneros or Mowry Shale.

Rocks of the Dakota Group overlie the continental deposits of the Morrison Formation of Jurassic age and underlie marine deposits of the Graneros Shale. The change from continental to marine deposition was fully accomplished only after several regressions had interrupted gross transgressive conditions. Consequently, the Dakota interval is characterized by marked vertical and lateral variations in lithology.

The "J" sandstone is a sandstone-bearing interval in the upper part of the Dakota sequence between two marine shales, the Skull Creek below and the Huntsman above. Part of the "J" correlates with the Newcastle of the Black Hills region. Eastward the sandstone coalesces with overlying and underlying sandstone sequences at the expense of the shale sections noted heretofore.

The "J" sandstone interval in the area studied

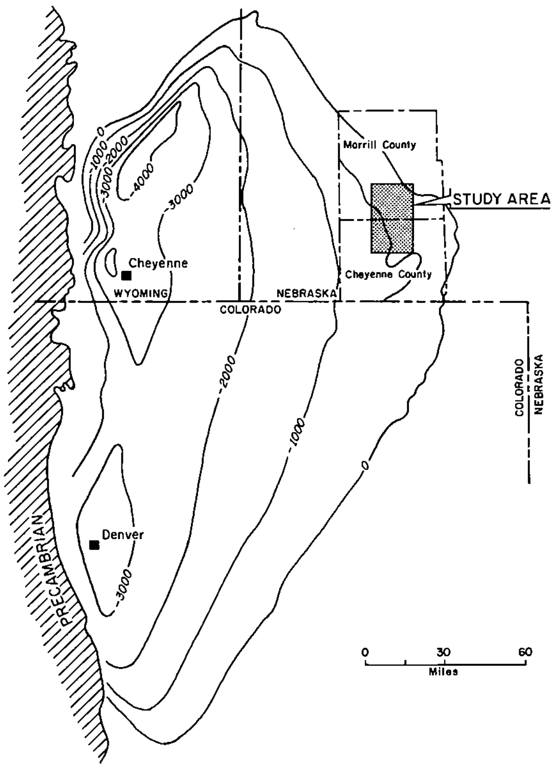

Figure 13-1. Structural-contour map of Denver basin, showing study area on northeastern flank. Contours depict top of "J" sandstone; contour interval, 1,000 feet. *Modified from* Harms (1966, fig. 1).

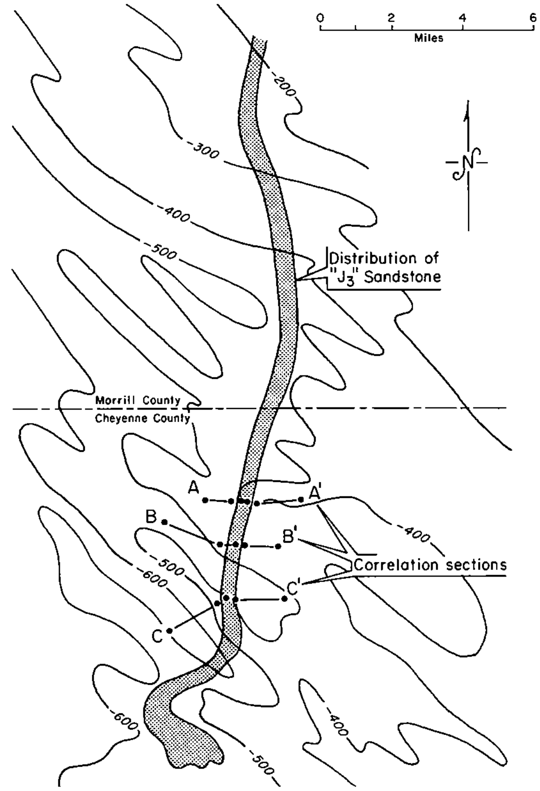

Figure 13-2. Structural-contour map of study area, showing distribution of "J_3" sandstone. Contours depict top of "J" sandstone; contour interval, 100 feet. *Modified from* Harms (1966, fig. 5).

by Harms (1966) and Exum and Harms (1968) is 38 to 77 feet thick. It has been divided by those workers into two members of about equal thickness, "J_1" and "J_2" in descending order (fig. 13-4). The "J_2" sandstone is widely distributed and homogeneous in appearance. It is very fine grained, well sorted, and contains low-angle cross laminae (fig. 13-5). The grain size increases in an upward direction, and authigenic kaolinite constitutes a larger proportion of the fine fraction than that for other sandstone beds. The lower part of the "J_1" interval is a shaly unit 5 to 10 feet thick. The basal contact is marked by irregular burrows into the top of the "J_2" sandstone. Grain size increases upward into the sandy unit of the "J_1" interval. Arenaceous foraminifers and carbonaceous plant fragments are common organic constituents. The upper unit of the "J_1" is characterized by burrowed, very fine-grained sand with thin interbeds of shale and siltstone (fig. 13-6). Thin beds of bentonite and a locally developed underclay are also present in the "J_1" interval. The fine-grained fraction contains less

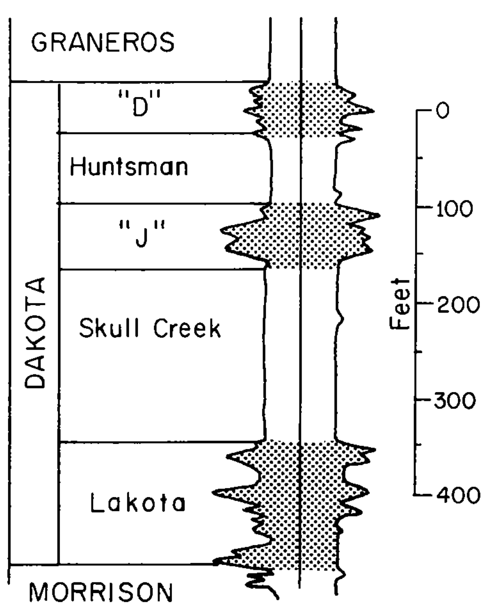

Figure 13-3. Typical electric-log section of Dakota Sandstone in Denver basin.

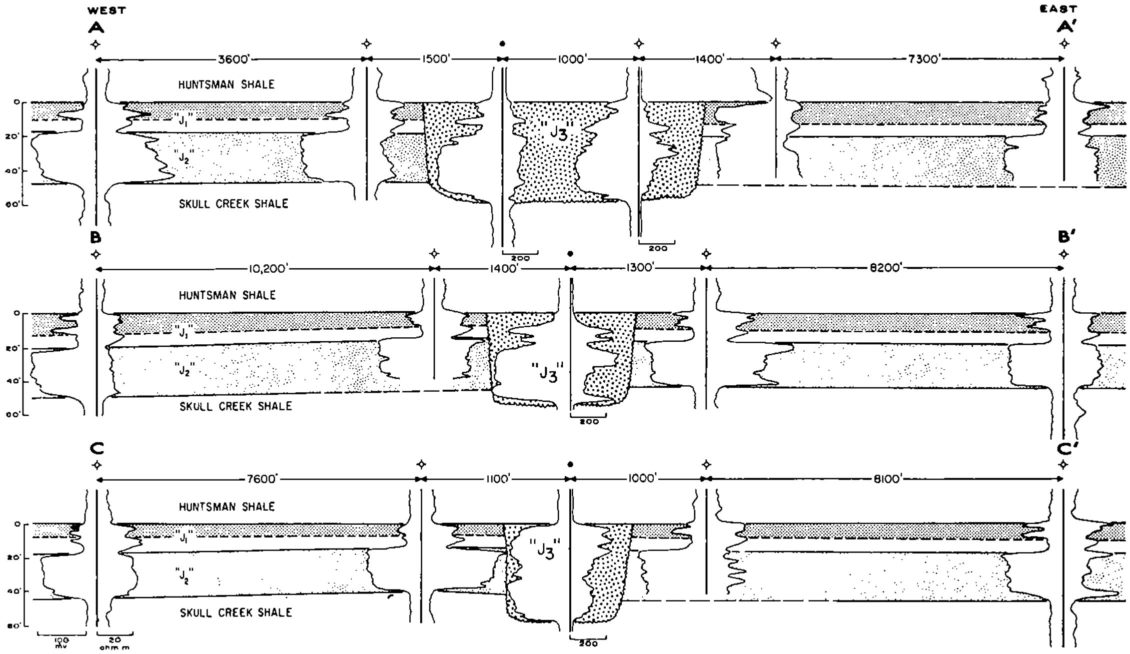

Figure 13-4. Electric-log correlation sections showing subdivision of "J" sandstone and sharp lateral and basal boundaries of "J_3" sandstone. Lines of sections shown in figure 13-2. *Modified from* Harms (1966, fig. 12).

kaolinite and more chlorite than the "J_2" sandstone.

At the top of the "J" is a thin, phosphatic, conglomeratic sandstone bed. Present are granules of bone and tooth fragments, along with fragments of phosphatic brachiopod shells. This bed overlies both the normal "J" section and the "J_3" sandstone body. The "J_3" is developed in a long but very narrow area and is the subject of the following discussion.

Geometry

Geographic position and trend.—The "J_3" sandstone is present in a narrow strip of southern Morrill County, Nebraska, and the adjoining part of northern Cheyenne County (fig. 13-2). The sandstone trends essentially north-south through the western part of R. 49 W. on the north and through R. 50 W. on the south.

Vertical position.—In the study area the "J_3" sandstone is present entirely in the subsurface and ranges in depth from approximately 4,000 feet in the north to 4,800 feet in the south.

Length.—The sandstone is known for a length of some 20 miles (fig. 13-2). Neither the northern nor southern edge has been defined from present subsurface control.

Width.—Where control is good the width does not exceed 2,500 feet and averages about 1,500 feet (figs. 13-2, 13-4). From limited data in the southernmost part of the area, the sandstone body is shown to be more than a mile wide.

Thickness.—The "J_3" sandstone varies in thickness from approximately 45 to 80 feet (fig. 13-4), and its thickness increases from north to south. The exact thickness is difficult to determine where "J_3" rests on "J_2" sandstone. In a given area of sand development the thickness is relatively constant in a direction normal to the sandstone trend; the resulting cross-sectional shape is more nearly rectangular than troughlike.

Boundaries.—Lateral and basal contacts are sharp (fig. 13-4). The latter is recognized easily in cores and from an abrupt deflection of electric-log curves, except where "J_3" rests directly on "J_2." The upper contact with the very thin, fossiliferous, conglomeratic sandstone is sharp lithologically, but it is difficult to recognize from electric logs. Although the uppermost part of the "J_3" interval locally contains siltstone and shale, generally the top of the "J" sandstone is sharply defined from the overlying Huntsman Shale.

Internal Features

Sedimentary structures.—The most common structures in the "J_3" sandstone are medium- and small-scale crossbedding and massive bedding with indistinct small-scale cross strata (fig. 13-7).

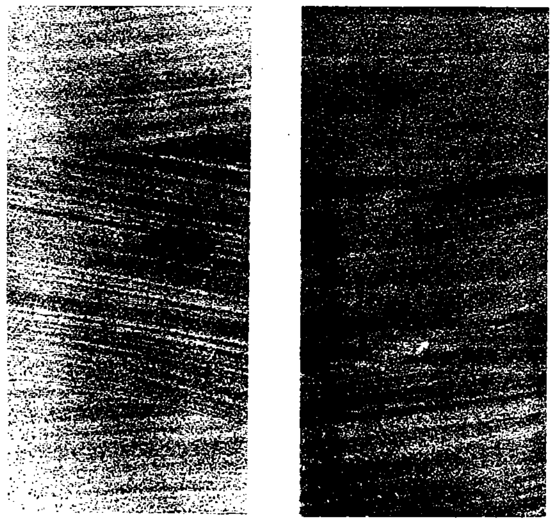

Figure 13-5. Cross stratification in "J_2" sandstone showing relatively low-angle cross laminae truncated and overlain by laminae with similar dip. *From* Harms (1966, fig. 3). Photographs by J. C. Harms.

Locally developed interstratified siltstone and shale are characterized by soft-sediment flowage and slippage.

Texture.—The "J_3" sandstone, which is generally coarser grained than the other "J" sandstones, is fine to very fine grained and well to very well sorted (fig. 13-8). Pebbles of locally derived siderite and shale range in maximum diameter from 2 to 60 mm. Vertically, no systematic variation in grain size was noted. Sandstone beds have porosity ranging from 10 to 30 percent and averaging 20 percent (fig. 13-8). The sandstone shows an upward decrease in porosity. Permeability varies from about 1 to more than 1,000 millidarcys, with an average of 350 millidarcys. Acoustic velocities in the sandstone average about 12,500 feet per second.

Constituents.—The common detrital minerals are quartz (90 percent), chert (3 percent), and feldspar (3 percent). The quartz/chert ratio and feldspar content are higher than those for the "J_2" sandstone but are indistinguishable from those for the "J_1." Siderite pebbles are a conspicuous constituent; scattered plant fragments are also present. Microfossils include abundant specimens of various pollen and spores and small numbers of hystrichospherids and dinoflagellates (fig. 13-8).

Depositional Environment and Geologic History

The "J_3" sandstone is thought to have been deposited in a south-flowing deltaic distributary.

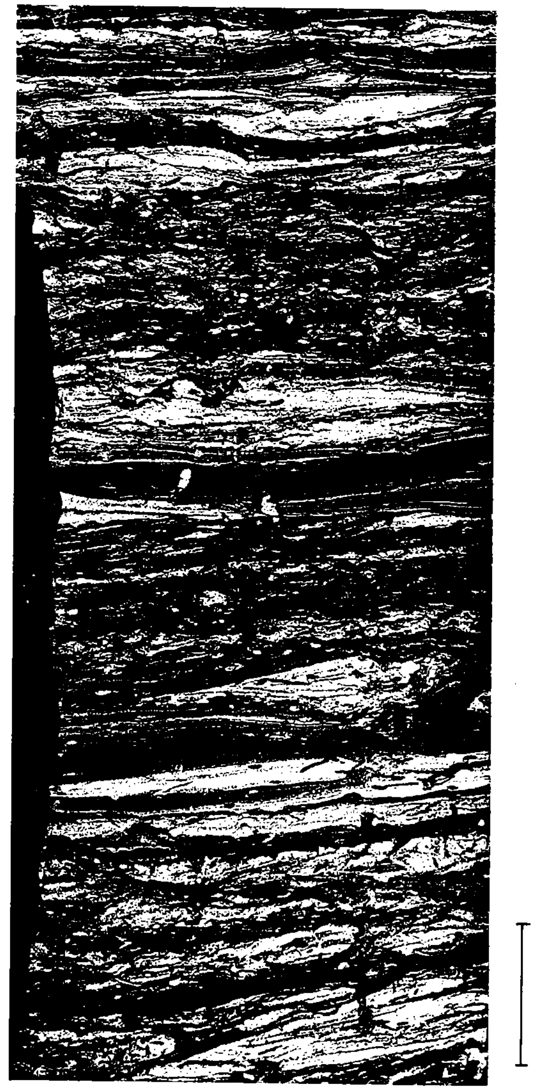

Figure 13-6. Interstratification, burrows, and mottled bedding in "J_1" sandstone. *From* Harms (1966, fig. 7). Photograph by J. C. Harms.

Evidence for stream deposition is the sharp basal and lateral contacts, medium-scale and small-scale crossbedding, and coarser grain size than other "J" sandstones. The width-thickness ratio of approximately 25 and the presence of only intraformational pebbles suggest distributary deposition to me rather than alluvial-valley deposition, which is favored by Harms (1966, p. 2137) and Exum and Harms (1968, p. 1865). For an interpretation of deposition in a stream valley, it seems compelling to consider the river width as no more than 100 feet and the sandstone as multistoried. The river would have deposited the sand during two or more

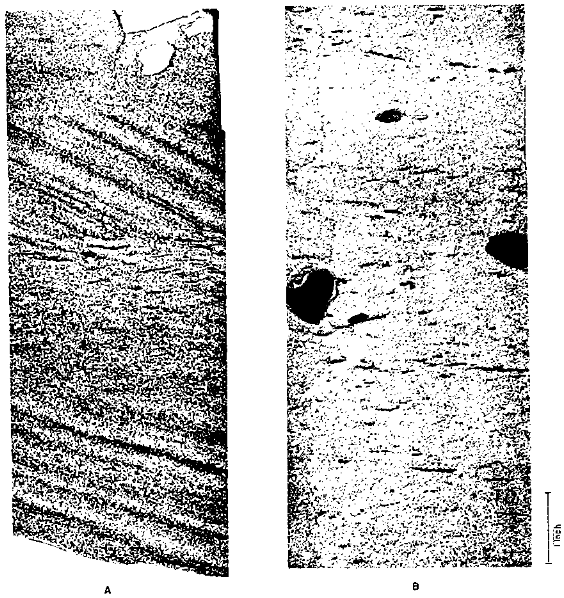

Figure 13-7. Medium-scale and small-scale crossbedding in "J_3" sandstone (A); massive bedding with indistinct zones of small-scale cross laminae (B). *From* Harms (1966, fig. 13). Photographs by J. C. Harms.

sequences of alluviation after the narrow valley had been carved as the result of uplift. Together, the size required for the river and the uplift required for erosion of a narrow valley seem less likely as geologic events than a straight distributary channel.

The "J_3" sandstone represents the culmination of a regression characterized by the following events:

1. Offshore marine deposition of clay (Skull Creek Shale) after a transgression (basal Skull Creek).
2. Deposition of nearshore and coastal sand ("J_2" sandstone).
3. Minor transgression (basal part, "J_1" sandstone).
4. Offshore marine deposition of silt and clay (lower shaly unit of "J_1").
5. Nearshore and coastal deposition of sand and clay ("J_1" sandstone).
6. Deposition of sand in deltaic distributary that flowed southward.

The transgression that terminated the regression is represented by the thin phosphatic, conglom-

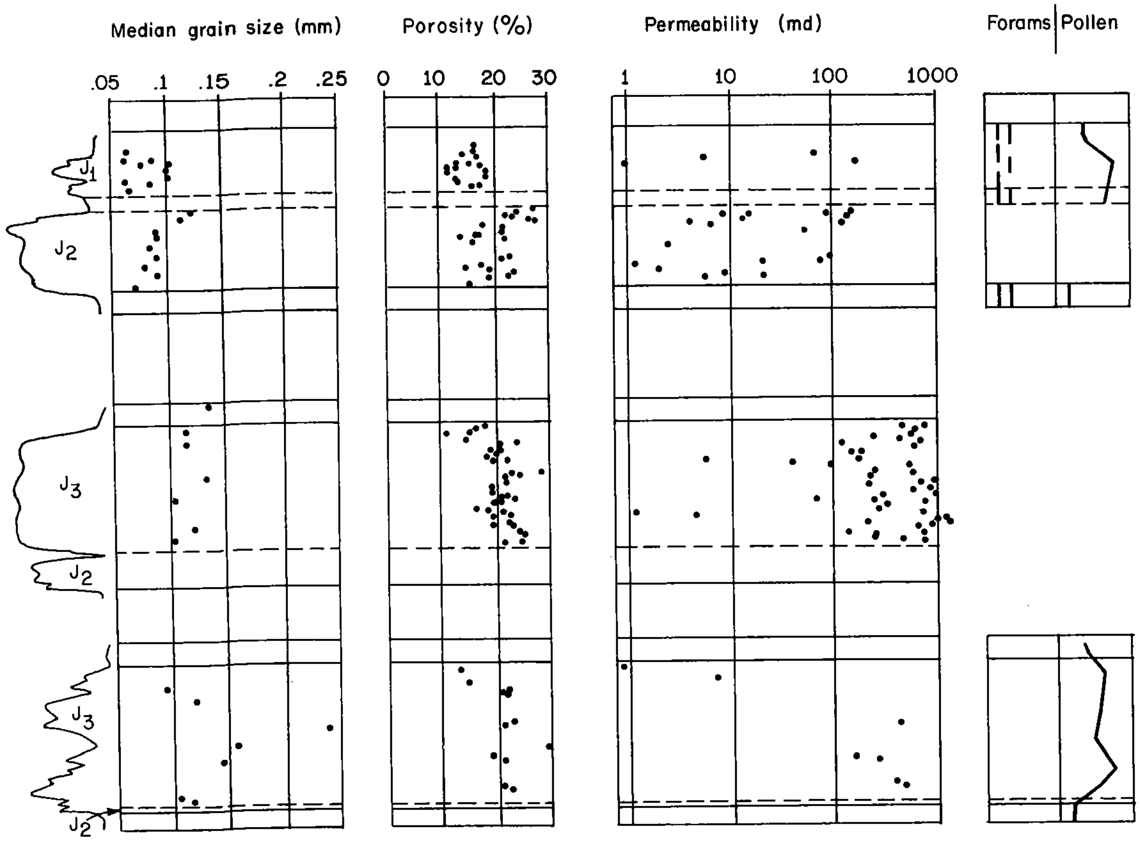

Figure 13-8. Textural and compositional features of "J" sandstones. *Modified from* Harms (1966, figs. 21-23).

eratic sandstone at the top of the "J" below the basal Huntsman Shale.

Acknowledgments

The American Association of Petroleum Geologists has kindly permitted use of the illustrations included in this study. J. C. Harms, Marathon Oil Company, kindly furnished photographs of sedimentary structures.

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Newcastle Sandstone, Cretaceous, North Dakota (14)

Structural Framework

At the level of Lower Cretaceous rocks, the center of the Williston basin lies in western North Dakota. The eastern part of the state is on the eastern flank of the basin, the northwestern part on the northern flank, and the southwestern part on the southern flank (fig. 14-1). A large south-plunging anticlinal nose with approximately 100 feet of closure is present at the Newcastle position over the Nesson anticline, east-northeast of the trough of the basin (fig. 14-1).

Stratigraphic Framework

Lower Cretaceous rocks in the Montana-Wyoming-North Dakota-South Dakota region include a number of named stratigraphic units that reflect the change of depositional conditions from nonmarine to marine. Much attention has been focused upon proper stratigraphic designation of variously named units. In an effort to avoid that discussion, the Newcastle Sandstone is herein regarded as the sequence, commonly containing coarse clastics, that is everywhere underlain and overlain by marine shale. The underlying shale in the general region is most commonly referred to as the Skull Creek and the overlying shale as the Mowry (figs. 14-2, 14-3). The Newcastle is the approximate equivalent of the Viking of Alberta, the Bow Island of Montana and Canada, the Muddy of central Wyoming, and the "J" of the Denver basin.

In much of North Dakota the Newcastle Sandstone represents the regressive phase of one transgressive-regressive couplet. Here, the upper surface, formed during the Mowry transgression, is an approximate time-stratigraphic horizon that is recognizable by characteristic electric-log features. On the other hand, the base of the Newcastle occurs at various stratigraphic positions. Although a myriad of genetic units is present, there is only limited vertical stacking in the Newcastle. The delineation of the Newcastle over some 60,000 square miles in the study by Reishus (1968) indicates stable tectonic conditions during deposition of the Skull Creek-Newcastle-Mowry sequence. East of the area of delineation the sandstone is part of the undifferentiated Dakota Group, composed of Upper and Lower Cretaceous sandstone-bearing units.

Geometry

Geographic position and trend.—The Newcastle interval has been recognized and delineated in all of North Dakota except for the easternmost part, which is one county wide in the north and two to three counties wide in the south (fig. 14-1). In that area the stratigraphic marker at the top of the Newcastle Sandstone and/or the marker at the base of the Skull Creek Shale have not been recognized.

Sandstone of varying thicknesses is present in the western part of the state (except for local areas) and in the southeastern and east-central parts of the state (fig. 14-1). A relatively narrow, linear belt of sandstone connects the two main areas, and another linear belt extends north-northwestward beyond the northwestern edge of development in the east.

Numerous gross sandstone trends are present with various orientations. The northeast-trending thickness lines in the southeast do not necessarily reflect a sandstone trend with that direction, but may reflect a northwest-thinning complex.

Vertical position.—The Newcastle is as little as 500 to 750 feet below the surface in the east and as much as 5,000 to 5,500 feet in the center of the Williston basin in western North Dakota.

Length and width.—In a north-south direction the western sandstone mass extends beyond the state in both directions, or for a distance greater than 210 miles (fig. 14-1). The east-west dimension for that complex is greater than 75 miles, as sand extends into Montana. In the east the sandstone mass is oriented in a northeast-southwest direction for more than 200 miles. The northeastern sandstone edge is present in the northeastern part of the state, but sand extends into South Dakota. The average width of delineation is approximately 75 miles. A west-projecting bulge, or finger, is present in the south-southwestern part of the state. The belt connecting the western and eastern areas of sandstone development and dividing two extensive areas of no sandstone is some 120 miles long and 25 miles wide (fig. 14-1). The belt extending into Canada from northeastern North Dakota is more than 50 miles long and 15 miles wide.

Thickness.—The range in thickness of the Newcastle Sandstone is from 0 to more than 280 feet in the southeast (fig. 14-1). In the east, sandstone thins rather uniformly west-northwestward. In that area one trend of thick sandstone of more than 60 feet extends northwestward toward the northeastern linear belt. Sandstone is more

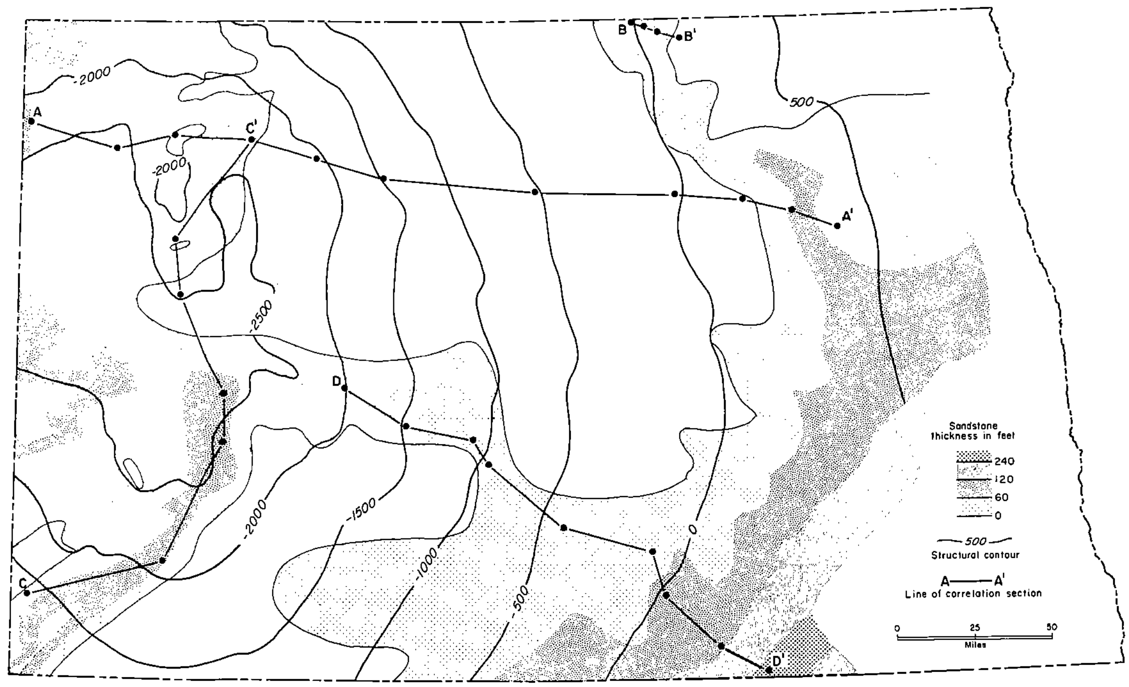

Figure 14-1. Thickness map of Newcastle Sandstone and structural-contour map on top of Mowry Shale in North Dakota. Newcastle shows two major areas of sandstone development. *Modified from* Reishus (1968, pls. 2, 3).

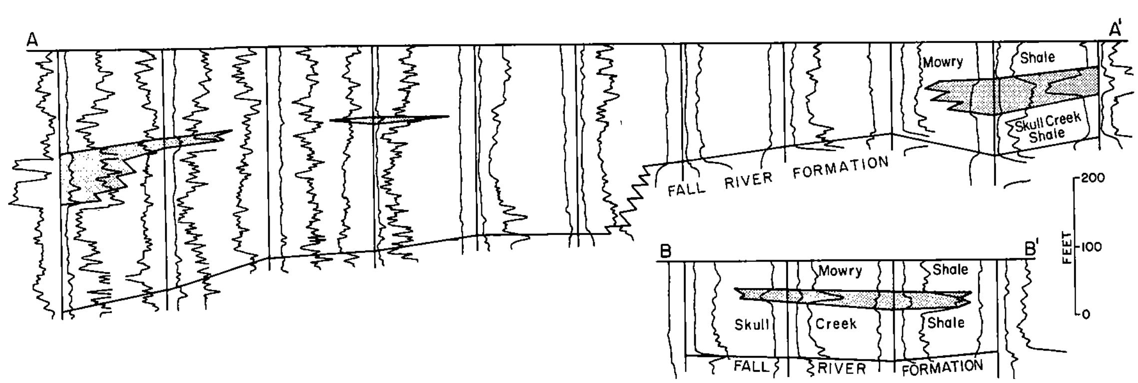

Figure 14-2. Correlation sections *A-A'* and *B-B'*, showing irregular development of Newcastle Sandstone (stippled pattern). Lines of sections shown in figure 14-1. *Modified from* Reishus (1968, pls. 6-11).

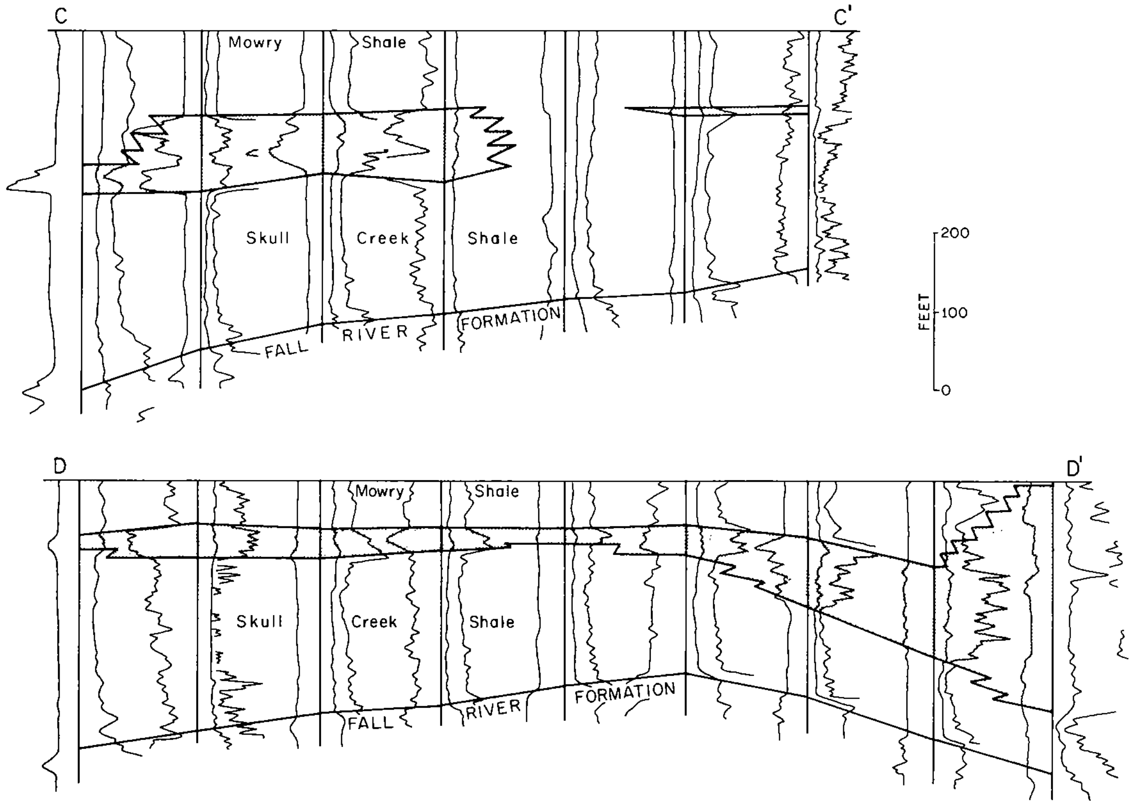

Figure 14-3. Correlation sections *C-C'* and *D-D'*, illustrating variations in development of Newcastle Sandstone (stippled pattern). In the southeast (section *D-D'*) sandstone is developed at expense of overlying Mowry and underlying Skull Creek. Electric logs show nature of lower boundary. Lines of sections shown in figure 14-1. *Modified from* Reishus (1968, pls. 6-11).

than 120 feet thick along the northeastern trend of southwestern North Dakota. In western North Dakota sandstone is as much as 140 feet thick, and it is more than 100 feet thick in a local area in the northwestern part.

Boundaries.—Based on electric-log characteristics, the lower and upper contacts may be either gradational or sharp (figs. 14-2, 14-3). The basal contact is commonly sharp where thick sandstone is developed, and it is gradational where the sandstone is thin. A gradational contact more commonly characterizes the upper boundary than the lower.

The nature of lateral contacts of individual sandstone units is not known. However, lateral contacts are thought to be sharp along the two linear belts and at the edges of thick trends which show marked variation in sandstone thickness.

Internal Features

From sample descriptions, the Newcastle Sandstone is very fine to medium grained and well sorted. In the Black Hills, the sandstone is quartzose with varying amounts of carbonaceous material. There the thicker, lenticular sandstone bodies commonly contain medium-scale crossbedding (Skolnick, 1958, p. 793).

Depositional Environment and Geologic History

Most of the Newcastle in North Dakota represents deposition on a broad, slowly subsiding deltaic plain, which formed as streams advanced west-northwestward from South Dakota and Iowa, westward from Iowa and Minnesota, northward from northwestern South Dakota, and southward from Saskatchewan. In the deltaic complex, Skull Creek prodeltaic clays underlie delta-margin coastal sands and deltaic distributary sands, which together are thought to represent the bulk of sandstone in the Newcastle. During the Newcastle regression, streams flowing from areas of the Canadian shield and the Appalachian Mountains built a widespread deltaic plain in the shallow Western Interior sea. Gentle slopes, shallow sea floor, and slow rate of subsidence were primary reasons for the widespread distribution of a relatively thin sandstone section and the wide variation in sandstone trends. The Mowry transgression, which terminated the regression, extended into eastern North Dakota and provided good marker beds for stratigraphic correlation in the study area.

Acknowledgments

Illustrations are modified after those of Reishus (1968) and are included with the permission of the North Dakota Geological Survey.

Primary Reference

Reishus, Mark, 1968, The Newcastle Formation in the Williston basin of North Dakota: North Dakota Geol. Survey Rept. Inv. 47, 26 p.

Selected Reference

Skolnick, Herbert, 1958, Stratigraphy of some Lower Cretaceous rocks of the Black Hills area: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 787-815.

INTERDELTAIC BARRIER-BAR ENVIRONMENTS

Galveston Island Sand, Holocene, Texas Gulf Coast (15)

Geographic and Physiographic Framework

Galveston Island, Bolivar Peninsula, and associated tidal deltas together compose a sand-barrier feature which separates the Gulf of Mexico from the Galveston Bay area. West Bay, the western part of the bay area, lies landward of the island (fig. 15-1). The sand mass of more than half a cubic mile, located slightly seaward of the Holocene-Pleistocene hinge line, is parallel to the shoreline and extends for a distance of more than 50 miles. The sand barrier is the easternmost part of a line of barriers which continue, with interruption by the Brazos, Colorado, and Rio Grande deltas, along the Gulf Coast from Texas to Mexico for approximately 600 miles. This feature has been reported by Bernard and others (1962, 1970) and recorded on motion-picture film by Humble Oil & Refining Company.

Galveston Island is about 3 miles seaward of the mainland; width at sea level averages 2 miles, and maximum elevation is 12 feet. The gulfward shoreline is smooth, whereas the bay side of the island is serrated. The most characteristic features of the island are beach ridges and swales (fig. 15-2), sand dunes, active and abandoned tidal channels, tidal deltas, and wash-over fans. Beach ridges are low, elongate ridges almost parallel to the present shoreline but recurved along the bay side and younger western ends of the island. They generally have a steep slope facing seaward and a gentle slope facing landward. The serrated bayshore is related to the large number of abandoned tidal channels, or "guts," and swale areas between hooked spit accretions at the southwestern end of the island. Commonly present in shallow water immediately off the Gulf beach are four breaker bars (longshore bars or balls).

During the initial standing-sea-level substage (3,000 to 5,000 years ago), Galveston Island began as a small bar on the southwestern side of the mouth of Galveston Bay about 4 miles offshore in 5 to 8 feet of water. Galveston Bay resulted largely from the drowning of the Trinity and San Jacinto River valleys after their entrenchment during the previous falling- and low-sea-level substage, corresponding to the late Wisconsin glacial stage. The lower parts of the valleys were filled with alluvial and deltaic sediments during the low and early-rising substages. Because of the relatively small volume of sediments contributed by the two rivers, the valleys were drowned during the latter part of the rising substage. Only within the past 1,000 years has the Trinity River begun to build a delta across the upper part of Galveston Bay. The bays are now less than 10 feet deep.

Sedimentologic Processes

Prevailing winds, waves, and currents along the southeast Texas coast are from the southeast and northeast quadrants. Their combined effect produces the dominant westerly longshore currents. Wave heights average 2 and 4 feet in 10- and 50-foot water depths, respectively, off Galveston Island. Formed during hurricanes, 10- to 20-foot waves are responsible for erosion and transportation seaward and longshore of much of the sand on the upper shoreface and beach foreshore. However, sand is added to the storm berm in this manner. The combination of wave height and direction and tide is responsible not only for the number, height, and position of breaker bars but also for their moving up the shoreface in the form of giant, asymmetric ripples. Sand is transported to the upper shoreface and beach by this process.

Severe storms apparently destroy most of the breaker bars.

Tides range in height from less than 1 foot to 2.5 feet. Currents in Bolivar Roads, between Galveston and Bolivar Peninsula, are as little as 1 knot to as much as 3.3 knots during flood and 4.3 knots during ebb tides. Similar currents occur in San Luis Pass at the southwestern end of Galveston Island. During hurricanes 15-foot tides may occur; low tides accompany strong northerly winds of long duration.

Surface-water temperature averages approximately 90°F in the summer and 60°F in the winter. Salinities vary from 30 parts per thousand during the late summer and early fall to 22 parts per thousand during the winter and spring.

The sand mass associated with the development of Galveston Island includes a number of genetic units, such as dune, tidal channel and delta, wash-over fan, and lagoonal, which are considered to be of secondary importance. It is thought that the bulk of sand has formed by the processes of shoreface and spit accretion. The gulfward growth of the island indicates a lateral shift of those depositional processes and, consequently, development of a multilateral sand deposit in the strictest sense.

Geometry

Geographic location and trend.—The body of sand at Galveston parallels the southeast Texas shoreline. The island trends approximately N. 55° E. (fig. 15-1). At Bolivar Roads the midline of Galveston Island is offset gulfward 2.5 miles from the midline of Bolivar Peninsula. Also, Galveston Island lies in a slight *en-echelon* pattern, which is related to the westward longshore drift.

Vertical position.—The upper surface of sand on beach ridges lies 12 feet or less above sea level. Offshore the top of the sand extends below sea level to a depth of approximately 30 feet (fig. 15-1). The base of the main sand mass is 6 feet below sea level along the bayshore. Offshore the base of the sand is coincident with the top at a depth of 30 feet. The slope of the beach averages less than 3°. Seaward from the beach the shoreface, or Gulf bottom, slopes approximately 13 feet per mile out to the 30-foot contour. Between the 30- and 52-foot contours the slope is about 4 feet per mile.

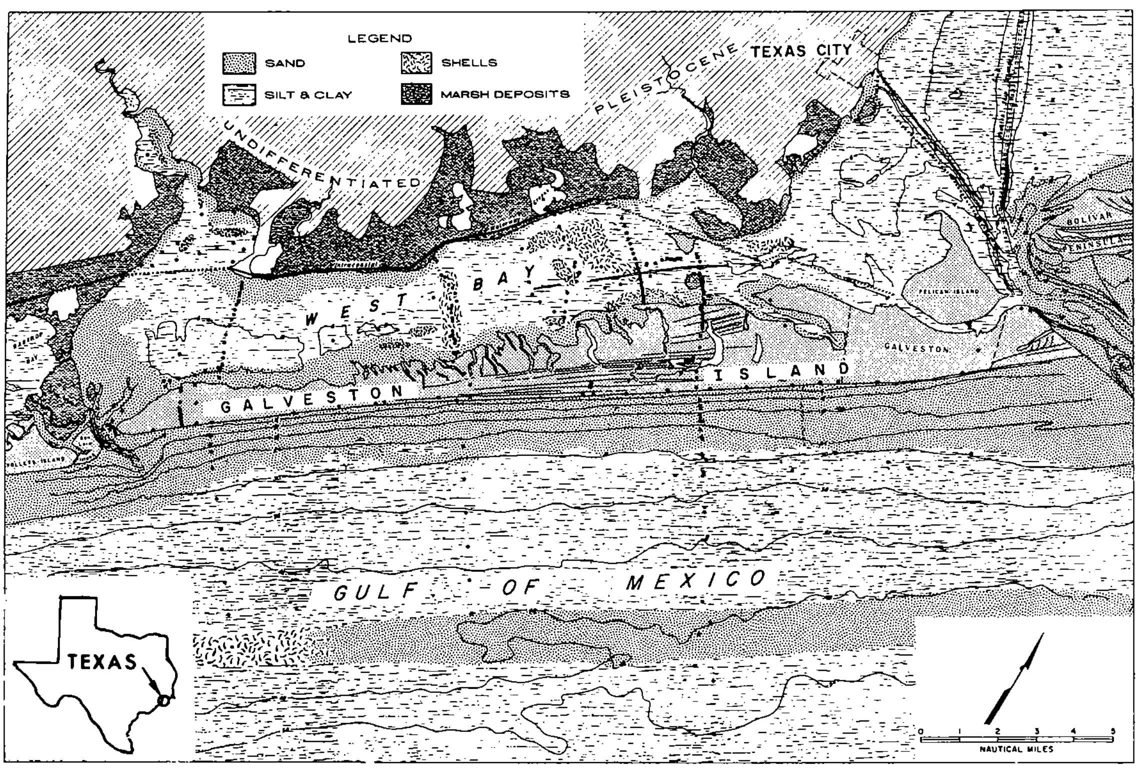

Figure 15-1. Facies map showing sand-barrier features of Galveston Island and Bolivar Peninsula and distribution of bottom and surface sediments. Linear sand feature offshore from Galveston sand body is thought to represent a barrier formed during rising-sea-level substage. *Modified from* Bernard and others (1962, fig. 8a).

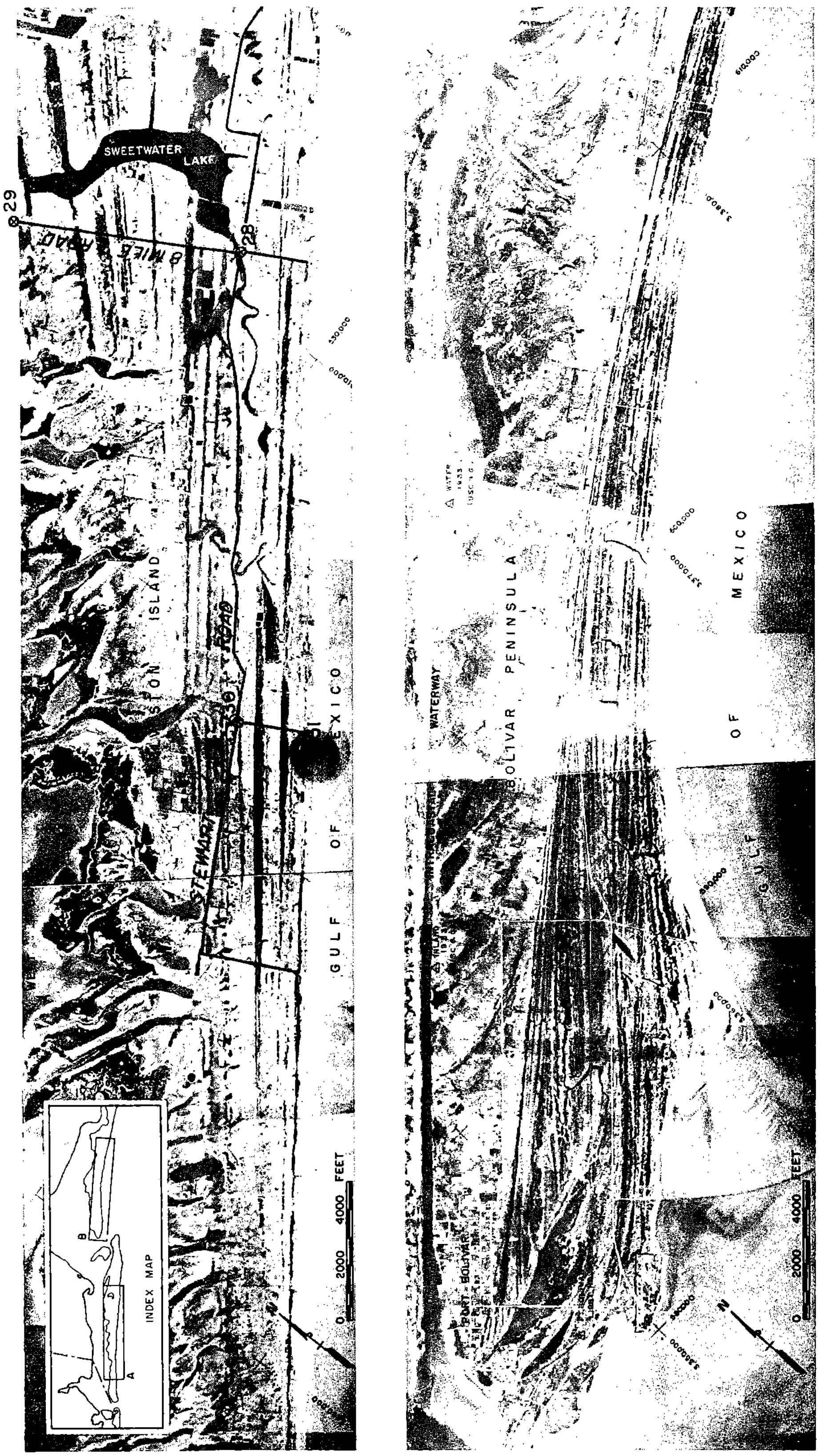

Figure 15-2. Aerial photograph (taken in 1954) showing beach ridges and swales, spits, and abandoned tidal channels on Galveston and Bolivar barriers. These features indicate seaward and longshore growth of barriers. Route and stops of 1962 field trips shown. *From* Bernard and others (1962, fig. 7).

Length.—At sea level Galveston Island is 25 miles long (fig. 15-3). Sand, however, extends unbroken for a distance of more than 50 miles, from Bolivar Peninsula to the Brazos River delta area to the southwest.

Width.—Galveston Island averages some 2 miles in width, but the sand mass is between 2.5 and 4 miles wide between the two tidal passes at the ends of the island (fig. 15-1). Both the belt of sand and island taper southwestward, in the direction of dominant longshore drift. Sand extends offshore for 1.5 to 2.5 miles. It extends into the bay for less than 1 mile and is commonly present as a narrow fringe. In the vicinity of tidal passes at the ends of the island, bulges of sand are present. The sand belt is more than 5 miles wide at the southwestern end and some 8 miles wide at the northeastern end (fig. 15-1). The bulges, which form across trend at high angles to the overall sand trend, are due to the tidal currents operating in the tidal-pass areas.

Thickness.—The sand body varies in thickness from 0 to approximately 50 feet. The maximum thickness is present along the gulfward edge of the eastern part of the island. A thickness of 30 feet or more characterizes most of the eastern two-thirds of the island (fig. 15-3). It is possible that eolian deposition there may have increased the thickness. It is known that sand is not present offshore below the 30-foot contour, and it is not developed below the 6-foot contour in the bay.

Boundaries.—The lower contact is gradational, for either interbedded sand or silt and clay lie below the sand mass (fig. 15-3). Lateral contacts are also gradational. Present in the bay are sand and clay; interbedded sand and clay are present gulfward of the main sand body (fig. 15-4). The lateral accretion of the island has resulted in similar facies changes both vertically and gulfward.

Internal Features

Sedimentary structures.—Lamination and extremely low-angle cross stratification are the most common features of sand deposited on the beach and upper shoreface (low tide to 5-foot contour) (figs. 15-4, 15-5). The angle of inclination reflects the depositional slope, which averages as much as 3° on the beach. Small-scale cross lamination and associated ripple marks are present in swales between the breaker bars of the middle and upper shoreface.

Deposits of the middle shoreface (5 to 30 feet

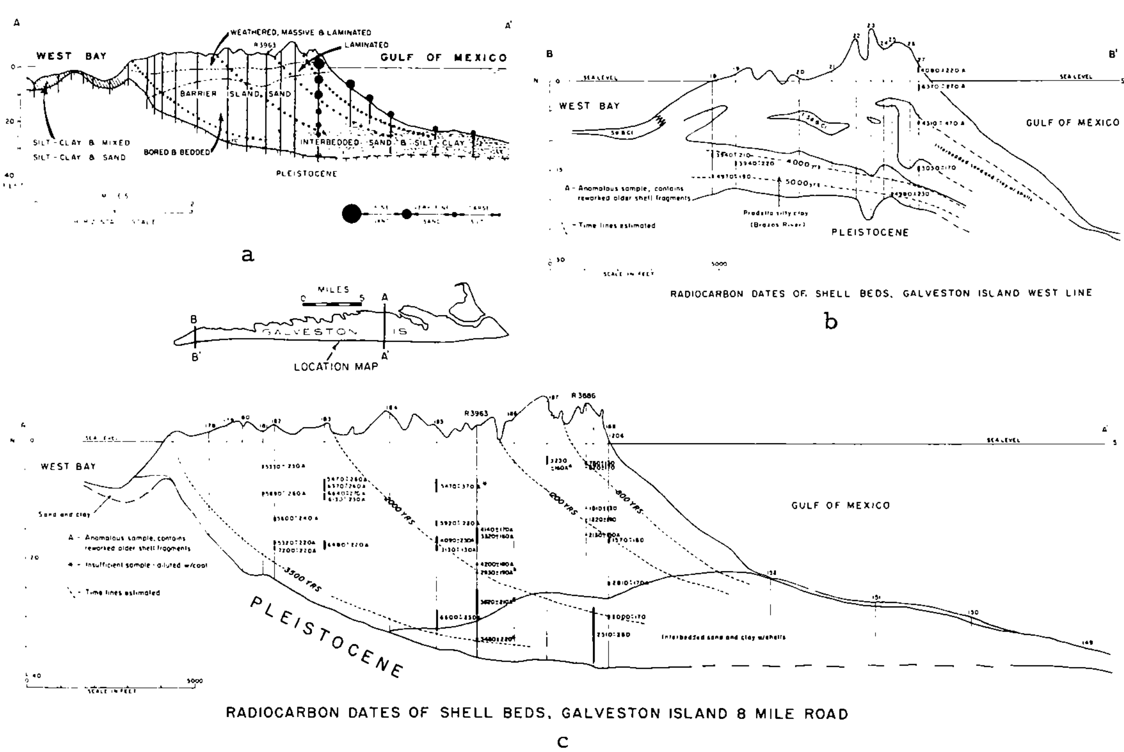

Figure 15-3. Cross sections of Galveston Island showing geometry of sand body, offlap sequence for structures and texture, and seaward accretion. *From* Bernard and others (1962, fig. 12a,b,c).

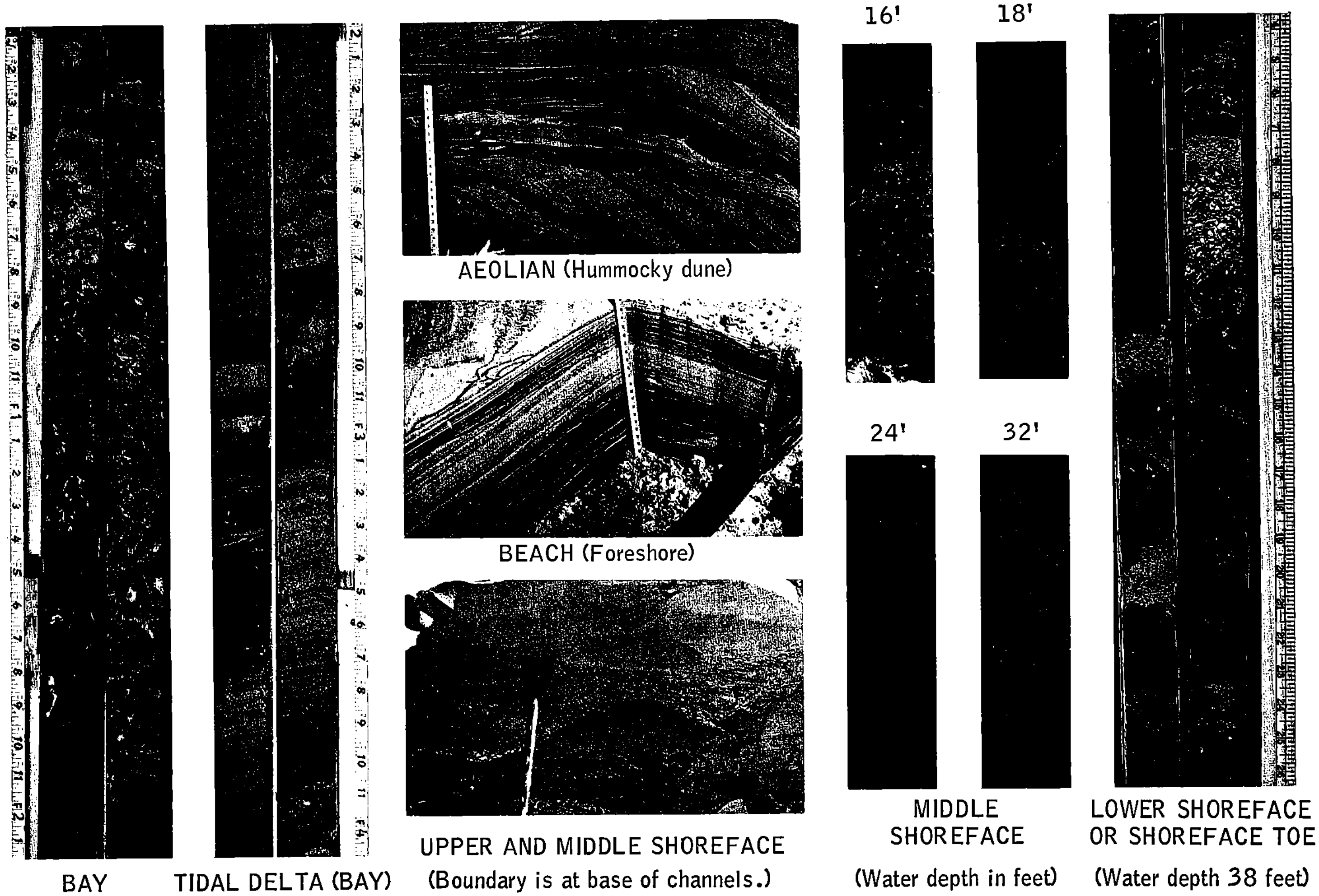

Figure 15-4. Sedimentary structures typical of sediments of Galveston Island and environs. Bay sediments are mixed and burrowed. Those of tidal delta show interstratification, cross stratification, and burrows; eolian with crossbedding; beach and upper shoreface with horizontal stratification; middle shoreface with burrows, mixed structure, and horizontal stratification; and shoreface toe with interbedding, burrows, and mixed structure. *From* Bernard and others (1962, fig. 10). Photographs by H. A. Bernard.

below sea level) contain laminations, burrows, mixed structure, some interstratification, and sporadic medium-scale crossbedding in shelly sand (figs. 15-4, 15-5). The interstratified zone comprises, in descending order, silty and peaty clay, sand, and coarse shells.

The shoreface toe (seaward from the break in slope at 30 feet to the 40-foot contour) is characterized by the interbedding of silt, sand, and clay; burrows; and mixed structure (figs. 15-4, 15-5).

Bay deposits are burrowed, massive, or show a mixed structure (fig. 15-4). Horizontal bedding and interstratification are common in deposits of tidal deltas (fig. 15-4) or the bay near tidal channels. Crossbedding is present in tidal-delta and channel sands (fig. 15-4). Abandoned tidal-channel sands are commonly burrowed or mixed. Eolian sands show medium- and large-scale crossbedding, horizontal and contorted bedding, and burrows (fig. 15-4). Weathering has destroyed or obscured most of the structures of older eolian and upper beach deposits. Pseudolaminae are common near the base of the zone of vadose water.

Texture.—The grain size increases in upward and landward directions (fig. 15-3). The average grain size of shoreface toe deposits on which the sand barrier was built is silt. The lower part of the sand body, corresponding to middle shoreface, is very fine grained. The upper shoreface, beach, and eolian sands are fine grained.

The average median diameter is 0.134 mm for 4 samples of beach sand at Galveston, and the sorting coefficient is 1.15 (very well sorted). By comparison, beach sand at Bolivar Peninsula, on the average, is a little coarser (0.145 mm) and is equally very well sorted (1.14).

Beach sands show a preferred grain orientation perpendicular to the trend of the island. Apparently the swash on the upper shoreface forms depositing currents approximately normal to the beach trend. On the middle shoreface and part of the upper shoreface, sand grains are oriented by longshore currents and, consequently, are parallel to the island (Nanz, 1960, col. 6). Because of gulfward accretion by the barrier, the lower part of the sand mass contains grains oriented parallel to the island trend, and the upper layer of beach sand shows orientation normal to the island.

Constituents.—The sand at Galveston is a subarkose, with about 90 percent quartz, quartzite, and chert and 8 percent feldspar (Hsu, 1960, p. 389). The alkali types form approximately 75 percent of the feldspar. The heavy-mineral suite is intermediate in maturity, compared with the mature sands of the eastern Gulf Coast and the immature sands of the Mississippi and Rio Grande provinces. The ratio of garnet to staurolite plus kyanite is 1 to 2 for the island sands, which are also intermediate between the garnet-poor sands of the eastern Gulf Coast area and the garnet-rich sands of the Mississippi delta province.

Shells and foraminifers are common in the Galveston sand body below the water table and in recently deposited sand near the shore. Arenaceous foraminifers characterize marsh or near-marsh sediments behind the barrier. Calcareous *Rotalia* and *Elphidium* are the most common foraminiferal forms in open bays or lagoons. They, along with a few open Gulf species, characterize sediments of the shoreface. Oysters and other pelecypods are the more common larger invertebrates in bay sediments. A gastropod genus is commonly found in marshes. The shoreface and tidal-channel macrofauna includes a variety of pelecypods and gastropods, crabs, and a coral genus.

Geologic History

Galveston Island is the subaerial part of a barrier-sand feature which began to form during the initial part of the present standing-sea-level substage. The island began as a small bar about 4 miles offshore in 6 feet of water where a change exists in the seaward slope of the Pleistocene-Holocene surface. The island emerged and grew seaward by beach and shoreface accretion and southwestward in the direction of longshore drift by spit, tidal-channel, and tidal-delta accretion (fig. 15-6). Bayward growth of the island is of secondary importance.

It is estimated that 20 percent of the sand is derived from the Mississippi River, 35 percent by offshore erosion of Pleistocene Mississippi delta deposits to the east, and 45 percent from small coastal streams entering the Gulf of Mexico east of Galveston (Hsu, 1960, p. 400).

Preservation of a barrier feature during burial depends in large measure on the extent of erosion accompanying a subsequent transgression. It is thought that the bulk of eolian deposits and the upper part of a beach sand tend to be eroded from a feature characterized by lateral accretion, leaving the preserved sand-bearing section composed largely of shoreface sediments.

Acknowledgments

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Figure 15-5. Sedimentary structures in Galveston Island section: 0-6 feet, eolian and beach sand with pseudolaminae near base; 6-12 feet, beach and upper shoreface with laminae; 12-30 feet, middle shoreface with laminae, burrows, and mixed structures; 30-36 feet, shoreface toe with interbedding and burrows; Pleistocene-Holocene unconformity at 36 feet 9 inches. *From* Bernard and others (1962, fig. 11). Photographs by H. A. Bernard.

Figure 15-6. Block diagram of Galveston Island showing depositional framework and sequence. *From* Bernard and others (1962, fig. 12d).

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New Orleans Barrier Sand, Holocene, Louisiana Gulf Coast (16)

Holocene Geologic Framework

New Orleans lies in that part of the Mississippi deltaic plain formed during advance of the Metairie subdelta (distributary) of La Loutre (St. Bernard) phase (fig. 16-1). The deltaic plain is presently in an advanced state of deterioration. Radiocarbon dates indicate that the barrier-sand body was formed contemporaneously with the older Maringouin and Teche phases of the Mississippi River and that the sand is covered by Metairie deltaic sediments. *Rangia* shells found in abundance at or near the surface represent the middens of the Tchefuncta Indians, who lived in

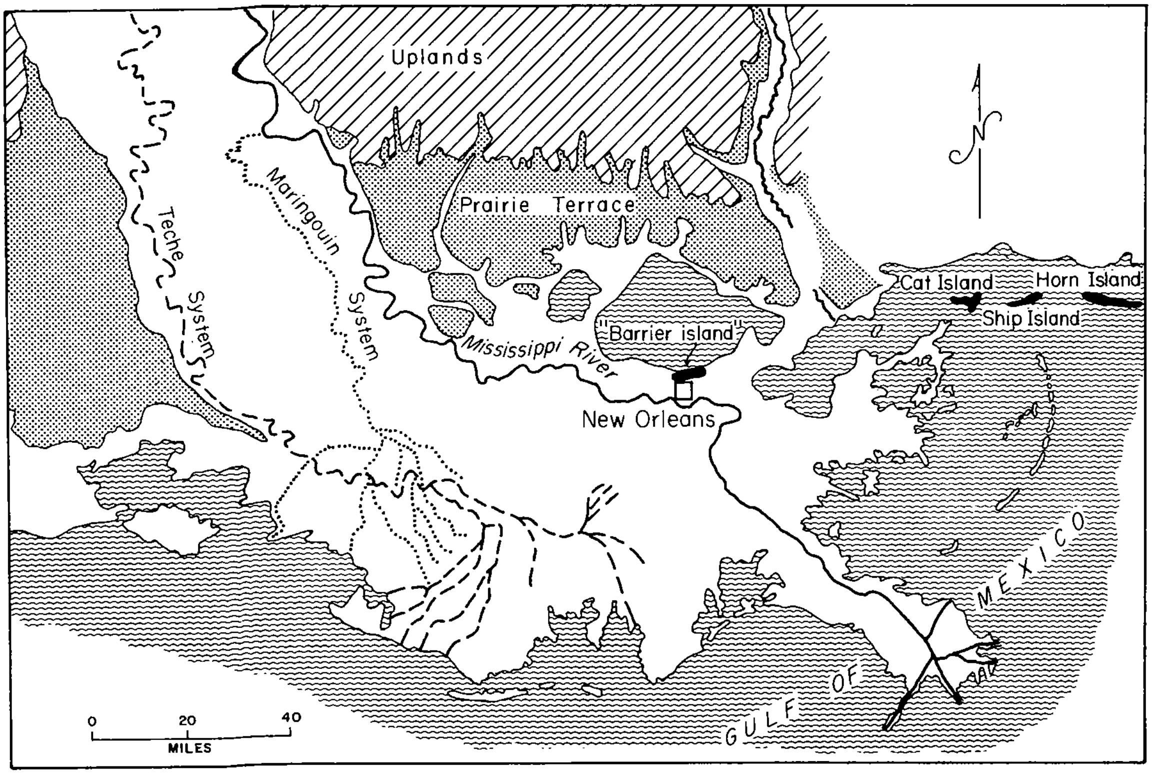

Figure 16-1. Index map of south Louisiana showing location of "New Orleans barrier island" with respect to deltaic systems that developed contemporaneously and to present-day barrier islands east of delta. *Modified from* McFarlan (1961, fig. 6).

the area after the eastward shift of the Mississippi River and the advance of the Metairie subdelta had brought a supply of fresh water. The New Orleans area has subsided during the past 4,500 years at about 0.4 foot per century; the present rate is estimated to be 0.7 foot per century. Subsidence has afforded the sedimentologist and stratigrapher an opportunity to study those features most likely to be preserved during burial.

Construction of streets, drainage, and water lines, along with borings and core holes, permitted a three-dimensional study of a sand mass which is partially buried. The sand body was designated "New Orleans barrier island" by Corbeille (1962) because it is composed of white sand similar to that of Gulf beaches along Florida and is parallel to them (fig. 16-1).

Geometry

Geographic location and trend.—The barrier sand is known from the metropolitan New Orleans area on the south side of Lake Pontchartrain. The unit is relatively straight along its trend, which is oriented approximately N. 70° E. (fig. 16-2).

Vertical position.—Along the midline of the sand body the top surface is 4 feet or less below ground level. It slopes gently both north and south from the crest. At the northern edge of development, sand is found at a depth of about 40 feet. At the southern edge, top and bottom surfaces coincide at a depth of 30 feet.

Length.—The barrier sand mass is known for a distance of more than 10 miles along its trend. Neither the eastern nor the western end of sand development is known.

Width.—The north-south extent of the sand mass is approximately 3 miles. At the eastern edge of the study area, sand is developed for a distance of 1½ miles south of the line of maximum development. On the west the point of thickest development is 2 miles from the northern edge of sand.

Thickness.—The sand reaches a maximum thickness of 35 feet along the midline of the sand body. It thins to a featheredge both to the north and the south.

Boundaries.—The lower contact, which is horizontal, is gradational with the underlying sequence

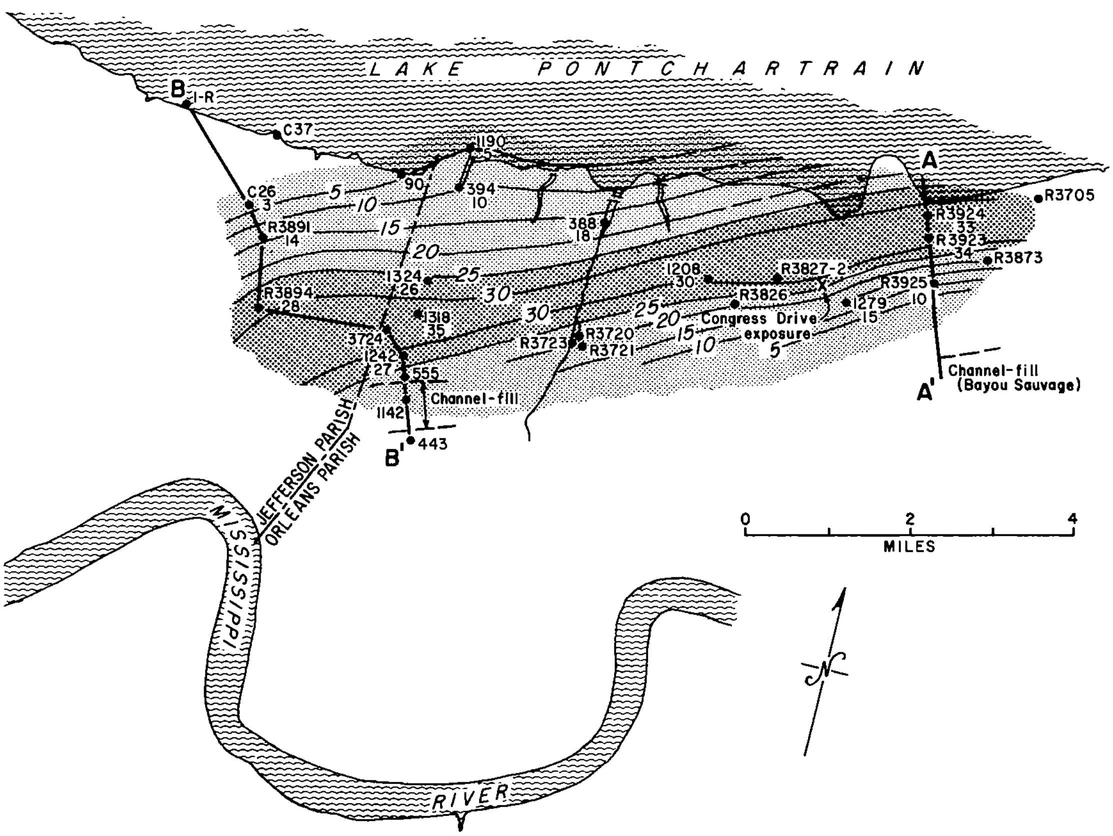

Figure 16-2. Sand-thickness map, in feet, "New Orleans barrier island." *After* Corbeille (1962, fig. 2).

of interbedded sand and clay (figs. 16-3, 16-4). The interbedded sequence grades downward into clay. Because the laterally equivalent section is composed of interbedded sand and clay below clay beds, lateral contacts also are gradational. The upper contact of the sand is gradational north and south of the area of maximum development where the interbedded section also overlies the sand. Beds overlying the thickest sand sections are clay, and their contact is abrupt.

Internal Features

Sedimentary structures.—The sand is characterized in its upper part by low-dip cross stratification and horizontal bedding. Where the sand is thick, roots obscure some bedding features down to a depth of 4 to 8 feet. Burrows are common in the lower part of the sand, which overlies an interstratified sequence.

Texture.—Grain size increases upward through the sand body. Median grain size is 0.180 mm in the upper third of the sand and averages 0.163 mm overall (fig. 16-3). The sorting coefficient ranges from 1.11 to 1.35 (very well and well sorted, respectively). Clay and silt content varies from 0.5 to 2.8 percent except in the uppermost 2 feet, which has undergone soil development and which contains 5.6 to 10 percent interstitial material.

Constituents.—The sand is a quartzarenite, with 3 to 5 percent feldspar. By comparison, the Mississippi River sands contain 20 percent feldspar and the eastern Gulf Coast sands contain 3 percent or less. The ratio of garnet to staurolite plus kyanite is less than 0.1, a typical value for the eastern Gulf Coast province. The value of the ratio for Mississippi River sands is more than 4.0. Other heavy minerals in the New Orleans barrier-sand body include hornblende, tourmaline, and pyroxene.

Within the sand body shell fragments are common. The fauna includes pelecypods and gastropods which have been dated as 3,900 to 4,600 years in age. *Rangia* shells at or near the surface represent an age of 2,160 to 2,380 years. Organic matter, especially roots, is common in surficial beds.

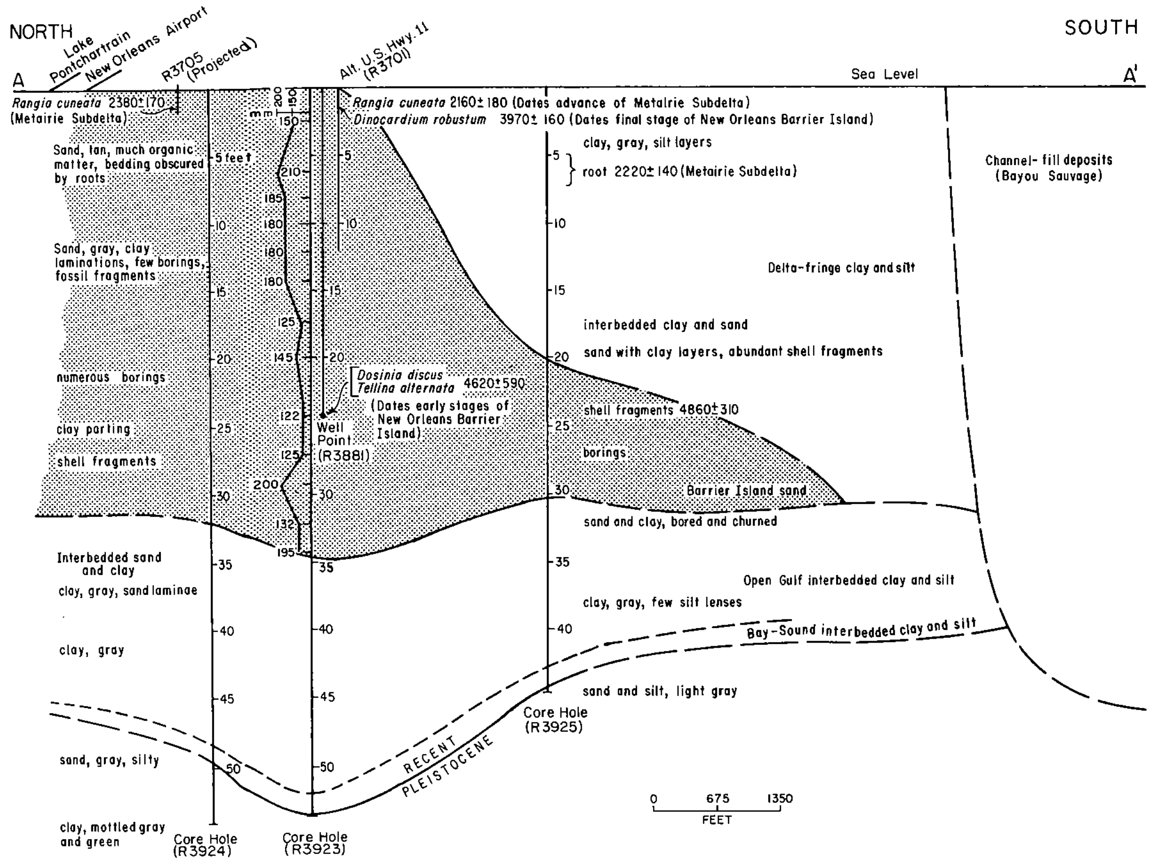

Figure 16-3. Stratigraphic cross section *A-A'*, showing relationship of barrier-island sand to older interdeltaic sediments and younger deltaic sediments which buried the island. Location shown in figure 16-2. *Modified from* Corbeille (1962, fig. 3).

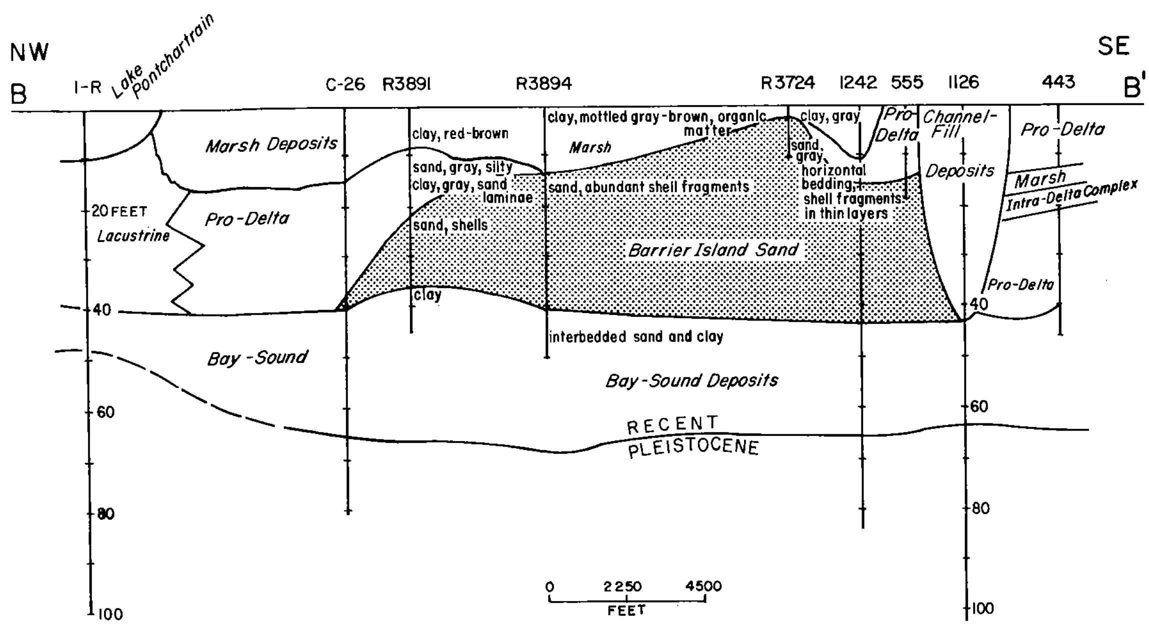

Figure 16-4. Stratigraphic cross section *B-B'*, illustrating buildup of barrier sand and its entombment by deltaic sediments. Location shown in figure 16-2. *After* Corbeille (1962, fig. 4).

Depositional Environment

The New Orleans barrier sand represents a barrier-bar feature which developed east of the Maringouin and Teche deltas of the Mississippi River. Upon emergence it became the westernmost barrier of the eastern Gulf Coast province, which today is represented by Cat Island, Ship Island, and Horn Island (fig. 16-1). Grain size of the New Orleans sand is consistent with the progressive westward decrease exhibited by the island sands to the east. Feldspar content and the garnet to staurolite plus kyanite ratio are also characteristic of eastern Gulf Coast sands. The fauna within the sand body is similar to that which characterizes the Gulf side of the barrier islands off Mississippi Sound. Horizontal stratification, a trend paralleling depositional strike, and a width-thickness ratio of approximately 500:1 are also significant features of barrier-bar sand bodies.

Acknowledgments

Figures 16-2 through 16-4 are used with the permission of the Gulf Coast Association of Geological Societies. R. L. Corbeille, Shell Oil Company, kindly furnished the compositional data for the sand. Figure 16-1 is reproduced by permission of The Geological Society of America.

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Frio Sand Complex, Oligocene, Texas Gulf Coast (17)

Structural Framework

The massive Frio sand complex in the northern part of south Texas lies on the downthrown side of the prominent Sam Fordyce-Vanderbilt fault zone (Frio-Vicksburg flexure), which is approximately parallel to the coastline (fig. 17-1). The area is limited on the south by the Rio Grande embayment and possibly on the north by a coastal extension of the San Marcos arch. The top of the Frio sand complex is characterized by a regional gulfward dip of 1°–2°. Numerous structural anomalies are associated with the normal, contemporaneous faults which so typify the Gulf Coast Tertiary section. In the updip (inland) part of the study area the regional dip of the base of the Frio varies from 2° near the Frio-Vicksburg flexure to 6° where depths are between 10,000 and 12,000 feet. The base is not mapped in the downdip part of the area. In detail, the structural configuration of the lower part of the Frio is much more complex than the upper and is affected by numerous contemporaneous faults.

Stratigraphic Framework

Originally the term "Frio" was used as a formational name for a surface section and later as a formational name for a subsurface section. In the study area in south Texas the Frio is a sand-bearing biostratigraphic unit, the age of which is considered Oligocene by some workers and Miocene by others (Holcomb, 1964, p. 24). Also, the stratigraphic and age relationships between the subsurface and surface Frio have not been resolved. Sedimentologically, Frio deposition represents the culmination of the regression in a transgressive-regressive couplet. In general, the Frio of subsurface workers lies above the *Textularia warreni* zone, which defines the top of the Vicksburg, and below the lowermost Anahuac zone, characterized by *Marginulina vaginata* or *M. howei*. The faunal zones have been determined from benthonic suites. Consequently, the specific fauna of each limiting zone changes in a downdip (gulfward) direction, as depositional water depths increased in that direction. Lithologically, the Frio is characterized by sand, whereas the underlying and overlying units in the area are characterized by shale.

For general work in the study area the Frio most commonly has been subdivided into two or three units. In the threefold division of Boyd and Dyer (1964, p. 317), the Lower Frio is generally considered to be below the top of the foraminifer *Textularia seligi* or *T. mississippiensis* zone. The top of the Middle Frio is defined as the top of the *Nonion struma* or *Nodosaria blanpiedi* zone. The extent to which subdivision is possible depends on the landward extent of the diagnostic fossils or associated marker beds (fig. 17-1). Generally, the Lower Frio is recognized with difficulty because structural complexity increases with depth; most downdip wells do not penetrate it, and sand beds are less continuous than younger sand units. It is

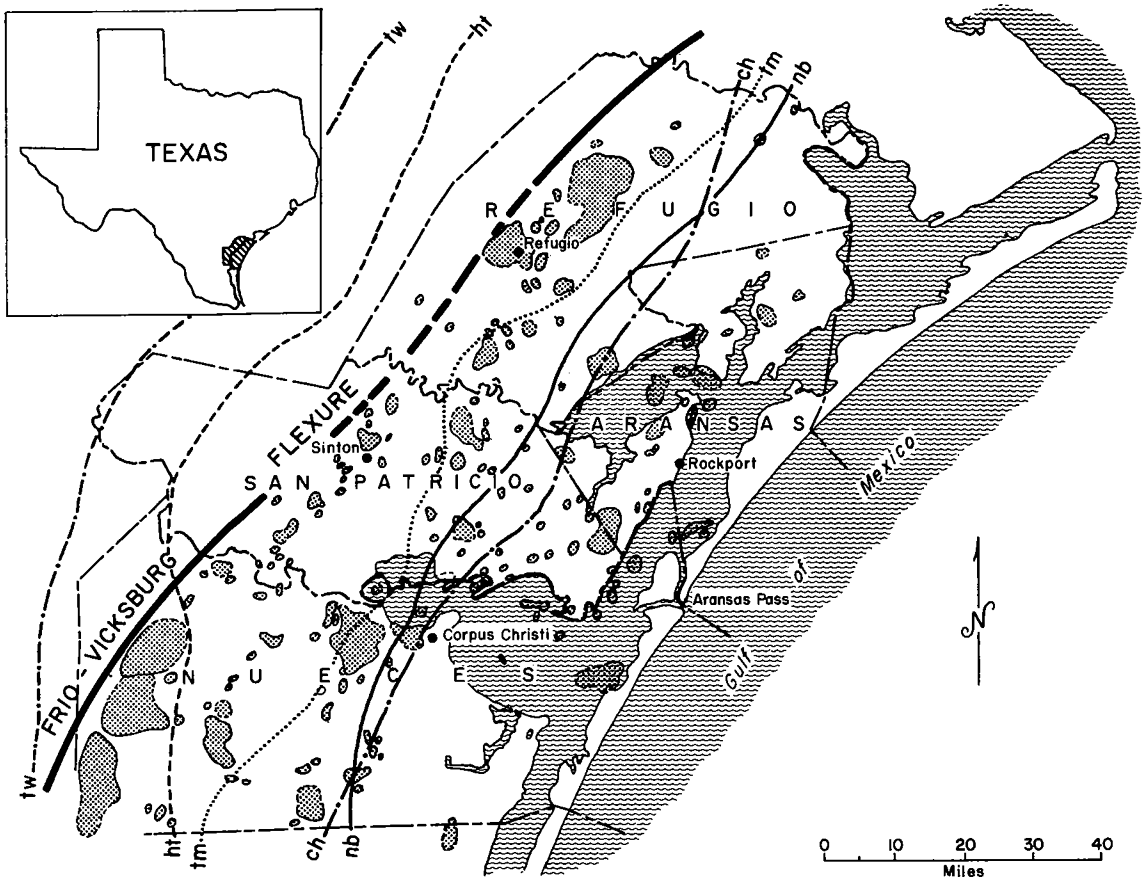

Figure 17-1. Location map of study area, showing Frio-Vicksburg flexure, Frio oil fields (stippled), and updip limits of foraminifers utilized in correlation of Miocene, Frio, and Vicksburg. Letter symbols: ht, *Heterostegina texana;* ch, *Cibicides hazardi;* nb, *Nodosaria blanpiedi;* tm, *Textularia mississippiensis;* tw, *Textularia warreni. Modified from* Boyd and Dyer (1964, fig. 1).

rather common practice for sandstone in the *Marginulina* zone to be included in gross mapping of the Frio sands.

Sand in the Frio shows less lateral variation in the subject area than to the south in the Rio Grande embayment and to the north along the upper Texas coast. Also, in the former area the associated shales are commonly mottled or purple in comparison with gray-green shale interbeds to the north. Inland (or updip) from good sand development, shales exhibit red and green colors and a brackish-water fauna. The shales immediately downdip (or gulfward) of sand are gray, green, and black and are characterized by marine-shelf foraminiferal assemblages.

Sand of the Frio in south Texas contains a myriad of genetic units. It is characterized by vertically multistoried units and, to a lesser extent, horizontal stacking (fig. 17-2).

Geometry

Geographic position and trend.—In the coastal bend of Texas, sand in the Frio is best developed inland from the coast (figs. 17-3 through 17-6). That part of south Texas with good Frio sand includes Refugio, Aransas, San Patricio, and Nueces Counties. The zone of maximum sand development is N. 30°–35° E., which is approximately parallel to the coastline (figs. 17-3 through 17-6). The zone of maximum sand is widest in the southernmost part of the area and becomes progressively narrower to the northeast. The zones of development for the three subdivisions are arranged in an offlap manner, with the Upper Frio sand (including *Marginulina* Greta sands) extending farthest downdip (fig. 17-6). The offlap arrangement is developed best in the southern part of the area. In the northeasternmost part the zones for Upper and Middle Frio sands are almost

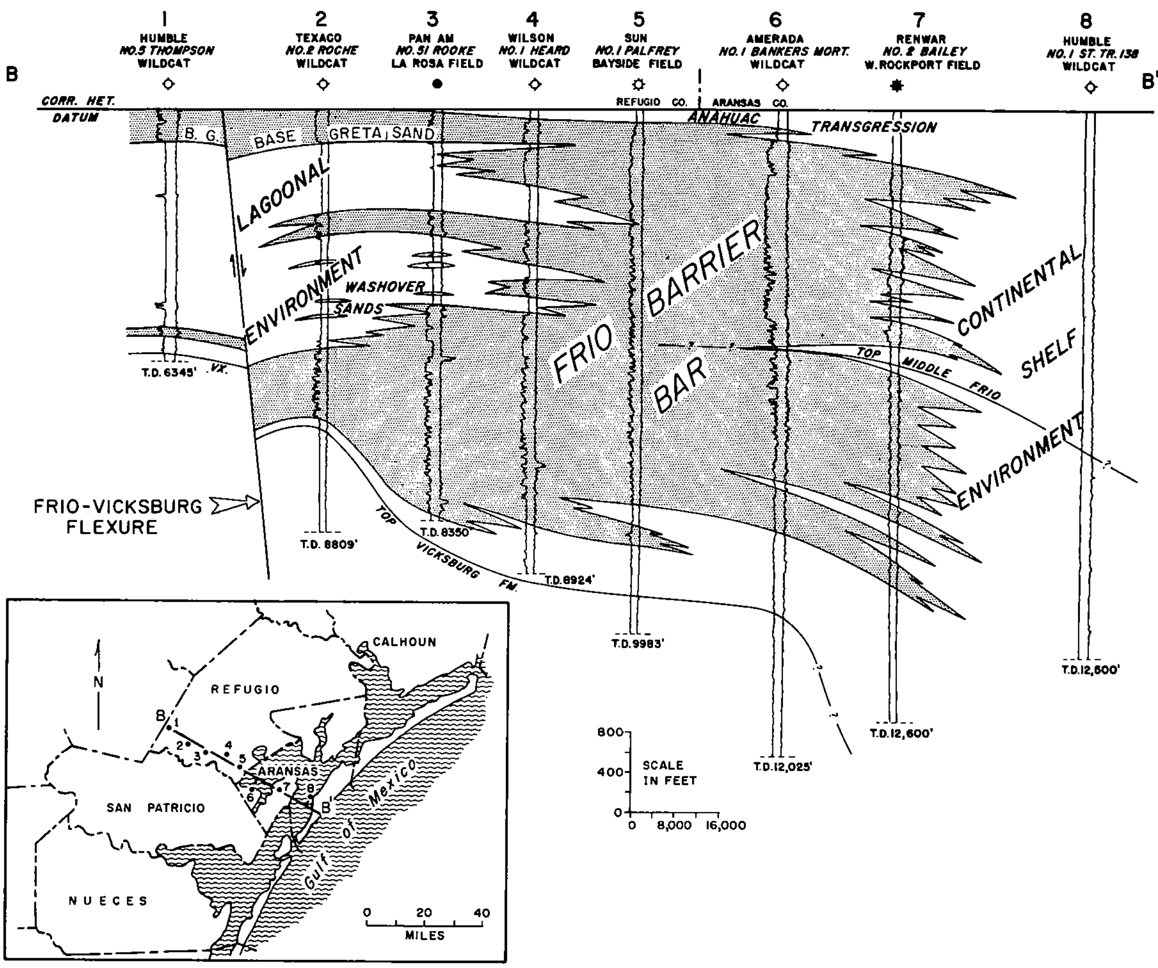

Figure 17-2. Stratigraphic section *B-B'*, showing correlations and distribution of lithologies in Frio. *Modified from* Boyd and Dyer (1964, fig. 4).

coincident geographically. The Upper Frio sand trends slightly more northerly than the coastline.

Vertical position.—The top of the Frio is approximately 4,000-5,000 feet below the surface along the northwestern edge of the study area adjoining the Frio-Vicksburg flexure. The shallowest depths are at the southwestern margin. The top of the Frio is some 8,500-9,000 feet at the coastline. Generally, the top of sand is coincident with the top of the Frio in updip positions but not in downdip positions.

The base of the Frio is 7,000 feet at the Frio-Vicksburg flexure to more than 12,000 feet some 20 miles inland from the coastline. In the downdip area a normal section of Frio has not been penetrated, and the depth to the Vicksburg is not known.

Length.—Frio sand extends in both directions beyond the area of study, which is approximately 140 miles long. However, the characteristic shape of vertically stacked sand with a width-thickness ratio of approximately 100:1 is restricted in large measure to the area of study.

Width.—The study area is some 55 miles wide in the northeast and 70 miles wide in the south. The downdip or gulfward limit of Frio sand is present within the northeastern part of the area. However, the Upper Frio sand extends beyond the eastern edge of the southern part of the area. The Lower Frio sand and Greta sand at the top of the interval studied extends beyond the area to the west and northwest. The zone of maximum development is 55 miles wide in the southern part and 25 miles wide in the northernmost part (fig. 17-6). Maximum development for the Lower Frio is farthest inland and is 20 miles wide in the northeast and 25-30 miles in the south. The Middle Frio sand is best developed along a belt which ranges in width from 15 to 25 miles, whereas the belt for upper Frio is 15 to 25 miles wide.

Thickness.—Net Frio sand varies in thickness from 0 to 3,700 feet (fig. 17-5). The gross sand section is as thick as 5,000 feet. Although the influence of contemporaneous faulting on sand thickness and local distribution is significant, it was not considered in this regional study. Northwest of the zone of maximum development, sand varies in total thickness from 200 to 500 feet. Gross sand percentage in the Frio section is 14 to 33 (fig. 17-3), whereas net sand percentage is 8 to 23 (fig. 17-4). Gross sand constitutes a maximum of 99 percent of the section; net sand is as much as 73 percent.

Boundaries.—The lower contact of the sand mass in the Frio is generally gradational. The upper contact is rather sharp. Shale "breaks" in the sand section most commonly give rise to a relatively sharp top below the break and a gradational base for the overlying sand unit. On the northwest side of the thick zone the base of the Greta sand is more abrupt than an ordinary lower contact.

Considering the overall thickness, the seaward edge of sand is abrupt in the northeastern part of the area (fig. 17-2). The inland edge of gross Frio

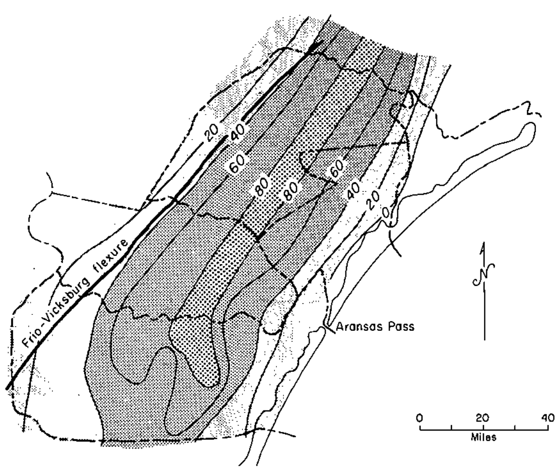

Figure 17-3. Gross-sand-percentage map of Frio, illustrating linear trend parallel to Holocene coastline. Data *from* Johnson and Mathy (1957) and Boyd (1964).

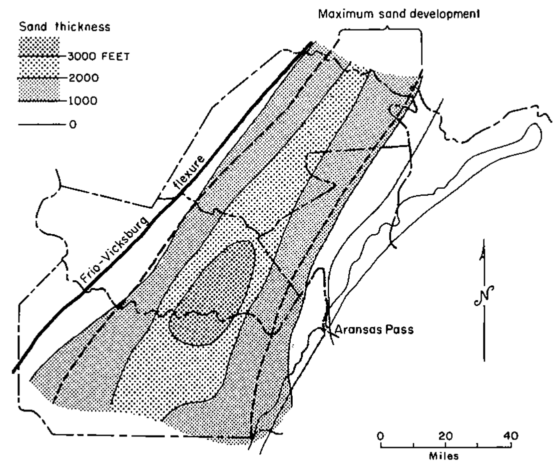

Figure 17-5. Net-sand-thickness map of Frio, showing northeast-converging linear belt paralleling Holocene coastline. Data *from* Johnson and Mathy (1957) and Boyd (1964).

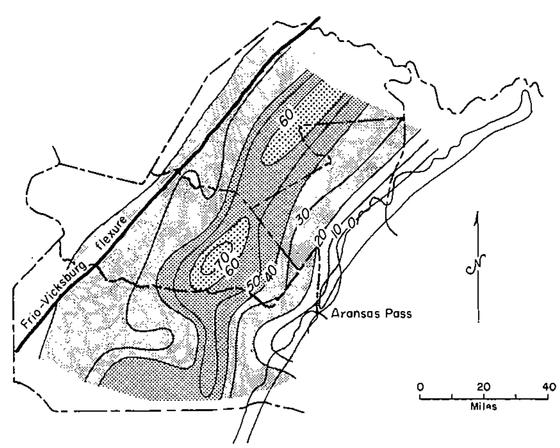

Figure 17-4. Net-sand-percentage map of Frio; linear trend is present in most of study area. Data *from* Johnson and Mathy (1957) and Boyd (1964).

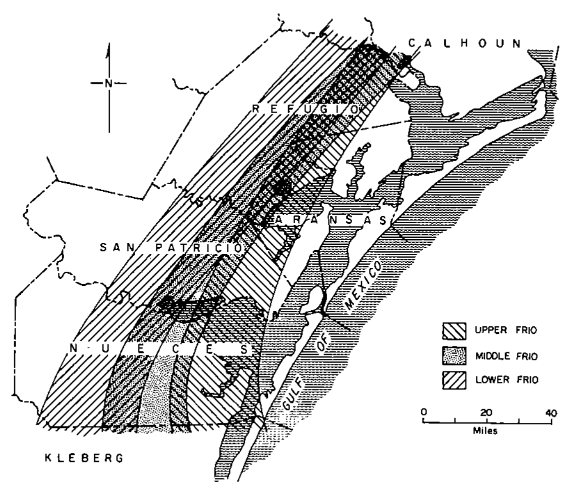

Figure 17-6. Zones of maximum sand deposition for Upper, Middle, and Lower Frio; offlapping zones converge toward northeast. *Modified from* Boyd (1964, fig. 8).

sand is not present inside the area, but a significant part of the sand section pinches out somewhat abruptly to the west and northwest (fig. 17-2). This zone of pinchout represents the inland limit of maximum sand development.

Internal Features

The Frio sands in the study area are fine to medium grained, well sorted, gray to gray green, and commonly cemented with calcite. Reservoir characteristics are most favorable in the updip part of the study area, near the Vicksburg flexure. There, average porosity is 33 percent, average permeability 1,500 millidarcys, and recoverable oil 700 barrels per acre-foot. In the downdip area porosity averages 28 percent, permeability 240 millidarcys, and recovery 450 barrels per acre-foot (Johnson and Mathy, 1957, p. 212). No other internal features were examined in the study.

Depositional Environment

The configuration of the Frio sand mass as a linear belt paralleling the coastline, along with the types of associated shales, is indicative of deposition at or near the strandline. Updip shales with mottled color and brackish-water fauna are lagoonal deposits; gray-green shales with marine fauna on the gulfward side of the sand formed offshore from sand-depositing currents.

The extreme multistoried nature of the Frio sand mass indicates that the rates of deposition and subsidence were essentially the same for a remarkably long period of time. Some regression did occur during sand deposition, as evidenced by the slight offlapping nature of zones of maximum sand. Minor marine transgressions apparently interrupted the long period of sand deposition, and their deposits permit subdivision of the Frio.

The average paleogeographic setting is thought to have been similar to that which exists presently along the coastal bend of south Texas. Barrier islands, such as Mustang, St. Joseph, and Matagorda, form a long, linear sand trend between clay deposits of the bays and those of the Gulf of Mexico. Much of the sand is apparently derived from the Brazos-Colorado River delta to the northeast. The internal features of modern barriers are probably characteristic also of the Frio barrier. The beach and shoreface sands contain more than 90 percent terrigenous sand, 65 percent of which is quartz, 23 percent plagioclase feldspar, and 12 percent potash feldspar (Shepard and Moore, 1955, p. 1505). The diagnostic heavy mineral, composing less than 1 percent of the sand fraction, is hornblende. It has been apparently introduced to the Gulf by the Colorado River and transported southwestward by longshore currents. Glauconite, shells, and plant fibers are additional constituents. By comparison, barrier-flat and inlet sediments of the islands are characterized by less terrigenous sand, more silt and clay, more plant fibers, and less glauconite. The sands are generally horizontally bedded, fine grained overlying very fine grained, and well to very well sorted.

Less continuous sands with mottled shales directly south of the study area are characteristic of the Oligocene-Miocene deltaic complex in the Rio Grande embayment. Zone 19b, Seeligson field (model 4) exemplifies alluvial-plain conditions in the updip part of the Frio complex.

Acknowledgments

Figures 17-1, 17-2, and 17-6 are used with the permission of the Gulf Coast Association of Geological Societies. The interest of D. R. Boyd in the compilation is greatly appreciated.

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Viking Sandstone, Cretaceous, Joffre Field, Alberta (18)

Structural Framework and History

The area of study, Joffre field, lies on the northeast flank of the Alberta basin. Regional dip is approximately 50 feet per mile toward the southwest. Structural anomalies are not present at the level of the Viking Sandstone, and the trap at Joffre field is stratigraphic in nature.

The oil in the Viking was discovered in 1953 during the drilling of a well designed primarily to test the oil potential of Devonian rocks. They were not productive in the Viking discovery well, but the Nisku Formation of Late Devonian age is productive in a wide belt at Joffre field but does not coincide with the area of Viking production. Cumulative Viking production from some 400 wells is approximately 35,000,000 barrels.

The Viking Sandstone also produces oil at Joarcam field 70 miles to the northeast at an average depth of 3,200 feet (fig. 18-1). This field trends northwest and is more than 30 miles in length.

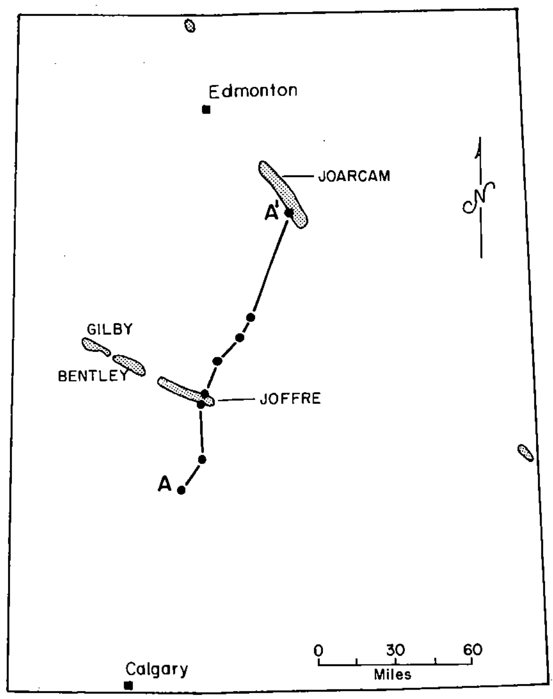

Figure 18-1. Index map of central Alberta showing location and trend of Joffre field and other fields producing from Viking Sandstone.

Stratigraphic Framework

The Viking Sandstone of Cretaceous age is a formation containing several sandstone units. Its stratigraphic position is in the lower part of a dominant shale section equivalent to the Colorado Shale of Montana. The Viking lies above the prominent Mannville section of coarse clastics and below the calcareous "Second white specks." The former is correlative with the Lower Cretaceous Kootenai of Montana; the latter, to the Greenhorn. The Newcastle Sandstone is approximately equivalent to the Viking. Underlying the Viking Sandstone is the Joli Fou Shale (Skull Creek or Thermopolis) (fig. 18-2). The overlying unnamed shale together with the "Fish Scale" sandstone corresponds to the Mowry Shale (fig. 18-2). The Viking and Joli Fou are not recognizable as distinct units in southern Alberta or in the foothills area of western Alberta.

In Joffre field the Viking, which is described by Love (1955), is about 90 feet thick and consists of 1 to 3 porous sandstone bodies. The top and base of the Viking are readily recognizable on logs and in cores. The uppermost bed is commonly a thin, black chert-pebble conglomerate. The productive sandstone is 15 to 30 feet below the top of the formation. The upper sequence consists of interbedded shale and shaly sandstone along with two thin but persistent bentonites. In any one well the productive zone may include up to three sandstone units. Therefore, the pay zone, the features of which are described herein, includes as many as three genetic units, which were not mapped separately by Love (1955).

Geometry

Geographic position and trend.—The productive Viking Sandstone is present north and east of the city of Red Deer, Alberta, 85 miles north of Calgary. The sandstone trends approximately N. 65° W., parallel to the structural strike (fig. 18-1).

Vertical position.—Within Joffre field, the Viking Sandstone is present 4,800 to 5,200 feet below the surface.

Length.—Viking production at Joffre field extends along trend for a distance of 18 miles (fig.

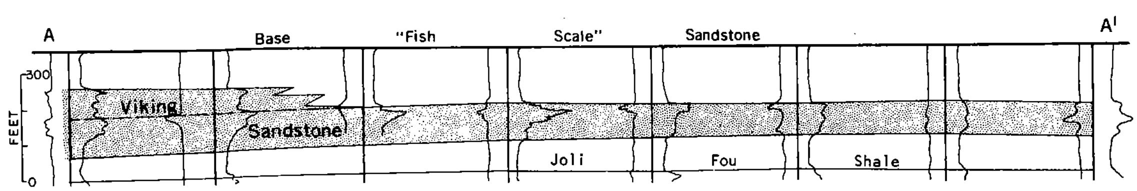

Figure 18-2. Regional correlation section (*A-A'*) of Viking Sandstone. Line of section shown in figure 18-1. *After* Love (1955, p. 22).

18-3). The Viking is productive also at Bentley and Gilby fields to the west-northwest; the known length of sandstone development in this two-field area is some 50 miles.

Width.—Joffre field is approximately 2 miles wide, and the productive Viking Sandstone is not much wider than the field. The distance from the zone or line of maximum sandstone development to the updip pinchout is less than 1 mile (fig. 18-3). In a downdip direction the distance is approximately the same from maximum development to the 5-foot thickness contour.

Thickness.—The thickness of the oil-producing sandstone is 0 to 23 feet and averages 10 feet. The sandstone shows a gradual thinning in an east-southeastward direction, parallel to the trend of the sand body.

Boundaries.—Based on the rates at which the sandstone thins, both the northeast and southeast boundaries are gradational. Deflections on electric logs suggest that neither the upper nor the lower contact is very sharp (figs. 18-4, 18-5). The logs most commonly show vertical symmetry opposite the Viking Sandstone. Examination of core samples indicates that porosity is reduced gradually toward the base of the sandstone and, consequently, that the upper contact is sharper than the lower.

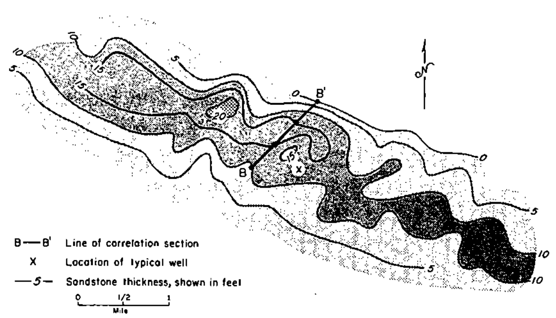

Figure 18-3. Thickness map (in feet) of oil-productive Viking Sandstone at Joffre field, which trends N. 65° W. *Modified from* Love (1955, p. 21).

Internal Features

Sedimentary structures.—Interstratification of shale in the productive sandstone is the only structure noted at Joffre field. However, the productive sandstone with similar geometric features at Joarcam field, northeast of the Joffre area, contains medium-scale crossbedding above mottled or mixed structure. South of the study area the Viking has small-scale crossbedding and ripple marks along with the mottled structure.

Texture—The oil-bearing Viking Sandstone is medium to coarse grained, with scattered, well-rounded chert pebbles up to 15 mm in diameter. The pebbles are abundant in 3- to 6-inch beds in the sandstone. The downward decrease in porosity reflects a similar decrease in average grain size.

The porosity of the sandstone averages 13 percent, and the average horizontal permeability is 190 millidarcys.

Constituents.—The Viking Sandstone is a "salt-and-pepper" sublitharenite, with a large percentage of dark-gray and black chert. The percentage of chert increases with the grain size; all pebbles and coarse-grained sand are of chert. Quartz grains are fine or medium and show secondary enlargement. Siliceous cement is common, and sporadic calcite-cemented zones are present within the sandstone.

Glauconite, which is common throughout the sandstone, is most abundant in the lower part and gives the rock a greenish tinge. Also present in the basal portion are concretionary siderite, pyrite, biotite, and chlorite. At Joarcam field, spore cases and fish scales are present at the top and near the base of the Viking Sandstone.

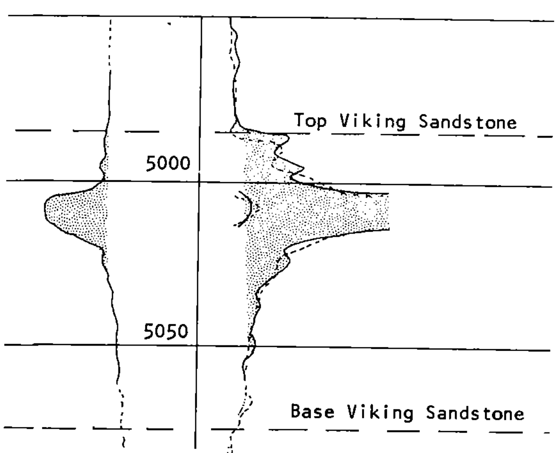

Figure 18-4. Typical electric log of section with Viking Sandstone showing apparent gradational lower and upper contacts. *After* Love (1955, p. 21).

Depositional Environment

The Viking Sandstone in the Joffre field area was deposited as a barrier-bar feature. Gradational lateral and basal boundaries, a width-thickness ratio of 500:1, mixed bedding, and glauconite are evidence of dominant bar deposition. The bar formed on the southwestern side of the shallow,

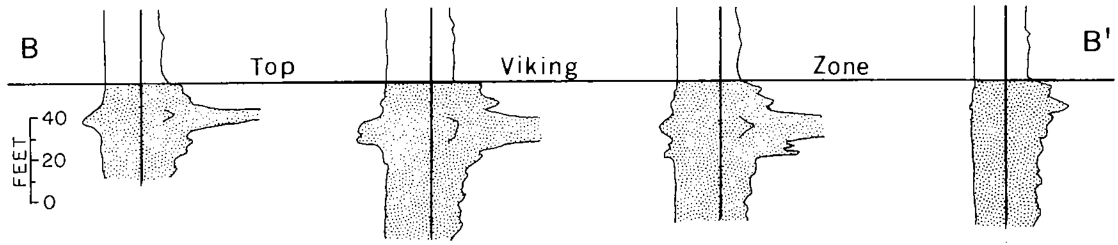

Figure 18-5. Correlation section (*B-B'*) of Viking Sandstone at Joffre field, where lateral contacts are gradational. Line of section shown in figure 18-3. *After* Love (1955, p. 26).

brackish-water sea which invaded the Western Interior of the continent from the Arctic. The distance from the offshore bar to the mainland on the southwest is not known. Sandstones at Joffre and Joarcam fields represent two lines of barrier-bar features, 70 miles apart. Although the sandstones are stratigraphic equivalents, they probably were deposited at different times. Under regressive conditions the Joffre bar would have formed before the Joarcam feature as the sea retreated to the northeast. A major source area for the Viking Sandstone lay to the southwest, and the paleoslope was to the northeast. Post-Viking subsidence of the Alberta basin resulted in southwesterly dip, opposite to that of the paleoslope.

Acknowledgments

Figures 18-2 through 18-5 are from Love (1955) and are used by permission of *Oil in Canada* and its successor publication, *Oilweek*.

Reference

Love, A. M., 1955, Geology and development, Joffre oil field, Alberta: Oil in Canada, v. 7, no. 38 (July 18), p. 20-24, 26.

Marine Environments

SHELF (SHALLOW) ENVIRONMENTS

Franconia Formation, Cambrian, Western Great Lakes (19)

Structural Framework

The area of study is part of the central stable region. It lies more or less along the boundary between the Canadian shield and the interior lowlands (fig. 19-1). In the Wisconsin-Minnesota area the beds dip south-southwestward away from the Wisconsin arch at a rate of approximately 10 feet per mile. In northern Michigan the Franconia is the outermost cuesta of the northern Michigan basin, and dip is predominantly to the south and east at an average rate of 20 to 40 feet per mile.

Local structures are present, such as the Baraboo, Fond du Lac, and Waterloo ranges. Although evidence is not overwhelming, it is thought that the area of central Wisconsin was uplifted several times in the Paleozoic.

Stratigraphic Framework

The oldest marine Paleozoic rocks of the northern Midcontinent are Late Cambrian and are referred to the St. Croixan Series. In the area of study the Dresbach Formation is the oldest Cambrian unit with marine fossils. The Franconia overlies the Dresbach and is overlain by the St. Lawrence Formation also of Cambrian age (fig. 19-2). In northern Michigan the Franconia equivalent is the Miners Castle Member of the Munising Formation (fig. 19-2). The Chapel Rock Member of the Munising is equivalent to the Dresbach. The Miners Castle Member is overlain unconformably by the Au Train Formation, a sandy dolomite of Middle Ordovician age.

The Franconia Formation is typically a greensand-bearing sequence, which is characterized regionally by a facies change and a moderate degree of heterogeneity of rock type. The most striking changes in rock type occur at the base and top.

Five lithic units have been recognized in the Franconia in the Wisconsin-Minnesota area by Berg (1954, p. 861) and Hamblin (1961, p. 11) (fig. 19-2). They are, in ascending order, the Woodhill Member, crossbedded, medium- to coarse-grained sandstone; the Birkmose Member, glauconitic, fine-grained sandstone; the Tomah Member, very

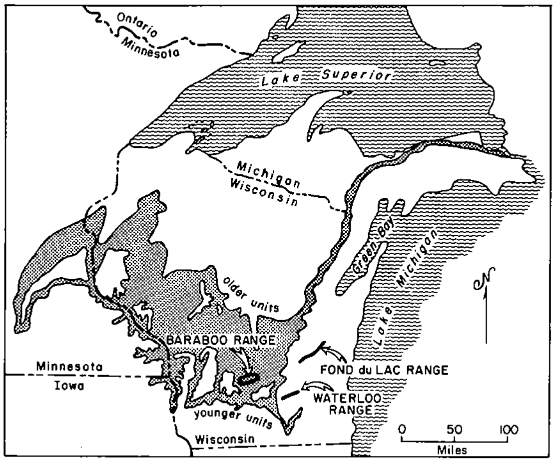

Figure 19-1. Index map of western Great Lakes region showing areal distribution of St. Croixan Series. *Modified from* Hamblin (1961, fig. 1).

fine-grained sandstone with interbedded shale; the Reno Member, glauconitic, fine-grained sandstone; and the Mazomanie Member, thin-bedded or crossbedded sandstone, which is equivalent primarily to the Reno. The Mazomanie is equivalent also to the Miners Castle Member of the Munising Formation in northern Michigan (Hamblin, 1958, p. 95) (fig. 19-2).

The Franconia Formation, as noted by Berg (1954) and Hamblin (1961), and as described herein, is dominantly a sandstone sequence which contains many genetic units, both vertically and laterally.

Geometry

Geographic location and trend.—The Franconia Formation has been studied in an arcuate area which includes a rather wide outcrop belt in southern Wisconsin and Minnesota and a narrower belt in northeastern Wisconsin and northern Michigan (fig. 19-1). One part of the area is on the flanks of the Wisconsin arch, and the other is on the edge of the Michigan basin. The formation is limited on the north and west by erosion, and it extends beyond the area to the south and east.

Trends of overall sandstone development subparallel the outline of the area of study. The trend is northwest or west-northwest in the south, southwest in the Green Bay area of Wisconsin, and west-southwest along Lake Superior (fig. 19-3). It is quite possible that these orientations are part of a general southwest trend, which is now obscured because the Franconia is not preserved in a broad, straight band.

Vertical position.—The Franconia in the study area is essentially at the surface. It becomes a part of the subsurface to the south and east, and its erosional edge is to the north and west. Some subsurface data were available for use in preparing the thickness map.

Length.—Because the study is necessarily subject to limitations inherent in analysis of outcropping beds, each apparent trend extends or originally extended an unknown distance beyond the values given herein. The west-northwest trend is exposed for some 250 miles, the southwest trend for 200 miles, and the west-southwest trend

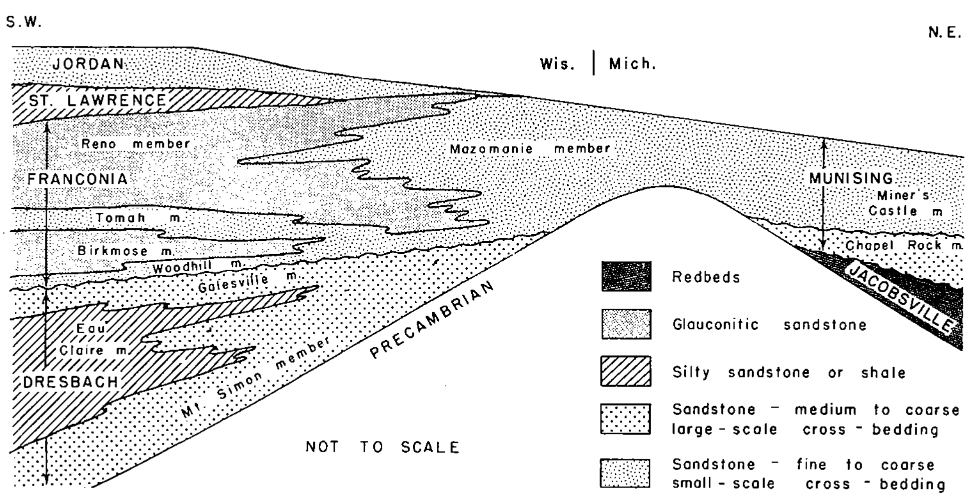

Figure 19-2. Diagrammatic correlation section of Upper Cambrian deposits showing subdivision and various facies of Franconia Formation. *From* Hamblin (1961, fig. 4).

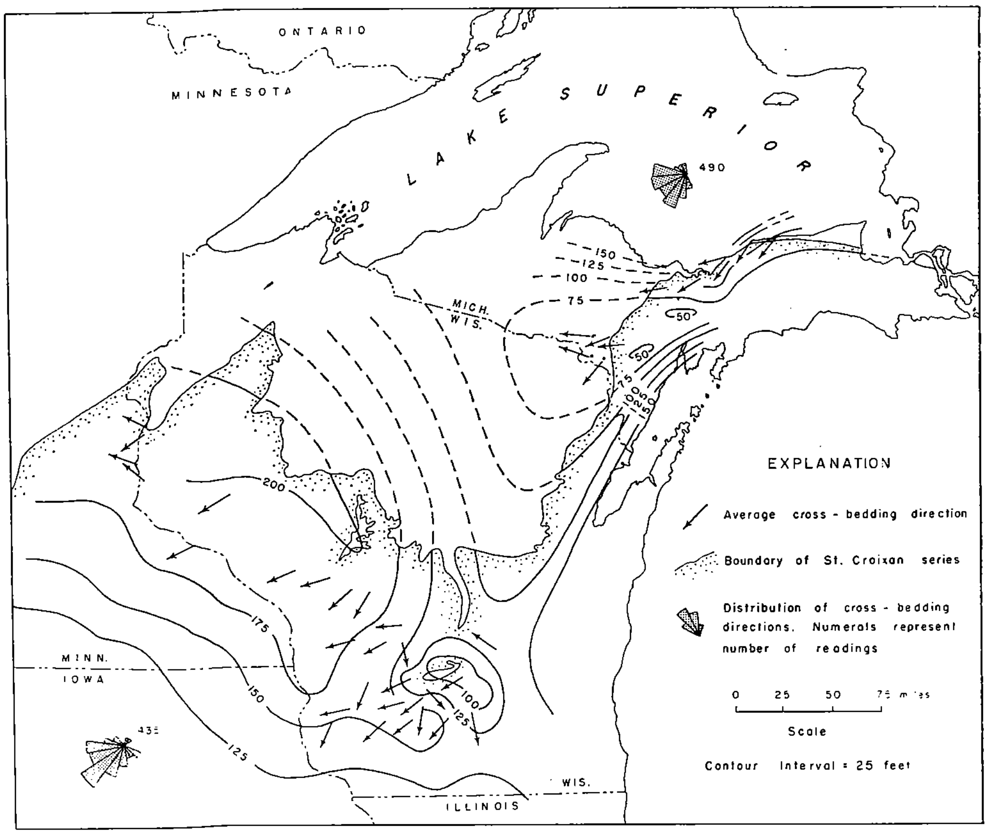

Figure 19-3. Thickness map showing paleocurrents of Franconia Formation. Paleocurrents show an overall southwesterly direction. *From* Hamblin (1961, fig. 7); southern part of thickness map *from* Berg and others (1956, fig. 3).

on the north for 120 miles (fig. 19-3). Based on outcrop data, the length is at least 380 miles for the postulated overall southwest trend.

Width.—The west-northwest trend is known to be at least 140 miles wide (fig. 19-3). The other trends of thick sandstone are at least 25 miles wide and are separated by a belt where the formation is thin.

Thickness.—The Franconia Formation is known to vary in thickness from less than 50 to more than 200 feet (fig. 19-3). The area where the formation is less than 50 feet thick is in the central part of the peninsula of northern Michigan. Another thin area is the Baraboo Range area. The area of greatest known thickness is in west-central Wisconsin. It is thought that the Franconia attained its greatest thickness outside the study area, in the Michigan and Lake Superior basins.

Boundaries.—The lower and upper contacts are sharp. The nature of formational lateral boundaries, however, is not known. Although both the Woodhill Member of the Franconia and the underlying Galesville Member of the Dresbach are composed of sandstone, the contact between them is lithologically distinct and abrupt and is considered an unconformity. A similar type of boundary is present in northern Michigan between the Chapel Rock and Miners Castle Members of the Munising Formation. The contact, which is readily recognized by the different weathering characteristics of the two units, is thought to be an unconformity because of significant changes in sorting, sedimentary structures, and heavy-mineral assemblages.

The upper contact of the Franconia in Wisconsin-Minnesota is sharp, with dolomite, dolomitic siltstone, or fine-grained sandstone of the St. Lawrence Formation overlying glauconitic sandstone. In northern Michigan the contact is an unconformity.

Within the Franconia, vertical and lateral contacts are generally gradational. Interfingering characterizes the lateral change of the Reno type of sandstone to the Mazomanie type.

Internal Features

Sedimentary structures.—Although a variety of structures are present, the most characteristic is probably small- to medium-scale, festoon crossbedding, troughs of which are 3-8 inches deep, 15-20 inches wide, and 20-40 inches long in a downcurrent direction. In the southern part of the area, burrows and mottled bedding are so common that the term "wormstone" has been applied to some beds (fig. 19-4). In general, crossbedding more nearly characterizes the nonglauconitic units, whereas organic structures are more typical of beds with abundant glauconite. Other typical structures include interbedding, horizontal bedding, initial dip, ripple marks, mud cracks, and concretions. In northern Michigan the lower part of the Franconia, or "Miners Castle," contains small sets of medium-scale crossbeds, with thin lenses of blue shale separating the sets.

Crossbedding shows a rather uniform southwesterly paleocurrent direction throughout the area of more than 8,000 square miles (fig. 19-3). To the north, average paleocurrent subparallels thickness trends, but to the south, it lies at a high angle to the trend. Locally near the Baraboo Range, the direction is south-southeast. Wherever ripple marks are present they are essentially perpendicular to the crossbed dips.

Texture.—A wide range exists in grain size and in sorting. The basal unit is coarse-grained sand and poorly sorted. The glauconitic sandstones are fine to very fine grained and commonly are well to moderately well sorted. The nonglauconitic units are more variable, ranging from very fine to coarse grained and poorly to well sorted. In general, the Franconia is recognized by the poorly sorted units within it. Overall, sorting improves and grain size increases upward. It is not uncommon in the central part of the area for very fine-grained glauconitic sand to be overlain by very fine-grained to fine-grained, horizontally laminated sand and fine-grained, crossbedded sand. In northern Michigan the sand changes upward from an average of 0.25 mm to 0.35 mm, and the sorting coefficient from 2.00 to 1.50.

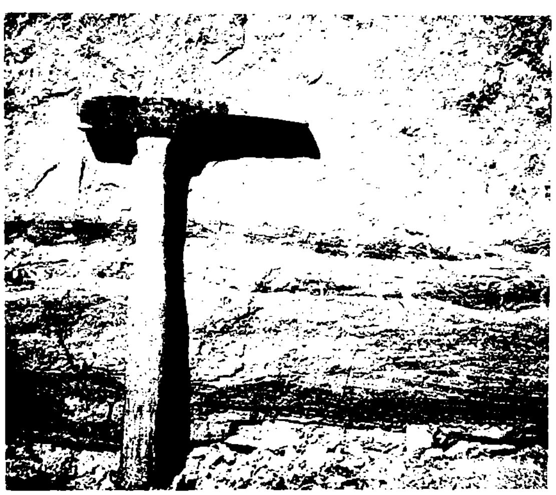

Figure 19-4. Burrows and mottled bedding above small- to medium-scale crossbedding in glauconite-rich sandstone. *From* Berg (1954, pl. 1). Photograph by R. R. Berg.

Constituents.—The most characteristic constituent is glauconite, which varies in abundance from 0 to 50 percent. In the south the fourfold vertical subdivision of the Franconia has been made largely on the basis of glauconite, with the two glauconite units containing greensand and "wormstone." Quartz dominates many beds; it constitutes more than 95 percent of the Miners Castle Member in northern Michigan. Other framework grains include pebbles of siltstone, dolomite, and greensand; other constituents are mica and the nonopaque heavy-mineral assemblage of garnet, tourmaline, and zircon.

The Tomah Member of the southern area contains a high percentage of diagenetic feldspar. Other authigenic or diagenetic minerals besides glauconite and feldspar are pyrite, calcite, and quartz. Dolomite beds are present in two of the Franconia members.

Fossils are present in all members of the Franconia, but apparently they decrease in abundance toward the northeast. Abundant trilobites and some inarticulate brachiopods are the fossil types described from the formation.

Depositional Environment

Sandstones of the Franconia are thought to have been deposited in a shallow-marine environment. The widespread distribution of the sandstone units, burrows and mottled bedding, interbeds of shale between crossbed sets, fossils, and glauconite point to a marine environment. Most of the glauconite is detrital, but the grains are thought to have been deposited ultimately near the site of origin. Mud cracks suggest an occasional exposure because of progradation and/or a high tidal range.

The glauconitic and thin-bedded sandstones were probably deposited offshore from the nonglauconitic nearshore sandstone and formed during slow sedimentation (fig. 19-5). The lateral and vertical uniformity in the southwesterly direction of crossbed dip suggests that the offshore currents were controlled more by regional slope than by longshore drift.

The unconformity at the base of the Franconia together with the basal, poorly sorted, coarse-grained sandstone reflects transgression after erosion of part of the Dresbach Formation. The sea transgressed across the entire area from the southwest. Islands existed in the early Franconia sea in the Baraboo area and in part of the northern Michigan highland areas. These islands apparently exerted only a local and temporary influence on sedimentation.

Only the lower part of the Franconia was deposited during the transgression. Most of the remaining part was deposited during stillstand conditions, although the upper part of the northern area probably formed during regression of the sea. The garnet-bearing source area, which lay to the northeast, contrasted sharply with the northern Michigan highlands. Before the Franconia transgression the latter had been the source for the garnet-poor sediments of the Dresbach.

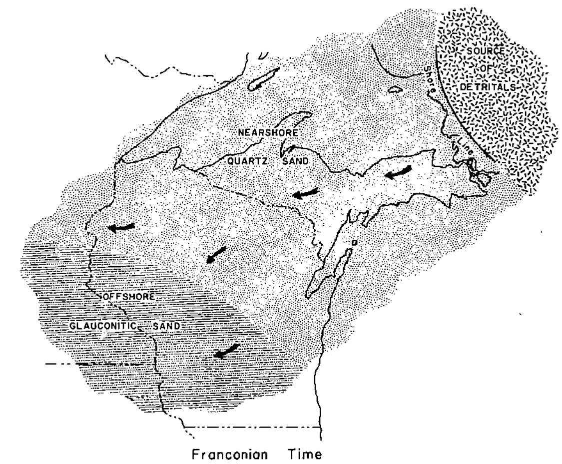

Figure 19-5. Paleogeographic map showing deposition of Franconia Formation in a shallow-marine environment. Marine currents flowed toward the southwest, and the source area lay to the northeast. *From* Hamblin (1961, fig. 8).

Acknowledgments

Maps and correlation sections are from the paper by Hamblin (1961) and are used with the permission of The Geological Society of America. Figure 19-4 is used with the permission of The Geological Society of America; it was kindly furnished by R. R. Berg, who also furnished information concerning the thickness map.

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Cardium Formation, Cretaceous, Pembina Field, Alberta (20)

Structural Framework

Pembina field is some 30 miles east of the eastern edge of the Foothills belt of Alberta (fig. 20-1), and the Cardium Formation of Cretaceous age and associated strata dip to the southwest at a rate of 30-60 feet per mile. The increase in dip which occurs across the field reflects the regional position of the field on a hinge line of the eastern flank of the Alberta syncline (Patterson and Arneson, 1957, fig. 8). At the level of the main producing sandstone, minor undulations are present as structural noses.

Stratigraphic Framework

The Cretaceous of the Alberta plains is similar to that of the Montana plains in that nonmarine basal beds are overlain by a section dominated by marine shale. In Alberta the latter thickens in the direction of dip. It includes and is overlain by coarse clastic wedges, or tongues, which reflect regressions. Also present are two calcareous zones, the "First white specks" and the "Second white specks" of the oil industry. They correspond to the Niobrara and the Greenhorn Formations, respectively, of the United States. The Cardium Formation, which represents one of the less impressive regressive units within the marine-shale sequence, lies between the two "White specks" zones. In formal terminology, it occurs between the Blackstone Formation below and the Wapiabi

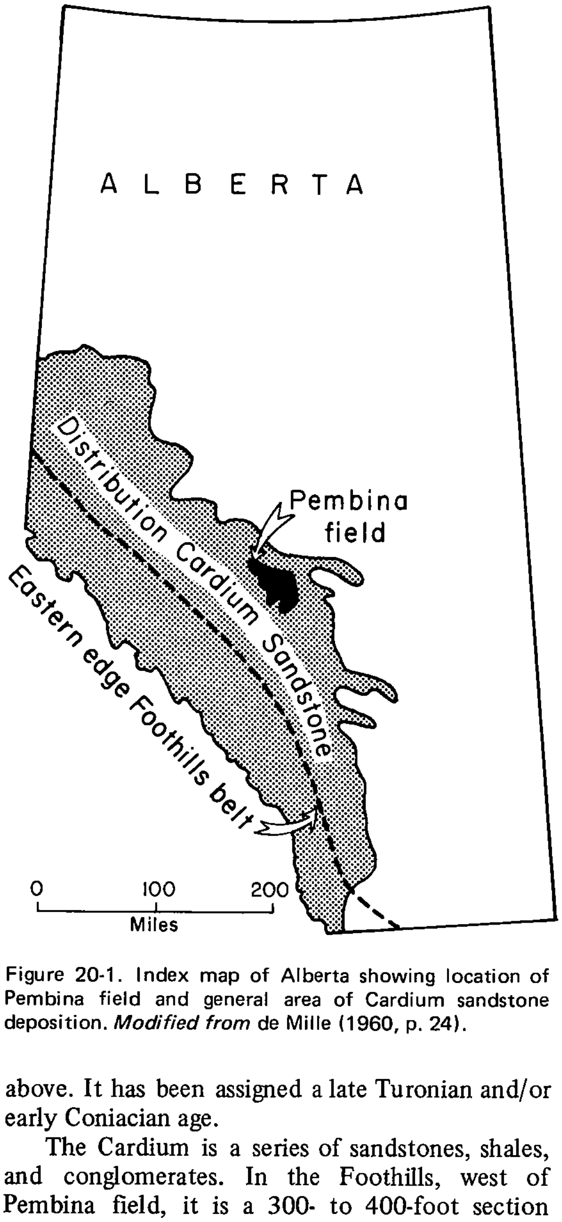

Figure 20-1. Index map of Alberta showing location of Pembina field and general area of Cardium sandstone deposition. *Modified from* de Mille (1960, p. 24).

above. It has been assigned a late Turonian and/or early Coniacian age.

The Cardium is a series of sandstones, shales, and conglomerates. In the Foothills, west of Pembina field, it is a 300- to 400-foot section which has been divided into 5 regressive-transgressive cycles or couplets (Michaelis,1957, p. 73). Cardium sandstones at Pembina are thought to represent the third cycle. However, the formation there is more inclusive, containing, in descending order, a shale, a conglomerate, an upper sandstone, a middle unit, and a lower sandstone (Nielsen, 1957, fig. 5; Patterson and Arneson, 1957, fig. 4) (fig. 20-2).

The upper shale unit is characterized in its uppermost part by a conglomerate in a matrix of silty shale and ironstone, which is an excellent electric-log marker. The shale thickness varies from 55 to 85 feet. The conglomerate is composed of varicolored chert pebbles up to 2 inches in diameter. The matrix is either sideritic shale or ferruginous sandstone.

The conglomerate is less than 4 feet thick over the greater part of the field. Locally, however, it is as thick as 30 feet. Porosity is developed in the conglomerate in various parts of the field, but more commonly in the eastern part. Nevertheless, because of limited distribution of reservoir qualities, it is not regarded as important in the overall picture of reserves for the field.

Sandstone units in the Cardium represent at least three genetic units, which are developed separately in some areas of the field but which are in other areas essentially a multistoried deposit.

Geometry

Geographic location and trend.—In southwestern Alberta, sandstone in the Cardium Formation is present as a blanket which extends eastward and northeastward to the plains. Pembina field lies near the eastern edge of sandstone development. Although considerable variation exists in local sandstone trends, the overall regional trend of the Cardium is northwest.

At Pembina two recognized areas of thick sandstone development are oriented west-northwest subparallel to the structural grain (fig. 20-3). Four areas of sandstone distribution have been recognized in approximately the eastern half of the field (fig. 20-4). The upper and middle units are essentially indivisible in the western part. Directly to the east is a narrow north-trending belt where all three units are developed, with the upper unit poorly developed. The next area to the east is widespread and is characterized by a well-developed upper unit, which accounts for much of the reserves in the field, and a highly irregular lower unit. The northeasternmost area has sandstone rather consistently in the upper and middle units, which cannot be readily differentiated, whereas the lower unit is developed irregularly.

Vertical position.—Surface beds are lower Tertiary sandstones and shales. The Cardium Formation is encountered at depths varying from 4,600 to 5,800 feet across the field.

Length.—For practical purposes, permeable sandstone in the 3 units is restricted to the field, which is 50 miles long. Sandstone in the Cardium Formation extends well beyond the field both to the northwest and southeast.

Width.—A major pinchout of the upper sandstone unit occurs along the eastern and northeastern edge of the field, and the other two units do not extend that far updip (fig. 20-2). Because effective sandstone is limited on the southwest by

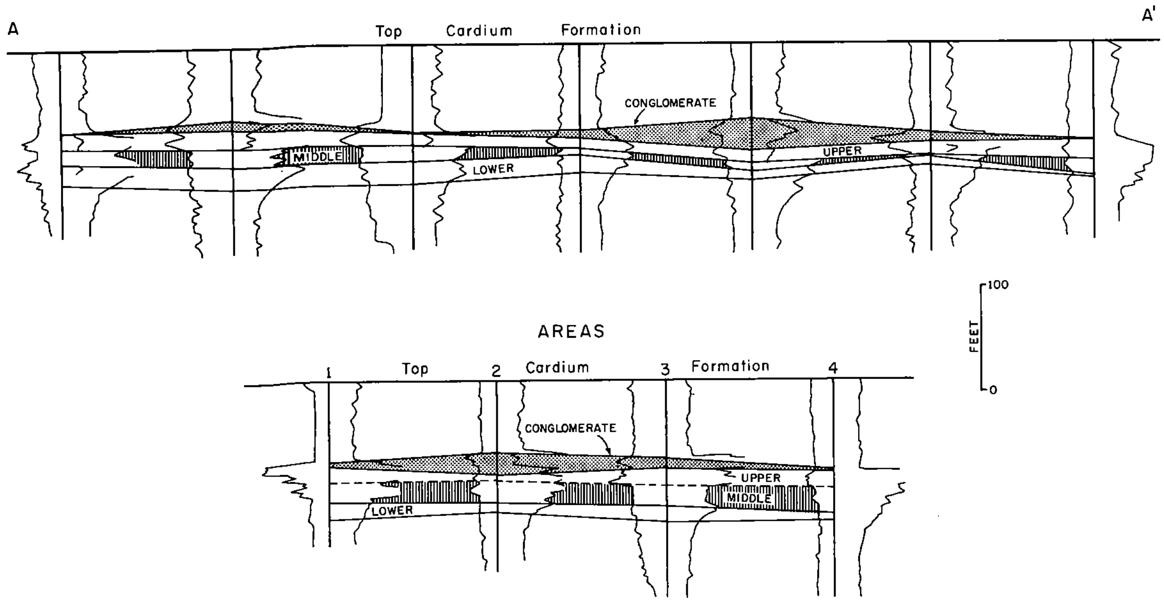

Figure 20-2. Correlation sections of Cardium Formation with subdivisions and sandstone characteristics. Line of section *A-A'* shown in figure 20-3; areas for typical logs shown in figure 20-4. *Modified from* Nielsen (1957, figs. 4, 5, 8).

a decrease in porosity and permeability, the field width of some 30 miles is the width of permeable sandstones. Sandstone in the Cardium is present for a great distance to the southwest and for at least 19 miles to the northeast, but the sandstones at Pembina seemingly are isolated. They are apparently "oil wet," with a connate water content of 10-15 percent.

Thickness.—The upper sandstone unit is as much as 30 feet thick. Maximum thickness is 20 feet for the middle unit and 15 feet for the lower. Total net sandstone thickness varies from 0 to about 40 feet.

Boundaries.—The lower contact of Cardium sandstone is gradational both lithologically and on electric logs (fig. 20-2), and contacts between the three units are also gradational. The upper contact with the conglomerate is sharp lithologically (fig. 20-5) but is not abrupt on electric logs (fig. 20-2).

The lateral boundaries are gradational, as significant changes in sandstone character develop only over substantial distances.

Internal Features

Sedimentary structures.—Where well developed, each unit is characterized by a sequence that contains burrows and/or interbeds below crossbedded sandstone (fig. 20-5). The crossbedding is medium and small scale. The former is commonly rather low angle, festoon, and laminated, with a marked change in grain size across the laminae. The upper part may also be interbedded and may show deformational features such as slump, convolute bedding, and load casts.

Texture.—The upper sandstone is very fine to fine grained and is well sorted in areas of good development. Although porosities as high as 29 percent have been measured, average porosity is 18-20 percent; permeability averages 35 millidarcys.

The middle unit is most commonly interbedded shale and very fine-grained sandstone, with low porosity and permeability. The lower sandstone contains lenses of very fine-grained sand averaging 12 percent porosity. Permeability is very low because of the numerous shale lenses.

Constituents.—The sandstones are quartzose; bands of concretionary siderite are not uncommon. Fish scales, spores, pyrite, and mica are present in shale beds.

Depositional Environment

The Cardium sandstones at Pembina field were deposited in shallow-marine waters. Evidence for that interpretation includes rather widespread distribution of the upper sandstone unit, gradational lower and lateral contacts with marine shale, burrows, and specific features of medium-scale crossbedding. It is thought that sand deposition occurred some distance offshore on a relatively featureless sea floor. However, the distribution of reservoir sandstone along and adjoining a hinge line suggests some subtle bathymetric anomaly during basinal subsidence. Production of some 500 million barrels of oil at Pembina would also suggest some depositional, as well as paleostructural, anomaly.

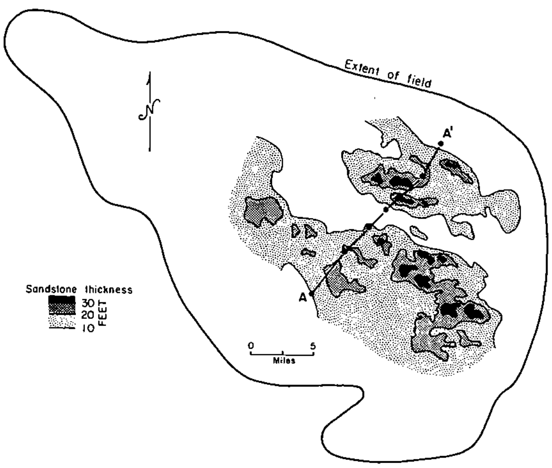

Figure 20-3. Sandstone-thickness map of upper and middle units of Cardium Formation in eastern part of Pembina field. *Modified from* Nielsen (1957, fig. 6).

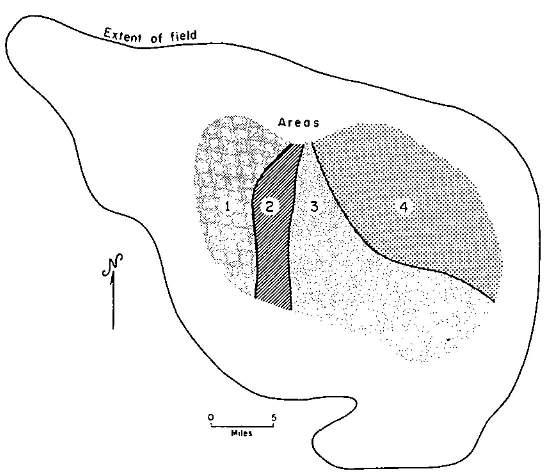

Figure 20-4. Areas of sandstone distribution in Pembina field. Typical electric logs for each area are shown on correlation section (fig. 20-2). *Modified from* Nielsen (1957, fig. 3).

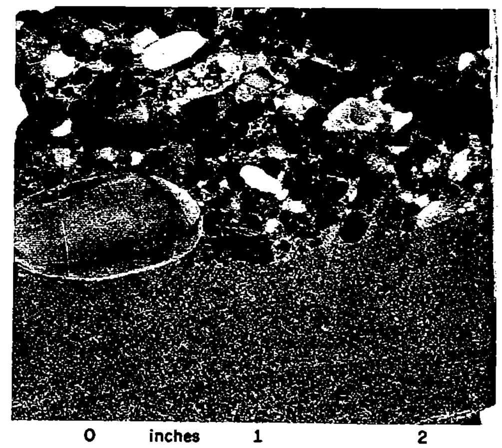

Figure 20-5. Cross stratification in sandstone below transgressive conglomerate, Cardium Formation, central Alberta.

The conglomerate represents a transgression which terminated local sand deposition. The conglomeratic clay some 70 feet above the Cardium coarse clastics at Pembina records the major transgression of the general area which followed deposition of the regressive Cardium tongue.

Acknowledgments

Figure 20-1 is modified from an illustration by de Mille (1960). It and figures 20-2 through 20-4 (Nielsen, 1957) are used by permission of the Alberta Society of Petroleum Geologists.

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Gatchell Sand, Eocene, East Coalinga Extension Field, California (21)

Structural Framework

The East Coalinga Extension field is located on the west side of the San Joaquin valley (fig. 21-1), where structural dip at the Eocene level is basinward at approximately 5° to 10° to the east or northeast (fig. 21-2).

In the field area are two anticlinal noses, the more prominent of which is the southeast-plunging Coalinga anticline on the south. The anticlines are part of the belt of *en-echelon* folds that are apparently associated with the San Andreas fault zone to the west.

Paleostructurally, the Coalinga anticline coincides with the basinal axis during deposition of the Eocene, but the Coalinga-East Coalinga area subsided less than the areas to the northwest and southeast (fig. 21-1).

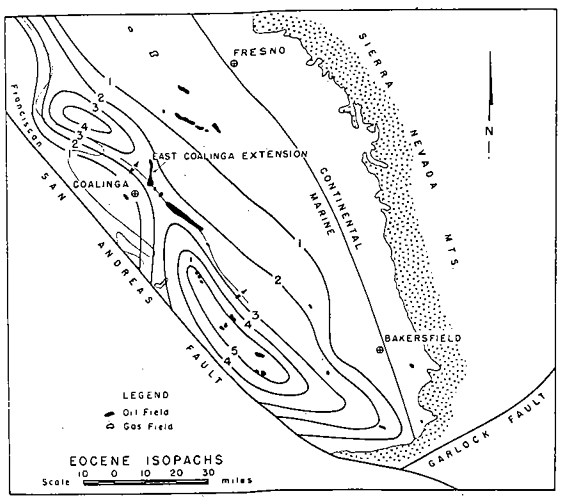

Figure 21-1. Index map of San Joaquin basin showing location of East Coalinga Extension field. Also shown are thickness of Eocene sediments (in thousands of feet), locations of fields producing from the Eocene, and outcrop belts of basement rocks on eastern and western sides of basin. *From* Simonson (1958, fig. 9).

Stratigraphic Framework

Upper Cretaceous and Cenozoic rocks of the San Joaquin basin form a stratigraphic section of unusual thickness and remarkably varied lithology. During Tertiary time the basin was probably similar to the present valley in size and shape (Hoots and others, 1954a). An inland sea occupying the subsiding basin was affected by numerous tectonically induced transgressions and regressions. The most pronounced Tertiary regression, during

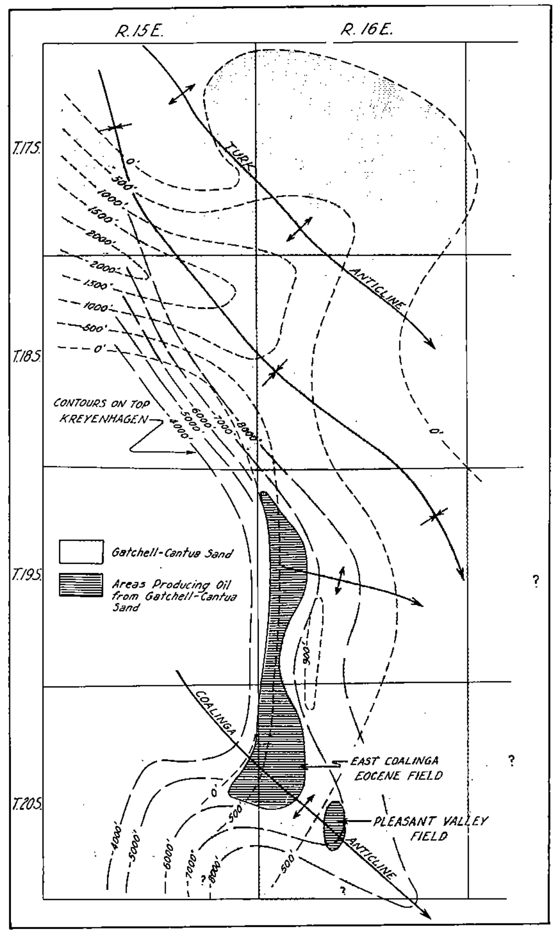

Figure 21-2. Thickness map of Gatchell sand, structural-contour map, and structural features in general area of East Coalinga Extension field. *From* Hoots and others (1954b, fig. 1).

the Oligocene, probably marked the end of a geosynclinal cycle during which the Gatchell sand was deposited. Eocene beds in the basin are more than 5,000 feet thick (fig. 21-1).

The Gatchell sand, middle Eocene in age, is essentially enclosed in a marine shale section. In the field area the lateral updip equivalent is known as the "Turritella" silt. Overlying the Gatchell-"Turritella" section is a thin sequence of coarse clastics, the Canoas sand and Domengine Grit, which in turn are overlain by the thick Kreyenhagen Shale (Kaplow, 1942, p. 23-24). Where the Gatchell sand is not developed the equivalent section in the East Coalinga Extension field has been considered as the upper part of the Arroyo Hondo Shale, the total thickness of which is some

750 to 900 feet. Outside the field area the term "Cantua" has been used for sand at the stratigraphic position of the Gatchell. The sand forms a multistoried section.

Geometry

Geographic location and trend.—The Gatchell sand is recognized in a north-trending belt in the East Coalinga Extension field area (fig. 21-2). There, the western edge of sand development is essentially north-south. North of the field the belt of development changes to a west-northwest trend, subparalleling the synclinal axis between the Turk and Coalinga anticlines (Hoots and others, 1954b, fig. 1) (fig. 21-2).

Vertical position.—In the field area the depth of the Gatchell ranges downward from approximately 6,200 feet. The sand extends downdip beyond the oil-water contact, which originally was −7,700 feet in the north and −7,300 feet in the south.

Length.—The field is approximately 9 miles long, and the northerly sand trend is known for a distance of 12 to 15 miles (fig. 21-2). The west-northwesterly trend extends beyond the area mapped. In the general area the sand is known to be more than 25 miles long (fig. 21-2).

Width.—The sand extends downdip, or eastward, beyond the East Coalinga Extension field. The extent of sand in that direction is generally not known. However, it is estimated to be about 5 miles wide near the northern edge of the field (fig. 21-2). North and northwest of the field the sand is as much as 10 miles and as little as 5 miles wide.

Thickness.—In the field the sand varies in thickness from 0 to 800 feet. Directly east of the field the thickness is more than 900 feet (fig. 21-2). The thickness is as great as 2,000 feet along the west-northwesterly trend northwest of the field.

Boundaries.—Based on electric-log characteristics, the upper and lower contacts are generally rather sharp (fig. 21-3). Within the field the sand, approximately 400 feet thick, pinches out in less than 1,000 feet. Although the western lateral contact is sharp, some interfingering occurs between the Gatchell and the "Turritella" silt (fig. 21-3). The nature of the eastern contact is not known, but some interfingering occurs with the Arroyo Hondo Shale. Apparently the maximum width of the sand is developed near the base, with interfingering of lithologic facies affecting the upper part of the sand section.

Internal Features

Sedimentary structures.—Much of the sand is massively bedded; some is characterized by horizontal bedding.

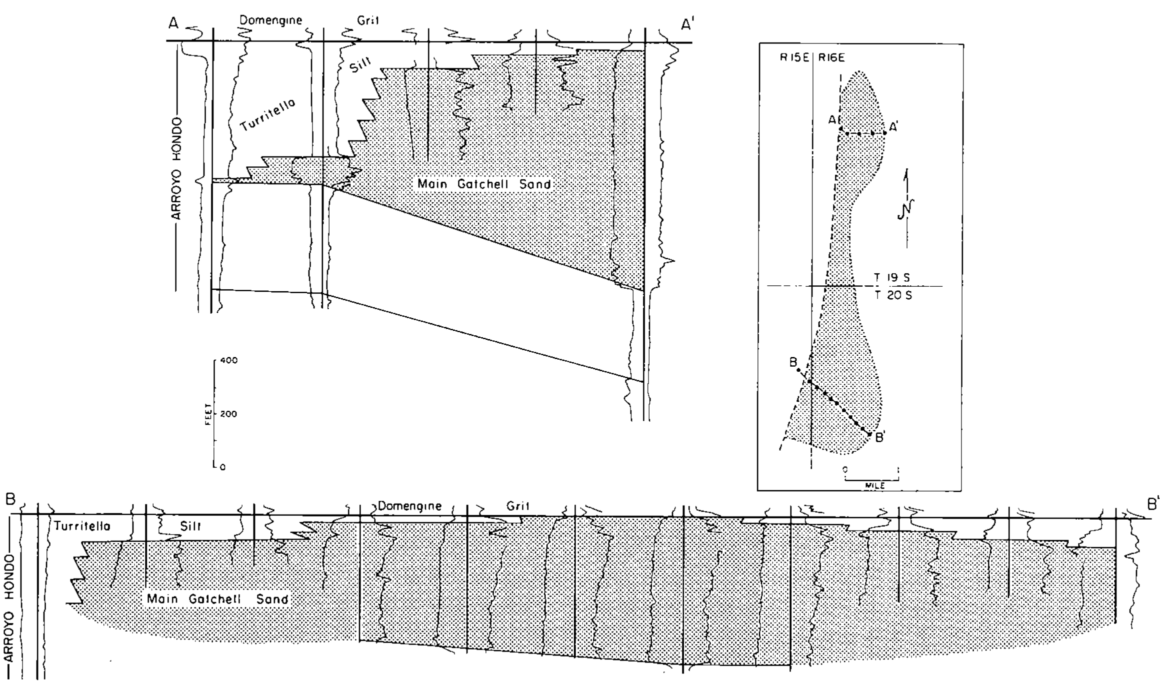

Figure 21-3. Cross sections *A-A'* and *B-B'*, illustrating thickness and boundaries of Gatchell sand.

Texture.—The Gatchell sand is generally a medium-grained, well-sorted sand. Throughout the main mass of sand no silt or shale is present (fig. 21-3).

The porosity ranges from 14 to 29 percent; the average of more than 1,000 measurements is 19 percent. The range in permeability is 0–1,516 millidarcys; the average is 500 millidarcys. In one well permeabilities normal to bedding average 62 percent of those parallel to bedding.

Constituents.—Kaolinite is known to be an interstitial constituent. In fact, kaolinite cement forms the permeability trap at Pleasant Valley field, southeast of East Coalinga Extension (fig. 21-2). It is thought that the kaolinite was formed by ground-water alteration of feldspar sand grains.

The updip Gatchell equivalent, the "Turritella" silt, contains some glauconite in addition to various fossil types.

Depositional Environment

The Gatchell sand is thought to have been deposited as a nearshore shallow-marine sand. Its multistoried nature suggests that during sand deposition the sea was occupying a relatively static position as the rate of subsidence equaled the rate of deposition. The development of sand east of anticlinal crests suggests that the sand-laden currents avoided the structurally growing positive features.

Acknowledgments

Figure 21-1 is used with the permission of The American Association of Petroleum Geologists; figure 21-2 is used with the permission of the California Division of Mines and Geology. Figure 21-3 is modified from illustrations by Kaplow (1942).

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DEEP-MARINE ENVIRONMENTS

Hackberry Sands, Oligocene, Port Acres Field, Texas Gulf Coast (22)

Structural Framework

Port Acres field lies in the western part of the short-lived but active Hackberry embayment of coastal Texas-Louisiana (fig. 22-1). The updip edge of the Oligocene basin is arcuate and is defined by one or more fault zones. In Port Acres field Hackberry beds dip rather uniformly to the east-southeast at a rate of about 1°. A down-to-the-coast, arcuate, normal fault with approximately 300 feet of throw is present in the southern part of the field (fig. 22-2). A second arcuate fault on the southeast separates Port Acres field from Port Arthur field, where Hackberry and other sands produce from a doubly plunging anticlinal feature on the downthrown side of the 400-foot fault. Present in the southwestern part of Port Acres field is a low-relief, southeast-plunging synclinal nose.

It is common for the Hackberry to be underlain by an unconformity, which locally is associated with significant stratigraphic cutouts.

Stratigraphic Framework

Hackberry sands are present in the lower part of the Hackberry shale, a thick shale wedge developed within the Frio in southeasternmost Texas and southwestern Louisiana. In the Port Acres area, which has been studied by Halbouty and Barber (1961), the Hackberry is 2,000-2,500 feet thick (fig. 22-3). Where the Oligocene (or Miocene) Frio is subdivided into three time-stratigraphic units, the Hackberry wedge, which is present below the *Marginulina texana* faunal zone and above the *Nonion struma,* is part of the upper Frio. The Hackberry shale is recognized by a foraminiferal assemblage interpreted to be repre-

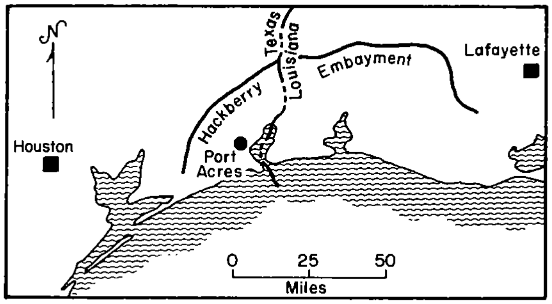

Figure 22-1. Index map of Hackberry embayment, showing location of Port Acres field. *Modified from* Halbouty (1969, fig. 9).

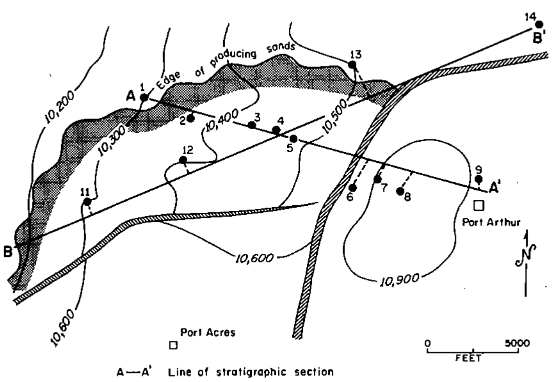

Figure 22-2. Structural-contour map of Port Acres and Port Arthur fields. Reference surface is top of lower Hackberry; elevations are subsea. Northwestern edge of producing Hackberry sands is also shown. *Modified from* Halbouty and Barber (1961, fig. 4).

sentative of bathyal water depths. During deposition of the Hackberry shale, water depths were much greater in the arcuate basin than in the areas along regional structural and depositional strike but outside the basin (or embayment). Immediately southwest of the basin, essentially no beds were deposited during the time of formation of the Hackberry.

Beds underlying the Hackberry range in age from late Frio to Vicksburg. The amount of erosion, marked by an unconformity, apparently depended upon paleostructural conditions which existed before the Hackberry transgression.

Producing Hackberry sands are developed irregularly in approximately the lower half of the Hackberry section (fig. 22-3). It should be noted, however, that the base of the Hackberry is difficult to recognize without paleontologic analysis from core material. Consequently, some of the lower Hackberry sands may be part of the sand section below the Hackberry but above the *Nonion struma* faunal zone. At Port Acres field the productive sands compose two sections in a 200- to 250-foot interval in the upper part of the lower Hackberry (figs. 22-3, 22-4). They represent a number of genetic sand units.

Geometry

Geographic position and trend.—The producing Hackberry sands at Port Acres field, in the Port Arthur area, are restricted to the field area on the northwest by pinchouts (figs. 22-2, 22-4). The extent of the sand units to the east and south is not known, but equivalent units are productive in Port Arthur field, east-southeast of the fault separating the two fields. The overall trend for the two sand sections is probably northeast or east-northeast, parallel to the average pinchout.

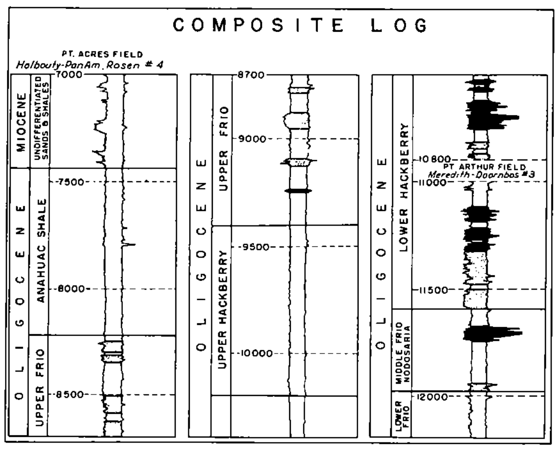

Figure 22-3. Composite electric log showing subdivisions and lithologic characteristics of the Frio. *From* Halbouty and Barber (1961, fig. 2).

Vertical position.—The top of sand in the lower Hackberry is approximately 10,200 to 10,700 feet below the surface in Port Acres field. The depth increases from northwest to southeast and south.

Length and width.—The gross horizontal dimensions of sand development are not known. Within the field, Hackberry sands are productive over an approximate distance of 4 miles in a direction parallel to the pinchout (fig. 22-2). A greater length for sand development probably exists downdip (southeast) of Port Acres. Sands extend beyond the field to the east and southeast. The overall width of development for producing sections is greater than 2 miles.

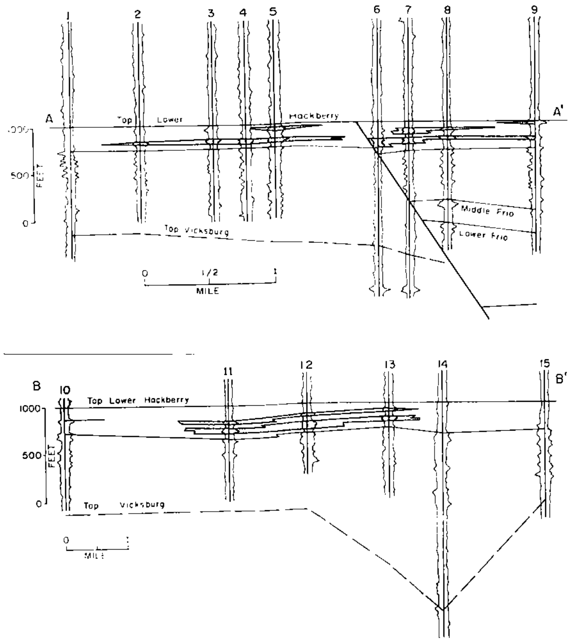

Figure 22-4. Stratigraphic correlation sections of part of Frio interval, showing distribution and gross characteristics of Hackberry producing sands. Lines of section shown in figure 22-2. *Modified from* Halbouty and Barber (1961, figs. 5, 6).

Thickness.—Net sand thickness for the interval containing productive sand beds varies from 0 to some 150 feet (figs. 22-3, 22-4). Individual sand-bearing units are as thick as 100 feet.

Boundaries.—Based on electric-log characteristics, especially the self-potential curve, the basal contacts of the well-developed sand sequences are generally sharp (figs. 22-3, 22-4). The base of each sequence and of each sand bed within it is sharp lithologically. The upper contacts of sand units on electric logs are commonly sharp, whereas the lithologic tops of sand units, and also of beds, are more gradational than the base. The intervals showing lithologic gradation, however, are generally thin—possibly too thin to be represented accurately by electric-log curves. The overall lateral boundaries for sand development are sharp on the north and west edges of the field, and within the field individual sand bodies in the interval studied have abrupt lateral boundaries (fig. 22-4).

Internal Features

Sedimentary structures.—Graded bedding is the most significant sedimentary structure in the productive sand sections of the Hackberry shale (figs. 22-5, 22-6). Each graded bed is generally no more than 2 feet thick; a number of such beds, along with interbedded shale, compose each sand sequence. The lower parts of the graded beds are characterized by randomly oriented lignite fibers (carbonized wood) (fig. 22-5). Laminae are present in finer grained graded beds and at the top of some other graded beds (fig. 22-5). Burrows are associated with laminae of the latter type. Load casts and flame structure are present at the base of graded beds (fig. 22-5). Also showing soft-sediment deformation are shale interbeds and shale clasts at the base of graded beds (figs. 22-5, 22-6).

That part of the Hackberry shale overlying the sand units is characterized by thinly bedded clay with thin beds of laminated, cross-laminated, or micrograded silt. Also present in the shale are sporadic laminated, graded sand beds.

Texture.—Grain size in the graded beds ranges upward from medium sand at the base to very fine sand and silt, which in turn changes upward into carbonized silt. Excluding shale clasts, maximum grain size is about 3 mm. The sands are generally moderately sorted. Porosity in producing sands ranges from 28 to 35 percent; permeability ranges from a few millidarcys to more than a thousand.

Constituents.—Shale clasts and lignitic detritus (carbonized wood) are the most conspicuous accessory constituents (figs. 22-5, 22-6). Glauconite is rarely present. In the shale above the sands and in shale interbeds the foraminiferal assemblage includes *Ammobaculites nummus, Gyroidina scalata,* and *Sphaeroidina variabilis.*

Depositional Environment

Foraminifera indicate that the Hackberry shale was deposited in deep-marine waters. The sands are turbidites, as evidenced by graded beds, moderate sorting, and flame structure. Sharp deflections on electric logs opposite the base of sand units are consistent with turbidite deposition.

Shale was deposited out of suspension as a pelagic clay in bathyal water depths. Turbidity currents formed along the edges of the steep-sided Hackberry embayment and flowed gulfward along circuitous routes because of growth of contemporaneous structures. Sand was probably introduced to the Port Acres area from the northeast. Laminated silt at the top of graded beds was deposited by bottom currents, which were effective after turbidity-current activity and before deposition of pelagic clay was resumed. They also formed the small-scale crossbedding in thin silt interbeds in the shale above the sand units.

Halbouty (1969, fig. 13) and Halbouty and Barber (1961, p. 233) followed common practice in considering the distribution of Hackberry sands and electric-log characteristics as evidence of del-

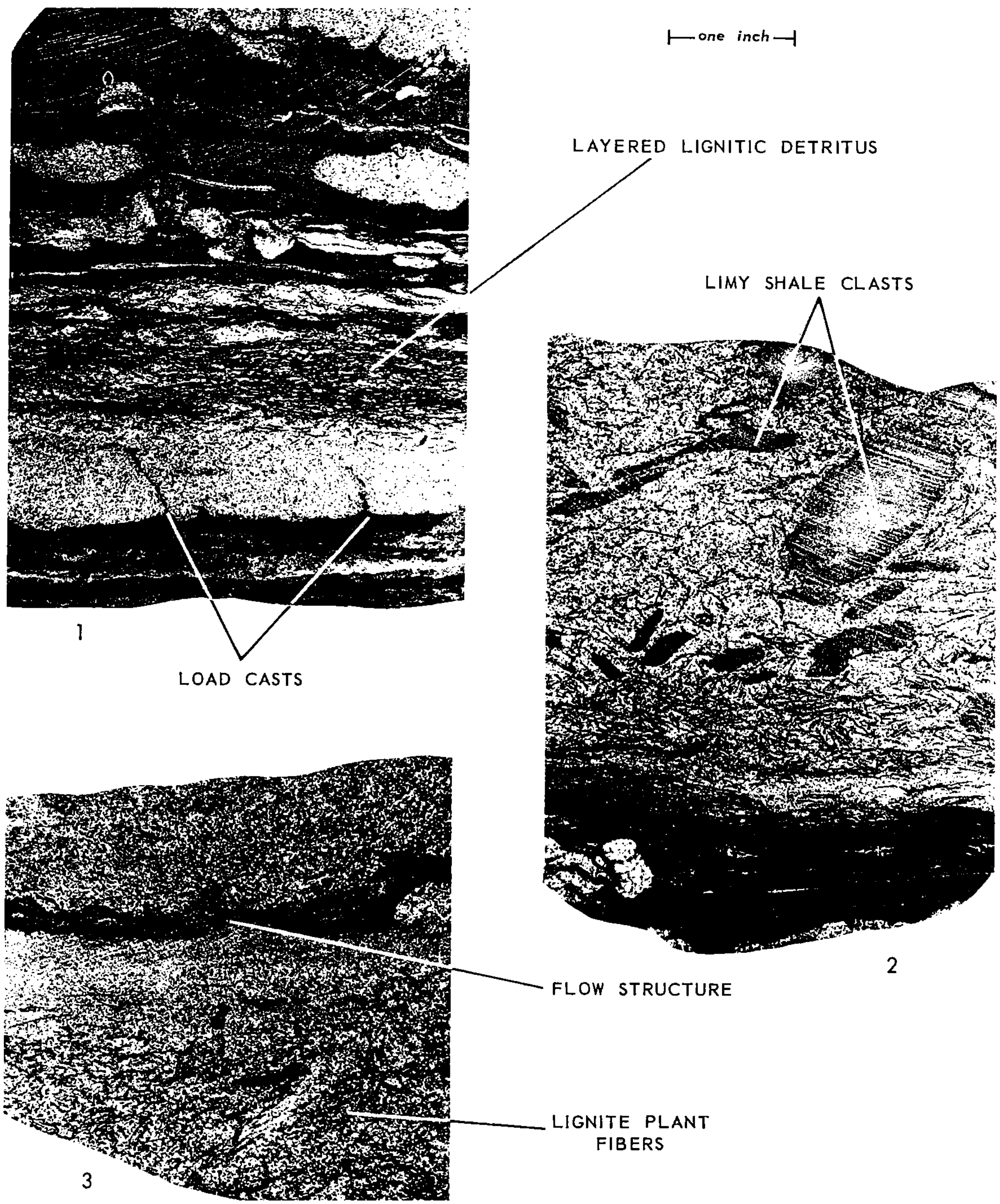

Figure 22-5. *1,* vertically graded sands and interbedded shale, the former showing sharp basal contacts and load casts. Layered lignitic (carbonized) detritus is present near top of lowest graded bed. Humble 1 L. C. Edwards *et al.;* depth, 10,549 feet. *2,* basal part of graded bed with plastically deformed shale clasts and randomly oriented lignite fibers. Depth, 10,551 feet. *3,* upper part of lower graded bed contains randomly oriented lignite fibers below thin silt; base of overlying graded bed shows load casts and flame structure. Depth, 10,553 feet. Photographs by Humble Oil & Refining Company.

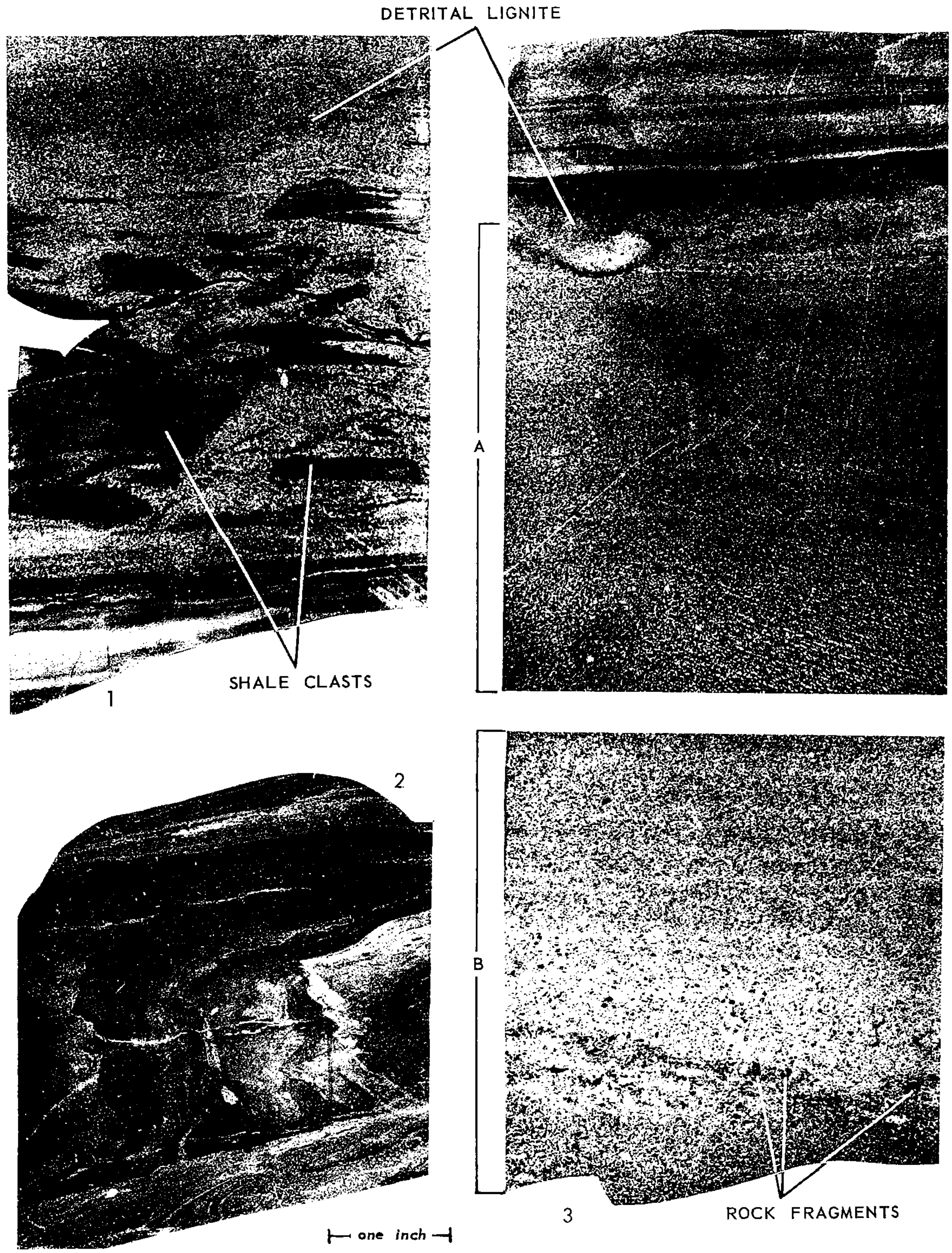

Figure 22-6. *1,* lower part of graded bed with abundant deformed shale clasts. Depth, 10,451 feet. *2,* deformed shale between turbidites; distortion probably resulted from loading by overlying turbidite. Depth, 10,446 feet. *3,* graded bed with scattered particles 3 mm in diameter in lower part (*B*); very fine-grained sand in upper part below silt with lignite (*A*). At top, laminated sand with initial dip of 12° is base of another graded bed. Depth, 10,454 feet. Photographs by Humble Oil & Refining Company.

taic deposition. Deep-water fans probably formed in those areas where sand trends are perpendicular to the edge of the embayment, and they superficially resemble deltas. At Port Acres the thin sand beds with massive graded bedding at the base possibly suggest deposition on the lower part of a fan. Fan deposition may be analogous to proximal deposition, but no bounding highlands rimmed the embayment.

Sand-bearing units at or near the base of deep-water shales in other arcuate embayments of the Gulf Coast are thought to represent deposition of turbidites. Included in this group are sands in the Miocene Abbeville and Harang shales of south Louisiana.

Acknowledgments

Photographs, including captions and sample descriptions, were furnished through the courtesy of Humble Oil & Refining Company, and in particular, E. D. Stout, to whom appreciation is expressed. Figures 22-2 through 22-4 are used with the permission of the Gulf Coast Association of Geological Societies; figure 22-1 is used with the permission of The American Association of Petroleum Geologists.

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Upper Member, Martinsburg Formation, Ordovician, Central Appalachians (23)

Structural Framework

The area of study is largely restricted to the narrow but long belt within the Appalachian Great Valley from Kingston, New York, to Staunton, Virginia (fig. 23-1). The arcuate outcrop belt of the Martinsburg Formation strikes north-northeast in the Virginias, changes direction twice as part of the salient and recess in Pennsylvania, and strikes northeast at the Hudson River. The regional dip is to the northwest. Within much of the Great Valley the Martinsburg occupies a small asymmetric synclinorium, which in places is overturned to the northwest. Key beds cannot be traced for any great distance because of complex local structural features, such as small thrusts and tear faults. In eastern Pennsylvania and in New Jersey the Martinsburg underwent major Taconic and minor Appalachian deformation.

Stratigraphic Framework

The early Paleozoic geosynclinal cycle in the central Appalachians may have been initiated in Middle Ordovocian time with deposition of shale of the Martinsburg Formation. Flysch-type sediments of the Martinsburg, described in the study by McBride (1962), are overlain by Upper Ordovician molasse-type Juniata-Bald Eagle beds and by Silurian and Lower Devonian orthoquartzites and carbonates.

The Martinsburg conformably overlies Trenton limestones in the south, but the contact is unconformable and complicated by faulting in Pennsylvania. The top of the Martinsburg is truncated by either the Bald Eagle Formation or the basal Silurian Tuscarora-Shawangunk rocks. It is common for the lower part of the Martinsburg Formation to grade into limestone northwest of the main outcrop belt. The limestones, Trenton in age, are overlain by the Reedsville Formation (fig. 23-1). Although confusion has arisen in application of the terms "Martinsburg" and "Reedsville," typical developments of each are distinctive lithologically.

The Reedsville is a 1,000-foot fossiliferous section which shows an upward increase in grain size. The lowest unit is a gray clay shale, and the uppermost unit is a massively bedded, fossiliferous subgraywacke sandstone, or sublitharenite. The upper formational contact is transitional with the Bald Eagle.

This description of the Martinsburg summarizes the findings of McBride (1962). The Martinsburg is a thick sequence of gray shale and graywacke sandstone, Trenton to Maysville in age. It is essentially composed of a lower, dominantly shale member which changes upward into a member of interbedded graywacke and shale. In New York, New Jersey, and western Pennsylvania the shale has been metamorphosed to slate. Most estimates of formational thickness range from 2,250 to 4,000 feet. However, in eastern Pennsylvania the entire thickness is thought to be about 9,000 feet.

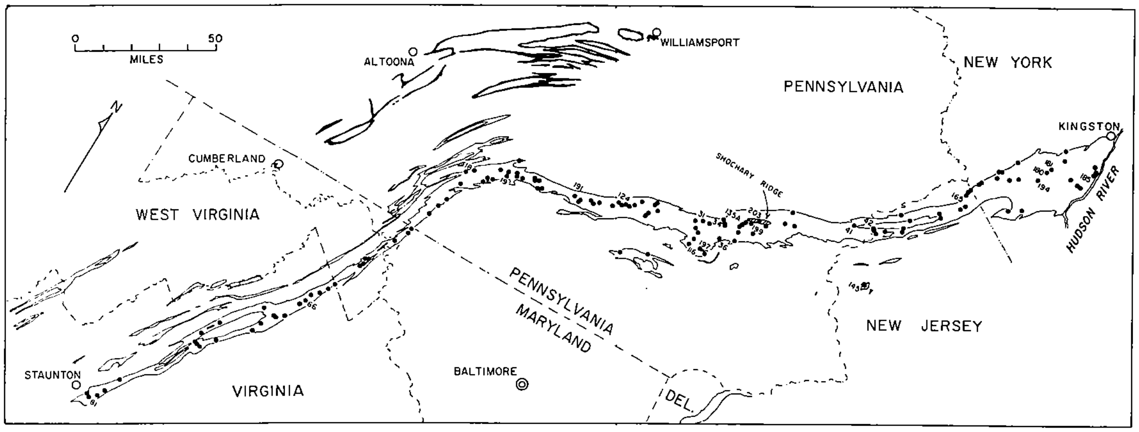

Figure 23-1. Map of central Appalachian region, showing outcrop belts of Martinsburg and Reedsville Formations. Outcrop area for latter is belt in central Pennsylvania. Black dots show localities where information was obtained. *From* McBride (1962, fig. 2).

Shale is thought to compose 95 percent of the lower member of the Martinsburg and 30 to 60 percent of the upper member. A few limestone interbeds are present at the base of the lower shale member. Thin beds of graywacke and siltstone are present higher in the section and increase upward in number. Three different lithologies have been recognized in eastern Pennsylvania: graded siltstone and fine-grained graywacke, ranging from thin laminae to beds more than 1 foot thick; gray slate, varying from laminations to beds several feet thick; and black, carbonaceous slate bands less than 1 inch thick. The gray and black shale is thought to represent pelagic deposits, and the coarser clastic layers are considered to be turbidity-current deposits. Characteristic of the upper member are repetitious alternations of shale and graywacke sandstone (fig. 23-2), 40 to 70 percent, and siltstone, 2 to 5 percent.

Other rock types, composing only a small percentage of the formation, are variegated shale, limestone, dolomite, siliceous shale and chert, limestone and quartz conglomerate, orthoquartzite, altered tuffaceous sediments, and mafic igneous rocks. Conglomerates compose less than 1 percent of the Martinsburg and occur as lenticular units rarely more than a few feet thick. They are present at the base of sandstone beds or are interbedded with them.

The Martinsburg Formation includes innumerable genetic sandstone units in the upper member, and characteristics of this type of sequence are noted in the following description.

Geometry

Geographic location and trend.—The Martinsburg has been mapped in the Great Valley of the central Appalachians, from the Hudson River southwestward to Staunton, Virginia (fig. 23-1). The overall trend of Martinsburg sandstones is thought to parallel the outcrop belt and structural grain, which are northeasterly with sinuous variations in Pennsylvania.

Vertical position.—Stratigraphic units of the Martinsburg are present at the surface over most of the area of study. In areas along synclinal axes the formation lies in the subsurface below resistant Bald Eagle or Tuscarora units.

Length.—The formation has been mapped along a belt 400 miles in length. The original distance along which Martinsburg sandstones extended is not known, but the formation is recognized in southwestern Virginia, some 175 miles southwest of Staunton.

Width.—The width of Martinsburg exposures is 3 to 18 miles. Martinsburg units interfinger with the Reedsville type of rock at approximately the northwestern edge of the Great Valley. It is uncertain how far to the southeast the Martinsburg extended prior to erosion.

Stratigraphic changes within short distances transverse to the Appalachian folded belt contrast sharply with the persistence of flysch-type sandstone sequences for at least 400 miles along the belt.

Thickness.—Sandstone is the dominant lithology of the upper Martinsburg member, which may be as thick as 3,000 feet. The maximum thickness of sandstone is thought to be as much as 2,000 feet. The Martinsburg-Reedsville beds thin in a northwestward direction from 9,000 to 1,000 feet in 50 miles (uncorrected for crustal shortening).

The geosynclinal axis is thought to parallel the present fold system.

The thickness of individual sandstone beds ranges from thin laminae to 12 feet. Each bed is characterized by a remarkably even thickness on outcrop.

Boundaries.—The lower boundary of the upper member, characterized by sandstone, is gradational. Thin beds of sandstone and siltstone in the lower shale member gradually increase in number up-section to the arbitrary base of the upper member.

In certain areas the uppermost part may pass gradually into the overlying molasse-type beds. However, in eastern Pennsylvania the top of the Martinsburg is an unconformity. The nature of the lateral boundaries for the Martinsburg type of sandstone is not known, but the narrow width of the thick sandstone-bearing section suggests a rather sharp northwestern boundary.

Individual sandstone beds are characterized by a sharp base. An even upper surface forms a less abrupt boundary, but rarely do the sandstones grade continuously upward into the overlying shale.

Internal Features

Sedimentary structures.—The types of bedding exhibited by Martinsburg sandstones are graded bedding, horizontal lamination, interbedding, small-scale cross stratification, convolute lamination, and massive bedding (figs. 23-3 through 23-5). Graded bedding is visible in 9 out of 10 beds. Some beds are represented by 1 cycle of graded bedding, whereas others contain more than 1 cycle. Over 60 percent of the graded beds are less than 1 inch thick; 95 percent are less than 20 inches. Horizontal lamination is common in the upper portion of beds, but it may be present throughout some thin beds. The upper member in its entirety may be considered as an interbedded sequence with relatively thin sandstones and thinner shales. Crossbeds occur as single or multiple sets above horizontal lamination. Commonly multiple sets are composed of planar units below the festoon type. Some sandstones and siltstones

Figure 23-2. Repetitious alternation of Martinsburg sandstone and shale, showing even bedding and range in bed thickness. Hat at base of thickest bed for scale. Hamburg, Pennsylvania. *From* McBride (1962, fig. 5). Photograph by E. F. McBride.

contain the climbing-ripple type of crossbedding. The maximum angle of climb measured is 17°, although most sets dip less than 8°. Convolute lamination is present in beds up to 12 inches thick. Although cross stratification is common, no ripple-mark surfaces were observed.

A wide variety of sole marks are present. They include groove and flute casts, furrow flute casts, scour and channel fills, and load casts (pockets). Groove casts range upward in size to more than 1 foot wide and 1 inch high. Intraformational shale fragments are thought to have been the most common scribing tools. Martinsburg flute casts have many specific shapes. On any one sole, flute casts rarely show current deviation of more than 30°. Also, it is uncommon for flute casts and groove casts to be present on the same sole. Flute casts are common on soles of the thicker beds. Groove casts are generally restricted to beds less than 2 feet thick. Beds with groove casts average 6 inches in thickness, whereas beds with flute casts average 9 inches.

Paleocurrent directions from sole marks are diverse. Considering the entire area, currents flowed toward directions ranging clockwise from south-southeast through west and north to east. However, dominant directions have been noted parallel to the structural and sandstone trends and also perpendicular to the trends (fig. 23-6). In fact, where more than 10 orientations were measured, both directions were found at most outcrops. In general, the transverse currents flowed northwestward, but they ranged clockwise from southwest to north. Longitudinal currents flowed northeastward in the southern part of the area. They flowed north-northeastward, northeastward, and eastward at positions progressively northward around the Pennsylvania salient. In New Jersey and New York

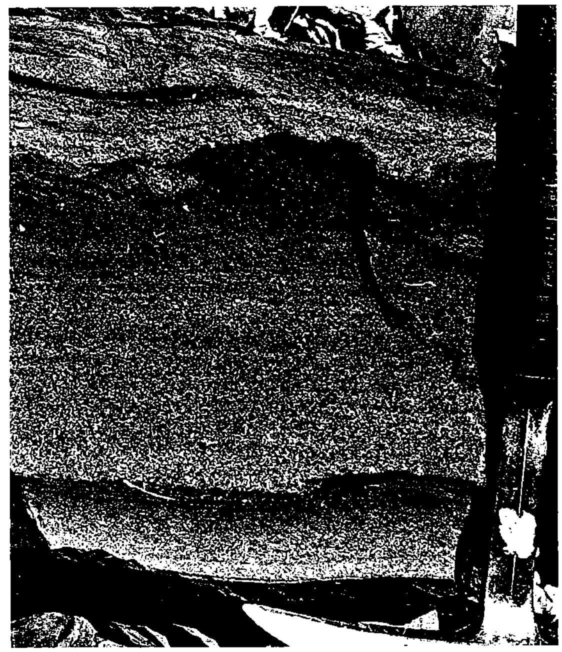

Figure 23-3. Graded bedding and associated structures in Martinsburg. Four graded units are present. Near Middletown, New York. *From* McBride (1962, fig. 7). Photograph by E. F. McBride.

Figure 23-4. Cross lamination, with some deformed units near top. Near Middletown, New York. *From* McBride (1962, fig. 9). Photograph by E. F. McBride.

Figure 23-5. Flute casts, showing current direction from lower right to upper left. Near Staunton, Virginia. *From* McBride (1962, fig. 14). Photograph by E. F. McBride.

the longitudinal current direction was predominantly to the southwest (fig. 23-6). Present also at various locations is a prominent current trend which is oblique to the length of the sandstone mass. The average paleocurrent from crossbedding at a particular locality coincides with one of the major trends indicated by sole marks.

Load casts, sandstone dikes, flame structures, and shale intrusions are deformational features associated with sandstone-shale boundaries.

Texture.—The sandstones are graywackes, which of course means that they are poorly sorted. Matrix constituents make up 22 to 50 percent of the sandstones; average content is 36 percent. Rocks with a matrix volume greater than 40 percent have a dispersed framework in which grains are "floating" in, or supported by, mud.

Excluding intraformational fragments, detrital grains rarely exceed 1.5 mm in diameter, and most are from 0.1 to 0.5 mm. Generally less than 6 percent of a sandstone is composed of recognizable detrital grains less than 0.06 mm in diameter. From thin section analysis of 6 samples, average grain size for the framework fraction varies from 0.34 to 0.65 mm, and sorting coefficient from 1.27 to 1.71. Sand grains and intraformational pebbles show an average upcurrent imbrication of about 20°. Grain orientation in a bed is generally parallel to the sole marks from the same bed. Larger grains show less scatter than smaller grains.

Constituents.—Framework constituents of the graywackes are largely quartz, rock fragments, and feldspar. Quartz constitutes 20 to 63 percent of the rock. The content of rock fragments varies from 3 to 44 percent and averages 24 percent. Shale is the dominant type of rock fragment. Feldspar composes 0.5 to 12 percent, with albite more common than potash feldspar. Accessory framework constituents make up less than 2 percent of the sandstones. With regard to the framework fraction alone, quartz, quartzite, and chert average 64 percent, rock fragments 30 percent, and feldspar 6 percent. Accordingly, the average sandstone is a litharenite.

The matrix is a microcrystalline aggregate composed primarily of chlorite, muscovite or sericite, quartz, and carbonate. Analysis of the fine-grained fraction shows the matrix has the same qualitative mineralogy as the interbedded shale. Authigenic or diagenetic carbonate averages 8 percent of the graywackes, and it replaces some of the matrix. Ankerite, siderite, and pyrite are other accessory constituents.

Sandstones show a notable southwest-to-northeast increase in the amounts of quartz and feldspar and a corresponding decrease in shale. Schist, phyllite, and metaquartzite increase in abundance toward the northeast, whereas fragments of chert and limestone decrease.

Conglomerates are characterized by either

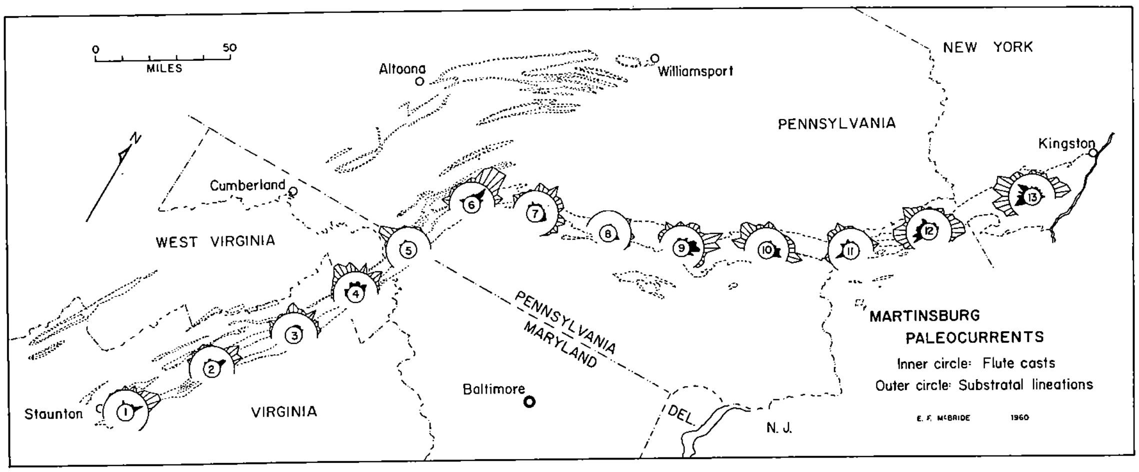

Figure 23-6. Paleocurrent map of Martinsburg sandstones based on orientation of 732 sole marks. Numbers refer to arbitrary geographic subdivisions for summarizing data. Longitudinal, transverse, and oblique directions are evident. *From* McBride (1962, fig. 32).

quartz pebbles or rock fragments. The latter include various limestone and shale fragments and lesser amounts of chert, graywacke, volcanic fragments, and fossil fragments.

Except in the Shochary Ridge area of eastern Pennsylvania, shallow-water fossils in the Martinsburg are scarce detrital particles. A meager fauna of graptolites and radiolarians is present in the shale. At Shochary Ridge, where the youngest rocks of the formation are preserved, fossil debris and burrows are common in a thin-bedded, interbedded sandstone sequence 300 feet thick.

Depositional Environment

The Martinsburg sandstones represent turbidity-current deposition. The graded bedding, sole marks, even thickness of beds, and interbedding with pelagic shale are internal evidence of distal turbidites. Accumulation of pelagic mud in the upper part of the lower member of the Martinsburg was interrupted at various intervals by geologically instantaneous deposition of thin beds from turbidity currents. For the upper member, the frequency of interruption by sand deposition increased as did the thickness of deposits. The result was the repeated alternations of pelagic shale and turbidites, typical of flysch deposits. Cross lamination records deposition by normal marine currents, resulting in tractionites.

Externally, the extreme length and narrow width indicate sand deposition by turbidity currents in the deepest part, bathymetrically, of a long subsiding basin, which corresponds to the axial part of the geosyncline. The pattern of longitudinal currents suggests that sea-floor slope was northeastward as far north as eastern Pennsylvania. The southwesterly direction of longitudinal currents in New Jersey and New York supports the conclusion that the deepest part of the basin was near the Pennsylvania-New Jersey line. The scarcity of transported fossils, slump features, and thick, nongraded beds, which are associated with deep nearshore basins, favors a longer and gentler sea-floor slope during Martinsburg deposition. The fossiliferous Shochary Ridge deposits record the beginning of shallowing conditions as rates of sedimentation exceeded those of subsidence.

The transverse current directions, generally toward the northwest, reflect flow down the regional paleoslope and point to a lateral supply of sediment. The oblique current patterns, most of which flowed toward the regional slope of the basin floor, record the transition between lateral flow into the basin and longitudinal flow along its axis. Variation in current directions suggests little local topographic control of current orientation and a flat basin floor. Much of the topography was probably produced by older turbidity-current deposits. Also, the path of the currents depended not only on the local topography but also on the orientation of the canyons or channels feeding the currents into the basin and on the velocity of the currents, among other factors. Any channel deposit that might have formed during deposition of Martinsburg units has been eroded, and only the basinal facies is preserved today.

The source for the Martinsburg sediments lay to the southeast of the area of study. In the south the source area was primarily a sedimentary terrane, whereas the graywackes farther north were derived from a provenance composed largely of low-grade metamorphic and plutonic rocks. The complex provenance is referred to as Appalachia. It is thought that as Appalachia emerged, the axis of uplift shifted progressively northwestward, initiating "cannibalistic" erosion of older Martinsburg sediments and associated volcanic rocks.

Turbidites that formed during a younger geosynclinal cycle in the Appalachian area make up a major part of the Jennings Formation of Devonian age (McIver, 1970, p. 74). However, the Jennings or "Portage" facies is finer grained than the Martinsburg and intertongues laterally with and grades vertically into shallow-marine and continental sediments. Because paleocurrents define a uniform westerly slope, the "Portage" is thought to be the distal, relatively deep-water facies of the Catskill deltaic complex (McIver, 1970, p. 80).

Acknowledgments

Figures are used with the permission of the Society of Economic Paleontologists and Mineralogists. Photographs were kindly furnished for reproduction by E. F. McBride.

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Rosedale Sandstone Member, Stevens Sandstone, Miocene Southeastern San Joaquin Basin, California (24)

Structural Framework

In the vicinity of Rosedale field, near Bakersfield, California (fig. 24-1), regional dip is less than 10° southward. Post-Miocene diastrophism has resulted in considerable faulting but little folding of beds in that part of the San Joaquin basin. The Sierra Nevada Mountains on the east and the Tehachapi Mountains on the south form bounding positive elements with history extending at least to the Miocene.

Stratigraphic Framework

Upper Cretaceous and Cenozoic rocks of the San Joaquin basin form a section of unusual thickness and remarkably varied lithology. The sediments, derived from source areas to the east, south, and west, were deposited in an inland sea of neritic to bathyal depths. Numerous lithologic facies accumulated contemporaneously, and the only interruption to deposition resulted from widespread tectonic events. The resulting unconformities, together with the complex lithologic section, increase the uncertainties in stratigraphic correlations.

From the eastern basinal edge, upper Miocene sediments thicken basinward from several hundred feet to 6,000 feet. Accompanying the variation in thickness is a facies change from coarse sand and conglomerate (Santa Margarita and lower Chanac) to organic shale with chert and diatomaceous sediments. The upper Miocene shale in the Rosedale area is known as the Fruitvale, which overlies the middle Miocene Round Mountain Silt. Within the upper part of the Fruitvale are several sand

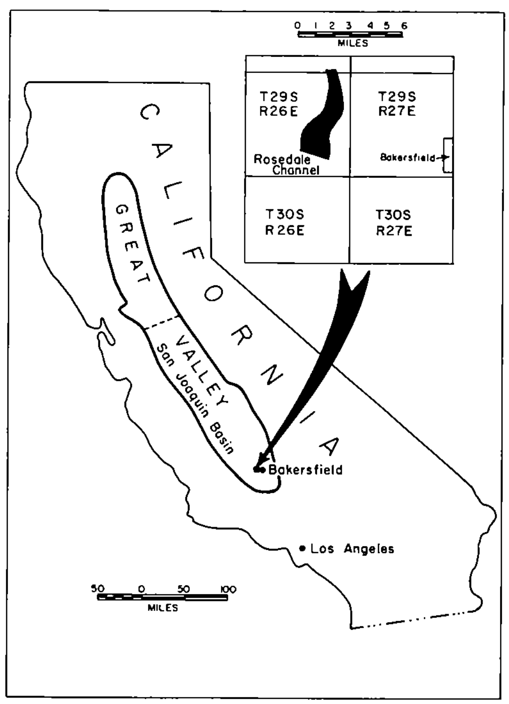

Figure 24-1. Index map of San Joaquin basin showing area of development of Rosedale Sandstone Member of Stevens Sandstone. *From* Martin (1963, fig. 1).

sequences known as the Stevens Sandstone (Martin, 1963). The deep-marine Stevens interfingers with the shallow-marine Santa Margarita. Both are major oil-producing sands (fig. 24-2). The sand thickness of the Stevens-Santa Margarita in the San Joaquin basin is elongated in a northwest-southeast direction, which is also the trend of preferred grain orientation in the Stevens.

The Rosedale is the locally developed basal member of the Stevens Sandstone, which has been described by Martin (1963). It occurs within the widespread lower Fruitvale Shale (fig. 24-3). Foraminiferal assemblages in the Rosedale Sandstone are considered middle late Miocene in age, whereas those in the lower Fruitvale Shale are early late Miocene. The sand contains a number of genetic units.

Geometry

Geographic location and trend.—The Rosedale Sandstone is present in the area some 7 miles west of Bakersfield, California (fig. 24-1). It trends generally north-south through the eastern half of T. 29 S., R. 26 E. (fig. 24-4).

Vertical position.—The top of the sand occurs at a depth which ranges from approximately 6,800 to 8,300 feet and averages 7,500 feet.

Length.—The sand extends both northward and southward beyond the area of study, which is about 6 miles in length (fig. 24-4). Wells south of the area may have penetrated the Rosedale, but stratigraphic correlations and relationships are obscured by faulting and variations in lithologic facies.

Width.—In the field area the width is 0.7 mile on the north, 1.7 miles in the center, and 1.3 miles on the south (fig. 24-4). The known areal extent is estimated to be 5.4 square miles.

Thickness.—The Rosedale Sandstone ranges in thickness from 0 to 1,200 feet (fig. 24-4). The known volume of the sand is approximately 1.1 cubic miles.

Boundaries.—The base of the sand, which lies either on the lower Fruitvale Shale or the Round Mountain Silt, represents a sharp erosional contact (figs. 24-5, 24-6). The lateral contacts are generally abrupt, but an interfingering relationship between the upper part of the Rosedale and the lower Fruitvale Shale is thought to be present on the

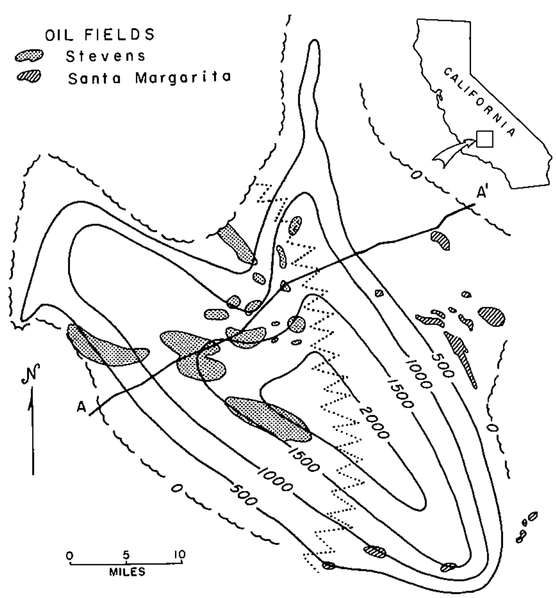

Figure 24-2. Net-sand-thickness map, shown in feet, Stevens-Santa Margarita sandstone section, upper Miocene, San Joaquin basin. Portion west of dotted line is Stevens Sandstone, a deep-marine turbidite facies; to east is shallow-marine Santa Margarita. *Modified from* Sullwold (1961, fig. 6).

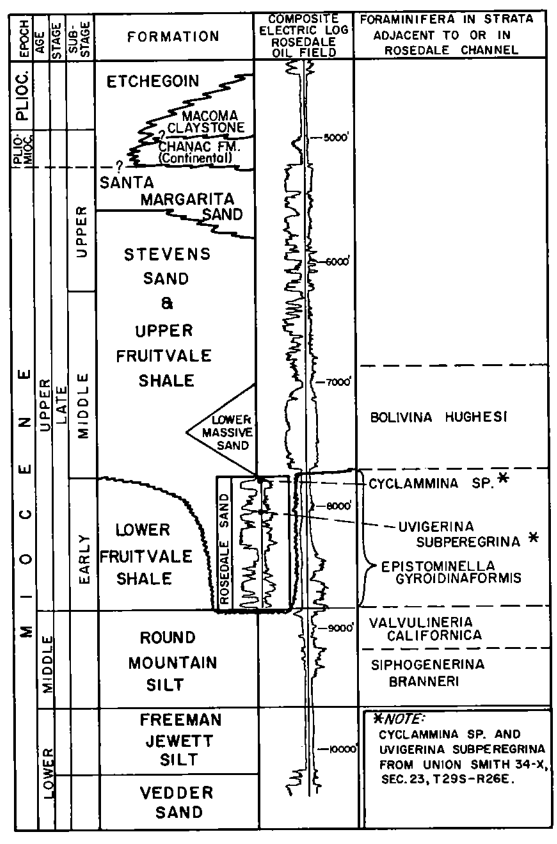

Figure 24-3. Stratigraphic section of Rosedale area, showing stratigraphic position of Rosedale Sandstone, Stevens Sandstone, and Fruitvale Shale. *From* Martin (1963, fig. 3).

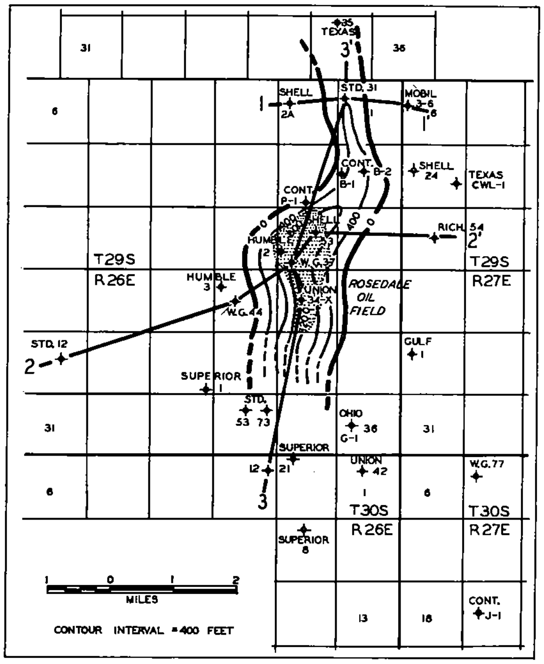

Figure 24-4. Sand-thickness map of Rosedale Sandstone, showing lines of correlation sections. *From* Martin (1963, fig. 2).

south (fig. 24-6). The upper boundary is considered sharp.

Internal Features

Sedimentary structures.—Two structures observed in cores of the Rosedale are graded bedding and interbedding of sand and shale.

Texture.—The average sand bed is apparently coarse grained and poorly sorted. Fine-grained, moderately sorted units, along with medium-grained sands, have been noted. Descriptions include "muddy conglomeratic sand" and "muddy fine sand." Also present are intraformational boulders and allochthonous pebbles up to 1¼ inches in diameter.

Constituents.—The Rosedale Sandstone is arkosic. In addition to feldspar, kaolinite and biotite are characteristic mineral constituents. Scattered fragments of megafossils, microfossils, and pockets of carbonaceous material are present in the sand. Microfossils in the sand beds are primarily shallow-water forms, whereas those in shale interbeds are bathyal forms. The latter group includes *Uvigerina subperegrina* and *Cyclamina* sp. The lower Fruitvale Shale contains the bathyal foraminifer *Epistominella gyroidinaformis.*

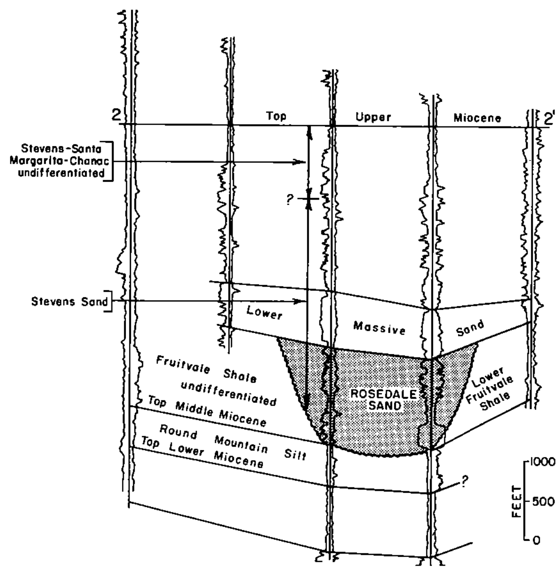

Figure 24-5. Correlation section 2-2′, showing stratigraphic position of Rosedale Sandstone. Line of section shown in figure 24-4. *Modified from* Martin (1963, fig. 6).

Depositional Environment

The Rosedale Sandstone units were deposited as proximal turbidites. Graded bedding, poorly sorted sands, displaced shallow-marine fauna, and bathyal indigenous fauna, together with the underlying deep-marine deposits, all point to turbidity-current deposition. Foraminiferal ecology indicates that water depths were greater than 1,300 feet.

The Rosedale Sandstone was deposited in a submarine canyon, which was eroded to a depth of approximately 1,200 feet. The axis of the canyon, or channel, sloped southward at a gradient of some 200 feet per mile. The slope of the channel sides is thought to have ranged from 10° to 22°. The head of the canyon may have extended as much as 15 miles farther north than the presently known areal limit (fig. 24-7). In that event, the head would have been close to shore and the canyon would have trapped the littoral drift of sand and channeled it into the basin. The shallow-marine Santa Margarita sediments began to accumulate only after the Rosedale channel was filled. Because Stevens turbidites continued to accumulate after the channel was filled, other source areas are thought to have contributed sediments to the basinal area and other canyons to have channeled those sediments basinward.

The Rosedale is similar to some of the deep-sea-channel deposits which have been recognized

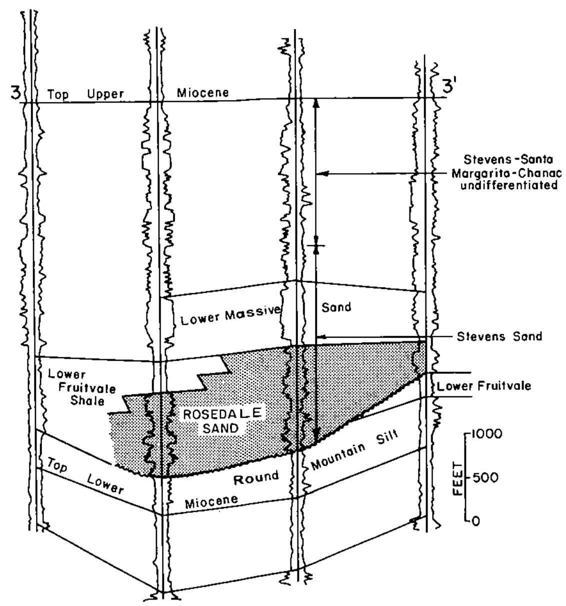

Figure 24-6. Correlation section *3-3'*, showing stratigraphic position of Rosedale Sandstone. Line of section shown in figure 24-4. *Modified from* Martin (1963, fig. 7).

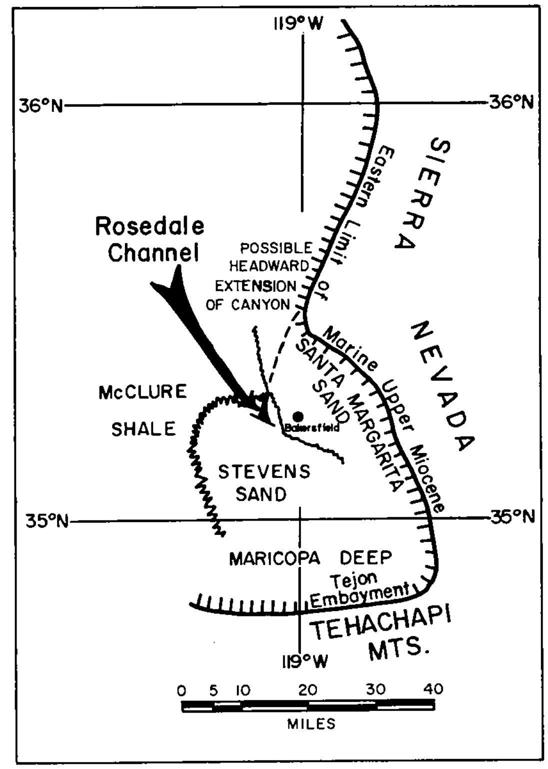

Figure 24-7. Paleogeographic map of southeastern part of San Joaquin basin during deposition of Rosedale Sandstone. *From* Martin (1963, fig. 4).

in the lower Pliocene of the Ventura and Los Angeles basins.

Acknowledgments

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(**Boldface** number indicates main reference; parentheses indicate figure explanations)