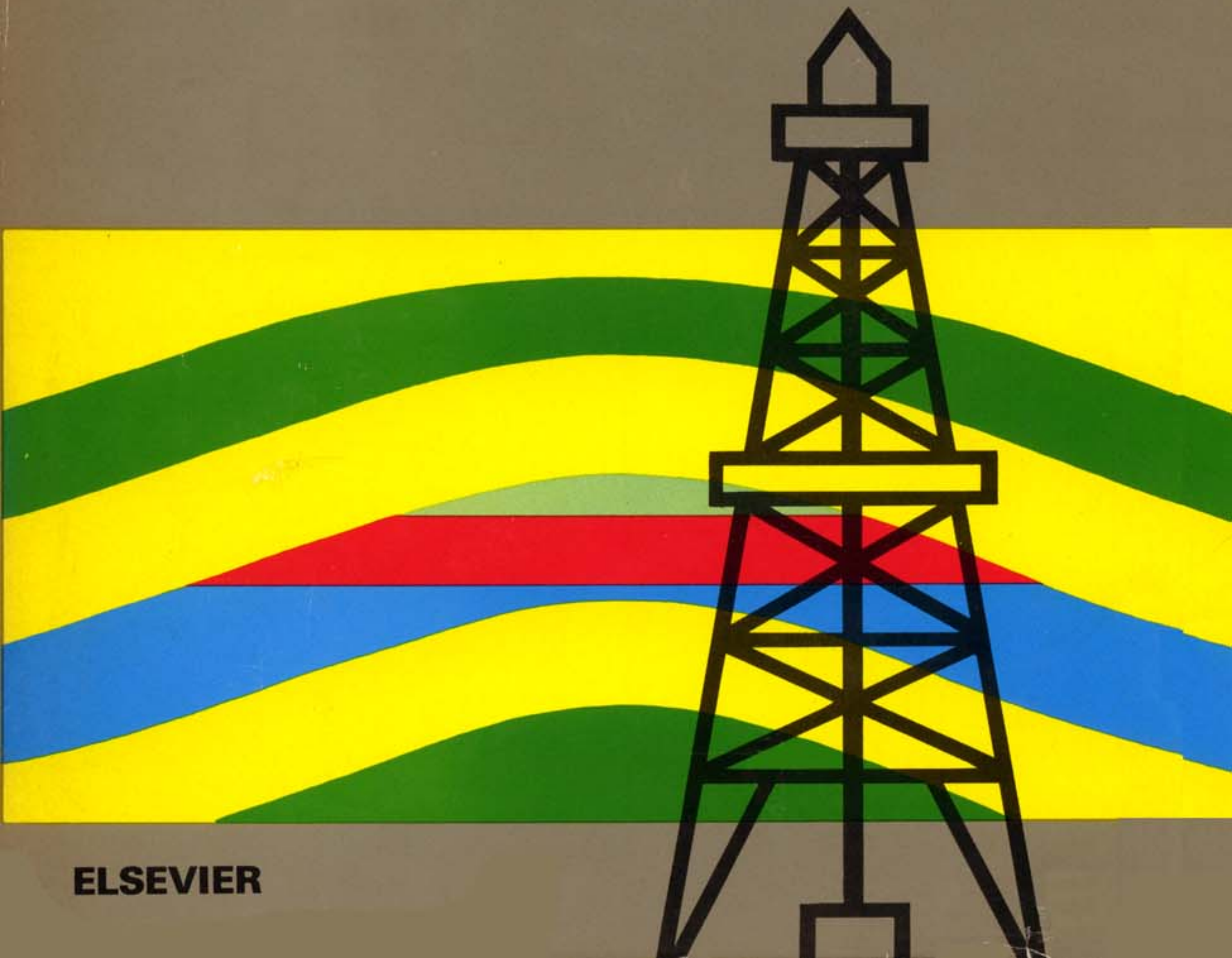
DEVELOPMENTS IN PETROLEUM SCIENCE 4

geomorphology of oil and gas fields in sandstone bodies

C.E.B. CONYBEARE



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Developments in Petroleum Science, 4

GEOMORPHOLOGY OF OIL AND GAS FIELDS IN SANDSTONE BODIES

C.E.B. CONYBEARE

Australian National University, Canberra (A.C.T.)

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PREFACE

This book is essentially about stratigraphic traps for oil and gas. Many of the examples discussed are geomorphologic features having inherent closures without any secondary structural element; others are primarily geomorphologic features modified by folding or faulting to produce local closures. The first category comprises traps that are purely stratigraphic, although the accumulation of hydrocarbons may have been assisted by regional or local tilting of the strata, or by deformation caused by compaction of the underlying sediments. The second category, which includes a much larger number of known examples, comprises structural-stratigraphic traps. Many of these traps have proved to be elusive, particularly those of the first category which commonly defy detection by seismic methods. In some cases, discovery has been accidental, and further exploration to delineate the accumulation has been empirical.

The purport of this book is to briefly present examples illustrating the main geological characteristics of geomorphologic features that have controlled or influenced the accumulation of oil and gas in particular fields, with a view to using such examples as models in the search for new fields in sandstone bodies. Many of the examples presented have been so well documented that they stand as classic examples of stratigraphic fields in which oil and gas accumulations are controlled by geomorphologic features. Others have yet to be defined unequivocally, but are included as additional references to assist in the interpretation of geophysical and sub-surface geological data.

The author is indebted to the many geologists who have written about the hydrocarbon accumulations and geological features described herein, without whose efforts it would not have been possible to compile this book.

Canberra, A.C.T.

C.E.B. CONYBEARE

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INTRODUCTION

Accumulation of oil and gas in a sandstone body depends on several factors including the state of generation and time of migration of hydrocarbons or their precursors, directional variations in porosity and permeability, the existence of stratigraphic or structural closure with a suitable seal, and the geometry of the sandstone body. Many holes have been drilled on the basis of geophysical interpretations that indicated structural closure within a prospective section, only to find the section lacking in suitable source beds for hydrocarbons, or with no impermeable seal above the potential sandstone reservoir. The sandstone itself may be locally tight. Further, the spatial relationships of depositional trends and geometry to permeable zones within the sandstone body are commonly unknown. To complicate our understanding of the situation, the depositional trends and geometry of the sandstone body itself may not be known. With these possibilities in mind, the following comments are offered on the classification of sandstone bodies.

A sheet or blanket sandstone body may be designated as a mappable stratigraphic unit, such as a member or formation, and yet lack continuity and homogeneity. At one locality it may consist of a single sandstone unit, and at another it may comprise two or more sandstone beds that have individual depositional trends, shapes, and petrophysical characteristics. At a particular location oil or gas may be encountered in Sandstone "A", where it occurs below the up-dip edge, but not in adjacent Sandstone "B" that pinches out elsewhere. This type of situation is common in alluvial point bar and channel-fill sands, in anastomosing delta distributary sands, and in off-lapping marine shoreline sands.

A classification of sand body shapes is proposed by Pettijohn, Potter and Siever (1972) after the classification of Potter (1962, b). They say that there are at least four different basic recurring shapes to sand bodies, illustrated by Fig. 1-1, and make the following statement on p. 440, "Equidimensional sand bodies have length-width ratios of approximately 1:1 and may cover a few to thousands of square kilometers. These have been called sheets and blankets. Elongate sand bodies, on the other hand, are those with long dimension notably exceeding width and are one of three types: pods, ribbons and dendroids (Potter, 1962, Fig. 3). Pods have length-width ratios of three or less where ribbons are much more elongate with length-width ratios of three or more and possibly as high as 20 to 1 or more. Rich (1923, p. 103) used the term shoestring for such bodies. Dendroids are commonly more sinuous and have branches, either tributaries or distributaries. By lateral migration, coalescent ribbons and dendroids may form belts, dendritic belts being the more common."

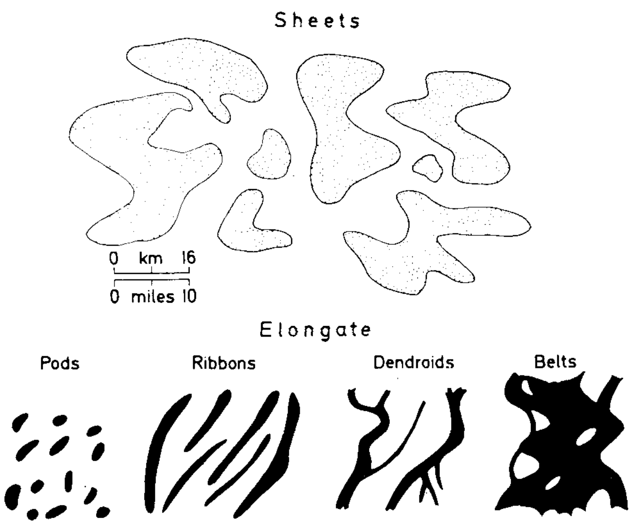


Fig. 1-1 Classification of sand body shapes. (Modified by Pettijohn, Potter and Siever, 1972, after Potter, 1962b).

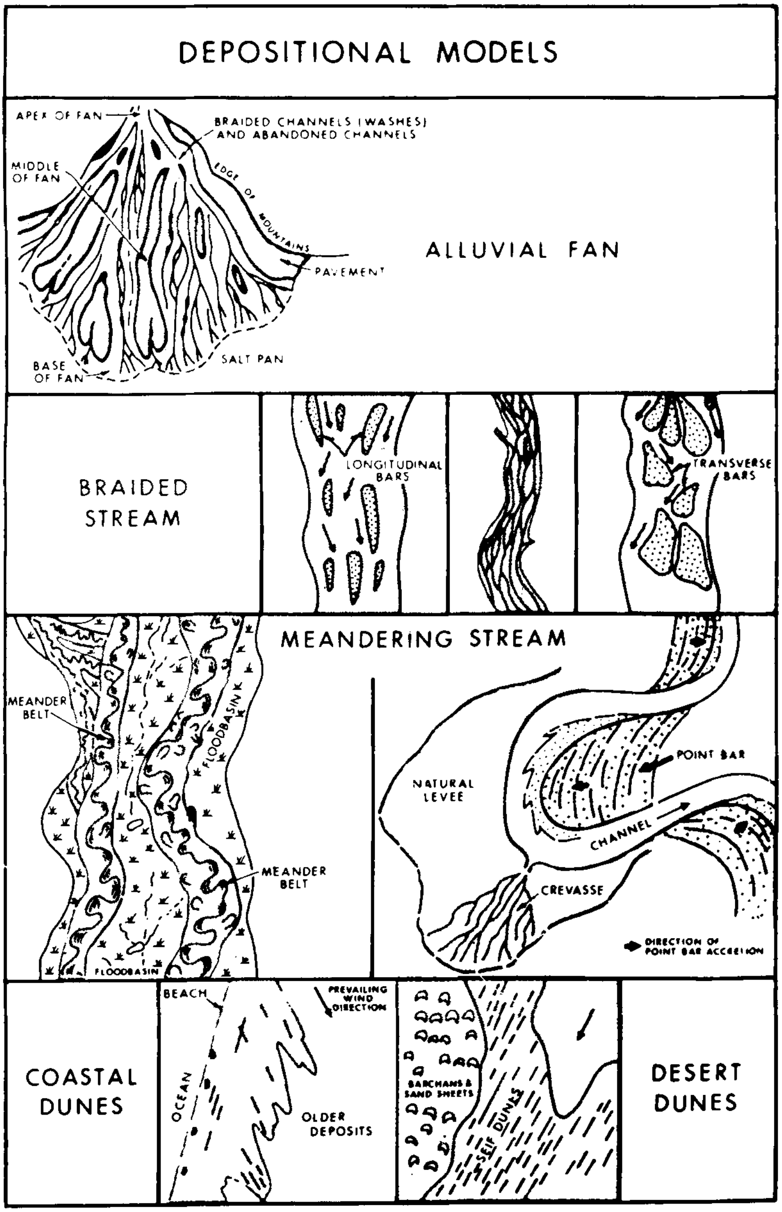
These designations are based on the geometry of the sandstone bodies and do not have any implicit connotation as to depositional environment or geomorphology. Also, they can be misconstrued and misapplied, with particular reference to some so-called sheet or blanket sandstones. Nevertheless, they serve a useful purpose in qualifying and to some extent quantifying the shapes of sandstone bodies.

Sheet-like stratigraphic units, consisting essentially of sandstone, may have originated as transgressive or regressive shoreline sands, as eolian sands, as widespread sand beds within coalescing alluvial fans, as braided and laterally migrating estuarine deposits, as river sediments on a broad plain, or as layers of sand swept out on abyssal plains of the ocean. Apart from the similarity of their gross dimensions, these units are markedly different in their internal structure and stratigraphic relationships. All are diachronous to some degree, although a layer of sand swept rapidly on to an abyssal plain will represent so short a period of time that it can be regarded as a stratigraphic marker bed. Internally, a sheet-like stratigraphic unit may consist of several distinct sandstone bodies that may be locally connected or entirely separated by impermeable shale layers. These separate bodies may be nearly equidimensional or elongate in shape. A sequence of off-lapping, elongate shoreline sands may have a wide areal distribution within a comparatively thin stratigraphic interval, and consequently form a sheet--like unit in gross dimensions. Within such an interval the preferred orientations of these elongate sandstone bodies are parallel to the original coastline; but the interval may also include other elongate sandstone bodies, oriented approximately normal to the coastline, that were formed as distributary sands filling channels cut into the shoreline sands. In many cases the distributary sands cannot readily be distinguished from the shoreline sands with which they are associated, although variations

ENVIRONMENTS				
CONTINENTAL	ALLUVIAL (FLUVIAL)	ALLUVIAL FANS (APEX, MIDDLE & BASE OF FAN)	STREAM FLOWS	CHANNELS
				SHEETFLOODS
				"SIEVE DEPOSITS"
			VISCOUS FLOWS	DEBRIS FLOWS
				MUDFLOWS
		BRAIDED STREAMS		CHANNELS (VARYING SIZES)
				BARS: LONGITUDINAL
				BARS: TRANSVERSE
		MEANDERING STREAMS (ALLUVIAL VALLEY)	MEANDER BELTS	CHANNELS
				NATURAL LEVEES
				POINT BARS
			FLOODBASINS	STREAMS, LAKES & SWAMPS
	EOLIAN	DUNES	COASTAL DUNES	TYPES: TRANSVERSE, SEIF (LONGITUDINAL), BARCHAN, PARABOLIC, DOME-SHAPED
			DESERT DUNES	
			OTHER DUNES	

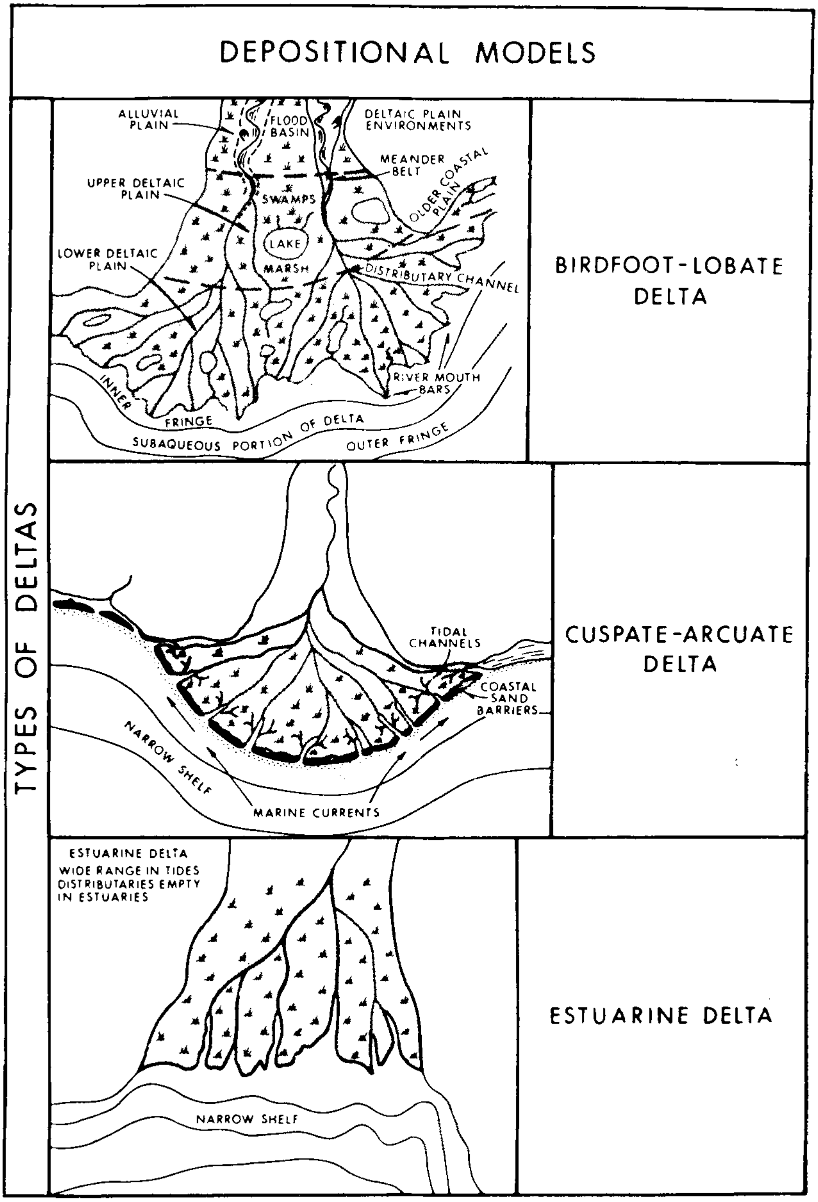
Figs. 1-2, 1-3 and 1-4

Classification of depositional environments of sand bodies and their related geomorphologic features. (After Le Blanc, 1972, and Bernard and Le Blanc, 1965).


DEPOSITIONAL MODELS
APEX OF FAN
BRAIDED CHANNELS (WASHES) AND ABANDONED CHANNELS
MIDDLE OF FAN
EDGE OF MOUNTAINS
PAVEMENT
ALLUVIAL FAN
BASE OF FAN
SALT PAN
BRAIDED STREAM
LONGITUDINAL BARS
TRANSVERSE BARS
MEANDERING STREAM
MEANDER BELT
FLOODBASIN
MEANDER BELT
FLOODBASIN
NATURAL LEVEE
POINT BAR
CHANNEL
CREVASSE
DIRECTION OF POINT BAR ACCRETION
COASTAL DUNES
BEACH
PREVAILING WIND DIRECTION
OCEAN
OLDER DEPOSITS
BARCHANS & SAND SHEETS
SEIF DUNES
DESERT DUNES

ENVIRONMENTS					
TRANSITIONAL	DELTAIC	UPPER DELTAIC PLAIN	MEANDER BELTS		CHANNELS
					NATURAL LEVEES
					POINT BARS
			FLOODBASINS		STREAMS, LAKES & SWAMPS
		LOWER DELTAIC PLAIN	DISTRIBUTARY CHANNELS		CHANNELS
					NATURAL LEVEES
			INTER-DISTRIBUTARY AREAS		MARSH, LAKES, TIDAL CHANNELS & TIDAL FLATS
		FRINGE	DELTA FRONT	INNER	RIVER-MOUTH BARS BEACHES & BEACH RIDGES TIDAL FLATS
				OUTER	
		DISTAL			

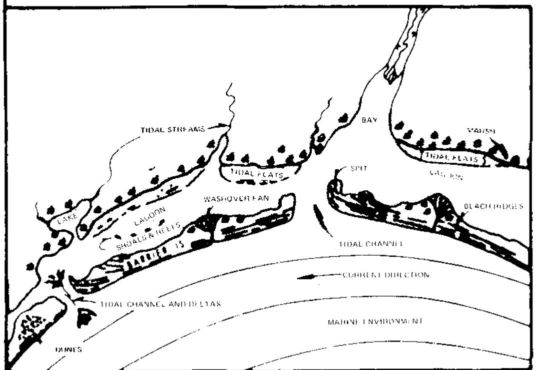
Fig. 1-3. For caption see p.4.


DEPOSITIONAL MODELS
TYPES OF DELTAS
ALLUVIAL PLAIN
FLOOD BASIN
DELTAIC PLAIN ENVIRONMENTS
MEANDER BELT
OLDER COASTAL PLAIN
UPPER DELTAIC PLAIN
SWAMPS
LAKE
LOWER DELTAIC PLAIN
MARSH
DISTRIBUTARY CHANNEL
RIVER MOUTH BARS
INNER FRINGE
SUBAQUEOUS PORTION OF DELTA
OUTER FRINGE
BIRDFOOT-LOBATE DELTA
TIDAL CHANNELS
COASTAL SAND BARRIERS
NARROW SHELF
MARINE CURRENTS
CUSPATE-ARCUATE DELTA
ESTUARINE DELTA
WIDE RANGE IN TIDES
DISTRIBUTARIES EMPTY IN ESTUARIES
NARROW SHELF
ESTUARINE DELTA

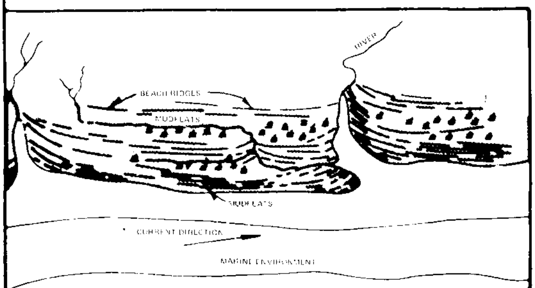
ENVIRONMENTS				
TRANSITIONAL	COASTAL INTER-DELTAIC	COASTAL PLAIN (SUBAERIAL)	BARRIER ISLANDS	BACK BAR, BARRIER, BEACH, BARRIER FACE, SPITS & FLATS, WASHOVER FANS
			CHENIER PLAINS	BEACH & RIDGES
				TIDAL FLATS
			TIDAL	TIDAL FLATS
				TIDAL DELTAS
		SUBAQUEOUS	LAGOONS	SHOALS & REEFS
			TIDAL CHANNELS	
			SMALL ESTUARIES	
MARINE	SHALLOW MARINE	SHELF (NERITIC)	INNER	SHOALS & BANKS
			MIDDLE	
			OUTER	
	DEEP MARINE	CANYONS		
		FANS (DELTAS)		
		SLOPE & ABYSSAL		
		TRENCHES & TROUGHS		

Fig. 1-4. For caption see p.4.

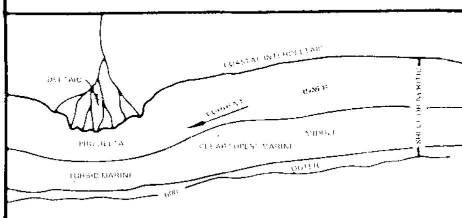
DEPOSITIONAL MODELS



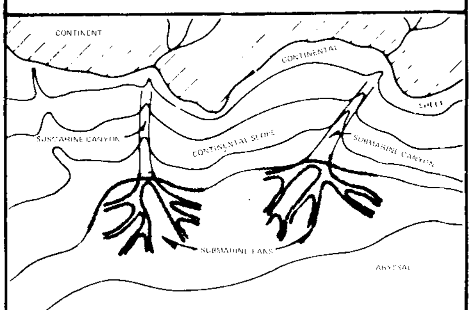
BARRIER IS. COMPLEX



CHENIER PLAIN



SHALLOW MARINE



DEEP MARINE

in grain gradation, which may be reflected in the geophysical log characteristics, and in sedimentary structures and fossil content may be diagnostic.

Discrete sandstone bodies may be the products of erosion, such as elongate strike-valley sands deposited along cuestas, or pod-shaped sandstone bodies formed as erosional outliers. Other elongate sandstone bodies, particularly those that are sinuous or branching, some of which are referred to as shoestring sands, owe their configuration entirely to depositional control. Some have been variously interpreted as off-shore bars, barrier islands, or channel sands depending on the criteria available or current trend of geological thought.

Le Blanc (1972), after Bernard and Le Blanc (1965), set up a classification (Figs. 1-2, 1-3 and 1-4) based on depositional environments and geomorphology. Other classifications have been presented by Laporte (1968), Selley (1970), Kukal (1971), and Crosby (1972). Le Blanc's classification depends in part on the geometry of large sedimentary accumulations such as deltas, barrier island complexes, and submarine fans, but not on the geometry of individual sandstone bodies. Nevertheless, where the geometry of a sedimentary accumulation is known, the probable geometry and depositional trends of sandstone bodies contained within that accumulation can be inferred. It is important to set up, as early as possible during the course of exploration, a conceptual model of the depositional relationships, bearing in mind that the model may be ephemeral and is certain to be subject to modification. Such a model will serve as a working basis with which to test the viability of various interpretations as new data come to hand.

The usefulness of such a model has been pointed out by Le Blanc (1972, p. 135) who states, 'The realm of clastic sedimentation can be divided into several conceptual models, each of which is characterized by certain depositional environments, sedimentary processes, sequences, and patterns.' This type of approach is of particular value in the interpretation of geomorphic and environmental origins of oil and gas fields in sandstone bodies.

Porosity and permeability trends in sandstone bodies are commonly influenced or controlled by depositional trends which in turn reflect geomorphic influences. Where closure in a sandstone body is effected by folding or faulting, the stratigraphic factors may be of minor importance to the distribution of oil and gas. But in the case of a purely stratigraphic trap, the sedimentologic and geomorphic factors, considered with reference to other factors such as regional tilting of the strata and hydrodynamics of formation fluids, are additional keys to future exploration for similar accumulations of hydrocarbons.

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Chapter 1

RIVER CHANNELS

Introduction

Geomorphology

Channel deposits, consisting of sand, silt and clay, fill the valleys cut by a river system. The erosional surface dissected by such valleys may subsequently become an unconformity in the stratigraphic sequence. The channel deposits, which include sediments filling subsidiary channels within the main channel, can have a very considerable aerial extent, as shown by Fig. 1-5, and in the case of a large river may range in thickness to more than 50 m. Within such deposits there may be numerous potential traps for oil and gas in separate sandstone bodies.

The term channel sand implies a cut-and-fill origin. Channels, which may have been cut into older strata exposed as an erosional surface, or into penecontemporaneous sediments of the same river system, such as flood plain deposits, may subsequently be filled with sand. The time lag between cutting and filling, within the same river course or branch, may be negligible and the two processes can be considered as contemporaneous.

Channel sands are deposited within an alluvial valley, or on the upper part of a delta plain. Farther down a river system, on the lower delta plain, the river distributaries form channel-like sand bodies by a process of deposition within their own courses, each distributary flowing out to sea within the confines of its own levee. Distributary sands, commonly referred to as 'shoestring sands' can be distinguished from channel sands by several criteria which will be discussed in the following pages.

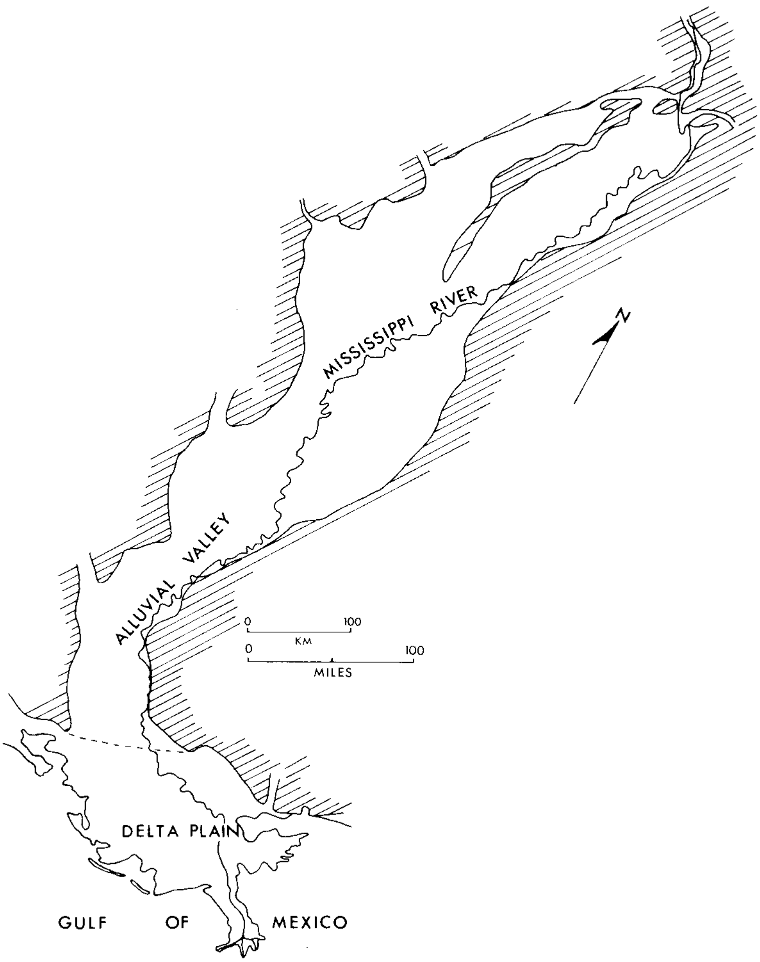


Fig. 1-5 Alluvial valley and delta plain of the Mississippi River. The alluvial valley is underlain by river deposits commonly 150-200 feet (46-61m) thick. (Redrawn from Fisk, 1947).

Individual sand bodies, filling erosional features cut by a river, may be elongate or arcuate depending on the course of the river. As the river course undergoes minor changes, these sand bodies may be entirely or partly re-worked, or may coalesce with younger sand bodies to form a

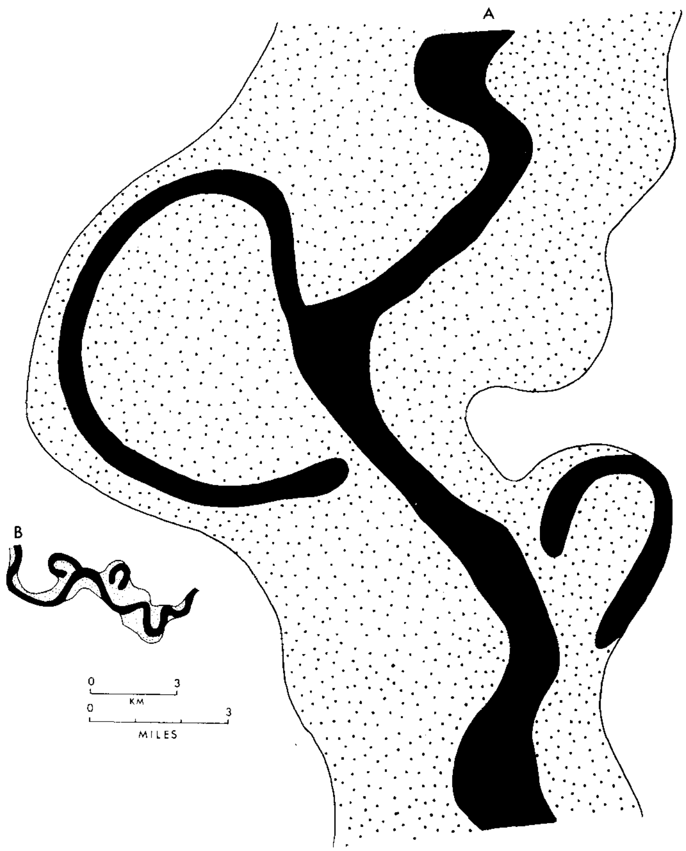


Fig. 1-6 Generalized distribution of meander belts of a large river 'A' such as the Mississippi, and a small river 'B'.

fairly straight or meandering belt up to several miles wide (Fig. 1-6). Such belts have been traced in the subsurface for more than 50 km (Figs 1-34, 1-36, 1-44, 1-50, 1-51). Major changes in a river course result in both lateral shifts of the old meander belt and in the development of new belts. These may eventually coalesce to form an anastomosing system of channel sands within a broad valley. In the case of a large river such as the Mississippi (Fig. 1-5), such a valley can be up to 150 km in width and 1,000km in length.

It will be noted that a distinction has been made between sand bodies formed by the filling of an erosional channel and those formed by a delta distributary that builds rather than cuts its course. Both sand bodies may have superficial resemblances in that both are narrow, linear, and deposited by a river. On closer examination, the assemblage of grain-size distribution, grain gradation, sedimentary structures, and paleontological associations afford criteria which distinguish their origins. These factors, which have been dealt with in great detail in the literature, will be discussed later. But it is recognized that erosional channels are also formed and filled with sand in shoreline environments. The in-filling sand bodies are not point bar deposits, although they may show certain similarities such as grain gradation and planar cross-bedding. The latter sedimentary feature is common in estuaries where the development of cut-and-fill deposits of sand is strongly influenced by tidal movements.

Channel sands, (*sensu stricto*), are deposited as alluvial sediments in a river-cut channel. As such, they consist largely of point bar deposits. Point bars develop along the inner curve of a main loop or meander of a river. As the river cuts into the bank along the outer edge of its curve, the point bar grows by accretion (Fig. 1-7). The basal part of the point bar, consisting of the coarsest fractions of the load such as coarse sand, grit, and gravel, is deposited adjacent to the undercut bank in the deepest part of the river where the current is strongest. On the more gently sloping inner bank of the river, where spill-over bars and large ripples of medium to fine sand are formed, the cross-bedded middle portion of the point bar is deposited. The upper portion of the point bar is normally above river level and is formed during times of flood when heavy loads of fine sand, silt and mud are deposited in shallower water where the velocity is lower than in the main channel. The uppermost beds are essentially horizontal but also show

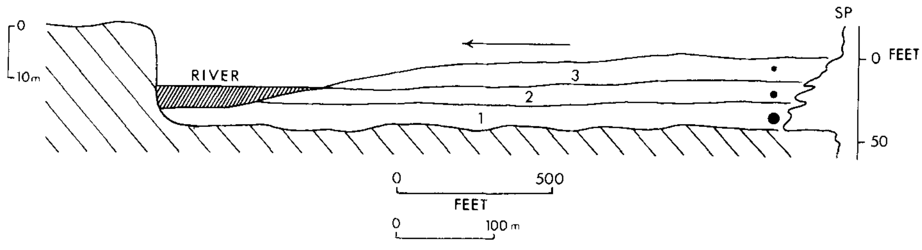


Fig. 1-7 Diagramatic section through a river point bar deposit to illustrate the gradation from coarse sand, grit, and gravel (1) at the base, through cross-bedded sands (2) to horizontal and rippled beds of fine sand and silt (3). The surface of the river is shown during a low water stage. The relationship of a typical E-log self-potential curve to the grain gradation is also shown. The arrow points to the direction of growth of the point bar.

small-scale cross-bedding, commonly of the climbing variety illustrated by Conybeare and Crook (1968, plate 17), formed by small ripples.

E-log Characteristics

As a river moves back and forth across its meander belt it cuts into older point bar deposits and redistributes the sediments. The new channel may not cut down to the base of the old. Consequently, within a thick alluvial section, the sequence shown in Fig. 1-7 could be repeated in whole or in part several times, but always in that order. This sequence of grain gradation, from coarser below to finer above, is characteristic of alluvial deposits and is commonly reflected in the self-potential E-log curve as a bell-shape, or in the case of several superimposed but incomplete sequences, as a block-shape. These shapes, characteristic of cut-and-fill sandstone channel deposits, commonly show a marked deflection at the base of the sandstone unit, indicating an abrupt erosional contact. With upward decreasing grain size the deflection of the self-potential curve also decreases to form a bell-shape. In the case of sandstone bodies of uniform grain size, such as those deposited by delta distributaries and those that have been formed as point bar complexes by successive truncation and deposition, the shape of the self-potential curve is cylindrical or blocky. Alluvial sandstone bodies filling channels are commonly of the latter type as shown in Fig. 1-8.

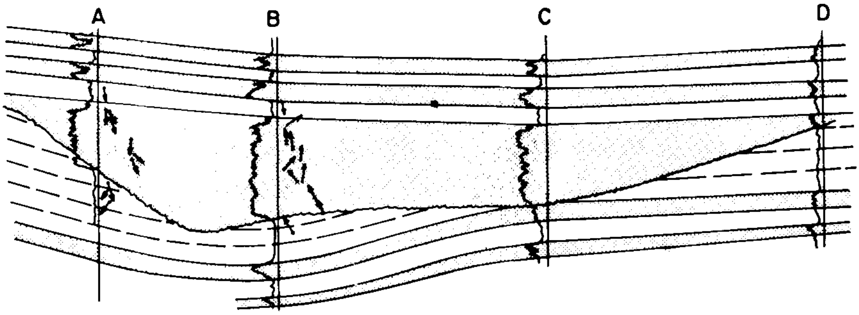


Fig. 1-8 Diagrammatic E-log section showing an erosional channel filled with alluvial sandstone, overlain by alternating beds of sandstone and mudstone. Note the blocky characteristic of of the self-potential curve of the valley-fill sandstone. (After Pirson, 1970, courtesy of Schlumberger Well Services).

The self-potential curve gives an indication of permeability which apart from the effects of cementation caused by the introduction of calcite, etc. and diagenesis, is commonly related to the clay content of the matrix in the original sand. In general the coarser the sand the lower the clay content and higher the permeability. Secondary cementation of the matrix and severe compaction of the sandstone will also affect the permeability and the degree of deflection of the self-potential curve. Consequently, the shape of the self-potential curve, as an indicator of grain-size gradation, must be used with caution.

An example of the relationship commonly obtaining between grain-size gradation and the shape of the self-potential curve is shown in Fig. 1-9 which contrasts the characteristics of sandstones of marine and alluvial origins. Lower Cretacious valley-fill sands (VF) of the Denver Basin, overlain by the Huntsman Formation and underlain by the "J2" Sandstone and Skull Creek Formation, have both blocky and bell-shaped self-potential

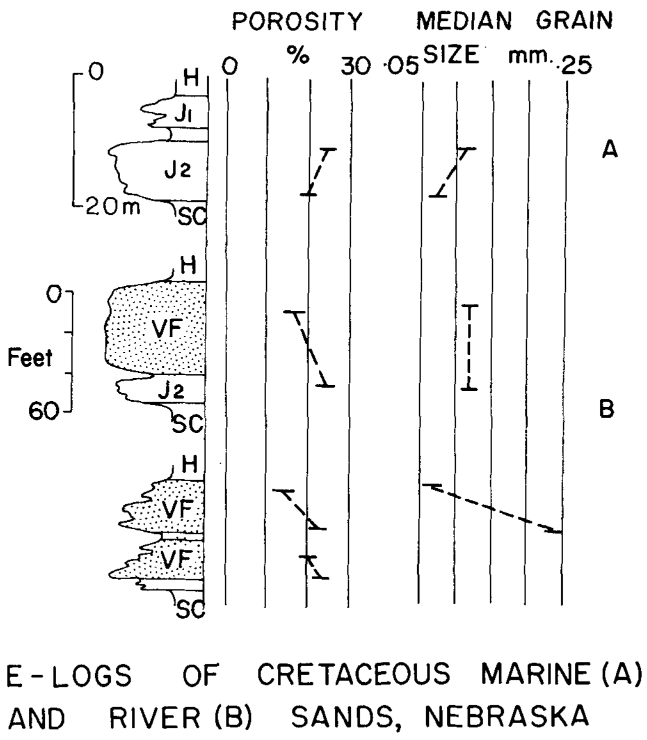


Fig. 1-9 E-log characteristics related to grain size and porosity in the Lower Cretaceous "J2" and valley-fill (VF) sandstones, Denver Basin, Nebraska. (Redrawn from Harms, 1966).

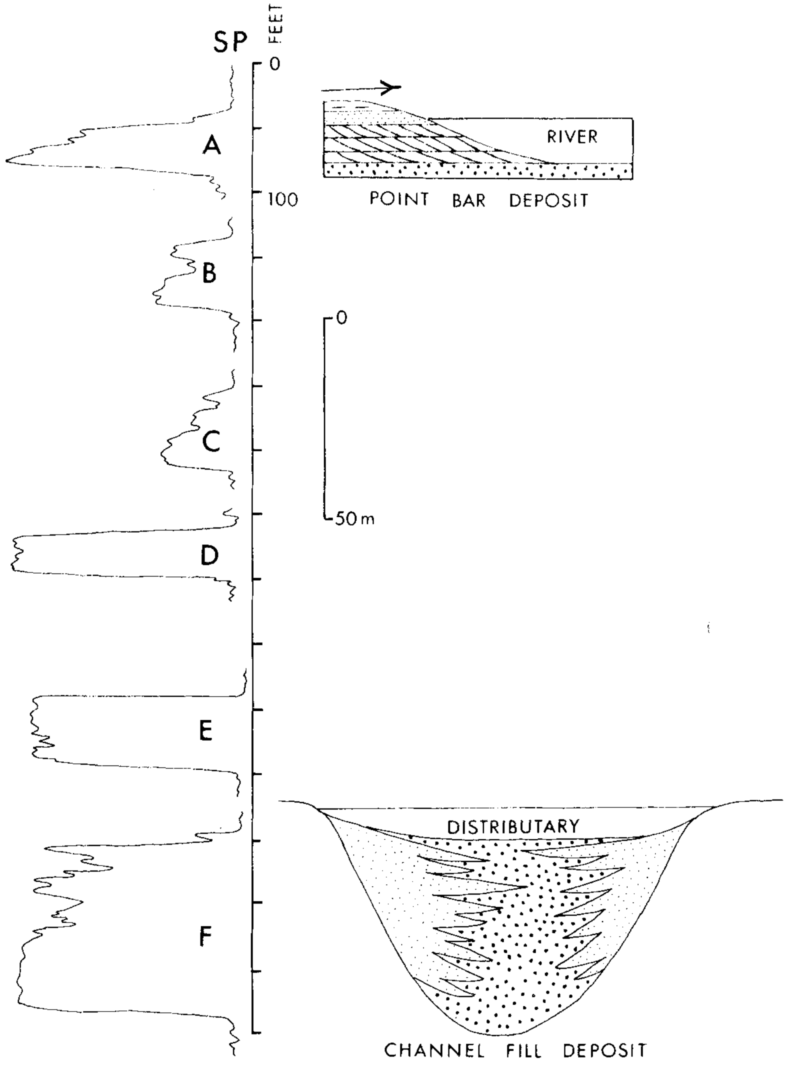
curves which reflect respectively a uniform grain size and a gradation from coarser below to finer above. In the example showing a uniform grain size there also appears to be little variation in permeability, although porosity increases toward the base of the sandstone body. In the example showing an increase of grain size toward the base of the unit both permeability and porosity increase, as indicated by the self-potential curve. In contrast the "J2" sandstone, which originated as a regressive marine shoreline sand, shows a decrease of porosity, permeability and grain size toward the base of the sandstone body.

In this example the main oil and gas production comes from the valley-fill sandstone units, but some is also obtained from the marine shoreline sandstones. The main valley-fill unit, which is above 450 km wide and 15 m thick, trends north-south and has been traced for 40 km. Seven fields have been located along this trend where the axes of north-west-plunging anticlines cross the trend of the ancient valley.

Fig. 1-10 Self-potential curves of electric logs, and generalized sections of point bar and channel fill deposits, showing bell-shape and cylinder-shape characteristics of the log and their relationship to alluvial and deltaic point bar and channel-fill deposits. Arrow indicates direction of growth of point bar. A - Upper Cretaceous Tuscaloosa Sandstone, Wisner Field, Louisiana. B - Oligocene 19B Sandstone, Seeligson Field, Texas. C - Lower Cretaceous Blairmore Sandstone, Carbon Field, Alberta. D - Upper Cretaceous Tuscaloosa "Q" Sandstone, Little Creek Field, Mississippi. E - Miocene "M" Sandstone, West Lake Verret Field, Louisiana. F - Miocene "S" Sandstone, Delta Duck Club Field, Louisiana.

RIVER DEPOSITS

ALLUVIAL AND DELTA DISTRIBUTARY



Other examples of the characteristics of E-log self-potential curves of river point bar and channel deposits are shown in Fig. 1-10. The upper three examples are as follows: A - Upper Cretaceous Tuscaloosa Sandstone, Wisner Field, Louisiana; B - Oligocene 19B Sandstone, Seeligson Field, Texas; and C - Lower Cretaceous Blairmore Sandstone, Carbon Field, Alberta. All show the typical bell-shape characteristic of alluvial sandstone grading from coarser at the base to finer at the top. These sandstones are interpreted as having originally been point bar deposits. The lower three examples have a blocky or cylindrical shape characteristic of sand bodies of uniform grain size, or of a sequence of successively truncated graded beds. They include the following: D - Upper Cretaceous Tuscaloosa "Q" Sandstone, Little Creek Field, Mississippi; E - Miocene "M" Sandstone, West Lake Verret Field, Louisiana; and F - Miocene "S" Sandstone, Delta Duck Club Field, Louisiana. These examples are considered to have been delta distributary sands. The paleogeographic distinction made between the upper and lower examples is somewhat arbitrary. In general, alluvial sand in the middle to upper reaches of a river system shows distinct grain gradation of the point bar type, whereas sand in the lower reaches, particularly in delta distributaries, shows much less gradation and commonly has a fairly uniform grain size.

Kraft, Sheridan and Maisano (1971, p. 671-672) show another example of bell-shaped self-potential curves. These are of meandering river channel sands in the Lower Cretaceous Potomac Group in Delaware (Fig. 1-11). They state, "Spoljaric (1967) presented a detailed analysis of Potomac channel sands (Fig. 12). A sand isolith contour map of one of the meandering Potomac sand units reveals that this Lower Cretaceous nonmarine sequence might well incorporate conditions suitable for petroleum entrapment, particularly in those areas where the Potomac Group sands and their equivalents are more deeply buried in the Baltimore Canyon trough. In

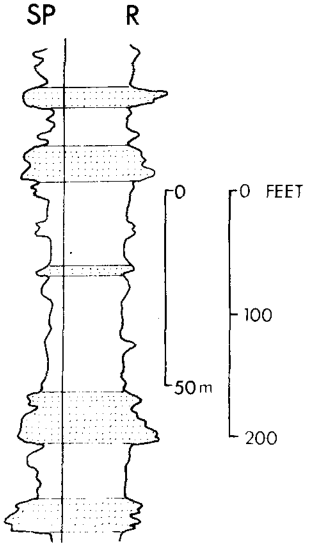


Fig. 1-11 E-log of section through stream channel sandstones (stippled) and floodplain deposits of siltstone and mudstone, in the Lower Cretaceous Potomac Group of Delaware. Note the bell-shaped E-log character of the channel sandstones. (Redrawn from Kraft, Sheridan and Maisano, 1971, after Spoljaric, 1967).

situations such as braided stream and floodplain areas where the Potomac sands comprise up to 50 percent of the total sequence, it is unlikely that separate distinct traps would have formed. However, where lateral facies changes occur in Arundel type paludal or backswamp lithologies, and sands constitute approximately 20 percent of the total section, a distinct separation of sand bodies is more likely, with updip entrapment possibilities in meandering channel sands".

Compaction

Some of the problems involving differential compaction and interpretation of the genesis of sandstone bodies are illustrated in Figs.

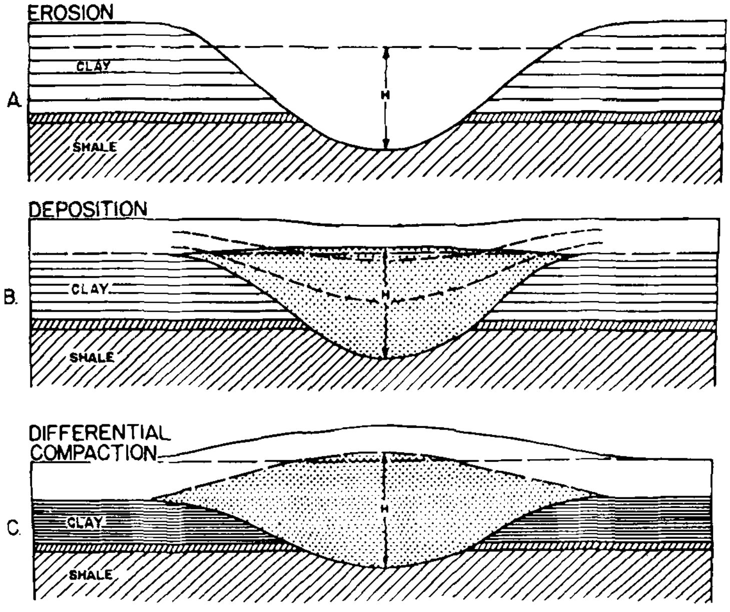


Fig. 1-12 Diagrammatic sections showing A, erosional channel in compacted shale and overlying uncompacted clay; B, channel-fill sand and flanking clay undergoing compaction; and C, compacted clay and warped sand body overlain by sediments draped by differential compaction. (After Pirson, 1970, courtesy of World Oil).

1-12 and 1-13. These problems have been pointed out by Rittenhouse (1961), Oswaldt and Sens (1963), Pirson (1970), and Pettijohn, Potter and Siever (1972). Interpretation of the original geometry of a sandstone body, in particular whether it formed a bar-shaped mound or filled an erosional channel, depends on its relationship to the enclosing beds. If some thin bed or zone within a bed can be chosen as a time-stratigraphic marker, then certain assumptions can be made regarding differential compaction of the

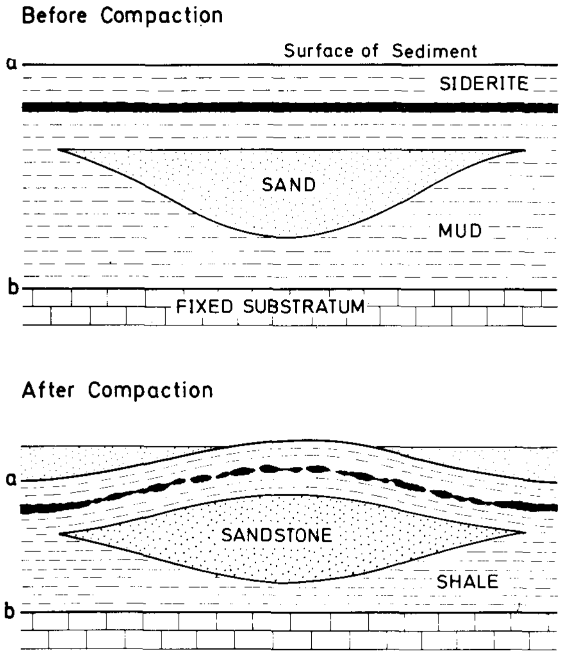


Fig. 1-13 Cross-sections showing distortion of a sand body (lower) resulting from compaction of a channel sand (above). (Modified by Pettijohn, Potter and Siever, 1972, after Dupuy, Oswaldt and Sens, 1963).

sandstone body and its enclosing strata. If such a marker is not available, then interpretation is likely to be equivocal. In all cases, the use of a marker implies certain assumptions as to its configuration at the time of deposition. Commonly, it is assumed that a marker was a fairly flat surface, possibly with minor undulations but with very little warping or tilting. These tacit assumptions can in some cases be misleading. In particular, it is obvious that the choice of a marker either above or below a linear sandstone body can lead to quite different interpretations. In the former case it may be concluded that the sandstone body was originally a channel-

-fill deposit, whereas in the latter case the sandstone body may represent a sand "build-up" such as a bar or barrier island. The implication of either interpretation, in association with the inferred paleogeographic trends, will have a bearing on the direction in which a sandstone trend is extrapolated.

Ancient Sand Bodies

Fluviatile sediments are known within all sequences from the Precambrian System to the Quaternary System. But oil and gas accumulations in fluviatile sediments are known only in Devonian and younger rocks. Some of the known examples of ancient fluviatile sediments have been demonstrated to be channel sands. The criteria for such recognition are mainly geometry of the sandstone body, sequences of grain gradation, and sedimentary structures as indicated by drill-hole and outcrop data. The presence of certain shells, commonly fresh-water gastropods and bivalves, and of abundant carbonized wood fragments is probably indicative of a non-marine origin, although both can be transported to an estuarine or coastal sand environment. Plant matter is also known to be fairly abundant in some deep-water deposits such as the fan formed by turbidity currents sweeping down the submarine canyon of the Congo River (Shepard, 1965).

Composition and sorting are not definitive of depositional environment, although in general, poorly sorted sandstones that are kaolinitic and quartzose, but with a fairly large percentage of lithic fragments, are likely to be of fluviatile origin, formed either as channel sands in a river system or as braided stream deposits on an alluvial fan. Fluviatile sands deposited by delta distributaries are also quartzose, but generally fine-grained, well sorted, and not readily distinguished by lithology from marine shoreline sands.

The oldest known fluviatile deposits, including the Torridonian

Formation of Scotland, are Proterozoic. The oldest known fluviatile deposits of the Cambrian System are molasse sediments of the western Siberian Platform. The oldest known channel sand deposits that have been delineated for distances of several miles are the Ordovician Pulaski and Fayettville Channels of Tennessee.

Pulaski and Fayettville Channels, Tennessee

The Upper Ordovician (Richmondian) Pulaski Channel and Fayettville

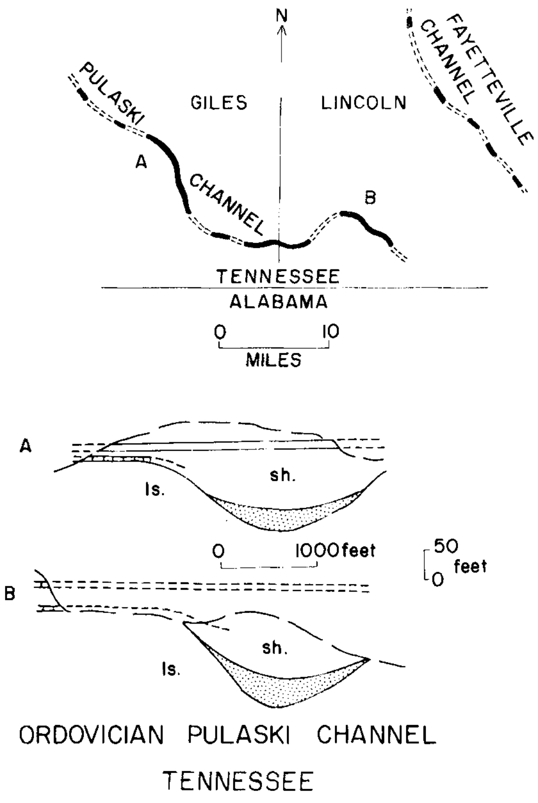


Fig. 1-14 Map and sections of the Ordovician Pulaski and Fayetteville river channels in Giles and Lincoln counties, Tennessee. (Redrawn from Wilson, 1948).

Channel (Fig. 1-14) in Tennessee are locally exposed by outcrops. The Pulaski Channel, entrenched in Lower Ordovician (Trentonian) limestone, is up to 40 m deep, has a width in the range 300-750 m, and has been traced in length for more than 50 km. The basal part of this channel is filled with quartzose, conglomeratic gritstone and abundant rubble of limestone cobbles and boulders. Above the basal section, but within the lower part of the channel, the fill consists of coarse sandstone containing a fairly high percentage of well-rounded quartz grains. Some outcrops of sandstone are up to 10 m thick and show cross-bedding indicating a general current direction from southeast to northwest. The sandstone unit is overlain by greyish green shale which fills the valley and is in turn overlain by sandstone and limestone.

It is of interest to note that the direction of transport of the sand, as indicated by cross-bedding, appears to be at variance with the interpretation of regional Richmondian geography, according to Wilson (1948, p. 743) who states, "These directions are upstream with reference to the direction the eroding stream flowed; landward with reference to the invading sea". He refers to these sands as estuarine and presumably attributes the direction of current bedding to the effect of tidal bores. The shales filling the upper part of the channel are also considered to have been deposited in an estuarine environment to the northwest of an encroaching sea.

Bedford Channels, Ohio

The Bedford Channels (Fig. 1-15), which lie within red shales of the Mississippian Bedford Formation in Ohio, are filled with quartzose sandstone and form a sinuous pattern that has been traced for 100 km in a north-south direction. The pattern shows a marked similarity to patterns of meander loops of the Mississippi River, and is interpreted as a drainage system

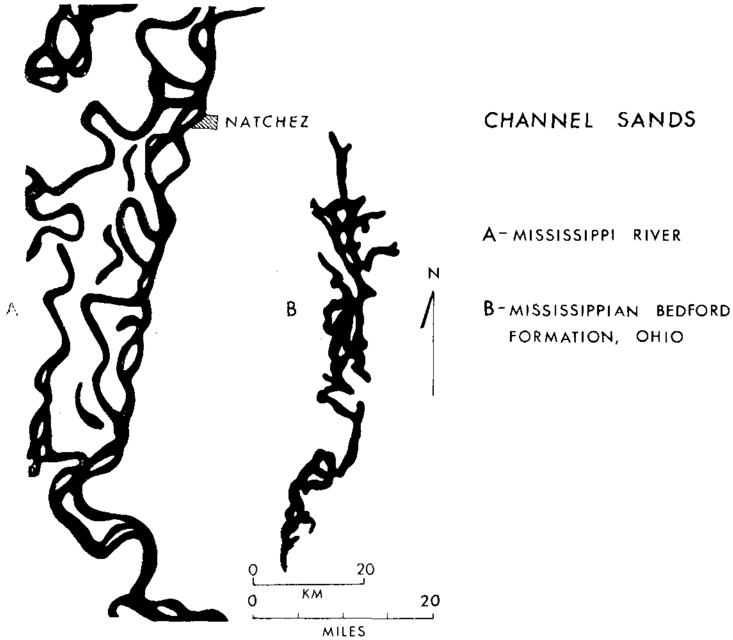


Fig. 1-15 A - Channels of the Mississippi River near Natchez, Mississippi. Drainage from north to south. (Redrawn from Fisk, 1944).

B - Channel sands within the Mississippian Bedford Formation in northern Ohio. Drainage from north to south. Same scale as (A). (Redrawn from Pepper, DeWitt, and Demarest, 1954).

within the Bedford Delta. A slightly younger system of sandstone-filled channels constitutes the basal unit of the overlying Mississippian Berea Sandstone. This basal unit of sandstone occupies channels cut into the Bedford Formation and also locally into the underlying Cleveland Member of the Upper Devonian Ohio Shale. Many of these channels commonly have a width in the range 300-600 m, and depths of up to 60 m. Oil and gas production has been obtained from these younger channels (Fig. 1-28), including the Cabin Creek Channel. In the Cabin Creek Field (Fig. 1-27) gas is obtained from friable quartzose sandstone overlain by a cap rock of silicified quartzitic sandstone. Pepper, De Witt and Demarest (1954) are of the opinion that silicification of the quartzose sandstone resulted from downward cementation of the sand-filled channel.

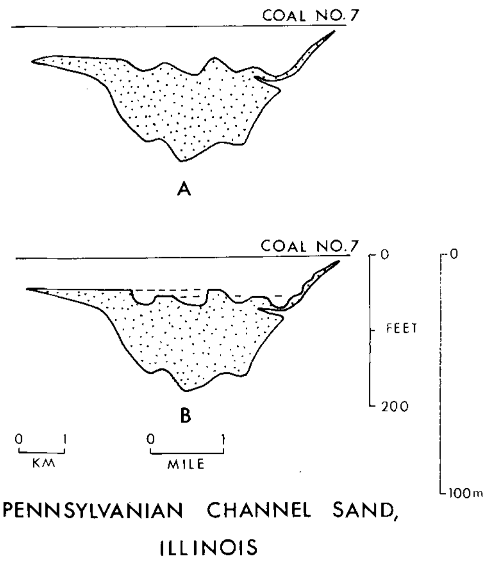


Fig. 1-16 A - Cross-section of Anvil Rock Sandstone, a Pennsylvanian channel sand, in the Illinois Basin. Coal seam No. 7 is taken as a datum. (Redrawn from Potter, 1963).

B - Reinterpretation of (A) to show possible concordance of elevation of remnants of river valley terraces.

Anvil Rock Channel, Illinois

The Pennsylvanian Anvil Rock Sandstone of the Illinois Basin fills channels formed by streams which meandered down a paleoslope and cut into deltaic sheet-like sands (Hopkins, 1958; Potter and Simon, 1961). The section illustrated by Fig. 1-16 shows one channel to have a width of more than 5 km and a thickness of nearly 60 m.

As mentioned earlier, in the section on compaction of channel sands, the choice of a datum may in itself have implicit assumptions as to the genesis and original geometry of a sandstone body. In constructing the shape of a linear sandstone body that may have originated as a channel-fill sand, a datum can be taken below, at the base, at the top, or above the sandstone body. If the sandstone body was, in fact, deposited as a channel sand, then a datum taken on some stratigraphic marker below the body may not be meaningful, as the marker would commonly be deformed by compaction occurring during the growth of the overlying sand body. In the case of a sand body directly overlying an unconformity, a marker below the sand body may have been tilted or otherwise deformed prior to the deposition of the sand. Similarly, if the sand body was originally a channel sand, a datum taken at the base of the body or channel would obviously result in an erroneous reconstruction. A datum taken at the top of the sand body will give a reasonable reconstruction of the cross-sectional shape of the channel sand at the time it was initially buried, provided the surface was nearly flat. But this may seldom be the case. A datum taken on some stratigraphic marker above, but close to the upper surface of the sand body will result in the best reconstruction and may facilitate the interpretation of structurally high parts of the sandstone unit formed as erosional remnants of river valley terraces, and buried as sand hills. Provided they have closure, these "highs" can form reservoirs for oil and gas such as the Bellshill Lake, Hughenden, and Alliance fields in the Lower Cretaceous Ellerslie Sandstone of Alberta (Figs. 1-41, 1-42, 1-43).

Fig. 1-17 Map showing the configuration of a channel sand within the No. 5 coal seam of the Pennsylvanian Carbondale Formation in southeastern Illinois. Medium coal is more than 5 feet (1.5m) thick. (Wanless, 1970, after Trescott, 1964, and Vail, 1965).

Carbondale Channel, Illinois

The Carbondale Channel of southeastern Illinois is an interesting example of an ancient meandering stream that flowed through a flat terrain of marsh and swamp. Within the Pennsylvanian Carbondale Formation the No. 5 coal zone contains a sandstone body that originated as a channel-fill sand. Reconstructed in considerable detail (Fig. 1-17) from subsurface data, the channel appears to have been part of the drainage system of a flat, marshy land that probably formed part of a delta complex. The channel, which is shown to be approximately 2 km in width, can be traced for 100 km. With reference to this channel Wanless (1970, p. 288) says "Because the sandstone does not extend stratigraphically higher than the coal, it does not seem likely that the coal was deposited and subsequently cut out by erosion, but instead the river was discharging through the winding channel while the coal was forming in the adjacent swamp". It is of interest to note that the thicker coal seams are located in a 10 - 15 km-wide belt along which the channel meanders, suggesting that this belt formed a valley in which vegetation accumulated more rapidly than on the adjacent uplands.

Fig. 1-18 illustrates another example of a Pennsylvanian channel sandstone in the Illinois Basin. This sandstone body ranges up to 25 m thick and has been traced along a meandering course for more than 30 km. The pattern of the isopach map is typical of patterns resulting from the superimposition of anastomosing tributaries draining into the main channel, and probably indicates a drainage pattern on a fairly flat terrain.

Another example of a channel cut into a coal-bearing section (Fig. 1-19) is given by Wier (1953). This channel, filled with cross--bedded sandstone, is within the Pennsylvanian Petersburgh Formation of the Illinois Basin. The channel, which has a thickness of up to 20 m and a width in excess of 2 km, has been traced for several kilometers in an

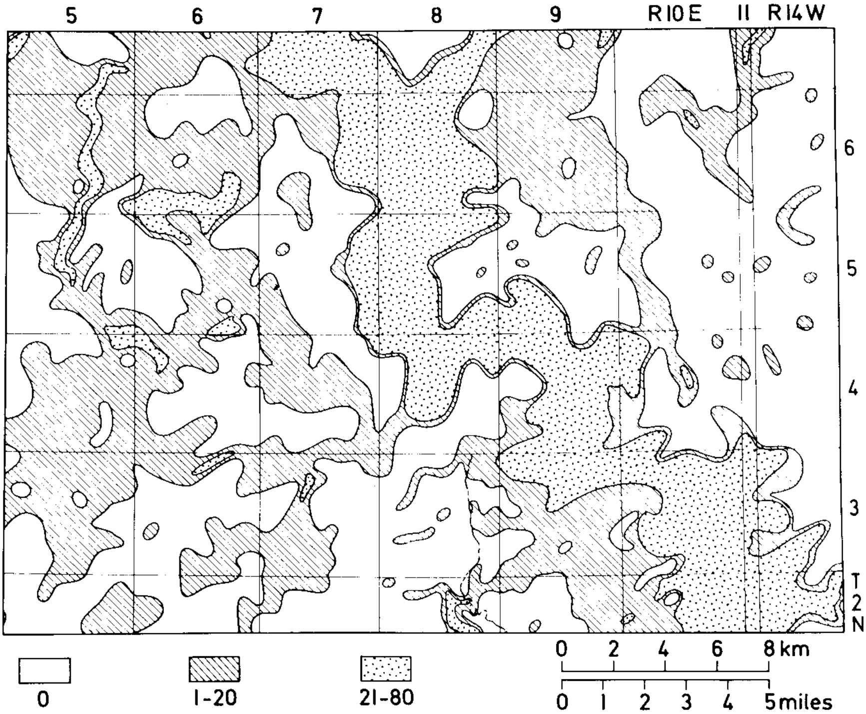
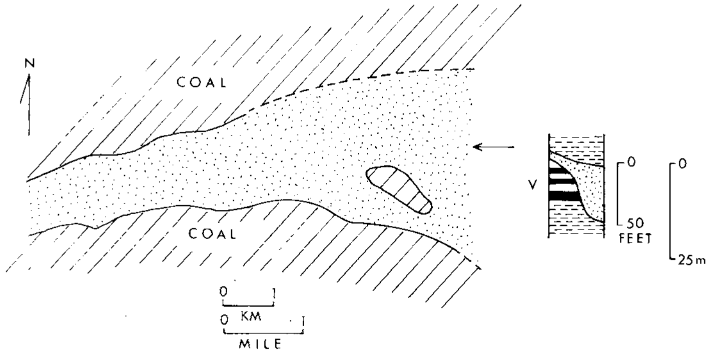


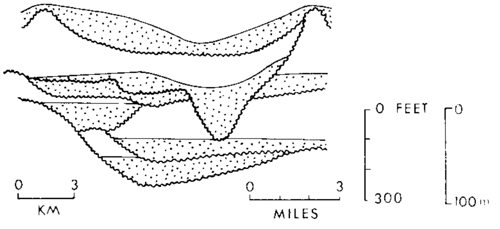
Fig. 1-18 Isopach map of a Pennsylvanian sandstone in the Illinois Basin, showing thickness in feet of a meandering body. (Modified by Pettijohn, Potter and Siever, 1972, after Potter, 1963).

east-west direction. The attitude of the cross-bedding indicates that the current flowed to the west. The channel is believed to have been formed by a delta distributary that flowed through a low-lying coastal marsh. The channel is overlain by siltstone and, of particular interest, by lenticular beds of limestone. This stratigraphic succession suggests that the depositional environment may have been similar to that seen today in parts of Florida, as described by Spackman, Scholl, and Taft (1964).



SANDSTONE CHANNEL IN COAL SEAM,
PENNSYLVANIAN PETERSBURGH FORMATION, INDIANA

Fig. 1-19 Cross-bedded sandstone channel formed in a washout in Coal V, Pennsylvanian Petersburgh Formation, Illinois Basin, Pike County, Indiana. (Redrawn from Wier, 1953).



CROSS-SECTION OF CHANNEL SANDSTONES,
PENNSYLVANIAN GRAHAM FORMATION,
BRAZOS BASIN, TEXAS.

Fig. 1-20 Stratigraphic relationships of unconformable channel sandstones within the Pennsylvanian Graham Formation, Cisco Group, Brazos Basin, Texas. (Redrawn from Lee, 1938).

Graham Channels, Texas

Sandstone-filled channels within the Graham Formation of the Upper Pennsylvanian Cisco Group in the Brazos Basin, Texas, have been described in detail by Lee (1938). The relationships of individual, superimposed channels is illustrated in Fig. 1-20 which shows overlying channels cutting into those below. Individual channels have widths of up to 15 km and depths up to 60 m. The sandstones filling these channels are quartzose, well-sorted, cross-bedded, and locally contain abundant fragments of carbonized plant remains.

The channels, thought to have been cut by a system of anastomosing distributaries, lie within beds of limestone and shale deposited in neritic to paralic environments that probably bordered an extensive and subsiding coastal plain.

Bartlesville Channels, Kansas

Linear sandstone bodies within the Lower Pennsylvanian Cherokee Shale of Kansas and Oklahoma have been variously interpreted. Rees (1972, p. 176) says, "Many workers have studied the "shoestring sands" of southeastern Kansas and northeastern Oklahoma. They have been described as off-shore bars, barrier-island bars, beach ridges, channel sands, dune sands, and point-bar sands. The wide diversence of opinion stems largely from different interpretations placed on the bed geometry." Fig. 1-21 illustrates the trends of two such oil-bearing sandstone bodies in the Chanute Field of Kansas. Reconstruction of the original geometry, by Dillard, Oak, and Bass (1941), shows them as offshore bars with flat bases; although it was noted by these authors that the cross--bedded sandstone bodies overlie a coal seam. Previous studies by Lewis (1929) and later work by Rees (1972) supported the view that the Bartlesville "shoestring sands" are fluviatile in origin and that they were

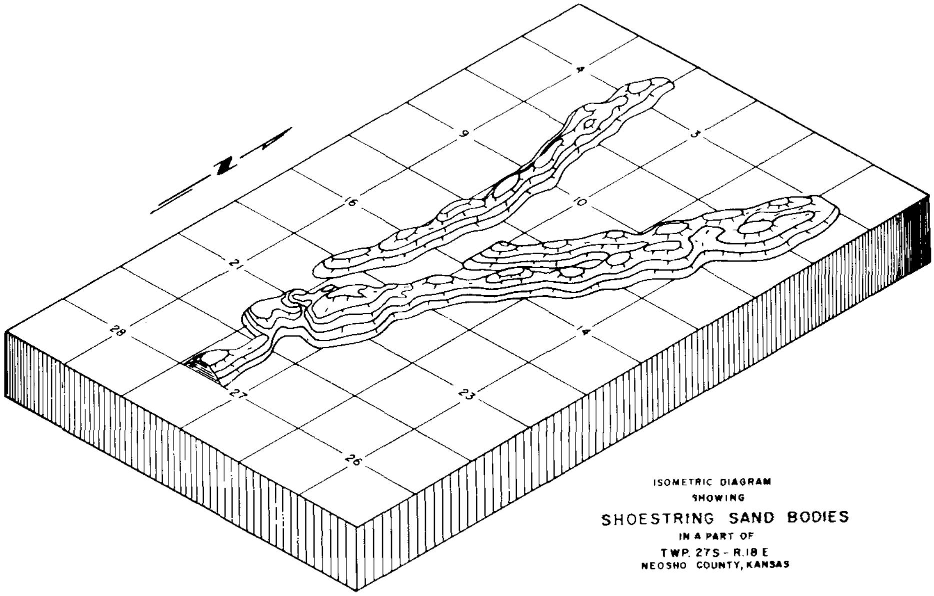
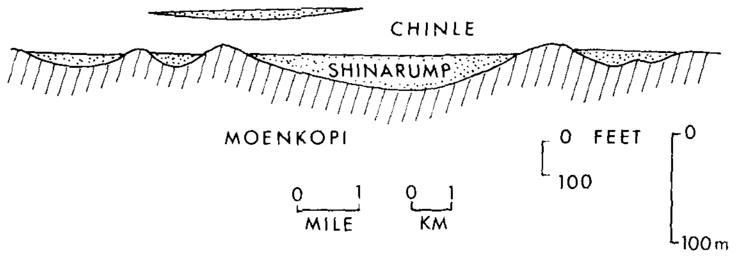


Fig. 1-21 Isometric diagram showing interpreted configuration of a shoestring sand body in the Lower Pennsylvanian Bartlesville Sandstone, Chanute Field, Kansas. The grid is ¼ mile (0.4km) square and the contour interval is 10 feet (3m). (After Dillard, Oak, and Bass, 1941).

deposited by distributaries. These long, narrow sandstone bodies are commonly less than 30 m thick.

Shinarump Channels, Utah

The Upper Triassic Shinarump Formation (Fig. 1-22) of Utah, Colorado, Arizona, and New Mexico comprises fluviatile sandstones and conglomeratic gritstones filling channels eroded in the underlying Lower Triassic Moenkopi Formation. These channels, which form sinuous courses at the base and within the lowermost part of the Upper Triassic Chinle Formation,



SANDSTONE CHANNELS IN TRIASSIC BEDS,

FOUR CORNERS AREA, U.S.A.

Fig. 1-22 Diagrammatic cross section showing sandstone channels at the base of and within the Triassic Chinle Formation. The basal channels, named the Shinarump Formation, cut into the Early Triassic Moenkopi Formation. These formations crop out in the Four Corners area (Utah, Colorado, Arizona and New Mexico) where the Shinarump contains uranium-vanadium mineralization. Contour interval in feet (1' = 0.305m). (Redrawn from Stokes, 1961).

are commonly less than 30 m deep. The channel sandstones are thought to have been point bars, spill-over bars and associated sand bodies deposited by a meandering river that developed an extensive system in the Four Corners region. Carbonized plant remains and cross-bedding are common features in these sandstones. Of particular interest is the fact that the lower parts of these sandstones are mined locally for uranium-vanadium minerals deposited by solutions moving along the more permeable courses of the channels.

Jackpile Channel, New Mexico

The Jackpile Sandstone (Fig. 1-23), which lies within the uppermost part of the Upper Jurassic Morrison Formation in New Mexico, fills a northeast-trending channel that is up to 20 km wide, 60 m deep, and more than 50 km long. The northeastern extension of this channel splits into three separate channels cut by distributaries which flowed to the northeast. The Jackpile, which also fills these subsidiary channels, varies in composition from calcite-cemented feldspathic sandstone at the base to kaolinitic, quartzose sandstone at the top. This variation is thought by

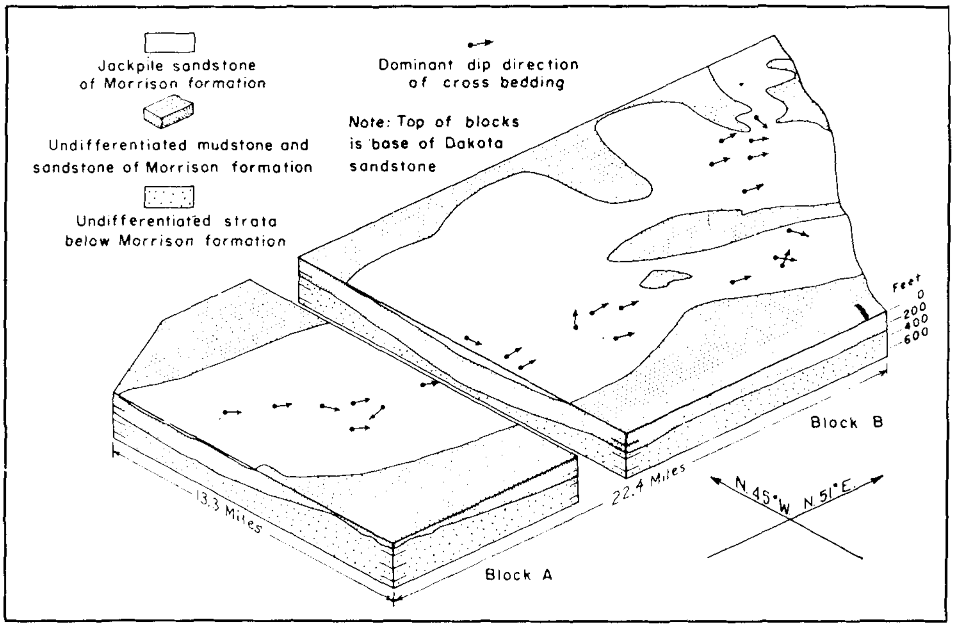


Fig. 1-23 Generalized isometric block diagram showing the configuration of the alluvial Jackpile Sandstone, the uppermost member of the Upper Jurassic Morrison Formation, New Mexico. (After Schlee and Moench, 1961).

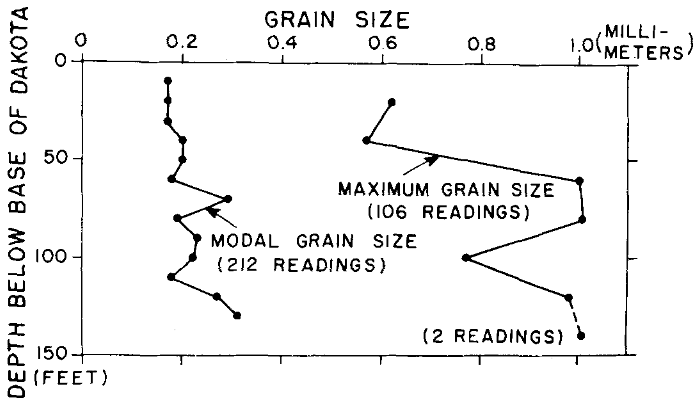


Fig. 1-24 Vertical gradation in grain-size within the alluvial Upper Jurassic Jackpile Sandstone, New Mexico. (After Schlee and Moench, 1961).

Schlee and Moench (1961) to be the result of weathering prior to the deposition of the overlying Lower Cretaceous Dakota sediments. These channel sandstones are moderately well sorted, cross-bedded, fine to medium-grained, and show an overall fining from bottom to top (Fig. 1-24). The Jackpile is an important host rock for uranium minerals mined in the Laguna area, west of Albuquerque, New Mexico.

Oil and Gas Fields

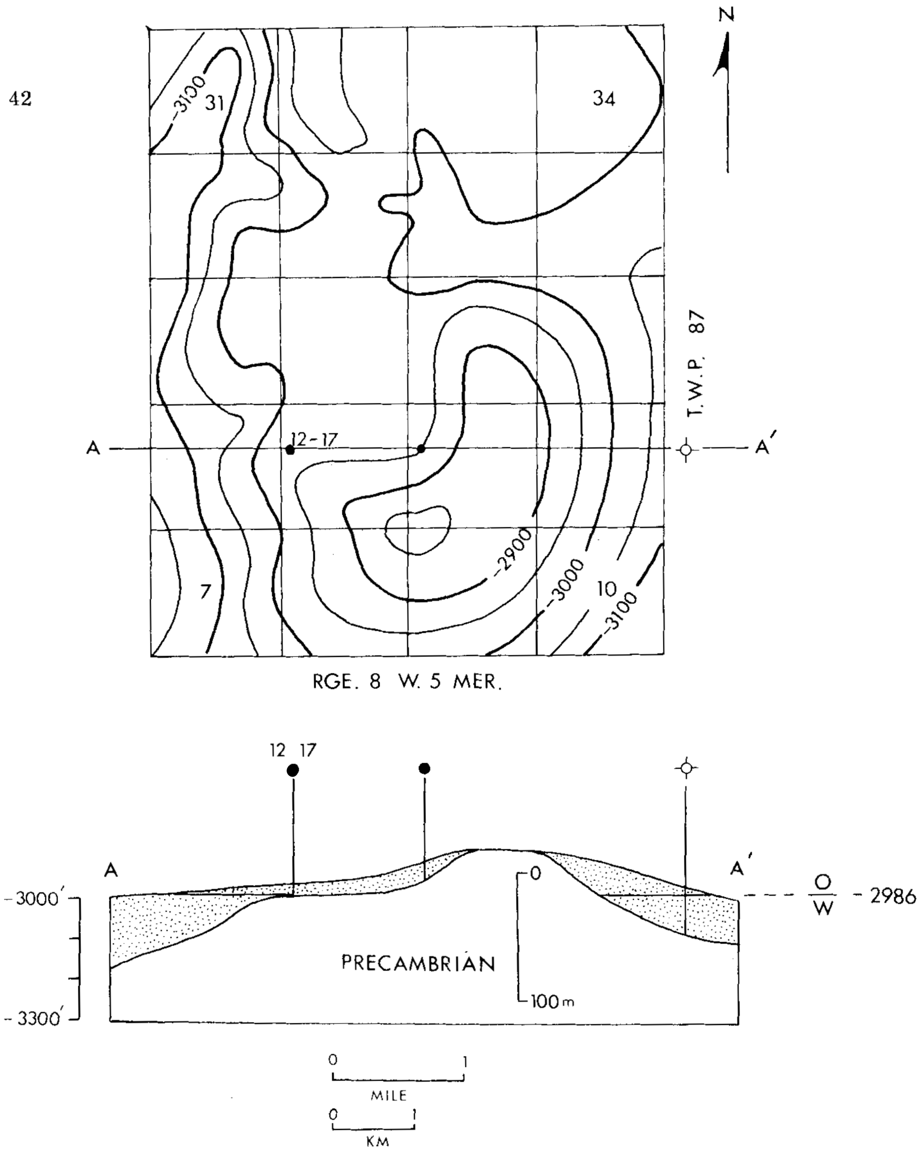
Fluviatile sandstones have been recorded in all Systems from Proterozoic to Quaternary inclusive, but oil and gas accumulations are not known in fluviatile sandstones older than the Devonian. The ages of twenty-eight examples given in this book are as follows: Devonian -2, Mississippian -3, Pennsylvanian -5, Permian -1, Triassic -1, Jurassic -1, Cretaceous -12, and Tertiary -3. Although it would appear from this limited sampling that the Cretaceous occupies a special place favouring the accumulation of hydrocarbons in river sediments, it must be pointed out that the examples given are from the Alberta, Powder River, and Denver basins where the Mesozoic has been extensively drilled. There is no basis for assuming, on a world-wide basis, that fluviatile deposits were more abundant in one Period than in another.

Red Earth Oil Field, Alberta

In the Red Earth Field (Fig. 1-25) of northern Alberta oil is produced from the basal Paleozoic Granite Wash which lies on the eroded Precambrian surface. The age of the Granite Wash has not been determined; but it is overlain by anhydritic and dolomitic carbonates of the Middle Devonian Muskeg Formation, and is probably Early Devonian. The Granite Wash is mainly a fine to very coarse, poorly sorted quartzose and feldspathic sandstone, of sub-rounded to angular grains, but contains thin beds of greenish shale having a waxy appearance. Lying on the basement topography it thins over the "highs" and thickens to 30 m of more in the "lows". Maximum thickness of the net porous sandstone is 20 m, and the average thickness of the net producing sandstone is 5m. Permeability is good, being in the range 120-120 millidarcys vertically, and 300-450 millidarcys horizontally. Porosity averages 14%.

The oil recovered has a gravity of 38°A.P.I., a paraffin base, and a sulphur content of 0.3%. The estimated amount of oil in place within two separate pools is 110 million barrels of which only 22 million barrels (3.5 million cubic metres) are likely to be recovered by means of the field's natural water drive.

The term 'granite wash' implies a sandy sediment, probably of quartzose and feldspathic composition, derived and transported from granitic and gneissic terrain. Flawn (1965, p. 885) says, "If it is not a transported sediment and it is not "washed", the terms weathered granite or altered granite or decomposed granite are more accurate". Filling topographic



STRUCTURAL MAP AND SECTION, RED EARTH FIELD, ALBERTA

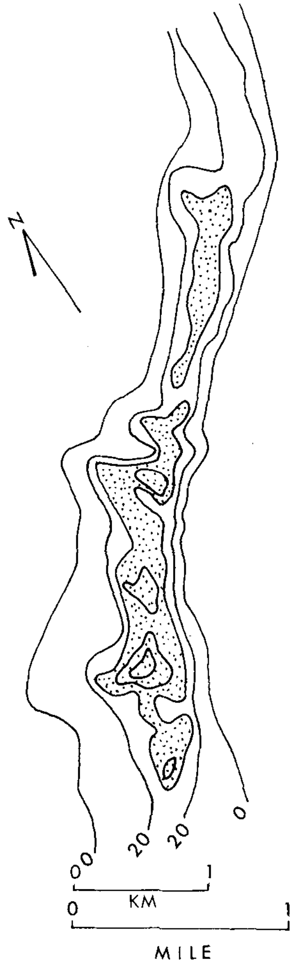
Fig. 1-25 Structural map showing configuration of the Precambrian surface under the Red Earth Field, Alberta. Contour intervals in feet sub-sea level. Structural section A-A' shows the oil-bearing Middle Devonian Granite Wash draped over a Precambrian topographic 'high'. The oil-water contact is at -2986 feet (-911 m) sub-sea level. (Redrawn and reinterpreted from Chilton, 1959, and Hunter, 1966) depressions, the poorly sorted Granite Wash in the Red Earth Field was evidently not moved very far from its area of origin and was apparently transported by surface-water which ran off the slopes and formed a drainage system along valleys eroded in the Precambrian basement. As the valleys filled with granitic debris, the basement hills were eventually buried by wedges of Granite Wash swept out on a fairly flat outwash-plain. On this surface the encroaching Muskeg Sea developed a carbonate bank fringed by coastal sabkhas in which gypsiferous deposits were formed.

The Granite Wash originally consisted of alluvial sands and minor muds, much of which were probably fluviatile. Little is known of the paleogeomorphology of this unit, and it can only be surmised that channels may exist which could contain accumulations of oil in structural--stratigraphic situations resulting from compaction over basement topography, regional tilting of the strata, and water drive.

Music Mountain Oil Pool, Pennsylvania

The Music Mountain Oil Pool (Fig. 1-26) in McLean County, Pennsylvania is in the Upper Devonian Sliverville Sandstone of the Canadaway Group. This sandstone is quartzose, medium to coarse-grained, in part conglomeratic, and consists of sub-angular to angular grains. Porosity averages 13%, and permeability ranges up to several hundred millidarcys. Angular claystone fragments, resembling fragments of sun-dried clay, are contained within the sandstone.

In the producing area the Sliverville Sandstone forms a channel-like body which trends northeast-southwest on the flank of an anticline. This sandstone body, which has been traced for more than 6 km, is 250-300m wide and up to 25 m thick. The Canadaway Group, of which it forms a part, consists of interbedded grey shale and fine to coarse brownish sandstones. Fettke (1941) considered the group to be marine, and interpreted the



GEOMETRY OF SLIVERVILLE SANDSTONE, PENNSYLVANIA

Fig. 1-26. Isopach map of Sliverville Sandstone in the Upper Devonian Canadaway Group, Music Mountain Oil Pool, McLean County, Pennsylvania. Contour interval in feet (1' = 0.305 m). (Redrawn from Fettke, 1941).

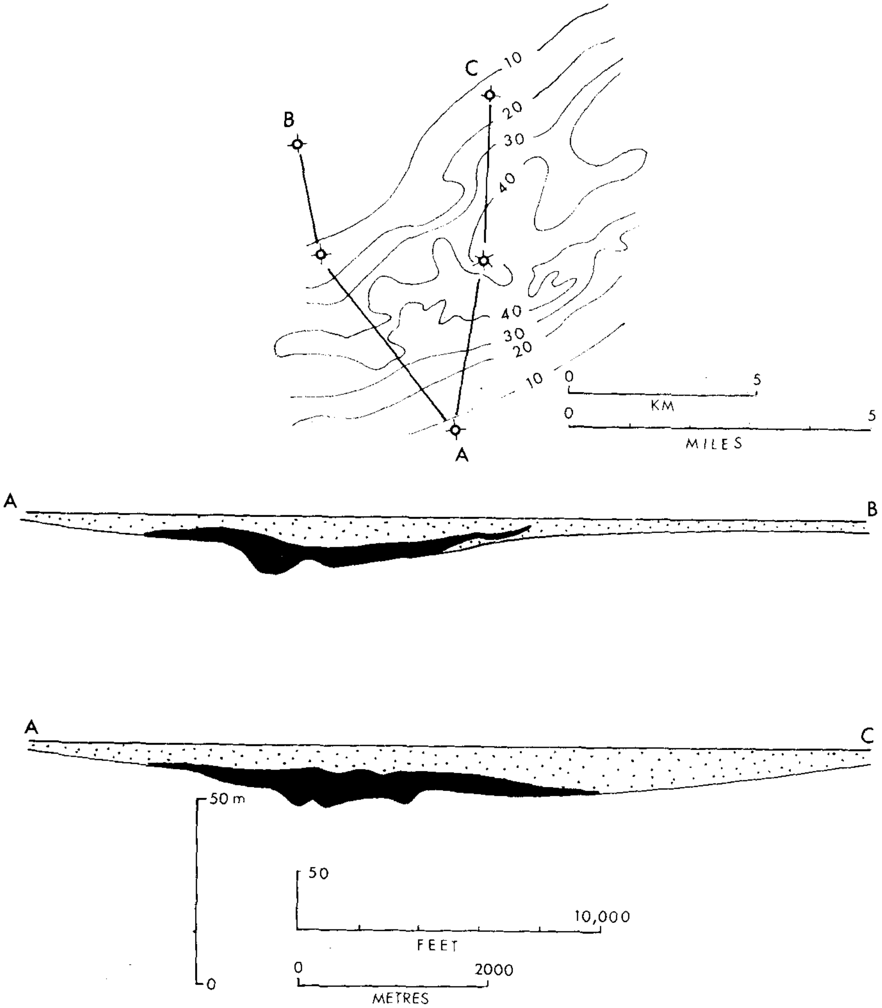
Sliverville Sandstone as an offshore bar. The nature of the sand (in part coarse-grained and pebbly, consisting of sub-angular to angular grains, and containing angular chips of claystone resembling fragments of dried mud) indicates a fluviatile rather than a wave-washed environment, and suggests that the Sliverville sand body was probably a delta-distributary sand.

The Music Mountain Oil Pool yields both oil and gas, the oil having a paraffin base and a waxy content. It is of interest to note, in this respect, that Hedberg (1968) concluded that waxy oils were characteristically derived from sandstone-shale sequences of non-marine or paralic origin. The field has a gas drive, and during its early history initial producing rates of up to 500 barrels of oil and 15 million cubic feet of gas per day were recorded.

Cabin Creek Gas Field, Ohio

Production of gas and some light (47° A.P.I.) oil in the Cabin Creek Gas Field, Ohio (Fig. 1-27) has been obtained from the Early Mississippian Berea Sandstone. In the field area the Berea occupies a broad, sinuous channel cut into the Mississippian Bedford Formation. This channel is 5-6 km wide, up to 15 m deep, and has been traced in the sub-surface for more than 15 km. It appears to be part of a drainage system that trended north-south for more than 80 km.

In the lower part of the channel the Berea Sandstone is light grey, quartzose, and coarse to gritty with well-rounded pebbles. The sand grains are angular. In the upper part of the channel the sandstone is finer grained, hard, and well-cemented by quartz. This quartzitic sandstone, which has a porosity of only 4% compared with an average porosity of 16% in the lower sandstone, forms a cap rock for the gas contained in the sandstone below.

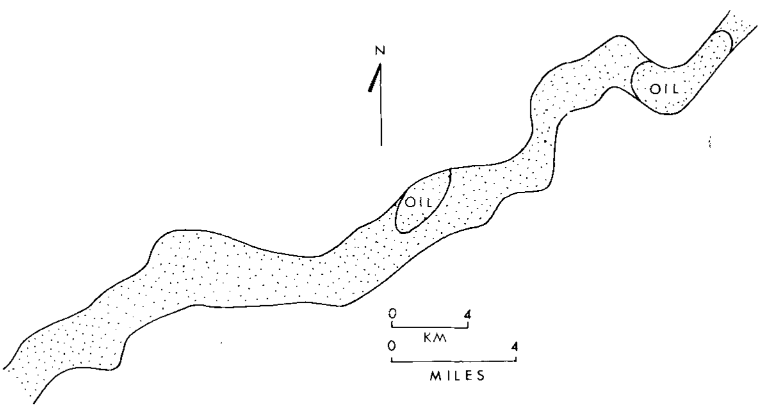


ISOPACH AND SECTIONS OF MISSISSIPIAN
BEREA SAND, CABIN CREEK GAS FIELD, OHIO

Fig. 1-27. Isopach map of part of the Mississippian Berea Sand in the Cabin Creek gas field, Ohio, showing thickness in feet of the sandstone body. Sections AB and AC show tightly-cemented quartz sandstone (stippled) and the basal poorly-cemented, gas-bearing quartz gritstone (solid). (Redrawn from Pepper, De Witt and Demarest, 1954).

Gay-Spencer-Richardson Trend, Virginia

Oil and gas production has been obtained from the Early Mississippian Berea Sandstone in the Gay-Spencer-Richardson fields (Fig. 1-28) of western Virginia. These fields merge with one another along a northeast-southwest trending channel filled with Berea Sandstone. The channel is up to 5 km wide and 40 km long in the field area, and extends a further 55 km to the northeast. The sandstone, which is similar in composition and texture to the Berea in the Cabin Creek Gas Field of Ohio, is underlain by grey, silty shale and overlain by brown shale containing abundant carbonized plant matter. The contact between the overlying shale and the Berea is marked by an abundance of pyrite.



DISTRIBUTION OF OIL AND GAS PRODUCTION IN BEREA SANDSTONE, WEST VIRGINIA

Fig. 1-28. Distribution of oil and gas production in the Early Mississippian Berea Sandstone, Jackson, Roane, and Calhoun Counties, West Virginia. (Redrawn from distribution of oil and gas wells plotted by Heck, 1941).

Gas has been produced along the entire Gay-Spencer-Richardson trend which is intersected by north-south trending fold structures. Of particular interest is the fact that the Berea in this locality is not water-bearing, and consequently the oil accumulations are within synclines. Although the sandstone is dry, the early producing wells showed that pressure within the sandstone was consistent with hydrostatic pressure for the depth of measurement. The oil was first obtained by gas drive and some early wells had initial production rates of up to 750 barrels of oil and 10 million cubic feet of gas per day.

Bethel Sandstone Trend, Kentucky

Several oil and gas fields in western Kentucky, including the Midland, St. Charles, Barnsley, Luzerne, Sharon School, and Elk Creek, have produced from the Upper Mississippian Bethel Sandstone. The Bethel fills a channel (Fig. 1-29) cut into the Middle Mississippian (Meramecian) limestones and shales, and is overlain by Upper Mississippian (Chesterian) limestones. The channel, which is 3 km wide, has been traced in the subsurface for a distance of more than 160 km southwest from where it crops out. Toward the southwestern limits to which it has been traced the channel branches and contains several oil and gas accumulations in structural-stratigraphic traps, including Midland Gas Field. Similar types of traps containing oil are found in sandstone-filled distributary channels cutting limestone and shaly beds in a deltaic sequence of the Upper Pennsylvanian to Lower Permian Cisco Group in north-central Texas (Galloway and Brown, 1973). Many of these are commercial oil fields.

The Bethel Sandstone in the Midland field has a gross thickness of up to 75 m and a maximum producing section of 55 m. The mean permeability is 117 millidarcys and the mean porosity is 13%. The Midland field is estimated to have originally contained 163,000 million cubic feet (4,560 million cubic metres) of recoverable gas averaging 98% methane, and several

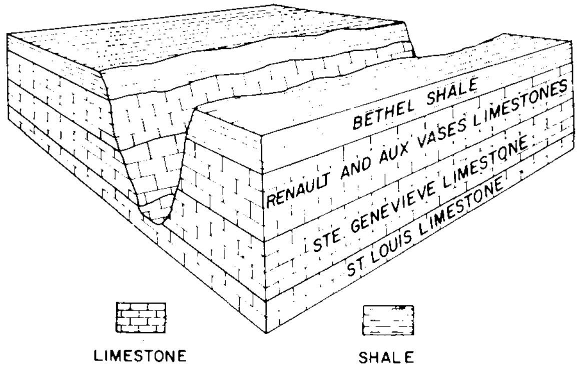


Figure 4A. Pre-Bethel erosion channel.

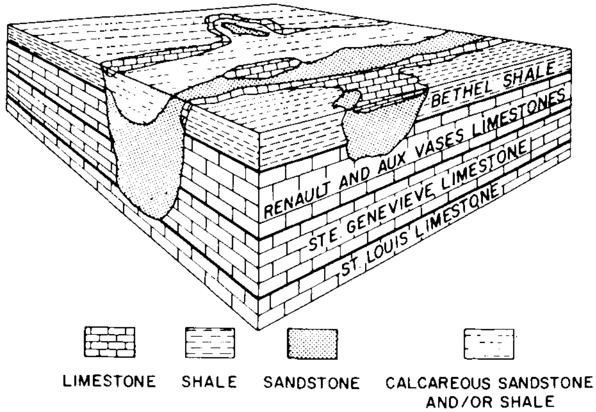


Figure 4B. Channel after Bethel deposition and backfill.

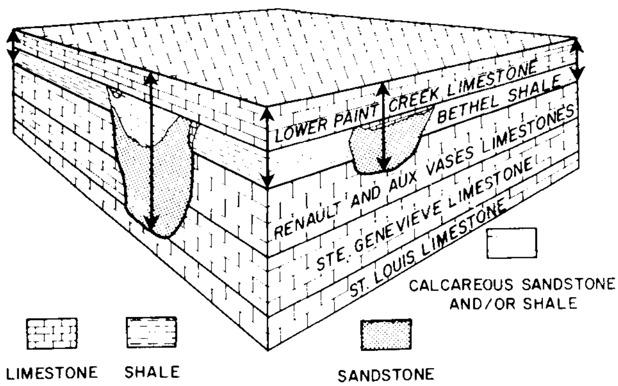


Fig. 1-29. Schematic block diagrams showing the stratigraphic relationships of the channel-forming Upper Mississippian Bethel Sandstone to the overlying Upper Mississippian (Chesterian) and underlying Middle Mississippian (Meramecian) sediments, Kentucky. (After Reynolds and Vincent, 1972).

tens of millions of barrels of heavy (24° A.P.I.) oil. The volume of gas--producing sandstone is estimated to be 542,000 acre-feet.

Tyler Oil Fields, Montana

Oil is produced from three sandstone members in the lower unit of the Lower Pennsylvanian Tyler Formation of central Montana. These sandstone members fill channels within a broad, meandering valley (Fig. 1-30)

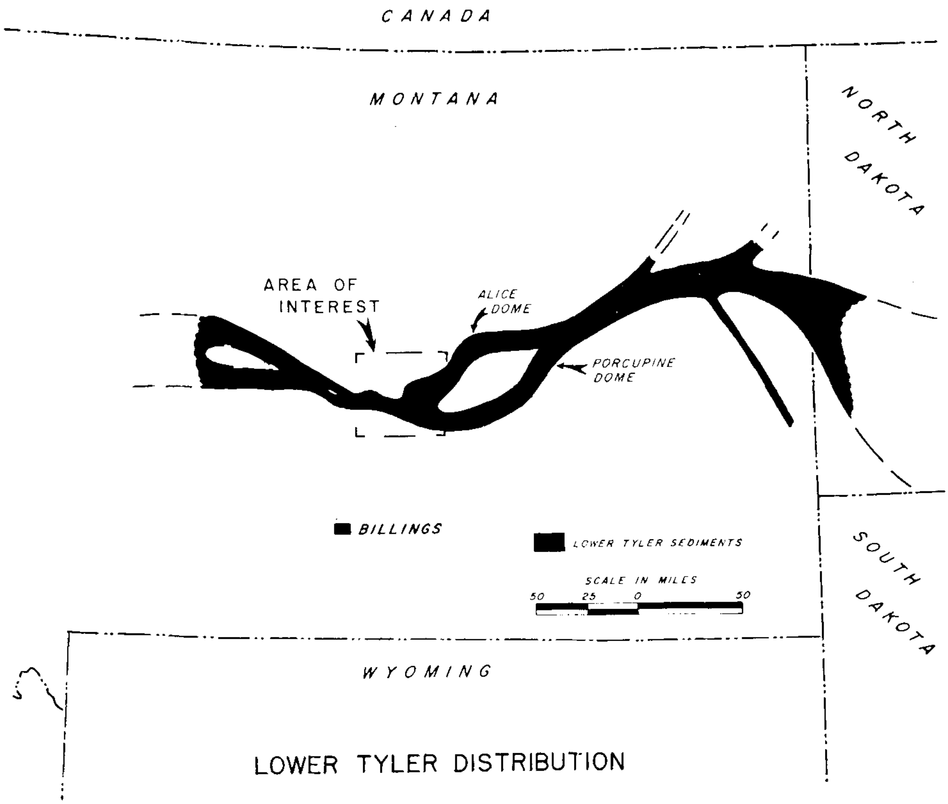


Fig. 1-30. Distribution of channel sandstone members in the lower unit of the Lower Pennsylvanian Tyler Formation, Montana. (After Kranzler, 1966).

trending for more than 500 km eastward across central Montana into North Dakota. This valley cuts into limestone and shale members of the Mississippian Heath Formation (Fig. 1-31). The lower two sandstone members lie on the erosional surface; the upper sandstone member, called the Stensvad Sand, occupies a stratigraphically higher position within the valley-fill sediments of the Lower Tyler.

The post-Mississippian valley, in which the Lower Tyler sediments

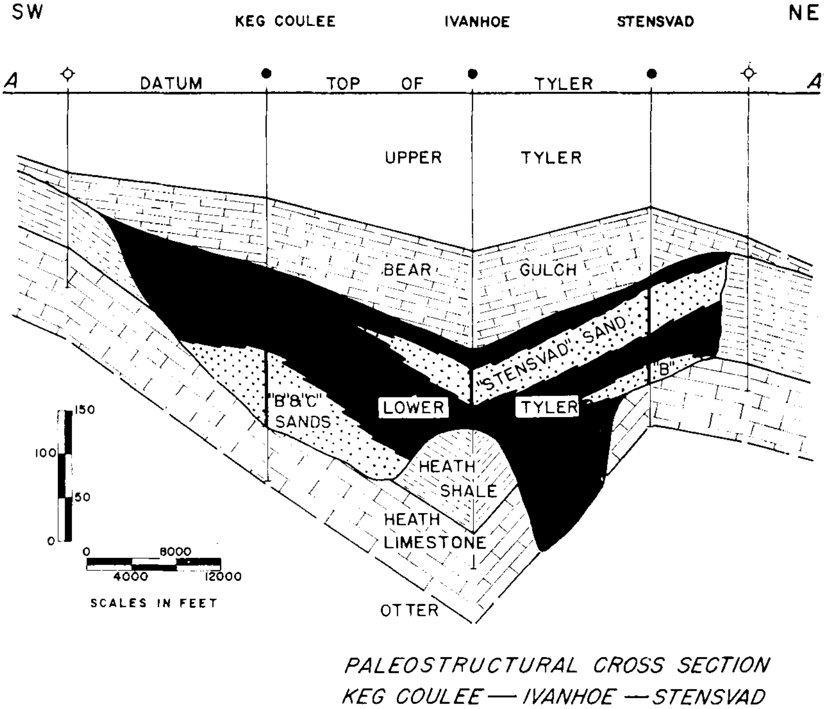


Fig. 1-31. Section of erosional valley in Mississippian Heath Formation, through the Keg Coulee, Ivanhoe and Stensvad fields, showing stratigraphic relationships of oil-bearing sandstone members within the lower unit of the Lower Pennsylvanian Tyler Formation, Montana. (After Kranzler, 1966).

lie, has a depth of up to 100 m and a width of up to 15 km. It is filled mainly with silts and grey shales (containing abundant carbonaceous plant remains) deposited as flood plain and backswamp muds. The sandstone members, which are fine-grained at the top, grading downward to grit and conglomerate at the base, are 10-45 m thick.

Oil has been trapped within these sandstone members at certain localities where local folding of the strata has formed structural closures, and apparently where the sandstone is in contact with the Heath Limestone which may be the source-rock. Local variations of permeability and lenticularity of the sandstone members, structural control, and proximity to limestone beds (through which the oil has migrated, and in which it may also have been generated) are key factors controlling the oil accumulations.

Eight fields producing from these sandstone members of the Lower Tyler contain estimated total cumulative reserves of 70 million barrels (11 million cubic metres) of recoverable oil.

Delaware Extension Oil Field, Oklahoma

Oil production in the Delaware Extension Field, Oklahoma, (Fig. 1-32) is obtained from the Bartlesville Sandstone in the middle part of the Lower to Middle Pennsylvanian Cherokee Formation, a shaly sequence. In the field area the Bartlesville forms a linear sandstone body 600 - 1800 m wide, and up to 20 m thick. It has been traced for more than 10 km and is interpreted by Lewis (1929) as a channel deposit having a northwesterly provenance. Dillard, Oak and Bass (1941), on the other hand, interpreted the Bartlesville Sandstone of the Chanute Oil Field, Kansas, as an offshore bar. They noted, however, that the Bartlesville was not only cross-bedded, but was immediately underlain by a coal seam. In a paralic environment either interpretation could be correct, although a cross-bedded sandstone overlying coal is probably of fluviatile origin. Lewis (1929, p. 364) states,

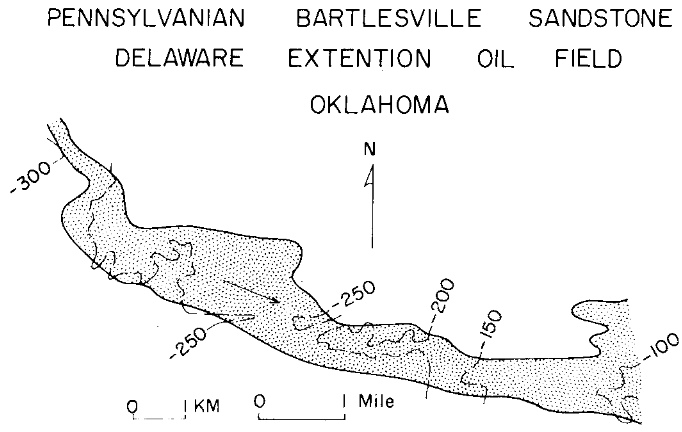


Fig. 1-32. Map showing the distribution and subsurface structure of the oil-bearing, lower Pennsylvanian Bartlesville sandstone, Delaware Extension Field, Nowata County, Oklahoma. The sandstone is interpreted as a channel sand deposited by a river flowing in a southeasterly direction indicated by the arrow. (Redrawn from Lewis, 1929).

"Conditions of the sand in the Delaware Extension pool indicate a condition similar to the northwest-southwest shoestring-sand pools of eastern Kansas". The correctness of this interpretation is further supported by the erratic distribution of the sandstone, typical of river deposits, which was noted by Lewis (p. 364) who says, "In several places, wells with thick sand and rich production offset locations in which no sand was found".

The Delaware Extension Field yields oil from a comparatively shallow depth. At the eastern end of the field the top of the producing Bartlesville Sandstone is 30 m below sea level and 240 m below the surface, and at the western end the sandstone is 335 m below the surface. Initial production from some wells was at rates exceeding 1,000 barrels a day, the best production being obtained from friable sandstone lenses or stringers along the trend of the main sandstone body. As noted by Lewis (1929), poor production, or no production was in some cases found in wells adjacent to those with good production from the friable sandstone lenses. The explanation probably lies in the interpretation that the productive lenses and stringers were deposited as local stream channel fillings of permeable sand, whereas the laterally adjacent beds were river flood plain deposits of relatively impermeable silts. The Bartlesville Sandstone in the area of the Delaware Extension Field is a westward extension of oil-bearing sandstones that are thought to have been marine offshore sands.

Bush City Oil Field, Kansas

Stratigraphically higher than the Bartlesville Sandstone, within the uppermost shaly section of the Lower to Middle Pennsylvanian Cherokee Formation, a sinuous sandstone body known as the Squirrel sandstone is the oil producer in the Bush City Field, Kansas (Fig. 1-33). This sandstone body, which is interpreted as a channel-fill sand, has a thickness of up to 15 m, a width of up to 300 m, and has been found to be oil-bearing for 24 km along its course. The channel-fill sediment, which shows a fining upward in mean grain size, consists of 5-6 m of fine-grained, micaceous, oil-bearing sandstone overlain by up to 10 m of alternating beds of sandy shale and shaly sandstone containing stringers of carbonaceous matter.

The producing sandstone, composed of sub-angular grains, has a porosity of 17-22% and a permeability of up to 60 millidarcys. Initial oil production from individual wells has ranged up to 800 barrels a day, but averaged 60 barrels a day. The oil, initially produced by gas-drive, has a gravity of 35^{o} A.P.I. Although the most productive wells have some structural control, the field is essentially stratigraphic, being

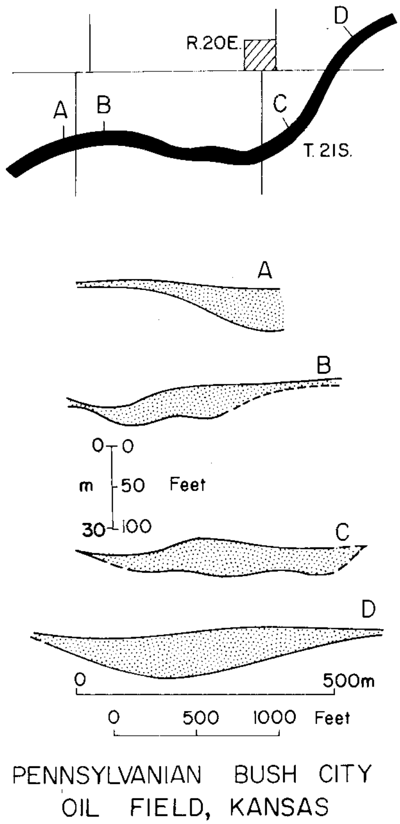


Fig. 1-33. Map and sections of the Bush City oil field, Anderson County, Kansas. The oil-bearing sandstone forms a sinuous body, and is thought to be an alluvial channel filling. (Redrawn from Charles, 1941).

terminated up-dip by an increase in the clay and silt content of the sandstone, with consequent decrease in porosity. The best wells are situated at the junctions of the sandstone body and the crests of low anticlines having closures of 3-12 m. Regional dip to the southwest is approximately 4m/km, and the depth to the producing sandstone is commonly in the range 200-300 m. It is of interest to note that the gravity of the oil at the down-dip end of the field increases abruptly to 14° A.P.I., and that beyond the down-dip limit the sandstone contains neither oil nor water. Secondary recovery methods by means of gas drive have increased the potential of producing wells, but ultimate recovery of oil from the field will probably not exceed 6 million barrels (less than 1 million cubic metres) of oil.

Red Fork Sandstone Production, Oklahoma

Several fields from the Middle in northern and northeastern Oklahoma produce oil and gas from the Middle Pennsylvanian (Desmoinesian) Red Fork Sandstone. These fields include the South Ceres Pool, Wakita Trend, Cheyenne Valley Field, and Shoestring Field.

The Red Fork Sandstone is approximately the same age as the Bartlesville Sandstone in the Cherokee Formation. It comprises linear sandstone bodies ranging in thickness to 20 m, in width to 3 km, and in length to 50 km. The sandstone is quartzose, generally fine to very fine-grained but locally showing some degree of coarsening toward the base.

Early writers, including Wright (1941), regarded the Red Fork Sandstone as having been a shoreline sand formed within the Cherokee Sea. Later writers, including Withrow (1968) and Lyons and Dobrin (1972), recognized that the Red Fork included sandstone bodies formed as river channel sands, such as the producing sands of the South Ceres Pool, Cheyenne Valley, and Shoestring fields. The Wakita Trend (Fig. 3-14) is described by Withrow (1968) as an off-shore bar and is included under that category in this book.

The South Ceres Pool (Fig. 1-34) is a remarkable horseshoe-shaped channel up to 2 km wide, that contains oil and gas throughout a length of 40 km. The sandstone, which is commonly up to 10 m thick, has an

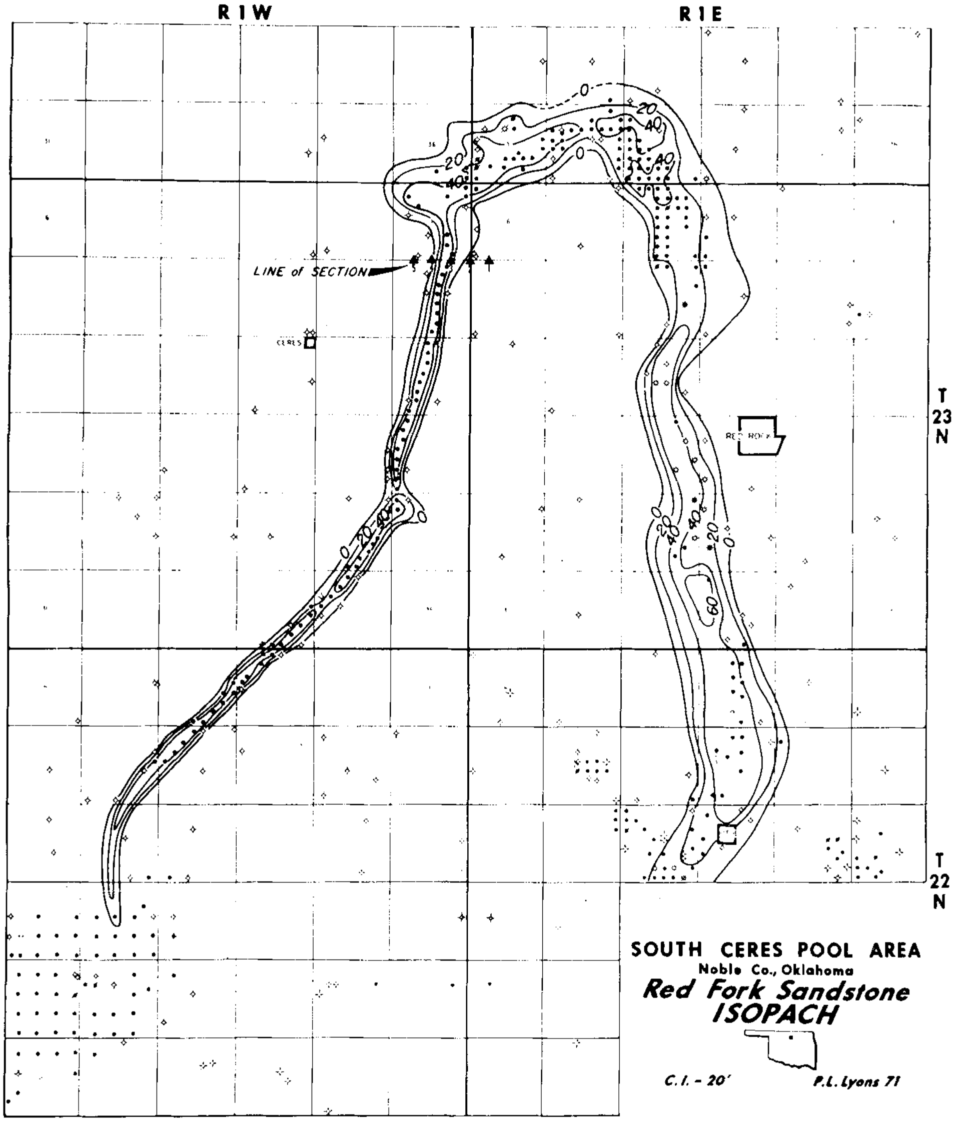


Fig. 1-34. Isopach map of the Middle Pennsylvanian Red Fork Sandstone, South Ceres Pool, Oklahoma, showing the sandstone distribution within a narrow channel. Contour interval is 20 feet (6.1 m). (After Lyons and Dobrin, 1972).

average porosity of 20% and an average permeability of 100 millidarcys. Of particular interest is the fact that the down-dip limb of the west yields 42° A.P.I. oil, and the up-dip limb yields mainly gas. Depths to the producing sandstone are in the range 1,300 - 1,350 m. The

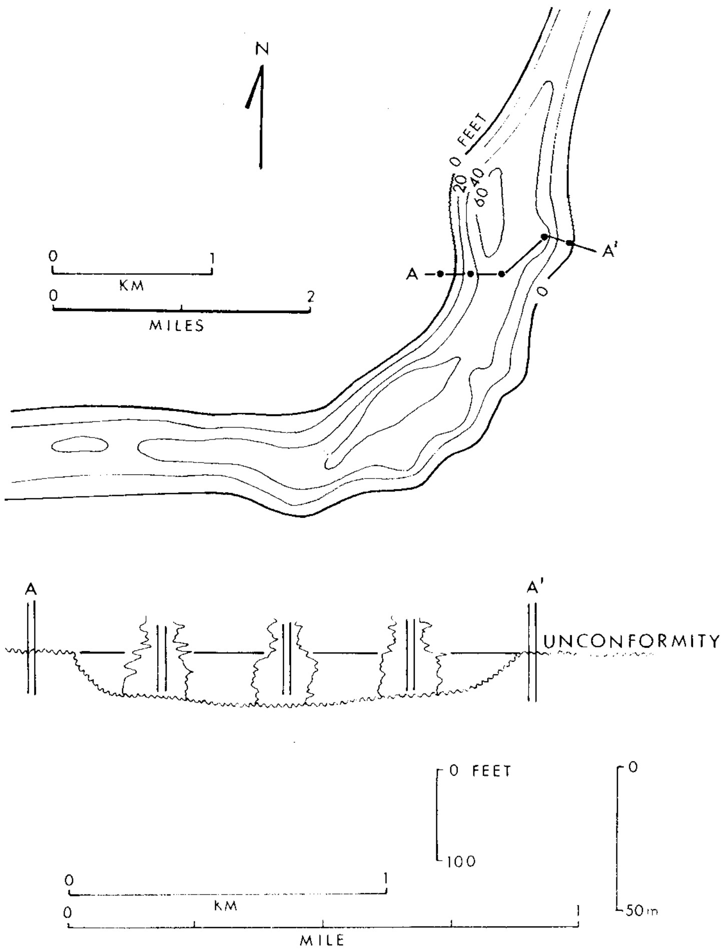


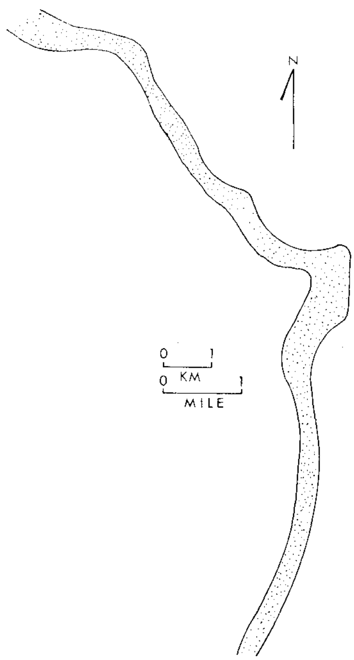
Fig. 1-35. Isopach and section of the Pennsylvanian Red Fork Sandstone in the Cheyenne Valley oil field, Major County, Oklahoma, showing a river sand filling a channel on the eroded surface of the Mississippian. (Redrawn from Withrow, 1968).

producing mechanism is water drive. Individual oil wells, each draining approximately 15 acres, may ultimately yield 75,000 barrels according to Lyons and Dobrin (1972). Maximum production from the field is not likely to be much in excess of 10 million barrels (1.6 million cubic metres).

The Cheyenne Valley Field (Fig. 1-35) is located within a linear sandstone body of the Red Fork Sandstone that trends generally east-west, stratigraphically higher and normal to the south-trending western extension (Oakdale Field) of the Wakita Trend of shoreline sands. It is pertinent to note that Withrow (1968) interpreted the upper part of the producing Red Fork Sandstone in the Oakdale Field as an off-shore bar, and the lower part as a river channel sand.

The Cheyenne Valley Field is situated where the linear trend of the Red Fork Sandstone bends locally to the south, in which direction the strata dip 10 m per kilometre. Average depth to the producing sandstone is 2,075 m, and the average thickness exceeds 10 m. The field is estimated to contain 6.5 million barrels (1 million cubic metres) of recoverable oil.

The Shoestring Oil Field (Fig. 1-36) in northeastern Oklahoma yields oil from a linear, northerly-trending sandstone body of the Red Forks Sandstone. This sandstone body was considered by Wright (1941) to be a shoreline sand, but its configuration suggests that it was a river channel sand. The producing sandstone is generally fine grained, in part silty, varying from poorly-cemented to well-cemented by calcite, and consists of sub-angular grains mainly of quartz and chert. The lower part of the sandstone body is generally more permeable and less silty. Production of 40^{o} A.P.I. oil is obtained by pumping, assisted by a weak gas and water drive. Average yields amounted to only 10-15 barrels a day from each well draining 15 acres.

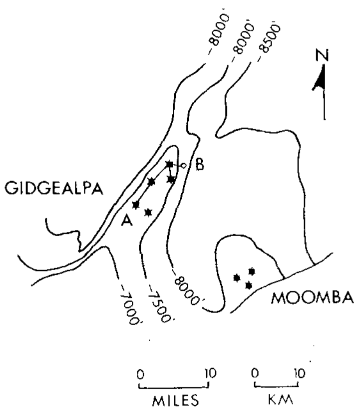


DISTRIBUTION OF OIL PRODUCTION IN
RED FORK SANDSTONE, OKLAHOMA

Fig. 1-36. Map showing distribution of oil production in the Pennsylvanian Red Fork Sandstone, Red Fork Shoestring Oil Field, Pawnee Creek and Tulsa Counties, Oklahoma. (Drawn from distribution of producing wells plotted by Wright, 1941).

Moomba Gas Field, South Australia

Gas and condensate production in the Moomba Field (Fig. 1-37) of the Cooper Basin, South Australia is obtained from sandstone beds within the Middle to Upper Permian (Kungurian) Toolachee Formation which is designated as the upper unit of the Gidgealpa Group. Production is also obtained from other sandstones in the Gidgealpa. The control for gas accumulation is



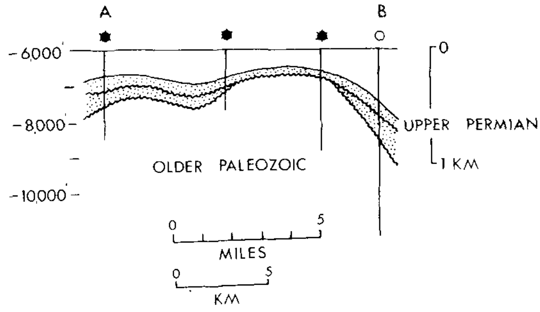


Fig. 1-37. Structural map of the Gidgealpa and Moomba gas-condensate fields, South Australia. Section A-B shows the Upper Permian gross sandstone interval draped over erosional features underlain by older Paleozoic rocks. (Redrawn from Greer, 1965, and Martin, 1967).

essentially structural, the Upper Permian and overlying Mesozoic beds having been folded over faulted basement blocks. Local variations in permeability, depending on depositional trends within the sandstones, are also important factors.

The Toolachee directly overlies a major unconformity that truncates older Permian beds, and consequently has a wider distribution than the underlying sandstones of the Gidgealpa. Greer (1965) considered the Gidgealpa sandstones were evidently deposited in a high energy environment. The fluviatile nature of these sandstones was recognized by Martin (1967) and Kapel (1972) who considered the Toolachee Formation to be river, lacustrine, and swamp deposits.

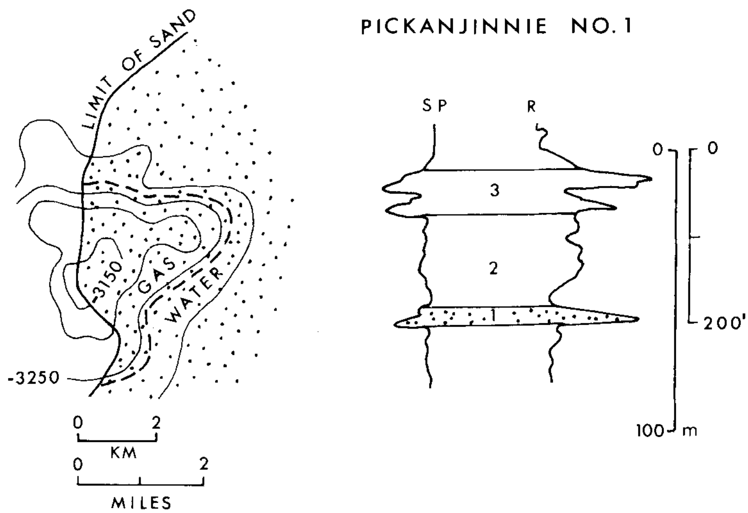
The Toolachee sandstone is grey, medium to coarse-grained, conglomeratic, quartzose, and cross-bedded. Rock fragments, including volcanics, are common, and the matrix consists largely of kaolin and illite. Interbedded with the sandstone are thin beds of dark grey, micaceous, carbonaceous shale, and coal. The Toolachee has a thickness of 20-40 m and the net producing sandstone is up to 26 m thick. Porosity is 10-20% and the permeability is good.

The approximate depth of the producing zone in the Moomba Field is 2,135 m. At this depth the pressure is approximately 3,000 p.s.i., indicating normal hydrostatic pressure for a section saturated with water in the upper salinity range (55,000 p.p.m.) for sea water. Initially, wells flowed gas at rates of up to 15 million cubic feet a day through a half inch choke. The gas, consisting of 77% methane with an unusually high content (20%) of carbon dioxide, yields up to 50 barrels of condensate per million cubic feet. Proven reserves of recoverable gas from the Moomba and adjacent Gidgealpa, Tirrawarra, and Moorari fields amount to 2,000,000 million (2 trillion) cubic feet (56,000 million cubic metres).

Pickanjinnie Gas Field, Queensland

Gas and condensate production in the Pickanjinnie Field (Fig. 1-38) of the Surat Basin, Queensland is obtained from the Upper Triassic Showgrounds Sandstone and Moolyember Sandstone, and also from the Lower Jurassic Precipice Sandstone. More than half of the production comes from the Showgrounds which is described by Gray (1969) as light grey, medium to very coarse-grained, poorly sorted and composed mainly of sub-angular grains of quartz. Porosity averages 16% and horizontal permeability is in the range of 200 - 2,000 millidarcys. The sandstone, which has a maximum thickness 6 m in the Pickajinnie Field, thickens to 15 m along the eastern flank of the Roma Shelf, according to Swindon (1968).

The electric log characteristics of the Showgrounds Sandstone and Precipice Sandstone indicate that the lower parts of the sandstone bodies



PICKANJINNIE GAS FIELD, QUEENSLAND

Fig. 1-38. Pickanjinnie gas field near Roma, Surat Basin, Queensland, showing a structural-stratigraphic trap formed by the pinch-out edge of the gas-bearing Upper Triassic Showgrounds Sandstone (1) where it crosses a nose indicated by structure contours of a marker within the Upper Triassic Moolayember Sandstone (2). The Moolayember is overlain by the gas-bearing Lower Jurassic Precipice Sandstone (3). (Redrawn from Swindon, 1968).

are more permeable and probably coarser. This accords with the interpretation that both the Showgrounds and Precipice are of fluviatile origin. The intervening Moolayember is considered to be lacustrine. Lying unconformably on the Lower Triassic Rewan Formation, the Showgrounds forms a southeast-trending drainage pattern. Entrapment of gas has resulted from the coincidence of a pinch-out edge of the sandstone crossing a structural nose draped over a buried hill on the eroded surface of the igneous-metamorphic basement. The field is consequently limited to the east by a stratigraphic permeability barrier, and in other directions by structural closure.

The Pickanjinnie Field contains proven producible reserves of gas amounting to more than 25,000 million cubic feet, of which approximately 15,000 million are within the Showgrounds. The gas, which consists of 96% methane, was initially contained at a pressure of about 1,900 p.s.i. at an approximate depth of 1,500 m. The field has a strong water drive, the water having a salinity of less than 5,000 p.p.m. which places it in the comparatively fresh to brackish water range.

Moonie Oil Field, Queensland

The Moonie Field (Fig. 1-39) is situated on the southeastern flank of the Surat Basin, Queensland, and produces 45° A.P.I. oil from the Lower Jurassic Precipice Sandstone. In the field area, the Precipice comprises a lower sandstone unit that lies unconformably on Permian and Triassic rocks, and an upper sandstone unit separated from the lower by a silty section. At Moonie the Precipice has a gross thickness of approximately 75 m, and is overlain by siltstone and mudstone of the Lower Jurassic Evergreen Formation.

Both the upper and lower sandstone units of the Precipice are oil--bearing. The upper unit is light grey, fine to medium-grained, poorly sorted, quartzose to lithic, and has a white, kaolinitic matrix. The lower unit is light grey, medium to very coarse-grained, in part conglomeratic, poorly sorted, quartzose to lithic, and poorly-cemented to friable. Porosity is in the range 13-25%. Permeability of the upper sandstone unit averages 300 millidarcys, and that of the lower unit ranges from several hundred to 2,000 millidarcys. In the Moonie Field these

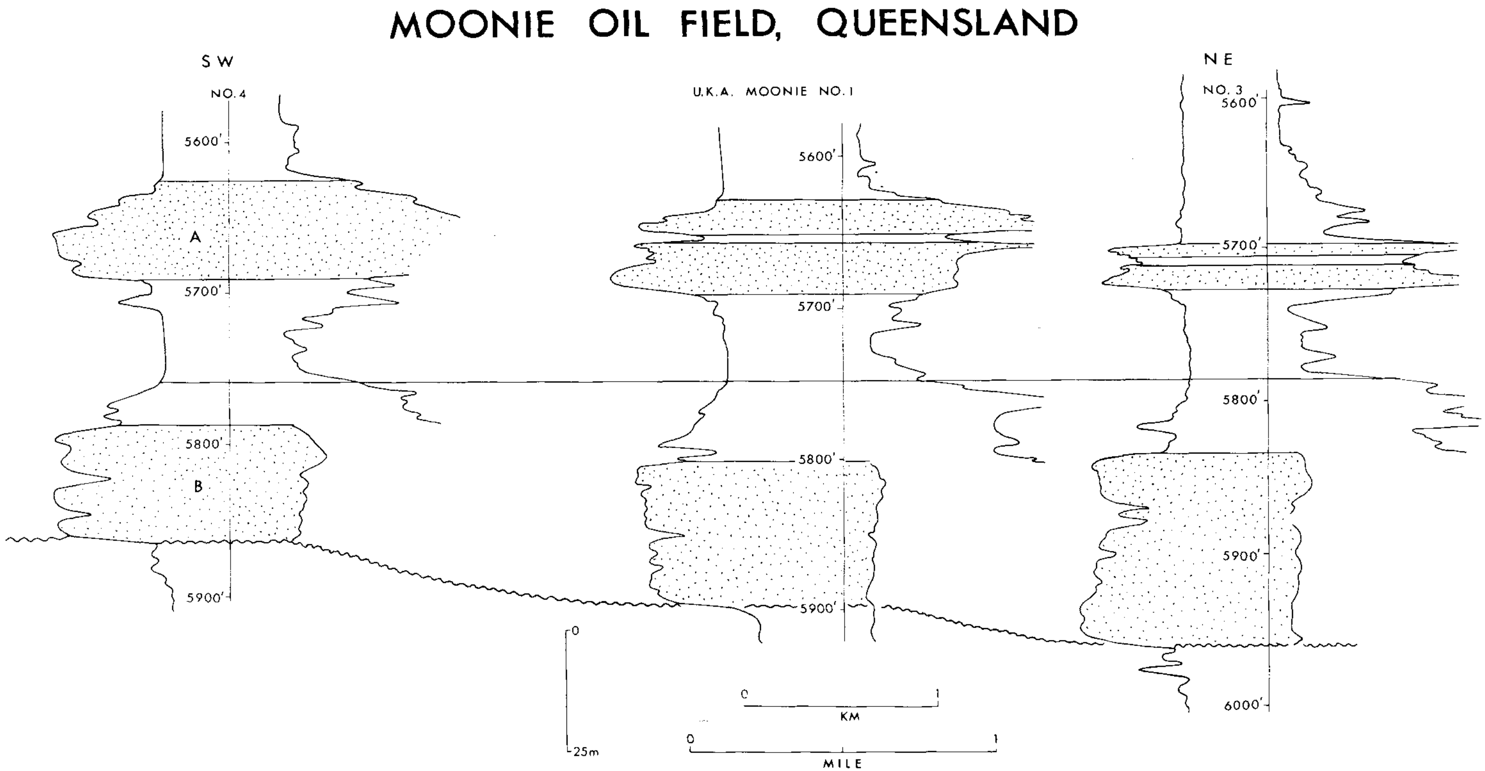


Fig. 1-39. Stratigraphic E-log section along the axis of Moonie Field, Queensland, showing the bell-shaped and blocky character of oil-bearing fluvial sands (A and B) of the Lower Jurassic Precipice Formation.

sandstone units are separated by 100 feet of light grey shale and siltstone containing thin sandstone layers and coaly laminae. This intervening unit is considered to have been deposited as river flood plain and lacustrine sediments. Both sandstone units are cross-bedded and of fluviatile origin. In general, they exhibit grain gradation from coarser below to finer above, a characteristic commonly found in river sand deposits. This feature is reflected in the blocky to bell-shaped self-potential curves of the E-logs shown in Fig. 1-39.

Oil accumulation in the Moonie Field has resulted from a structural-stratigraphic situation where permeable zones within the Precipice Sandstone overlie a basement 'high' of block faulted and truncated Permian and Triassic beds. The structure within the Precipice is a northeast-trending closed dome, six miles long and two miles wide. The volume of oil in the reservoir is estimated to be about 125 million barrels (19.9 million cubic metres), but ultimate recovery will probably not exceed 35 million barrels (5.6 million cubic metres). The oil is underlain by fairly fresh water (approximately 2,500 p.p.m.), indicating a hydrodynamic condition. Production problems have arisen as the result of invasion of the oil-bearing zone by water.

Athabasca Oil Sands, Alberta

The Athabasca Oil Sands (Fig. 1-40) consist of tarry oil-saturated sands of the Lower Cretaceous McMurray Formation in northern Alberta. These uncemented to poorly-cemented sands, which overlie Devonian limestones, have a very gentle regional dip to the west and consequently crop out, or are close to the surface, over a wide area. In places the sands can be mined in open cuts, a method currently being employed; elsewhere the overburden is too thick and oil production will depend on sub-surface methods such as fire-flooding or steam injection and the use of solvents.

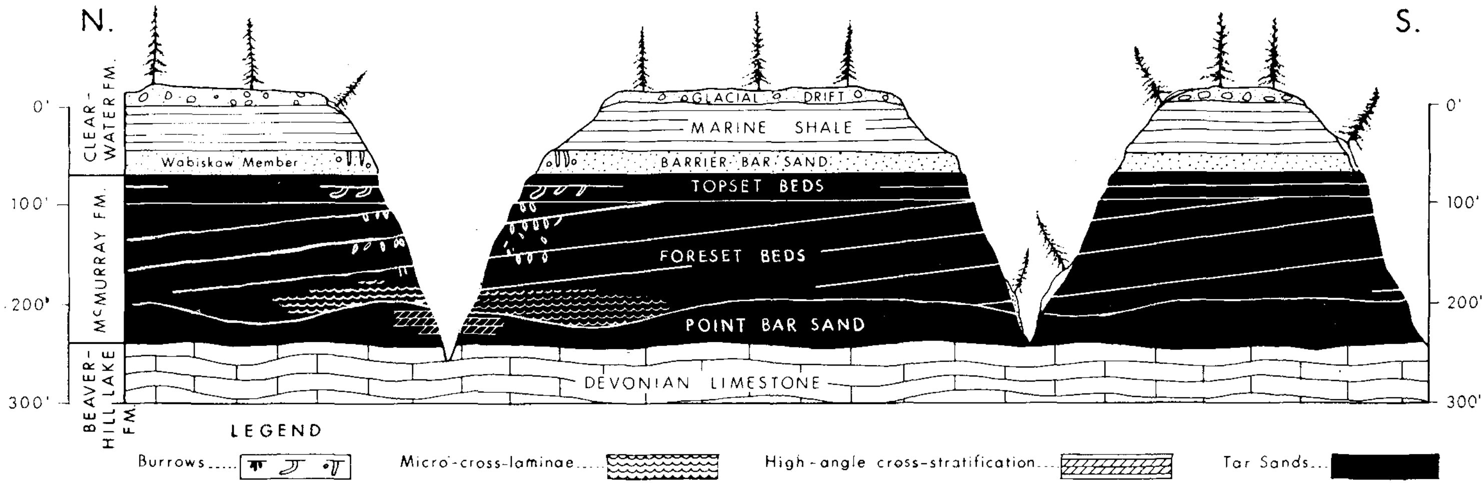


Fig. 1-40. Generalized section through the Athabasca Oil Sands of the Lower Cretaceous McMurray Formation, Alberta, showing the oil-saturated basal river sands and grits, and overlying fluvial beds of the McMurray Delta. (After Carrigy, 1971).

The oil-bearing sands are quartzose and of fluviatile and lacustrine origin. The lowermost sands have a thickness of 10-13 m. These consist of river deposits, are coarse to very coarse, and commonly have lenses of coarse gritstone and fine conglomerate composed of poorly-rounded pebbles. Cross-bedding of the type found in point bars is very common. These sands are overlain by a section, 30-45 m thick, of sands and silts containing variable amounts of tarry oil. Oil saturation is controlled by the original porosity and permeability of the sands, the higher values in oil content being found in the clean, well-sorted fluviatile sands. Maximum oil content amounts to 18-20% by weight of the saturated sand.

The Neocomian McMurray Formation is overlain by marine beds of the Lower Cretaceous (Albian) Clearwater Formation, the basal unit of which is the Wabiskaw Member. This unit is referred to in Fig. 1-40 as a barrier bar sand, which it may be in part. Certainly it is a transgressive marine sand. The McMurray, which has a higher sand content in the lower part of the section, has a thickness of 50-100 m. The formation was deposited by a river system that drained an area of the Precambrian Shield to the east, and flowed northwesterly to the Clearwater Sea. Subsequent transgression of the sea resulted in burial of McMurray sediments by the Clearwater sands and muds.

Regional dip of the McMurray Formation, amounting to less than 2m/km, may have permitted the up-dip migration of oil to its present location, and constitutes the only basis for a structural element to this vast accumulation of oil. The reservoir, and the mechanisms controlling the local concentrations of oil are entirely stratigraphic. Much has been written by many writers (Convbeare, 1966) about the possible origins of the oil, and this problem has not been explained to the satisfaction of all. The question may be of academic interest only, but the problems concerning production from lenticular beds of variable permeability and oil saturation are of consequence to the future application of sub-surface production methods. These problems may be solved as drilling proceeds and subsurface details are evaluated and interpreted to show the relationships of permeability trends to depositional trends within the pattern of the basal McMurray drainage system.

In the area north of Fort McMurray the Athabasca Oil Sands are estimated to contain more than 300,000 million barrels (57,700 million cubic metres) of oil. Similar accumulations in other areas of northern Alberta contain additional potential reserves. The total potential reserves of oil in place probably amount to 500,000 - 600,000 million barrels, but how much of this oil can ultimately be produced as a viable economic operation is open to question. The economic limit may prove to be less than 200,000 million barrels (31,800 million cubic metres).

The oil which occupies up to 90 percent of pore space in the water--wet quartz sand, can be separated by treatment with steam and hot water. It has a gravity of 10 degrees A.P.I., a naphthene base, and a relatively high content of sulphur, nitrogen and trace elements.

Bellshill Lake and Hughenden Oil Fields, Alberta

Oil production in the Bellshill Lake and Hughenden fields of east-central Alberta is obtained from stratigraphic traps in the Lower Cretaceous (Neocomian) Ellerslie Sandstone. This sandstone was deposited as a river sand in a broad valley (Fig. 1-41) cut into the regionally tilted Devonian carbonates and shales. The valley, which is 15-65 km wide and more than 150 km long, terminates in the area of the Ellerslie delta and trends eastward to a drainage source on the Precambrian Shield. Heavy mineral content of the Ellerslie Sandstone indicates that the sands were derived from granitic Precambrian rocks.

Oil accumulations in the Ellerslie Sandstone are contained within

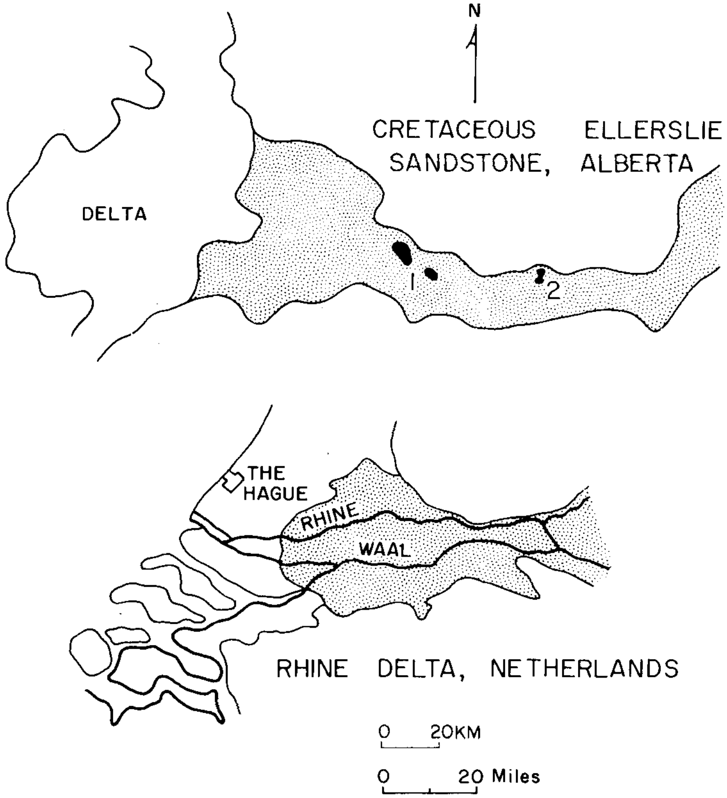


Fig. 1-41. Upper-Map showing the distribution of the Lower Cretaceous Ellerslie Sandstone (stippled) filling a broad valley in Devonian carbonates and shales (hatchured), east-central Alberta. Locations of the Bellshill Lake Field (1) and Hughenden Field (2) are shown. The configuration and scale of the areas of alluvial and deltaic sediments are remarkably similar to those of the Rhine and Waal Rivers shown below.

Lower-Map showing the distribution of fluvial sands and silts deposited in the lower reaches of the Rhine and Waal Rivers, the Netherlands. These sediments fill a broad valley in Pleistocene deposits (hatchured). (Redrawn from Geological Map of the Netherlands, compiled by Geologische Dienst, 1951).

topographic elevations (i.e. buried sandstone hills) that have structural closure. These elevations were originally referred to as sand bars, not only because of their geometry but because they are flanked by shales and a thin limestone bed containing forams and ostracods. Subsequent work (Conybeare, 1964, 1972, and Martin, 1966) indicated that the elevations are structurally high portions of eroded river terraces (Fig. 1-42) and that the river valley was subsequently inundated by an estuary that produced

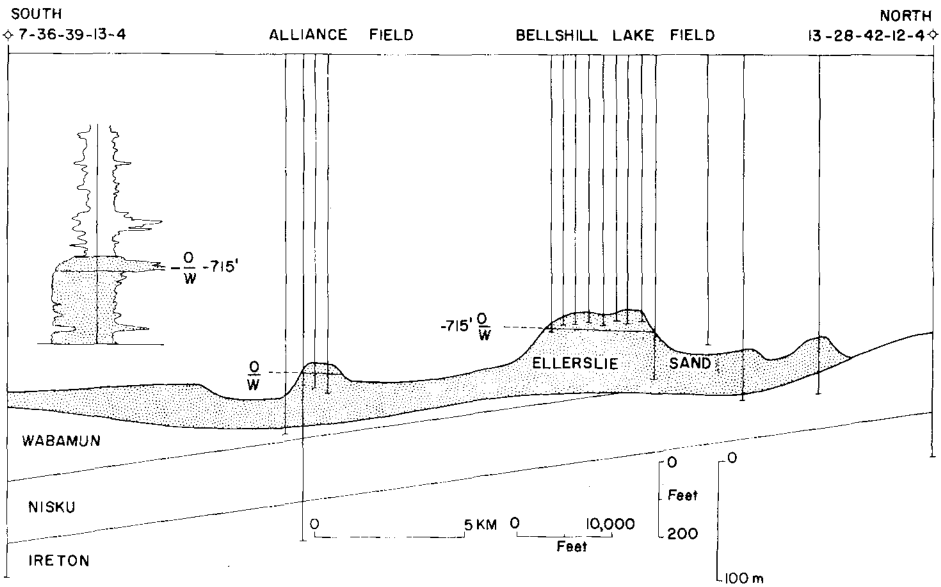


Fig. 1-42. Structural section trending north-south across the Bellshill Lake and Alliance Fields of east-central Alberta, showing the oil and gas-bearing Lower Cretaceous Ellerslie Sandstone overlying the eroded surface of the Devonian Wabamun and Nisku carbonates. The inset shown the E-log of Richfield, McLennan 6-32, a well in the Bellshill Lake Field. The oil-water contact is shown at -715 feet (-218 m) below a sea level datum. (E-log redrawn from Rudolph, 1960).

a brackish-water, coastal marsh environment in which muddy sediments were deposited to form a relatively impermeable seal over the Ellerslie sands. The geometry and size of this Neocomian river valley is strikingly similar to that of the present valley of the Rhine River in the Netherlands (Fig. 1-41).

The Ellerslie Sandstone, which ranges in thickness to 75 m is commonly medium to coarse-grained, fairly well sorted, and quartzose. Cross-bedding, of the planar type found in river point bar deposits, is common. Grain gradation, from coarser below to finer above in repeated, truncated sequences within the Ellerslie Sandstone interval is also evident. Porosity and permeability are generally good, although locally affected by calcite cementation. Rudolph (1959) states that in the Bellshill Lake Field the average porosity exceeds 26%, and the average permeability is 630 millidarcys. Locally, the permeability ranges up to 7,000 millidarcys.

In the Bellshill Lake Field the oil column has a maximum thickness of 16 m and an average thickness of 10 m. Flow rates from individual wells were initially in the range 100-200 barrels of oil per day, but production rates were subsequently cut back to 25 barrels per day. The oil has a gravity of 28° A.P.I. Estimated oil in place amounts to 180 million barrels, but water drive problems have caused difficulties in production and the ultimate yield will probably be less than 35 million barrels (5.5 million cubic metres).

The Hughenden Field (Fig. 1-43) contains 15 million barrels of oil, but according to Suey (1960) only 1.5 million barrels will ultimately be recovered. The maximum thickness of the oil-bearing sandstone is 11 m, and the average thickness is 7 m. Allowable production of the heavy oil, which has an average gravity of 17° A.P.I., was initially at the rate of 30 barrels per day.

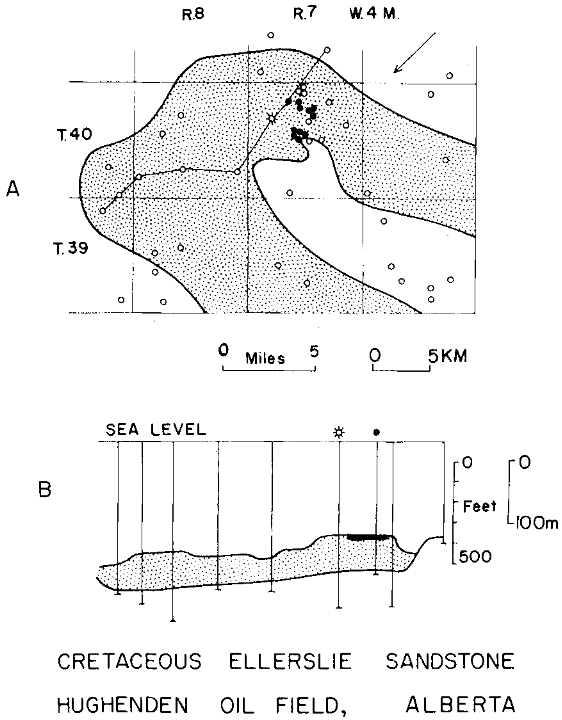


Fig. 1-43. Map and structural section of the Hughenden Field, east-central Alberta, showing the distribution (stippled) of the Lower Cretaceous Ellerslie Sandstone occupying a U-shaped loop in a river valley within the eroded carbonates and shales of the Devonian Nisku and Ireton Formations. Regional dip to the southwest is indicated by the arrow. The field area lies within Township 40, Range 7, West of the 4th Meridian, as shown in A, and occupies a structurally high part. (Redrawn from Martin, 1966).

South Glenrock Oil Field, Wyoming

In the South Glenrock Field (Fig. 1-44) situated on the southwestern flank of the Powder River Basin, Wyoming, part of the oil production comes

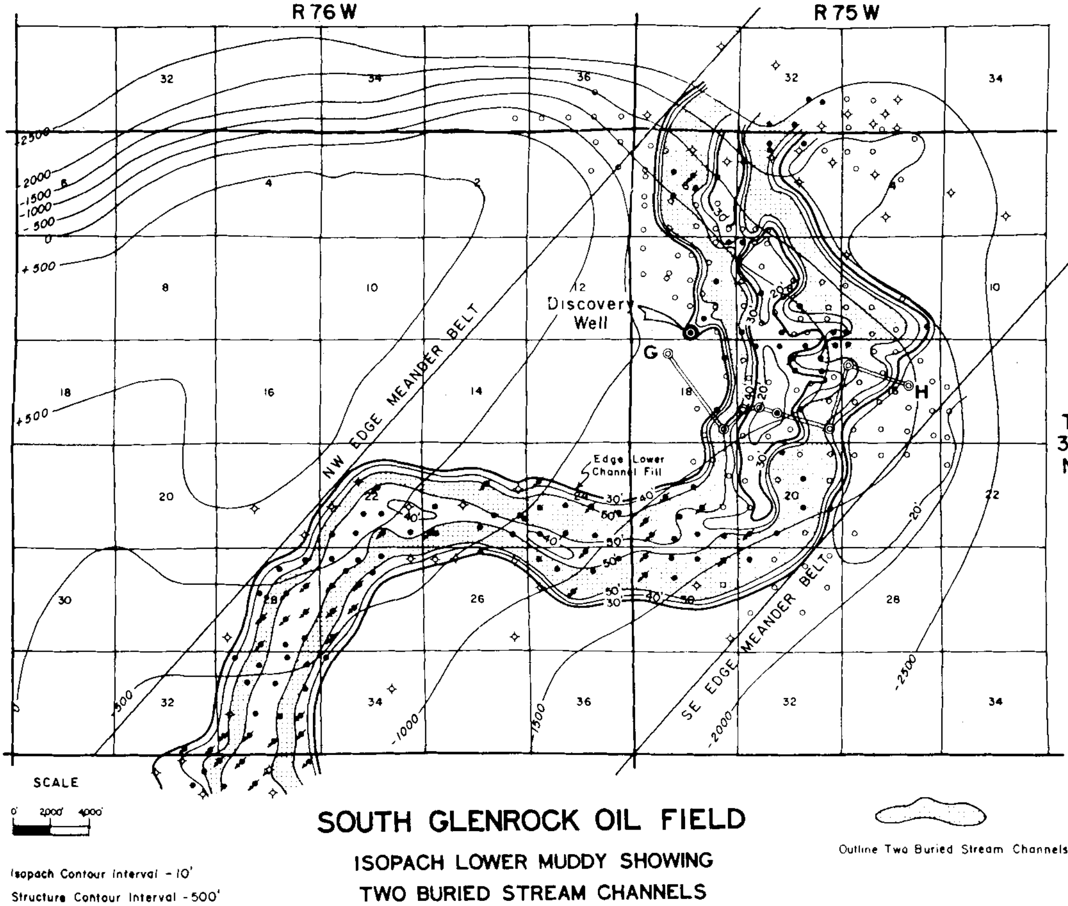


Fig. 1-44. Isopach map of Lower Cretaceous Muddy Sandstone, South Glenrock Field, Wyoming, showing a meandering belt comprising two channels. Contour interval is 10 feet (3 m). (After Curry and Curry, 1972).

from channel sandstones at the base of the Lower Cretaceous Muddy Formation. These channels, which are cut into the eroded surface of the marine Lower Cretaceous Skull Creek Formation, form a belt up to 3 km wide and more than 2 km long.

The sandstone bodies filling these channels are up to 20 m thick and consist mainly of fairly well-rounded, well-sorted grains of quartz and chert in a matrix of silt and clay. Carbonized plant remains are commonly abundant. Grain gradation varies from coarser below to finer above, porosity averages 14%, and permeability averages 82 millidarcys.

The oil, produced from depths in the range 1,700 - 1,800 m, has a gravity of 37° A.P.I. Following discovery of the field in 1950 the estimated recoverable reserves of oil amounted to 50 million barrels. This estimate was based on recovery from three producing horizons including, from older to younger, distributary and shoreline sands of the Dakota

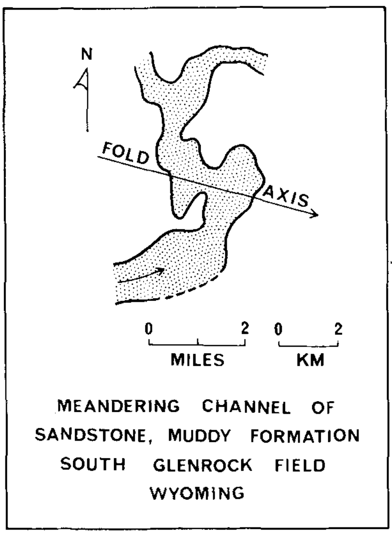


Fig. 1-45. Map of South Glenrock oil field on the southwestern flank of the Powder River Basin, east-central Wyoming. The stippled area ahows the distribution of a clean, permeable sandstone in the lower part of the Lower Cretaceous Muddy Formation. The arrow indicates direction of sediment transportation. (Redrawn from Curry and Curry, 1954).

Formation, basal river sands of the Muddy Formation, and younger Muddy shoreline sands. Later estimates of Curry and Curry (1972) indicate that the ultimate recovery, by means of water flood, may be 75 million barrels (12 million cubic metres). The field has resulted from a combination of stratigraphic and structural factors, the oil accumulation being situated in a trap where the channel is intersected by the axis of a structural fold or nose (Fig. 1-45).

It is of particular interest to note that the oil-water contact in the producing Dakota sandstone, along the south side of the field, has 225 m of tilt downdip to the east along the crest of the structural nose. This indicates a hydrodynamic condition with a very marked potentiometric gradient.

Recluse Oil Field, Wyoming

The Recluse Field (Figs. 1-46 and 1-47) is situated on the northeastern flank of the Powder River Basin, Wyoming. Oil is obtained from the Recluse Sandstone at the base of the Lower Cretaceous Muddy Formation at a depth of approximately 2,300 m. This sandstone, which also yields oil in the nearby East Sandbar, Hilight, and Kitty fields, is interpreted by Woncik (1972) as a marine shoreline sand, possibly a barrier island. On the other hand, Forgotson and Stark (1972) interpret the sandstone body as a channel--fill sand. In fact, the sandstone body comprises two units, each with a different oil-water contact in the Recluse Field. The body trends northwest for more than 24 km and is up to 5 km wide. The oil field itself has dimensions of roughly 12 km by 3 km.

The sandstone, which has a maximum thickness of 15 m and an average oil-bearing section of 8 m, is quartzose, has an average porosity of 19% and an average permeability of 300 millidarcys. Reservoir pressure is approximately 2,150 p.s.i., which is comparatively low for that particular depth.

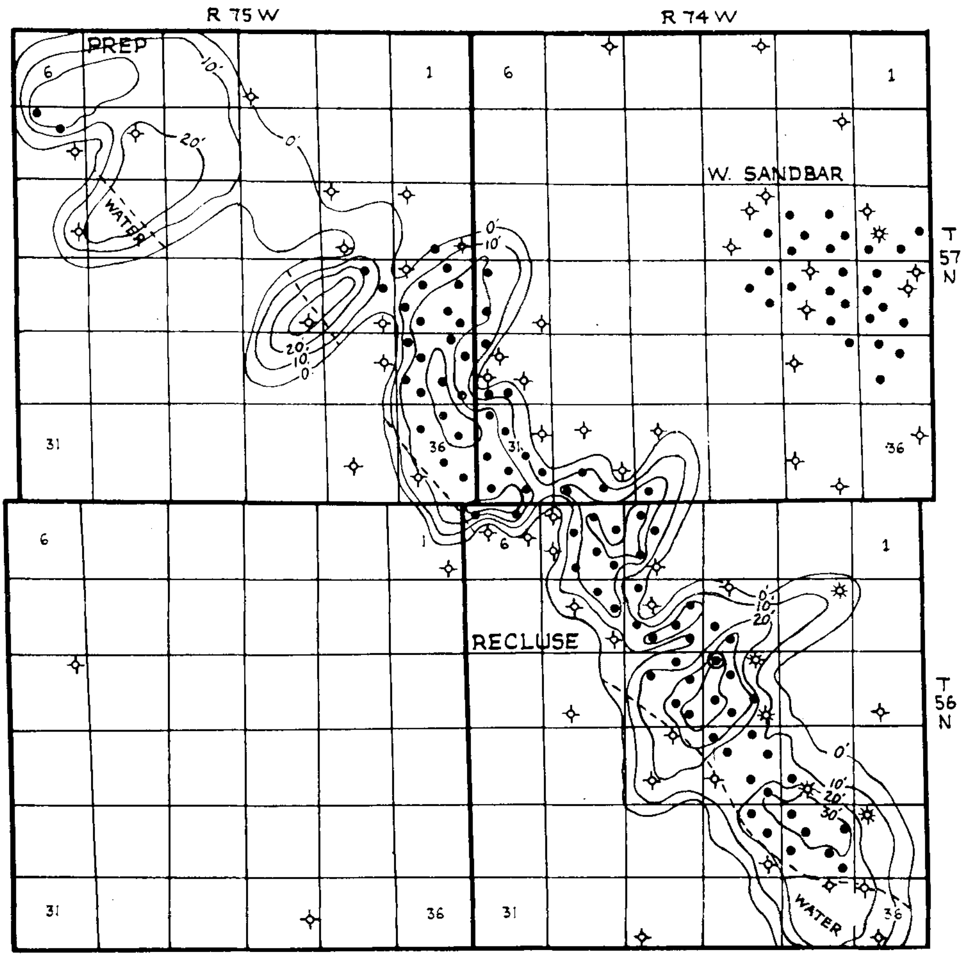


Fig. 1-46. Isopach map of Lower Cretaceous Muddy Sandstone, Recluse Field, Wyoming. Contour interval is 10 feet (3 m). (After Woncik, 1972).

The oil, which is produced at an allowable rate of 300 barrels per day, has a gravity of 42° A.P.I. Cumulative production to 1973 was 17 million barrels. Total oil in place is estimated to be 150 million barrels, of which 20-40% (5-10 million cubic metres) may ultimately be

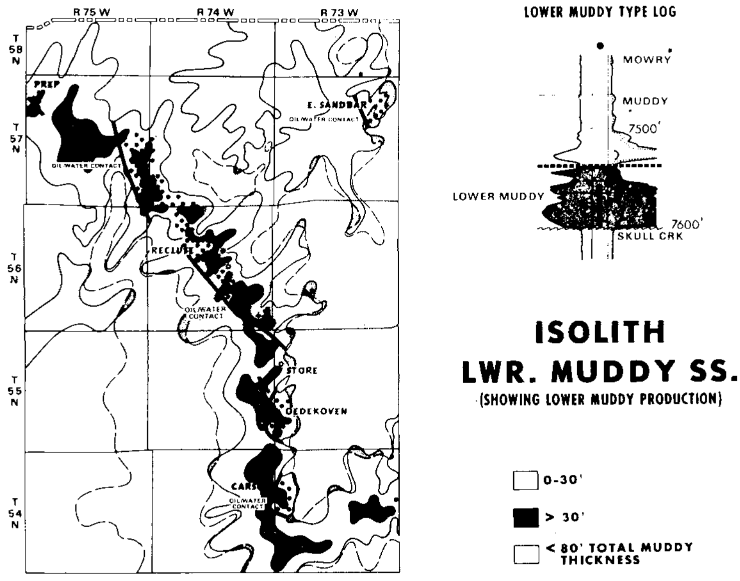


Fig. 1-47. Isolith of the Upper Recluse Sandstone and Recluse Sandstone which constitute the lower part of the Muddy Formation, showing a linear pattern where the Recluse Field is more than 30 feet (9 m) thick. (After Stone, 1972).

recovered economically, depending on the reservoir response to pressure maintenance. The recovery mechanism is gas-solution drive, the down-dip portions of the sandstone body being only partly saturated with water. The field is purely stratigraphic, the oil being trapped by up-dip permeability barriers caused by pinching out of the sandstone. The only structural element is a regional southwest dip, although Stone (1972) says that in some Lower Muddy oil fields entrapment is provided by a combination of sandstone pinch-out and structural nosing where a structure intersects the trend of a distributary channel (Fig. 1-38).

Donkey Creek, Rozet, and O'Connor Oil Fields, Wyoming

On the eastern flank of the Powder River Basin, Wyoming, several fields produce oil from the Lower Cretaceous Newcastle Sandstone (Fig. 1-48). Stapp (1967) records that the Newcastle, which has an average thickness of 9 m was deposited in a dendritic river system that drained northward. This river system was developed penecontemporaneously with that which deposited the basal sands of the Muddy Formation in the South Glenrock Field (Fig. 1-44) to the south, as evidenced by the fact that the channels of this system are also cut into the eroded surface of the marine Lower Cretaceous Skull Creek Formation, as is the situation in the South Glenrock Field. The stratigraphic sequence on the eastern flank of the basin is similar to that of the South Glenrock Field area on the southern flank. Reservoirs in Lower Cretaceous beds have been formed not only in the

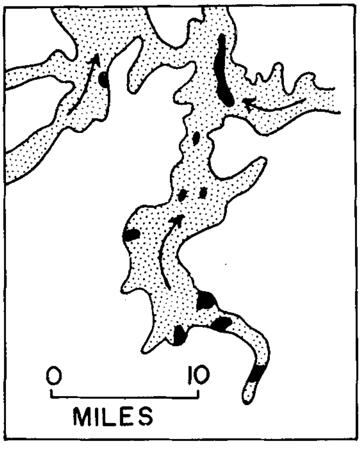
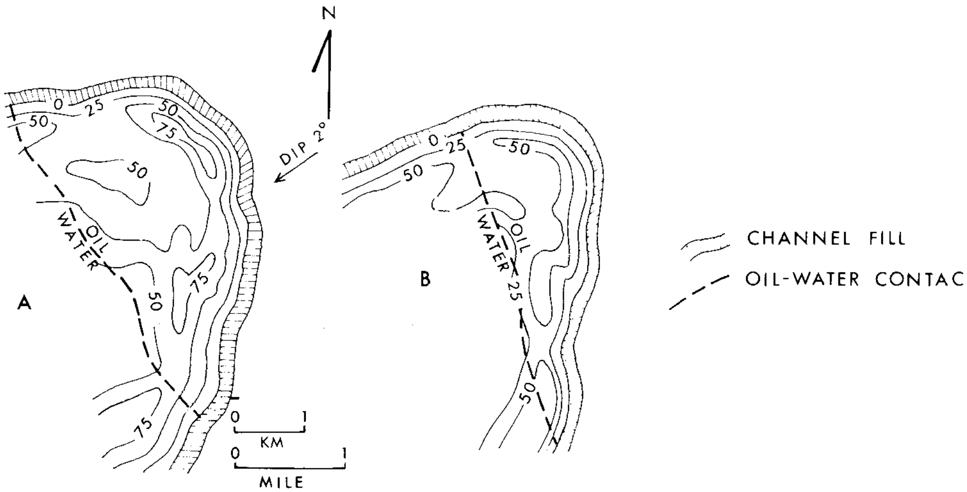


Fig. 1-48. Dendritic distribution of the Lower Cretaceous Newcastle Sandstone in part of the Powder River Basin, Wyoming. Areas where oil is produced from the Newcastle are shown in black. Arrows indicate northward directions of sediment transport in the Newcastle river system. (Redrawn from Stapp, 1967).

Newcastle but also in the underlying marginal-marine (distributary and shoreline sands) Fall River Sandstone and in the overlying transgressive marine Dynneson Sandstone. Oil accumulations in the Newcastle are confined within more permeable zones of sandstone beds where they are bounded by up-dip edges, and consequently are purely stratigraphic traps. Stapp (1967, p. 2055) concludes, "Oil accumulation is present in the up-dip edges of the offshore, blanket-type sandstone of the Dynneson, the channel sandstone of the Newcastle, and the complex marginal-marine sandstone of the Fall River. Prospecting for such stratigraphic traps requires an understanding of the paleodepositional environments of the rocks".

Coyote Creek and Miller Creek Oil Fields, Wyoming

The Coyote Creek Field and Miller Creek Field (Fig. 1-49) are also situated on the eastern flank of the Powder River Basin, Wyoming, approximately 15 km southeast and northeast respectively from the Rozet Field. The producing zone is the Lower Cretaceous Fall River Sandstone which lies approximately 60 m below the Newcastle Sandstone. Stapp (1967) says that the Fall River comprises three separate sandstone bodies which locally merge, as in parts of the Coyote Creek Field, to form a single porous unit approximately 25 m thick. Elsewhere, the Fall River ranges in thickness up to 50 m. Stapp describes these sandstone bodies as having been deposited in a marginal-marine environment, the lower two bodies being shoreline sands deposited by a regressing sea. The upper sand is interpreted as the basal unit of a marine transgressive sequence referred to as the Skull Creek Formation. Berg (1968), on the other hand, states that the Fall River Sandstone bodies were, in part at least, deposited as delta distributary point bars flanked by muddy sediments within the same channel. He says, p. 2116, "Because the Fall River is largely of marine and deltaic origin, the reservoir sandstone was believed to have been



ISOPACH OF POROUS SANDSTONE IN POINT BARS OF FALL RIVER SANDSTONE, WYOMING

Fig. 1-49. Isopach of net porous sandstone in the oil-producing Lower Cretaceous Fall River Sandstone, Coyote Creek Field (A) and Miller Creek Field (B), Crook and Weston Counties, Wyoming, showing oil accumulation in river point bars. (Redrawn from Berg, 1968, and Truchot, 1963).

deposited in a littoral environment, perhaps as a series of barrier-bar sands flanked by lagoonal clays. Recently, however, a fluvial origin has been proposed for these sandstone beds at the West Moorcroft field (Mettler, 1966) and at Coyote Creek field (Bolyard and McGregor, 1966, p. 2236)." Bolyard and McGregor interpreted the Fall River Sandstone bodies as point-bar channel deposits associated with a delta front. They say, p. 2238, "The lithology, cross-bedding, clay galls, and other features are very similar to those of thick, massive, channel-filling sandstone beds observed in outcrop. It is difficult to reconstruct a pattern of convincing facies relations that would be consistent with either the offshore-bar, barrier-island, or beach-deposit interpretations".

In the Coyote and Miller Creek fields the Fall River Sandstone is light grey to whitish, quartzose, fine to medium-grained, and well sorted. Carbonized plant matter is present throughout the interval. The net pay comprises 10-15 m having a porosity of 15-18% and a permeability that averages 200 millidarcys but ranges up to 1,000 millidarcys. Both fields are interpreted by Berg (1968) as point bar segments of a river meander belt that trends in a north-south direction for more than 50 km. This trend contains several other oil fields of similar origin.

The Coyote Creek and Miller Creek fields have estimated producible reserves of 20 million barrels (3.2 million cubic metres) of 41^{o} A.P.I. oil and 5 million barrels of 33^{o} A.P.I. oil respectively. Ultimate recoveries are also estimated to be in the range 150-250 barrels per acre-foot. The recovery mechanism is an active water drive in the Coyote Creek Field and a combined water and gas-solution drive in the Miller Creek Field. The areas of the Coyote Creek and Miller Creek fields are approximately 2,000 and 1,000 acres respectively.

Reimers-Lane-Hart Trend, Nebraska

In the Denver Basin of western Nebraska the Reimers, Faro, Dalton, Lane, Deep Creek and Hart Oil fields form a north-south trend (Fig. 1-50) within a Lower Cretaceous linear sandstone body. This body fills a channel cut into the "J" Member which is overlain by the Lower Cretaceous Huntsman Shale and underlain by the Lower Cretaceous Skull Creek Formation, both of which are marine. The channel is also locally cut into the Skull Creek. It has an average width of 450 m, a depth of 15-20 m, and a length of more than 30 km.

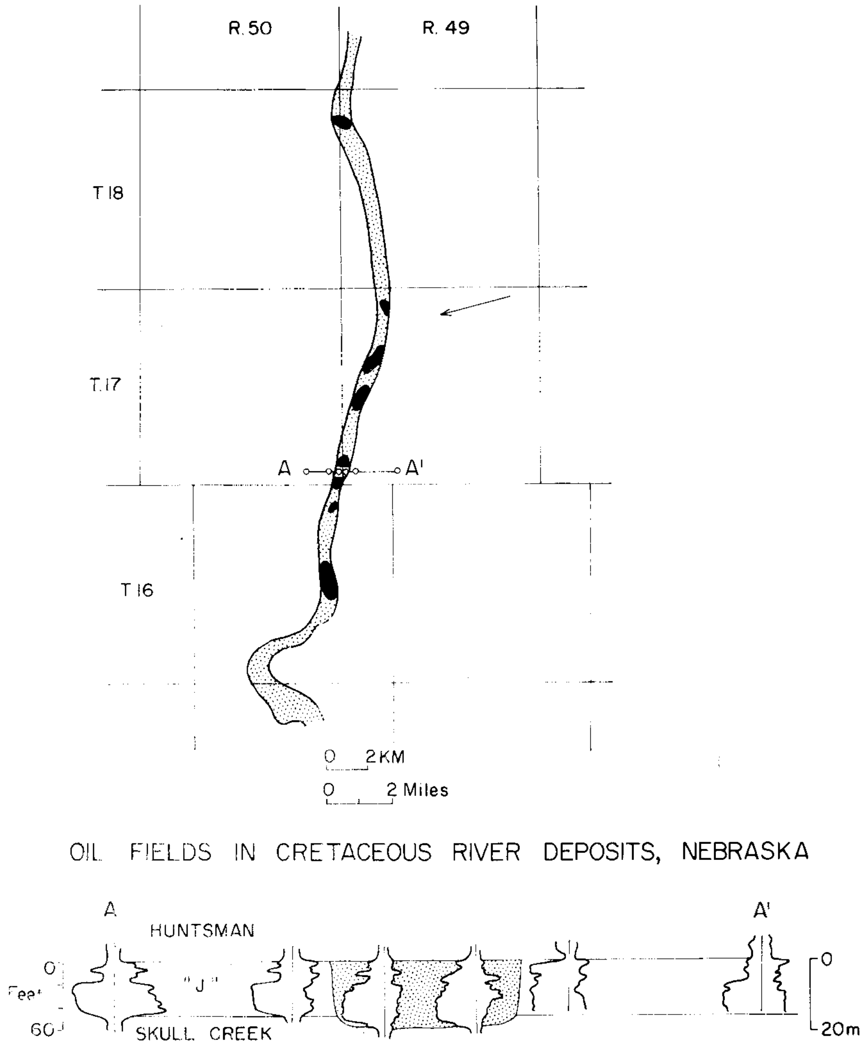


Fig. 1-50. Map and section showing oil accumulations in river deposits filling a valley in the Lower Cretaceous "J" sandstone, Denver Basin, Nebraska. Arrow indicates the direction of regional dip. (Redrawn from Harms, 1966).

The channel-fill sandstone is predominantly light grey, quartzose, fine to medium-grained, and cross-bedded. Claystone chips, probably derived from the erosion of dried and cracked mud on the river banks, are fairly common within the sandstone. Some thin beds of layered sandstone and dark grey siltstone show slump structures similar to those formed in the silty, upper layers of point bar deposits. Scour structures are also common, as are carbonized plant remains. In general, the sandstone body appears to have been deposited by a river, possibly a distributary flowing on a coastal plain.

Oil has accumulated in more permeable parts of the sandstone body where it is gently folded by northwest-plunging anticlines that cross the trend of the channel. In these producing sections the sandstone commonly has porosity and permeability in the ranges 15-25% and 100 - 1,000 millidarcys respectively. The oil-water contacts in all fields along the sandstone body are horizontal but at various elevations. Salinity of the formation water varies from 90,000 to 110,000 ppm according to Harms (1966). Individual wells have an average production rate of 25,000 barrels of oil per year, and the estimated cumulative production that will ultimately be obtained from all fields along the trend is less than 10 million barrels (1.6 million cubic metres).

Cut Bank Oil Field, Montana

In northwestern Montana oil production in the Cut Bank Field, situated on the west flank of the Sweetgrass Arch, is obtained from the Lower Cretaceous Cut Bank Sandstone. This sandstone, which fills channels cut into shales and silty marine beds of the Upper Jurassic Swift Formation and Rierdon Formation, is the basal member of the Kootenai Formation and is overlain by several hundred feet of non-marine, varicolored mudstones and silty sandstones. The channels form a meandering pattern that trends

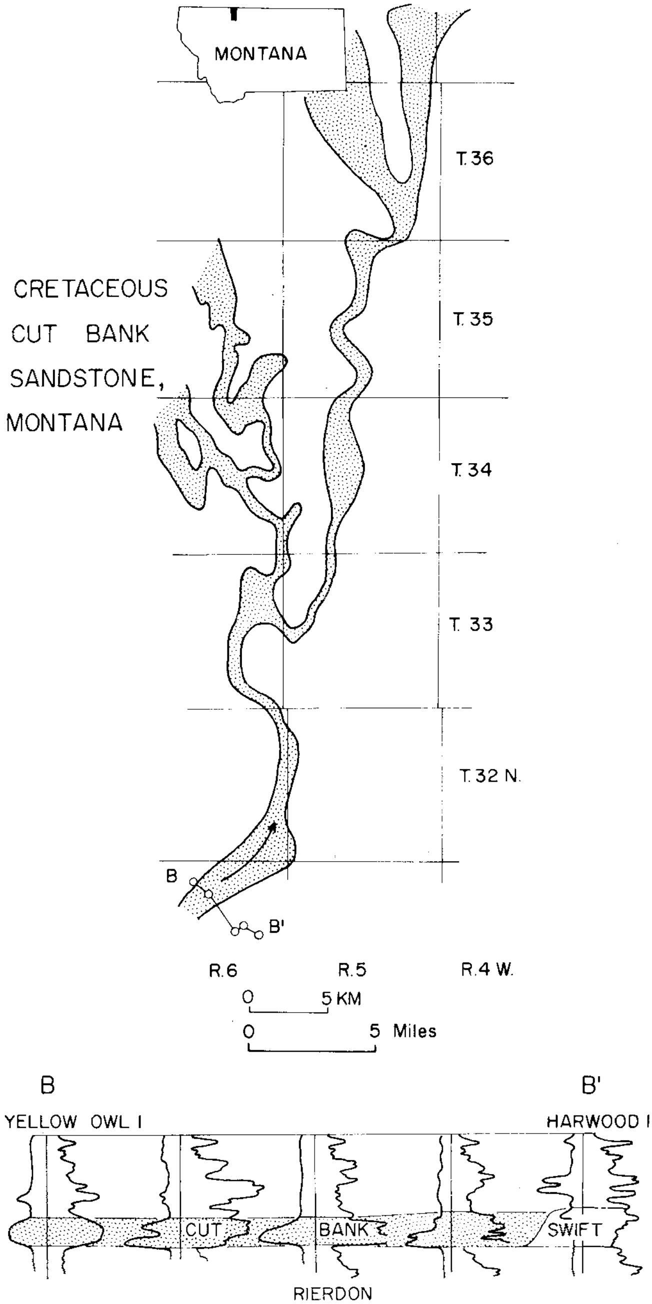
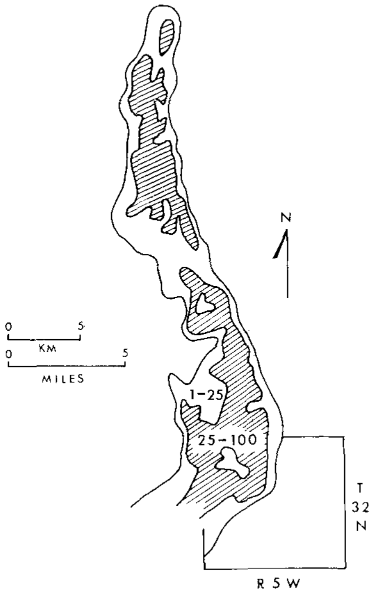


Fig. 1-51. Distribution of the Lower Cretaceous Cut Bank Sandstone where it is more than 50 feet (15 m) thick in the Cut Bank oil field area, Montana. Inset shows the location. The arrow indicates direction of flow. (Redrawn from Shelton, 1967).

north-south. Drainage was to the north and individual channels bifurcate in that direction. The limits of the Cut Bank Sandstone are broadly defined by a depositional edge flanking the up-dip boundary of the oil field and by outcrops 50 km westward. Northward, the pattern of channels extends for more than 80 km into Alberta. The Cut Bank drainage system, comprising a number of separate channels, was formed on a broad and fairly flat coastal plain. The pattern of channels within the Cut Bank Field (Fig. 1-51) can be defined by an isopach map of the Cut Bank Sandstone showing thicknessss exceeding 15 m (Shelton, 1967). These meandering channels commonly have a width of 450-1,200 m and a thickness of up to 25 m. Where the Cut Bank Sandstone crops out, 50 km southwest of the field, it has a thickness of up to 70 m.

The sandstone is composed mainly of grains of quartz and dark grey chert. Within individual layers the grains are fairly well sorted, but grain size gradation is well defined within sequences of layers, ranging from coarse below to fine above. Locally, the coarse-grained layers are conglomeratic, the maximum pebble size being 15 mm. Cross-bedding is a common feature; other sedimentary structures include burrows (?), claystone chips (probably fragments of dried mud), and deformation probably caused by slumping of the unconsolidated sediment in a hydroplastic state (Conybeare and Crook, 1968). A shale bed, locally present within the upper part of the Cut Bank Sandstone, contains fresh-water ostracods and gastropods. Porosity of the sandstones is in the ranges 12-19%, permeability ranges up to 300 millidarcys and averages 100 millidarcys. The best values for porosity and permeability are found in the medium-grained sandstone, whereas poorer values are found in both the fine-grained and conglomeratic sandstones.

Oil production (Fig. 1-52) is more prolific in the thicker parts of the sandstone bodies within the channels, but is not precisely confined



INITIAL DAILY PRODUCTION IN BARRELS,
CUT BANK SANDSTONES, MONTANA

Fig. 1-52. Initial daily production (first 10 day average) of oil wells producing from the Cut Bank Sandstone. Locally, the initial Production exceeded 100 barrels a day. (Redrawn from Blixt, 1941).

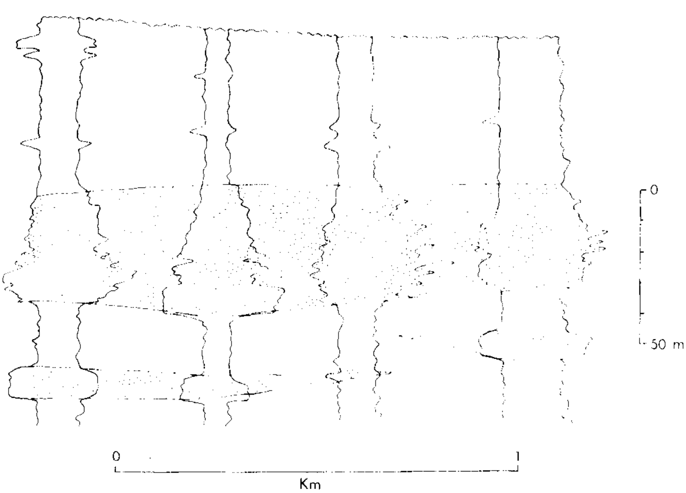
to these locations. Rates of production depends on variations of porosity and permeability within the field area where the oil and gas is trapped against the up-dip edge of the Cut Bank Sandstone. The main producing zone, comprising approximately 5 m of net sandstone, is in the lower part of the Cut Bank at a depth of approximately 900 m. The oil has a gravity of 38^{o} A.P.I. Production is assisted by gas solution and a gas-cap drive. Initial daily production per well during the first 10 day period averaged 56 barrels.

Fairly fresh water, having a salinity of approximately 10,000 ppm, underlies the oil, indicating movement of surface water into the Cut Bank

Sandstone. This hydrodynamic situation may have caused some slight degree of tilting of the oil-water contact. The Cut Bank Field may ultimately yield more than 30 million barrels (4.8 million cubic metres) of oil and 80,000 million cubic feet (2,200 million cubic metres) of gas.

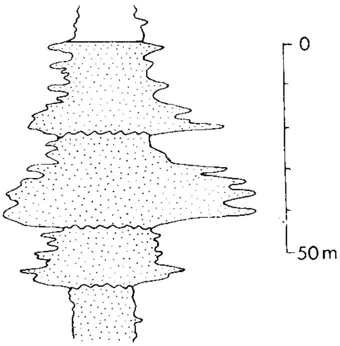
Nahorkatiya Oil Field, Assam

Oil production in the Nahorkatiya Field of Assam is obtained from sandstones within a 300 m interval in the upper part of the Oligocene Barail Series. These sandstones originated as river channel sands (Fig. 1-53) deposited on a fairly flat floodplain of silt and clay in the upper reaches of a delta. Individual channels, which range in thickness to 30 m and in width to more than 450 m, are interbedded with thin beds of coal and lignite formed in backswamp areas of a river floodplain. More than 50



E-LOG SECTION OF CHANNEL SANDS. NAHORKATIYA FIELD. ASSAM.

Fig. 1-53. E-log section showing oil-bearing river channel sands in the Oligocene Barail Series, Nahorkatiya Field, Assam. (Redrawn from Azad, Bhattacharyya, Datta, and Stevens, 1971).



E-LOG OF CHANNEL SANDS,
NAHORKATIYA FIELD, ASSAM.

Fig. 1-54. E-log of a composite channel sand in the Oligocene Barail Series, Nahorkatiya Oilfield, Assam. Three separate channels are superimposed, each grading upward from coarse sand to silt. Note the characteristic bell-shape of the log of each channel. (Redrawn from Azad, Bhattacharyya, Datta, and Stevens, 1971).

separate channels have been recognized in the Nahorkatiya Field. At some locations, two or more channels are superimposed (Fig. 1-54) to form sandstone units more than 50 m thick. The electric log character of many of these channel sands shows the typical bell-shape indicating grain gradation from coarser below to finer above.

Oil accumulation is controlled by a combination of stratigraphic and structural factors. Regionally, the Barail Series dips away from a basement ridge. This structural element has probably been important in controlling the direction of migration and extent of the area underlain by accumulations of oil. Locally, the oil has accumulated in traps controlled by faulting and pinching out of the channel sands. The oil, which is waxy and has a gravity of 33° A.P.I. in all the separate reservoirs, is thought to have originated in marine shales and limestones of the underlying Eocene sequence.

Maikop Oil Field, U.S.S.R.

The Maikop Field (Fig. 1-55) in the Black Sea rea, U.S.S.R., produces oil from meandering Tertiary channel sands. These shoestring sand bodies meander at various levels within a clay-filled valley cut into Cretaceous marly limestone. The main producing sand body, which is stratigraphically the highest, is 150-300 m wide and more than 8 km long. It is generally confined to the valley, but in places meanders out of the valley on to the surrounding flood plain. The sands, which are encountered at very shallow

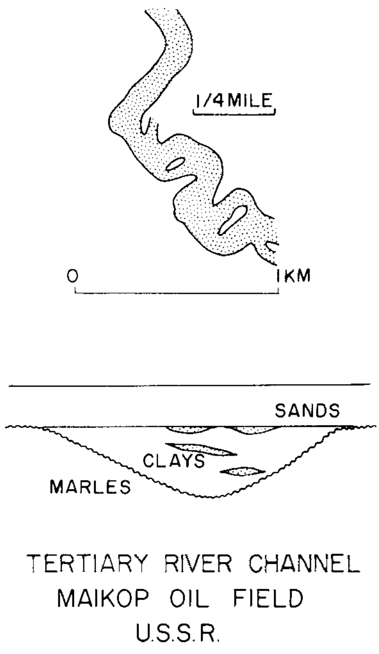


Fig. 1-55. Map and sections of buried stream-channel sands in a clay-filled Tertiary valley, Maikop oil field, Black Sea area, U.S.S.R. (Redrawn from Prokopov and Maksimov, 1937).

depths of a few hundred metres, have good porosity and permeability. They are commonly medium to coarse-grained, but locally include grit and gravel.

Entrapment of oil has resulted from a combination of stratigraphic and structural factors by which closure results from the coincidence of meander belts and a monocline dipping northward from the Caucasus Mountains. Initial rates of production from some wells have ranged up to 7,000 barrels of oil per day, and the amount of oil that can ultimately be recovered from the field is estimated to exceed 15 million barrels (2.4 million cubic metres).

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Chapter 2

DISTRIBUTARY AND DELTA-FRINGE SAND

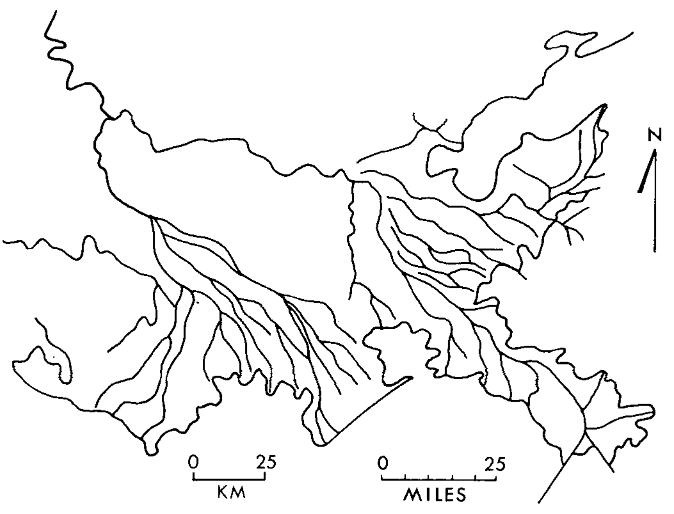
Introduction

Geomorphology

Patterns of deltas are ephemeral. They change continuously in response to, (a) shifts in the courses of distributaries, (b) to fluctuations in the load of sediments transported to the delta and seashore, (c) to variations in rates of compaction causing uneven subsidence in different parts of the delta, (d) to the effects of storms and tidal changes and, (e) to the bathymetry of the continental shelf on which the delta is building outward. The dendritic pattern of the classic birdsfoot delta of the present-day Mississippi River has been formed as a result of the shallowness of the continental shelf and the comparative slight variations in tidal levels. By contrast, the Niger River cuspate-arcuate delta (Fig. 1-3), currently building outward on a very narrow continental shelf subject to large tidal variations with strong current and wave action, has smooth, curved shoreline of delta-fringe sands.

Viewed in three dimensions, an ever-changing delta pattern is only the surface or geographic expression of a prograding lobe of sediment, of irregular outline and variable thickness, that is building seaward in response to fluctuations in the rate of sedimentation. As a river periodically changes course and discharges its load of sediment in other parts of the delta, it successively builds a sequence of lobes. These lobes not only prograde seaward, but merge laterally to form piles of sediment which themselves may merge with piles from adjacent rivers to constitute the paralic facies of a sedimentary basin. From a paleogeomorphic point of view, the dendritic and anastomosing pattern of distributaries in the Mississippi River delta complex (Fig. 2-1) is three dimensional. The pattern extends downward into Recent and Tertiary sections underlying the present-day delta, substantiating the view that depositional patterns and sedimentological processes observed today in the Mississippi Delta are repetitions of those marking the geological history of the underlying Tertiary.

Of particular interest in the field of petroleum exploration are the three-dimensional patterns of modern distributary and delta-fringe sand bodies, the geometry of these bodies, and their internal features such as sedimentary structures, grain gradation, and lithologic variations. The spatial associations of these bodies with adjacent beds, and the nature of these beds, are essential to the interpretation of the origins of the sandstone bodies.



DISTRIBUTARY CHANNELS, MISSISSIPPI DELTA

Fig. 2-1. Pattern of active and abandoned distributary channels of The Mississippi delta. (Redrawn from Kolb and van Lopik, 1966).

In the lower reaches of a delta bordering the shore, where the surface of the subsiding landmass has an elevation of less than one metre above sea level, the main distributaries flow through areas of marsh. The channels, bounded by levees, are commonly higher than the surrounding marshlands which receives mud and silt during times of flood when the distributaries overflow their banks. Sands are confined to channels in which they are transported to the distributary mouths where they are deposited and subsequently swept by ocean currents to form distributary mouth bars (Fig. 2-2). As the distributary continues to grow seaward it continuously over-rides the sand bars at its mouth to form a prograding, linear sand body referred to by Fisk (1961) as a bar-finger. The upper and central part of such a sand body, being confined to the channel, is fluvial and may show internal features characteristic of this origin. The lower and laterally more extensive part of the sand body may show internal features, such as grain gradation from coarser above to finer below (Fig. 2-2C), characteristic of a shoreline sand. This apparent anomaly in the depositional environment of the sandstone body pertains only to that part of the distributary sand body that has been built out into the sea. The remainder of the body, which in many examples probably represents the longer portion of the distributary, is entirely of fluvial origin. These relationships illustrate some of the difficulties encountered in recognizing the origin of a sandstone body in the subsurface.

The progradational sequence of delta distributaries, characterized by grain gradation from coarser above to finer below, is seen not only in bar-finger sands building out to sea on a shallow sea floor, but also in the seaward extension of coastal sand bodies such as barrier bars. Upstream, the bar-fingers merge into sand bodies deposited in distributary channels where the fluvial sequence is characterized by grain gradation from coarser below to finer above, provided that the sand is not uniform in grain size.

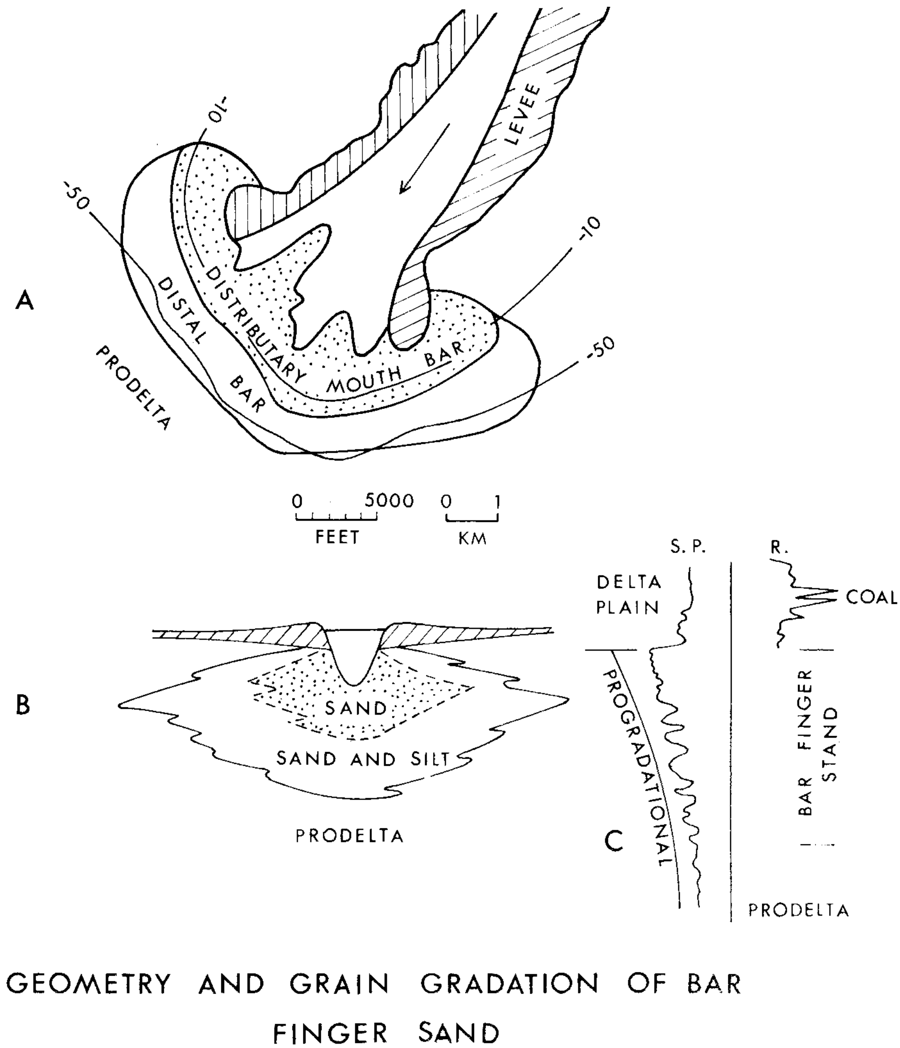


Fig. 2-2. A - Plan view of a bar-finger sand body formed at the mouth of Southwest Pass, a main distributary in the birdfoot delta of the Mississippi River, showing the distribution of sands in the distributary mouth bar, and of sands and silts in the distal bar over-riding the prodelta silts and clays. (Redrawn from Coleman and Gagliano, 1965).

Another possible factor in the development of bar-fingers has been pointed out by Moore (1970). He says that the linear bodies of fine-grained sand in the Mississippi River distributaries, termed bar-fingers, are formed not only by the seaward growth of prograding distributary-mouth bars, but also by the intrusion of a salt water wedges into the distributary channel during periods of less than maximum discharge. A wedge causes reduction in the bottom-carrying power of the distributary and results in deposition of a sand sill (Fig. 2-3) that migrates with the ebb and flow of the wedge along the lower course of the distributary.

The geometry of bar-finger sand bodies has been described by Fisk (1961) and Gould (1970). Each bar-finger is a prograding, linear body formed by accretion of distributary-mouth sand bars (Fig. 2-4). At any point in time, the sand bar forms an arcuate body of sand that has a width, normal to the course of the distributary, of 5-8 km. Deposited in shallow

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B - Cross-section of a bar-finger sand at the mouth of a delta distributary, showing the channel flanked by levees and underlain by sands deposited as a distributary mouth bar, and by sand and silt deposited as a distal bar overriding prodelta silts and clays. No scale. (Redrawn from Fisk, 1961).

C - E-log characteristics of a progradational sequence from coarser-grained above to finer-grained below, such as the sequence shown in the bar finger sand body illustrated by A and B. (Redrawn from Fisher, 1969 and Fisher *et al.*, 1969).

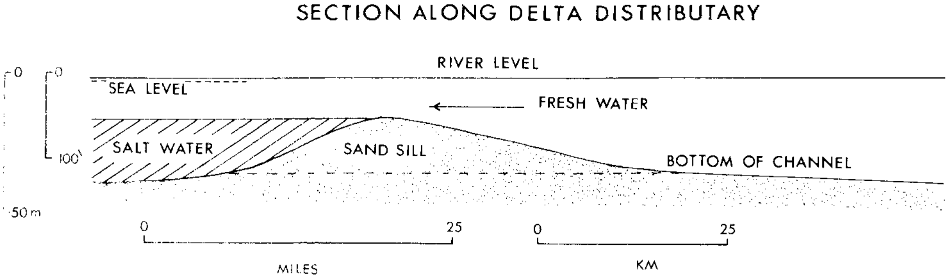


Fig. 2-3. Diagrammatic section along the channel of a delta distributary, showing the relationships of a sand sill and wedge of salt water within the fresh-water channel. (Redrawn from Moore, 1970).

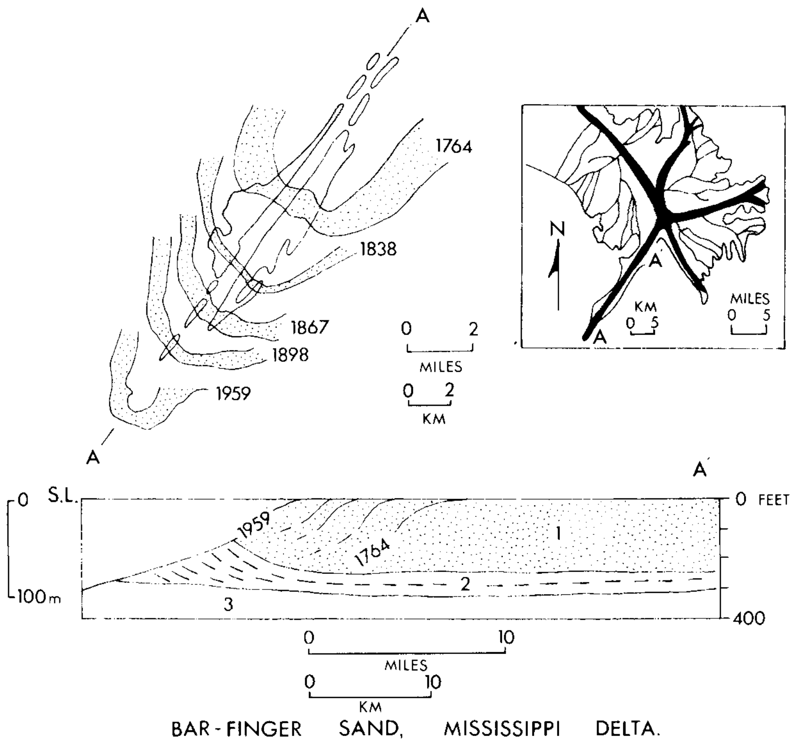


Fig. 2-4. Plan and sectional views illustrating progradation during the years 1764 to 1959, of the bar-finger sand body forming Southwest Pass, Mississippi River. Section A-A' shows the traces of time planes within the bar-finger sand body (1) which overlies delta-front silts (2) and prodelta clays (3). (Redrawn from Gould, 1970, after Fisk, 1961).

water at the mouth of a distributary, the sand grades seaward to silt and clay. *Prograding seaward, the bar-finger grows as a diachronous sand body,* time-planes (or their traces seen in sections having an *en echelon* and diagonal arrangement within the sand body. Bar-finger sand bodies can be up to 75 m thick and 30 km long. Lateral and vertical growth of the delta complex results in the ever-changing pattern of bar-finger sand bodies

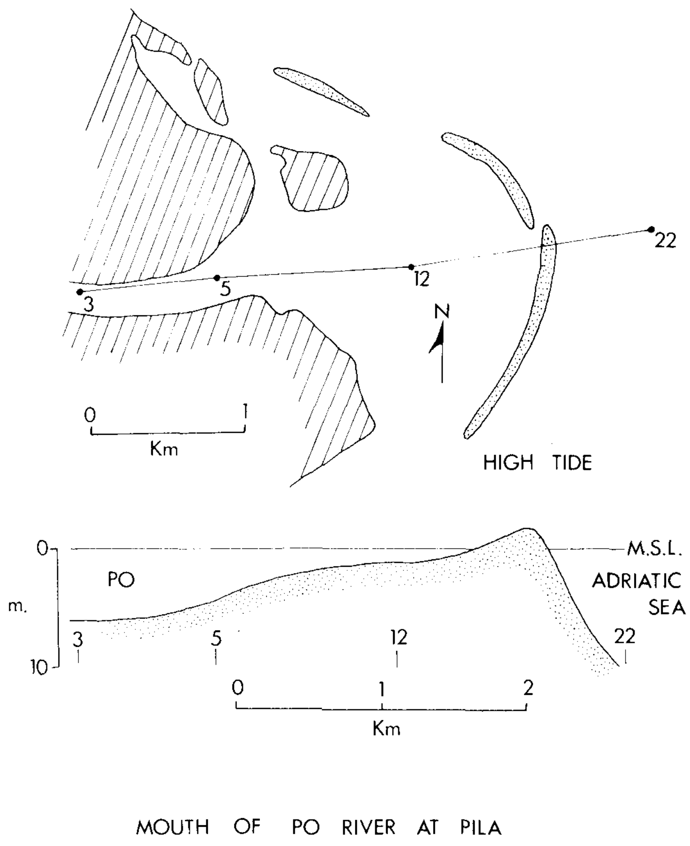


Fig. 2-5. Arcuate sand bars (stippled) formed at the mouth of the Po River at Pila, and a section through stations 3 to 22 showing the configuration of the wave-built bars and underlying wedge of sand. (Redrawn from Nelson, 1970).

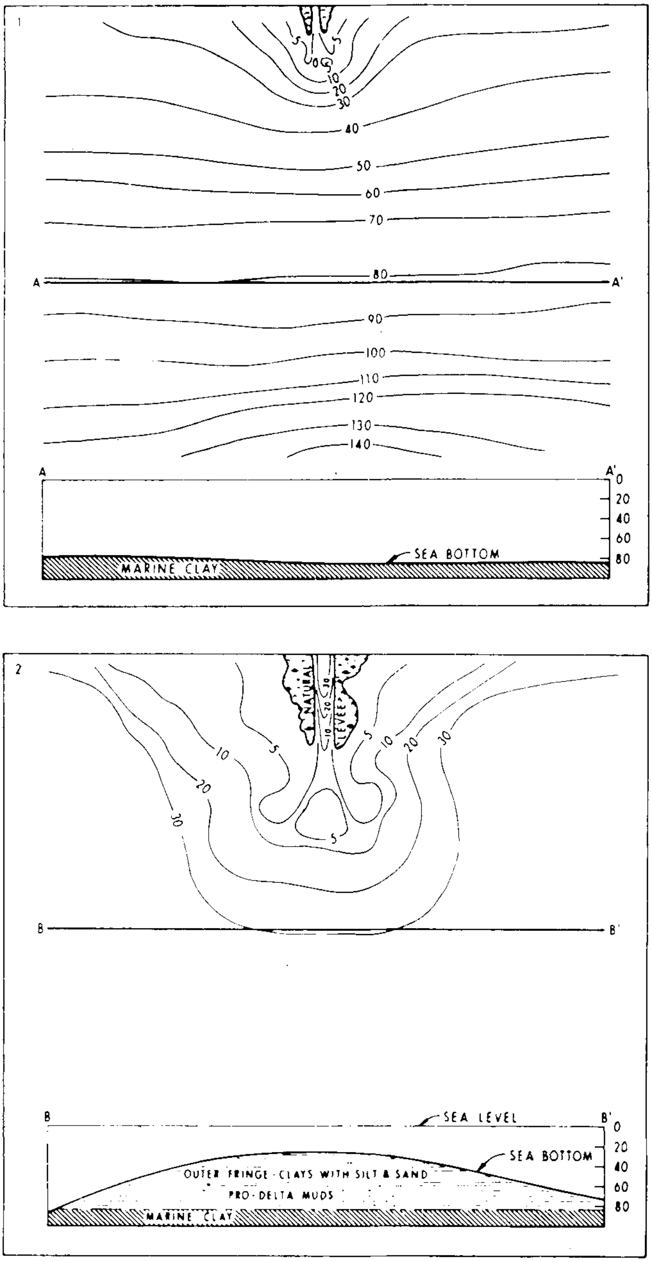
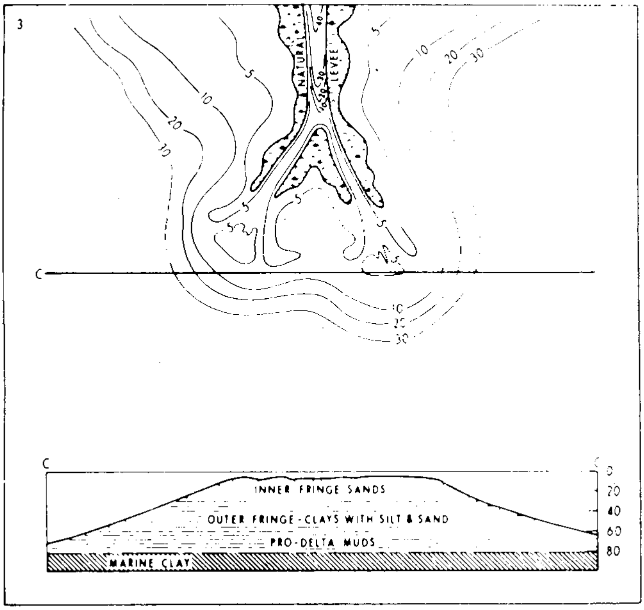


Fig. 2-6. Stages in development of a birdfoot delta and deposition of a deltaic sequence, showing growing pattern of bifurcating distributaries, and stratigraphic sequence through a section at various stages. (After Le Blanc, 1972, and Fisk, 1961).



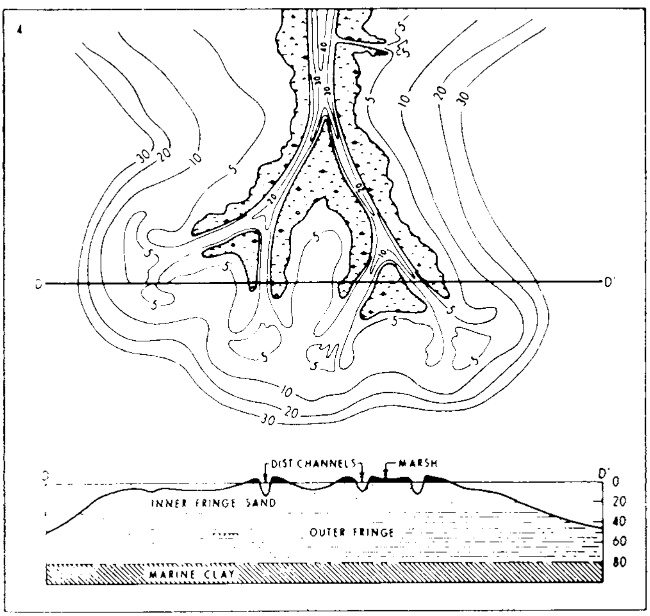
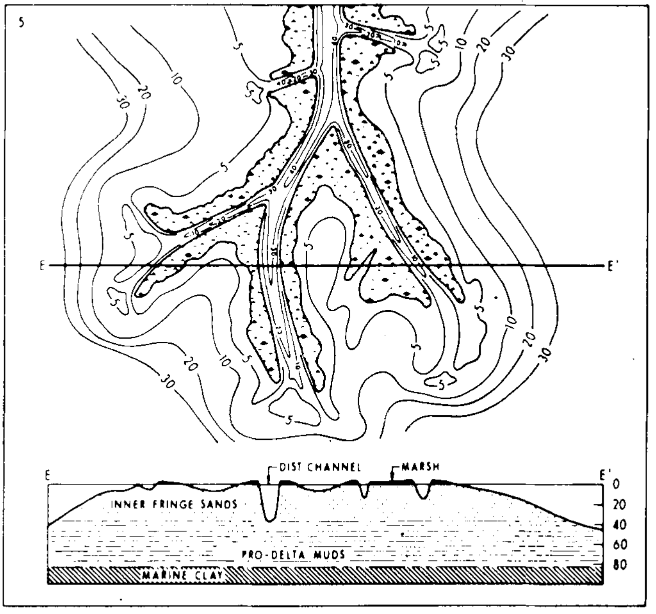


Fig. 2-6. (Continued).



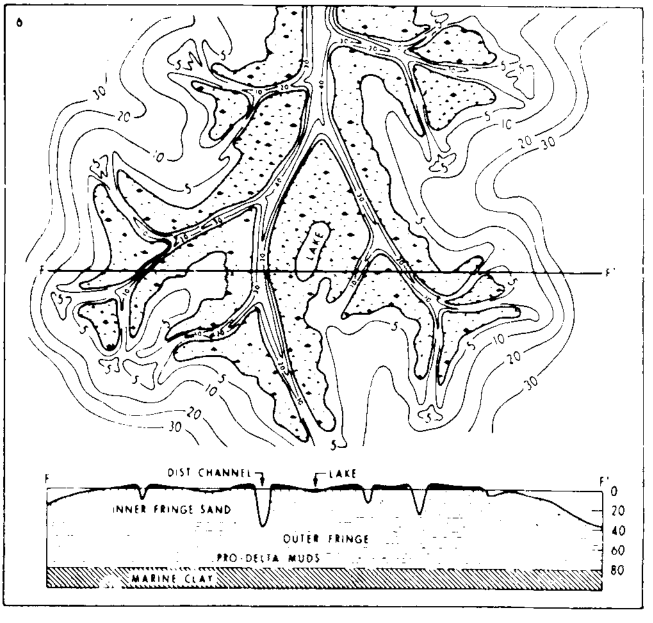


Fig. 2-6. (Continued)

building up through the section to form a complex of anastomosing shoestring--sand bodies separated by lenticular layers of silt and clay.

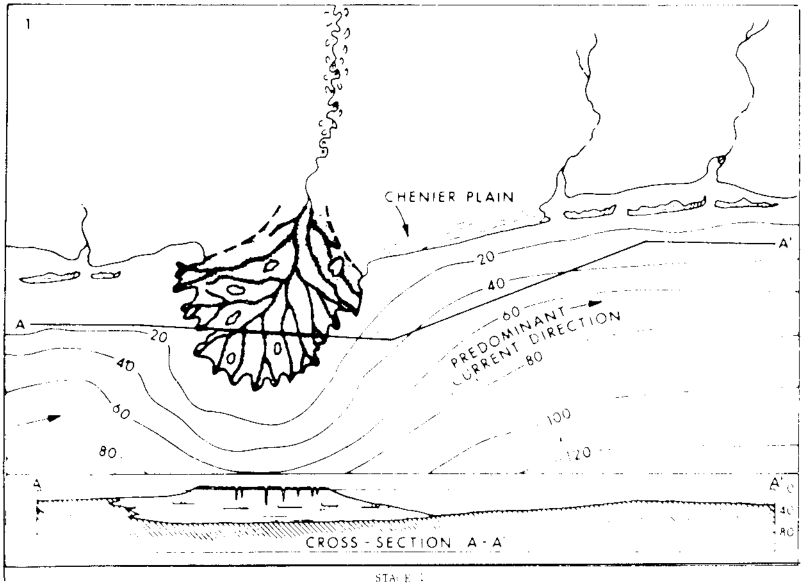
Another modern example of distributary-mouth sand bars has been described by Nelson (1970). This is the complex of sand bars at the mouth of the Po River at Pila, Italy (Fig. 2-5). These bars form arcuate islands on the seaward periphery of a prograding wedge of sand which is up to 15 m thick and 3 km wide.

Le Blanc (1972), based on studies of the Mississippi delta bar-finger sands, (Fisk, 1961) illustrated the growth of a delta complex in Fig. 2-6. These diagrams show the stages of development of a birdfoot delta in a delta complex comprising bifurcating distributaries separated by swamp. As lobes of the delta prograde and shift laterally, the sand bodies deposited in older distributary channels are buried to form a system of anastomosing shoestring-sands in the subsurface.

Le Blanc (1972) further points out (Fig. 2-7) that such lobes coalesce, by lateral shifting resulting from changes in the courses of the distributaries, to form a delta plain that may have a width exceeding 160 km. In the subsurface a buried delta plain is underlain by a stratigraphic complex of silts and clays interbedded with sand bodies formed as distributary channel sands, bar-finger sands, beach bars, and barrier islands. In general, depositional trends of the channels and bar-fingers are approximately normal to those of the shoreline bars and barrier islands.

E-log Characteristics

The coastal fringe of each delta lobe includes bar-finger sands which prograde seaward. Progradation results in the sand over-riding prodelta silt and clay, the resulting grain gradation being reflected in a serrate, funnel-shaped self-potential curve on the E-log. This shape indicates, (a) a gradational contact, sand lenses being interbedded with layers of



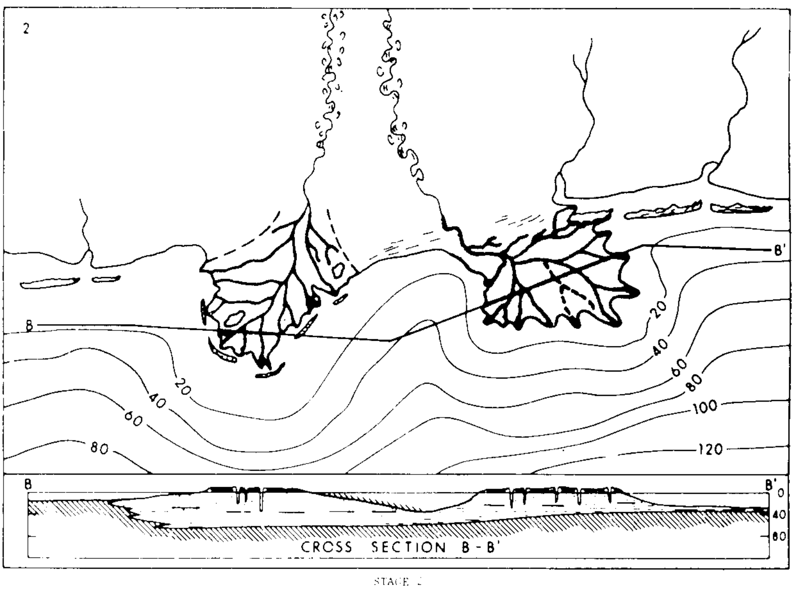
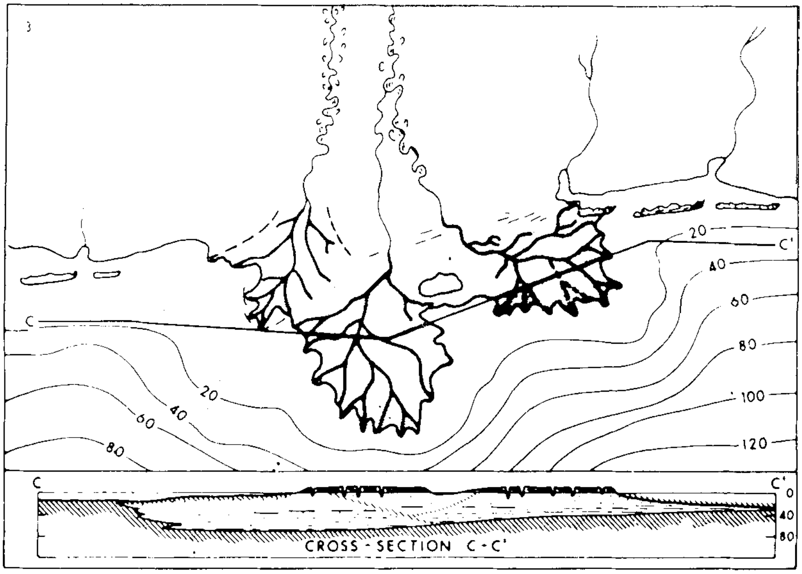
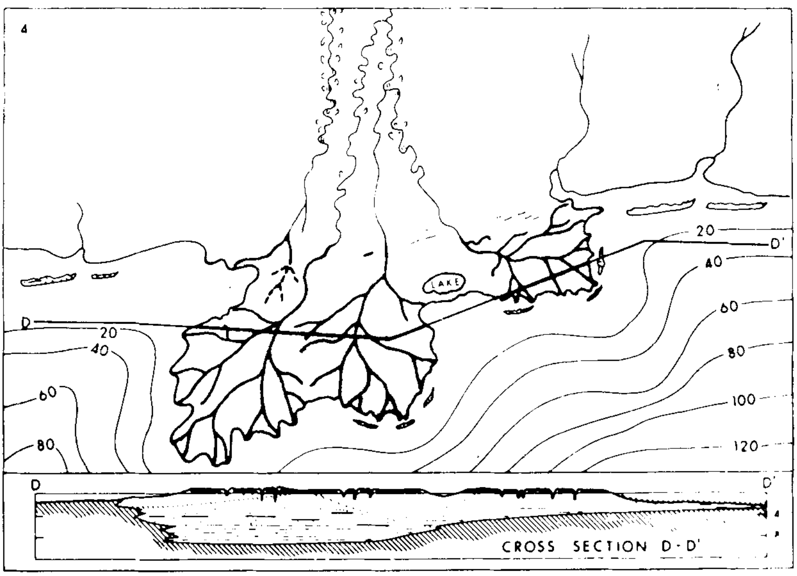


Fig. 2-7. Stages in development of a delta-plain complex and stratigraphic sequence resulting from the coalescence of separate delta lobes. (After Le Blanc, 1972).



STAGE 3



STAGE 4

silt and clay and, (b) a general thickening upward of the sand layers, commonly with an increase in grain size. In the lower part of the bar--finger sequence, interbedded layers of sand, silt, and clay are deposited as the result of fluctuations in the river flood cycles. During flood stages sand is deposited seaward from the distributary mouth, whereas during low-water stages the sediment deposited consists mainly of silt or clay. As the distributary advances, and the bar-finger progrades seaward, the sediment deposited at any location within the lower reaches of a distributary channel becomes increasingly sandy. The result is that a section through a distributary channel near its mouth shows an overall upward increase in grain size.

Distributary channel sand bodies may over-ride or cut through delta--marine fringe sands, and locally can be distinguished from the latter by their bell-shaped or cylindrical self-potential curves. In the upper reaches of a distributary channel the curve tends to be bell-shaped, indicating grain gradation from finer above to coarser below. In the lower reaches, subsidence of the distributary channel sand body, and fairly uniform rates of flow and sedimentation, can result in a thick sand body of uniform grain size. This type of sand body is characterized by a cylindrical self-potential curve. A serrated curve indicates interbeds of silt and clay deposited during periodic decreases in the velocity of the distributary.

Compaction

Prograding bar-finger sand bodies are over-ridden by distributary channels as the shore-line retreats. These channels, which commonly are only one third to one fifth as wide as the seaward-trending bar-finger sand bodies, converge landward to form larger channels. The bar-finger sand bodies, merge laterally at the surface. Compaction of the surrounding muds and silts, may cause them to merge or locally come into contact in the subsurface. In consequence, where viewed in three dimensions, these bar--finger sand bodies may have an *en echelon* arrangement in sections both normal and parallel to the general depositional trend. This arrangement facilitates the movement of fluids through the sand bodies during compaction. The movement is generally lateral and upward in the strata, along more permeable zones that trend up the depositional slope toward the margin of the sedimentary pile. It may be inferred that fluids expelled from compacting muds will move into bar-finger sand bodies and migrate upward along the buried distributary channel sand bodies. In fact, the movement of formation fluids through the sand bodies may be inhibited by penecontemporaneous slumping of large blocks of sediment, forming faults which restrict the movement of fluids and result in above-normal fluid pressures in isolated bodies of sand.

Local warping of distributary channel and bar-finger sand bodies, caused by compaction or tectonic deformation, may result in numerous closures which can become multiple stratigraphic or stratigraphic-structural traps for oil and gas. Many such multiple pay-zones are known in Tertiary beds of the Gulf Coast area of the United States (Hartman, 1972). Other examples are found in oil fields in the Booch Sandstone of the Pennsylvanian McAlester Formation (Busch, 1971).

Ancient Sand Bodies

Ancient examples of delta distributary and delta-fringe sand bodies occur in many parts of the world and are known from both outcrop and subsurface data. Most examples are within Mississippian, Pennsylvanian, Cretaceous, and Tertiary sequences. Selley (1970) describes some of the features of these sandstone bodies known from outcrops of Carboniferous rocks in northern England. Selley points out (p. 77) that, "In searching for ancient deltas, therefore, we must look for thick clastic sequences showing repeated cycles of upward-coarsening grain size. Each cycle should begin, at the base, with a marine shale which passes up through silts into coarser fresh-water channel sands at the top. In plan the channels should show a radiating shoestring pattern and be cut into freshwater shales and coals." Coal seams are also commonly present just above the distributary channel sand bodies (Fig. 2-22).

Appalachian Delta, U.S.A.

In the northern Appalachian region, Middle Pennsylvanian sandstone bodies were deposited as distributary channels, bar-fingers, and other delta-fringe sands. Progradation, lateral shifting and coalescence of delta lobes are illustrated by Ferm (1970) in Figs. 2-8 (a) and (b). The association of carbonate and non-carbonate rocks shown is not typical of modern deltas but is characteristic of Pennsylvanian deltas in the Appalachians of the eastern U.S.A., and also in north-central Texas (Galloway and Brown, 1973).

These schematic diagrams show the development of older and younger delta lobes formed in response to major shifting of the main river channel and its distributaries. Subsidence of abandoned delta lobes, resulting from near-surface compaction of muds and silts, causes transgression of the sea and the development of a drowned coastal topography. Local winnowing of the sediments, particularly during periods when parts of the coast remain relatively static, forms shoreline sands such as beaches and bars which transgress over the sinking landmass. In such a situation, marine delta-fringe sand bodies overlie non-marine delta-fringe channel sands. Subsequent shifts of the river system may result in new delta lobes building out over parts of older lobes. In this way, the cycle may be repeated two or three times. Further repetitions are unlikely because progradation results in the original depositional site being buried deeper and removed farther inland.

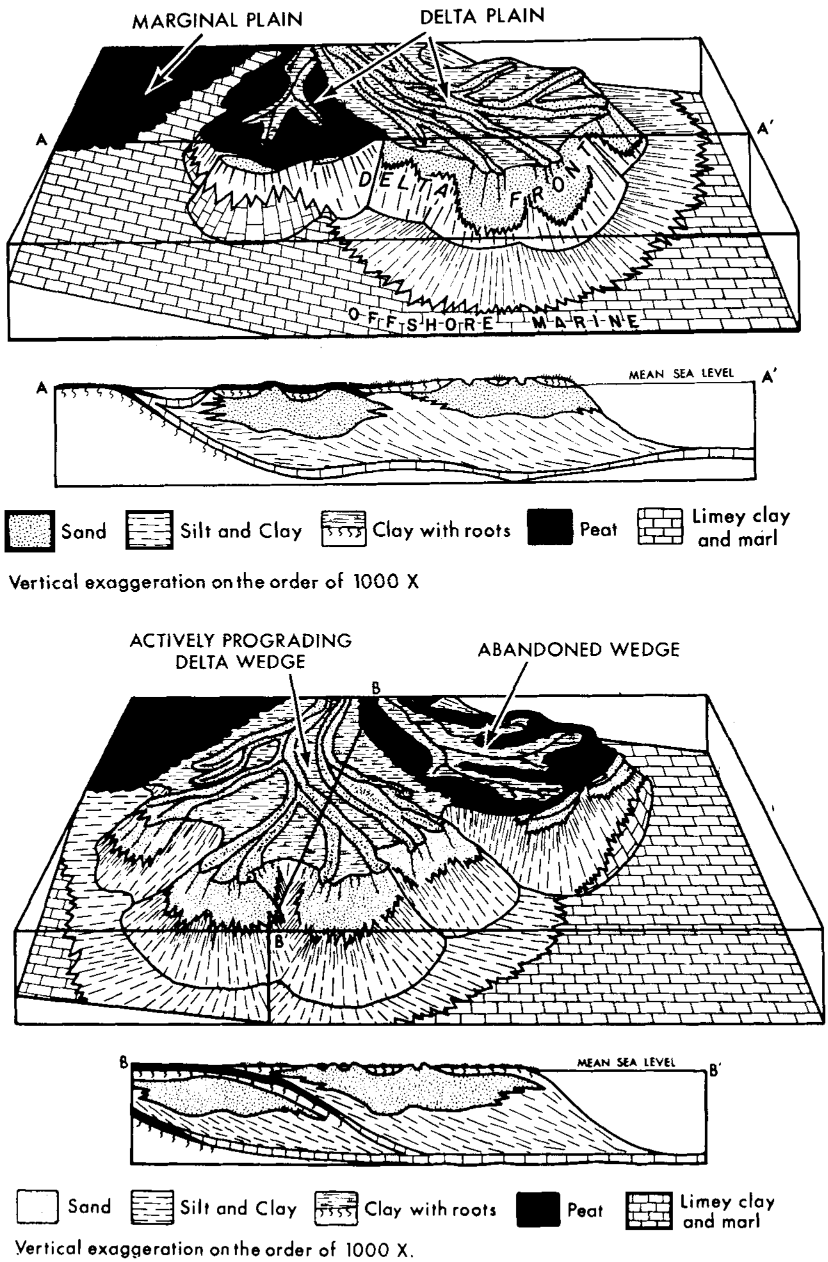
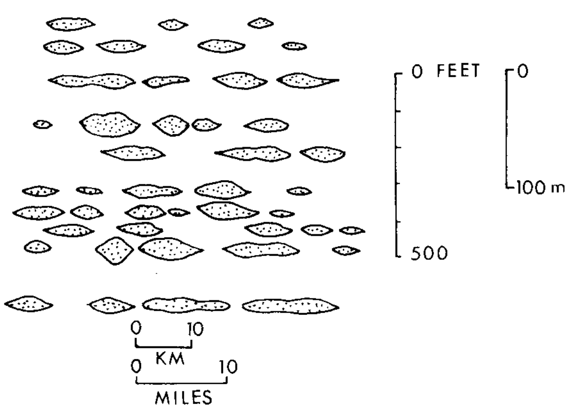


Fig. 2-8 (a) and (b) Schematic diagram showing reconstructed and generalized plan and sectional views A-A[1] and B-B[1] of a Middle Pennsylvanian prograding delta in the northern Appalachian region. (After Ferm, 1970).

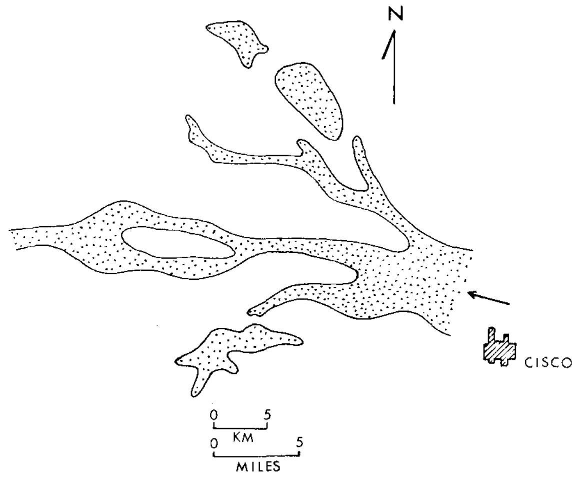
Cisco Delta, Texas

Within the Upper Pennsylvanian to Lower Permian Cisco Group of north--central Texas, anastomosing shoestring sands form a cross-sectional pattern shown in Figs. 2-9 and 2-10. These sandstone bodies, which originated as channel-fill sands in the Cisco Delta, form contemporaneous sets, each set occurring at a different stratigraphic horizon. Individual sandstone bodies tend to offset one another in adjacent horizons, a relationship that has been noted also in Oligocene channel-fill sands of the Seeligson Field, Texas (Nanz, 1954). This arrangement is probably the result of contemporaneous deposition of sands within the channels confined by the topographically higher levees, and compaction of the silts and clay deposited in the topographically low backswamps between the distributaries. Younger channels, which subsequently form adjacent and stratigraphically higher



VERTICAL ARRANGEMENT OF SANDSTONE CHANNELS, PENNSYLVANIAN CISCO GROUP, TEXAS

Fig. 2-9. Cross section, normal to the paleoslope, of sandstone-filled channels in the Upper Pensylvanian Cisco Group, central Texas. (Redrawn from Brown, 1969).



QUARTZOSE SAND TRENDS IN PENNSYLVANIAN
LIMESTONE SECTION, TEXAS

Fig. 2-10. Total sand isolith exceeding a thickness of 40 feet, showing trends of quartzose sands within the Upper Pennsylvanian - Lower Permian Cisco Group (Crystal Falls and Saddle Creek limestone section) in central Texas. (Redrawn from Galloway, 1969).

sets, tend to follow the topographic depressions between the older channels.

The Cisco Delta has been described in considerable detail by Galloway and Brown (1973). They say, p. 1187, "The Cisco fluvial-deltaic system is updip from associated shelf edges and consists of sandstone and mudstone interbedded with subordinate amounts of limestone and coal. Facies composition of the system is similar to, and its areal extent coincident with, the Cisco Group as defined at the outcrop. Components of both fluvial and deltaic systems are closely associated with this system and cannot be areally segregated at the system level. Facies of the delta system include distributary-mouth bar sandstone, delta-margin sandstone, delta-plain mud and siltstone, and prodelta and interdistributary mudstone. Fluvial facies include channel sandstone, crevasse splay sandstone and siltstone, overbank mudstone, and lacustrine deposits". They say further, p. 1189, "The Cisco fluvial deltaic system extends 50-70 mi westward from the outcrop belt into the subsurface, where it grades into limestone facies of the Sylvester shelf-edge bank system".

Several structural-stratigraphic traps for oil have been found in channel-fill sandstone bodies of the Cisco Group, including the Morris, Buie-Blaco, Cook Ranch and Bluff Creek fields.

Volgograd Delta, U.S.S.R.

Part of a Lower Carboniferous system of delta distributaries, situated north of Volgograd (Stalingrad) U.S.S.R., is illustrated in Fig. 2-11. The pattern shown is the gross distribution of distributary channel-fill sands

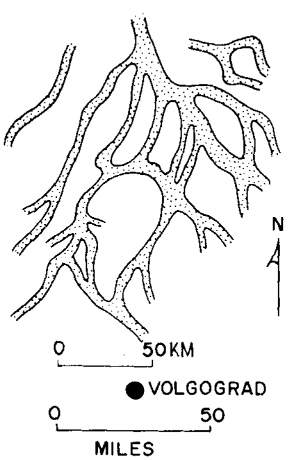


Fig. 2-11. Lower Carboniferous paleodelta, near Volgograd (Stalingrad), U.S.S.R. (Redrawn from Markovskii, 1967).

within a particular straitgraphic interval. It consequently represents the superimposition of successive distributary systems that grew southward within the time span represented by the stratigraphic interval. Individually, these channel-fill sands have a width of 3-8 km and collectively they have been traced for 160 km. Smaller sandstone bodies are commonly 10-20 m thick, but range up to 45 m. The pattern of distributaries is similar to that of the Mississippian Bedford Formation (Fig. 1-15) in Ohio, and of the Pennsylvanian Booch Sandstone in (Fig. 2-15) in Oklahoma.

Identification of Delta Distributary Channel Sands

Previous examples illustrating the branching and anastomosing geographic pattern of shoestring sands, and the stratigraphic relationships of individual sandstone bodies, clearly indicate that the shoestring sands originated as delta distributary channel-fill sands. Where only one sandstone body is known, its possible depositional environment and paleogeographic setting may be difficult to determine. In such cases, differences of opinion may arise as to the origin of the sandstone body and its significance to the stratigraphic history of the region.

A case in point is illustrated in Fig. 2-12, an isopach map showing three parallel trends in the Upper Mississippian Palestine Sandstone of Illinois. The Palestine Sandstone, which ranges in thickness to 30 m, is an upper unit of the Chester Series which includes thirteen major sandstone units (see Fig. 2-20) constituting 25% of the section in the Illinois Basin. A general characteristic of all these sandstone units is that they have sharp erosional contacts with the underlying beds, a feature reflected in the blocky to bell-shaped self-potential curve of their E-logs. Locally, these sandstone units are underlain by erosional channels up to 15 m in depth. The sandstones are fine to very fine-grained,

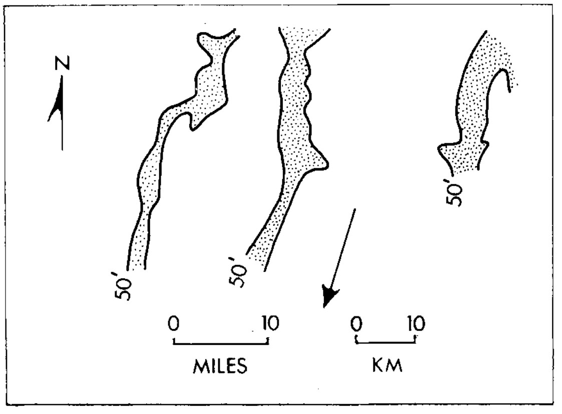


Fig. 2-12. Isopach map showing trends in the Upper Mississippian Palestine Sandstone, Illinois. Arrow indicates mean direction of cross-bedding, indicating southward transport of sand. (Redrawn from Potter *et al.*, 1958, Fig. 13).

and are composed almost entirely of moderately well-rounded quartz grains, with generally less than 1% feldspar. Cross bedding is particularly well developed in the thicker parts of the sandstone units which also contain ripple marks and plant remains.

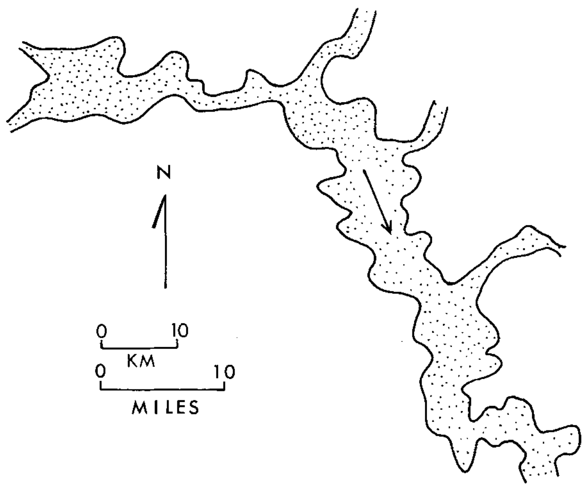
Potter, *et al.* (1958) say that although marine fossils are not common within the basin, they have been found in some parts of the basin in nearly every sandstone unit of the Chester. Could they have been re-worked from penecontemporaneous adjacent marine beds? Some sandstone units contain calcareous zones that locally grade into sandy limestone. On the other hand, Potter, *et al.* (1958, p. 1016) say that, "Thin coal beds are associated with the Chester sandstones at eight horizons".

The origin of these linear sandstone units is problematical. Off (1963) was of the opinion that they may have been tidal current ridges. Alternatively, they may have been deposited in distributaries on a delta characterized by a relative scarcity of non-carbonate mud and by the formation of calcareous beds. This sedimentologic and litholigic association is not common today, but is typical of Pennsylvanian deltas in the Appalachian region.

Many of the Chester sandstone bodies form good reservoirs for oil. With reference to the lateral variation of sands in the Upper Mississippian of southern Illinois, Levorsen (1967, p. 289) states, "These Mississippian rocks are characterized by sand patches, lenses, bars, channels, and facies changes, and in addition they are truncated toward the north by overlapping Pennsylvanian formations, which contain lenticular sands. A great many oil pools are found in these Mississippian and Pensylvanian sands; most of them are associated with folding, but many are limited on one or more sides by the edges of permeability". The lateral variations of these sandstone bodies have been pointed out by Swann and Atherton (1948).

One of the many Pennsylvanian channel-fill sandstones of the Illinois Basin is shown in Fig. 2-13. This sandstone unit has a thickness of 5-25 m, a width of 3-8 km, and trends in a meandering course to the southeast, the direction of flow of the ancient river system. The sandstone lies adjacent to and stratigraphically between the Summun and Harrisburg coal seams, a relationship that suggests a marshy environment. The meandering pattern of the sandstone body, and also its association with coal seams, points to its origin in the channel system of a river flowing through a low-lying terrain that was probably the coastal plain of a delta.

An interesting example of distributary channel sands, mapped in outcrop as discrete sandstone bodies, but shown by extrapolation to be parts of a branching distributary system, is shown in Fig. 2-14. These sandstone bodies are within the nearly flat-lying Upper Cretaceous



MEANDERING PENNSYLVANIAN SANDSTONE CHANNEL, ILLINOIS

Fig. 2-13. Meandering Pennsylvanian sandstone channel between the Summun and Harrisburg coal seams in east-central Illinois. The sandstone body outlined ranges in thickness from 20 to 80 feet (6-24 m). Direction of sediment transport is to the south-east. (Redrawn from Potter, 1962).

Bearpaw Shale of central Montana. Although on a much smaller scale, the pattern of Bearpaw distributaries resembles that of the Lower Carboniferous Volgograd delta in the U.S.S.R., and also the deltaic Pennsylvanian Booch Sandstone of Oklahoma. These Bearpaw shoestring sands have a thickness of up to 20 m, and a width of up to 2km. Individually, they have been traced in outcrop for several kilometres. They consist of light grey, fine to coarse-grained, cross-bedded lithic sandstones containing claystone (mud) balls and abundant carbonized plant remains. Overlain and underlain by siltstones and shales, they are considered to

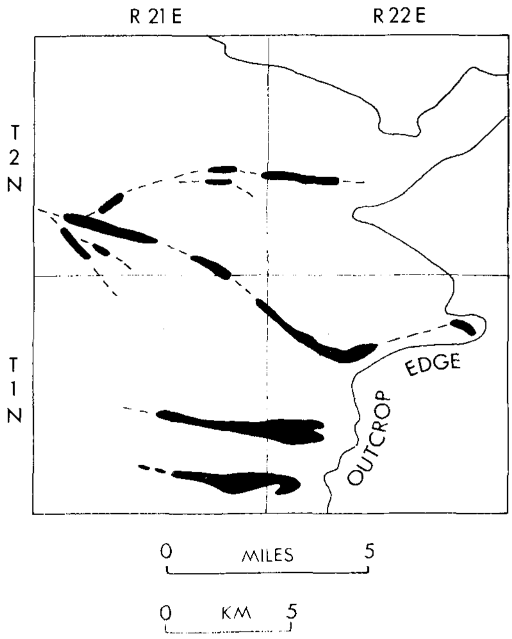


Fig. 2-14. Distribution of shoestring sandstone bodies formed as channels in the nearly flat-lying Upper Cretaceous Bearpaw Shale, central Montana. (After Wulf, 1964).

be distributaries formed on part of a Bearpaw delta-complex that prograded eastward.

The area shown in Fig. 2-14 overlies the Lake Basin oil and gas field, a structural dome. In the subsurface, the pattern of Bearpaw shoestring sands now cropping out could form potential structural--stratigraphic traps for hydrocarbons.

Oil and Gas Fields

The following examples of oil and gas fields in distributary and delta-fringe sand bodies range in age from Late Paleozoic to Middle Cenozoic. Of these, four are Pennyslvanian, two are Mississippian, three are Cretaceous, and four are Tertiary. Eight examples are in the U.S.A., two in Canada, and one each in Venezuela, Nigeria, and the U.S.S.R. This distribution is not presented as being representative of the world or of North America, as it is obviously biased by a very limited sampling.

Booch Sandstone Oil Fields, Oklahoma

The Early Pennsylvanian Booch Sandstone of the McAlester Formation in Oklahoma (Fig. 2-15) forms a branching system of distributary shoe--string sands that cover an area at least 112 km wide. Flowing to the south, this distributary system comprised a central main channel, in which sand bodies more than 60 m thick were deposited, and also secondary channels which commonly contained sand bodies less than 30 m thick. Fig. 2-15 shows the generalized pattern formed by the composite distribution of these sand bodies. In the northeastern part of the area, the upper sandstone member of the Booch Sandstone is the predominant unit, whereas in the southwestern part the Booch Sandstone is represented by members lower in the sequence. Busch (1971) says that the Booch distributaries were formed on a large delta-complex that covered an area of approximately 5120 sq. km within the Arkoma Basin. It is interesting to note that the present-day configuration of composite channels within the delta of the Rio Grande River, Texas, is comparable in size and shape to that of the Booch Sandstone (Fig. 2-15). The Booch Sandstone is commonly very fine-grained and lithic, with a fairly high (ave. 15%) content of clay. Permeability improves where, locally, the sandstone is medium to coarse-grained.

There are numerous oil fields producing from the Booch Sandstone, most of which are not in the thicker main channel but in the thinner distributaries. Many of these are purely stratigraphic traps, the

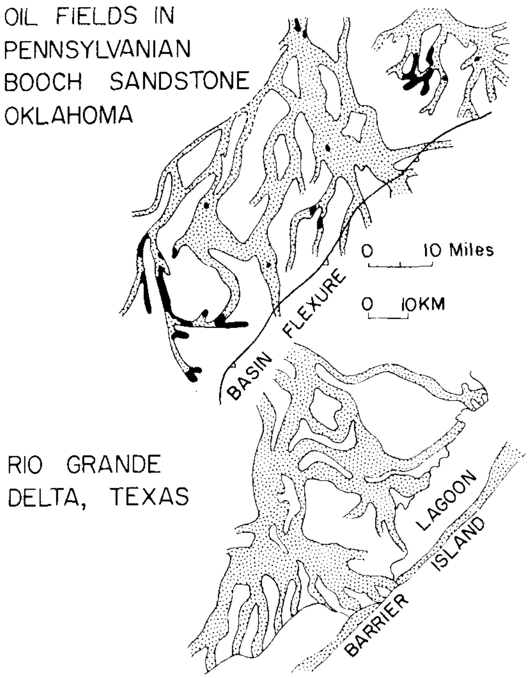
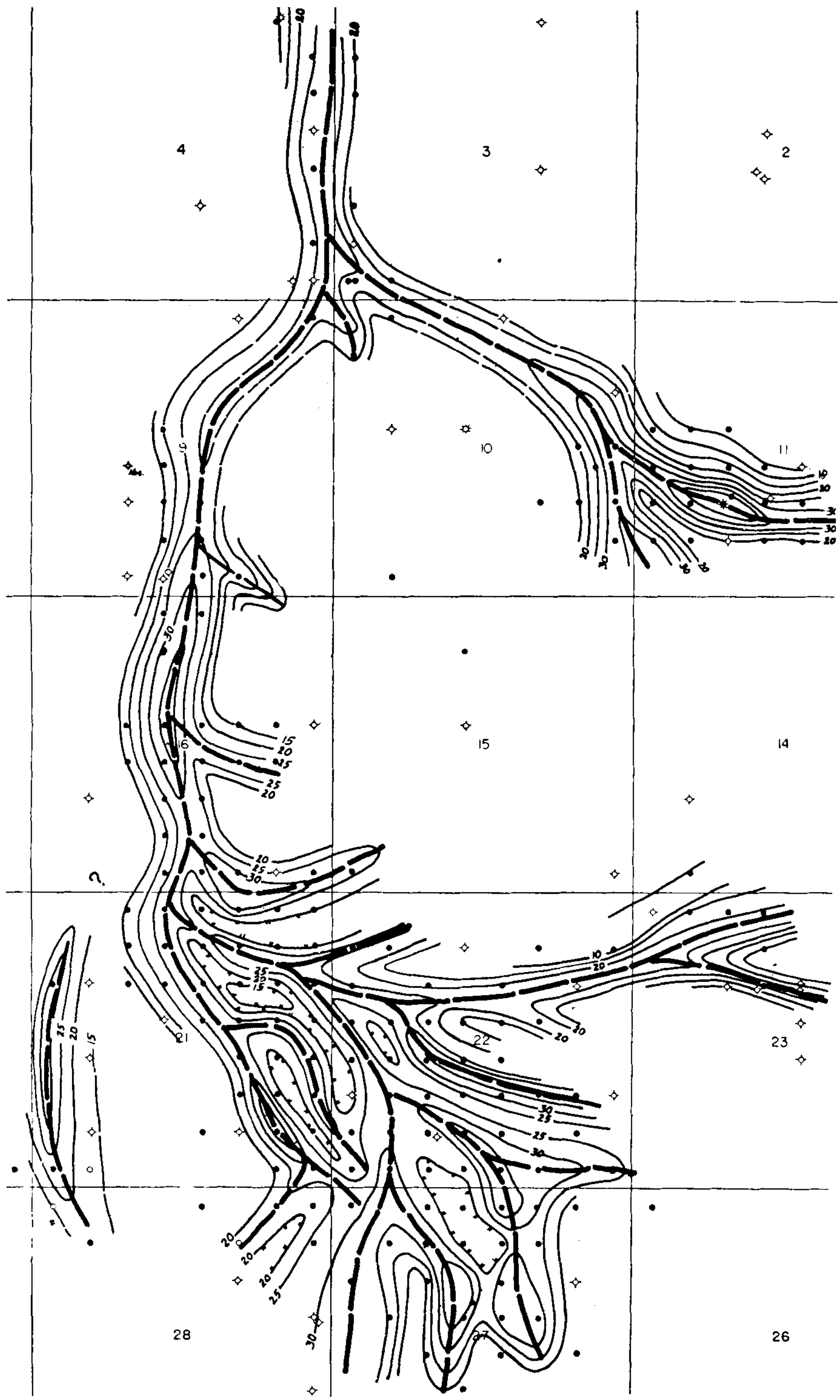


Fig. 2-15. Upper - Map showing composite distribution of the Booch Sandstone member in the Pennsylvanian McAlester Formation, Seminole district, Oklahoma. Numerous oil fields, where production is obtained from the Booch, are shown in black. (Redrawn from Dicky and Rohn, 1958, after Busch, 1953; Busch, 1971).

Lower - Map showing present-day distributary channels on the delta of the Rio Grande River, Texas. This delta has grown across the lagoon where its extension is currently limited by wave and current action that forms the barrier island. Continually changing course, the distributary channels build up a complex pattern of sinuous shoestring sands. Same scale as above.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oil being confined by permeability barriers where the sandstone pinches out and is flanked by shales and siltstones which originated as sediments deposited in a backswamp environment between the distributaries. Others have a structural influence where westward-plunging noses intersect more permeable sandstone zones within the distributary trends.

The Hawkins Oil Field, located at the southwestern extremity of the Booch delta (see inset in Fig. 2-15), produces from the Booch Sandstone shown in Fig. 2-16. This figure is an isopach map of a member comprising distributary sand bodies situated in the middle of the Booch stratigraphic interval. This oil-bearing sandstone member was deposited in a main north--south trending distributary channel that branched to the south-east and south-west. The maximum thickness of sandstone in the main channel is 10 m. Entrapment of oil has resulted from the coincidence of these shoestring sands and a structural "high" that has resulted from compaction. Busch (1971) shows that rates of production coincide with trends of maximum sandstone thickness, the oil yield being greater where the sandstone is thicker.

South Pine Hollow Gas Field, Oklahoma

In the South Pine Hollow Gas Field (Fig. 2-17) of Oklahoma the producing unit is the Early Pennsylvanian Lower Hartshorne Sandstone. This sandstone, which is the basal unit of the Desmoinesian Stage, is

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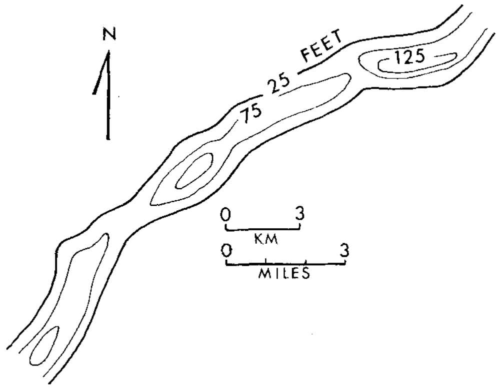
Fig. 2-16. Isopach map of the oil-bearing middle member of the Booch Sandstone in the Pennsylvanian McAlester Formation, Oklahoma. The area shown covers the Hawkins Oil Field. Scale of grid in square miles (1 mile = 1.6 km). Contours show intervals of 5 feet (1.5 m). (After Busch, 1971).



ISOPACH OF NET SANDSTONE, LOWER HARTSHORNE SANDSTONE, OKLAHOMA

Fig. 2-17. Isopach of net sandstone, Pennsylvanian Lower Hartshorne Sandstone, South Pine Hollow Gas Field, Pittsburg County, Oklahoma. This linear sandstone body is interpreted as filling a distributary channel. (Redrawn from McDaniel, 1968).

underlain by the Atokan Formation and overlian by the McAlester Formation which includes the Booch Sandstone.

The Hartshorne Sandstone is a linear sandstone body which is interpreted as having been a delta distributary sand. This sandstone body has been traced for more than 25 km. It has a fairly constant width of about 2-3 km, and a gross thickness which ranges in excess of 60 m. The net sandstone thickness is approximately half the gross thickness at any particular location, and has a maximum of 40 m. Permeability and porosity increase toward the thicker parts of the sandstone body.

Of particular interest is the fact that the sandstone body lies in a structurally low feature, and that the gas accumulation is controlled entirely by stratigraphic parameters including variations in porosity, permeability, and net sandstone thickness. Recoverable reserves in the South Pine Hollow Gas Field are estimated to be in excess of 100,000 million cubic feet (2,800 million cubic metres).

Pokrovsk Oil Field, U.S.S.R.

In the Pokrovsk Field (Fig. 2-18) of south-central U.S.S.R., oil is produced from a sinuous sandstone body enclosed within a claystone bed overlain and underlain by Carboniferous limestone. The sandstone body, which has been traced by drilling for nearly 15 km along its length, has a width of up to 2 km and a maximum thickness of 10 m.

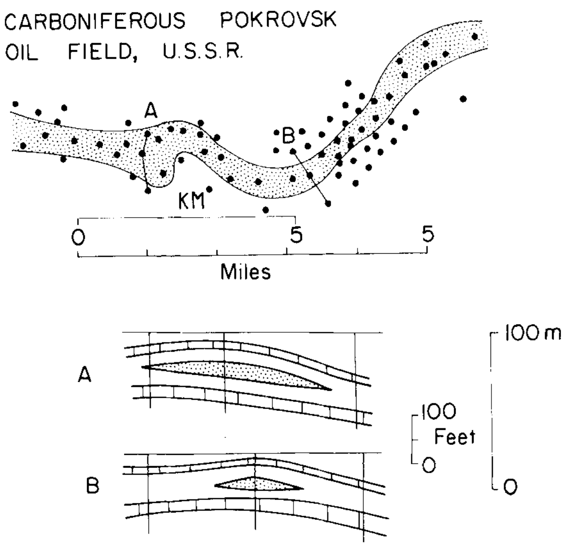


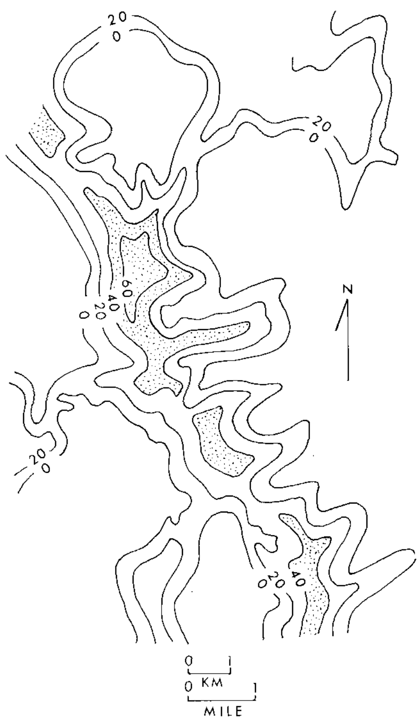
Fig. 2-18. Map and sections of the Pokrovsk oil field in the Russian Platform, U.S.S.R. The oil-bearing sandstone, considered to have been deposited by a river flowing in the direction indicated by the arrow, forms a sinuous body within a claystone bed that lies between layers of Lower Carboniferous limestone. (Redrawn from Markovskii, 1965).

The sandstone is considered to have been a channel-fill sand deposited by a distributary flowing over a flat coastal plain during a period of limited emergence of the land preceded and followed by the development of carbonate shoals. The sandstone is quartzose, fine to medium-grained, and well sorted. The mean porosity is 20% and the permeability, which is generally good, increases in the central parts of the body where the sandstone is thicker and coarser. The pattern of holes suggests that oil accumulation in the field is controlled essentially by stratigraphic features related to the distribution of the sandstone body, and that exploration proceeded on a hit-or-miss basis.

East Tuskegee Oil Field, Oklahoma

The Misener Sandstone is one of the main producing members in the East Tuskegee Field of Oklahoma, yielding oil having a gravity of 39° A.P.I. This sandstone unconformably overlies the Ordovician and is conformably overlain by the Early Mississippian Chattanooga Shale which is a very widespread, diachronous unit. The uppermost part of the Misener Sandstone is composed mainly of angular to rounded grains of quartz, and contains conodonts and phosphatic gastroliths (Borden and Brant, 1941). The lower part is coarse-grained, commonly gritty, and quartzose with abundant grains of chert.

The origin of the Misener Sandstone has been the sugject of controversy. White (1928) was of the opinion that the sandstone was eolian, whereas Borden and Brant (1941) concluded that the sandstone was deposited near shore in a marine environment. The stratigraphic position of the sandstone, lying directly on an unconformity, and the coarse nature of the lower section suggest a fluvial origin for the lowermost part. When the Misener was deposited the land must have been very flat and near sea level to allow extensive transgression of the sea in Chattanooga time. It is not surprising then, that the upper part of the Misener should contain a marine fauna. The pattern of distribution and thickness of the Misener, as shown in Fig. 2-19, may represent a composite picture of a distributary sand body that has been re-worked in the upper part by a transgressing sea, possibly in an estuarine environment.



GEOMETRY OF MISENER SANDSTONE, EAST TUSKEGEE OIL FIELD, OKLAHOMA

Fig. 2-19. Isopach map of Mississippian Misener Sandstone, East Tuskegee Oil Field, Creek County, Oklahoma. (Redrawn from Borden and Brant, 1941).

Dale Consolidated Oil Field, Illinois

In the Dale Consolidated Field of Illinois, oil production is obtained from the Upper Mississippian Hardinsburg Sandstone, one of several hydrocarbon-bearing sandstone units in the Chester Series (see Fig. 2-12). Fig. 2-20 illustrates the sharp erosional contact of the Hardinsburg Sandstone with the underlying beds, and the upward decrease of mean grain size in the upper part of the Hardinsburg. These characteristics are typiaal of sandstone units in the Chester and are indicative of their origin as channel-fill sands. The use of a closely underlying limestone marker as a datum restores the original configuration of the channel and suggests that when the channel was initially filled with coarser sand, characterized by the blocky self-potential E-log curve, the limestone marker and other beds underlying the erosional channel had a low regional dip.

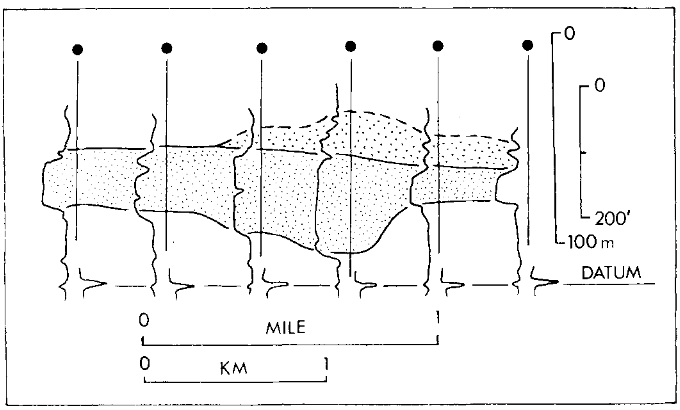


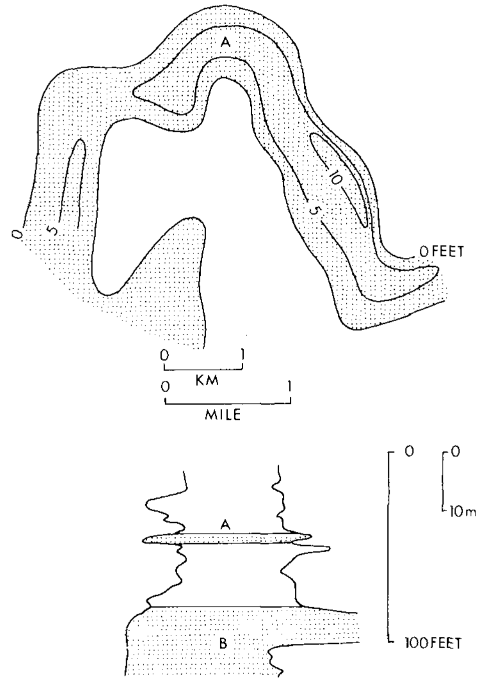
Fig. 2-20. Stratigraphic section of channel filled with Upper Mississippian Hardinsburg Sandstone, Dale Consolidated oil field, Hamilton County, Illinois. Datum is a limestone bed. (Redrawn from Potter *et al.*, 1958).

The Hardinsburg Sandstone and other sandstone units of the Chester are considered by Potter *et al.* (1958) to have been derived from pre--existing sediments, as they are quartz arenites composed almost entirely of moderately well-rounded grains. Indicative of their origin as channel-fill sands, these sandstone units commonly show fluvial-type cross-bedding. Also indicative of their depositional environment is their stratigraphic relationship with thin coal seams, which suggest that the channels meandered over a marshy deltaic plain.

Bellshill Lake Oil Field, Alberta

The Bellshill Lake Field of east-central Alberta produces oil from the Ellerslie Sandstone, the basal unit of the Lower Cretaceous Blairmore Group. The Ellerslie, which fills a broad,east-west trending valley (Figs. 1-41, 1-42) on the eroded surface of the Devonian carbonates, is composed of quartzose sandstone derived from Precambrian rocks. Fluvial-type cross-bedding is a common feature, indicating that the Ellerslie was deposited by a river. Paleogeographic reconstruction (Conybeare, 1972) suggests that this river flowed eastward from the Precambrian Shield to a Lower Cretaceous sea transgressing southward. Transgression subsequently resulted in drowning the Ellerslie river system, the sands of which are overlain by estuarine, coastal marsh, and brackish to fresh-water lacustrine sediments.

Fig. 2-21 illustrates a portion of a shallow stream channel that meandered on a coastal plain overlying the Ellerslie river sand at Bellshill Lake Oil Field. In this case, hydrocarbon accumulation in the meandering sand body is not significant with respect to production from the Ellerslie, but where such an arcuate body is thicker and convex up-dip, it may form an excellent stratigraphic trap. A similar example (Fig. 1-43) is illustrated by Martin (1966) who states that in the



ISOPACH MAP OF MANNVILLE SANDSTONE 'A', BELLSHILL LAKE FIELD, ALBERTA.

Fig. 2-21. Upper - Isopach map of a thin sandstone 'A' in the lower part of the Blairmore Group, Bellshill Lake Field, Alberta. This sandstone was deposited as a stream meander on a coastal plain.

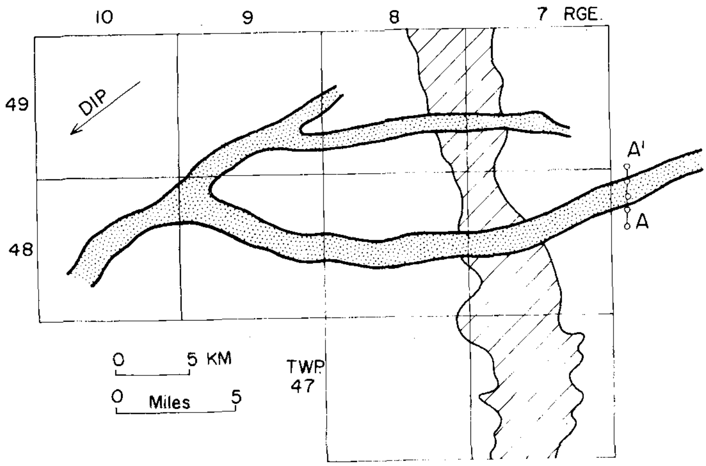
Lower - Electric log showing the relationship of sandstone 'A' to the oil-producing basal quartz sandstone (B) of the Ellerslie Formation in the Bellshill Lake Field.

Hughenden Field, which also produces from the Ellerslie, oil is trapped within the Ellerslie against a clay-filled meander that intersects the regional strike. Both examples require a closure formed by the coincidence of a meander loop and regional dip; but in Fig. 2-21 the trap is a sand-filled loop, whereas in Martin's example the trap is within a sand-filled loop of the Ellerslie where it is locally sealed by a younger clay-filled loop. Other examples of a similar nature are illustrated by Conybeare (1972), Swindon (1968), Berg (1968) and Truchot (1963).

The Ellerslie Sandstone is cross-bedded, quartzose, fine to coarse-grained and up to 75 m thick. It has variable porosity and permeability, in part determined by local cementation with calcite and clay minerals. In the Bellshill Lake Field the porosity and permeability are commonly in the range 25-28% and 1,000-1,500 millidarcys respectively, the latter ranging up to 6,000 but averaging 600 millidarcys. Production problems derive mainly from an effective water drive that invades the oil-bearing zone. The oil has a gravity of 28° A.P.I. and a gas content of approximately 150 cubic feet per barrel of oil (approximately 20 cubic metres of gas per cubic metre of oil). The estimated oil in place is approximately 180 million barrels (28.6 million cubic metres), but water drive problems preclude the production of very little more than 36 million barrels (5.7 million cubic metres).

Belly River Pool, Pembina Oil Field, Alberta

In the Pembina Field of west-central Alberta, the main oil production comes from the Upper Cretaceous Cardium Sandstone, approximately 300 m below the basal sandstone number of the Upper Cretaceous Belly River Formation. Additional production is obtained from the Belly River Pool which yields oil from this basal sandstone member. Overlying a thick sequence of marine shales of the Upper Cretaceous Lea Park Formation, the basal member of the Belly River is found throughout a wide area. It is diachronous and consists of two or more genetic units. One of these units is a marine shoreline sand, another is a sand that fills channels cut into the marine sand by distributaries of the eastward prograding Belly



CRETACEOUS BELLY RIVER SANDSTONE, PEMBINA OIL FIELD, ALBERTA

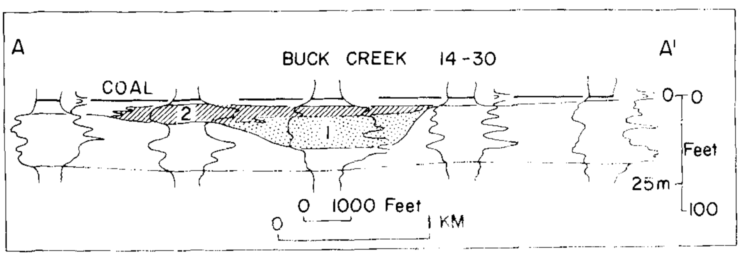


Fig. 2-22. Map and stratigraphic section A - A[1] showing depositional trends of the basal sandstones of the Upper Cretaceous Belly River Formation, Pembina Field, Alberta. The map shows river distributary sands (stippled) cutting across a marine shoreline sand (hatchured). The stippled and hatchured areas also indicate where the sandstones are more than 30 feet thick. The arrow shows the approximate direction of regional dip. The section shows coarse to medium sand (1) filling the lower part of a channel overlain by fine sand (2). This fine sand is in turn overlain by silts and a coal seam. (After Conybeare, 1944, 1972).

River delta. The marine sand is generally fine-grained, with poor porosity and permeability, whereas the channel sands are coarser and more permeable. The Belly River Pool is contained within one of these channels (Fig. 2-22).

The producing sandstone is lithic, consisting of grains of quartz, quartzite, chert, feldspar, argillite, and volcanic rocks derived from a western source. The sandstone grades from coarse to medium at the base to fine at the top. Mudstone, containing a thin coal seam, overlies the sandstone. Within the channel, which is about 2 km in width, the maximum thickness of sandstone is 20 m. The maximum thickness of the oil-bearing zone is 10 m. Porosity averages 18% and permeability is fair but variable. The pool is purely stratigraphic, oil being contained within the thicker and coarser parts of the sandstone where it is trapped by permeability barriers on the flanks of the channel.

The Belly River Pool is estimated to contain more than 30 million (4.8 million cubic metres) of 36° A.P.I. oil, but recoverable reserves are estimated at only 2 million barrels (0.2 million cubic metres). Gas solution drive is the main producing mechanism, the initial gas content of the oil amounting to 350 cubic feet per barrel of oil (approximately 50 cubic metres of gas per cubic metre of oil). Allowable production rates are 25-30 barrels a day per well.

Afiesere and Eriemu Oil Fields, Nigeria

The oil-producing sandstones in the Afiesere and Eriemu Oil Fields (Fig. 2-23) of the Niger Delta, Nigeria, originated as a Late Cretaceous to Paleocene complex of barrier bar and delta distributary sands. In this paralic environment, the complex of sand bodies developed in a cyclical sequence of off-lapping sedimentary beds, grading upward from marine clays to fluviomarine, interlaminated silts and sands overlain

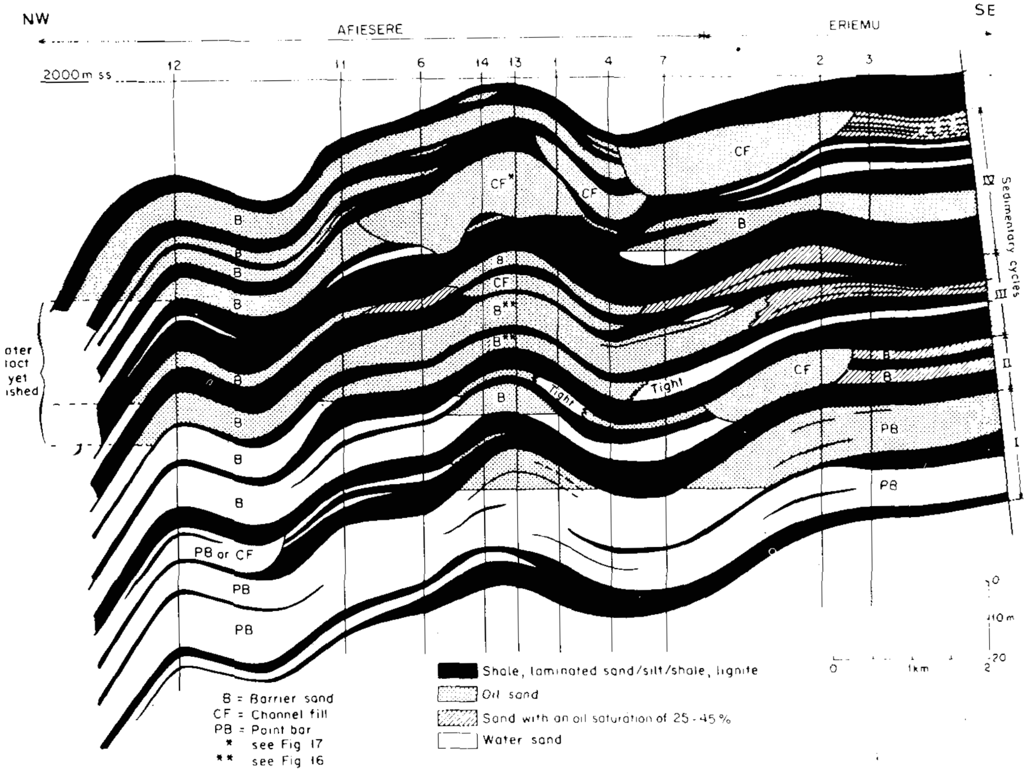


Fig. 2-23. Structural section across the Afiesere and Eriemu oil fields in the Niger Delta, Nigeria, showing separate reservoirs in a barrier bar and channel fill complex of Late Cretaceous and Paleocene sandstones. (After Weber, 1971).

by barrier bar and distributary channel-fill sands. Each cycle, ranging in thickness from 15 to 100 metres, is terminated by a marine transgression which eroded part of the off-lap sequence, leaving a thin layer of fossiliferous and glauconitic coarse sand. These transgressions are probably local, in response to lateral shifts in the main river course which would have periodically swung back and forth across the delta front, building an off-lap sequence wherever it entered the sea.

Individual barrier bars in the Afiesere and Eriumu fields have a length of up to 20 km, a width of several kilometers, a thickness of up to 12 m. They consist generally of fine-grained, variably-sorted sand. As shown in Fig. 2-23, these bars are cut by channels filled with sand which is somewhat coarser. Separated by intervals of mudstone, laminated sandy silt, and lignite, these barrier bar and channel sand bodies form several individual traps for oil. The accumulations are essentially stratigraphic, but localized by gently, elongated domes termed 'roll over' structures (Weber, 1971). These structures are associated with growth faults believed to have been caused by gravitational sliding and rotation of unconsolidated blocks of sediment, during the period of formation of the delta.

Wilcox Oil and Gas Fields, Texas

In the Texas Gulf Coast area of the U.S.A., several oil and gas fields are producing from multiple pay zones in the lower part of the Early Eocene Wilcox Group. The Lower Wilcox, comprising up to 1,500 m of sandstone, siltstone, and carbonaceous mudstone, was deposited as a deltaic complex (Fig. 2-24), the shape and dimensions of which are similar to the present-day Mississippi delta. Shelton (1973), states that this complex, known as the Rockdale delta system, constitutes 80% volumetrically of the known deposits of the Lower Wilcox. The Rockdale system is characterized by southerly-trending lobes (Fisher and McGowan, 1969) consisting mainly of sandstone. Total net sandstone thickness within the Rockdale ranges from 750 m to less than 30 m at the southern pinch-out (seaward) edge.

The Wilcox sandstones are quartzose and generally fine to medium--grained. They have an average porosity and permeability of 20% and 100 millidarcys respectively. Small-scale cross-bedding is common, and carbonized plant fragments are locally abundant.

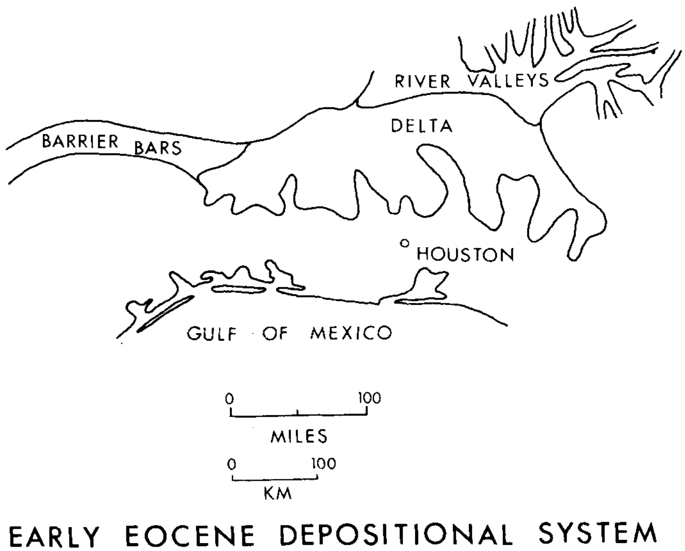


Fig. 2-24. Generalized distribution of the Lower Wilcox Group (Early Eocene) depositional system, Texas. (Redrawn from Fisher and McGowen, 1969).

Interfingering of pro-delta muds with barrier-bar sands, distributary channel-fill sands, and littoral sands has provided numerous separate reservoirs similar to those of the Afiesere and Eriemu fields of Nigeria (Fig. 2-23). Fisher and McGowan (1969) state that larger fields in this category include Fall City, Sheridan, Columbus, Lake Creek, New Ulm, and Quicksand Creek. Most fields in the Lower Wilcox are essentially stratigraphic, but local growth faults and diapiric structures, associated with thicker parts of the delta lobes, coincide with stratigraphic trends to form traps.

Seeligson Oil Field, Texas

One of the main oil-bearing zones in the Seeligson Field of Texas is the Oligocene Zone 19-b Sandstone. Situated in the Frio-Vicksburg trend of oil fields, Zone 19-b forms an irregular, easterly-trending belt of sandstone that has been traced along its length for 11 km, and is known to have a width of 3-8 km. The geometry of this sandstone belt, which trends in a direction approximately normal to the regional depositional strike of adjacent marine sandstone beds in the Oligocene sequence, suggests that it was formed by a branching river system on a delta plain. In the Seeligson Field area three subsidiary channels, 1,000-2,000 m wide, branch from the main channel which has a width of 2,000-2,000 m. An isopach map of Zone 19-b (Fig. 2-25 shows the main body of the channel-fill sandstone to have a maximum thickness of more than 20 m; the subsidiary channels have a thickness in the range 6-12 m.

The sandstone is predominantly lithic. It contains fragments of rock and feldspar, but includes up to 50% quartz, and 5-20% interstitial silt and clay. Commonly well-sorted, and fine to medium-grained, the sandstone bodies in Zone 19-b show distinct grain gradation from coarser below to finer above, a feature characteristic of river deposits. Sedimentary structures commonly present include medium-scale cross-bedding and claystone fragments probably derived from the erosion of mud-cracked clay along the river banks. Variable porosity and permeability suggest that the original composition of the sandstone varied from clean sand to silty and muddy sand. Local cementation by calcite and illite has also decreased porosity and permeability.

Oil entrapment in Zone 19-b has resulted from the coincidence of permeable zones within the distributary channels and three gentle domal structures on the downthrow side of a major normal fault. Although the Zone 19-b Sandstone has been a major contributor to oil production, several other zones in the Seeligson Field are productive. Shelton (1973, p. 30) says, "At Seeligson Field more than 40 sands, all of which are irregularly developed, have combined with the structural

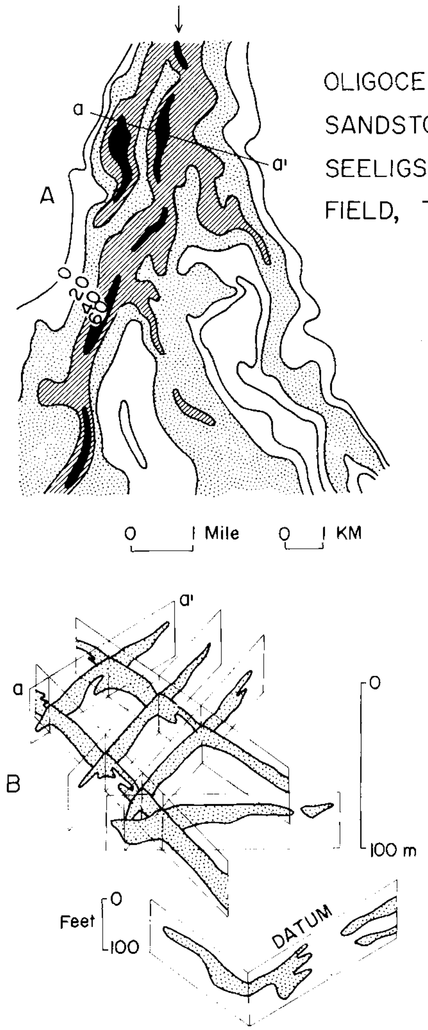


Fig. 2-25. Isopach map and fence diagram of the Oligocene 19B sandstone, Seeligson Field, Gulf Coast area, Texas. This sandstone body is interpreted as a branching river deposit. (Redrawn from Nanz, 1954).

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".

Ostra Oil Field, Venezuela

In the Ostra Field, Venezuela (Fig. 2-26), oil is produced from lenticular sandstone beds of the Oligocene Oficina Formation. These sandstone beds are not only markedly lenticular, but also relatively thin, commonly having a thickness of not more than 12 m, but locally ranging up to 60 m. They overlie non-marine beds of the Oligocene Mercure Formation and are considered to be delta distributary channell--fill sands and fringing shoreline sand deposits. Young (1971, p. 250) says, "The sandstones are part of a cyclic series of siltstones, lignites, sandstones, shales and claystone deposited in deltaic and paralic environments through repreated alternation of lagoonal-swamp, brackish-water and shallow-water marine conditions".

The sandstone lenses are separated by shale beds that form an effect-

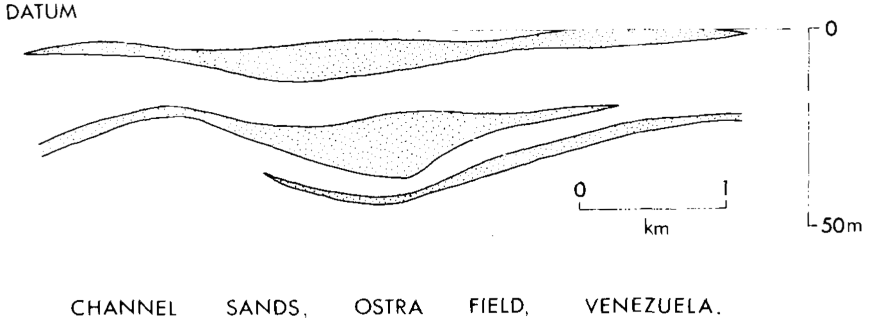
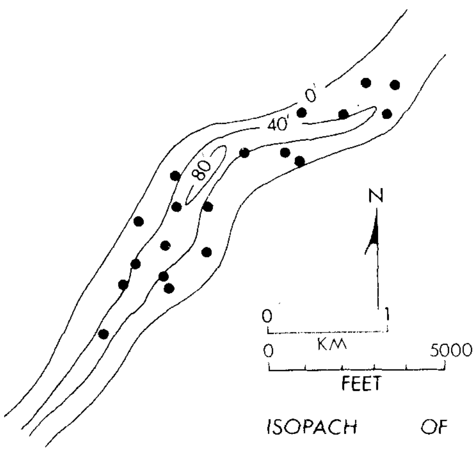


Fig. 2-26. Section through oil-bearing channel sands of the Oligocene Oficina Formation, Ostra Field, Venezuela. (Redrawn from Young, 1971).

ive seal for oil. Although warped by compaction, there is only slight folding of the sandstone lenses, and the oil accumulations are in structural--stratigraphic traps controlled by faults and pinch-out edges of the sandstone bodies. The depositional origins and structural-stratigraphic situations of the oil-bearing sandstone bodies are similar to those found in the Eocene beds of the Niger delta, Nigeria, and in the Oligocene beds of the Frio-Vicksburg trend in the Gulf Coast area of the U.S.A.

Main Pass Block 35 Oil Field, Louisiana

Oil production in the Main Pass Block 35 Field (Fig. 2-27) of the Mississippi delta, Louisiana, comes from the Miocene "G2" Sandstone which was deposited as a channel-fill sand in a delta distributary. This sandstone is quartzose, but up to 20% of its volume consists of fragments



ISOPACH OF CHANNEL SAND, BLOCK 35 FIELD, LOUISIANA.

Fig. 2-27. Isopach map showing net feet (1' = 0.305 m) of sandstone in the Miocene "G2" channel sandstone, and the wells producing from this sandstone, Main Pass Block 35 Field, Mississippi delta, Louisiana. (Redrawn from Hartman, 1972).

of rock and feldspar. It is generally clean, well sorted, and fine-grained. Average porosity and permeability are 34% and 3,000 millidarcys in the thicker and coarser parts of the sandstone body, but decrease to 26% and 75 millidarcys in the thinner parts, flanking natural levee and backslope deposits, of very fine-grained sandstone and siltstone. The main channel--fill sand body, which has a width of 600-900 m and a maximum thickness of more than 25 m, has been traced by drilling for more than 5 km in the field area.

Entrapment of oil within the "G2" Sandstone results from a combination of stratigraphic and structural factors; oil being trapped where the linear sandstone body crosses a faulted dome. Hartman (1972) says that the "G2" Sandstone, which is the largest single reservoir in the Main Pass Block 35 Field, is a classic example of oil production from a stream channel. Ultimate production from the Block 35 Field, in which oil is obtained from 23 individual Miocene sandstone bodies, is estimated to be 100 million barrels (15.9 million cubic metres), of which more than 12 million barrels (1.9 million cubic metres) will come from the "G2" Sandstone. Production is assisted by a strong water drive.

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Chapter 3

BARRIER AND OTHER OFFSHORE BARS

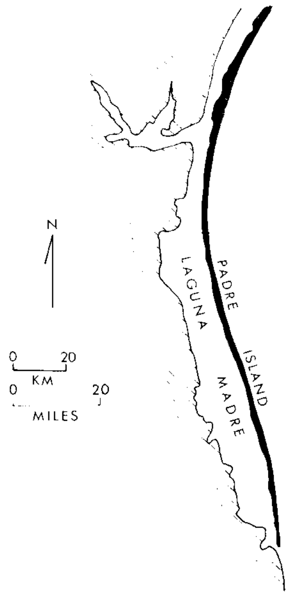
Introduction

Geomorphology

Barrier and other offshore bars are linear sandstone bodies which commonly have a thickness in the range 5-15 m. Barrier bars are exposed above sea level as barrier islands that commonly form a chain trending for many miles along the main coastline, separating lagoons and coastal bays from the open sea (Figs 3-1, 3-2). These islands are commonly a mile or more wide and several miles long. Other offshore bars may develop within the outer part of a bay where the seaward edge of a shallow-water shoal slopes downward into deeper water, or off a headland to form a spit.

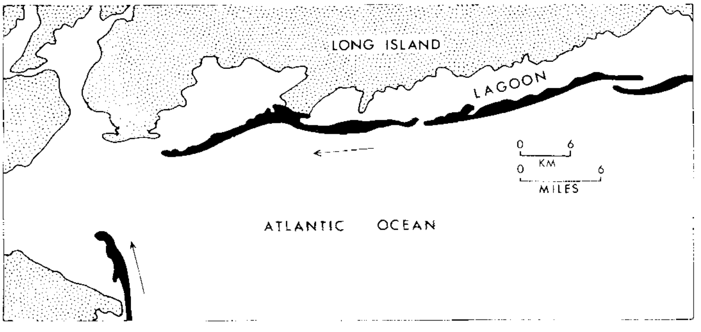
The seaward coast of a barrier island forms a nearly straight to gently curved flat beach washed by waves and currents that winnow the sand and transport it both seaward and along the coast. The lagoonal coast of a barrier island is irregular, with numerous small embayments and coastal flats of silty sand and marsh. Other islands that rise from offshore bars within a bay, or that form spits, commonly show the same shoreline characteristics.

The area exposed as islands represents less than half the area of most sand bodies, the seaward and landward outlines of which are equally irregular as indicated by isopach maps of both recent (Fig. 3-5) and ancient (Figs. 3-10, 3-14, 3-15, 3-18) barrier bars. Continuously shifting, although not necessarily at a constant rate, these islands tend to migrate parallel to the main coastline, in the direction of the long-shore current (Fig. 3-3). The up-current end of each island is consequently eroded, the sand being transported along the outer coast and deposited on the



PADRE ISLAND, A BARRIER ISLAND,
GULF OF MEXICO

Fig. 3-1. Padre Island, a barrier island off the coast of Texas, Gulf of Mexico. Laguna Madre lies between the barrier island and the mainland. (Redrawn from Rusnak, 1960).



OFFSHORE BARS, LONG ISLAND, NEW YORK

Fig. 3-2. Offshore bars, Long Island, New York, showing their distribution and geographical relationships. Arrows show the longshore current directions. (Redrawn from Bass, 1934).

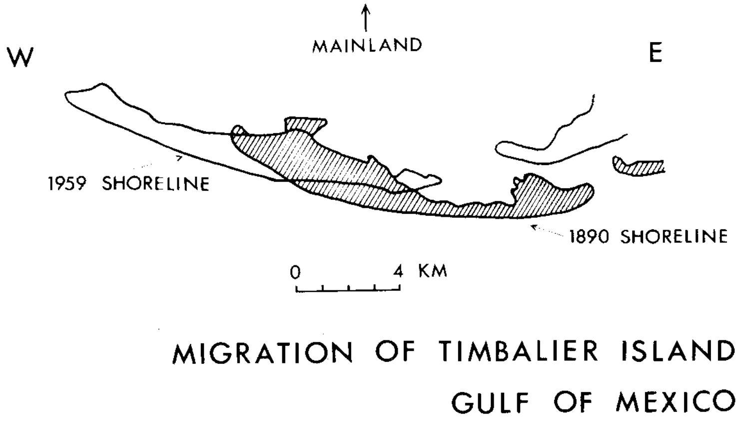


Fig. 3-3. Shoreward and westward migration of Timbalier Island, Louisiana, during the years 1890-1959, in response to northwesterly movement of coastal currents. (Redrawn from Otvos, 1970).

seaward extension of beaches and at the down-current end of the island where it may form a spit. Wave action moves the sand up the depositional slope to the beaches, except during periods of exceptionally high tides and heavy storms when beaches are eroded and massive quantities of sand are transported along the coast. Some sand is swept inland over the island during storms, and some is moved inland as sand dunes.

Unequal rates of erosion and deposition, and variations in the rates of flow in tidal channels between adjacent islands, results in merging or further separation of the islands, although the sub-sea distribution of sand may form a single sand body. In some cases, an island may shift back to a location it previously occupied, so that a hole drilled through it will show two sand units separated by siltstone or shale. These sand units are commonly not completely separated, but merge laterally across or along strike when viewed in three dimensions (Figs. 3-5, 3-18, 3-23).

A typical cross section of a simple barrier bar is shown in Fig. 3-4). The surface exposed above sea level, forming a barrier island, has an irregular topography formed by sand dunes. The seaward slope is a smooth, gently undulating time-plane on which the sand grade size ranges from coarser on the beach, where the energy level caused by waves and currents is higher, to finer in deeper water where the fine sand grades into silt and clay. Sub-parallel to the seaward slope, older time-planes lie within the sand body. The traces of such time-plane with the plane of a section cut across a barrier bar are shown by the dotted lines in Fig. 3-4. Although not usually visible, and commonly difficult to detect by geophysical methods in a fairly homogeneous sand body, it is possible for part of the area of a time-plane to be a useful time-stratigraphic marker, particularly where it can be distinguished by some sedimentologic characteristic or fossil content. The coincidence of any time-plane and its contemporary depositional slope clearly indicates the manner in which transported sand accretes to the offshore extension of beaches to form a sequence of seaward-prograding layers. As a consequence of the gradation of sediment on the depositional slope, from courser sand on the beach to finer sand

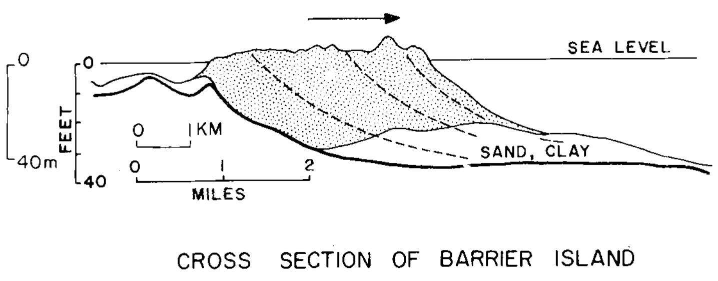


Fig. 3-4. Cross section of a typical barrier island off the coast of the Gulf of Mexico. (Redrawn from Bernard *et al.*, 1962).

silt, and mud in progressively deeper water, sand size gradation within the sand body decreases fro top to bottom, the reverse relationship to channel-fill river sands.

Sands of barrier bars and other offshore bars have a terrigenous origin, having been transported along distributaries to bar-finger r sand bodies then swept along the coast by currents and wave action. At Grand Isle, Louisiana (Fig. 3-5) the sand is fine-grained, locally silty, and has a composition of approximately 80% quartz and 20% feldspar. Locally, lenticular layers of grit or pebbly sand may be present within a

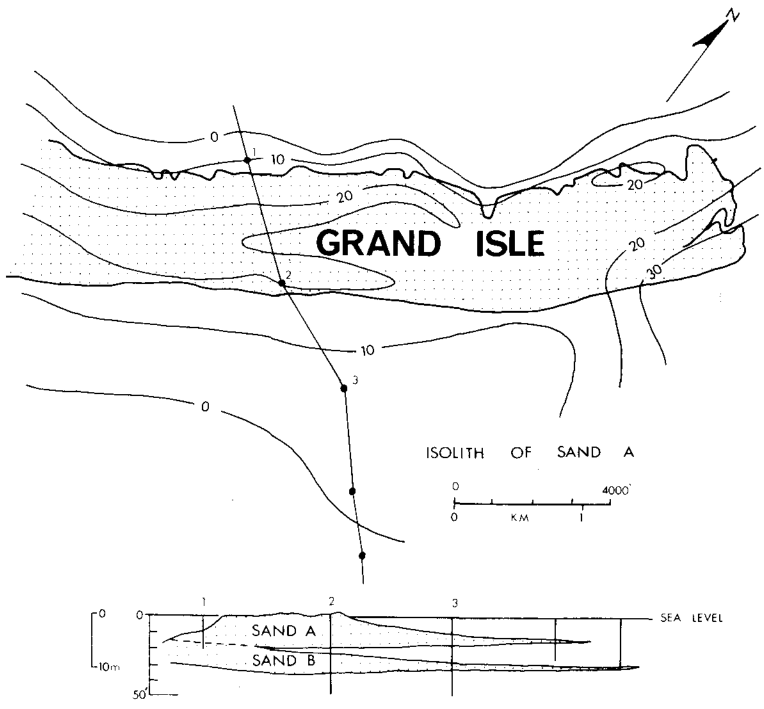


Fig. 3-5. Eastern end of Grand Isle, Louisiana, showing configuration of the island, lateral extent of the upper Sand A (isolith contours in feet), and a cross-section of the barrier island complex. (Redrawn from Conatser, 1971).

barrier bar, having formed where some topographic feature along a beach causes the sand to be winnowed more vigorously. Cross-bedding is also an internal feature, but in most cases is of the low-angle type (less than 10°) in contrast to the higher angle of fluyiatile cross-bedding. In barrier and other bars the cross-bedding commonly reflects changes in the depositional slope of an undulating beach, but may also result from current action caused by tidal movements through channels between bars. In such channels, a high-angle type of cross-bedding, similar to that observed in river point bars, may be developed. In fact, the relationships of cross-bedding to the geometry of a barrier bar that is prograding into a migrating tidal channel are not fully understood.

Grain orientation within the intertidal beach unit is characteristically more-or-less normal to the coastline, the long axes of the sand grains being aligned parallel to the predominant direction of swash movement caused by waves and tides moving up and down the mean beach slope. This facies of a modern beach is probably seldom preserved in the geological record, although an exception is noted by Shelton (1970, p. 1108) who says, "Grain orientation is normal to the sandstone trend of the lowermost unit of the Eagle Sandstone at Billings, Montana. Grain imbrication in that barrier-bar sandstone suggests that oncoming surf was the most important depositing current during local westward accretion". Within that part of the sand body formed in deeper water, where the predominant current direction is along the coast, grain orientation tends to be parallel to the coast and consequently to the direction of trend of the sand body. This deeper-water facies, deposited several hundred metres seaward from the beach, is commonly preserved in the geological record. An important corollary is that the relationship between grain orientation and geometry of a marine sandstone body can be an important key to exploration, for sandstone trends, although it must be used with some reservation.

E-log Characteristics

Within a prograding barrier bar or other offshore bar, the grain gradation from coarser above to finer below is reflected in the character of the E-log self-potential curve which tends to be funnel-shaped. As previously discussed, this shape is the reverse of that river sands in which the grain gradation is from coarser below to finer above. The self-potential character is indirectly related to the sand grain size, but directly related to the petrophysical properties of the matrix in the sand. In sands that have not been extensively altered by diagenesis and cementation, there is a relationship between grain size and silty clay content, the coarser sand being cleaner than the finer sand, and consequently more permeable.

Typical barrier bar E-log characteristics, as seen in a marine transgressive sequence, are illustrated by Pirson (1970), and by Conybeare and Jessop (1972) in Fig. 3-6. The funnel-shaped self-potential curve of the Eocene sands is well marked. The lower sands of the Miocene barrier bar complex show the same characteristics, but the upper sands tend to be blocky, possibly reflecting a fairly uniform grain size and little variation in the silty clay content. A Lower Cretaceous complex of stacked sandstone bodies, showing a similar relationship of E-log characteristics to the Miocene bars, is also interpreted as a sequence of off-lapping marine sands, probably formed as barrier bars. These sandstone bodies are quartzose and have good porosity and permeability. At the location shown they are separated by silty mudstone, but it is probable that at other locations they merge in various ways, as shown in Fig. 3-5 .

Compaction

Compaction of the muddy sediments flanking and interfingering with a barrier bar complex may cause difficulties in reconstructing the paleogeomorphic relationships of the various sand bodies within the

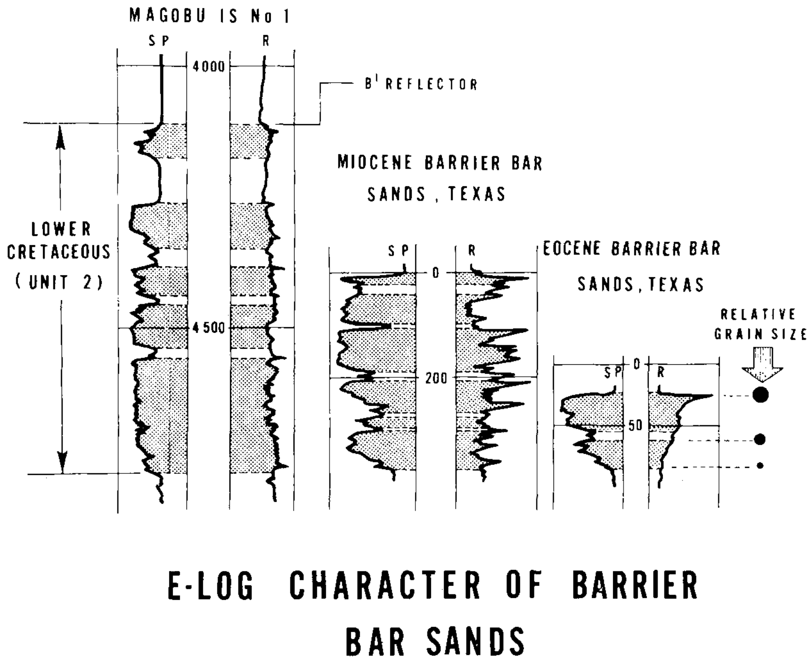
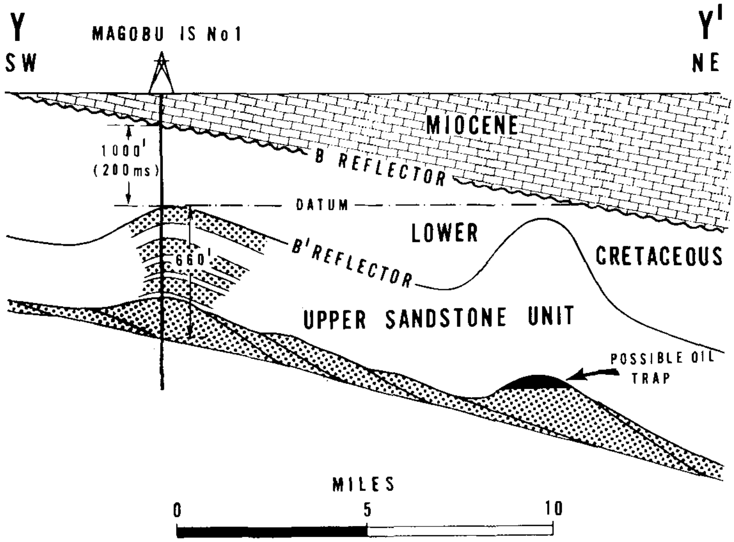


Fig. 3-6. E-logs of Tertiary barrier bars in Texas, and a Lower Cretaceous sandstone in Papua, showing the similarity of configuration and the relationship of the self-potential characteristics to grain gradation. (After Conybeare and Jessop, 1972).

complex. Figs. 3-7 and 3-8 illustrate an example in a Lower Cretaceous complex of marine shoreline sands (Fig. 3-6) penetrated by Magobu Island No. 1 Well in Papua. An isotime map of the interval between the erosional surface of the Lower Cretaceous (B reflector) and the top of the sand body complex (B' reflector) is shown in Fig. 3-8. This map indicates a linear, northeast-trending sandstone unit at the Magobu location, and suggests the possibility of a thicker sand development along a parallel trend to the northwest (Fig. 3-7). But what is not known is the stratigraphic



DIAGRAMMATIC STRUCTURAL SECTION

DRAPING OF B' SEISMIC REFLECTOR OVER BARRIER BARS

Fig. 3-7. Diagrammatic structural section Y-Y' showing the inferred relationship of the B' seismic reflector to the upper configuration of a Lower Cretaceous sandstone (Unit 2) in the Fly River Area, Papua. (After Conybeare and Jessop, 1972).

relationship of the sand body or bodies in the northwest trend to those at Magobu. Consequently, any paleogeomorphic interpretation is questionable. Fig. 3-7 is based on two inferences: firstly, that the erosional surface of the Upper Cretaceous, which is overlain by shallow-water marine limestone, is fairly flat and gently dipping; and secondly, that essentially the same complex of sandstone bodies at Magobu is present in the northwest trend. An alternative interpretation could show the structural relationship between the B and B' reflectors to be as indicated, but with only the uppermost Magobu sand body present in the northwest trend. Another interpretation could show the B' reflector to follow an erosional depression

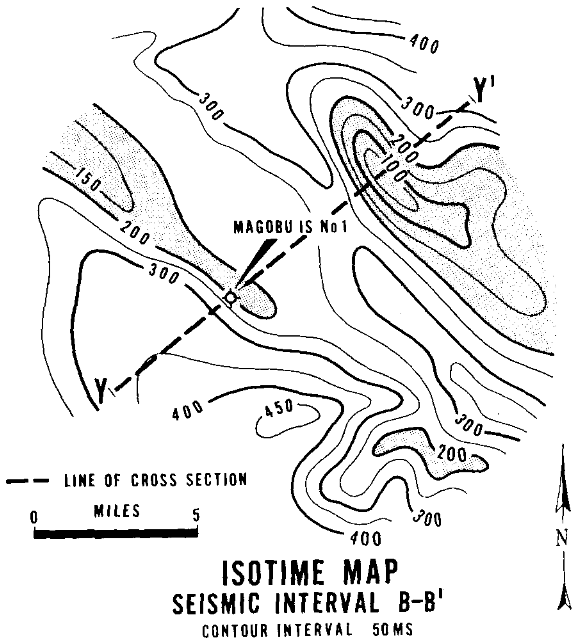


Fig. 3-8. Isotime map of the interval between the seismic reflectors B and B', showing the line of section Y-Y' (Fig. 3-7) and the topography of sandstone Unit 2. (After Conybeare and Jessop, 1972).

over the northwest trend, with only the lowermost sand body present. Other interpretations showing faulting, or inferring mis-correlations in plotting the B' reflector, may be valid.

Parallel trends of sandstone bodies, formed as off-lapping barrier bar and other sand body complexes, can contain excellent traps for oil and gas, particularly where they are intersected by anticlines, domes, and faults. Such traps are essentially stratigraphic and geomorphic, with structural modifications. Their discovery may, in some cases, hinge largely on interpretation of the compactional effects within and flanking a known or inferred bar complex.

Ancient Sand Bodies

Numerous examples of ancient barrier bars and other bars are known, many of which are recorded in the literature, and some of which are described in the following section on oil and gas fiels. Only a small percentage of known examples are so well exposed in outcrops that they can be seen as a continous section measuring several kilometres across the trend of the bar. One such example is the lower unit of the Upper Cretaceous Eagle Sandstone (Fig. 3-9) that crops out as rim-rock in the escarpent at Billings, Montana, and has been described by Shelton (1965).

The lower unit of the Eagle is a well-sorted, lithic and glauconitic marine sandstone that shows an upward gradation in grain size from very fine to fine. The unit trends north-northwest, has a known length of 65 km, a width of 30-50 km, and a maximum thickness of 30 m. In the upper part of the unit low-angle (less than 10^{o}) cross-bedding is a common feature. This cross-bedding could have been formed by continual changes in the depositional slopes of a sand body, probably

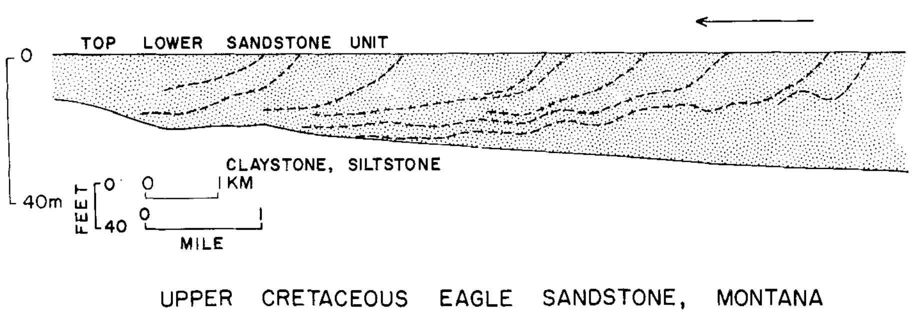


Fig. 3-9. Section of the Upper Cretaceous Eagle Sandstone that forms rim-rock in the escarpment at Billings, Montana. (Redrawn from Shelton, 1965).

in a part of the body deposited in water too deep for it to be exposed at low tide, and which is consequently preserved in the geological record. In the lower part of the section bioturbation is a common feature.

In Fig. 3-9 the intersections of bedding planes with the face of the outcrop are shown as broken lines. They have the same relationship to the gemorphology of the barrier bar as is shown in Fig. 3-4, and indicate progradation in a direction toward the coastline, as inferred from paleogeographic reconstruction. This geographic relationship suggests that the barrier bar was situated on a shallow continental shelf, more than 80 km from the shore toward which it was building. In such a geographic situation the bar, which externally and internally has the features of a barrier bar, may in fact not have formed a barrier.

Oil and Gas Fields

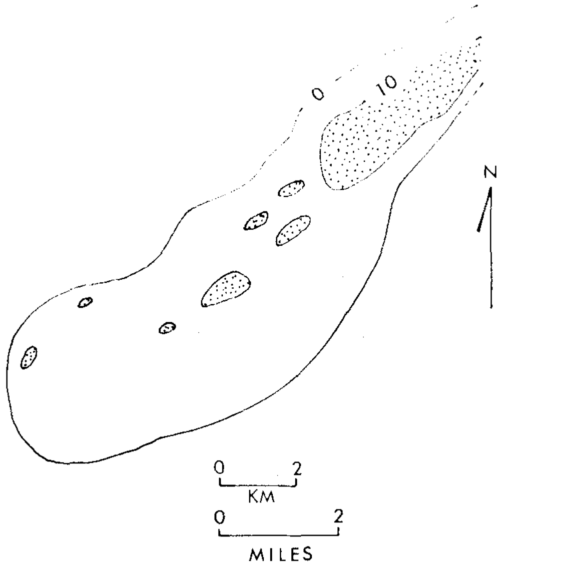
Oil and gas fields in barrier and other offshore bars are well represented in the literature where they have often been recorded since the early 1920's. In fact, many of the earlier recorded sand bodies, referred to as bars, have subsequently been found to be distributary channel sands. Lacking the criteria to adequtely interpret the origin of certain hydrocarbon-bearing, lenticular and linear sandstone bodies, geologists commonly referred to then as bars. In some cases the term bar was probably used only to describe the morphology of the sandstone body, with no implication as to its origin. In other cases the connotation of origin as a barrier or other offshore bar was implicit. Not until the 1960's were geologists, in general, describing such sandstone bodies in more precise geomorphologic terms. Even so, geologists were not always in accord as to the interpretation of the data, and even in the early 1970's these differences were apparent. For example, with reference to the Recluse Field in Wyoming, where production is obtained from the Recluse Sandstone at the base of the Lower Cretaceous Muddy Formation, Woncik (1972) interpreted the producing sandstone as a marine shoreline sand that may have formed a barrier island, whereas Forgotson and Stark (1972) interpreted the sandstone body as a channel-fill sand.

Interpretations of the genesis and geomorphology of a sandstone body can be critical in cases where further exploration and acquisition of petroleum leases depends upon, or is influenced by the possible or probably trends of a prospective sandstone body.

Eighteen examples of oil and gas accumulations in barrier bars and other offshore bars are given in the following pages. With the exception of one example in Brazil, they are all in North America. They range in age from Devonian to Tertiary, but do not include examples from the Triassic or Jurassic. More than half are from the Cretaceous. As with the examples given of oil and gas accumulations in river distributary and other channel-fill sand bodies, the number of examples of accumulations in bars is too small for their age and geographic distributions to be significant. The distributions given relate in large measure to be geographic density of drilling. Many more cases could be cited of accumulations in Eocene to Miocene bars trending parallel to the coast in the Gulf Coast region of the U.S.A. and Mexico, and it does appear that in North America the majority of examples are Cretaceous to Tertiary.

Shira Streak Oil Field, Pennsylvania

The Shira Streak Oil Field (Fig. 3-10) of Pennnsylvania produces from the Shira Sandstone in the upper part of the Third Sandstone interval of the Upper Devonian Venango Group. The Shira, which is overlain and underlain by dark grey shales, is quartzose, meduim to coarse



GEOMETRY OF SHIRA SANDSTONE,

PENNSYLVANIA

Fig. 3-10. Isopach map of Shira Sandstone in the Upper Devonian Venango Group, Shira Streak Oil Field, Pennsylvania. Contours in feet (1' = 0.305 m). (Redrawn from Sherrill, Dickey, and Matteson, 1941).

grained, with local lenses of grit containing pebbles of quartz up to an inch in diameter. Ranging up to 5m in thickness, the sandstone forms a thin lenticular body more than 20km in length and up to 5km in width.

Sherrill, Dickey, and Matteson (1941) state that at the time of deposition of the Shira Sandstone a continental environment was situated to the southeast, and a marine environment to the northwest. They suggest that the sandstone was possibly formed as an offshore bar. If so, it must have been in very shallow water, possibly in part exposed as a beach subject to scouring and winnowing action by waves and currents. The coarseness of the sand, and the presence of pebbles, suggests that if it had been an offshore bar, it would also have been near shore.

The Shira Streak Field, which yields oil having a gravity of 45° A.P.I., is essentially a stratigraphic trap. Other accumulations within the Shira, yielding mainly gas, are located further up-dip where a low, southeast-plunging fold crosses the trend of the sandstone body.

The Third Sandstone interval (Fig. 3-11) comprises two main sandstone bodies, the upper one being the Shira. Several oil and gas accumulations are known within the Third Sandstone. Initially, some wells flowed oil at rates up to 3,000 barrels a day from the more permeable zones within the pebbly, coarse sandstone zones, and early production from many well approached 100 barrels a day. Flows of wet gas at rates of 3-4 million cubic feet a day are also recorded. Most of these accumulations have long since ceased to be of any economic significance. Sherrill, Dickey, and Matteson (1941, p. 509) state, "The productive sands of this district lie at shallow depths - generally less than 1,000 feet. The pools discussed were discovered during the period extending from 1859 to about 1900. They were found through random drilling, prospecting near oil seeps, or through following trends. Many of them have been partly or entirely abandoned one or more times and then reclaimed through drilling between old locations, de-watering, air or gas drive, or other methods".

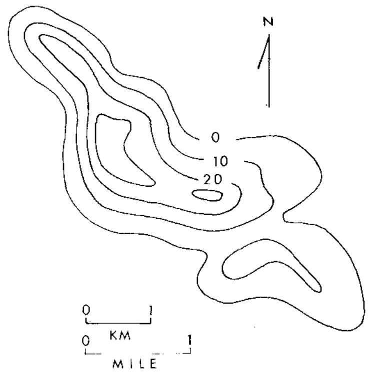
Austin Gas Field, Michigan

The Austin Field, Michigan (Fig. 3-12), produces gas from the Michigan Stray Sand of the Mississippian Michigan Formation. The Michigan Stray rests unconformably on the eroded surface of older Mississippian rocks and occurs intermittently, as discrete sandstone bodies, over a distance of 50-65 km. Ball, Weaver, and Crider (1941)

GEOMETRY OF THIRD SANDSTONE, PENNSYLVANIA

Fig. 3-11. Isopach map of Third Sandstone interval, Upper Devonian Venango Group, Pennsylvania. Contour interval in feet (1' = 0.305 m). (Redrawn from Sherrill, Dickey, and Matteson, 1941).

interpet these sandstone bodies as offshore bars, and show them to be built up on erosional ridges that more-or-less overlie and follow a pre-Mississippian anticlinal trend. They show further a remarkable coincidence between the structural configuration and the thickness of the sandstone body in the Austin Field, the body being thickest where it is highest. In view of the fact that no datum is indicated on



GEOMETRY OF MICHIGAN STRAY SAND, AUSTIN FIELD, MICHIGAN

Fig. 3-12. Isopach map of the Michigan Stray Sand in the Mississippian Michigan Formation, Austin Gas Field, Michigan. Contour interval in feet (1' - 0.305 m). (Redrawn from Ball, Weaver, and Crider, 1941).

the structure contour map, their interpretation of the original shape of the sand body is suspect. These discrete sand bodies were deposited on an unconformity, and overlain by dolomitic and gypsiferous muds that probably indicate littoral and evaporitic conditions fluctuating from very shallow water to coastal mud flats. Deposited by a transgressive sea, these sand bodies may have accumulated in erosional depressions, rather than as sand bars buil-up from the sea floor. Such an alternative interpretation can be derived, using the same sub-surface data, as discussed in an earlier section on compaction of sandstone bodies (Figs. 1-12, 1-13).

The sandstone body comprising the Austin Field is approximately 8 km in length and up to 2 km in width. The sandstone has a maximum thickness of 10-12 m and is said by Ball, Weaver, and Crider

(1941) to be more permeable where it is thicker. The Austin Field is one of several gas fields within the Michigan Stray Sand which originally contained an estimated 150,000 million cubic feet (4,200 million cubic metres) of gas.

Sallyards Trend Oil Fields, Kansas

In Butler and Greenwood Counties, Kansas, a number of oil fields form a northeast-trending chain known as the Sallyards Trend (Fig. 3-13). A shorter chain of oil fields, the Teeter Trend, lies nearly parallel to the Sallyards along the border between Chase and Greenwood Counties. Three other trends, from south to north respectively, known as the Haver-

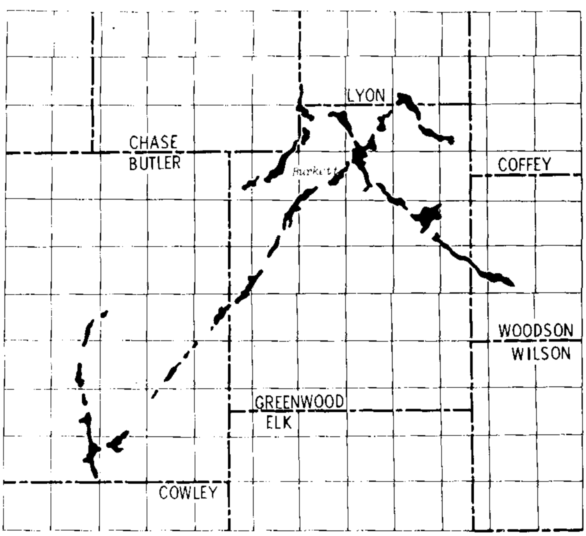


Fig. 3-13. Geographical distribution of oil fields in shoestring sandstone trends within the lower part of the Pennsylvanian Cherokee Formation, Kansas. Small squares are townships of 36 square miles (92 sq. km). (After Hilpman, 1958).

hill, Quincy, and Lamont Trends, cut more-or-less at right angle, and at different horizons, across the Sallyards Trend. All of the oil fields along these trends are in shoestring sandstone bodies within the lower part of the Lower to Middle Pennsylvanian Cherokee Formation.

These sandstone bodies form elongate lenses 15-30 m thick, up to 10 km long, and commonly more than 2 km wide. Arranged in a linear pattern like a string of beads, they form trends up to 100 km long, and are interpreted by Bass (1936) and Hilpman (1958) as offshore bars. The sandstone bodies are completely surrounded by shale containing a fairly high organic content. In the upper part of the Cherokee Formation this organic-rich shale contains coal beds and oil-bearing shoestring sandstone bodies, including the Bush City Oil Field (Fig. 1-33), which are interpreted as distributary channel-fill sands.

The sandstones in the Sallyards and associated trends are quartzose, poorly cemented, and fine-grained. They have fair to good permeability. Cumulative production to 1970 amounted to 250 million barrels (39.8 million cubic metres).

Wakita Trend, Oklahoma

The Wakita Trend of the Anadarko Basin, Oklahoma has several separate oil and gas accumulations in the Pennsylvanian Red Fork Sandstone (Fig. 3-14). The Red Fork comprises a complex of sandstone bodies forming an arcuate trend, interpreted as a seuqence of parallel offshore bars, intersected by two main sinuous trends interpreted as younger distributary channel-fill sands. The Wakita Trend, which has a length of more than 50 km, and a width of 2-3 km, was formed during a late phase of the offshore bar deposition. The trend, consisting of three bars that are wider at the base than at the top, is terminated fairly abruptly on both sides by thinning of the sandstone bodies and inter-

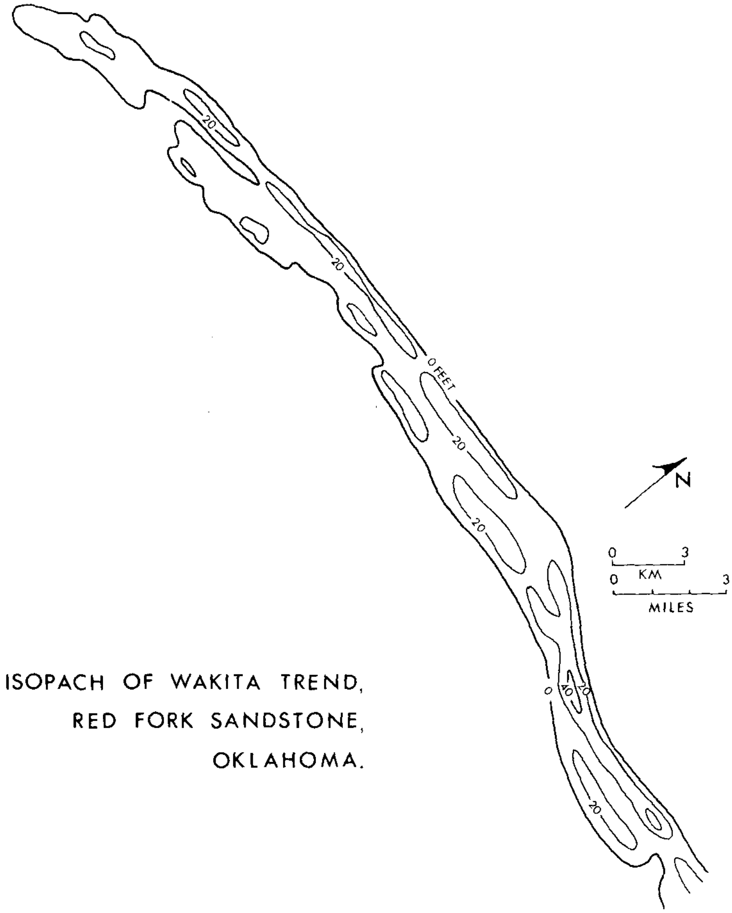


Fig. 3-14. Isopach of the Wakita trend, Pennsylvanian Red Fork Sandstone, Grant and Alfalfa Counties, Oklahoma, showing east-west trending composite offshore bars. (Redrawn from Withrow, 1968).

fingering with shale. The sandstone bodies comprising the Wakita Trend have a maximum composite thickness of 15 m and consist of fine to very fine-grained quartzose sandstone that is generally micaceous and locally argillaceous. Cementation by calcite and silica has reduced porosity and permeability which average 15% and 2 millidarcys respectively.

During the first decade of production, since discovery of the Wakita Trend in 1953, not much more than 500,000 barrels of oil were produced, mainly from the western half of the trend. Gas is also produced, mainly from the eastern half of the trend. Producible reserves have been estimated to be in excess of 65,000 million cubic feet (1,800 million cubic metres). Withrow (1968) points out that although the Wakita Trend has yielded the poorest reservoirs, other Red Fork reservoirs in the Anadarko Basin are much more profitable; and that additional accumulations may be found on the basis of interpretations of the depositional environments and trends of the Red Fork Sandstone.

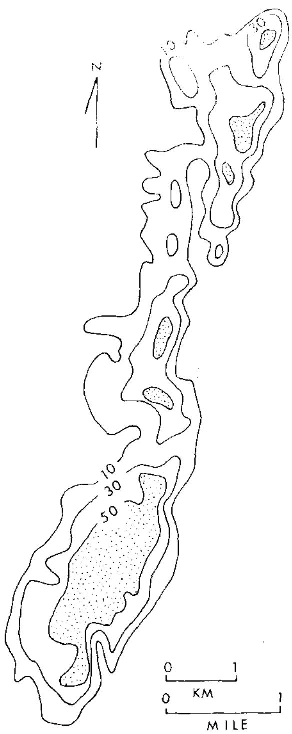
Olympic Oil Field, Oklahoma

Production in the Olympic Oil Field, Oklahoma, is obtained from the Pennsylvanian Olympic Sandstone (Fig. 3-15) which is developed as a linear trend more than 10 km in length and up to 2 km in width. The Olympic is a composite unit, up to 20 m thick, comprising two or more overlapping sandstone bodies that are interpreted as marine offshore bars. The sandstone is quartzose, well-sorted and fine-grained. Thin layers of sandy shale, and carbonaceous fragments are locally present. Average porosity and permeability are 20% and 35 millidarcys respectively.

The Olympic dips to the northwest and is locally folded into gentle noses. Entrapment of oil is essentially stratigraphic, but with some structural control. Production of greenish-black, 34^{o} A.P.I. oil is obtained from a shallow depth of about 550 m. Recovery to date has amounted to more than 12 million barrels (19 million cubic metres).

Mata-Catu Trend, Brazil

In the Salvador area of the Reconcavo Basin, Brazil (Fig. 3-16), oil is produced from several reservoirs in the "A" Sandstone of the Lower Cretaceous Itaparica Formation. This sandstone unit forms two narrow



GEOMETRY OF PRODUCING SANDSTONE,
OLYMPIC OIL FIELD, OKLAHOMA

Fig. 3-15. Isopach map of the Pennsylvanian Olympic Sandstone, Olympic Oil Field, Okfuskee County, Oklahoma. (Redrawn from Dillard, 1941).

parallel trends and a braoder, less well-defined trend sub-parallel to the other two. The longest trend, the Mata-Catu, has a length of 40 km and a width of 3-5 km. The sandstone bodies comprising this trend have a maximum composite thickness of 45 m.

The "A" unit is a white to light grey, predominantly quartzose, very fine to very coarse-grained sandstone that locally contains grit-size grains and small pebbles. Other constituents include grains of black

OIL FIELDS IN CRETACEOUS
"A" SANDSTONE, BRAZIL

Fig. 3-16. Distribution of oil fields in linear trends of the Lower Cretaceous "A" Sandstone, Salvador area, Brazil. Arrow indicates inferred direction of sand transport. (Redrawn from Bauer, 1967).

chert, feldspar, flakes of mica, and heavy minerals. The sandstone matrix consists of clay minerals and carbonaceous matter. Grain gradation, where it has been noted, is from finer below to coarser above, a common relationship in prograding sand bars. This sandstone unit is commonly thick-bedded and massive, with silty and carbonaceous laminations. Minor features include low-angle cross-bedding, with scour and slump structures. The sandstone bodies comprising this unit, which overlies shales containing fresh-water ostracods, are considered by Bauer (1967) to be bar-shaped lenses of sand deposited by currents and shaped by wave action. He was of the opinion that these sand lenses formed on shelves and shoals in shallow water, but at some distance from shore, in a lacustrine environment.

The oil reservoirs have good porosity, in the range 12-20%, and excellent permeability, commonly 200-1,300 millidarcys but ranging up to 4,000 millidarcys in some medium-grained and well sorted sandstones. Oil, having a gravity of 40^{o}A.P.I., has accumulated in structurally high parts (accentuated by compaction) of the sandstone bodies where they overlie up-thrust blocks of basement rocks. It is thought by Bauer (1967) that basement structure is reflected in the paleotopography, and that the sand bars were developed on the higher areas. On the basis of this interpretation, he suggests that the search for new fields will be assisted by an understanding of the paleostructural and related paleogeomorphic features within the Reconcavo Basin.

Bell Creek Oil Field, Montana

The geographic and paleogeomorphic relationship of the Bell Creek and Recluse oil fields, Powder River Basin, Montana and Wyoming, are shown in Fig. 3-17, after the interpretation of Forgotson and Stark (1972). This interpretation differs from that of Woncik (1972) who considered the producing sandstone of the Recluse Oil Field (Fig. 1-46) to be a marine shoreline sand, possibly a barrier island. The producing zone in both fields is the Lower Cretaceous Muddy Sandstone. The interpretation placed on their paleogeomorphic relationship, by Forgotson and Stark, is that the oil-bearing sandstone body in the Bell Creek field (Fig. 3-18) is a barrier bar complex. This complex is located near the intersection of northeast--trending littoral marine bars and a southeast-trending delta system. The sandstone body in the Recluse field is interpreted as part of a distributary channel-fill sand within the delta system.

The Muddy Sandstone in the Bell Creek Oil Field is a composite

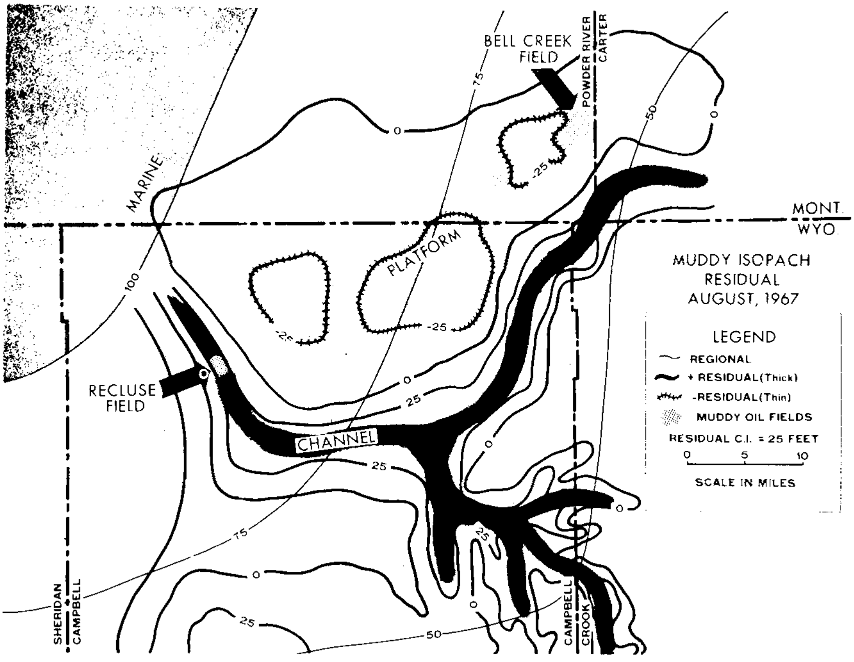
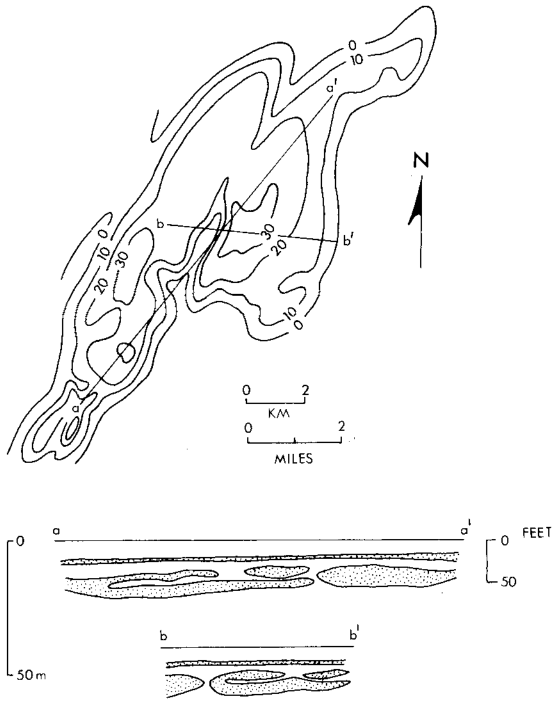


Fig. 3-17. Residual isopach values in feet (1' = 305 m) of the Lower Cretaceous Muddy Sandstone, Powder River Basin, Montana and Wyoming. Residual values obtained by removal of 3d-degree polynomial values of regional surface, shown by thin contours, from isopach values. (After Forgotson and Stark, 1972).

bar complex formed by merging, linear sandstone lenses, the Muddy has a cumulative maximum thickness of 10 m, and an average thickness of 6 m. Four units have been described: (a) an upper, massive unit of fine-grained sandstone, (b) an underlying, slightly coarser and strongly laminated sandstone, showing small-scale cross bedding, (c) a massive, very fine--grained, slightly laminated sandstone with minor bioturbation, and (d) a thin basal unit of interlaminated shale and siltstone with extensive



MUDDY SANDSTONE, BELL CREEK FIELD, MONTANA.

Fig. 3-18. Isopach showing gross thickness in feet (1' = 0.305 m) of Lower Cretaceous Muddy Sandstone, Bell Creek Field, Montana. Lines of sections a-a' and b-b' are approximate. Sections show lenticularity of oil-producing sandstone bodies. (Redrawn from McGregor and Biggs, 1968, and Berg and Davis, 1968).

bioturbation. The sandstone is quartzose (ave. 86% quartz), well sorted, and fine to very-fine-grained. The average grain size increases with increasing quartz content. Porosity and permeability are exceptionally good, ranging up to 30% and 3,500 millidarcys respectively.

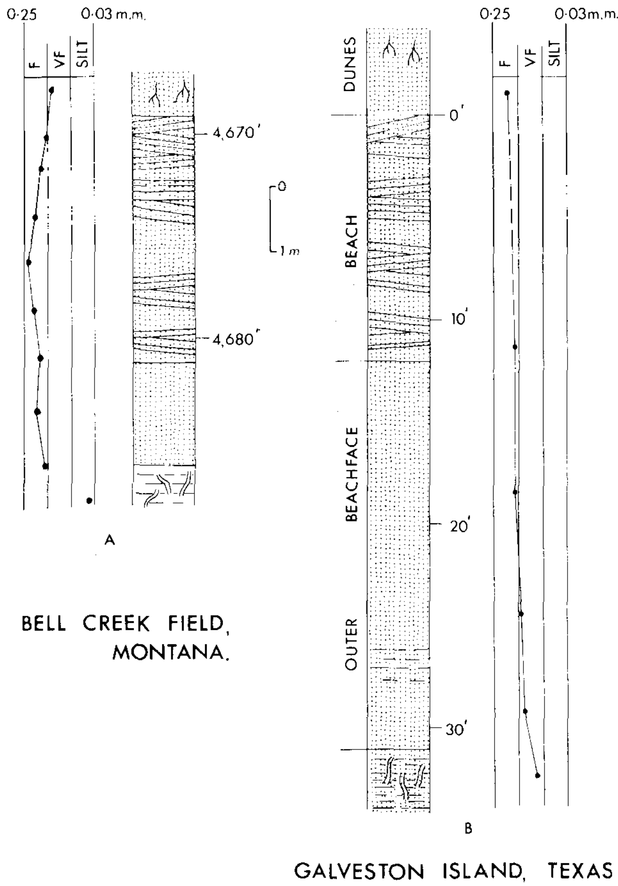


Fig. 3-19. A - core from the oil-producing Lower Cretaceous Muddy Sandstone in Well No. 6-14, Bell Creek Field, Montana. B - core No. R 3963 from Recent sediments on Galveston Island, Texas, a typical barrier island. (Redrawn from Davies, Ethridge, and Berg, 1971).

Davies, Ethridge, and Berg (1971) made a comparison of textures and structures in cores (Fig. 3-19) from the Muddy Sandstone in the Bell Creek Oil Field and from Galveston Island, Texas, a typical barrier island. The lengths of the Muddy and Galveston cores are approximately 6 m and 9 m respectively. The Galveston Island core shows an uppermost unit of eolian sand, with occasional plant roots, overlying a unit of sand containing intervals showing low-angle cross-bedding of the type found within beach deposits. This type of cross-bedding reflects variations in depositional slopes of the beach. The cross-bedded unit overlies a homogeneous to faintly laminated unit of sand deposited as the seaward extension of an intertidal beach. The lowermost unit is of extensively bioturbated clayey silt interbedded with very fine-grained sand. Grain size decreases from a fine sand in the uppermost unit to a very fine sand in the lowermost unit. This gradation is typical of barrier island and other off-lapping shoreline sand deposits.

The Bell Creek Field core shows the same sequence in lithology, with minor variations. The uppermost unit is of very fine-grained homogeneous sand containing traces of plant root structures. The intertidal beach unit contains some organism burrows; and the outer beach surface unit contains some rounded inclusion of claystone, possibly formed from mudcrack fragments washed to sea from a beach. The lowermost unit consists entirely of extensively bioturbated claystone and siltstone laminae showing some very fine cross-laminations. Grain size is within the fine sand range, 0.25 - 0.12 mm, with the exception of the lowermost unit which is of silt, 0.06 - 0.03 mm.

The Bell Creek Field was discovered in 1967. It is a stratigraphic trap in which the four separate accumulations of oil have different oil-water contacts. The oil, pumped from a depth of about 1,400 m, is sulphur-free and has a gravity of 34^{o} A.P.I. During the period of peak production the field yielded 65,000 barrels a day from wells having an average daily production of 500 barrels. Cumulative production to 1973 amounted to 45 million barrels (7.2 million cubic metres). It is estimated (McGregor and Biggs, 1968) that the reserves of producible oil amount to 200 million barrels (31.8 million cubic metres).

Gas Draw Oil Field, Wyoming

The Gas Draw Oil Field (Fig. 3-20) in the Powder River Basin, Wyoming, produces oil from the Gas Draw Sandstone in the Lower Cretaceous Muddy Formation. The Gas Draw overlies the oil-producing sandstone in the Bell Creek Field (50 km northeast), and forms a composite linear sandstone body more than 40 km long, 2-3 km wide, and up to 10 m thick. The main oil accumulation of the field extends along the central part of this trend for a distance of 20 km.

The Gas Draw, consisting of very fine to fine-grained quartzose sandstone, is thought by Stone (1972) to have originated as a sequence of offshore bars and beaches along the same shoreline trend as the Bell Creek Sandstone in the upper part of the Muddy Formation. In this context it is interesting to note the funnel-shaped character of the E-log of both the Gas Draw and Bell Creek sandstones (Fig. 3-21). As in the Bell Creek Field, the producing sandstone of the Gas Draw Field has excellent reservoir characteristics including good porosity and permeability. The Bell Creek, Ute, and Kitty fields also obtain part of their production from the Gas Draw Sandstone.

Garrington and Crossfield Oil Fields, Alberta

The Garrington and Crossfield fields in Alberta (Fig. 3-22) produce oil from the Upper Cretaceous Cardium Sandstone. In this area the Cardium is defined by two parallel, ribbon-shaped sandstone trends about 15 km apart. The younger trend, lying farther to the northeast, is the producing sandstone of the Garrington Field. It has been traced in a northwest direction for more than 100 km. The Crossfield trend extends for more than 115 km. Both of these sandstone trends are 2-5 km wide and range in thickness up to 6 m. They were formed as offshore bars, possibly as barrier bars, during a period of marine regression in the early Late

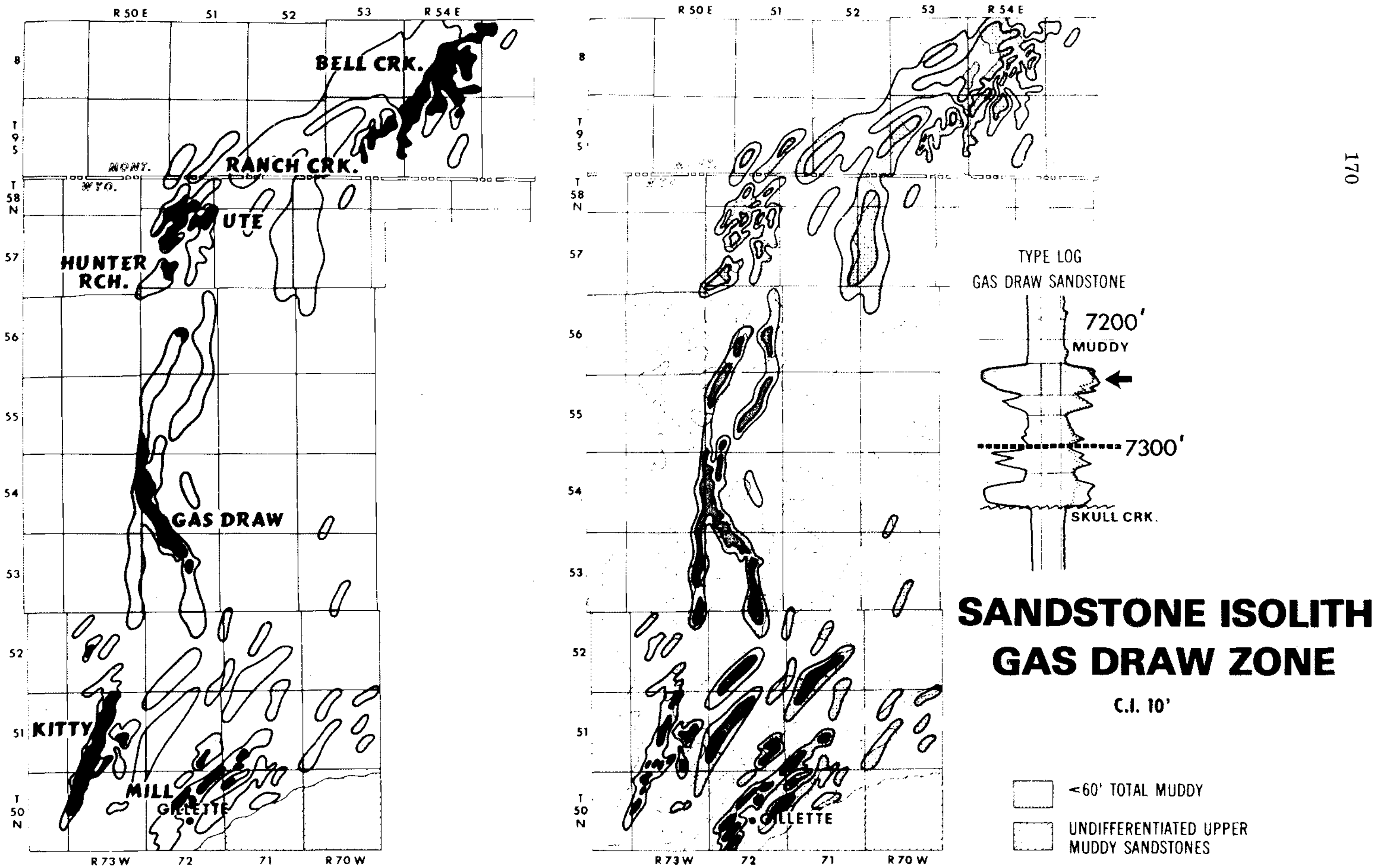


Fig. 3-20. Isolith of the Lower Cretaceous Gas Draw Sandstone showing a linear pattern where the thickness ranges in excess of 30 feet (9 m). Contour interval is 10 feet (3 m). (After Stone, 1972).

TYPE MUDDY LOG

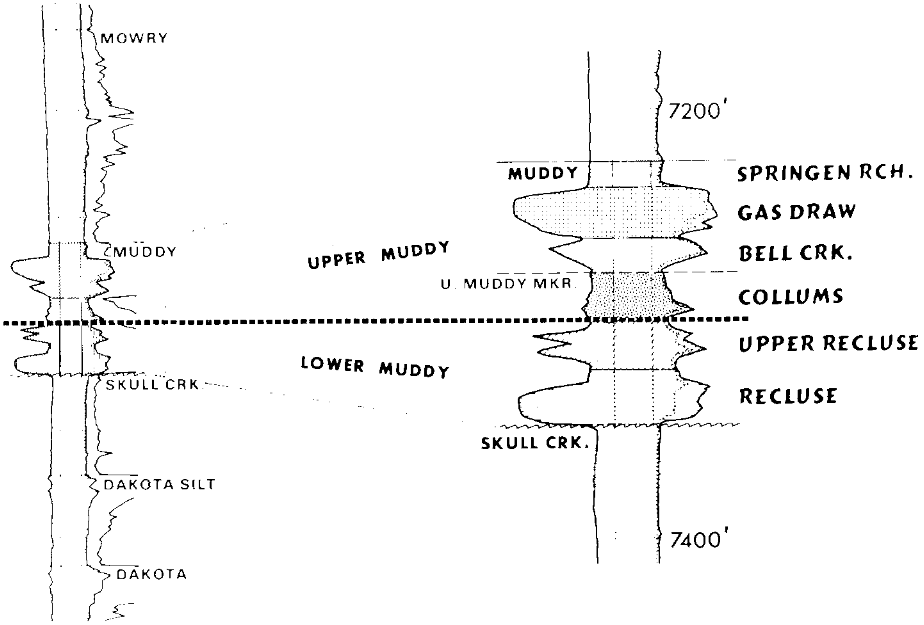


Fig. 3-21. Type E-log from the Gas Draw oil field, Powder River Basin, Wyoming. (After Stone, 1972).

Cretaceous. Subsequently, they were buried by dark silts and muds of the Colorado Group when the sea again transgressed westward.

The Cardium Sandstone is lithic, being composed of grains of chert, quartz, quartzite, silicified argillite, and other rock fragments. In general, the sandstone is fine-grained, the grains being angular to sub-rounded. In the upper part of the section the sandstone is locally gritty to pebbly, the larger grains and pebbles being well rounded and consisting of light grey and black cherty rock. The cement in the matrix is largely siderite, illite and chlorite. Diagenesis and compaction have reduced porosity and permeability which have mean values of approximately 10% and 35 millidarcies respectively.

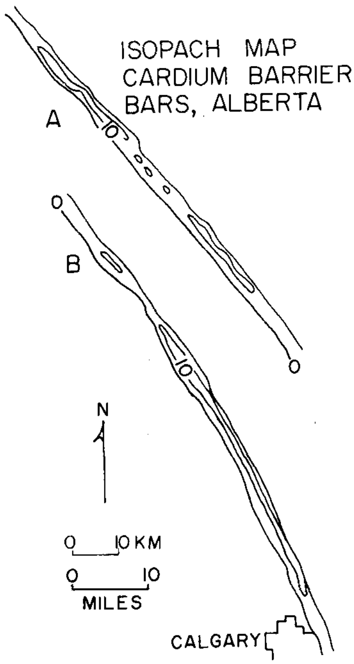


Fig. 3-22. Isopach map of barrier bars of the Upper Cretaceous Cardium Formation, Garrington (A) and Crossfield (B) oil fields, Alberta. Isopach interval is 10 feet (3 m). (Redrawn from Berven, 1966).

The oil accumulations are in purely stratigraphic traps controlled by the up-dip limites of pinch-out edges on the flanks of the sandstone bodies, and by the distribution of zones of variable porosity and permeability along the trends. Regional dip of the strata is about 10 m/km to the west-southwest. The net producing sandstone in both fields has a range of only 1-2 m, and fracturing of the oil-bearing zone is necessary. The initial reservoir drive was by solution gas, but secondary recovery methods involve the use of waterflooding.

In the Garrington Field there are two producing sandstone units, each having an average thickness of about 3m. The upper sandstone body is ribbon-shaped and has similar dimensions to the sandstone body in the Crossfield Field. The lower body has the same trend, but is much more irregular in shape, ranging in width up to 10 km. Most wells produce from either one sandstone or the other, but some produce from both where the units overlap. The paraffin-base oil has a gravity of 37° A.P.I. and is sulphur-free. Original oil in place in both sandstone bodies amounted to 190 million barrels (20.2 million cubic metres), of which it is estimated (Tyrell, 1966) that 40 million (6.4 million cubic metres) can ultimately be recovered. Javeri (1966) estimates that the Crossfield had an original oil content of 160 million barrels (25.4 million cubic metres) of which 16 million (2.5 million cubic metres) may be recovered. The daily production rate per well is the range 20-40 barrels.

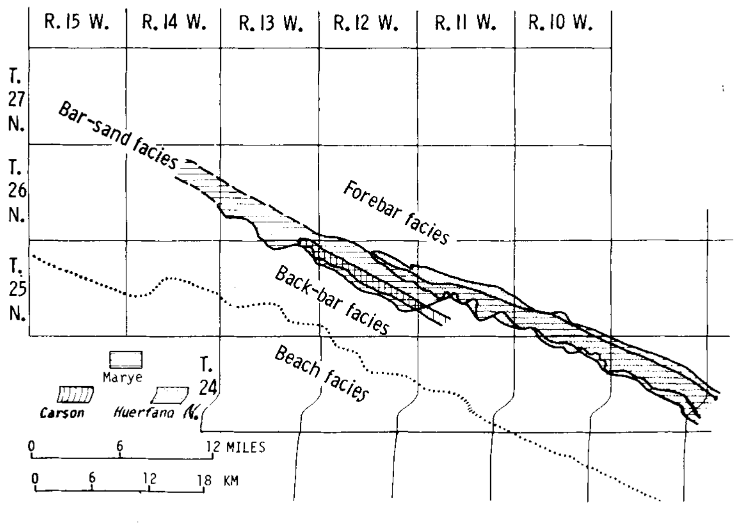


Fig. 3-23. Facies map of Bisti oil field, San Juan Basin, New Mexico, showing barrier bar complex comprising the Marye, Carson, and Huerfano oil-bearing sand bars of the Upper Cretaceous Gallup Formation. (After Sabins, 1963).

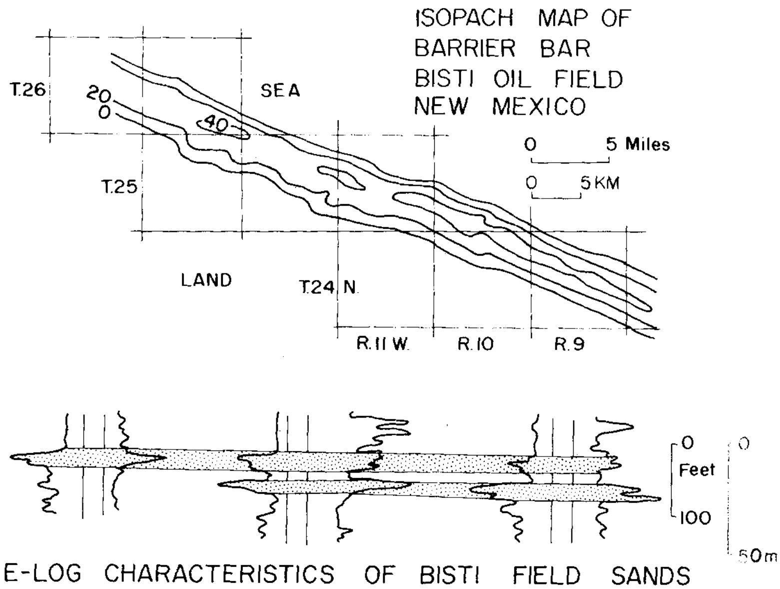


Fig. 3-24. Isopach map of a producing barrier bar, Bisti oil field, San Juan Basin, New Mexico. Contour inverval in feet (1' = 0.305 m). The spontaneous-potential curves show a funnel-shape characteristic of barrier-bar sands. (Redrawn from Sabins, 1963).

Bisti Oil Field, New Mexico

The Bisti Oil Field in New Mexico (Figs. 3-23 and 3-24) has been described by Sabins (1963) who states that production is obtained from three overlapping sandstone bodies designated the Marye, Carson, and Huerfano members of the Upper Cretaceous Gallup Formation. These linear sandstone bodies are interpreted by Sabins as sand bars that formed a barrier-bar complex. He recognized that the linearity of these sandstone bodies coincides with the topography of the upper surface of the underlying Gallup Sandstone, but that the bodies are not necessarily better developed in the topographic depressions, some thicker parts of the bodies overlying escarpments. Sabins states, p. 224, "In summary, the depositional topography of the upper surface of the Main Gallup Sand resembles longshore bar and trough topography with some seaward-facing depositional escarpments. This topography was formed during the final deposition of Main Gallup Sand and was the surface upon which the Bisti bar complex was deposited". Sabins interprets the Main Gallup Sandstone underlying the Marye, Carson, and the Huerfano sandstone bodies as a regressive marine sheet-sand on the surface of which sand bars and associated facies (Fig. 3-23) were developed.

McCubbin (1969) on the other hand, interprets the upper surface of the Main Gallup Sandstone as an erosional surface on which linear sandstone bodies were deposited in marine strike valleys flanking cuestas during the transgression of the Niobrara sea. McCubbin's study did not specifically deal with the Bisti Field, but with the nearby Horseshoe, Many Rocks, Mesa, South Waterflow, Cha Cha, and Totah fields which are producing from the same stratigraphic horizon. McCubbin states, p. 2116, "Most previous studies of these oil fields led to the interpretation that the reservoir sandstone bodies were deposited as "offshore bars" or "marine bars" contemporaneously with the beach and nearshore-marine sandstones of the Gallup, and that their location and trend are related to the maximum extent of the Gallup regression (Knight and Budd, 1959; Sabins, 1963; Tomkins, 1957). Penttila (1964) recognized that the sandstone beds in the northwestern part of the basin overlie an unconformity which separates them from the older Gallup Sandstone, and that the distribution of the sandstone bodies is related to erosional lows on the unconformity". If McCubbin's interpretation can be applied also to the Bisti Field, then the Marye, Carson, and Huerfano sandstone bodies are basal members of the Upper Cretaceous Niobrara Formation, and as strike-valley sands flanking cuestas should be assigned to Chapter 5 on transgressive marine shoreline sand bodies. They are placed in this chapter, because:

(a) the question of their origin does not yet seem to have been satisfactorily resolved,

(b) they were apparently formed in a nearshore marine environment, and

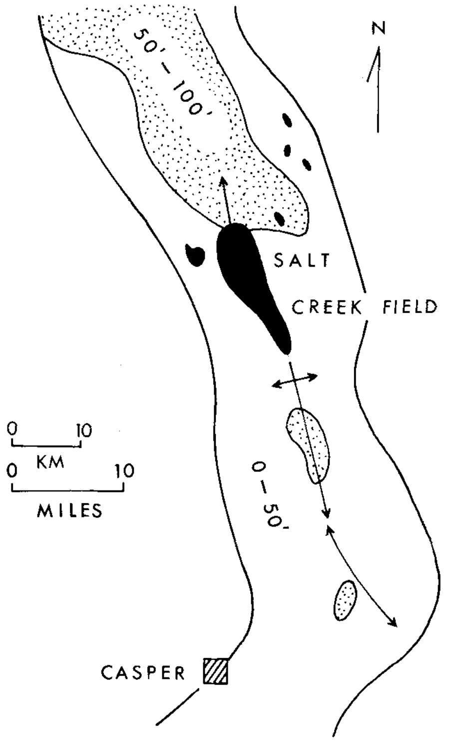
(c) their funnel-shaped E-log character (Fig. 3-24) suggests that they were sand bars

The producing sandstones of the Bisti field form a linear trend more than 55 km long, 3-5 km wide and up to 20 m thick. The sandstones are quartzose, glauconitic, and consist of fine to medium, sub-rounded grains. Grain gradation is from finer below to coarser above, a relationship that is characteristic of barrier bars. The funnel-shaped E-logs (Fig. 3-24) reflect this gradation. Porosity is in the range 10-20% but is commonly 12-55%. Permeability in the coarser sandstones ranges up to 400 millidarcys, but the average sandstones are within the range 50-175 millidarcys.

The Bisti Field is a stratigraphic trap, there being no structural influence by noses or closures either above or below the producing sandstone units in the field. Well completions normally require fracturing of the sandstone to yield an average production of more than 900 barrels per well per month. The primary producing mechanism is by means of gas solution drive. It is estimated that ultimate recovery from the field will amount to 50 million barrels (8 million cubic metres).

Salt Creek - Teapot Dome Oil Field, Wyoming

The Salt Creek Field (Fig. 3-25) and the adjacent Teapot Dome to the south are prolific oil fields producing mainly from the Second Sandstone member of the Upper Cretaceous Frontier Formation. The Second



OIL FIELDS IN OFFSHORE BAR, FRONTIER FORMATION, WYOMING

Fig. 3-25. Salt Creek oil field within a structural nose along the trend of the Second Sandstone, an offshore bar in the Upper Cretaceous Frontier Formation. (Redrawn from Barlow and Haun, 1966).

Sandstone lies about 60 m stratigraphically below the First Sandstone, at depths of 400-900 m.

The Second Sandstone is interpreted by Barlow and Haun (1966) as a marine offshore bar fringing a deltaic lobe that prograded eastward. The sandstone body trends north-northwest for more than 100 km. It averages about 15 km in width, and is up to 30 m thick. The trend coincides with the axis of an undulating anticline along which separate closures, such as the Teapot Dome, have developed. The sandstone is quartzose, well sorted, very fine to medium-grained and locally cross--bedded. It has an average porosity of 20%. Glauconite is a common constituent, and in places the sandstone contains carbonaceous fragments. The grains, which are sub-rounded to sub-angular, show a gradation in size from finer below to coarser above. This gradation is reflected in the funnel-shaped E-log character of the Second Sandstone. Locally, the sandstone body contains lenses of pebbles, and within the uppermost part there is a widespread pebble bed. A similar pebble bed, which represents a period of scouring of the offshore bars, is present at the top of the oil-producing Cardium Sandstone (Fig. 3-22) of Alberta.

Bech (1929) shows different oil-water contacts within the Salt Creek - Teapot Dome structure. These are possibly the result of faulting, rather than tilting of the oil-water surface. The salinity range of the water in the Second Sandstone is 8,000-15,000 p.p.m., well below the average sea water range of 30,000 p.p.m., which suggests that there has been some dilution of the connate water with meteoric water, and that consequently there may be some movement of water within the sandstone body. Lack of early pressure data, however, precludes the possibility of making a satisfactory hydrodynamic analysis.

Barlow and Haun (1966, p. 2195) summarize the field as follows, "Salt Creek field commonly has been selected as an outstanding example of an anticlinal accumulation. It has been cited as an example of differential entrapment by Gussow (1954) and as an example of fields with tilted oil-water contacts by Levorsen (1954, p. 295)*. The writers have attempted to show that the major accumulation, in the second Frontier

Footnote: p. 151 of the 2nd Edition (1967).

sandstone, is within a sand bar that was deposited at the seaward margin of a lobate concentration of coarse, terrigenous clastics (a delta?), which were derived from a land area on the west and northwest. The bar was subjected to strong wave and current action which produced relatively high porosity through sorting processes. The bar became a stratigraphic trap during the early stages of sediment compaction and accumulated petroleum derived from the surrounding source beds in the Frontier. During Laramide folding, the oil migrated to approximately its present structural position. Subsequent hydrodynamic gradients may have modified slightly the structural position of the oil".

The Salt Creek - Teapot Dome Field has yielded up to 1966, a total of 420 million barrels (66.8 million cubic metres) of oil having a gravity range of 33^{o}-38^{o} A.P.I. Initially, production was partly assisted by gas-solution drive, and the average daily production from early wells drilled during the period 1917-1921 was 670 barrels per well.

Big Piney Gas Field, Wyoming

The Big Piney Field of the Green River Basin, Wyoming, produces gas from lenticular sandstone units in the Paleocene Almy Formation. One of these units, the "La" Sandstone member (Fig. 3-26) is a major producer. This sandstone unit comprises two separate sandstone bodies with a slight *en echelon* alignment in plan view. Both bodies trends north, are linear, lenticular, and ranges in thickness up to 40 m. They pinch out fairly abruptly to the west and become silty to the east. These sandstone bodies are interpreted as offshore bars. Other associated sandstone bodies are interpreted as estuarine or deltaic in origin.

The Big Piney field was discovered in 1938. One of the early wells blew in while being cored at a depth of about 300 m. Gas flowed at the

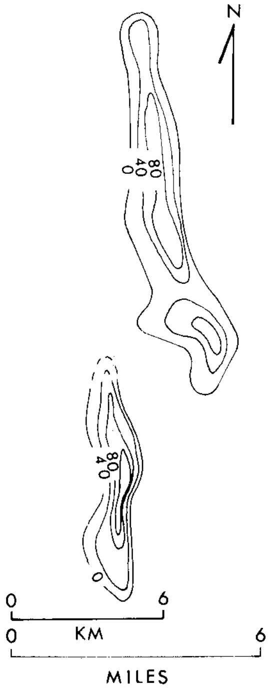


Fig. 3-26. Isopach map of the "La" Sandstone in the Paleocene Almy Formation, Big Piney Gas Field, Green River Basin, Wyoming. Contour interval in feet (1' = 0.305 m). (Redrawn from Krueger, 1968).

rate of 70 million cubic feet a day for 10 days before being brought under control. The producing sandstone at this location is approximately 30 m thick. Within the field, 20 separate and lenticular sandstone bodies within the Almy Formation, of which the "La" member is one, contain gas and minor quantities of oil. These hydrocarbon accumulations are essentially stratigraphic, the gas and oil being confined by porosity and permeability barriers on the flanks of the sandstone bodies. Within the producing zones the porosity is commonly 26-28% and the permeability 50-200 millidarcys.

The gas, which is sulphur-free, contains 89-99% methane, up to 6% ethane, and 3% propane. Cumulative production to 1966, from Almy Formation sandstone bodies in the Piney and adjacent La Barge fields, amounted to 650,000 million cubic feet (18,200 million cubic metres).

Hardin Oil Field, Texas

The Hardin Oil Field, Texas, has nine producing sandstone units within the Upper Eocene Yegua Formation. One of these, in the *Eponides*

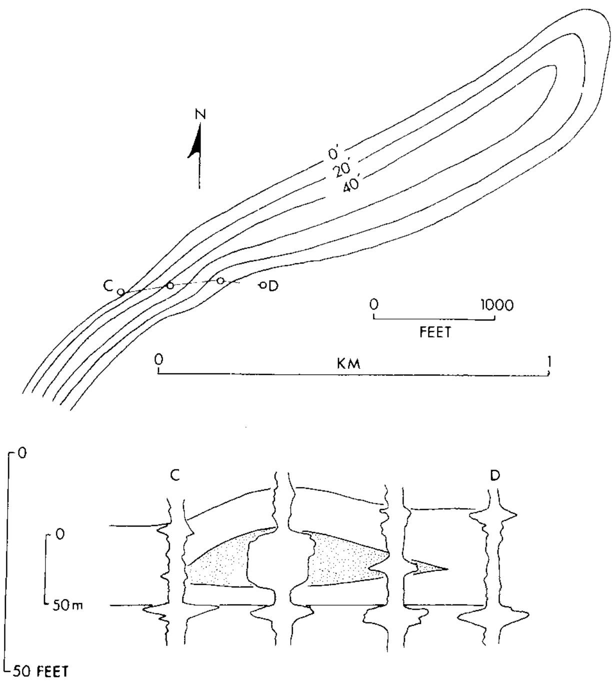


Fig. 3-27. Isopach and section C-D of the Davis Sandstone, Upper Eocene Yegua Formation, Hardin oil field, Texas. Isopach interval in feet (1' = 0.305 m). (Redrawn from Casey and Cantrell, 1941).

yeguaensis zone of the Tegua, is the Davis Sandstone (Fig. 3-27) which yields gas, distillate, and oil. The Davis is a linear and lenticular body having a length of 3.3 km, a width in the range 150-350 m, and a maximum thickness of 15 m. In general, it forms a massive sandstone body and shows no stratification except in the shaly zones, along the flanks of the body, where it exhibits some cross-bedding. The sandstone is medium--grained and consists of approximately 98% quartz. The grains are sub-angular to angular. Carbonized plant fragments are common. The sandstone body is interpreted as a marine offshore bar deposited in a regressing sea. The E-log characters of the Yegua sandstone units are distinctly funnel-shaped, which suggests that the units originated as sand bars. The E-log character of the Davis Sandstone is less well defined, possibly because it is fairly uniform in grain size.

The sandstone has excellent petrophysical properties, the average porosity and permeability being 27% and 2,200 millidarcys respectively. The presence of brackish water, having a salinity of 12,000 parts per million, suggests some degree of dilution of the connate water by meteoric water. Consequently, there is a possibility that a hydrodynamic condition exists in the field. The Davis Sandstone, encountered at a depth of about 2,285 m below the surface, yields gas, 55° A.P.I. distillate, and 37° A.P.I. oil.

Chapter 4

REGRESSIVE MARINE SHORELINE SAND

Introduction

Geomorphology

Regressive marine shoreline sand bodies consist of stratiform and lenticular bodies of sand deposited as beaches or off-shore sands during a period of regression of the sea. These sand bodies are linear and trend along the coast. They commonly exhibit a parallel arrangement in plan view and an *en echelon* arrangement in sectional view. The latter view is not always evident without vertical exaggeration of the section, particularly where internal stratigraphic markers cannot clearly be defined. A sandstone unit that appears to have a sheet-like distribution, and which has been referred to as a 'blanket sand', may in fact comprise a sequence of separate, off-lapping sandstone bodies that constitute a diachronous unit. Other sandstone bodies, such as beach ridges, may be clearly separated by shale or siltstone. Included in the category of shoreline sand bodies deposited by a regressing sea are some delta-front sand bodies such as bar-finger sands, and also some inter-deltaic sand bodies such as barrier island sands and other offshore bars. Delta-front sand bodies are not dealt with in this chapter because they are essentially the prograding seaward extensions of delta distributary sand bodies (Figs. 2-2 and 2-4) that trend, in general, normal to the coastline. Some barrier and other offshore bars could properly be included in this chapter, but because they can also form in marine transgressive situations (Fig. 3-9) they are included in a separate chapter.

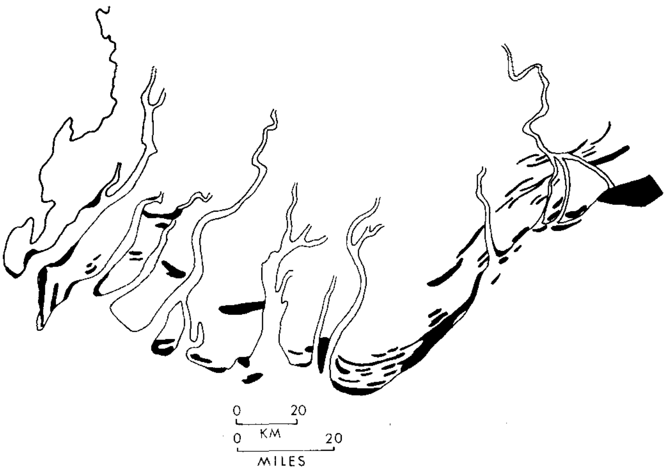
Regressive and transgressive situations can arise where the landmass adjacent to the sea is flat and low. Depending on the geological nature of the terrain, low-relief topography may be developed to a large extent by erosional processes. Very flat coastal areas adjoining the low-relief topography are formed essentially by prograding depositional processes. Vast areas of coastal flat-lands can, subsequent to their formation by sediments accreting to the coast during a period of marine regression, be subsequently inundated and partly re-worked during a period of marine transgression.

Progradation, and the consequent seaward extension of flat coastal plains, can be rapid in situations where the deltas of large river systems are growing out on a shallow continental platform. In this situation, beach ridges, barrier bars, and other offshore sand bodies can be seen as topographic features, commonly as vegetation-covered, low-lying sandy ridges, for many kilometers inland. Subsequent drowning of the coastal topography, during a period of marine transgression, may bury these features in mud and preserve them in the geological record. Although world-wide rises of sea level are known to coincide with periods during which the ice caps were melting, and may also reflect major tectonic movements, transgressions do not necessarily imply an absolute rise of sea level. Local marine transgressions commonly occur in areas of large deltas where progradation is no longer taking place because the river system has changed its course and is not supplying sediment to that part of the coast. In this situation the coastline ceases to migrate seaward by the accretion of sediment, but the delta sediments beneath the coastal plain continue to compact. As much of the swampy surface of the delta is less than one meter above sea level, the surface sinks beneath the sea. Drowning of these flat coastal plains can take place over a period of a few years, although the advance of the sea may not be at a constant rate. During periods of slow advance, conditions approximating a still-stand may be reached during which shoreline bodies of silty sand may be formed by winnowing of the sediments by waves and currents.

Continual progradation of a delta front, compaction of sedimentary layers, local re-working of surficial sediments, and widespread deposition of muds during transitory periods of marine transgression are processes that determine the stratigraphic nature and external geometry of sandstone bodies. These bodies and their enclosing beds form a sinking pile of sediments that will eventually constitute part of a sedimentary basin. Depositional features observed in modern sediments are formed by sedimentary processes that were operative in the past. Although the three-dimensional configuration of a delta-complex changes continuously, the distribution of sedimentary facies and geomorphic features seen on the surface of a modern delta can be matched by the distribution of lithofacies and sandstone bodies within particular stratigraphic intervals in the subsurface beneath the delta. Recent history of sedimentation is thus seen to be a recapitulation of the past.

The geography of modern deltas is controlled or influenced by many factors, including the nature and mass of sediment discharged, pattern of sediment distribution by distributaries, bathymetry of the continental shelf on which the delta is building out, and the strength of wave and current action. Three examples are shown by Figs. 4-1, 4-2, and 4-3.

The Irrawaddy River of Burma (Fig. 4-1) is prograding rapidly on to a broad, shallow continental shelf underlying the Andaman Sea. The entire delta covers an area of nearly 50,000 sq. km. In the southern part of the delta the annual sediment discharge is stated by Fisher *et al.* (1969) to be about 300 million tons of mud, silt, and fine-grained sand. Along the coast, accretionary sand bars have been formed by the winnowing action of waves and currents on the silty sands. Continual growth, at rates varying from one location to another depending on shifts of the



DISTRIBUTARIES AND SAND BARS,
IRRAWADDY DELTA

Fig. 4-1. Pattern of main distributaries, tidal channels, and accretionary sand bars in the southern part of the Holocene delta of the Irrawaddy River, Burma. (Redrawn from Fisher *et al.* 1969).

distributaries and changes in their volume of discharge, has resulted in the abandonment of older accretionary bars. These gradually retreat farther inland where they form linear trends outlining the pre-existing shorelines. Later periods of regional or local marine transgressions may bury these inland sand bodies with mud, thus preserving them in the geological record. Subsequent growth of the sedimentary pile results in the burial of sand bodies to depths of hundreds or thousands of metres where hydrocarbon generation, fluid movements, and penecontemporaneous deformation by compaction, slumping, and growth structures combine to concentrate oil and gas within some of the sand or sandstone units.

Regions where the depositional environments are of this nature, and where they have been similar in the geological past, are attractive areas in which to explore for oil and gas. Such regions are likely to have a relatively high organic content not only in the present-day muds but also in the subsurface mudstones or shales. Depositional environments that have not been tectonically disturbed or subjected to extensive periods of erosion are less likely to have lost an appreciable volume of hydrocarbons. Furthermore, the broad and shallow continental shelves on which such deltaic systems grow are amenable to drilling.

In contrast to the delta of the Irrawaddy River, the Nile delta (Fig. 4-2) in the United Arab Republic has marked differences in geometry, and probably also in internal structure. These differences are the result

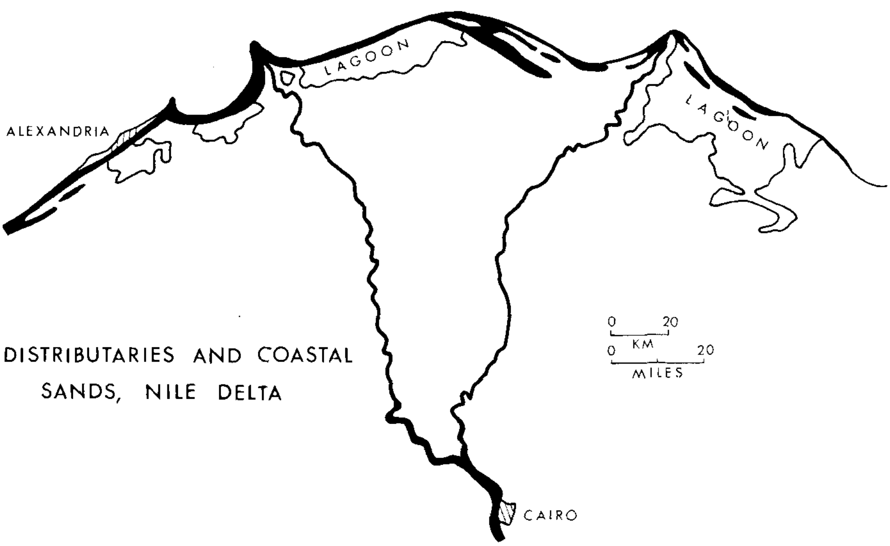


Fig. 4-2. Pattern of the main distributaries and coastal sands that form barrier-strand plains in the Holocene delta of the Nile River, United Arab Republic. (Redrawn from Fisher *et al.*, 1969).

of several factors related to rates of sediment discharge, climate, and the bathymetry of the Mediterranean Sea east of Alexandria. The two main distributaries of the Nile River, shows in Fig. 4-2 are the western Rosetta branch and the eastern Danietta branch. The total annual discharge of sediment from these distributaries is stated by Fisher *et al.* (1969) to be approximately 60 million tons, or one fifth of the discharge from the Irrawaddy River. However, much of the fine-grained sediment carried by the Nile River during periods of flood never reaches the sea, but is deposited on the flood plain when the river level falls. The lower rate of discharge into the sea is reflected not only in size, the Nile delta covering 15,000 sq. km. which is less than one third the area of the Irrawaddy delta, but also in the greater development of offshore bars. In particular, barrier bars have formed across large lagoons, almost completely cutting them off and consequently raising the salinity so that they are surrounded by coastal salt marsh and evaporite mud flats. Farther inland the delta forms an extensive flood plain.

Externally, the Nile delta contrasts markedly not only with the Irrawaddy delta, but also with the classic Mississippi delta. In the Mississippi delta the predominant sandstone bodies are distributary and bar-finger sands; barrier bars are only developed away from the delta front where sands are transported along the coast by currents. In the Irrawaddy delta the rapid rate of sediment discharge largely precludes any significant development of barrier bars; whereas in the Nile delta they are a major feature. Internally, the Mississippi delta shows sedimentary facies and geomorphologic features similar to those present in the surface. The same relationship probably obtains in the Irrawaddy delta, and may also obtain in the Nile delta. If so, buried barrier bars and other offshore sand bodies should prove to be prospective targets for petroleum exploration.

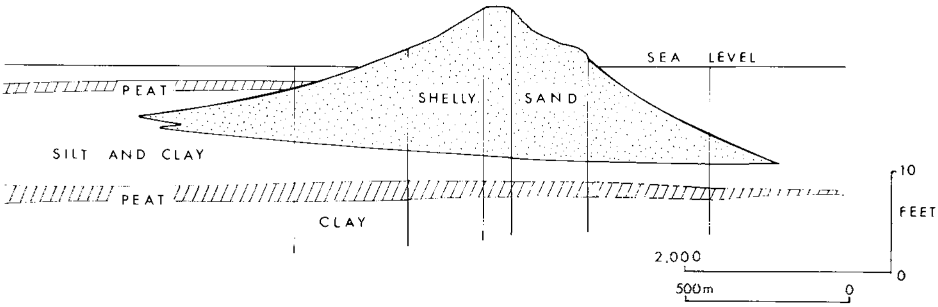
DISTRIBUTARIES AND BARRIER BARS, PO DELTA

Fig. 4-3. Pattern of distributaries and barrier bars in the Holocene delta of the Po River, Gulf of Venice, Italy. (Redrawn from Fisher *et al.*, 1969).

The Po River (Fig. 4-3) of northern Italy is rapidly building a delta into the Adriatic Sea. The area of this delta is approximately 500 square kilometers. Although very much smaller than the Nile delta, it has a comparable rate of sediment discharge into the sea, stated by Fisher *et al.* (1969) to be 70 million tons per year. Most of this sediment load is carried by the two main distributaries, the Po di Goro to the south, and the Po delle Tolle to the north. Locally, this load of sediment is sufficient to build the coastline seaward at rates of up to 60 m per year. During the Pleistocene and Holocene this rapid rate of progradation has been maintained, and sand bodies formed as regressive marine shoreline sands are now buried at depths of up to 450 m. In the subsurface these bodies form lenses, some of which are stratigraphic traps from which low pressure gas production is obtained. Between the main and subsidiary distributaries are bays and marshy coastal plains. Shoreline sands, offshore sands, and barrier bars have formed along the coast.

Where the seaward migration of a delta shoreline coast is fairly rapid, the sediment deposited is commonly silt and mud with some fine sand. The rate of sedimentation is related to the proximity of the shoreline to the mouth of the river distributary discharging sediment into the sea, and also to the mass of sediment discharged. The latter factor depends on the sediment load carried by the distributary to its mouth, and obviously is related to seasonal variations controlling periods of flood or low water. The former factor depends on changes in the course of the river distributary itself. In times of flood a distributary may burst through its levees and abandon its old channel. Such a change of course may almost completely cut off the source of sediment supply to a particular part of the coast. Subsequently, a distributary may again change course to debouch its load near the mouth of its older, abandoned channel. This cyclic, although commonly irregular, variation in the rate of sedimentation along a shoreline may result in the alternate development of mud flats and beach ridges of sand to form a prograding sequence of cheniers.

During periods when the rate of sedimentation is high, the sediment accreting to the coast is predominantly fine-grained, resulting in the rapid seaward growth of coastal mud flats. During periods when the rate of sedimentation is very much lower, the sediment along the shoreline is winnowed by wave and current action. The mud is swept away and the residual sand content remains to form a beach. With time, wind action may carry some of the beach sand landward to build dunes that form a barrier between the sea and the now land-locked coastal mud flats and cheniers. The development of a beach ridge depends on the periodicity of sedimentary accretion to the coast. Sooner or later the rate of sedimentation increases beyond the capacity of winnowing action to sort out and concentrate the sand, so that mud accretes on the seaward side of the sandy beach which



CROSS SECTION OF CHENIER ON PECAN ISLAND, LOUISIANA

Fig. 4-4. Cross section of a chenier on Pecan Island, Gulf Coast of Louisiana, showing drill hole locations. (Redrawn from Gould and Morgan, 1962).

in turn becomes land-locked as a low, sandy ridge lying between mud flats. These ridges, or cheniers (Fig. 4-4), are named after the French word chêne, meaning oak, because trees called scrub oaks commonly grow on these ridges in Louisiana.

Cheniers have a parallel, gently arcuate alignment reflecting the migratory history of the shoreline. Individually they can be traced for several kilometres. The surficial width of an individual chenier may be less than 300 m, but its subsurface width may be up to 1,500 m. Thickness commonly ranges up to 5 m. Viewed in three dimensions, without vertical exaggeration, cheniers are ribbon-shaped. Internally, they consist of fine-grained, shelly sand with a variable content of silt and mud. In the subsurface, ancient cheniers are illusive stratigraphic targets for petroleum exploration, and because of their thinness are not especially attractive. Nevertheless, where found to contain economically viable accumulations of oil or gas it should be kept in mind that other parallel-

-trending cheniers probably exist nearby, and that some of these may form hydrocarbon reservoirs.

E-log Characteristics

Regressive marine shoreline sand bodies, barrier bars, and other offshore bars that are prograding seaward, or landward (Fig. 3-9) in particular situations, tend to have an internal grain gradation from finer below to coarser above. This gradation, which is discussed in the introduction to Chapter 3 on barrier and other offshore bars, is reflected in the funnel-shaped character of the E-log self-potential curve. The similarity of this character in linear sandstone bodies of different ages, and from widely separated localities, is illustrated in Fig. 4-5. The sandstone unit designated 'A' constitutes an off-lapping sequence of sandstone bodies in the Lower Cretaceous Viking Formation of the Joarcam Oil Field, Alberta. The Viking forms a sequence of parallel and arcuate trends, each of which is a complex of separate but locally connected sandstone bodies deposited as shoreline sands. These trends were formed during a period of inconstant marine regression. Sandstone 'B' is a unit within the lower part of the Upper Cretaceous Belly River Formation in the Pembina Oil Field, Alberta. This sandstone body, and others at the base of the formation, also form a sequence of shoreline, off-lapping sandstone bodies (Fig. 4-7) deposited during a regressive phase of the sea. The sandstone units in the interval designated 'C' are stacked, off-lapping sandstone bodies formed as bars in a regressive sequence of the Oligocene Frio Formation in Texas.

The Viking Formation (Fig. 4-6) is an interesting example of regressive marine shoreline sand bodies that show a typical funnel-shaped self-potential curve. In central Alberta the Viking comprises a sequence of sub-parallel, linear sandstone bodies that have a regional arcuate trend

SHORELINE DEPOSITS

BARRIER BARS AND REGRESSIVE SANDS

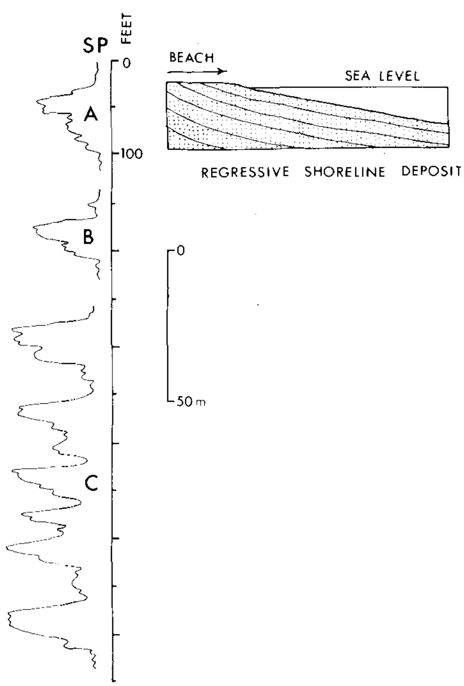


Fig. 4-5. Self-potential curves of electric logs, and a generalized section of a regressive shoreline sand deposit, showing funnel-shape characteristic of the log and its relationship to off-lapping coastal sands such as barrier bars. A - Lower Cretaceous Viking Sandstone, Joarcam Field, Alberta. B - Upper Cretaceous Belly River Sandstone, Pembina Field, Alberta. C - Oligocene Frio Sandstone, Texas.

to the northwest. This trend takes a broad sweep across the whole of southern and central Alberta, and extends also into southern Saskatchewan. Each sandstone body in the sequence tends to have an off-lapping relation-

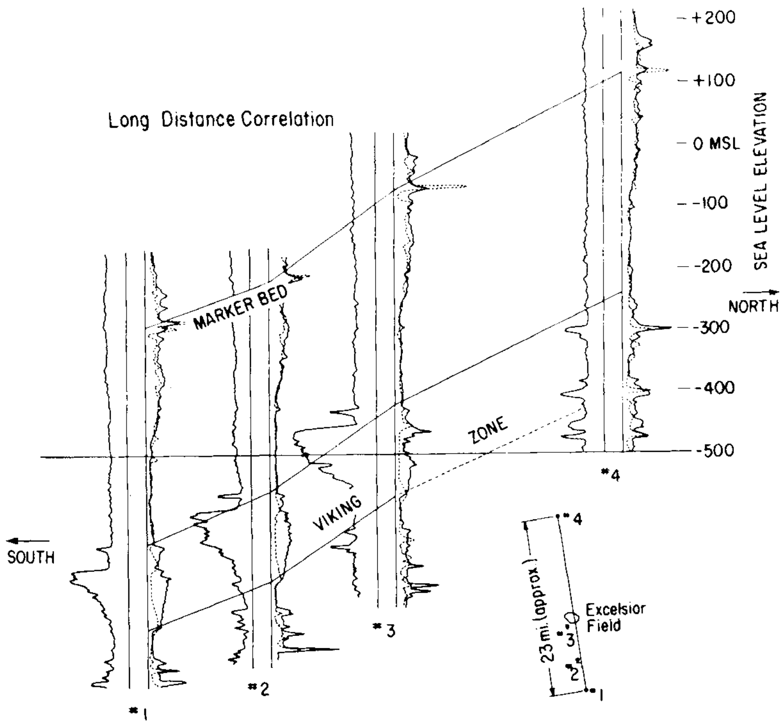


Fig. 4-6. Electric-log structural section showing funnel-shaped characteristic of the self-potential curve of oil and gas-bearing Lower Cretaceous Viking Formation near Edmonton, Alberta. (After Tixier and Forsythe, 1951).

ship and represents a shoreline sand formed during a time of eastward regression of the sea.

Referring to the lithology and grain gradation of sandstone bodies in the Viking Formation, Gammell (1955, p. 65) says, "These sands are often concentrated into beds averaging 25 feet in thickness, though beds over 100 feet are found near Edmonton. The sands are subgraywackes, being made up of white quartz and rounded black chert grains secondarily cemented with silica. Glauconite, white chert, kaolin and ironstone concretions are found in the sands in varying amounts. Regionally the sands are finest at the northeast pinchout edge of the member and become slightly coarser at the southwest, closer to the source. Locally, however, considerable variation in grain size may occur in a single bed. The regressive type of sand bed, with upward decreasing amounts of shale and silt to a sandstone followed above by a thin black chert conglomerate, is common. The Viking shales are usually silty or sandy and contain carbonaceous material and fish remains". The upward-fining of the Viking sandstone referred to by Gammell is clearly indicated by the funnel-shaped character of the self--potential curve shown in Fig. 4-6. The same E-log characteristics are exhibited by the off-lapping basal sandstone units of the Upper Cretaceous Belly River Formation in the Pembina Oil Field, Alberta (Fig. 4-7).

Compaction

Where sandy sediment is accreting continuously at a constant rate, and where the current and wave action does not vary appreciably, the unit deposited has a homogeneous texture and composition. A marked increase in the load of silt and mud, or a decrease in current and wave action, will cause the seaward flank of the sand body to grade into, or abruptly terminate against, a layer of silty mud. Repetition of these depositional events will produce a sequence of off-lapping sand bodies separated by layers of silty mud. Prior to compaction and lithification, the boundaries of each sand body are clearly defined. Following compaction, thin layers of silty mud separating the sand bodies may become squeezed into shale--breaks that are not defined by E-logs. A sandstone unit may then superficially appear to be one continuous sandstone body, whereas in fact it was deposited as a regressive stratigraphic zone comprising several off--lapping bodies of sand. Thicker layers of silty mud will compact into shaly beds that may effectively seal off the subsequent movement of hydrocarbons within the sandstone body. Recognition of the internal structure

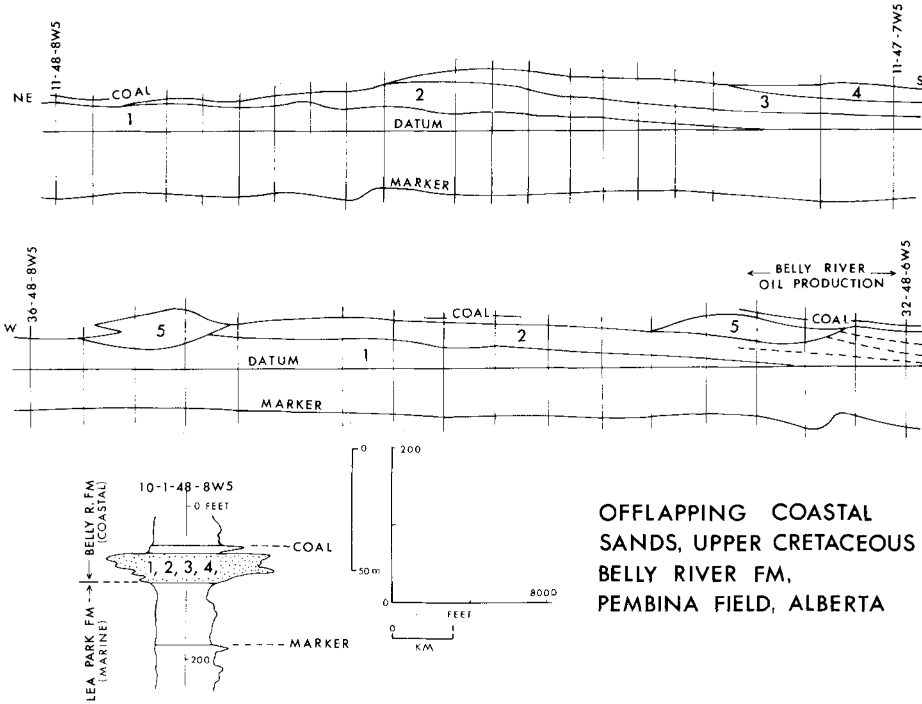


Fig. 4-7. Stratigraphic sections through eastern and southeastern parts of Pembina Field, Alberta, showing offlapping marine coastal sands (1, 2, 3, and 4) trending north-south at the base of the Upper Cretaceous Belly River Formation which overlies marine shales of the Lea Park Formation. These sands are cut by channel-fill sands (5) deposited by distributaries trending east-west at the front of a delta prograding from west to east. Note the funnel-shaped self-potential surve of the E-log, typical of coastal sands such as barrier bars.

of such a sandstone units is essential to paleogeographic and paleogeomorphic reconstructions applied to the search for oil and gas in sandstone bodies.

Ancient Sand Bodies

Regressive marine shoreline sand bodies that have an off-lapping relationship, commonly with angles of less than one degree (Shelton, 1965), are developed as widespread sheets of sand that ultimately form thin, diachronous units of sandstone. These units constitute excellent stratigraphic marker beds, as they overlie shaly marine sequenees, and where exposed as a nearly horizontal layer they resist erosion to form the rim-rock in canyons and mesas. Examples include the Upper Cretaceous Eagle Sandstone (Fig. 3-9) that forms a rim-rock in the escarpment at Billings, Montana, and the lower sandstone beds of the Upper Cretaceous Mesaverde Formation in New Mexico. In the subsurface, examples comprising off-lapping bodies can be seen in the Lower Cretaceous Viking Formation (Fig. 4-11) in Saskatchewan, and in the basal sandstone unit of the Upper Cretaceous Belly River Formation (Fig. 4-7) in Alberta.

The basal unit of the Belly River Formation is a sheet-like sandstone that comprises a sequence of off-lapping marine shoreline sand bodies locally cut by distributary channels filled with coarser sand of the Buck Creek Member (Fig. 73). This widespread sandstone unit is overlain by Belly River shales, siltstones, and coal seams deposited in a deltaic environment; and is underlain by several hundred feet of marine shales of the Upper Cretaceous Lea Park Formation on which the basal Belly River sands transgressed during a regressive phase of the sea.

In the Pembina Oil Field region, where some oil production is obtained from the Buck Creek Member, the basal sandstone unit has a fairly uniform thickness of 35-45 m. Superficially, this unit resembles a homogeneous sheet of fine-grained sandstone, but detailed E-log correlations (Fig. 4-7) show the internal structure to consist of separate sandstone bodies off-lapping to the east, and cut into by distributary channels filled with medium to coarse-grained sand. This sequence was deposited during an eastward regression of the sea in response to progradation of a large delta.

At the close of Lea Park time the Pembina region lay under a shallow sea. Marine regression continued into Belly River time, beginning with the deposition of basal marine shoreline sands. As the sea withdrew, the marine shoreline sands migrated eastward, forming an off-lapping sequence of separate sand bodies. These were followed and overlain by a delta consisting of deposits formed in bays, lagoons, estuaries, coastal marshes and river distributaries. These deposits now form beds of sandstone, siltstone, shale and coal overlying the basal sandstone unit of regressive shoreline sands. The regressive nature of this sandstone

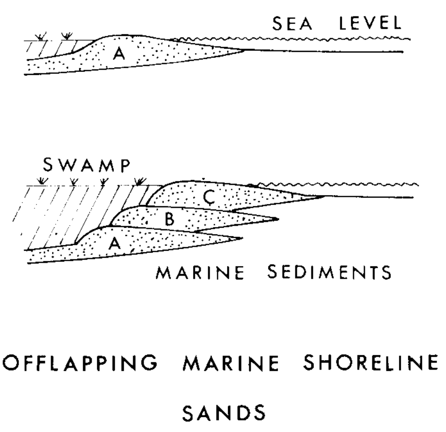


Fig. 4-8. Diagram illustrating accretion of offlapping marine shoreline sands, such as the regressive lower member of the Mesaverde Sandstones (Upper Cretaceous) in New Mexico. (Redrawn from Hollenshead and Pritchard, 1961).

unit is reflected in its grain size distribution which tends to range from fine above to very fine below, a gradation reflected in the funnel-shaped self-potential curve of the E-log (Fig. 4-7).

The spatial relationships of such off-lapping sandstone bodies is illustrated with considerable vertical exaggeration in Fig. 4-8, with reference to the internal stratigraphic relationships of sandstone bodies in the Mesaverde Formation. A general feature of a sandstone unit comprising off-lapping sandstone bodies formed as beaches, bars, and other off-shore sands, is that it will, although widespread, have some degree of linearity.

Oil and Gas Fields

Significant accumulations of oil and gas are known within regressive marine shoreline sand bodies. In contrast to transgressive marine shoreline

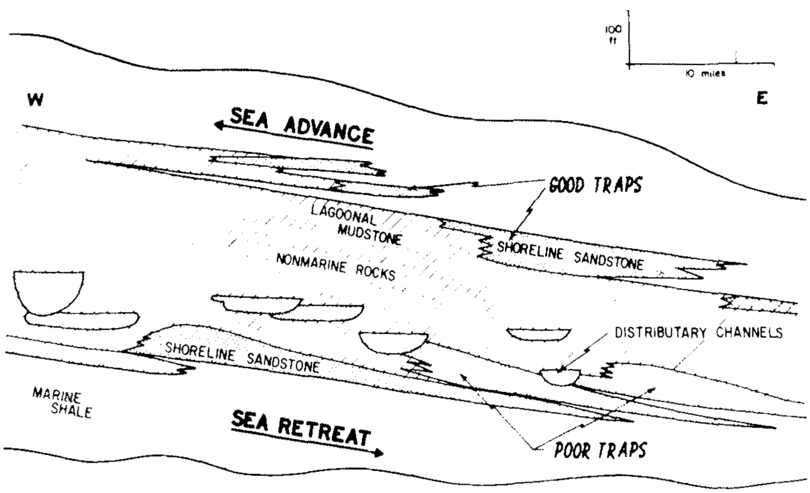


Fig. 4-9. Schematic diagram illustrating types of sand bodies formed during regression and subsequent transgression of a sea. A general evaluation of petroleum entrapment potential is indicated. (After MacKenzie, 1972, Fig. 5).

sands MacKenzie (1972) contends that regressive sand bodies are less attractive as exploration targets. He says, p. 57, "During periods of overall regression, shoreline sand bodies, if present, may be replaced updip by deltaic deposits (Fig. 4-9 this text). These deltaic deposits, because of their many associated types of sands - particularly distributary channel sands - probably would be relatively poor barriers to up dip migration.

In contrast, during periods of overall transgression, the shoreline sand bodies would be replaced updip by sand-poor lagoonal muds which, when compacted, would be relatively good barriers to updip migration of oil. Furthermore, the sands would be overlain by marine shales, which should be effective barriers".

The correctness of this contention is open to question, as some marine regressive sandstone bodies are the reservoirs for many oil and gas fields. Important examples include the Wattenberg Gas Field producing from the Lower Cretaceous "J" Sandstone of the Denver Basin in Colorado, and several fields producing from the Lower Cretaceous Viking Formation in Alberta and Saskatchewan.

Wattenberg Gas Field, Colorado

The Wattenberg Gas Field covers an overall area of approximately 2,500 square kilometres. The field, which is situated on the axis of the Denver Basin, is considered to include several stratigraphic traps, the gas being contained in a blanket sandstone unit, the Lower Cretaceous "J" Sandstone, comprising regressive marine sandstone bodies deposited in the front of a northwesterly prograding delta. Entrapment of gas is controlled by decreasing permeability along the edges of the sandstone bodies. Encountered within the depth range 2,200-2,600 m, the average net thickness of the gas-bearing sandstone, or pay, is 8 m. Average porosity is 9.5%.

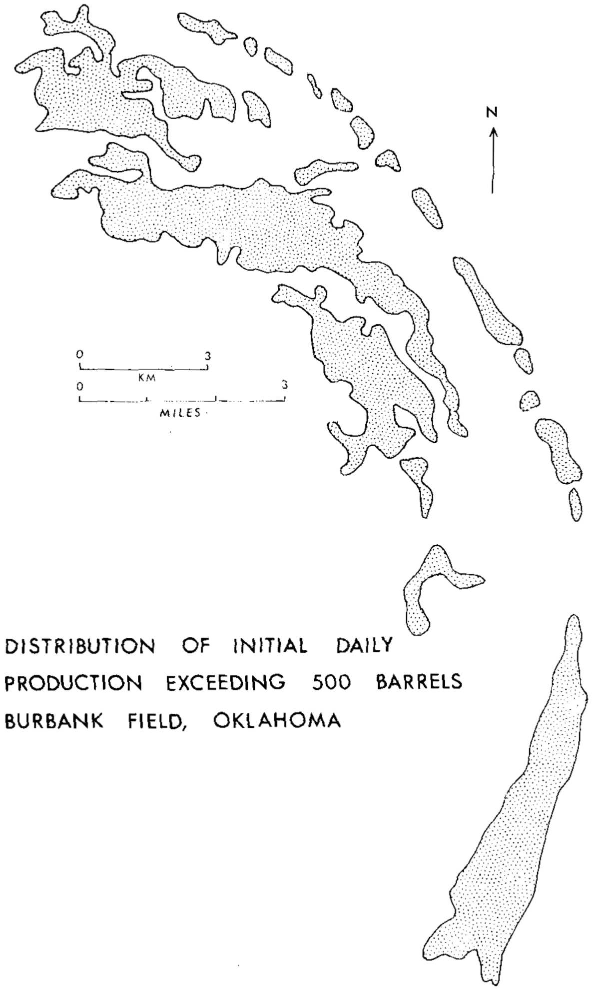


Fig. 4-10. Distribution of initial daily oil production exeeeding 500 barrels per day per well, Burbank and South Burbank fields, Osage and Kay Counties, Oklahoma, Figure shows spatial relationship of production to thicker parts of curved, linear bodies of Pennsylvanian sandstone deposited as shoreline sands. Note <u>en echelon</u> trends east of the main curvilinear belt. (Redrawn from Bass, 1941).

Permeability, averaging less than one millidarcy, is extremely low, and gas flows only after the sandstone has been fractured. After completion, the average well yields gas and 64^{o} A.P.I. condensate at rates of 300-600 thousand cubic feet and 10-20 barrels per day. Ultimate gas production is estimated to be 1.3 trillion (thousand billion) cubic feet (36,400 million cubic metres) over a 40 year period, each well on a 320-acre spacing producing 2 billion cubic feet.

Burbank Oil Field, Oklahoma

Production in the Burbank Oil Field of Oklahoma (Fig. 4-10) is obtained from a number of Pennsylvanian sandstone bodies that form four parallel and arcuate trends, the central and northern trends showing an *en echelon* arrangement. These trends constitute a belt, the thicker and more productive part of which has a width of 5 km and a length of 25 km. The sandstone bodies range in thickness up to 30 m and consist of well--sorted grains which show a gradation from fine in the thicker parts to very fine near the edges of the bodies. Porosity and permeability trends consequently conform to the depositional trends and are higher where the sandstone is thicker along the axis of each body. Interpretation of the depositional environment of these sandstone bodies suggests (Bass, 1941) that they were deposited as a sequence of off-lapping beaches and bars along shoreline trends that migrated to the northeast. The curvature of these trends also suggests that they were developed as a peripheral margin of shoreline sands flanking the prograding edge of a delta lobe.

Initial daily production from some wells exceeded 2,000 barrels of oil a day. Fig. 4-10 shows linear trends where the initial daily production per well exceeded 500 barrels a day. These production trends, including part of the South Burbank field, have yielded more than 40 million barrels (6.4 million cubic metres).

Viking Oil and Gas Fields, Alberta and Saskatchewan

In Alberta and Saskatchewan, several fields produce oil and gas from the Lower Cretaceous Viking Formation. In Alberta, the main oil fields are the Joarcam, Joffre, Hamilton Lake, and Gilby-Bentley; the main gas fields are the Viking-Kinsella, Provost, Beaverhill Lake, Bindloss, Fairy-dell, Sedalia, Cessford, and Fort Saskatchewan. The main oil and gas fields in Saskatchewan are the Milton, Hoosier, Smiley-Dewar, Whiteside, Colville-Smiley, Eureka, Beaufield, Dodsland, and Avon Hill. All of these accumulations occur in up-dip sections of linear and lenticular sandstone bodies, particularly where stratigraphic traps have been modified by closures resulting from draping over hills on the eroded surface of the Paleozoic, or from draping over sections flanked by collapse features resulting from the solution of salt layers within the Paleozoic.

The Viking Formation is a diachronous stratigraphic unit, comprising beds of sandstone and shale, that forms an arcuate belt trending north--westerly across southern Saskatchewan and south-central Alberta. These linear sandstone beds are markedly lenticular, locally separated by shale layers, and stratigraphically arranged as an off-lapping sequence. Deposited as shoreline and near-shore sands in a regressing sea, they formed beaches and off-shore bars. The lithology and E-log characteristics of the Viking sandstones are described in an earlier section of this chapter. These sandstones are underlain by marine shales of the Joli Fou Formation, which is the lowest unit of the Lower Cretaceous Colorado Group, and are overlain by shales and siltstones of the same group. In Saskatchewan, a minor disconformity at the base of the Viking Formation indicates that locally there was withdrawal of the Joli Fou sea prior to deposition of the Viking sands. The Joli Fou, which overlies the Mannville Group (see Carbon Gas Fields, Fig. 5-9), consists of dark grey, fissile, non-calcareous, bentonitic shales with some laminations

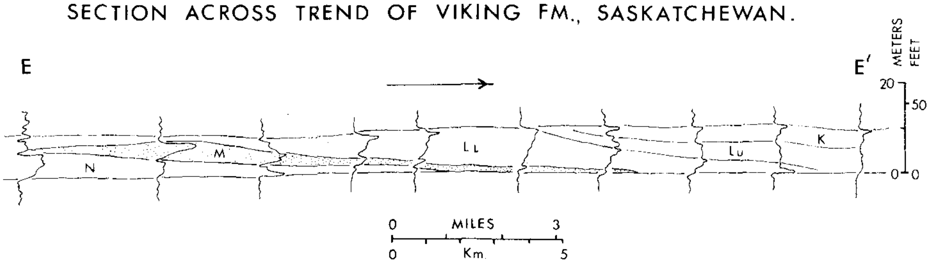
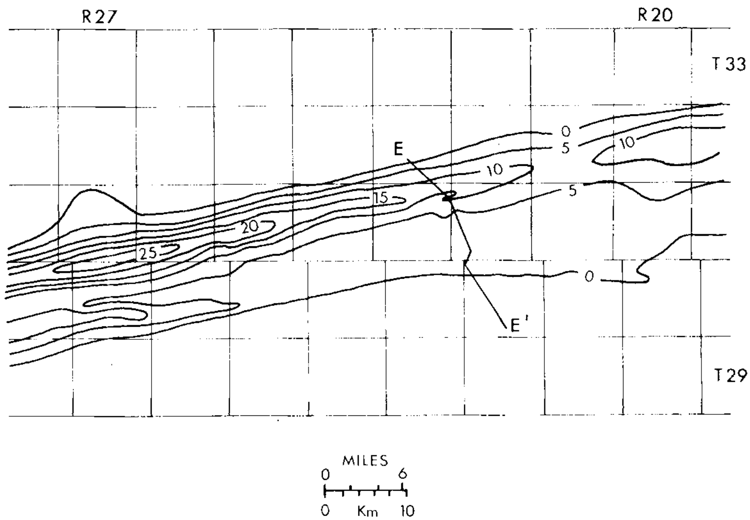


Fig. 4-11. Laterolog section E-E[1] of the Lower Cretaceous Viking Formation showing off-lapping relationship of sandstone members N, M, Ll, Lu, and K through Eureka and Avon Hill oil and gas fields, Saskatchewan. Arrow indicates direction of retreat of the Colorado Sea. (Redrawn from Evans, 1970).

of siltstone and very fine-grained sandstone. It thickens northward, over a distance of 300 km, from 6 m near Calgary to 30 m near Edmonton, and also thickens eastward to 45 m in west-central Saskatchewan. The fauna in the Joli Fou consists mainly of bivalves and arenaceous forams, suggesting a shallow-water, near-shore marine environment.

The off-lapping relationship of Viking sandstone bodies is illustrated in Fig. 4-11 which is a section across the Viking Formation trend in the vicinity of the Eureka and Avon Hills fields in Saskatchewan. This trend strikes west-southwest to near the Alberta-Saskatchewan boundary where it joins the main Viking trend in a wide northwesterly-trending arc. The main production comes from the 'M' sandstone member shown in Figs. 4-11 and 4-12. This member forms a lenticular ribbon of sandstone, 10-20 km wide and up to 8 m thick, that follows a remarkably straight west--southwest trend for well over 100 km. The 'M' member is separated from the underlying 'N' member (Fig. 4-11) by a bentonite layer which probably originated as a fall of volcanic ash. Grain gradation within the 'M'

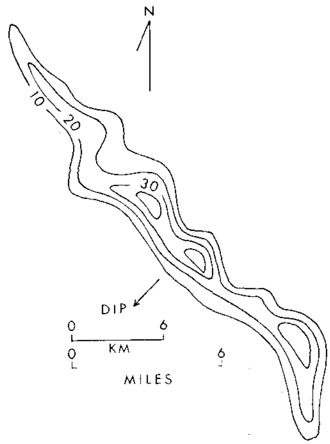


ISOPACH MAP 'M' MEMBER VIKING FM, SASKATCHEWAN

Fig. 4-12. Isopach map of 'M' member, Lower Cretaceous Viking formation, in area of Hoosier, Smiley-Dewar, Colville-Smiley, Eureka, Beaufield, and Dodsland oil and gas fields, Saskatchewan. (Redrawn from Evans, 1970).

layer is from finer below to coarser above. Porosity increases in the thicker parts of the sandstone body, and particularly improves in the chert pebble zones. These pebble zones were probably formed as lag deposits on beaches, where current and wave action has more vigorously winnowed the sediments.

Oil and gas accumulations within the numerous sandstone bodies of the Viking Formation are in the more porous and permeable up-dip sections. Thicker parts of a sandstone body may be water-bearing, whereas the thinner and less permeable parts up-dip may be oil-bearing. Fig. 4-13 is an isopach map of the net-producing sandstone of the Viking Formation



GEOMETRY OF VIKING SANDSTONE, FORT SASKATCHEWAN GAS FIELD, ALBERTA

Fig. 4-13. Isopach map of net producing sandstone body in Lower Cretaceous Viking Formation, Fort Saskatchewan gas field north-east of Edmonton, Alberta. Contour interval in feet (1' = 0.305 m). (Redrawn from White and Orr, 1968).

in the Fort Saskatchewan Gas Field. Fig. 4-14 is a sand-percentage map of the Viking Formation in the same area, showing structure contours (feet below sea level) in the gas field. The gas accumulation is not, in this example, related to the ratio of sandstone to shale within the formation, but to the up-dip position of an individual sandstone body. The net producing zone of this sandstone body ranges in thickness up to 15 m, and has an average porosity of 22%. Down-dip the Viking sandstones are saturated with water.

As of early 1966, the Fort Saskatchewan Gas Field alone had yielded

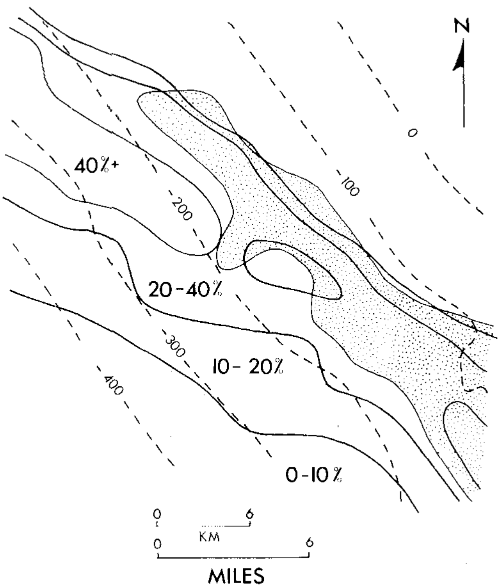
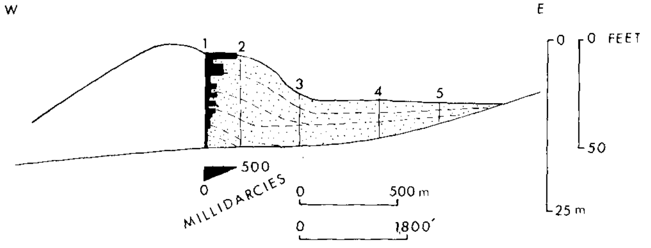


Fig. 4-14. Sand-percentage map of Lower Cretaceous Viking Formation, Fort Saskatchewan gas field, Alberta, showing field area (stippled) and Viking structure contours (broken lines) in feet (1' = 0.305 m) sub-sea level. (Redrawn from White and Orr, 1968).

more than 87 billion (thousand million) cubic feet of gas from estimated recoverable reserves of 205 billion (5,740 million cubic metres). Estimates of total gas initially in place in the Viking sandstones of Alberta are placed at about 4.3 trillion (thousand billion) cubic feet, of which recoverable reserves are estimated to be in excess of 3 trillion (84,000 million cubic metres), which is about 7% of the total recoverable gas reserves in Alberta, as of 1970. The estimated total oil initially in place in the Viking sandstones of Alberta is more than 320 million barrels, of which 110 million (17.5 million cubic metres), representing less than 1.5% of the initial total recoverable oil reserves in Alberta, may ultimately be produced.

Sabre Oil Field, Colorado

Production in the Sabre Oil Field (Fig. 4-15), situated on the westward-dipping eastern flank of the Denver Basin, Colorado, is obtained from a sandstone body within the Upper Cretaceous "D" Sandstone unit. The "D" Sandstone is overlain and underlain by marine sediments of the Upper Cretaceous Graneros Shale and Huntsman Shale respectively. The Huntsman overlies the off-shore marine "J" Sandstone which is the producing sandstone of the Wattenberg Oil Field, Colorado, mentioned earlier in this chapter. In Nebraska, the "J" Sandstone on the eastern flank of the Denver Basin is cut by river channels filled with sands which locally form structural--stratigraphic traps for oil (Fig. 1-50). The oil-bearing sandstone body of the Sabre Field is a linear, northward-trending lens that has a thickness of up to 15 m, a width of approximately 2 km, and a length of more than 15 km. This body, referred to as the Sabre Bar, shows variations in thickness



SECTION ACROSS SABER BAR

Fig. 4-15. Section across Upper Cretaceous "D" Sandstone where it forms an oil-bearing barrier bar known as Saber Field, Logan and Weld Counties, Colorado. Internal structure is suggested from correlation of permeability in five wells shown. (Redrawn from Griffith, 1966).

along strike, so that the geometry of the body is that of a connected string of pod-shaped, lenticular sandstone beds. The sandstone is micaceous and very fine-grained. Porosity and permeability are variable, the latter ranging up to 500 millidarcys. Reconstruction of the probable original shape of the Sabre sandstone body (Fig. 4-15) shows it to be bar-shaped. This interpretation is substantiated by correlation of wells across the body, which indicates that the permeability increases upward, a characteristic associated with barrier bars and other off-shore bars in which the grain gradation is from finer below to coarser above.

Wells in the Sabre Field require hydraulic fracturing treatment in order to rpoduce oil at rates of 10-60 barrels per day, accompanied by small flows of gas. Gas-oil and oil-water contacts within the sandstone body appear to be horizontal.

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Chapter 5

TRANSGRESSIVE MARINE SHORELINE SAND

Introduction

Geomorphology

Transgressive marine shoreline sand bodies are formed in an inner neritic to littoral environment where the sea level is rising relative to the land. The sand bodies, which commonly coalesce to form discontinuous sheets of sand, grow landward over a delta plain or an erosional surface. Depressions on the land surface, such as strike valleys flanking cuestas, are filled with sand. Subsequent erosion of a transgressive sheet of sand may leave only remnants within these depressions. Where the remnants are within ancient strike valleys, the sand bodies form linear lenses parallel to the strike of the underlying beds. These remnant sand bodies commonly tend to be parallel to the shoreline trend of the sea in which they were deposited. Where a sheet-like complex of sand bodies transgresses a coastal plain or flat erosional surface, the individual sand bodies, formed as beach ridges, also trend along the coast. Recognition of the origin of sand bodies, and the nature of their linearity, is essential to reconstruction of the paleogeographic and paleogeomorphic situations that may have a bearing on exploration for oil and gas. As stated by Selley (1970, p. 111), "Obviously a considerable understanding not only of sedimentology but also of geomorphology is needed to predict the location of hydrocarbon reservoirs in the basal sands of transgressive clastic shorelines".

A distinction is drawn between sand bodies transgressing over a delta plain or erosional surface and sand bodies, situated on a continental shelf many miles from land, that are prograding toward the coast. An example of the latter type is the Upper Cretaceous Eagle Sandstone of Montana (Fig. 3-9). This sandstone unit exhibits all the characteristics of a barrier bar complex, but was apparently growing toward a coast situated more than 50 miles away (Shelton, 1965). A further distinction must be drawn where transgressing marine sands over-ride alluvial sands. There are examples where alluvial sand bodies have been mistaken for marine sand bars, because of their shape. A case in point is the Lower Cretaceous Ellerslie Sandstone in the Bellshill Lake Oil Field, Alberta (Figs. 39 and 40). The producing sandstone body in this field was originally thought to be a sand bar flanked by marine to brackish-water silty muds and limey beds containing forams and ostracods. Conybeare (1964, 1972) and Martin (1966) showed the sandstone body to be a remnant of an eroded alluvial terrace situated in a broad valley that was inundated by brackish-water as the sea advanced southward. Other examples, where interpretations of depositional environment must proceed with caution, are cited by Selley (1970, p. 110) and Levorsen (1967, p. 336-337). Selley cites Levorsen's references to the Lower Cretaceous Cutbank Sandstone of Montana, and the basal sandstone of the Pliocene Quirequire Formation, Venezuela, as examples of transgressive sand units. Both units are of non-marine origin, the Cutbank filling channels of an ancient drainage system (Fig. 1-51).

Transgressive sheet-like units of marine sand are comparatively thin and widespread. Where transgression takes place over a delta the sands overlie coastal-marsh peat, bay muds, and distributary sands. Where transgression is over an unconformity the sands overlie eroded rocks, soils, and alluvial or lacustrine sediments. Transgressive sand units are formed from the re-working of pre-existing sediments and soils, from the erosion of sandstone headlands cropping out along beaches, and from the accretion of sand carried from river mouths by longshore currents. The last factor is probably of minor importance in a transgressive situation in which the sediment load carried to the sea is probably much lighter than in the regressive phase. The lower rate of sedimentation in transgressive units results in a greater degree of winnowing of the sediment, comparative thinness of the unit, and in some situations is also reflected in a relatively high quartz content of the sands.

E-log Characteristics

Transgressive, sheet-like units of sand are built up by the gradual encroachment of a beach upon a land surface. Encroachment is facilitated where the land surface is low-lying with respect to sea level, such as on delta plains and other coastal lowlands. The encroaching sand body includes a beach exposed at low tide and a broad, sub-sea extension of the beach. Landward, in the zone of strongest wave action, the beach sand is a mixture of coarser grain sizes. Seaward, in deeper and quieter water, finer-grained sand is deposited. In still deeper water, the sand grades into silts and muds which, with continuing transgression of the beach, progressively buries the sand unit. The physical principle involved in the differential deposition of sand grains on a transgressive beach is the same as that previously described with reference to the development of a prograding barrier bar, except that in the former case, the depositional front is migrating landward, and in the latter seaward.

Grain gradation within a transgressive sandstone unit is from finer above to coarser below. The same gradation is found in river sand deposits such as channel-fill and point bar sand bodies. For this reason, caution is necessary in the interpretation of some basal sandstone units, and may in part explain why a sandstone such as the Lower Cretaceous Cutbank Sandstone of Montana should have been referred to as a transgressive unit (Selley, 1970, p. 110). Grain gradation is not always evident, but where present is commonly reflected in the bell--shaped self-potential curve of the E-log. These characteristics of transgressive sands are illustrated by Pirson (1970) in diagrams combining self-potential curves and dipmeter plots. They are also shown by Pate (1959) in E-log sections of the stratigraphic interval including the transgressive Pennsylvanian Tonkawa Sandstone of the Anadarko Basin, Oklahoma. Pirson further shows theoretical self-potential curves of the regressive Point Lookout Formation and transgressive Cliff House Formation of the Upper Cretaceous Mesaverde Group in the San Juan Basin of New Mexico. These formations merge laterally, passing upward from a regressive to a transgressive phase. Pirson states that the rapidity of transgression can be gauged by the accentuation of the bell-shaped self-potential curve. The accentuation is indirectly a measure of the degree of grain gradation effected by winnowing which will be greater under more vigorous energy conditions such as those existing along the shoreline of a rapidly advancing sea.

Compaction

Transgressive marine shoreline sand bodies are comparatively thin and widespread. They are deposited on the land surface of a coastal plain which may be an erosional surface or the depositional surface of a delta. Where the transgressive sand unit is lying on eroded rocks, compaction of the overlying beds will have little or no effect on its geometry. The important factor controlling the original geometry is the configuration of the surface on which the sands are deposited. Subsequent erosion of the overlying beds and of the sandstone unit itself will modify its geometry, leaving isolated sandstone bodies such as wedges, strike valley lenses, and sandstone patches in the older topographic depressions. Where erosion of the underlying beds occurs, remnants of the sheet-like transgressive sandstone unit may be left as cap rock on buttes and mesas. Cessation of uplift and erosion, subsequent transgression of the sea, and burial of the individual residual sandstone bodies by fine-grained estuarine and marine sediments may result in the formation, by compaction of the overlying sediments, of a number of potential reservoirs for oil and gas.

Where the transgressing sand unit is lying on poorly consolidated to unconsolidated sediments, such as clays and silts underlying the surface of a delta coastal-plain, compaction of these underlying beds may have a marked effect on the subsequent geometry of the unit. Gentle variations in the dip of the sheet-like sand unit may reflect differences of sand-mud ratio in various parts of the underlying pile of sediments undergoing compaction. More accentuated variations in dip may reflect local draping of underlying clays over a deeper body of sand such as a barrier bar. Other factors influencing variations in the post-depositional dip of a transgressive sand unit are compaction of the underlying pile of sediments over basement topographic features, and penecontemporaneous faults caused by mass slumping within the underlying section. The latter may result in local deformation of the transgressive sand unit to form monoclinal structures.

Ancient Sand Bodies

A classic exmaple of a transgressing sand is the Ordovician St. Peter Sandstone of Minnesota. This friable sandstone is composed entirely of well-rounded grains of quartz having a fairly uniform size. The rounded quartz grains are pitted, a feature that has been regarded as indicative of an eolian origin. The sandstone, as a unit, is remarkably sheet-like; it has an average thickness of 23 m but ranges up to 90 m, and covers an area of approximately 575,000 sq. km according to Dapples (1955). The St. Peter is associated with shelf carbonates and was regarded by Dapples as a continuous series of coalescent shoreline sands migrating over a stable shelf. The Devonian Oriskany Sandstone of West Virginia, a quartz arenite cemented by quartz to form an orthoquartzite, is also considered to be a transgressive sandstone unit. These examples are probably exceptional in that they are composed entirely of quartz grains, although in general it can be said that transgressive sands are commonly quartzose. Regressive sands are commonly lithic, but can also be quartzose, as is the case with some present-day beach sands in the Gulf of Mexico. The composition of river sands is a mixture of quartz and lithic grains, with the former commonly predominant.

The origin of sands composed entirely of quartz grains is by no means certain. They may have formed from the erosion of quartzose sandstones, from sand dunes, or from pre-existing sands. It is probable that the sand grains in all such quartz sands have been re-cycled several times. Arguments bearing on this problem are discussed by Pettijohn, Potter, and Siever (1972, p. 224-225).

Another classic example of a transgressive marine sandstone is the Lower Cambrian Tapeats Sandstone exposed in the Grand Canyon of Arizona. The Tapeats overlies Precambrain rocks, and is overlain by marine shales of the Middle Cambrian Bright Angel Formation. Referring to the great unconformity on which the Tapeats rests, McKee (1969, p. 79) says, "Its record is plainly seen from many vantage points on the canyon rims, but it is perhaps even more impressive where observed from closer sites along the Colorado. In places this unconformity is a remarkably flat, even surface for a distance of miles; it bevels the upturned ends of schists and other metamorphic rocks of early Precambrian time and is covered by flat-lying strata of the Cambrian. Elsewhere it is seen as cross sections of rugged hills or ridges, some hundreds of feet high, of late Precambrian quartzites and other resistant rocks, surrounded by and buried beneath sediments deposited in the Cambrian sea". The great span of time represented by this unconformity is cited by McKee, after estimates by Sharp (1940), to be 100 million years.

The Tapeats Sandstone is described by McKee (1969, p. 80) as follows.

"The Tapeats Sandstone is a massive, cliff-forming unit with a thickness ranging from 100 to 300 feet throughout the canyon area. In most places it is chocolate brown, but in some places it is grey or cream--coloured and in others, a deep red brown. The sand is coarse to medium grained; coarse particles are dominant except in parts of the upper half, where medium-size grains are more common. Bedding is conspicuous because of contrasts in degree of cementation that cause layers to weather into alternating resistant ledges and shallow recesses. Flat, even beds up to a few inches thick are common, but by far the more abundant structural features is crossbedding within layers ranging in thickness from ½ to 2 feet. Most cross-strata are tabular planar or wedge planar but locally some are of trough type. Asymmetrical ripple marks, trilobite trails, and problematical worm borings are widely distributed and numerous at some localities. In many places the Tapeats grades upward into the Bright Angel through a zone in which coarse sandstone beds alternate with green shaly mudstones".

Oil and Gas Fields

Transgressive marine shoreline sand bodies are known to contain oil and gas, although more examples are known in regressive sands. MacKenzie (1970) has advanced the idea that the percentage of good traps in transgressive sandstones should be higher than in regressive sandstones, because the former are overlain by less permeable marine shales, whereas the latter are overlain by delta sands and silts which on compaction would form a less effective seal. Argued on this basis MacKenzie has a point, although it can be said that on the basis of statistics, the number of known oil and gas reservoirs in regressive sandstone bodies considerably exceeds the number known in transgressive bodies. A factor that probably has considerable relevance to the hydrocarbon potential of transgressive and regressive sedimentary sequences is the relative amounts of organic matter incorporated with the sediments. In regressive sequences the river systems drain large areas and carry organic matter as colloids and macerated plant fragments. This organic matter is carried to the sea where the macerated plant remains are deposited and the colloids are precipitated by intermingling of fresh and salt water. Also, the delta sediments deposited in brackish-water bays and coastal swamp environments are rich in organic matter, both plant and animal. Transgressive sequences, on the other hand, are commonly deposited over flat coastal areas that border on lowlands from which little sediment or organic matter is being derived. The transgressive nature of the coastline itself, subject to active erosion by wave action, is not conducive to the growth of coastal swamps, nor to the many forms of organisms that thrive in more protected environments. Furthermore, high energy environments are not conducive to the retention of organic matter in muds.

A third consideration is the nature of the surface over which the sand unit is transgressing. Where the surface is erosional and underlain by consolidated material and bedrock, the source of oil or gas that subsequently becomes entrapped in the transgressive sand unit is probably within the overlying marine sediments. But where the surface is a delta plain underlain by unconsolidated, organic-rich muds and silts, the source may be either the underlying deltaic sequence of the overlying marine sediments.

It is of interest to note that the first significant flow of oil in Australia, although not the first discovery, was obtained in 1953 from a Lower Cretaceous transgressive unit in Western Australia, the Birdrong Sandstone. The well, Rough Range No. 1, initially flowed 30° A.P.I. waxy oil at rates of up to 600 barrels per day, but later proved to be non-commercial. The accumulation within the Birdrong, a sheet-like sandstone unit unconformably overlying Jurassic and older rocks, is located in a structure formed by draping of the sandstone over an elongate buried hill. The Birdrong, a clean quartzose sandstone, is glauconitic in its upper part. It has good porosity and permeability and is the main fresh-water artesian aquifer in the Carnarvon Basin.

Yardarino-Dongara Gas Field, Western Australia

In the Yardarino-Dongara Field of Western Australia gas and oil are produced from the basal Yardarino Sandstone of the Lower Triassic Kockatea Formation. This sandstone, which lies unconformably on Precambrian and Permian beds, is a transgressive marine unit. It consists of light grey, quartzose, very fine to coarse-grained sandstone with conglomeratic layers. In the field area the sandstone is about 55 m thick and is overlain by marine shales. Porosity ranges up to 25% but averages about 17%; permeability ranges up to several thousand millidarcys, but is commonly in the range 100-700 millidarcys.

The field is essentially a structural-stratigraphic trap, the Yardarino Sandstone showing marked thinning over a basement erosional high. Production consists mainly of gas containing approximately 97% methane, with a condensate content of up to 15 barrels per million cubic feet of gas, and minor quantities of 35° A.P.I. waxy oil. Producible gas reserves are estimated (Cope, 1972) to be in the order of 500,000 million cubic feet (14,000 million cubic metres) containing a minimum of 500,000 barrels (79,500 cubic metres) of condensate. Formation water underlying the gas and oil is brackish to salty.

Red Oak, Wilberton, and Kinta Gas Fields, Oklahoma

Gas production in the Red Oak, Wilberton, and Kinta fields of the McAlister Basin, Oklahoma, is obtained from sandstones at the base, and in the lower section of the Lower Pennsylvanian Atoka Formation. The basal sandstones, termed the Foster Sand, consist of four separate belts trending to the southeast (Fig. 5-1). These lie unconformably, in erosional depressions, on limestones and shales of the Pennsylvanian Wapanucka Formation. The Foster Sand, which has a thickness of up to 9 m, is composed predominantly of well-rounded, fine to medium quartz grains.

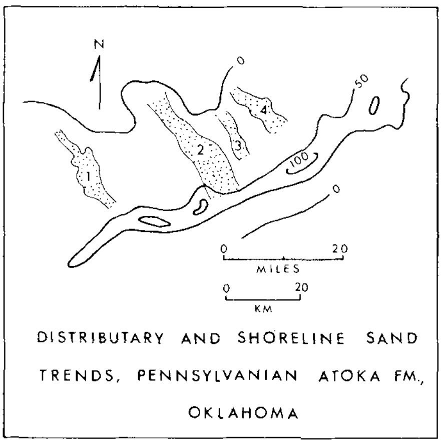


Fig. 5-1. Foster Sand trends 1, 2, 3 and 4, formed as distributaries filling erosional depressions, overlain by northeast-trending shoreline Spiro Sand ranging in thickness to 100 feet (30 m). The Foster is the lowest number of the Lower Pennsylvanian Atoka Formation, McAlister Basin, eastern Oklahoma. (Redrawn from Lumsden, Pittman and Buchanan, 1971).

It is commonly cross-bedded and contains shale clasts and fragments of fossil wood. The origin of this basal sandstone unit is evidently alluvial, the sands having been deposited in a system of parallel river distributaries that trended southeast across a coastal plain that was at least 60 km in width. Some gas production, including that of the Kinta Field, is obtained from the Foster Sand.

The Foster Sand is overlain by the Spiro Sand, a transgressive marine unit up to 30 m thick. The Spiro forms an elongate sandstone unit that trends southwest, normal to the Foster trend, for more than 100km. The Spiro Sand is also quartzose, probably having been in large part derived from the Foster Sand. It is moderately well sorted, and very fine to fine-grained. As a whole, the Spiro is referred to as a blanket sandstone but consists of massive, lenticular beds, deposited as shoreline sand bodies, interbedded with thin layers of silty sandstone and shale. Low-angle cross-bedding and bioturbation have been described, the former probably resulting from variations in depositional slopes of the seaward extensions of beaches.

The Spiro Sand, which transgressed to the northwest, is not uniformly developed, some localities along its trend being thicker and more permeable. Dry gas accumulations, which are largely related to stratigraphic control, include the Red Oak and Wilburton Fields.

Morrow Oil Fields, Oklahoma

Oil production from several fields in the Anadarko Basin of Oklahoma is obtained from the Cherokee Sandstone, the basal unit of the Lower Pennsylvanian Morrow Formation. The Cherokee, which lies unconformably on Mississippian beds of limestone and shale (Fig. 5-2), is a marine transgressive unit that forms a corrugated sheet of sandstone comprising parallel trends along which the sandstone is thicker.

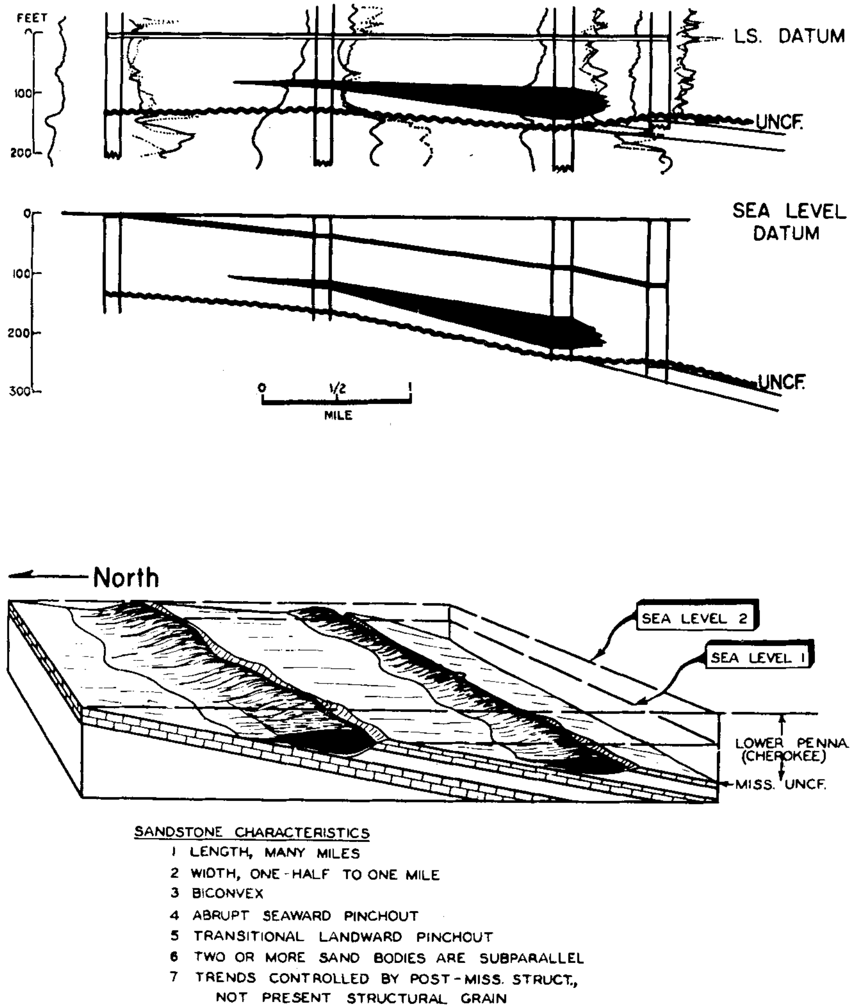


Fig. 5-2 a, b. E-log section (a) and generalized block diagram (b) showing relationship of oil-bearing Pennsylvanian Cherokee Sandstone, developed as strike-valley sands, to cuestas formed on eroded surface of the Mississippian in Anadarko Basin, Oklahoma. (After Busch, 1959).

Depending on whether the top or bottom of the sandstone unit is taken as a datum, these thick trends appear respectively as topographic depressions or as ridges. The interpretation placed on them by Busch (1959) is that they are bar-shaped sand bodies deposited in erosional depressions at the base of cuestas formed by unequal erosion of outcropping layers of limestone and shale. As such, they can be defined as strike valley sands. Busch (1959, p. 2832) says, "Strike valley sands derive their name from the fact that they are deposited in the low areas between cuestas at the

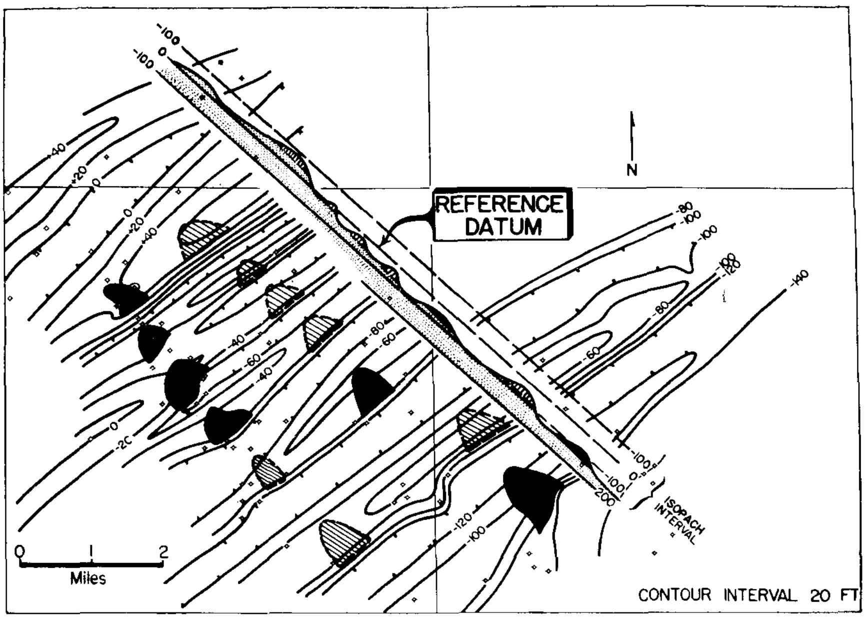


Fig. 5-3. Isopach map of interval [above (+) or below (-)] between a datum and the top of a sandstone unit in the Pennsylvanian Morrow Formation, northwestern Oklahoma. Figure shows known (black) and inferred (hatchured) oil fields developed where sand ridges are intersected by northwest-plunging folds. (After Busch, 1959).

time the land surface is inundated by a transgressive sea. Such cuestas may be either erosional escarpments or fault-scarps."

These thick, linear sandstone bodies are lenticular in section, ranging in width up to 3 km, in thickness to 15 m, and in length to 65 km. They terminate fairly abruptly along the thicker edge where they merge into a shale facies, the landward edge pinching out on the flank of each cuesta. These parallel sandstone lenses are intersected by northwest--plunging folds which form structural closures within the sandstone at some of the intersections. Within these closures oil has accumulated to form two parallel strings of separate pools (Fig. 5-3).

Milligan Oil Field, British Columbia

In the Milligan Oil Field of northeastern British Columbia, production is obtained from the Upper Triassic Halfway Sandstone. The Halfway unconformably overlies silty dolomite beds of the Doig Formation, and is overlain conformably by silty dolomite beds of the Charlie Lake Formation (Fig. 5-6). It has a linear northwest trend and is lenticular in section (Figs 5-4, 5-5). In the field area this trend, which bifurcates into two parallel but connected sub-trends, is known to have a length of more than 80 km. Each sub-trend has a width of approximately 3-5 km, the overall width of the main trend ranging up to 10 km.

In the Milligan Field the gross thickness of the Halfway ranges up to 15 m. The sandstone is quartzose and fine to very fine-grained, except at the base which is commonly gritty. The grains are sub-angular to sub-rounded. Porosity ranges up to 28%, but averages 22%, and permeability is in the range 400-600 millidarcys (Clark, 1961). The E-log (Fig. 5-6) of the Halfway is characterized by a blocky, slightly bell-shaped self-potential curve. Both top and bottom boundaries are

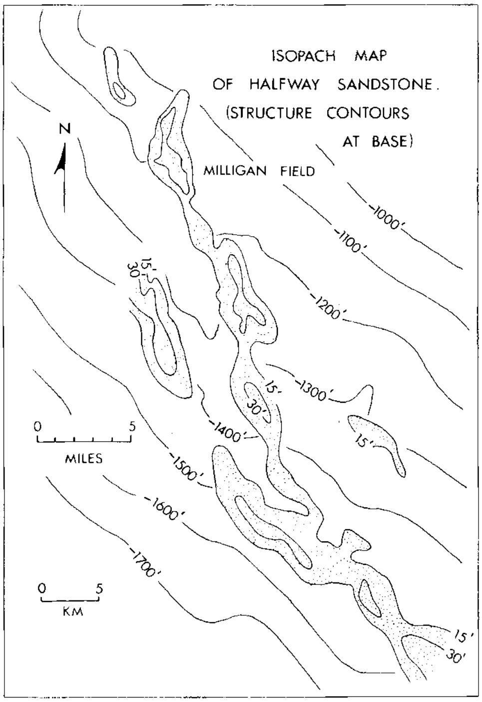


Fig. 5-4. Isopach map of the oil-bearing Upper Triassic Halfway Sandstone, British Columbia. Structure contours show the configuration of the base of the sandstone. (Redrawn from Mothersill, 1968).

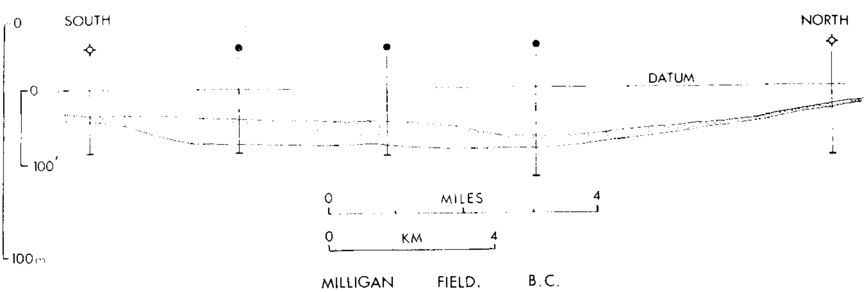


Fig. 5-5. Stratigraphic section through the Milligan Field, British Columbia, showing inferred configuration of the oil-bearing Upper Triassic Halfway Sandstone at the time of deposition. (Redrawn from Clark, 1961).

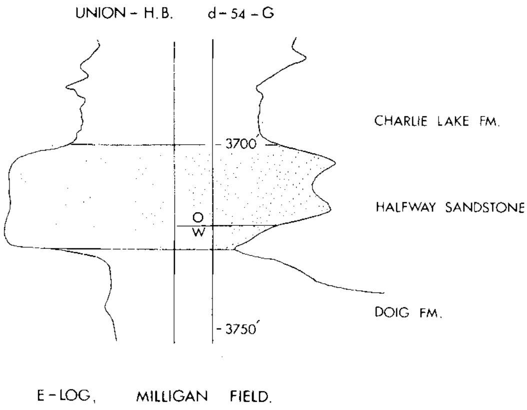


Fig. 5-6. Typical E-log of the Upper Triassic Halfway Sandstone interval in Union - H.B. d-54-G, Milligan Field, British Columbia, showing the blocky characteristic of the self-potential curve, and the oil-water contact. (Redrawn from Clark, 1961).

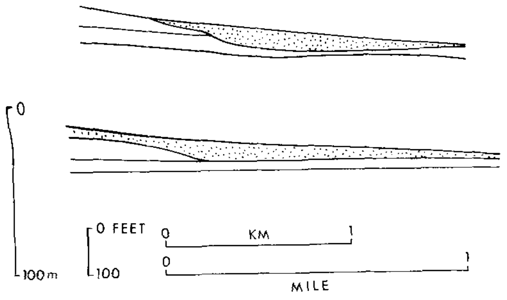
sharp. The blocky character reflects the excellent sorting of fine- to very-fine quartz grains, and the slight deflection at the base reflects a thick gritty layer. Cross-bedding is a notable feature, the foreset beds commonly dipping at angles of less than 20° (Mothersill, 1968). The amplitudes of the cross-beds range from less than an inch to several inches, placing them in the small to medium size category (Conybeare and Crook, 1968) of ripples formed by currents. In the southern part of the Halfway Sandstone trend, in the vicinity of the Peejay and Currant oil fields, the upper part of the Halfway, which is the oil-bearing section in these fields, contains thin beds of coquina consisting mainly of bivalve shells.

In the Milligan Field area the Doig Formation, which unconformably underlies the Halfway Sandstone, dips southwest at 7 m/km, whereas the

Halfway dips southwest at about 5 m/km. This relationship suggests that at the time of deposition of the Halfway, the Doig beds must have had a southwesterly dip of about 2 m/km. The lower part of the Halfway crops out along the foothills of northeastern British Columbia and thickens southwestward in the subsurface. Although the Halfway was deposited as an irregular sheet of sand, during a period of marine transgression to the northeast, its linear trends, current-bedding characteristics, and coarser basal layer raises problems concerning the relationships of the sand body geometry to its paleogeographic setting. In particular, it is pertinant to know whether, in the Milligan Field area, the sandstone trends represent deposition as shoreline sand bars or as distributaries. The use of several datums in the construction of stratigraphic sections depicting the depositional relationships of the Halfway suggest different possibilities. Probably the most reasonable interpretation (Clark, 1961), using a datum just above the Halfway, shows the sand bodies filling depressions, interpreted as strike-valleys, in the underlying Doig Formation. Parallel sub-trends of the Halfway in the Milligan Field area are thought to have resulted from concentration of sand in separate strike-valleys between cuestas along the coast. Subsequent structural deformation of these trends has formed several traps for oil, including the Milligan Field.

Horseshoe Oil Field, New Mexico

The Horseshoe Field of the San Juan Basin, New Mexico, yields oil from the basal sandstone unit of the Upper Cretaceous Niobrara Formation. This sandstone lies unconformably on gently folded beds of sandy shale, and limestone which constitute part of the Upper Cretaceous Gallup and Carlile Formations. Distribution of the sandstone shows a marked parallelism of lenticular trends, resulting from concentration of the original sand in strike valleys flanking cuestas formed by differential erosion of shaly and sandy beds beneath the unconformity (Figs. 5-7 and 5-8).



CROSS-SECTIONS OF BASAL NIOBRARA SANDSTONE
HORSESHOE FIELD, NEW MEXICO

Fig. 5-7. Stratigraphic cross-sections of the Upper Cretaceous basal Niobrara Sandstone in the Horseshoe oil field, San Juan Basin, New Mexico. The sand bodies were formed along cuestas on the eroded surface of the Gallup Formation and Carlile Formation during transgression of the Niobrara sea. (Redrawn from Penttila, 1964).

Work by Penttila (1964) and McCubbin (1969) established the depositional and stratigraphic relationships of the basal Niobrara Sandstone which they believe to have been deposited as a shoreline sand by a transgressive sea. The importance of this interpretation lies in the fact that the unconformity which underlies the Niobrara and bevels the Gallup, was previously not recognized. Consequently, the basal Niobrara Sandstone was thought to be equivalent to the basal Gallup Sandstone. McCubbin says that individual sandstone bodies are localized on the seaward side of cuestas, the steeper slopes of which faced seaward. As the sea advanced, these cuestas formed ridges which temporarily impeded transgression, resulting in a stationary shoreline, with the consequent deposition of a thicker body of sand.

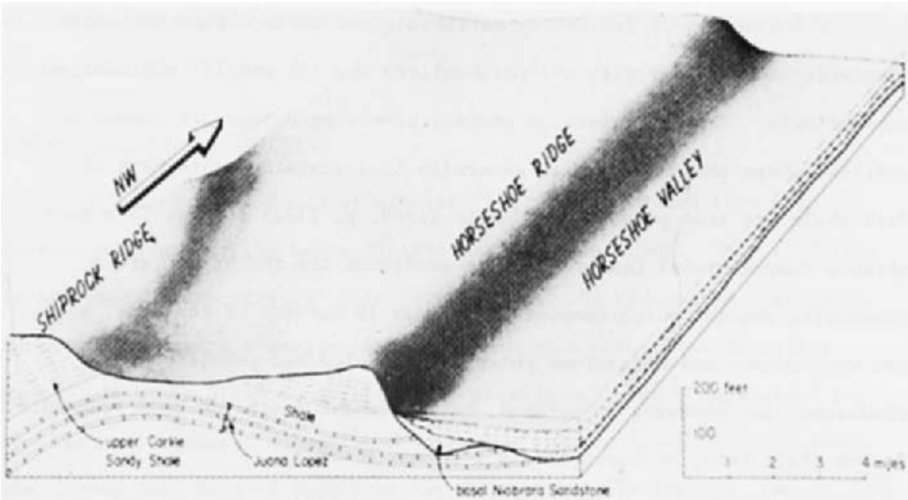


Fig. 5-8. Generalized diagram showing the stratigraphic relationship of the Upper Cretaceous basal Niobrara Sandstone to cuestas and strike-valleys formed on the eroded surface of the Upper Cretaceous Carlile Formation during transgression of the Niobrara sea. (Modified by MacKenzie, 1972, after McCubbin, 1969).

The basal Niobrara Sandstone in the Horseshoe Field area comprises three units which lie in different stratigraphic positions resulting from deposition against separate ridges at various times during the overall period of marine transgression. The oldest unit is the lower reservoir in the Horseshoe Field. This sandstone body strikes southeast for a distance of more than 40 km. The main sandstone body in the Horseshoe trend has a width of 6 km, and a thickness of up to 15 m. It divides to the northwest into two separate oil-bearing trends, the Many Rocks and Mesa, each of which has a width of about 2 km.

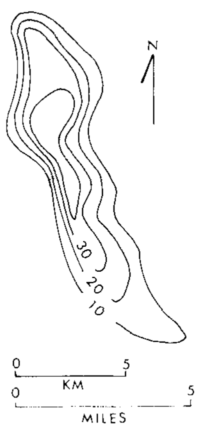
The Niobrara is texturally variable, grading from fine to coarse--grained. Average porosity and permeability are 15% and 175 millidarcys respectively. Thin stringers of coarse, pebbly sandstone are common in sections where the sandstone is generally fine-grained. Interbeds of dark shale are also present. McCubbin (1969, p. 2122) states, "The most notable compositional features of the sandstone are the bright green glauconite grains, which compose as much as 10 percent of the rock, and the very common and widespread phosphatic nodules and pebbles". The sandstone also contains Inoceramus, Ostrea, shark teeth and bone fragments. In the shaly beds, bioturbation is a common feature.

The sandstone is commonly cross-bedded, individual sets ranging in thickness from a few centimetres in the subsurface to more than a metre in outcrops. The dips of these cross-beds exceed 20°, indicating their derivation as current-bedded sands. The depositional environment is indicated to have been one of fairly high energy on beaches, probably associated with tidal channels cutting through sand bars and re-working sands in local inlets.

In the Horseshoe Field the oldest sandstone member of the Niobrara forms a long, narrow body that trends southeast for up to 60 km toward the Cha Cha Field which also produces oil from the Niobrara. Entrapment of oil and gas has resulted from stratigraphic factors modified locally by structure. At most locations, pinch-out of the sandstone body is solely responsible; in others the accumulation of gas, in particular, has resulted from the intersection of the sandstone body trend with northeast--plunging folds. In the Horseshoe-Mesa Fields the gas-oil column exceeds 990 m (McCubbin, 1969). The estimated ultimate recovery of oil from the Horseshoe-Mesa and Many Rocks fields is in excess of 46 million barrels (7.3 million cubic metres). An additional estimate of 13 million from the Cha Cha Field suggests that the lower unit alone of the Niobrara Sandstone will ultimately yield more than 60 million barrels (9.5 million cubic metres) of oil.

<u>Carbon Gas Field, Alberta</u>

The Carbon Gas Field of Alberta (Fig. 5-9) produces from the Carbon Sandstone of the Lower Cretaceous Mannville Group. This sandstone is the approximate stratigraphic equivalent of the widespread Glauconite Sandstone, a marine transgressive sandstone unit within the Mannville Group. In other areas of Alberta, the stratigraphic zone equivalent to the Glauconite sandstone includes sandstone members known by other names. The marine Home Sand of Turner Valley in southwestern Alberta, the Wabiskaw member of north-central Alberta, the glauconite sandstone at the base of the Clearwater Formation in northeastern Alberta, and the Bluesky Sandstone of the Peace River area in west-central Alberta are all considered by Workman (1958) to be stratigraphic equivalents of the Glauconite Sandstone.



GEOMETRY OF CARBON GAS SAND, ALBERTA

Fig. 5-9. Isopach map of net porous sandstone in the producing sandstone of the Early Cretaceous Mannville Group, Carbon Gas Field, Alberta. Contour interval in feet (1' = 0.305 m). (Redrawn from Workman, 1968).

The Glauconite Sandstone is a persistent stratigraphic unit over much of central Alberta. It overlies the Ostracod Member (a thin argillaceous limestone containing a brackish water fauna) and consists of one or more glauconitic sandstone bodies. Over a wide area the composition and texture of the Glauconite Sandstone shows considerable variation. It is essentially a fine-grained quartzose sandstone containing variable amounts of lithic constituents. East of the Fifth Meridian and south of Edmonton the Glauconite Sandstone is commonly not glauconitic. Glaister (1959, p. 623) states, "The member is predominantly marine in the Edmonton area but becomes more non-marine toward the south and gradually loses its lithologic identity". The thickness of the Glauconite member, which is commonly in the order 6-9 m but ranges up to more than 30 m, changes markedly over a distance of a few kilometres. This is particularly noticeable in the area lying east of the Fifth Meridian where the sands are commonly alluvial. In the Carbon and Ghost Pine gas fields for example, the producing sandstones are non-glauconitic and vary in thickness within the range 6-25 m. East of the Fifth Meridian, the alluvial sandstones that are the approximate stratigraphic equivalent of the Glauconite Sandstone trend northwest, west, and southwest. The trends were formed by a river system draining lowlands lying to the east. West of the Fifth Meridian the Glauconite Sandstone is generally glauconitic and contains a higher percentage of lithic fragments. In this region, the sandstone bodies fringe a marine shoreline trending approximately north-northwest.

In the area of the Carbon Gas Field, the Carbon Sandstone, encountered at a depth of 1,460 m, consists of several lenticular sandstone bodies separated by shaly layers. These sandstone bodies, which thin and become less porous, to the east, form a northwesterly--trending belt up to 5 km in width and 25 km in length. The Carbon Sandstone lies approximately 15 m above the Ostracod member, and 15-23 m feet below a coal seam. It ranges in thickness from 6 to 25 m, the maximum net-porous sandstone being in the range 12-15 m. The basal sandstone body is thicker and coarser than the upper bodies, a relationship indicated by the bell-shaped self-potential curve of E-logs of the producing zone in the Carbon field. The sandstone is generally quartzose, fine to medium--grained, fairly well sorted, and predominantly of sub-angular grains. Porosity is in the range 15-25%, averaging 21%. Permeability ranges up to 3,000 millidarcys but averages only 80 millicarcys.

The Carbon Sandstone has been placed in the category of transgressive sands because it was deposited during a period of widespread inundation of alluvial-deltaic sediments by the Early Clearwater sea transgressing to the south. The beds adjacent to the Carbon Sandstone, both above and below, contain arenaceous forams, suggesting an inner neritic environment such as a salt-water bay of tidal estuary. Smooth--shelled ostracods within an underlying stratigraphic unit comprising two or more thin, discontinuous layers of argillaceous limestone, indicate local brackish-water conditions. Overlying coal seams must have been formed by the accumulation of vegetation in coastal marshes. The paleogeomorphic origin of the Carbon Sandstone is not known, but it may have been formed from bodies of sand, filling a tidal channel on a coastal plain.

Regional dip of the strata in the Carbon Gas Field area is westerly; and within the field, a stratigraphic marker at the top of the Carbon Sandstone interval indicates a local monoclinal structure. Entrapment of gas may in part be controlled by this structure, although the field is considered to be essentially a stratigraphic trap. Initial gas in place is estimated to be 155 billion (thousand million) cubic feet, of which 130 billion (3,640 million cubic metres) will ultimately be recovered.

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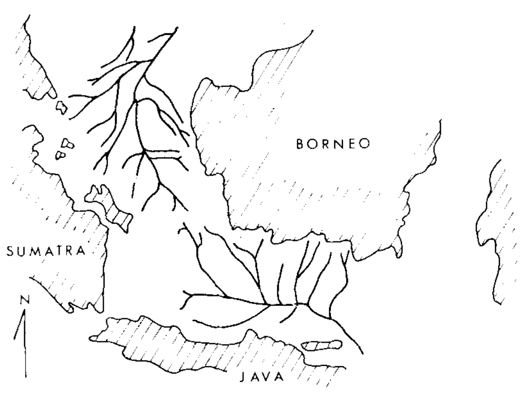
Chapter 6

SUBMARINE VALLEYS

Introduction

Geomorphology

The existence of present-day submarine valleys on continental shelves and slopes has been known for many years. But it was not until the advent of marine seismic surveys that ancient valleys, commonly buried by Tertiary to Quaternary sediments, could be demonstrated. Present-day valleys trend seaward from the landmass, some apparently forming dendritic patterns, but others following broadly sinuous or arcuate courses. Although some submarine valleys are known to bifurcate



SUNDA SHELF VALLEYS

Fig. 6-1. Inferred dendritic pattern of submarine valleys on the Sunda Shelf off the coast of Indonesia. (Redrawn from Kuenen, 1950).

at their landward extremities, the development of dendritic patterns is open to question. An example is the Sunda Shelf of Indonesia (Fig. 6-1). During the Pleistocene much of the Sunda Shelf was a landmass, and the inferred dendritic system of submarine valleys, as interpreted by Molengraaff (1922), is thought to have originated as a fluvial stream system. Molengraaff gave the name Sunda River to the main valley in the northern dendritic system. His interpretation was endorsed by Kuenen (1950) who referred to these submarine valleys as drowned river channels deepened by tidal scour. Shepard and Dill (1966), however, did not accept this explanation without reservation and pointed out that interpretations based on the possible existence of a dendritic pattern are somewhat speculative.

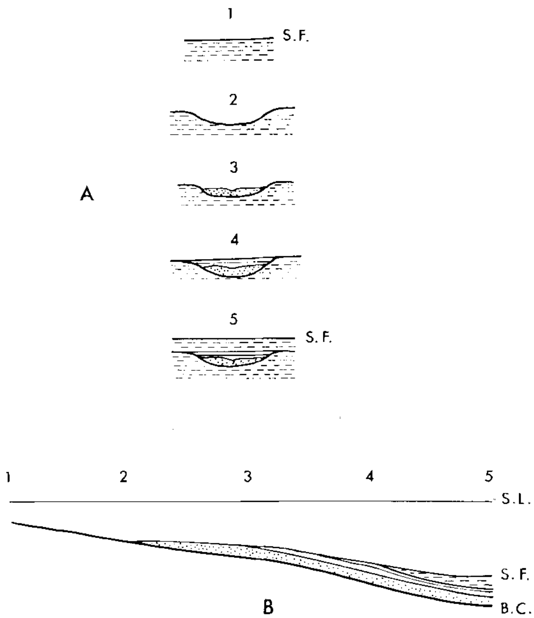
Some submarine valleys and canyons extend to the upper parts of a continental shelf, others are confined to the region of the continental slope. Many large rivers terminate at the upper reaches of submarine valleys which may, in part, owe their genesis to the river's development during some earlier period when sea level was lower and much of the continental shelf was exposed as a coastal plain. Other submarine valleys have no apparent relationship to any present or previous river system, and their genesis is not understood. They may have been formed by submarine currents sweeping down the continental slope. Such currents could have resulted from tidal action influenced by Coriolis force. Submarine canyons, having formed by whatever mechanisms, are the present--day courses for strong currents which are periodically augmented by turbidity currents flowing down the lower reaches. Hypotheses concerning the origins of submarine valleys and canyons are discussed by Kuenen (1950, 1953), and are extensively dealt with by Shepard and Dill (1966).

Scholl and Hopkins (1968, p. 266), in describing the gigantic submarine canyons of the Bering Sea, say that although their location, trend, and general shape are structurally determined, erosion of the canyons was effected by sliding masses of sediment which began their movements in the Late Tertiary, aided by the sluicing of fluvial sediment from a large river. They describe these canyons as follows, "Bering Canyon, the world's longest known submarine slope valley, and Zhemchug Canyon, possibly the world's largest, incise the northeastern continental margin of the Bering Sea. A third valley, Pribilof Canyon, also cuts this margin and also is very large in comparison to most submarine canyons. Bering Canyon is nearly 400 km in length and has a volume of about 4300 km^3. Zhemchug Canyon has a volume of nearly 8500 km^3, and is 15 to 20 times larger than the most "large" submarine canyons (for example, Monterey Canyon). Zhemchug and Pribilof Canyons are further distinguished by an unusual headward bifurcation that has contributed to the formation of deep, elongated, outer-shelf basins".

Of particular interest to petroleum geologists is the presence of coarse, well-washed, ripple-marked sand within submarine valleys (Heezen and Hollister, 1971; Shepard and Marshall, 1973). These sands are worked by currents that flow within the valleys. In the case of canyons off the coast of California, Shepard and Marshall (1973) record currents of less than 50 cm/sec that alternately flow up and down the canyons during periods ranging from 20 minutes to 12 hours. The net movement of the sand is down the canyons. Shepard and Marshall state, p. 257, "We are not yet in a position to assign definite causes to the canyon-floor currents. It is obvious that at most deeper water stations the tides have an important influence. However, the much shorter cycles, with a peak around 4 hours (Marshall, in prep.) are not related to the tides. These shorter cycles can best be explained by internal waves".

The nature and stratigraphic sequence of sediments filling a submarine valley or canyon will depend on several factors related to the composition of source material and the dynamics of the environment. Included in these factors, which obtain in varying degrees at different points along the course of a submarine valley, are the relative volumes of sediment of various size grades being transported, the rates of sedimentation, the current velocities, and the rates at which sea level may rise or fall. These factors are inter-related during periods of normal sedimentation. Interuptions by turbidity currents introduce other factors characteristic of that particular hydrodynamic state. The normal sedimentary and stratigraphic sequence deposited in a submarine valley during a period of rising sea level is described by Normark and Piper (1969) and illustrated by Fig. 6-2. This sequence of sediments is based on the assumption that, in general, currents flowing along the bottom of a submarine valley tend to wane with increasing depth, and ultimately disperse on the submarine fan at the base of a valley. The result of such a flow pattern is to deposit coarser sediment up-current and finer sediment down-current, a lateral gradation of sediment that forms a wedge of sand pinching out at some point down the valley. The overall vertical sequence is also graded and is, in effect, a transgressing sequence of sediment in which the coarser grades, such as sand, are deposited in the upper reaches of a valley and are subsequently buried by finer sediments as the sea level rises. The resulting wedge of basal sand may ultimately by completely buried by muds.

The possible application of this concept to petroleum exploration is evident. Where such wedges of sand are deposited, their initial dip is commonly increased by regional tilting along the flank of the sedimentary basin. In such a situation, the overlying marine muds could be source beds for hydrocarbons, or their precursors, which would then migrate into the wedge of sand during subsequent compaction of the section. Tertiary submarine valleys off the Gippsland coast of Australia, for



SECTIONAL VIEWS OF SUBMARINE
CUT-AND-FILL CHANNELS

Fig. 6-2. A - Cross-sectional views showing development of a submarine cut-and-fill channel during a period of rising sea level. (Redrawn from Normark and Piper, 1969).

B - Longitudinal section interpreted from cross-sections above.

example, should be considered as possible targets for oil and gas accumulations. Certain of these valleys appear to be largely filled with Oligocene mudstone, but the bottoms of these valleys have not been tested at various locations by drilling. It is possible, and particularly so as the area is a prolific petroleum province, that if wedges of sandstone are locally present at the base of these Tertiary submarine valleys, they may prove to be traps for oil and gas at their up-dip, wedge-out extremities.

E-log Characteristics

Sand bodies in submarine valleys and canyons are linear, but commonly bifurcate on a submarine fan at the mouth of the canyon. Some bodies are formed during long periods of normal sedimentation, others are deposited during short periods by turbidity currents. In the former, the sand may be well sorted and clean, in the latter it is poorly sorted and exhibits graded bedding from coarser below to finer above. The sand bodies deposited during periods of normal seidmentation may also be graded. Locally, and probably rarely, they may have grading from finer below to coarser above. This type of grading is normally characteristic of barrier bars and other regressive shoreline sand bodies. In submarine valley sands the possible existence of this inverse gradation may be explained by a situation in which the sand is being deposited by a current that locally flows down the valley with decreasing velocity. This decrease may result from variations in the topography of the valley, such as a downstream increase in width. The coarser sand is deposited first, followed by finer sands farther down the valley. Addition of more sand, carried from the upper reaches of the submarine valley, results in further accretion to the sand body which progrades down the valley. This growth is reflected in the development of grain gradation from coarser up-current to finer down-current on the depositional surface of the sand body. As accretion continues, gradation is also developed within the vertical sequence of the sand body, in the same way as in shoreline regressive sands, from finer below to coarser above.

The overall section of sediment in a submarine valley or fan at the base of a canyon, is a composite sequence of sand-bodies formed under differing hydrodynamic conditions, interbedded with muds and silts. There is no orderly or predictable sequence. In general, the graded bed, which is the genetic unit in turbidity current deposits, is too thin and poorly

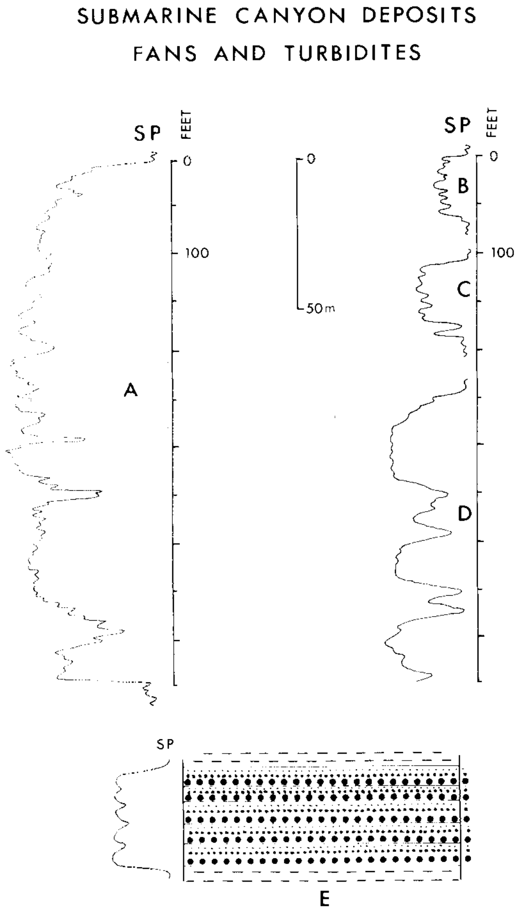


Fig. 6-3. Self-potential curves of electric logs of a submarine canyon fan (A) and turbidity current deposits (B,C, and D). Generalized section (E) shows self-potential curves of graded sandstone beds deposited by turbidity currents in a submarine canyon.

A - Upper Miocene Stevens Sandstone, Rosedale Field, California. This unit is oil-bearing and overlies the Rosedale Sandstone which fills a channel (Fig. 6-7). B and C - Upper Pliocene Pico Sandstone, Saticoy Field, California. D - Lower Pliocene Repetto Sandstone, Ventura Field, California.

separated from other graded beds to be detected as such on the E-log. A sequence of graded beds, on the other hand, shows on the self-potential curve as a serrated or fairly smooth cylinder (Fig. 6-3, B, C, and D) with abrupt upper and lower contacts representing boundaries between the sequence and muds deposited during periods of normal sedimentation. The serrations represent individual graded beds, but do not reflect the grain gradation. Such a sequence may be up to 100 feet or more thick.

In Fig. 6-3, sequences B and C are sections of the Upper Pliocene Pico Sandstone in the Saticoy oil field, California, and sequence D is a section of the Lower Pliocene Repetto Sandstone in the Ventura oil field, California. Sequence A is a section of the Upper Miocene Stevens Sandstone in the Rosedale Field (Fig. 6-7), California. All of these sequences are oil-bearing. Sequence A shows a section composed of several sub-sequences. Some are interpreted as turbidity current deposits, some are shale beds deposited as muds during periods of normal sedimentation, and others may be sandstone bodies formed by strong currents, but not necessarily by turbidity currents.

Compaction

The effects of compaction on a sedimentary sequence deposited in a submarine valley depends on the volumetric and spatial relationships of beds of mud and sand, and also on the geometry and petrophysical characteristics of individual sand bodies. These sand bodies are linear, and commonly forked where they spill over the surface of a submarine fan. Some are composed of clean sand; others, deposited by turbidity currents, are composed of poorly sorted, dirty sand. The latter commonly consists of superimposed graded beds. Both types of sand bodies may be overlain or underlain by beds of fine-grained sediments or by each other; and the whole sequence may attain a thickness of several thousand feet.

Within a submarine valley the effects of compaction on the geometry of a sandstone body at the base of the valley is minimal, because the valley cuts into consolidated sediments and rock. Within the upper part of a valley-fill section sand bodies overlying the flanks of the valley will be tilted. Within a submarine fan, where the sands are deposited near the mouth of a submarine canyon and the muds are deposited near the fringes of the flank, the effect of compaction is to accentuate the wedge shape of the sandy section. Individual sand bodies within this section are broadly lenticular.

Of primary concern to petroleum geologists is the effect of compaction on the petrophysical characteristics of sand bodies deposited by turbidity currents. Poorly sorted, lithic, and silty, these sands do not resist compaction as well as quartzose sands. With increasing depth of burial, and by tectonic deformation, both static and dynamic pressures cause shattering of sand grains, accompanied by diagenetic alterations which progressively decrease the porosity and permeability. This feature will be dealt with specifically in later pages describing the Ventura Oil Field where compaction has been effected not only by depth of burial but additionally by folding and thrust-faulting.

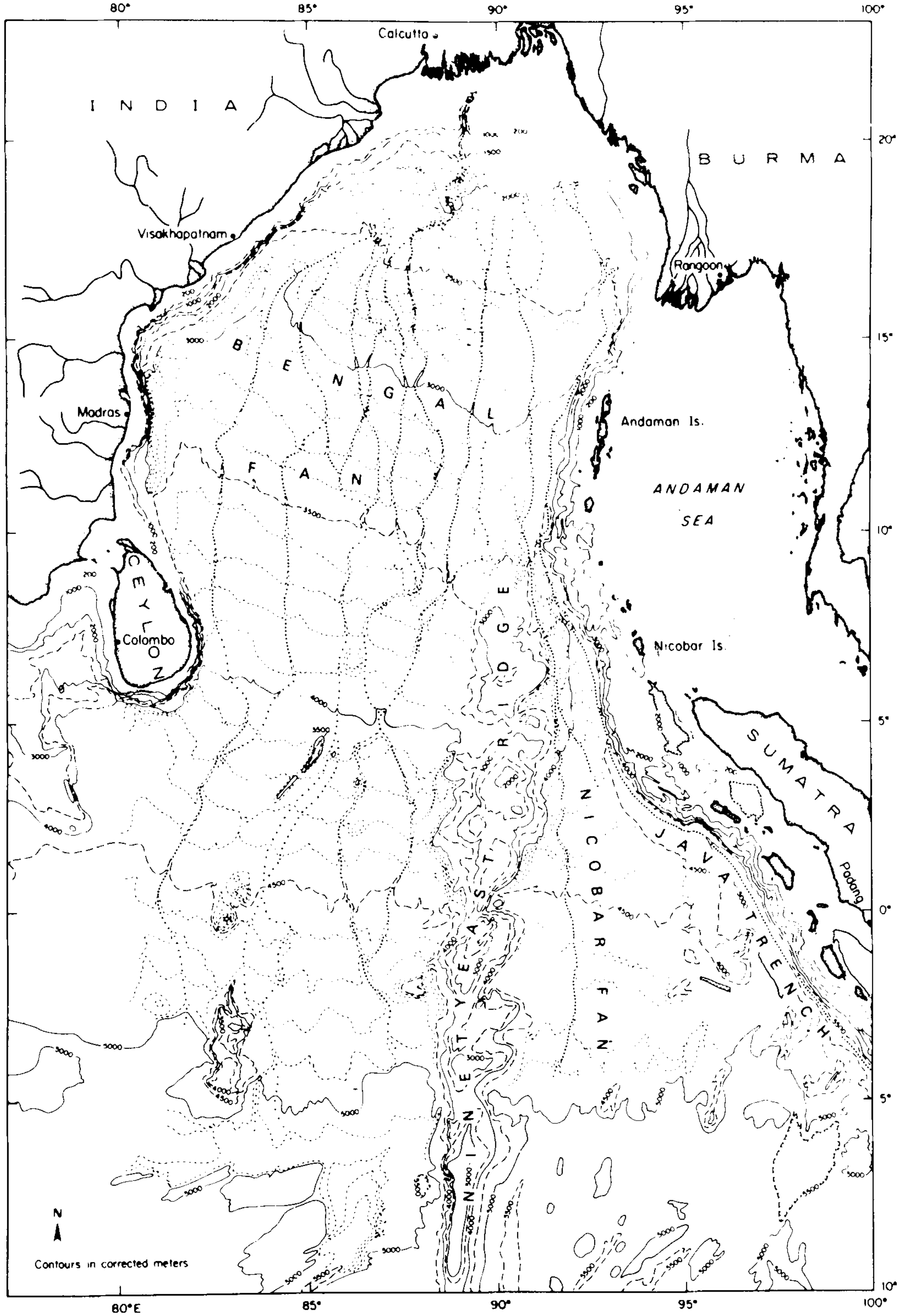
In the absence of large structures, turbidity current sand bodies are not attractive targets for exploration. Exploration for such sand bodies is difficult because of lack of well-defined lithologic sequences suitable to the containment of stratigraphic traps. Furthermore, where the oil-bearing zone is deep, exploitation of the reservoir may be hindered by recovery problems involving exceptionally low permeability. Apart from depth and permeability, the volume and geometry of the hydrocarbon-bearing sandstone body may preclude economically viable production.

Ancient Sand Bodies

Submarine valley sediments and their associated submarine fan sediments are deposited in valleys situated on the outer fringes of continental shelves, in canyons cutting into continental slopes, and as fans spreading down the lower continental slopes to the abyssal plains. They are commonly included in the flysch facies characterized by thick sequences of sediment deposited in a deep-sea environment in a tectonically active, rapidly subsiding sedimentary basin. The flysch facies probably contains the majority of sandy sequences deposited by turbidity currents, including the oil-bearing sandstone beds of the Ventura anticline, a giant oil field in California. Most submarine valley sediments are deposited in relatively deep water but some, including bodies of well sorted, clean sand are deposited in the upper reaches of submarine valleys in relatively shallow water. The latter can be referred to an outer neritic facies characterized by well-stratified sediments deposited in a relatively stable to gently warping sedimentary basin. This category of outer neritic depositional environments probably includes the sedimentological conditions that obtained during the period of formation and infilling of the Oligocene submarine valleys that influence the entrapment of gas in the Marlin field of the Gippsland Basin, Victoria.

Large submarine fans at the mouths of major submarine valleys comprise a complex of erosional and depositional features, including minor canyons and valleys, valley-fill deposits, levees, and sheets of sediments. The whole complex forms a prograding wedge that thins away from the mouth of the major submarine valley. The Bengal Fan complex (Figs. 6-4 and 6-5)

Fig. 6-4. Bathymetric chart of Bengal Fan based on soundings. Contours, ranging from 200 meters to 5,000 meters, have variable intervals. (After Curray and Moore, 1971).


Calcutta
INDIA
BURMA
Visakhapatnam
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FAN
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CEYLON
Colombo
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SUMATRA
Padang
NINETYEAST RIDGE
NICOBAR FAN
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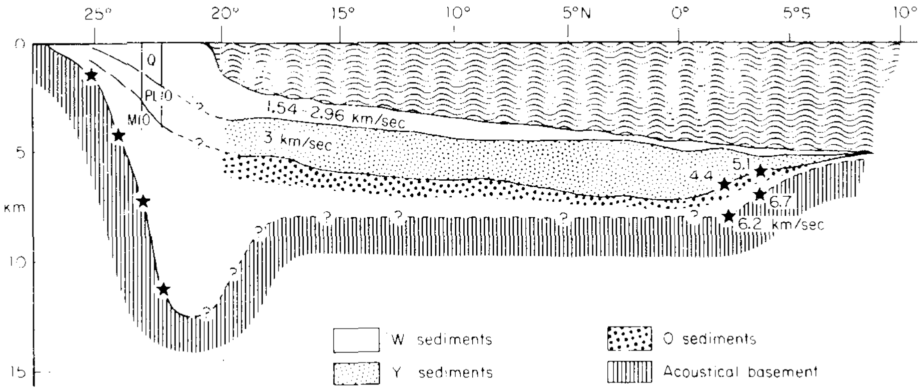


Fig. 6-5. Hypothetical longitudinal section, from north to south, of the Bengal Fan complex. (After Curray and Moore, 1971).

lying between the Andaman Islands and the east coast of India is an outstanding example. This complex has a length of 3,000 km, a width of 1,000 km, and a thickness ranging up to 12 km. The sediments in this gigantic accumulation have been derived from the delta of the Ganges-Brahmaputra River system in Bangladesh. Curray and Moore (1971) state that the fan has been formed by turbidity currents sweeping sediments from the delta along a main submarine canyon, and dispersing them into a braided network of fan valleys. On the basis of seismic reflection profiles the Bengal Fan is divided into three stratigraphic units deposited during the Miocene, Pliocene, and Quaternary respectively. These units, which are separated by prominent disconformities, are believed to have formed during periods of increased uplift of the Himalayan orogenic belt. The Quaternary sediments are largely undeformed, whereas the older sediments are folded and faulted, probably by gravity sliding of unconsolidated sediments beneath the continental slope.

The surface of the Bengal Fan shows features similar to those of some river systems. Curray and Moore (1971, p. 566) say, "Details of shallow sub-bottom structure show a great variety of channel types. In some parts of the fan surface, channels are partly or completely filled. Elsewhere the channels appear to be braided or are incised for over 100 m into sedimentary fill within formerly much deeper valleys. The most significant feature brought out by these records is the unmistakable evidence for pronounced migration of the channels by cut-and-fill processes analagous to those of subaerial streams. The turbidity current channels, in fact, show all of the depositional and erosional capabilities of subaerial streams for adjusting to variable base levels, stream loads, and discharge volumes". These similarities of depositional and erosional features suggest that submarine fans probably contain numerous potential stratigraphic traps of the types found in alluvial sequences formed by river systems. Abandoned submarine channels, cutting flat-lying to gently-dipping beds, are filled with sediment which may subsequently form a barrier to the movement of oil or gas within the adjacent incised beds. Curray and Moore (1971, Fig. 3c) include one seismic profile that shows abandoned, sediment-filled channels 60 m deep, and 2 km wide. These are reminiscent of the Marlin Channel, believed to be of submarine origin, flanking the up-dip side of the Marlin Field (Fig. 6-11) in Victoria. The Marlin Channel, however, is more than 300 m deep.

Viewed in three dimensions, the Bengal Fan complex comprises a sedimentary basin in which the lower and possible thickest unit rests on basement rocks and is of unknown origin, whereas the upper units are primarily turbidites.

Yoakum Channel, Texas

The Yoakum Channel (Fig. 6-6) in Lavaca County, Texas, was formed as a submarine valley during the Early Eocene and later filled mainly with fine-grained muddy sediment, now shale, of the Eocene Wilcox Group. This

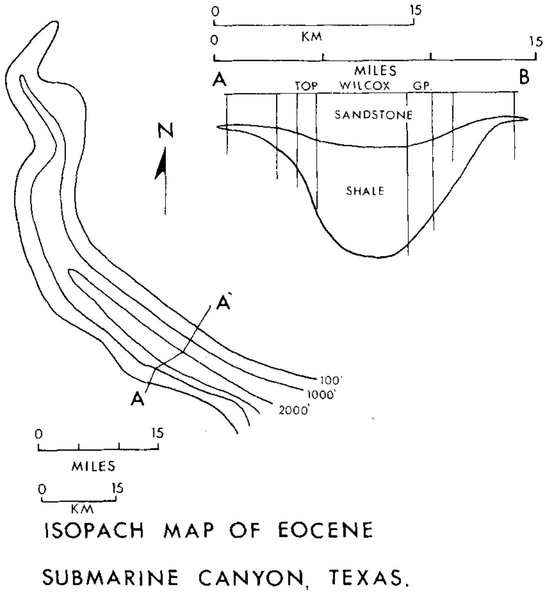


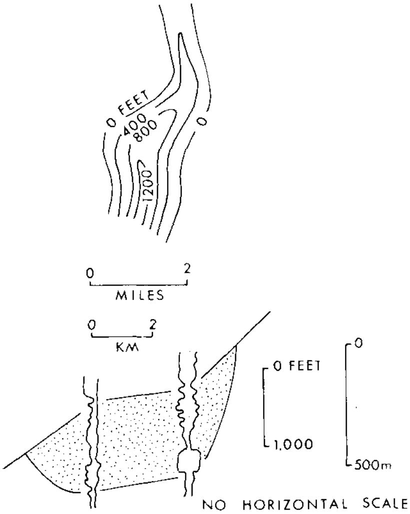
Fig. 6-6. Isopach map and section of the Yoakum Channel, Lavaca County, Texas. This channel was a submarine canyon and is filled with shale of the Eocene Wilcox Group. (Redrawn from Halbouty, 1969 after Hoyt, 1959).

shale section, which is locally up to 750 m thick, is overlain by massive sandstone beds of the same group. The channel, which has a fairly uniform width of 10-15 km and a length of more than 100 km, was the site for a hole drilled to a depth of 5,490 m to test the hydrocarbon-bearing potential of a possible sandstone section at the base. Halbouty (1969, p. 27) comments on this exploration venture as follows. "The play was based on the idea that the Yoakum shale channel (Hoyt, 1959) in western Lavaca County, Texas, originally had been filled with lower and middle Wilcox sandstone and shale similar to the sediments on the channel flanks. It was thought that the original fill, with an estimated volume of 75 cu mi or 250,000 acre-ft, was eroded from the channel and redeposited downdip from the Lavaca County area. The channel then was filled with shale and covered with typical upper Wilcox sandstone deposits". Halbouty also says, "The drilling venture, which was an attempt to learn more about the sandstone-distribution pattern of the downdip Wilcox at the mouth of the Yoakum channel, was not successful because expected sandstone beds were not present beneath that particular drill site". Halbouty mentions the possibility that the sediments eroded from the Yoakum Channel may have been re-deposited farther downdip from the mouth of the channel than the site of the unsuccessful wildcat test.

The concept of hydrocarbon entrapment within the up-dip part of a sandstone wedge within a submarine channel is attractive, particularly where the channel is situated within an oil or gas-bearing province. But finding the location of such a sandstone wedge may ultimately depend on technological developments in geophysical methods.

Rosedale Channel, California

The Rosedale Channel in California (Fig. 6-7) is filled with the Late Miocene Rosedale Sandstone, a coarse to fine-grained, feldspathic to lithic sandstone which locally shows graded bedding. The Rosedale Channel ranges from less than 2 km to nearly 3 km in width, has been traced for more than 10 km, and is at least 360 m deep. Microfossils in the Rosedale Sandstone suggest that deposition occurred at water depths of more than 300 m. Martin (1963, p. 454) says, "From the investigations of the characteristics of the Rosedale Channel and the Rosedale Sandstone such as the sediments, microfaunal ages, depth of water, and displaced faunas, the evidence strongly suggests that erosion and filling occurred entirely within the marine environment". He says further, p. 455, "Turbidity currents or gravity flows of sediment are considered to have affected the downcutting;



ISOPACH AND SECTION OF ROSEDALE CHANNEL SANDSTONE

Fig. 6-7. Isopach and section of Late Miocene Rosedale Sandstone filling a submarine channel, Great Valley, near Bakersfield, California. (Redrawn from Martin, 1963).

however, it seems likely that the lower Fruitvale Shale into which the canyon cut probably was not indurated to any great degree during this time and because of the lack of much induration, erosion probably was facilitated".

Oil or gas have not been discovered within the Rosedale Sandstone, although the overlying Lower Massive Unit of the Stevens Sandstone (Fig. 6-3), which is the producing zone in the Rosedale Oil Field, may be a facies of beds that can be traced down-channel to the Rosedale Sandstone. Martin holds out some hope for the Rosedale and says, p. 455, "Little or no petroleum has been discovered in the sediments of the Rosedale Channel, but this does not preclude the possibility that future discoveries may be made. Filled and buried submarine canyons should have an excellent potential for any exploratory efforts although from the nature of the sandstone bodies, location and recognition may be difficult".

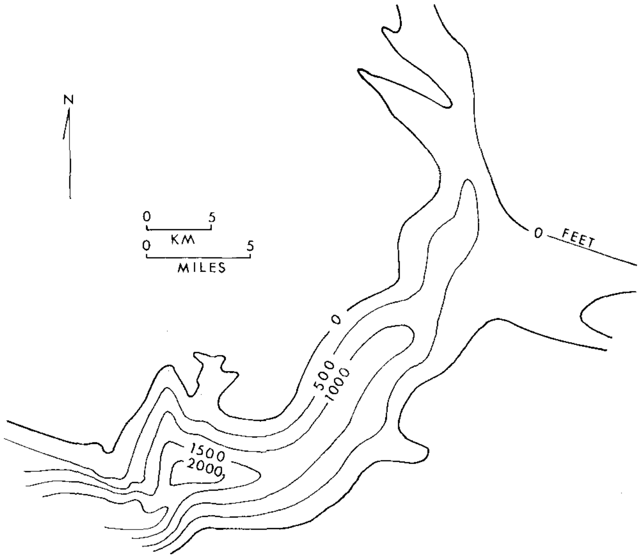
Oil and Gas Fields

Sediments in ancient submarine valleys have not often been stratigraphic targets for oil and gas exploration, although such features are present on all continental margins and appear to have been so in the past. The difficulties that arise in searching for a stratigraphic trap in a buried submarine valley have hitherto precluded much enthusiasm for such an exploration programme. With few exceptions, such as the previously mentioned exploratory hole drilled into the Yoakum Channel in Texas, exploration in submarine valley and fan deposits has been restricted to areas such as the Ventura Oil Field of California, where folding of the beds affords structural closure. And yet, as pointed out by Hedberg (1970, p. 3), "For the petroleum geologist, it is significant that through the ages the continental margin has been the great mixing bowl in which has been brewed most of the world's petroleum and from which most of its petroleum production to date has been derived". Commenting on the depositional environment and petroleum potential of submarine fans on a continental rise, Emery *et al.* (1970, p. 103) say, "The large mass movements that remove thick sequences of sediments from the continental slope bring them to the upper part of the continental rise. Because these displaced sediments are fine grained, when deposited *en masse* they can retain most of their organic matter out of reach of the overlying oxygen-rich water. Continuous seismic reflection profiles and cores suggest that sandy turbidites also are present throughout most of the continental rise, and some of them are interbedded with the displaced silts and clays from the continental slope. Under such conditions, we might expect the displaced silts and clays to serve as oil source beds and the sandy turbidites to be reservoir beds. The sesimic data also reveal the presence of many stratigraphic and structural traps". The Ventura Oil Field, one of the world's large fields, is an important example. Other oil and gas accumulations in submarine valley and fan deposits may in the future be found far out to sea underlying the upper slopes of a continental rise. As pointed out by Beck and Lehner (1974), technological advances in deep-sea drilling are bringing these geologically attractive regions within the realm of exploration feasibility. Whether exploration in these off-shore regions will ultimately prove to be economically feasible is a question for the future.

Brentwood, Dutch Slough and West Thornton Oil and Gas Fields, California

The Brentwood, Dutch Slough, and West Thornton fields in the Scaramento Valley, California, yield oil and gas from massive sandstone beds of the Paleocene Martinez Formation. These beds are truncated by the Meganos Channel (Fig. 6-8) which is filled mainly with Paleocene silty shale which forms a cap rock for oil and gas accumulations within the sandstone beds. Entrapment of both oil and gas results from a structural--stratigraphic situation (Fig. 6-9), the hydrocarbon-bearing beds having been folded and tilted, then truncated by the Meganos Channel which was filled with impermeable sediments.

Dickas and Payne (1967) say that 95% of the sediments filling the Meganos Channel are shales, locally glauconitic, that grade into silty beds in the lower part of the section. Some thin basal sandstone beds are present in the northern and upper part of the channel, but these have proved to be unproductive. These valley-fill sediments are believed to have been deposited in a submarine valley in water depths ranging from neritic to upper bathyal. The Meganos Channel, which has a length of more than 80 km and a width of 3-10 km, is filled with up to 600 m of sediment. These dimensions are comparable to those of the Congo River

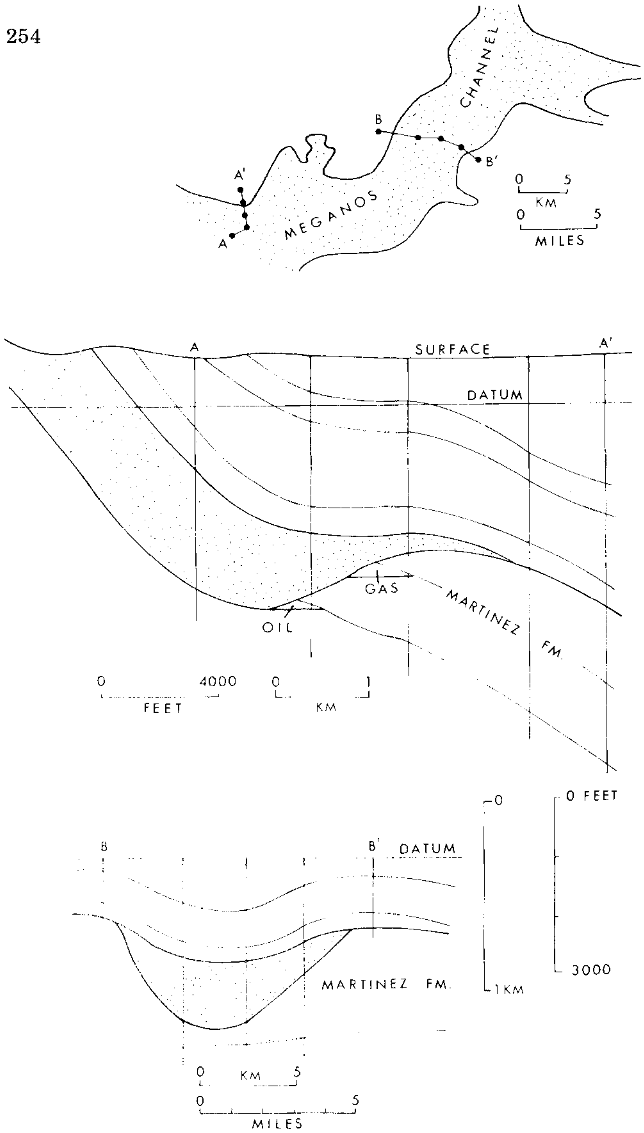


ISOPACH OF MEGANOS CHANNEL, CALIFORNIA

Fig. 6-8. Isopach of the Paleocene Meganos Channel, Sacramento Valley, California. This channel erodes Paleocene sandstone beds and is filled mainly with shale and siltstone deposited as mud in water depths ranging from neritic to upper bathyal. (Redrawn from Dickas and Payne, 1967).

submarine canyon which according to Heezen *et al.* (1964) has a length of 320 km, a width of up to 8 km, and a depth of up to 900 m below the canyon rim. Shepard and Emery (1973 a) further describe the Congo River canyon as V-shaped and ranging in depth up to 1,400 m from the rim to the base.

Although the Brentwood, Dutch Slough, and West Thornton fields are not producing from sediments within the submarine valley, their locations depend on the juxtaposition of folded and upturned hydrocarbon--bearing sandstones with impermeable shaly beds in the Meganos Channel.



STRUCTURAL SECTIONS ACROSS MEGANOS CHANNEL, CALIFORNIA

Fig. 6-9. Structural sections A-A' and B-B' across the Paleocene Meganos Channel, Sacramento Valley, California, showing oil and gas accumulations in Paleocene beds of the Martinez Formation, Brentwood field. (Redrawn from Dickas and Payne, 1967).

Stratigraphic and structural control is similar to that of the Marlin Field (Fig. 6-11) in the Gippsland Basin, Victoria. The Brentwood and Dutch Slough, considered to be major fields, are located in the south--western part of the channel shown in Fig. 6-8, whereas the West Thornton field lies in the northern part. Ultimate producible reserves of gas in the Dutch Slough field are estimated to amount to more than 300,000 million cubic feet (8,400 million cubic metres).

Marlin Gas Field, Victoria

In the Marlin Field (Figs. 6-10 and 6-11) of the Gippsland Basin, Victoria, gas and some light oil are produced from five sandstone units within the Paleocene to Eocene Latrobe Group. These units are tilted, truncated by an erosional surface, and flanked on the east by a submarine channel filled with mudstones of the Oligocene to Miocene Lakes Entrance Formation. The mudstones provide an effective seal. The gas-bearing sandstones lie within a section approximately 180 m thick. Individual sandstone beds have a thickness of up to 30 m, and the cumulative net-pay thickness for all five units exceeds 100 m. The sandstones are light grey, friable, quartzose to lithic, generally fine-grained, micaceous, and locally silty with carbonaceous flakes. Porosity and permeability have ranges of 15-30% and up to 1,000 millidarcys respectively. The five sandstone units are separated by carbonaceous mudstones including beds of coal.

These gas-bearing sandstones were deposited in a paralic to alluvial environment, but detailed information concerning their paleo-geomorphic origins have not been published. Griffith and Hodgson (1971) are of the opinion that they are braided stream deposits. The Latrobe Group comprises a wedge of sediments, thickenning to many thousands of feet offshore, that formed as a deltaic complex. Coal beds in the Marlin Field area, 50 km offshore, are individually up to 6 m thick, but onshore

MARLIN GAS AND OIL FIELD
GIPPSLAND BASIN, VICTORIA

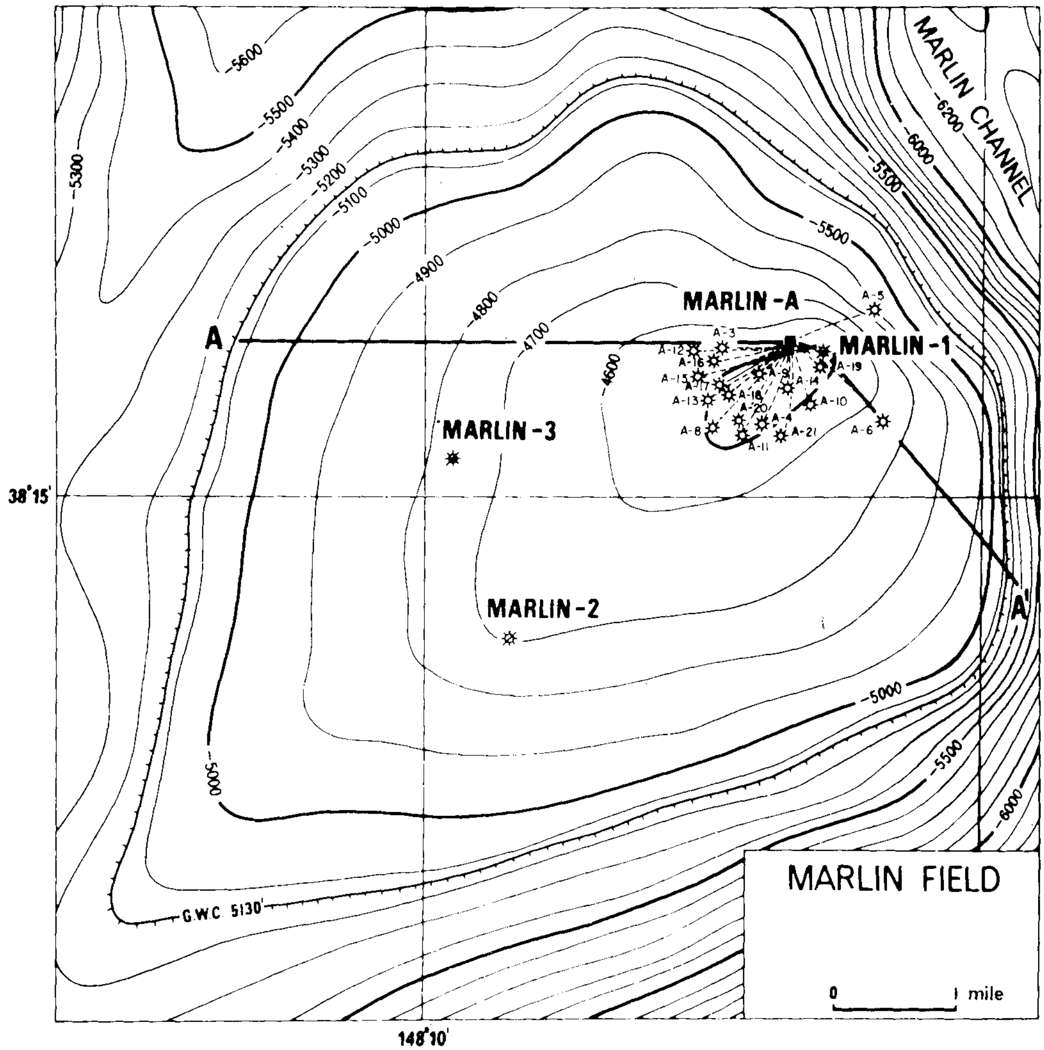


Fig. 6-10. Structure map showing sub-sea level configuration of the erosional surface of the Latrobe Group, Marlin Gas Field, Victoria. Section A-A' extends to the upper level of the Marlin Channel, a submarine valley. Contour interval is 100 feet (30 m). (After Griffith and Hodgson, 1971, modified by Beddoes, 1973).

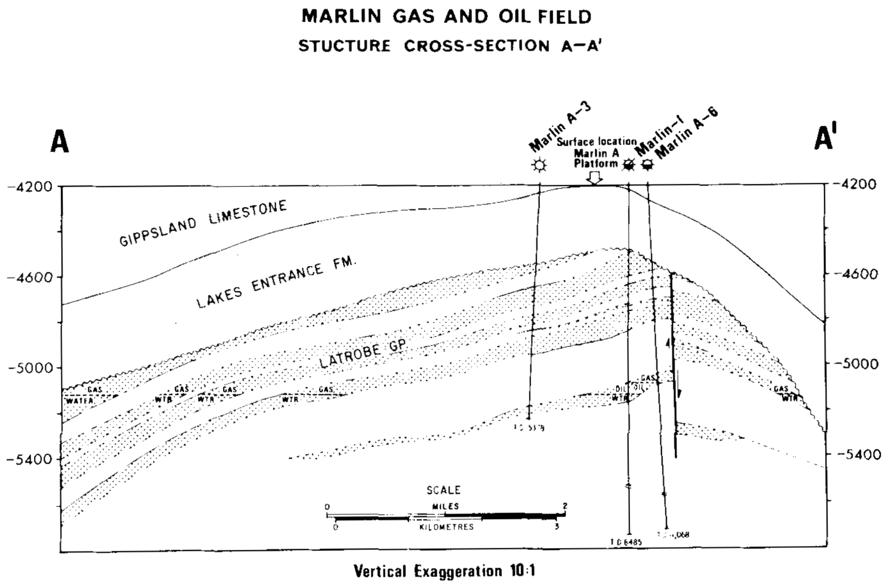


Fig. 6-11. Structure section A-A' across the Marlin Gas Field, Victoria, showing a fault bounding the western flank of the Marlin Channel shown in Fig. 6-10. (After Griffith and Hodgson, 1971, modified by Beddoes, 1973).

they range up to 90 m thick. In the offshore areas stratigraphic zonation within the Latrobe Group depends on the assemblage of pollens and spores. During the late history of the Latrobe Group a marine transgression, which began in the Late Eocene, resulted in the deposition elsewhere of up to 300 m of marine mudstone and up to 30 m of glauconitic, very fine-grained sandstone. These beds are included in the Latrobe Group, although they were deposited during the initial stages of a regional marine transgression that later laid down the Lakes Entrance Group.

The field, which has a strong water drive, is a structural-stratigraphic trap. A southwest-plunging fold was eroded during the Late

Eocene to form a closed erosional feature (a dome-shaped hill) flanked on the east by a valley (subsequently a submarine channel). Maximum vertical closure is approximately 275 m. The estimated ultimate producible reserves of gas amount to 3,500,000 million cubic feet (98,000 million cubic metres) containing 175 million barrels (27.8 million cubic metres) of condensate. Estimates of ultimate recovery of the light oil have not been published. Of particular interest is the fact that the filling of the Marlin submarine channel with muds has been a prime factor in forming an up-dip seal for gas in the tilted and eroded sandstone beds of the Latrobe Group. The structtural-stratigraphic situation is similar to that of the Brentwood Field (Fig. 6-9) in California.

Ventura Oil and Gas Field, California.

Production in the Ventura Oil Field of the Ventura Basin, California, is obtained from the Upper Pliocene Pico Sandstone and the Lower Pliocene Repetto Sandstone. Both units form a continuous sequence, more than 3,000 m thick, of oil-bearing sandstones, sandy siltstones and organic-rich silty claystones. The sequence comprises turbidity current deposits and normal deep-sea sediments that formed a submarine fan in a tectonically active basin (Natland and Kuenen, 1951). Coincidence of the area of optimum sand deposition and the area of growth of the Ventura anticline has resulted in a thick oil-bearing section. This section has been divided into several oil-producing zones at depths ranging from 300 to 2,700 m. The upper most zone yields gas and condensate (56^{o} A.P.I.), the upper zones yield light oil (42^{o} A.P.I.), and the lower zones yield heavier oil (30^{o} A.P.I.). These accumulations, which occur in a number of individual traps in separate fault blocks within a reverse and thrust-faulted anticline, have different reservoir pressures and oil characteristics (Levorsen, 1967). Other accumulations having a similar depositional and structural genesis are present in the Lower Pliocene of the Los Angeles

Basin, and in the Upper Miocene of the San Joaquin Basin, both in California.

Within the 2,700 metres of oil-bearing section in the Ventura Field, permeability of the sandstones decreases progressively with depth from a range of 60-250 millidarcys in the upper zone to less that 5 millidarcys in the lower. The oil-bearing sandstones in the lowermost zone commonly have a permeability of only one millidarcy, suggesting that the permeability of this unit has been reduced by a factor of several hundred times since it was deposited. This drastic reduction has resulted directly from the shattering and compaction of grains by a combination of static and dynamic pressures caused by depth of burial and the stresses that produced folding and faulting, and indirectly by the plugging of pore space resulting from diagenetic alterations. There is no evidence (Natland and Kuenen, 1951) that sedimentological differences in the upper and lower parts of the section account in any way for the variations in permeability. The Ventura Field area was the site of deposition by turbidity currents during most of the Pliocene, and this facies characterizes the entire oil-bearing section.

Hertel (1929) estimated that ultimate recovery from the Ventura Field would amount to more than 250 million barrels of oil and 600,000 million cubic feet of gas. Since then, additional producing zones within the field have been discovered. Halbouty (1978) states that at the beginning of 1967 the cumulative production plus the estimated recoverable reserves of oil in the Ventura field amounted to approximately 818 million barrels (130 million cubic metres). He also states that at the beginning of 1966 the cumulative production of gas was 1,847,000 million cubic feet (52,000 million cubic metres). It is of interest to note that more recent estimates of ultimate production in this field, discovered in 1916, have proved to be about three times greater than the earlier estimates.

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Chapter 7

TIDAL CURRENT SAND BODIES

Introduction

Geomorphology

Tidal current ridges of sand and silt are known in many parts of the world. They are developed as ribbon-shaped sand bodies aligned parallel to the tidal current direction. These sand bodies are commonly found at depths within the range 10-100 m, on parts of the continental shelf subject to strong tidal currents flowing at velocities of up to 5 km/hr. Of those described, examples in the North Sea (Pettijohn, Potter, and Siever, 1972; Blatt, Middleton, and Murray, 1972; Houbolt, 1968; and Stride, 1963), in the Gulf of Korea (Off, 1963), and in Taiwan Strait (Boggs, 1974) are mentioned here. The dimensions of these ridges are remarkably similar. In the North Sea (Figs. 7-1 and 7-2) they have a thickness of up to 50 m, a length of up to 70 km but commonly less than 50 km, and a width of 3-5 km. In the Gulf of Korea (Fig. 7-3) they have a thickness of 10-35 m, a length of 10-60 km, and a width of 2-3 km. In Taiwan Strait they are 5-30 m thick, and up to 3.5 km wide. Swift and McMullen (1968) also describe tidal sand bodies in the Bay of Fundy, Nova Scotia. These bodies are up to 30 m thick and 30 km long.

In the North Sea tidal ridges were extensively studied by Houbolt (1968). On the surface of these asymmetrical ridges, and trending obliquely across their strike, are large current ripples referred to as tidal sand waves. Although very little is known about the internal structure of tidal current ridges, the movement of sand waves across their surfaces is reflected internally as cross-bedding. The nature of this cross-bedding is not well known, but is indicated by sparker surveys to be planar and sweeping.

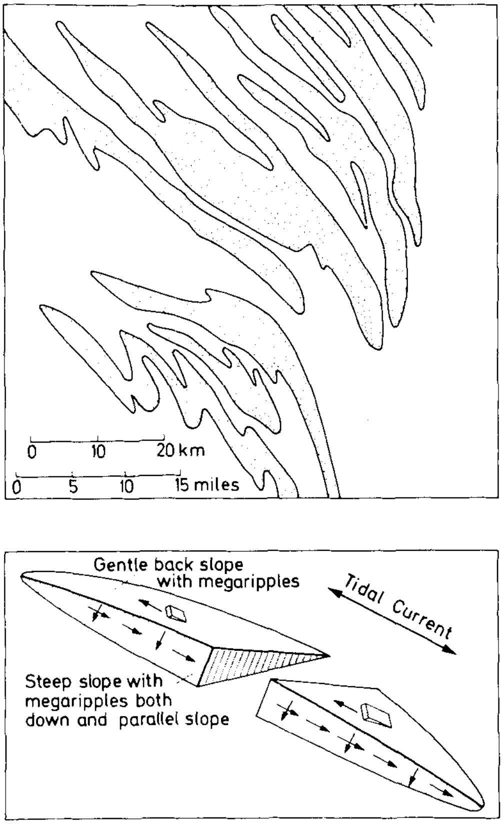

Fig. 7-1. Outlines and generalized cross-section of sand ridges in the southern bight of the North Sea. (Redrawn by Pettijohn, Potter and Siever, 1972, after Houbolt, 1968).

These North Sea sand ridges, formed on the flat sea floor of an open shelf, appear to have flat bases and convex tops. This interpretation is indicated by sparker surveys which outline the geometry of the ridges, and is further suggested by the fact that the sand bodies migrate across the sea floor like giant ripples. The sand which is not directly derived from any present--day river but from the sea floor itself, is extremely well sorted and fine--grained. Coring does not show any grain gradation within the ridges.

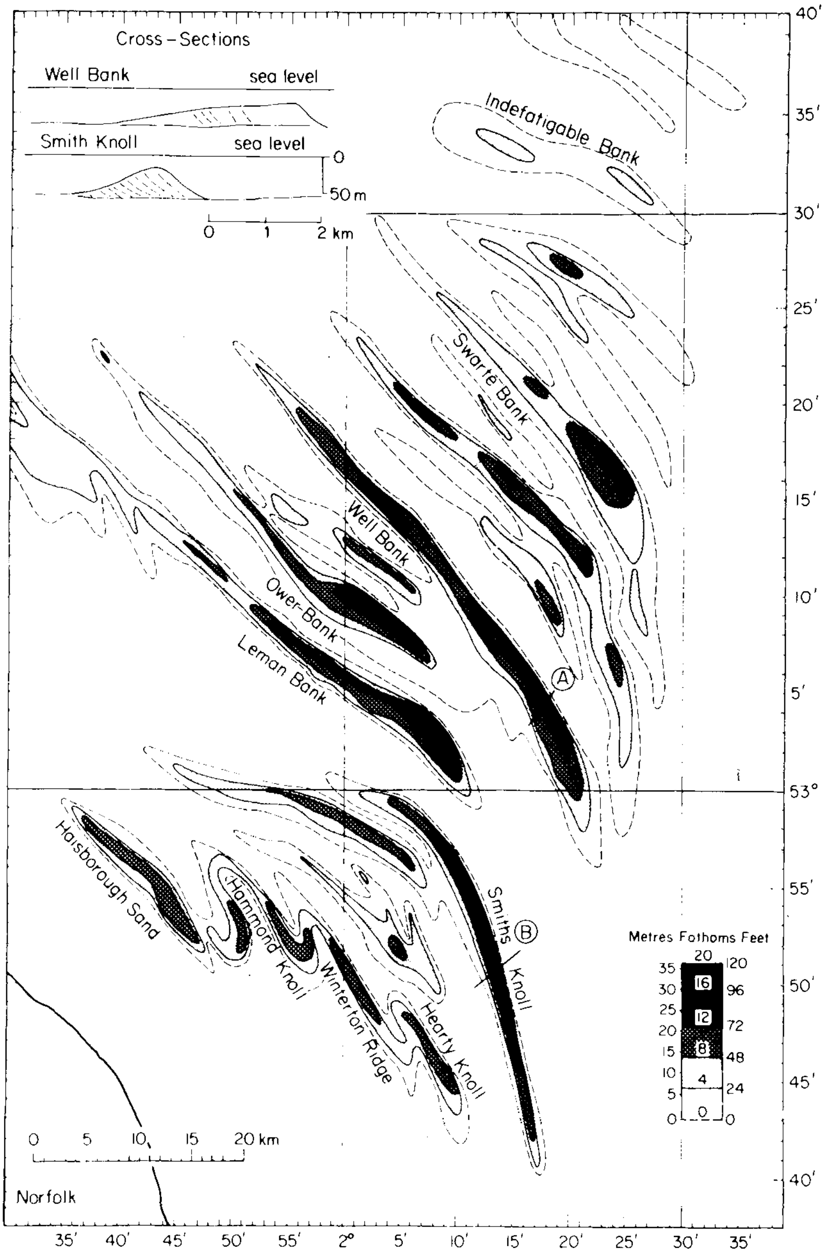

Fig. 7-2. Isopach map of sand ridges formed by tidal currents in the southern bight of the North Sea. (Modified by Blatt, Middleton, and Murray, 1972, after Houbolt, 1968).

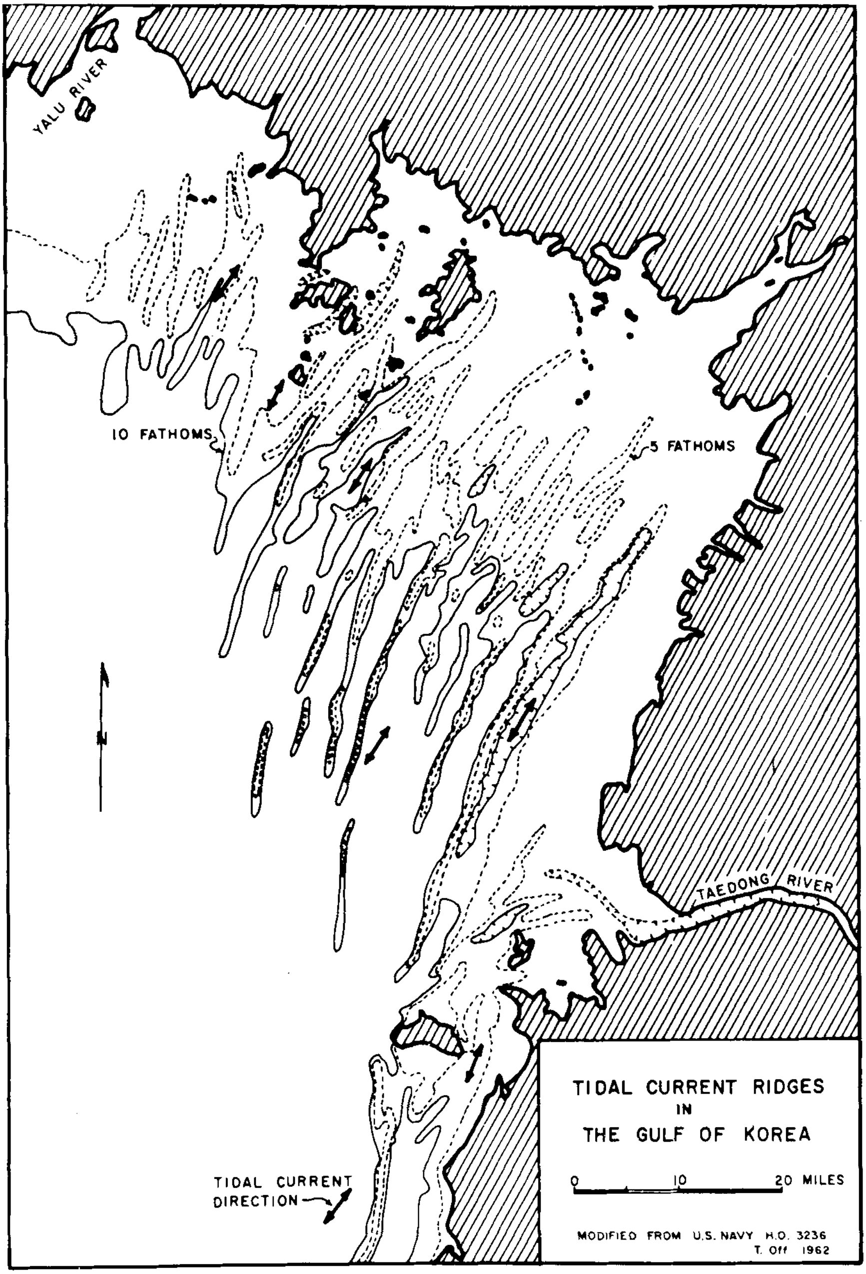

Fig. 7-3. Tidal current ridges of sand in the Gulf of Korea. Tidal current directions indicated by arrows. (After Off, 1963, redrawn from U.S. Navy Hydrographic Office charts.)

Measurements of grain orientation indicate a preferred direction at 45^{o} to the strike of the sand ridges, a result that is not surprising in view of the oblique movement of current ripples across the leading edges of the sand ridges. The non-parallelism of average grain orientation to the trend of the sand ridges suggests that measurements of mean grain orientation in sandstones should be applied to the interpretation of sandstone body trends with some reservation.

Off (1963) describes tidal current ridges (Fig. 7-3) in the Gulf of Korea. These ridges have developed on a flat and shallow continental shelf where in places the water depths, at distances up to 65 km from shore, do not exceed 40 m. The ridges form an arcuate pattern trending parallel to the direction of flow of the tidal currents. Of particular interest is an example showing the alignment of ridges both parallel and normal to the coast line. Other examples illustrated by Off show the alignment of tidal current ridges in straits and estuaries to be essentially parallel to the coast. These geomorphologic relationships will have some bearing on the interpretation of ancient sand bodies such as off-shore bars and barrier islands which also lie parallel to the coastline. Off (1963, p. 327) describes the tidal current ridges in the Gulf of Korea as follows, "Here, the ridges are spaced with an average of 3 miles between crests and rise an average of 65 feet from their base. They are oriented approximately parallel with the west coast of Korea and perpendicular to the north end of the Yellow Sea".

With reference to sand ridges in Taiwan Strait, Boggs (1974, p. 253) says, "The rather widespread development of large, asymmetrical sand waves in Taiwan Strait suggests active transport of bottom sediment. The pattern of sediment transport, although not yet accurately determined, appears to be complex; transport in a seaward direction, transport in a landward direction, and longshore transport are all indicated in various parts of the strait. The sand waves are developed in areas of sandy bottom sediments that Niino and Emery (1961) considered to be relict Pleistocene sediments; it appears quite likely, however, that the sediment has been extensively reworked since Pleistocene time by bottom currents that may have markedly altered original sedimentary structures and mineral concentrations, as well as local topography of the sea floor".

E-log Characteristics

In the North Sea the sand in tidal current ridges is commonly fine--grained and extremely well sorted, having been derived from older beds deposited in the sea or on a surface subsequently inundated by the sea. Some ridges consist of muddy sand or muddy silt. Sand ridges, being composed of re-worked sediment of fairly uniform grain size, have a homogeneous texture and show no significant grain gradation. As shown by Houbolt (1968) some ridges internally reflect shock waves from a sparker, indicating cross-bedding or inclined bedding having minor variations of texture and composition, whereas other ridges give no reflections and appear to be internally homogeneous. In either case it can be expected that the E-log self-potential curve of an ancient tidal current sand body will show neither a tendency to be bell-shaped nor funnel-shaped, but exhibit a blocky characteristic similar to that of some distributary channel sand bodies.

Compaction

At some stage in the geological history of tidal current sand ridges, provided they remain below sea level, they are buried in a sedimentary pile. Thus preserved in the geological record, they are subjected by increasing depth of burial to the effects of compaction. These will result in subsidence of the sandstone body, and in draping of the overlying finer sediments. Subsidence may be minimal, depending on the degree of compaction and thickness of the underlying section of sediments. In the case of the North Sea tidal current sand ridges, the section of sediment resting on consolidated rock is comparatively thin. The flat sea-floor between the sand ridges is covered with a gravelly lag deposit, composed of chert pebbles and skeletal fragments, which overlies a bed of stiff bluish-grey clay. Similarly, where tidal current sand ridges are formed in a marine transgressive situation, the compactional effects resulting from subsidence of the sand body will not greatly alter the original shape of the body. Consequently, its topographic configuration will be preserved, although somewhat modified, in the strata in which it is buried. Interpretation of the original geometry of such sandstone bodies can best be done by means of sections and maps drawn with a datum beneath the body.

Ancient Sand Bodies

Many examples have been cited of sandstone bodies deposited as sand bars on shallow marine shelves subject to the action of waves and ocean currents. Some of these ancient sands were swept on to a sea floor of clay and silt, and some accumulated on a carbonate shelf. Others appear to transgress both carbonate and non-carbonate environments. Selley (1967) describes a Miocene section in Libya where fluvial and paralic sands deposited in a deltaic environment can be traced into limestone beds deposited on a shallow marine carbonate shelf. Descriptions of sandstone bodies are commonly incomplete, and the interpretations placed on their origins may be equivocal. Pettijohn, Potter and Siever (1972, p. 493) say, "In the absence of plentiful, good descriptions of ancient marine shelf sand bodies, we have attempted to summarize and synthesize their properties from few and scattered data (Table 11-6). Much remains to be learned". They further describe some of the general characteristics of ancient marine shelf sands as follows.

"The sand of many ancient marine shelves tends to be mineralogically mature, especially on cratons, presumably because it has passed through the shoreline complex. Thus argillaceous rock fragments and unstable minerals generally are not very abundant. Glauconite, detrital carbonate skeletal debris, marine fossils, and collophane are commonly present. A relict fauna and anomalously coarse grains are common in the upper few feet of some shelf sands. Gravel or conglomerate may be derived locally. Cementing agents are mostly chemical, but may include appreciable detrital material proximal to clay or shale transitions. Sorting generally is good to excellent, and there is perhaps a tendency for better-than-average rounding. The variability of textural parameters between samples is generally very low".

Tidal current sand bodies probably have fossil counterparts, but none have been proven. The Elaterite Bar in the Lower Permian White Rim Sandstone of Utah (Baars and Seagar, 1970) has morphological similarities. So do some of the arcuate sand bodies of the Lower Cretaceous Viking Formation in Alberta and Saskatchewan (Evans, 1970), although other Viking sand bodies are interpreted as shoreline and near-shore sands deposited as beaches and off-shore bars. Off (1963) has suggested that tidal currents were effective in the deposition of the Upper Mississippian Palestine Sandstone, which lies stratigraphically above the channel-forming Bethel Sandstone (Fig. 1-29), and also in the deposition of the Upper Cretaceous Cardium Sandstone of Alberta. With reference to the Palestine Sandstone he says, p. 335, "In a recent study of the Chester sands of the Illinois Basin (Potter *et al.*, 1958), attention was called to the alignment of sand bodies parallel with the current directions indicated by cross-bedding, and perpendicular to regional strike. The relative positions of some of these sand bodies (as shown by Potter's Figure 13 for example) and their unique dimensional scale, both as to individual thickness and distance of separation, combined with the presence of cross-bedding and suggestion of a marine environment, strongly suggest that they are tidal current ridges". The Palestine is interpreted by Potter *et al.* (1958) as a channel sandstone. The Cardium (Fig. 3-22) sand bodies are considered by Berven (1966) and others to be off-shore bars.

The Elaterite Bar (Fig. 7-4) is composed of fine-grained, well sorted, quartzose sandstone that is fairly uniformly saturated with heavy asphaltic oil that seeps out as bitumen from this exhumed stratigraphic trap. The sandstone body, which trends in a slight arc, is up to 60 m thick, 2-3 km wide, and 16 km long. Internally, the sandstone exhibits large-scale sets of sweeping cross-stratification that dip 20-25 degrees southeast and have long tangential basal contacts.

The origin of the Elaterite Bar is not entirely clear. Several investigators have agreed that although the White Rime Sandstone was in part deposited in shallow water, it was mainly eolian. The chief proponent

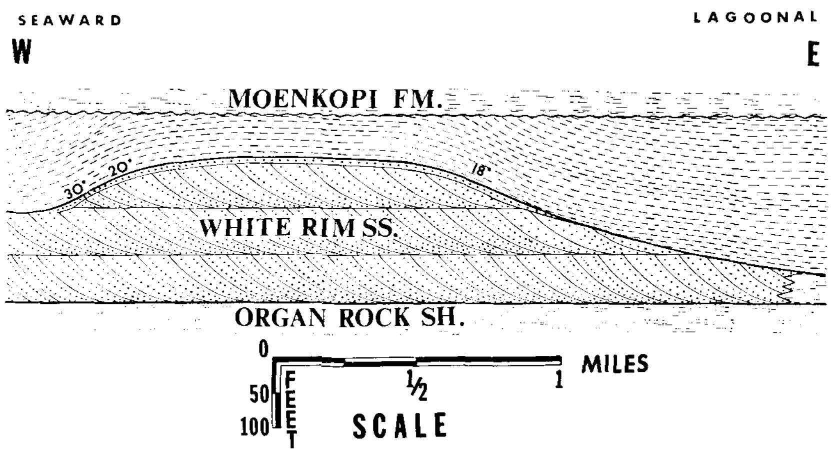

Fig. 7-4. Generalized cross-section of Elaterite Bar in the Lower Permian White Rim Sandstone, southeastern Utah. (After Baars and Seager, 1970).

of this interpretation is Baker (1946). Baars and Seager (1970) have refuted this interpretation for the Elaterite Bar which they describe as a definite and regular sand build-up conformably overlying the Organ Rock Shale. They say, p. 716, "It is probable that the White Rim Sandstone is of shallow-marine origin. The best evidence is the geometric and geographic configuration of its contained sand bars, the nature of the cross--stratification and ripple marks, the regional relations of the formation, the presence of a problematic alga, and the absence of tracks". The Elaterite Bar is conformably overlain by Lower Permian shaly beds which in turn are unconformably overlain by the Triassic Moenkopi Formation. No evidence has been advanced to suggest that the Elaterite Bar may be (other than the uppermost part which has been re-worked) an erosional feature formed by current scouring. In fact, Baars and Seager offer evidence to suggest that this is not the case. With reference to the configuration of the Elaterite Bar they say, p. 714, "The topography is of sedimentary rather than erosional origin, as shown by the gradual change of wavelength of the ripples along continuous bedding planes from 2 in. at the top to 6 in. at the margin in response to deepening of the water over the edge of the bar. From this evidence, it is apparent that the Elaterite Bar was built where water depths reached at least 50 ft along its seaward margin". Further investigations may clarify these differences of interpretation and determine the origin of the Elaterite Bar. Externally and internally this sandstone body has similarities of dimensions and apparent depositional environment to those of the North Sea sand ridges described by Houbolt (1968).

The potential of tidal current sand ridges as reservoirs for oil and gas has been pointed out by Houbolt (1968, p. 264) with reference to marine transgressive situations where large, thick and elongated sand bodies can be formed. He says, "These sand bodies will consist of clean, well-sorted sand, without a vertical gradation in grain size and will be overlain by clayey marine sediments if the transgression continues. Hence they will form excellent reservoirs for oil". To illustrate his point he cites the Well Bank, one of the large tidal current ridges in the North Sea. Assuming that this sand body has a porosity of 30%, the pore space being completely filled with oil, and that 20% of the oil can be recovered, he estimates that the body could yield 950 million barrels (151 million cubic meters) of oil. This is a theoretical consideration but illustrates the possible potential of sandstone bodies having similar dimensions and good porosity-permeability characteristics.

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Chapter 8

ALLUVIAL FANS AND SHEETS

Introduction

Geomorphology

Alluvial fans and sheets are composed of gravel, sand, and silt derived as detritus from the rapid erosion of an uplifted crustal belt or block that is commonly bounded by an active fault. The surface expression of coalescing fans and sheets, fed by valleys dissecting the uplifted block (Fig. 8-1), is seen as a pediment or alluvial plain. In the subsurface fans commonly merge to form a wedge of sediment several thousand feet thick, whereas sheets are very much thinner and more widespread. Where such fans are formed in a semi-desert environment, particularly where block faulting movements of the earth's crust have formed a basin and range topography, great thicknesses of accumulated fans, commonly exceeding 3,000 m, but in places up to 8,000 m (Crowell, 1954) are known to exist. Bull (1972, p. 63) defines alluvial fan deposits as follows, "Fans consist of water-laid sediments, debris-flow deposits, or both. Water-laid sediments occur as channel, sheetflood, or seive deposits. Entrenched stream channels commonly are backfilled with gravel that may be imbricated, massive, or thick bedded. Braided sheets of finer-grained sediments deposited downslope from the channel may be cross-bedded, massive, laminated, or thick bedded. Seive deposits are overlapping lobes of permeable gravel". Leopold, Wolman, and Miller (1964) describe an alluvial fan flanking the Sandia Mountains, New Mexico. They say that within half a mile of the mountain front, which is bonnded by a normal fault, wells penetrated 10-30 m of sand and gravel overlying granite, whereas wells

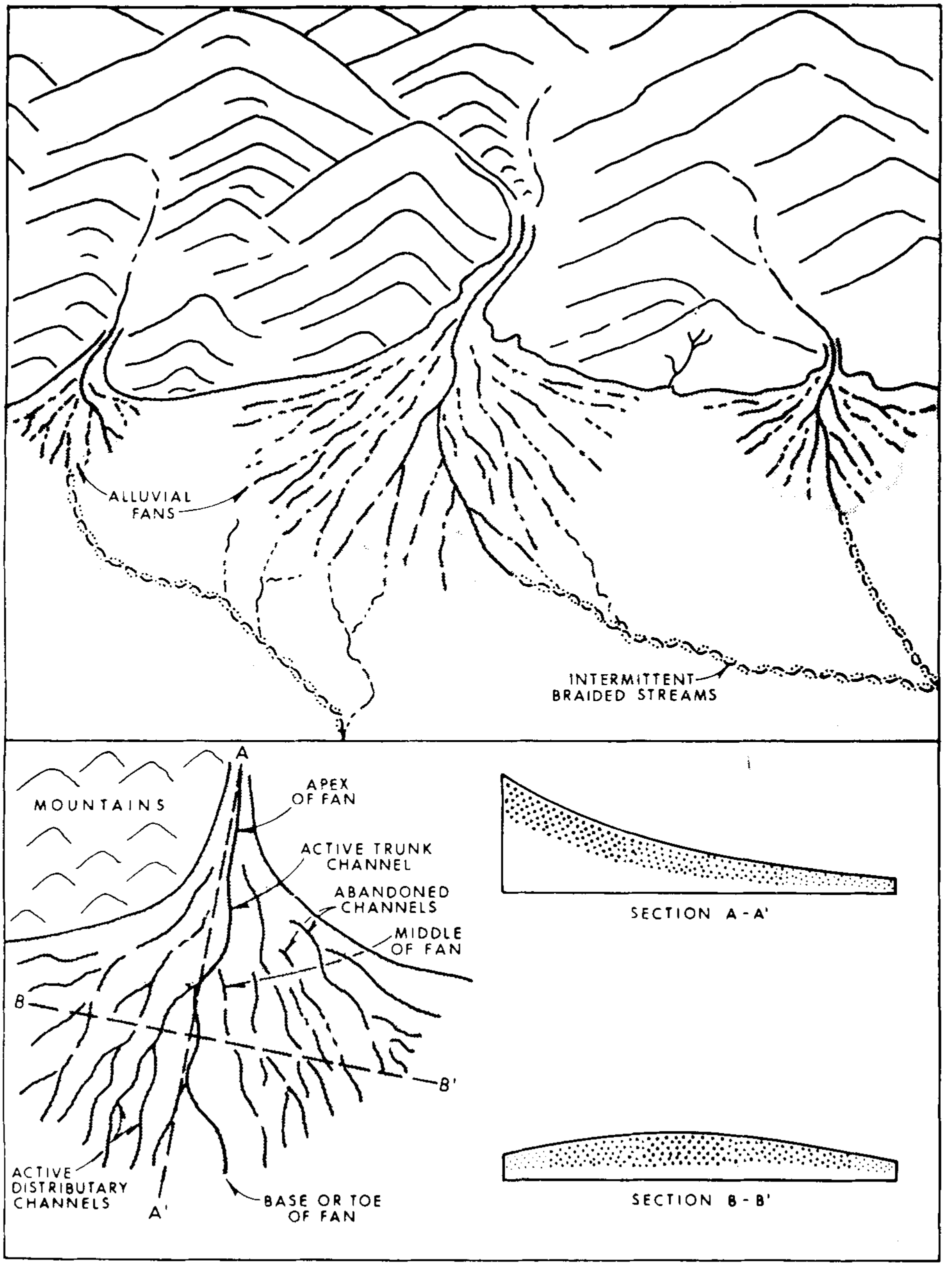

Fig. 8-1. Sketch of coalescing alluvial fans, showing original depositional slopes (Sections A-A' and B-B'). (After Le Blanc, 1972).

drilled only a short distance farther from the mountains penetrated more than 100 m of sand and gravel, indicating a rapid thickenning of the alluvial wedge. Farther from the source, both fan and sheet gravels and sands become transitional with river and lake sands, silts, and muds (Fig. 8-2), or with marine sediments where the pediment slopes down to the sea.

The middle to lower slopes of alluvial fans and sheets are commonly remarkable for their braided stream deposits which characterize drainage patterns heavily laden with sediment. Selley (1970, p. 24) says, "Many present-day braided rivers are found on piedmont fans at the edge of mountains where there are large amounts of sediment and discharge is often, but not always, seasonal. Examples have been described from the hot deserts of the mid west of U.S.A. and from the periglacial mountains of

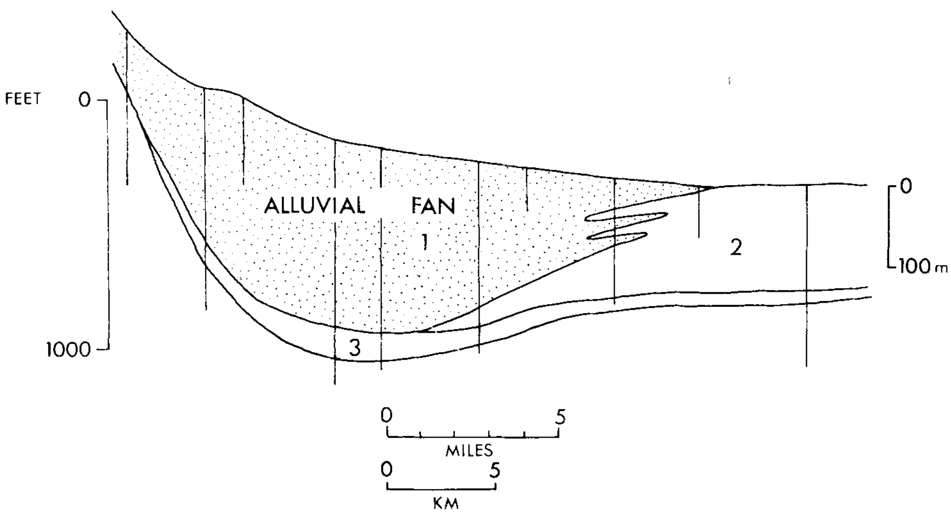

Fig. 8-2. Section of an alluvial fan (1) grading into river deposits (2) and overlying Pleistocene lake clays (3) in a valley flanking the Sierra Nevada mountains of California. (Redrawn from Bull, 1972 after Magleby and Klein, 1965).

the Yukon in Canada (e.g. Blissenbach, 1954, and Williams and Rust, 1969). In these regions erosion is rapid, discharge is sporadic and high, and there is little vegetation to hinder runoff. Because of these factors rivers are generally overloaded with sediment. A channel is no sooner cut than it chokes in its own detritus. This is dumped as bars in the centre of the channel around which two new channels are diverted. Repeated bar formation and channel branching generates a network of braided channels over the whole depositional area. Thus the alluvium of braided rivers is typically composed of sand and gravel channel deposits to the exclusion of fine-grained overbank silts and clays. Due to repeated channel switching and fluctuating discharge there is generally an absence of laterally extensive cyclic sequences similar to those produced by meandering channels. Fining-upward gravel, sand, silt sequences have been recorded however and are attributed to waning current velocities as a channel is gradually infilled (William and Rust, 1969)".

The term fan refers to the topographic shape of an accumulation of sediment discharged on the gentle slope of a pediment (commonly 2-3 degrees) from a narrow valley cutting into an adjacent range of hills or mountains. The distal portions of fans merge down the slope to form sheets of sediment which are generally finer grained than those deposited closer to the mountains. Fans are built up by an accumulation of layers of sediment deposited largely as seasonal outwash during rainy periods. The deposit consequently progrades into the valley, which may be a broad topographic feature. The subsurface configuration of a fan deposit is somewhat linear, it having been deposited along the flank of a valley. It is also wedge--shaped to lenticular (Bull, 1972). Variations in the rates of seasonal run-off, and tectonic influences such as fault movements of the valley floor or flanks will influence the development of the alluvial wedge. Individual layers, which grade from coarser to finer away from the mountains, and which may also show grain gradation from coarser below to finer above, will not have any regular sequence with respect to one another. Layers of coarse gravel may overlie layers of sand and grit, and the layers themselves may thicken and thin to such an extent that they are indistinguishable as stratigraphic units. Whether or not such layers can be traced laterally depends largely on the line of section taken, and on the geometry of the alluvial fan body. As pointed out by Bull (1972), individual beds may be traced for long distances along radial sections, but along cross-fan sections the beds appear to be lenticular and are commonly cut by channels. These channels are most common near the apex of the alluvial fan body, whereas in the distal parts, away from the source of the sediment, the layers are more sheet-like. The total section of sediment in an alluvial fan body may appear in the subsurface, and possibly also in outcrop, as a single unit comprising poorly sorted, unsequential layers and lenses of gravel, sand, and silt.

E-log Characteristics

Alluvial fan deposits consist largely of poorly sorted clastics deposited by drainage systems that commonly form braided streams, but which may also discharge their sediment loads during intermittent periods of sheet run-off. Consequently, these sediments accumulate rapidly to form thick sections of superimposed layers and lenses, each of which may have no grain gradation or may show some degree of gradation from coarser below to finer above. Where present, in an individual layer or lens, grain gradation may be reflected in the character of the self-potential curve, indicated by a poorly defined bell-shape. Superimposed one on the other, or intercalated with portions of the self-potential curve that show no meaningful character, the over-all configuration of the E-log may indicate merely a thick section of poorly defined layers. In this respect, where the section is several hundred feet thick, there may be similarities between the E-logs of alluvial fan and turbidity current deposits. In general, the E-log self-potential of an alluvial fan deposit tends to be blocky and serrated.

Compaction

Wedges of clastic sediments accumulating along a sinking trough underlain by a graben complex, or piling up along the flank of an upthrusting range of mountains, are relatively uncompactible and so retain to a large degree their original shape after burial. Essentially, alluvial fan deposits are flat on the top and markedly but irregularly concave at the base. The deposits are always flanked on one side by older rock which is probably in large part the source material for the deposit, and may also be underlain by alluvial and lacustrine sediments. In some areas where the uplifted belt of mountains is flanked by a marine coastline, or where the belt flanks a valley invaded by the sea, the alluvial fan deposit may overlie and merge laterally into marine carbonate or non-carbonate sediments. Depending on the nature of the base on which an alluvial fan is deposited, subsequent compaction will modify the shape of the fan which nevertheless retain its characteristic of being regular at the top and irregular at the base. The choice of a datum for constructing a cross section consequently lies in the sequence of beds immediately overlying the alluvial fan deposit.

The original porosity and permeability of alluvial fan sediments is excellent, and surface water permeates downward so rapidly that only the lowermost beds are water-bearing. With reference to alluvial fan deposits flanking the Sandia Mountains, New Mexico, Leopold, Wolman, and Miller (1964) state that in bores drilled near the base of the mountain range water is usually obtained from the thin edge of the alluvial fan deposit, consisting of gravel lying on the rock of which the range is composed. In bores drilled slightly farther from the range, where several hundred feet of alluvial fan sand and gravel were penetrated, the sediments are dry.

Compaction, with increasing pressure and temperature, decreases the permeability of the lithic clastics which are much more readily altered than quartzose sands. Alterations are effected by mechanically fracturing the grains, particularly those of rock fragments, feldspars, and the ferro-magnesian minerals, by diagenetic alteration of the mineral constituents to form clay minerals which partially plug the pore space, and by cementation of the grains with calcite, iron oxide and other constituents deposited by circulating water. The effect on water movements within deeply buried alluvial fan deposits is to decrease the vertical permeability and to develop trends of relatively greater permeability along depositional and laterally directional features such as channels.

Ancient Sand Bodies

Examples of ancient alluvial fan deposits are not common, but some have been described in the literature. Other deposits, which probably are alluvial fans, have been described but not specifically defined, as to their origin. Selley (1970, p. 30), based on Selley (1965), describes Precambrian alluvial fan deposits in northwest Scotland as follows. "The coarse grain size, angularity, poor sorting, and petrography of the basal facies deposits clearly show that they were derived locally from the Lewisian gneiss. Their geometry and the radiating depositional dips leaves little doubt that they are ancient piedmont fans. Deposition was probably due to avalanches, mud-flows, and sheet floods such as occur on steep slopes near the apices of Recent fans (e.g. Blackwelder, 1928)". Several samples, which may in part be of alluvial fan origin, are mentioned by Selley (1970). Some of these are sequences, many hundreds of metres thick, which show a lateral transition from braided stream deposits near their source to fluvial sediments deposited in a meandering stream system, or to lacustrine sediments. Others constitute widespread but comparatively thin (more than 100 m) sheets of conglomeratic sandstone. These examples, in various parts of the world, range in age from the Precambrian to the Cenozoic.

Of particular interest, because locally they form reservoirs for petroleum, are Late Paleozoic to Mesozoic alluvial fan and sheet deposits in North Africa. These have collectively been referred to as the Nubia Sandstone. Considerable confusion exists in the literature on the Nubia Sandstone (Pomeyrol, 1968). The term, used at various localities in North Africa, includes beds ranging from Carboniferous to Early Cretaceous. Beds referred to as Nubia Sandstone (*sensu stricto*) are predominantly of terrestrial and fresh-water origin, although some stratigraphic sequences which have been loosely referred to as Nubia include beds with marine fossils. McKee (1963) studied the sequence and types of sedimentary structures within beds referred to as Nubia and concluded that they were deposited in fluviatile, lacustrine, estuarine and lagoonal environments on a broad continental plain that was continually but irregularly subsiding. Such beds of terrestrial origin occur around the margins of the Saharan and Arabian Precambrian Shields. They have an extensive distribution and are noted for cross-bedding of the type found in braided stream deposits. Selley (1970) advanced the interpretation, after views expressed by Stokes (1950) and Williams (1969) with respect to beds in other parts of the world, that these deposits were laid down as piedmont fans formed of detritus derived from the erosion of retreating scarps of older beds of sandstone and conglomerate.

In the Sirte Basin, Libya, vast quantities of terrigenous clastics were derived from the erosion of a Precambrian massif to the south. These clastics are mentioned by Conant and Goudarzi (1967, p. 721) who say, "Widespread over southern Libya is a thick sequence of continental beds

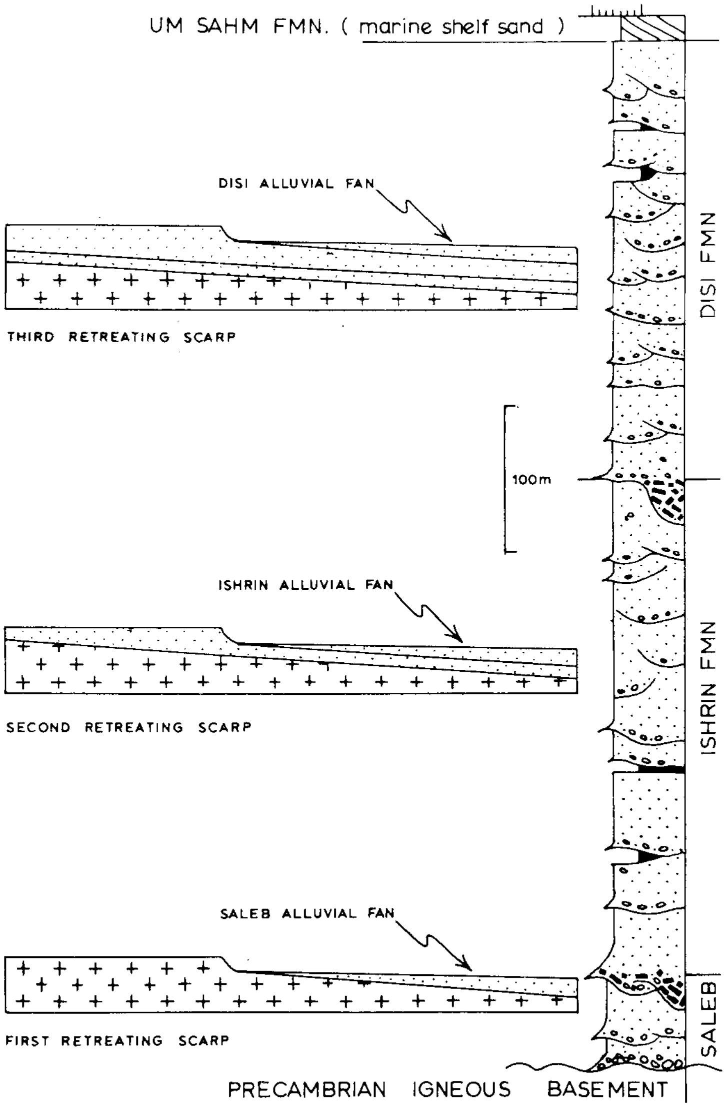

Fig. 8-3. Cambro-Ordovician section in Jordan showing origin as on-lapping alluvial fans resulting from repeated uplift and pedimentation. (After Selley, 1970).

long known as the Nubian Sandstone, which is also present in much of northeastern Africa and the Arabian Peninsula, though locally known by different names". Selley (1970) describes Cambro-Ordovician conglomeratic sandstone beds in Jordan (Fig. 8-3) which, he says, are similar in lithology and sequence of sedimentary structures to terrestrial beds of the Nubia Sandstone in Egypt. The beds in Jordan, comprising a thickness of 700 m of coarse, cross-bedded alluvial sandstones, are believed to have been laid down by braided streams flowing over a coalescing complex of broad, imbricated alluvial fans that formed a piedmont plain. This sequence of beds rests on the Precambrian igneous basement and is overlain by sandstone deposited as marine shoreline sands.

Oil and Gas Fields

Lower Cretaceous sandstones in the Sirte Basin, Libya, referred to by Conant and Goudarzi (1967) as Nubian Sandstone, and a lithologically similar sequence of non-marine Carboniferous sandstones in the Gulf of Suez region of the United Arab Republic, also referred to as Nubian by Weeks (1952) contain oil in structural-stratigraphic traps. Selley (1970, p. 47) refers to these oil accumulations in the Sirte Basin as follows, "Here Lower Cretaceous alluvial fans are banked against an irregular (? faulted) basement topography. They were buried by marine shales of the Cenomanian transgression. Where structurally high relative to the shales, these fan deposits, still largely uncemented, contain some interesting oil fields". In the eastern embayment of the Sirte Basin deposition of these alluvial fan deposits was penecontemporaneous with subsidence and block faulting. Conant and Goudarzi (1967) state that oil accumulations in these Lower Cretaceous beds are at depths in the range 2,700-4,300 m. In the Gulf of Suez region the oil accumulations are in Carboniferous sandstone where the up-dip edges of the sandstone form fault scarps overlain by Miocene marine mudstone. It is of interest to note that in both the Sirte Basin and the Gulf of Suez region, where in the former area the accumulations may be essentially stratigraphic-structural and in the latter are certainly structural, the reservoir beds of alluvial fan deposits are overlain by marine shales or mudstone. The generality can be stated that where alluvial fan deposits are overlain by marine transgressive sediments, traps for petroleum can occur within them, depending largely on the presence of structural closure. This type of stratigraphic-depositional situation may arise where an upthrust block of the earth's crust forms a belt of mountains adjacent and parallel to a marine coastline, or where a valley, flanked by alluvial fans derived from adjacent mountains, and underlain by an actively sinking graben complex, is flooded by a transgressing sea. Where the alluvial fan deposits are overlain by marine mudstones, which may be calcareous, the petroleum generated in the marine beds and trapped in the alluvial fan deposits may consist of both oil and petroliferous gas. But where the overlying beds are notably carbonaceous, having formed in a coastal swamp to river backswamp environment, the hydrocarbons generated are more likely to predominantly consist of natural gas.

In Libya, very considerable production of oil is obtained from Cretaceous sandstones which generally are referred to as Nubian. Lador (1971) gives figures for the cumulative production of oil, to 1971, from a number of fields, all of which have been brought on stream since the early 1960's. These fields are producing either exclusively or mainly from the Cretaceous. The Zelten Field has a cumulative production of approximately 1,000 million barrels (159 million cubic metres) from Cretaceous and Paleocene beds; the Sarir Field has a cumulative production of approximately 380 million barrels (60 million cubic metres) from Upper Cretaceous beds; and the Waha Field has a cumulative production of approximately 300 million barrels (48 million cubic metres) from Cretaceous and Eocene beds. All of the other fields producing from the Cretaceous have a cumulative production of 320 million barrels (51 million cubic metres). These fields include the Dor, Kotla, Magid, Mansour, L-65, Jebel, Lehib, Ora, Bahi, Bel Hedan, and Samah. The total cumulative production of all these fields, to 1971, amounts to approximately 2,000 million barrels (218 million cubic metres) of light gravity oil. A new discovery mentioned by Lador (1971), which is situated some 16 km southwest of the Zelten Field, yielded a flow of 49^{o} A.P.I. oil, at rates up to 1,000 barrels per day, from a sandstone at a depth of about 3,350 m. Lador refers to this sandstone as Nubian.

Chapter 9

EOLIAN SAND

Introduction

Geomorphology

Eolian sands accumulate on a land surface that may be preserved as an unconformity or a disconformity in the stratigraphic record. Discontinuity may be profound as in the case of a widespread desert, or of very minor significance as in the case of sand dunes formed in river point bars or marine and lacustrine shoreline deposits. In deserts where sand dunes are forming, the sand is initially derived from areas of deflation, noted for their lag deposits of sand-blasted pebbles or fron the wind-swept beaches of a coastal environment. Sand is secondarily derived from the continual shifting of the sand dunes themselves.

Sand dunes exhibit a variety of shapes which have been variously classified (Pettijohn, Potter, and Siever, 1972) with reference to physical parameters, such as volume of sand supply and velocity of wind, which have determined or influenced their morphology. But all such dunes are characterized by large amplitude, high angle (> 30°), sweeping cross-beds (Fig. 9-1). These features have been described by McKee (1966).

Sets of cross-beds, piled one on the other, are known to form accumulations several hundred feet thick. The base of such an accumulation may be a sheet of horizontally bedded, coarser-grained, poorly sorted, pebbly sand over-ridden by a moving front of dunes. Such sand sheets are formed by deflation of the desert surface and can cover vast areas. The sand removed is borne by the wind and deposited on dunes which may in turn migrate over some other area of the sand sheet. Reineck and Singh (1973,

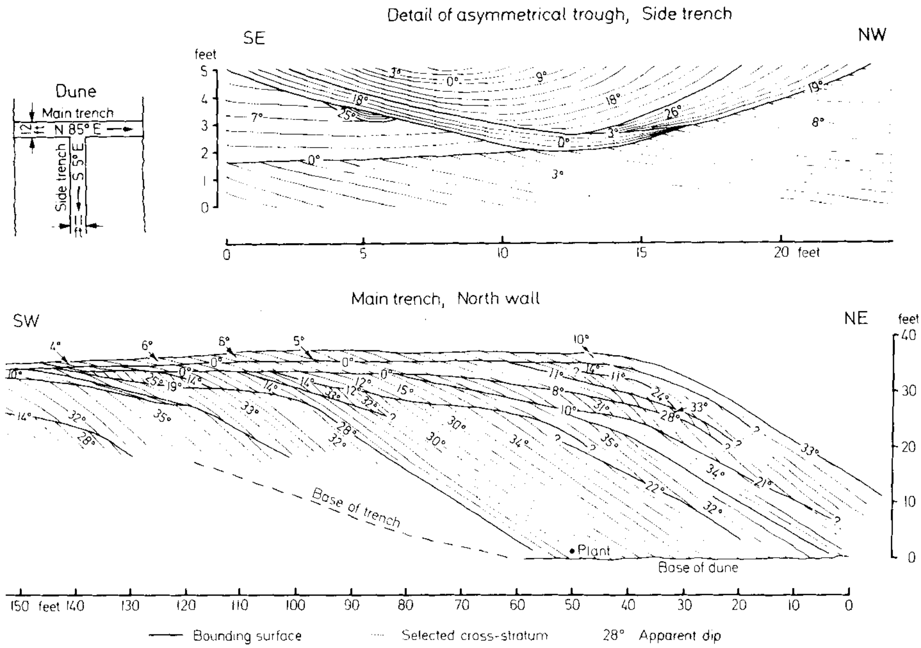

Fig. 9-1. Internal structure of a sand dune at White Sands National Monument, New Mexico, showing a SW-NE section in the direction of sand transport, and a SE-NW transverse section. (After McKee, 1966).

p. 196) describe such sheets in present day deserts as follows, "Sand sheets are usually very large areas of desert country, more or less flat in nature. Slight undulations or small dune-like features may be present. The surface rarely shows such features as wind sand ripples or wind granule ripples. However, during storms sand strips commonly develop (cf. Bagnold, 1954). The surface of sand sheets is sprinkled with coarser sediments - pebbles. Internally a sand sheet is made up of horizontally bedded sand layers separated by single layers of pebbles. Such evenly laminated sand (horizontally bedded sand) is also a common type of bedding in interdune areas". And further, "There are vast areas of sand sheets known which are devoid of any kind of pebbles. Such sand sheets are made up of well-sorted aeolian sand with well-developed horizontally laminated sand. A combination of rapid sedimentation, high wind velocities, and fairly uniform grain size of the sand cause deposition of sheet sand with an abundantly developed evenly laminated sand bedding (cf. Bagnold, 1954; Glennie, 1970)."

Reineck and Singh (1974, p. 212) after Glennie (1970) list the following criteria as characteristic of wind-deposited sands.

1. Bedding can be horizontal but usually exhibits large-scale cross--bedding, showing fairly constant orientation.
2. Individual laminae are well sorted, especially in the finer grain sizes; sharp grain size differences between laminae are common.
3. Grain sizes commonly ranges from silt to coarse sand. Maximum size for granules and small pebbles transported by wind is in the order of 1 cm, but particles exceeding 5 mm in diameter are rare.
4. The larger sand grains 0.5 - 1.0 mm) tend to be well rounded.
5. Clay drapes are rare.
6. Sands are free of clay.
7. Uncemented quartz grains exhibit a frosted surface.
8. Mica is commonly absent.

E-log Characteristics

Sand dunes that have been preserved in a sequence of marine or lacustrine shoreline sands, or in river point bar deposits, commonly appear to be lacking in stratification. Close examination may indicate that the dune deposit is in fact cross-bedded, but that its equidimensional grain size tends to mask the laminae. In other dunes, adjacent laminae may be readily apparent where they exhibit a marked degree of variation in grain size. But within the dune as a whole there is commonly little variation in mean grain size from top to bottom. Also, there is little intergranular material, the sands being clean and very well sorted. Winnowing by the wind, repeated continually, results in the segregation of sands into accumulations of various but consistent ranges in grain size. Subsequent cycles of winnowing, caused by a change of climate or wind pattern, may result in the development of younger over-riding dunes composed of sand with a different mean grain size. Consequently, an accumulation of sand dunes, that may be more than 100 m thick, will have a consistent mean grain size within each individual dune, but may show variations, between dunes. The self-potential curve reflecting a sequence of superimposed dunes will be characterized by its cylindrical shape, but the curve may show either a fairly constant amplitude, or superimposed segments (representing superimposed dunes) of different amplitudes.

Compaction

With the exception of small sand dunes in river point bars and shoreline sand bodies, eolian sands are deposited in desert environments on a land surface. This land surface may be an unconformity, or it may closely represent an hiatus within an alluvial fan or sheet hundreds of feet thick. It may also represent an hiatus in a paralic to inner neritic environment where a carbonate shelf or tidal flat is exposed by a regressing sea to form an extensive coastal plain that subsequently is encroached upon by sheets and dunes of sand. The effects of compaction on individual sand bodies such as discrete but composite dunes, and on sand sheets or sand beds composed of merging dunes will depend on the stratigraphic relationships that obtain. Where a sand dune, simple or complex, lies on an unconformity, or on a thick section composed essentially of alluvial fan sands, it will retain to a large degree its original shape, which is mainly planar at the base and convex at the top. But where a dune overlies compactible sediments, such as coastal deposits of mud, its original planar base may be deformed so that the sand body becomes bi-convex. In this context it might be difficult to distinguish such a dune, subsequently buried by marine sediments, from a tidal current sand body (Fig. 7-4).

Discrete eolian sand bodies of this type are the exception, and most wind-deposited sands form beds lying on fairly flat surfaces which have been bevelled prior to or penecontemporaneously with the deposition of the overlying bed. Compaction of such a bed is comparatively uniform and does not present problems of morphology different from those encountered in the compaction of sandstone beds of other origins.

With reference to the effects of compaction on the porosity and permeability of eolian sands, the original differences in composition between wind deposited and water-lain sands are significant. Eolian sands are commonly, but not always, quartz sands. They are of fairly uniform grain size, and do not have an appreciable original content of silt or clay deposited as dust with the sand. Exceptions are found in the delta of the Rio Grande River, Texas, where dunes of extremely fine sand and silt are referred to as 'clay dunes'. Diagenetic alterations resulting from compaction after burial are minimal in most eolian sands, although meteoric waters moving through a bed of sand may cause some solution and re-precipitation (Rittenhouse, 1971) resulting in pitting of the grains and in the development of intergranular growths of quartz that decrease porosity and permeability. In general, eolian sands retain much of their original pore space, and compaction has less effect on them than it does on sands of other origins. In many eolian sandstone bodies the porosity and permeability is fairly uniform throughout the body, a condition that obtains in some marine sands, but rarely in fluvial sands.

Ancient Sand Bodies

Among the many ancient eolian sand deposits, some clastic examples are found in the Jurassic Navajo Sandstone (Stokes, 1961) of the Colorado Plateau, the Jurassic Entrada Formation (Tanner, 1965) of New Mexico, the Triassic Botucatú Formation (de Almeida, 1953) of the São Paulo area, Brazil, the Permian Coconino Sandstone (McKee, 1969) of the Grand Canyon, and the Pennsylvanian to Permian Caspar Formation (Conybeare and Crook, 1968) of Wyoming. These sandstone beds exhibit the large-scale, sweeping cross-beds characteristic of sand dunes. Fossil sand sheets, on the other hand, do not have the marked diagnostic features of eolian dunes, and consequently have not been readily recognized.

Beds of ancient eolian sands commonly range in thickness to more than 100 m. The Navajo, which is a highly porous medium to fine-grained quartz sandstone (Lessentine, 1965), ranges up to 300 m. It is of interest to note that present-day accumulations of sand dunes in the Sahara are known to locally attain a thickness of 200-300 m. The Entrada, which is overlain by beds of anhydritic limestone, has an upper sandstone member that is partly of eolian origin. This sandstone is described by Peterson *et al.* (1965) as massive, orange to grey, friable, fine to medium-grained, and ranging in thickness up to 150 feet. They regard the Entrada Sandstone as a porous and permeable blanket sandstone that forms essentially one hydrologic unit. The Coconino Sandstone, which in cross-bedded outcrops resembles the Navajo, is described by McKee (1969) as a well-sorted quartz sand that forms a wedge, ranging in thickness to more than 150 m, across northern Arizona. McKee (1969, p. 88) describes the Coconino as follows:

"The most distinctive structure in the Coconino is the large-scale, wedge planar cross-stratification that is prominently displayed in the white cliff faces of this sandstone throughout the region (McKee, 1933). The inclined laminae, having dips of as much as 34 degrees, have gently curving surfaces that in places are 60-70 feet long. The bevelled upper edges of individual sets are formed by low angle erosion surfaces that constitute the bases of higher sets of cross-strata. Other structures typical of the Coconino are long, parallel ripple marks, with rounded crests and oriented with axes parallel to the dip slopes".

The above description is typical of many outcrops of ancient eolian sands which form massive and magnificently sculptured geological monuments in some of the national parks of the U.S.A., and in other parts of the world. The Botucatú Formation, which extends southward from Brazil into Uruguay and Argentina, is of particular interest because it may be, according to Sanford and Lange (1960), the largest continuous eolian deposit in the world, covering an area of more than 1,300,000 sq. km. This formation, which commonly ranges in thickness up to 200 m but is more than 300 m thick in the São Paulo area, consists of fine to medium-grained quartzose sandstone. The sand grains are well rounded, have pitted surfaces, and are covered with a red ferruginous pigment. A striking feature of the outcrops is the characteristic eolian cross-bedding similar to that of the Coconino described above. The Botucatú lies on an unconformity and is unconformably overlain by Upper Triassic volcanics.

The Botucatú has good porosity and permeability, and in favourable stratigraphic and structural conditions could be a potentially attractive reservoir bed for oil or gas. Sanford and Lange (1960, p. 1344) say, "In the state of São Paulo are large areas in which these sandstones are impregnated with residual asphalt derived from oil seeping up through faults".

Oil and Gas Fields

Referring to the economic significance of eolian deposits, Selley (1970, p. 63) says, "Eolian sandstones are potentially of high porosity and permeability because they are typically well-rounded, well-sorted, and generally only lightly cemented. Regional permeability is likely to be good due to absence of shale interbeds. Because of these features eolian sandstones can be important aquifers and hydrocarbon reservoirs". Selley is of the opinion that in general eolian deposits can be rated as poor prospects because they commonly occur within continental basins, although these may overlie, or be overlain by a sequence of marine to paralic strata that includes source beds for oil or gas. The Lower Permian Rotliegendes red-beds of northwest Europe and the North Sea contain examples of gas--bearing eolian sandstones overlying source beds.

North Sea Gas Fields

Major gas fields producing from the Rotliegendes in the North Sea include Groningen on the north coast of the Netherlands, and Indefatigable, Leman, and West Sole in British waters off the coast of East Anglia and Lincolnshire. The Rotliegendes, which includes eolian and other desert environment sandstones, lies unconformably on Carboniferous coal measures. Glennie (1972) shows that the distribution of the Rotliegendes is confined to northwest Europe and the southern part of the North Sea where it extends to the east coast of England. From south to north the facies grade from those formed in a fluviatile environment characterized by wadis, to desert sand dunes formed on a coastal plain, and farthest north to shaly sediments and evaporites on a tidal plain similar to the present day sabkha environment of the Persian Gulf. With reference to the thickness and lithologic variations of these beds, Kent (1967, p. 739) remarked, "It is not possible at the present time to comment on the regional variation of the Lower Permian Rotliegendes. The critical point is that it includes the main objective of the North Sea gas search: a basal sandstone unit with a thickness in some places measured in hundreds of feet. This sandstone contains in the discovery fields at Slochteren and probably elsewhere an important proportion of almost uncemented dune sandstone of high porosity and permeability". The Slochteren wells are situated near Groningen on the north coast of the Netherlands. Some five years later, with reference to sections in the southwestern and south-central parts of the Rotliegendes basin, Glennie (1972, p. 1055) was also reticent about quantifying thickness or general lithology and stated, "Total thickness and relative proportions of each facies change from place to place, hence no scale can be given. One or more of these sedimentary facies may be absent in any particular area".

In general, the Rotliegendes comprises a lower unit of conglomeratic sandstone interbedded with cross-bedded sandstone, and an upper unit of well-sorted, planar cross-bedded sandstone which is overlain by beds of dolomite and evaporites. The lower unit is interpreted by Glennie (1972) as comprising dune and fluviatile sands formed in a mixed eolian and wadi environment. The upper unit he interprets as an accumulation of sand dunes. These gas-bearing sandstones form a facies which is distributed from Groningen west to England, covering an area approximately 1,000 km long and up to 300 km wide. The Rotliegendes basin, as a whole, also trends east--west and is up to 2,000 km long and 500 km wide.

The geological history of these gas-bearing sands and associated beds has been outlined by Glennie (1972). Uplift and levelling of the Carboniferous coal measures was accompanied by the inland regression of an escarpment incised by wadis and flanked by alluvial fans. Wind-blown sands formed a sheet of dunes over a plain extending to the sabkhas which fringed the coastline of a large inland body of salt water. Subsequent transgression of this desert sea over the coastal plain resulted in reworking of the uppermost part of the dune sands, and subsequently in deposition of the Kupferschiefer, the cupriferous shales that are the basal unit of the Zechstein evaporites.

With reference to the lithology of the gas-bearing dune sands Glennie (1972, p. 1058) says, "The grain size of these sands ranges from very fine to medium and, locally, particularly near the base of an intra-formational sequence, may be coarse. The finer grains are subangular and the coarser ones subrounded or, rarely, rounded. Frosted grains are common. No argillaceous material is present apart from authigenic clay. The sandstones generally are cemented with hematite and authigenic clay, but locally dolomite and anhydrite are important as cements, together with minor authigenic quartz. Depending on the amount of cement present, the sandstone may be hard or quite friable. Where primary porosity is preserved, these sandstones form the main reservoir rock for the Rotliegendes gas".

According to Glennie (1972) the probable producible reserves of gas from known major fields within the Rotliegendes amount to about 2,500 billion (thousand million) cubic meters. This is the equivalent of 85 trillion (million million) cubic feet. This amount includes 1,800 billion cubic meters in the Groningen field and 700 billion cubic meters in off--shore North Sea Fields (Indefatigable, Leman, and West Sole). Additional recoverable reserves of about 250 billion cubic meters (8.5 trillion cubic feet) are estimated to be contained in smaller fields yielding gas from the Rotliegendes in the Netherlands and West Germany.

Hassi R'Mel and Houd Berkaoui Gas and Oil Fields, Algeria

The Hassi R'Mel Gas Field and the Houd Berkaoui Oil Fields are situated 600 km and 800 km respectively southeast of Oran, Algeria. Both of these fields are producing from gently elongate domes within Lower Triassic sandstones which unconformably overlie an undulating surface of Paleozoic (in part Cambro-Ordovician) rocks. The dome structures appear to result from draping of the Lower Triassic sandstones over buried hills of Paleozoic rock. These sandstones, which have not been named, are described by Ali (1973). They cover an area of at least 150,000 sq km in northwestern Algeria, and range in thickness up to 200 m depending on the topography of the underlying Paleozoic. In the north-central area of the Algerian Sahara the Lower Triassic lies directly on the Precambrian.

The Lower Triassic has been divided by Ali (1973) into four units as follows: a basal Series Inferior comprising 70 m of shale, andesite and sandstone; a lower unit "C" consisting of 50 m of sandstone; a middle unit "B" containing 40 m of shale and sandstone; and an upper unit "A" of quartzose sandstone having a thickness in the range 10-30 m. Unit "A" is conformably overlain by shale and evaporites. In the Hassi R'Mel Field, the main reservoir is Unit "A", whereas in the Houd Berkaoui Field production is obtained largely from sandstone beds in the Series Inferior. Ali (1973) describes Unit "A" as fine to medium-grained, consisting of sub-rounded grains, partly cemented with anhydrite. The sandstone is fairly well sorted and has fair to good porosity ranging up to 16%. Sandstone beds in the Series Inferior are fine to coarse-grained. In general, the Lower Triassic sandstones are quartzose, consisting of sub-rounded to sub-angular grains. Porosity is commonly in the range 12-15% but ranges up to 20%. Permeability averages 500 millidarcys and ranges up to 1,300 millidarcys.

Ali (1973) states that gas reserves in Hassi R'Mel Field are estimated to be 70 trillion cubic feet (1,960 billion cubic metres). No estimates of production capabilities are given for Houd Berkaoui Field which contains 13 m of net sand.

No fossils have been found in the Lower Triassic sandstones in the northwestern part of the Algerian Sahara. The sandstones lie unconformably on a gently undulating erosional surface of Paleozoic and Precambrian rocks and are conformably overlain by a Middle to Upper Triassic evaporitic sequence. These stratigraphic relationships are similar to those of the Rotliegendes in the North Sea area and suggest that the Lower Triassic gas and oil-bearing sandstones of Algeria are largely non-marine and probably, in part at least, of eolian origin.

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