U. S. DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

OPEN FILE

SUBSURFACE GEOLOGY OF THE DAKOTA SANDSTONE IN THE OIL-FIELDS AREA OF THE DENVER BASIN, COLORADO AND NEBRASKA

by

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FEBRUARY 1958

58-10

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INTRODUCTION

The area of this report includes parts of northeastern Colorado, southwestern Nebraska, and extreme southeastern Wyoming, which embraces most of the recently-developed oil and gas fields of the Denver basin. The report area will be referred to herein as the oil-fields area, although some of the maps cover a somewhat broader region. The limits of the Denver basin and the outline of the oil-fields area are shown on figure 1. The oil and gas fields are confined to lenses of sandstone in three sand zones--known by the oil industry as the D, J, and M sands--in the Dakota sandstone of Early Cretaceous age; each lens occupies a relatively small area. The J and D sands are the principal oil-producing zones, yielding high-gravity (38°-39° API) oil in the oil-fields area. The oil pools that yield oil from each of these zones are shown on figures 5 and 6. The M sand has yielded shows of oil in many wells but only a few wells have yielded commercial quantities of oil, which is of low gravity (about 15° to 16° API).

ACKNOWLEDGMENTS

Lithologic logs of many wells in the area, prepared from microscopic examination of well cuttings by the American Stratigraphic Company, Denver, Colorado, were used extensively for thickness data of formations and lithologic descriptions of sands. Base maps shown in several of the figures, locations of oil and gas wells and dry holes, altitudes of wells, and production data were obtained from maps and well-completion cards compiled by Petroleum Information, Inc., Denver, Colorado. Electrical logs by Schlumberger Well Surveying Corporation, Houston, Texas, were used extensively. The writer is particularly grateful to George D. Volk of Plains Exploration Company, Denver, Colorado, for furnishing many cores of the J and D sands and associated beds. Other cores were supplied by the Skelly Oil Company. Certain maps showing oil and gas fields and other data were furnished by Dunn & Boreing, geological consultants, Denver, Colorado. The writer is grateful to the U. S. Bureau of Mines for analyzing many samples of crude oil from the oil fields in the area, and particularly to John S. Ball of that Bureau for a memorandum in which the many items of the analyses were compiled and certain interpretations were made.

Footnote: The U. S. Geological Survey uses the term Dakota group in the Front Range foothills in Colorado and the term Dakota sandstone for the subsurface in northeastern Colorado.

STRUCTURE

Structurally the oil-fields area lies on the gently dipping east flank of the Denver basin (fig. 6). The strike of the Lower Cretaceous rocks in the subsurface is generally northeastward in the Colorado part of the oil-fields area, thence northward in Nebraska and northwestward in the northernmost part of the area. The average dip westward across the oil-fields area at the Colorado-Nebraska boundary is 31 feet to the mile.

Throughout much of the oil-fields area the oil and gas fields occur in sandstone lenses and the areas of the fields appear to be controlled by the extent of the sandstone bodies. The oil and gas fields in the central and southern parts of Cheyenne County, Nebraska, however, are chiefly on local anticlines (Finch, Cullen, and Sandberg, 1955). In other words, the chief occurrence of pools of oil and gas in this area is in stratigraphic rather than structural traps.

An area (Tps. 2 S., to 2 N., Rs. 55 to 58 W.) in the southern part of the oil-fields area, which includes many oil fields in the D and J sands was selected to illustrate the structure of the subsurface rocks (see fig. 2). The contours are drawn at intervals of 10 feet on the "bentonite marker" bed in the Graneros shale. The most apparent feature of the structure contour map is that the contours are smooth-flowing between the oil fields where the control points are spaced widely, and are very irregular in the oil fields where the control points are closely spaced. The general strike of the subsurface rocks of the area shown on figure 2 is northeastward and the rate of regional dip northwestward is about 40 feet to the mile. At the north end of each of the D sand oil fields in Tps. 1 N. to 2 S., Rs. 56 to 57 W., (see fig. 9 for location of D sand pools) the structure contours bend sharply to the east. This structural feature may be due to compaction of the sediments overlying the D sand zone, including the contour datum bed--the "bentonite marker".

STRATIGRAPHY

The oil- and gas-bearing sand lenses in the Denver basin of Colorado and Nebraska and the extreme southeastern corner of Wyoming are in the Dakota sandstone of Early Cretaceous age. Depth to the top of the Dakota sandstone ranges from about 4,000 feet to 7,500 feet in the main oil-bearing area (see fig. 5).

Rocks overlying the Dakota sandstone

In the oil-fields area the rocks overlying the Dakota sandstone are of Tertiary and Cretaceous age (see table 1).

System	Series	Formations or group		Members or subunits
Tertiary	Pliocene	Ogallala formation		
Tertiary	Miocene	Arikaree formation		
Tertiary	Oligocene	White River group		
Tertiary	Paleocene	Denver formation		
Cretaceous	Upper Cretaceous	Arapahoe formation		
Cretaceous	Upper Cretaceous	Laramie formation		
Cretaceous	Upper Cretaceous	Fox Hills sandstone		
Cretaceous	Upper Cretaceous	Pierre shale		Hygiene sandstone zone
Cretaceous	Upper Cretaceous	Niobrara formation		Smoky Hill chalk member
Cretaceous	Upper Cretaceous	Niobrara formation		Fort Hays limestone member
Cretaceous	Upper Cretaceous	Benton shale (Front Range foothills, Colo., and western Nebraska)	Carlile shale (northeast Colo.)	Codell sandstone member
Cretaceous	Upper Cretaceous		Greenhorn limestone (northeast Colo.)	
Cretaceous	Upper Cretaceous ?		Graneros shale (northeast Colo.)	(contains "bentonite marker" bed about 90 feet above base.)
Cretaceous	Lower Cretaceous	Dakota sandstone		D sand zone
Cretaceous	Lower Cretaceous			Upper shale unit
Cretaceous	Lower Cretaceous			J sand zone
Cretaceous	Lower Cretaceous			Lower shale unit
Cretaceous	Lower Cretaceous			M sand zone
Jurassic	Upper Jurassic	Morrison formation		

Table 1.--Rocks exposed or penetrated by wells in report area. (Older rocks which were penetrated by some wells are not shown.)

Beds of clay, conglomerate, and sandstone of Tertiary age unconformably overlie the Laramie formation, Fox Hills sandstone, and Pierre shale; the Pierre underlies the Tertiary formations in most of the oil-fields area. The rocks of Tertiary age in most of the oil-fields area include, in descending order, strata assigned to the Ogallala and Arikaree formations and to the White River group. The total thickness of these rocks ranges from a few feet to about 1,400 feet or more. The maximum thickness observed is slightly less than 1,400 feet in Stanolind Oil & Gas Company's No. 1 Barret in sec. 23, T. 18 N., R. 56 W., Banner County, Nebraska, as shown in the well log by American Stratigraphic Company. In the extreme southwestern part of the oil-fields area, the Denver formation of Paleocene and Late Cretaceous age and the Arapahoe formation of Late Cretaceous age overlie the Laramie formation.

The Laramie formation of Late Cretaceous age is present in the western part of the area. It consists generally of interbedded fine-grained gray to tan sandstone, dark-gray carbonaceous shale, coal, and gray shale. Its thickness is about 800 feet near Boulder, 50 miles west of the oil-fields area (F. D. Spencer, personal communication), and its thickness diminishes eastward to a tapering wedge in the oil-fields area.

Underlying the Laramie formation in the western part of the Denver basin is the Fox Hills sandstone, about 400 feet or less in thickness. It consists, according to Blair (1951), of light-gray to tan fine-grained calcareous sandstone and light-gray slightly micaceous sandy shale and a little carbonaceous material.

The Pierre shale consists largely of gray to dark-gray marine shale. It is divisible into three parts. The upper part, which consists largely of shale, is sandy in its upper part and becomes increasingly less sandy downward. The uppermost sandy beds constitute a transition zone below the overlying Fox Hills sandstone. The middle part of the Pierre consists of interbedded sandy shale, shaly sandstone and shale 1,000 to 2,000 feet or more in thickness and is known as the Hygiene sandstone zone of local usage (Blair, 1951). The basal part consists largely of shale that is darker gray than the rest of the formation. The thickness of the Pierre shale decreases eastward across the area (Mather, Gilluly, and Lusk, 1928, p. 86-92; Blair, 1951) as indicated by thicknesses of 7,900 feet in Continental Oil Company's No. 1 Borra in sec. 5, T. 1 S., R. 69 W. (Blair, 1951); 6,650 feet in Frontier Refining Company et al. No. 1 Hankins in sec. 22, T. 5 N., R. 67 W.; and 5,765 feet in Honolulu Oil Company's No. 1 State in sec. 16, T. 4 N., R. 63 W.

The Niobrara formation, about 450 feet thick, consists of limy shale and thin beds of chalky limestone. The upper beds constitute the Smoky Hills chalk member, and the basal 50 feet, which consists mostly of beds of chalky limestone, constitute the Fort Hays limestone member.

The Benton shale of Late and Early Cretaceous age underlies the Niobrara formation and overlies the Dakota sandstone; it is about 400 feet thick. Equivalents of the Benton shale in the oil-fields area, in descending order, are the Carlile shale, the Greenhorn limestone, and the Graneros shale. The Carlile shale consists mainly of gray shale, much of which is limy, and is about 220 feet thick. The top 10 to 20 feet of the Carlile is fine-grained micaceous sandstone and sandy shale which constitutes the Codell sandstone member. The Greenhorn limestone consists of interbedded limy shale and thin beds of fossiliferous limestone about 40 feet in thickness. The Graneros shale is largely dark-gray to black marine shale about 140 feet thick. A persistent bed of bentonite about 2 feet thick is present about 90 feet above the base of the Graneros. This bed is known as the "bentonite marker" because it is readily identified as a sharp indentation on the resistivity curves of electric logs, and is widely used as a key bed. Fish scales and fish-bone fragments are common in the Graneros, particularly below the "bentonite marker", and suggest that the Graneros is in part equivalent to the Mowry shale of Early Cretaceous age in Wyoming.

Dakota sandstone

A sequence of interbedded units of sandstone and shale of Early Cretaceous age constitutes the Dakota sandstone. The total thickness of the group in the oil-fields area of the Denver basin ranges from about 350 feet at the southwestern end of the oil-fields area to about 600 feet at the northeast end. The northeastward increase in thickness continues beyond the oil-fields area and the southwestward decrease in thickness continues southwestward beyond the oil-fields area (fig. 3). In the oil-fields area the Dakota sandstone generally contains three main units of sandstone--in descending order, the D, J, and M sands (table 1)--and two intervening units of dark-gray to black shale. Some writers have designated the upper of these two shale units the Huntsman shale and have correlated the lower shale unit with the Skull Creek shale of southeastern Wyoming (Sternberg and Crowley, 1954, p. 38; Jensen and Sharkey, 1954, p. 62). In western Nebraska, northeastward from the oil-fields area, these shale units grade into sandy shale and sandstone (fig. 4), merging with the D, J and M sand units to form a thick Dakota sandstone.

D sand zone.--The D sand zone, the uppermost zone in the Dakota sandstone, ranges in thickness from a feather edge to more than 75 feet. It is composed of interbedded sandstone, sandy shale, and shale. It yields high-gravity oil.

The distribution of the oil- and gas-bearing sandstone lenses of the D sand zone known to date is shown on figure 5. The dotted line on figure 5 extending northward across Arapahoe, Adams, and Weld Counties, Colorado and in southeastern Wyoming near the Nebraska-Wyoming boundary, shows the approximate position of the wedge-edge or pinchout of the D sand. Westward from this dotted line the horizon of the D sand is occupied by marine gray shale and locally silty shale in the Graneros formation. Eastward from this line the D sand zone is present throughout the parts of northeastern Colorado and southwestern Nebraska containing oil and gas fields. Many miles northeast of the main area of oil and gas fields the D sand merges with other members of the Dakota to form essentially a single thick sandy sequence that occupies the entire Dakota stratigraphic interval. In general, the D sand oil- or gas-bearing sandstone lenses have a northeastward-trending alinement in broad, somewhat poorly defined belts. A broad belt of country trending westward across northern Washington County, thence northward across northeastern Morgan and eastern Weld Counties appears to be devoid of oil- or gas-bearing sandstone bodies at the stratigraphic position of the D sand.

The D sand zone is characterized by the lenticularity of its beds. Although in some fields the D sand forms a single lens that is mostly sandstone the oil-bearing sandstone of a given pool commonly consists of two or more thin beds of sandstone separated by non-oil-bearing beds of sandy shale or shale. In some pools certain beds yield oil in some wells and other beds of the zone yield oil in other wells. The beds of sandstone are noncalcareous, light gray, light tan, or light buff, and are composed chiefly of clean, angular to subangular, very fine to fine, and locally medium well-sorted grains of quartz, a little mica, and locally glauconite. Carbonized plant fragments and grains of pyrite are present locally. The sandstones are fairly tightly bonded, commonly with silica. New quartz growth is common.

The beds of sandstone in the D sand zone appear as massive bedded sandstone in many cores; on the other hand, crossbedding at angles up to 8 degrees is not uncommon. The porosity of the oil-bearing sandstone beds commonly ranges from 17 to 22 percent, although lesser porosities have been recorded in many oil fields and larger porosities are present in a few fields (Jensen, Sharkey, and Turner, 1954). The horizontal permeability of the oil-bearing sandstones is less than 300 millidarcys for many of the oil fields tabulated, ranges between 300 and 800 millidarcys for many other fields, and is more than 800 for a few fields (Jensen, Sharkey, and Turner, 1954).

The partings and shale beds interbedded with the beds of sandstone commonly consist of gray to dark-gray silty or sandy shale, dark-gray to black shale and so-called "contorted" or "reworked" siltstone and shale. These beds are micaceous and locally pyritic.

Beds of clean sandstone of the D sand zone commonly are present in the oil fields; outside the boundaries of the oil fields, and interbedded with clean sandstone in some fields are tiny lenses and irregular shaped bodies varying from 1/8 inch to several inches in diameter of very fine to fine sand or siltstone intermingled with lenses and irregularly shaped pieces of black shale. This rock is commonly referred to in the oil fields as "reworked" sand and shale. The boundaries between lenses and pieces of sandstone and shale are generally sharp. Animal borings that pass through the "reworked" sand and shale are relatively common, suggesting deposition in shallow water. Carbonized plant fragments are common constituents of the rock. Some tiny lenses and irregular masses of sandstone in some cores are saturated with oil. These oil-saturated lenses are sharply defined from other similar lenses that are clean and barren of oil. This irregularity in bedding suggests that the sand and shale was disturbed a short while after its deposition and may have been produced by burrowing animals that lived on the shallow sea bottom and constantly rearranged the newly-formed deposits of shale, silt, and sand. Moore and Scruton (1957, p. 13) describe similar sedimentary structures in present-day sediments of the Gulf Coast and attribute them to disturbance by benthonic organisms. Cores of "reworked" silt and shale from the D and J sand zones were sent to Scruton, who identified the structures in the cores as being similar to those in the recent Gulf Coast sediments (P. C. Scruton, written communication, April 11, 1957).

Upper shale unit.--A unit of dark-gray to black shale, which is designated the Huntsman shale by some writers (Sternberg and Crowley, 1954, p. 38), lies between the D and J sand zones. Its thickness ranges from less than 25 to more than 80 feet. A thin bed of sandstone known locally as the G sand (fig. 4) is present in places in the northeastern part of the oil-fields area in the upper part of this shale unit. It is similar in composition and physical character to the D sand and may be equivalent to part of the D sand. The upper shale unit commonly contains scales and bone fragments of marine fish, and shells of the brachiopod *Lingula*. In western Nebraska, northeastward from the oil-fields area and eastward near the Colorado-Kansas boundary, it grades laterally into sandstone.

J sand zone.--The J sand zone, the middle sand zone in the Dakota sandstone, is composed dominantly of sandstone and sandy shale. The J sand zone is more extensive than the D sand zone; it is present throughout the oil-fields area and westward to the outcrops of the Dakota group along the Front Range foothills, where it constitutes the uppermost sandstone unit of the Dakota group. Shells of the brachiopod *Lingula* are present in the top beds of the J sand in cores from many wells. The J sand zone is, in general, thicker than the D sand zone, its thickness ranging from a few feet to more than 150 feet. The J sand zone, like the D sand, yields high-gravity oil in the oil-fields area of the Denver basin.

The J sand zone is similar to the D sand zone in many respects and many of the lithologic characteristics discussed in the section on the D sand zone apply equally well to the J sand zone. It commonly consists of interbedded sandstone, sandy shale, and shale, and has a basal unit, 25 to 50 feet or more thick, of water-bearing sandstone. A characteristic feature of the J sand zone, as well as the D sand zone, is the lenticularity of the beds of sandstone that compose the zone. Commonly the oil-bearing sandstone of a given oil pool consists of two or more thin beds of sandstone separated by non-oil-bearing beds of sandy shale or shale. In some pools certain beds yield oil in some wells but are barren of oil in other wells. The oil pools in T. 14 N., R. 55 W., Nebraska, exhibit this feature in the J sand, as illustrated by the logs of three wells shown in figure 8.

The beds of sandstone of the J sand zone are noncalcareous, light gray to light tan, and are composed chiefly of clean, angular to subangular very fine to medium grained, though more commonly very fine to fine grained quartz with a little mica and locally glauconite. Carbonized plant fragments and grains of pyrite are present locally. The sand grains are fairly tightly bonded, commonly with silica. New quartz growth is common. The sand grains are well sorted; for example, a sieve analysis of a sample of the oil-bearing part of the J sand in Sohio Petroleum Company's No. 1 Bennett Reservoir Unit, in sec. 22, T. 15 N., R. 55 W., Kimball County, Nebraska, shows 90.8 percent of the grains to be fine sand, 3.5 percent very fine sand, 0.5 percent medium sand, and 3.1 percent silt and clay.

Cores of the J sand commonly show massive beds of sandstone, but crossbedding at angles up to 8 degrees is not uncommon. The porosity of the oil-bearing sandstone beds commonly ranges from 17 to 22 percent, although the range is much greater than this (Jensen, Sharkey, and Turner, 1954). The horizontal permeability of the oil-bearing sandstones ranges between 300 and 800 millidarcys for some fields, although the range also is much greater (Jensen, Sharkey, and Turner, 1954). The partings and beds of shale interbedded with the sandstone commonly are micaceous and locally pyritic, and consist of gray to dark-gray silty or sandy shale, dark-gray to black shale, and so-called "reworked" sand and shale.

Like the D sand zone, beds of clean sandstone are present in the oil fields; and outside the oil fields the sand zone commonly consists of the so-called "reworked" sand and shale.

The distribution of oil and gas pools in the J sand zone in the oil-fields area of the Denver basin is shown in figure 6. The broad area containing the oil- and gas-bearing sandstone lenses has a general northeast alinement. Moreover, several groups of oil- and gas-bearing sandstone lenses form northeastward-trending belts within the broad area of J sand oil fields. No oil- or gas-bearing J sand lenses are known to date in a belt of country extending westward across northwestern Washington County and east-central Morgan County, thence northwestward across northwestern Morgan County and across Weld County, Colorado. This area, in which no oil and gas pools have been found, coincides roughly with a similar belt of country for the younger D sand.

Lower shale unit.--A unit about 100 feet thick composed of dark-gray to black shale lies between the J and M sands (table 1) and is called the lower shale unit in this report. It is generally considered to be equivalent to the Skull Creek shale of eastern Wyoming (Jensen and Sharkey, 1954, p. 62; Sternberg and Crowley, 1954, p. 38). This unit contains marine fossils and fossil fragments in well cuttings from wells throughout the region. In western Nebraska, northeastward from the oil-fields area and eastward near the Colorado-Kansas boundary, the shale disappears by lateral gradation to sandstone.

M sand zone.--The M sand zone constitutes the basal unit of the Dakota sandstone in the subsurface. The M sand yields oil in sec. 6, T. 9 N., R. 52 W., and sec. 26, T. 11 N., R. 53 W. Most wells are not drilled deep enough to reach the M sand inasmuch as it has yielded only low-gravity oil (about 15° to 16° API) in a few wells, and therefore does not offer sufficient economic appeal to operators to encourage them to make the additional expenditure to test it. The thickness of the M sand ranges from less than 50 to more than 250 feet. Regionally it thickens northeastward across the area (see fig. 7). It is noteworthy that a broad indefinitely-bounded area containing thick M sand extends southwestward through the oil-fields area and roughly coincides with an area shown on figure 3 wherein the total thickness of the Dakota group is uncommonly large.

The M sand is the most variable of the three principal sand zones of the Dakota sandstone. It is composed of interbedded light-gray to buff sandstone, dark-gray to varicolored shale, and conglomerate. A chert-pebble conglomerate ranging from 5 to 50 feet thick is present at the base of the unit throughout most of the region. The records of wells indicate that the conglomerate is absent, however, in a large area occupying much of Kimball County, Nebraska, and northern Logan County, Colorado. The beds of sandstone above the conglomerate are composed chiefly of fine- to medium-grained quartz although beds of coarse-grained sandstone are not uncommon. Some beds are slightly micaceous. The beds of shale are commonly dark gray, and some beds are greenish gray and maroon. Carbonaceous shale, coaly shale, and coal are relatively common. Siderite concretions and pyrite are common. Shows of heavy oil and dead oil are reported from many wells.

Correlation of exposed and subsurface Dakota

The Dakota group crops out and forms an almost continuous hogback at the foot of the Front Range at the west margin of the Denver basin (fig. 3). As a result of a detailed investigation of the stratigraphy and paleontology of the Dakota group on the outcrop along the Front Range, Waage (1955, p. 18) observed that the most noticeable feature of the group in eastern Colorado is its divisibility into two distinctive parts--the Lytle formation below and the South Platte formation above. The Lytle formation is equivalent to most of the M sand zone of the subsurface as used in this report, and the South Platte formation is equivalent to the uppermost part of the M sand zone, the lower shale unit, and the J sand zone (fig. 4). The Lytle formation is described by Waage as consisting of irregular lenses of light-gray, white and buff porous sandstone and conglomerate that are irregularly interbedded with varicolored claystone similar to that of the underlying Morrison formation. On the outcrop these rocks are characterized by their variable color; in the sandstones buff and gray predominate and pink and yellow stain is common. Variability characterizes the formation. At some places the Lytle formation contains beds of conglomerate at its base and is separated from the Morrison by a disconformity; at other places the conglomerate is absent and no break between the formations is apparent. The Lytle formation is equivalent to the Cheyenne sandstone member of the Purgatoire formation of southeastern Colorado and the Cheyenne sandstone in southwestern Kansas (McLaughlin, 1954, p. 96-97). There it is generally a massive sandstone about 100 feet thick and is water bearing. The Lytle formation is also equivalent to the Lakota sandstone and to part or all of the Fuson shale of northeast Wyoming (table 2).

Northeast Wyoming	Central Wyoming		Northern Front Range foothills, Colorado		
Mowry shale		Mowry shale	Benton shale		
Newcastle sandstone		Muddy sandstone	(first sandstone subunit)	South Platte formation	Dakota group
Skull Creek shale		Thermopolis shale (restricted usage)	Van Bibber shale member	South Platte formation	Dakota group
			Kassler sandstone member	South Platte formation	Dakota group
			(shale and sandstone)	South Platte formation	Dakota group
Fall River sandstone	Cloverly formation	Upper sandstone member	Plainview sandstone member	South Platte formation	Dakota group
Fuson shale	Cloverly formation	Shale member		South Platte formation	Dakota group
Lakota sandstone	Cloverly formation	Conglomerate sandstone member	Lytle formation		Dakota group

Table 2.--Correlation chart, after Waage (1955, p. 42, 46)

On the outcrop the upper unit of the Dakota group, the South Platte formation, is separated from the Lytle formation by a persistent disconformity which constitutes the most obvious physical break occurring between the Morrison and Graneros formations, according to Waage (1955, p. 19). He observed the disconformity throughout the outcrop of the Dakota group in eastern Colorado and in adjacent states. The South Platte formation is more regular in lithology, bedding, and thickness than the Lytle formation. It consists of relatively thick units of light-gray to light-buff sandstone interbedded with units of dark-gray shale. Waage observed that south of about the latitude of Denver, the South Platte formation is composed predominantly of thick units of continental sandstone and relatively thin units of shale, only a few of which are marine. Northward from Denver most sandstone units become thinner and are marine; the shale units thicken and many beds in them contain marine fossils. For example, on the South Platte River, about 12 miles southwest of Denver, five thick units of sandstone are present in the Dakota group (Waage, 1955, p. 21, 43), but on Box Elder Creek, 10 to 12 miles south of the Colorado-Wyoming boundary, only two thick units of sandstone are present, one near the base and the other at the top of the group. The total thickness of the group is a little less than 400 feet at the first locality and a little less than 300 feet at the latter.

ENVIRONMENT OF DEPOSITION OF THE DAKOTA SANDSTONE

Waage (1955, p. 19) concluded from his investigation of the Dakota group on the outcrop that the Lytle formation in Colorado consists of flood-plain deposits much like the Morrison formation, and that much of the sediment comprising the Lytle was derived from the Morrison. He described the disconformity at the base of the Lytle as a transgressive feature affording the first evidence of an invading Cretaceous sea. The initial deposits above the disconformity consist chiefly of brackish water beds presumably deposited in local deltas or in local water bodies on the coastal plain marginal to the invading sea. The available subsurface data on the M sand, including the basal chert-pebble conglomerate, varicolored Morrison-type shale, coaly shale and coal, and the low gravity of the oil in two pools and the shows of heavy oil suggest that it, like its equivalent the Lytle formation, represents flood-plain deposits marginal to an invading Cretaceous sea.

The evidence on the outcrop indicates that the sediments which form the South Platte formation were deposited in deltaic, estuarine, littoral, and neritic environments that existed around a spreading Cretaceous sea (Waage, 1955, p. 44). The subsurface data available about the uppermost beds of the M sand zone and the overlying shale and sandstone units indicate that they were deposited contemporaneously with the South Platte formation and in environments similar to those of that formation. Actually, the deposition of sediments like those of the South Platte formation continued in the oil-fields area longer than in the area of outcropping Dakota, shown by the fact that the D sand zone does not extend westward as sandstone as far as the outcropping Dakota. A few data, including the lenticular character and crossbedding of the sands, the evidence of abundant animal borings, and the presence of "reworked" sand and shale suggest a shallow-water environment. The variable character of the rocks suggest deposition near a fluctuating strand line.

The existence of local positive areas in east-central and southeastern Colorado is indicated by the presence of thick continental sandstones in the South Platte formation south of Denver (Waage, 1955, p. 44). Simultaneously with the deposition of deltaic deposits near the positive areas, marine sedimentation was going on elsewhere in the Denver basin. In the subsurface, the great increase in thickness of the sandstones of the Dakota northeastward, and the general facies change to continental beds of all parts of the Dakota far to the northeast in Nebraska (Sternberg and Crowley, 1954, p. 38; Jensen and Sharkey, 1954, p. 62) suggest that one of the sources for Dakota sediments (and likely the principal source for the D sand) lay in western Nebraska, northeastward from the oil-fields area, as was earlier pointed out by Henderson (in Lavington, 1941, p. 28) for the D sand.

The general distribution of the oil and gas pools in the D and J sand zones in northeastward-trending belts of country suggests that the shoreline of the Cretaceous sea trended northeastward through the oil-fields area and fluctuated to and fro across that area. The position of the D sand lenses is more definitely defined than that of the J sand lenses; the line of pinchout for the D sand appears to represent the boundary between sand deposition in shallow water and shale deposition to the west in deeper water. Moreover, the northeastern boundary of the D sand lenses between shallow water sand deposition on the southwest and continental sand deposition on the northeast is probably at some place in a broad belt of country trending northwest in western Nebraska (see fig. 4).

The regional features of the D and J sands in the Denver basin suggest that the general depositional environment for these sandstones was that of a shallow marine sea whose shoreline probably fluctuated over a considerable area in northeastern Colorado and southwestern Nebraska. The general distribution of the D and J sand lenses forms a northeastward-trending broad belt. For the most part, however, no systems of elongate sandstone lenses like the shoestring sand systems of Kansas and Oklahoma

(Bass, 1934, 1936; Bass, Leatherock, Dillard, and Kennedy, 1937) or the systems of coastal bars on the Atlantic and Gulf Coasts are apparent. Moreover, most of the individual sandstone bodies are not narrow, elongate bodies, several times longer than wide, such as are coastal bars. The D and J sand lenses, whose extent is believed to be represented by the oil and gas pools on figures 5 and 6, appear for the most part to be distributed at random. In local areas, certain trends of sandstone bodies can be recognized, however. Such an area is that in the southern part of the oil-fields area, in Tps. 1 N. to 2 S., Rs. 56 and 57 W., and T. 2 N., R. 55 W., where the D sand lenses are distributed in a northeastward-trending system, and in Tps. 2 and 3 S., Rs. 55 and 56 W., where the J sand lenses suggest a similar systematic arrangement (see figs. 9 and 10). Another such area is southeast of Kimball, Nebraska, in Tps. 14 and 15 N., R. 55 W., where several J sand lenses form a well-defined northwestward trend (fig. 6). Detailed study of individual D and J sand bodies, however, reveals many features that are characteristic of the shoestring sands and the modern coastal sands.

The D and J sandstone lenses in the oil and gas fields are composed chiefly of quartz grains of fine to veryfine size which are characteristically well sorted and clean. The beds of sandstone are sharply defined from beds of shale and sandy shale. A few of the sandstone bodies examined showed more shale partings near the margins of the sandstone bodies than in their centers. Overgrowths of quartz grains by silica are common. Small siderite concretions are reported to be common; mica, glauconite, and pyrite are accessory minerals. These features are found in the shoestring sands of Kansas and Oklahoma and some of them are present in modern shoreline sand bodies but are not restricted to such deposits.

Two J sand lenses in the Enders and Dietz fields in T. 13 N., R. 55 W., Nebraska, contain many features common to coastal bars. The oil-bearing beds are composed of fine- to medium-grained, angular to subrounded quartz sands and contain some shale partings (Pearl and Hodder, p. 77 and 93, in Finch, Cullen, and Sandberg, 1955). The sand bodies are well defined lenses, asymmetrical in cross section (figs. 11 and 12). The crest of the Enders lens is nearer the northeastern margin than the southwestern margin of the sand body. The crest of the Dietz lens is nearer the southwestern margin than the northeastern margin of that sand body. Each lens is composed of solid sand on the side of the short steep slope. The Enders lens contains partings of shale on the gently sloping margin.

A structure-contour map of the Enders and Dietz oil fields, drawn on the "bentonite marker" bed of the Graneros shale (which here lies 240 feet above the J sand), is shown on figure 13. The regional dip is westward at about 35 feet to the mile and a slight bending of the contours above each oil field shows a structural nose over each field. These structural features could have been formed by compaction of the sediments over the lenses of J sandstone in the two oil fields. The bending of the contours is more pronounced over the Enders field than over the Dietz field, possibly because the oil-bearing sandstone body of the Enders field is thicker than that of the Dietz field.

A map of the two oil fields showing the initial daily oil yields of the wells is shown in figure 14. It is noteworthy that the initial daily yields of wells correspond with the thickness of the J sandstone in the two oil fields as shown on figure 11; wells with large initial daily yield are in thick J sandstone and those with small yield are in thin J sandstone. This is interpreted to mean that the thicker permeable parts of the sandstone lenses occupy northwest-trending courses across the oil fields; for the Enders field the crest of the sandstone lens as so interpreted lies northeast of the mid-line of the field and for the Dietz field the crest lies southwest of the mid-line of the field, thus corresponding with the thickest parts of the sandstone bodies as shown by the isopachous maps on figure 11.

A group of sandstone-lens oil fields in the southern part of the oil-fields area, for example the D sandstone fields shown in figure 9, possess some of the features common to the shoestring sands of Kansas and Oklahoma and to modern beach sands. The arrangement of the D sand bodies, although somewhat imperfect, suggests a northeastward-trending system. The individual sandstone lenses, represented by the Badger Creek, Little Beaver, Bobcat, and Sand River fields, present an offset arrangement in the trend. These individual sandstone lenses are from 2 to 3 times longer than wide; their long axes trend northeastward, in the northeastward trend of the system of sandstone lenses. According to R. K. Peckler, A. L. Bergren, Jr., A. A. McGregor, and W. R. Thurston (in Jensen, Sharkey, and Turner, 1954, p. 89, 105, 193, 263) the D sandstones in these fields vary from massive to thin sandstone beds interbedded with dark-gray to black shale. The sandstone beds are composed chiefly of well sorted fine to medium quartz grains, and contain a minor amount of carbonized plant fragments. The sandstone beds are locally crossbedded. Porosity and permeability varies greatly in the D zone but within sandstone beds of the zone are generally fair to good. Cores of the sandstone in the Little Beaver field in Tps. 1 and 2 S., R. 56 W. show crossbedded sandstone in some beds and mudballs are common in other beds (Fentress, 1955, figs. 12 and 13). Clay balls are not uncommon in the shoestring sands of Kansas and Oklahoma and are present in modern beach deposits (Bass, Leatherock, Dillard, and Kennedy, 1937, p. 53-54). They also are reported from stream deposits.

The Little Beaver field was selected as representative of the group of oil fields in the southern part of the area after a study of many fields, including preparation of many cross sections of the sandstone bodies, structure-contour maps on several horizons, maps showing initial daily yields of wells, and maps showing thicknesses of the reservoir sands. The detailed data and maps contained in papers on several of the fields by MacQuown and Millikan (1955, p. 635, 639, 643-646) and Fentress (1955) also were studied.

The map of the Little Beaver field (fig. 15) showing the total thickness of the D sandstone shows the sandstone is thickest in a relatively narrow northeastward-trending belt near the middle of the field; the sandstone is not only thickest here but contains fewer beds of sandy shale. The sandy shale and shale beds increase in number and thickness toward the margins of the oil field. Fentress (1955, figs. 20 and 21) has shown that each of the two principal oil-bearing benches of the D sandstone is lens shaped and has the thickest part of the lens trending lengthwise of the oil field near its middle. The cross section on figure 15 shows also that the top of the sandstone lens is convex upward and the base is slightly convex downward, features that were noted by Fentress (1955, p. 174-175, 180) and MacQuown and Millikan (1955, p. 641-647). The convex upward surface is a common feature of coastal bars and other sand bars. The convex basal surface of these D sandstone bodies requires further explanation, however, inasmuch as it is generally assumed that most shoreline or near-shore bars are deposited on an essentially smooth base that has a gentle seaward slope.

The black shale unit lying directly below the D sandstone body must have been a water-saturated carbonaceous mud at the time of deposition of the D sandstone. A load such as the D sandstone lens probably would sink into the mud, and it might be expected that the central thickest part of the sand lens would sink deeper and the mud so displaced would move slightly outward toward the margins of the sand lens. It is noteworthy, therefore, that the black shale unit underlying the D sandstone lens is thinnest near the middle of the field, approximately beneath the thickest part of the sandstone body (see fig. 16).

The initial daily oil yield of the wells in the D sandstone in the Little Beaver field is shown in figure 17. Although the distribution of the wells with large initial daily yields is somewhat erratic, essentially all large wells are in the area where the total thickness of the D sandstone exceeds 50 feet. The wells with small initial daily yields are near the margins of the field where the sandstone is relatively thin and contains many partings of sandy shale and shale.

Cross sections across the short dimension of the sandstone bodies in the Kansas and Oklahoma shoestring sands showed the sand bodies to have a depositional slope. This was interpreted to be a slope seaward (Bass, Leatherock, Dillard, and Kennedy, 1937, p. 46-47). Many cross sections of the D sandstone were drawn for the Badger Creek, Little Beaver, Bobcat, and Sand River fields, whose D sandstone lenses appear to form a system of sandstone lenses. Two of these cross sections are shown in figure 18. The electric logs used in cross section A-A' of the Badger Creek field (fig. 18) are alined on the top of the J sandstone. It is apparent from this cross section that the interval from the top of the J sand to the base of the D sand decreases northwestward across the field. If it is assumed that the top of the J sand was horizontal when the D sand was deposited, the D sand was deposited on a northwestward slope.

In the resistivity curves of the well logs the first projection above the D sand identifies a persistent key bed. If the logs are alined on this bed instead of the top of the J sand, the northwestward slope of the base of the D sand is still apparent. Cross sections of the Beaver Creek field show only that the base of the D sand slopes toward the middle of the field. At the margins of the field the base appears to be about horizontal. Cross sections of the Bobcat field, one of which is shown as B-B' on figure 18, appear to show an original northwestward slope to the base of the D sand similar to the condition in the Badger Creek field.

On the basis of the preceding discussion and assuming from the data that these sandstone bodies represent coastal bars, an arm of the Cretaceous sea at the time of deposition of these sandstone lenses probably lay northwest of the system of sandstone bodies. The offset arrangement of the sandstone bodies suggests that the longshore currents were probably northeastward past Badger Creek and Little Beaver Creek fields and were southwestward past Sand River and Bobcat fields. The other sandstone bodies represented by the Kejr, East Little Beaver, Phegley, and South Woodrow fields may have been deposited at slightly different times than those of the four fields just described.

The above data suggest that in some local areas in the oil-fields area of the Denver basin sandstone bodies originated as shoreline deposits. For the most part, however, the sandstone lenses do not seem to be systematically arranged, or to have the elongate shape of typical shoreline sand bodies. The clean well-sorted sand that characterizes the oil-bearing sandstone bodies, however, suggests their deposition in places where waves and longshore currents winnowed out the very fine and coarse grains and sorted the sand throughout. Possibly there were originally many more systems of shoreline sand bodies, some of which were later destroyed by an advancing sea. On the other hand, the water body may have been very shallow and the coast line very irregular and marked by many estuaries and projections of land. Whatever its shape, the sea seems to have preserved in its deposits many small lenses of clean well-sorted sandstone. These sandstones interfingered with and were surrounded by black marine carbonaceous shale that likely constitutes the source beds for the oil.

CRUDE OILS

Analyses of more than 100 samples of crude oil from the oil-fields area in the Denver basin were made by the U. S. Bureau of Mines in its laboratory at Laramie, Wyoming. In this type of analysis (known as "routine" by the Bureau of Mines) the crude oil is distilled, and fractions, or cuts, of the oil are extracted at intervals of 25° C. A total of 15 cuts is made. A number, the correlation index, is calculated for each fraction; this number represents the relationship between the average boiling point and the average specific gravity of the fraction (Smith, 1940; Neumann and others, 1941, p. 96-100). The correlation index indicates the general hydrocarbon composition of the fraction. Correlation indexes from 0 to 20 show that the fraction is composed dominantly of paraffines; indexes 20 to 50, that the fraction is composed dominantly of naphthenes; and indexes above 50, a predominance of aromatics.

Many properties of the crude oils from the Denver basin, including the gravity, percent of sulfur, percent of nitrogen, specific gravity of the residuum, viscosity and cloud point of certain fractions, pour points, gasoline yield, and correlation indexes, were studied by the chemists of the Bureau of Mines. They report (J. S. Ball, U. S. Bureau of Mines, written communication, Jan. 1957) that "the plots (including maximum and minimum indexes for each cut) of correlation indexes give a broad band for the oils from the 'D' sand and likewise a broad band for oils from the 'J' sand. For the most part, these two bands coincide; however, the average value for the 'J' sand oils is about 1½ units (numbers) above that for the 'D' sand oils [see fig. 19]. A similar relationship holds for most of the other properties [listed at the beginning of this paragraph] which we have studied...There appears to be a definite trend for the oils from the 'J' sand to have a higher correlation index" than the oils from the D sand. Thus the oils from the J sand are on the average slightly more naphthenic than the oils from the D sands.

The oil from the M sand is quite different from the oils in the J and D sands. The curve of correlation indexes on figure 19 shows that the oil from the M sand is highly naphthenic and aromatic as contrasted with the oils from the J and D sands.

The API gravity of the oil from the M sand is only 15.3 degrees. The gravity of 50 samples of oil from the D sand in Nebraska and Colorado ranges from about 32 degrees to 70 degrees, according to J. S. Ball (U. S. Bureau of Mines, written communication, Jan. 1957), and the gravity of 61 samples of oil from the J sand ranges from about 24 degrees to 58 degrees. The average gravity for the 50 samples from the D sand is 38.9 degrees and for the 61 samples from the J sand is 39.2 degrees; the gravity of the oil from most fields is within a few degrees of the averages.

In addition to the properties reported on by Ball and summarized above, the hydrocarbon composition of the crudes from individual fields and significant groups of fields in the Denver basin was studied by the writer by comparing curves of the correlation indexes of the several fractions of the crudes obtained by the analyses. Oils from the Badger Creek, Little Beaver, Bobcat, and Sand River fields, which yield oil from the D sand, are quite similar according to the analyses. The curve for the average of the correlation indexes for each fraction of the eight oil samples (2 from each field) is shown by curve A on figure 20. A comparison of the curves for the correlation indexes for samples of oil from the D sand in the East Little Beaver, South Woodrow, East Woodrow, and Rago fields, made individually with curve A, shows that these oils are somewhat more paraffinic throughout fractions 4 to 15 than the oil from the Badger Creek, Little Beaver, Bobcat, and Sand River fields. A curve of the average correlation indexes for the oils from the East Little Beaver, South Woodrow, East Woodrow, and Rago fields is shown by curve B on figure 20. If the oil-bearing D sand bodies of the Badger Creek, Little Beaver, Bobcat, and Sand River fields were deposited simultaneously along or near the shore of the Cretaceous sea or an estuary of that sea, it is probable that the environment, especially its effect on the plant and animal life, was similar along this part of the shore and in the marshes which probably were present on the landward side of the sand bars. It might be expected, therefore, that the oil in these four reservoir sandstone bodies would be similar. The local environment at the sites of the East Little Beaver, South Woodrow, East Woodrow, and Rago fields might have been slightly different. It is not unlikely that the sandstone bodies of these latter-named fields were deposited at a slightly different time from the Badger Creek to Sand River system of sand bodies.

A comparison of curves of the correlation indexes of four oil samples, two each from the J sand in the Big Beaver and Plum Bush Creek fields, shows that the oils of these two fields are similar. Curve A on figure 21 represents the average correlation indexes of the four samples. Other oil-bearing J sand lenses of the same general area contain slightly different kinds of oils, however, as shown by their correlation index curves. The analyses of oil samples show the oil in the Badger Creek field (curve D, fig. 21) to be somewhat more paraffinic than the oil from Big Beaver and Plum Bush Creek (curve A, fig. 21). Oil from the J sand in the East Mountain View field--one well, in sec. 15, T. 1 S., R. 57 W. (curve not shown on fig. 21)--is very similar to the oil from the J sand at Badger Creek. The oil from the J sand at Middlemist is similar to the oil at Little Beaver; an average of the samples from these two fields is shown as curve B, figure 21. This oil is more naphthenic than the oil from the Big Beaver and Plum Bush Creek fields. A fourth type of oil (curve C, fig. 21) is found in the J sand in the McRae field in sec. 23, T. 1 N., R. 55 W., which is distinctly more naphthenic than the oils of nearby fields.

It was suggested earlier in this report that the J sand in the Big Beaver and Plum Bush Creek fields may represent sand bars which were deposited simultaneously along a northeastward-trending shore; accordingly, it might be expected that the oil of the two fields should be similar. The sandstone lenses of the other fields were probably deposited at slightly different times than the Big Beaver and Plum Bush Creek lenses, although some may have been deposited at the same time. Nevertheless, the local environment surrounding these sand lenses probably varied somewhat from that surrounding the Big Beaver and Plum Bush Creek sand lenses and may have supported slightly different plant and animal life--hence the different kinds of oil.

Analyses of J sand oil samples from fields in Logan and Weld Counties, Colorado; Cheyenne, Kimball, and Banner Counties, Nebraska; and one field in southeastern Laramie County, Wyoming, indicate several classes of oils as revealed by a comparison of the correlation index curves, shown on figure 22. The location of the oil fields from which the various classes of oil come (see fig. 6) suggests that the geographic distribution of the oil classes may have geologic significance. Class A includes oils from 23 fields.

Class B includes the oils from 7 fields southeast of Kimball, Nebraska, in an area about 12 miles wide and 25 miles long. The curves on figure 22 show that oils A and B are fairly similar up to the 11th cut; in cuts 12 to 15 oil B is more naphthenic than oil A. Class P oils include those from five fields that lie in a northeastward-trending belt of country in northeastern Cheyenne County, Nebraska. This oil is more paraffinic than oils A and B in all cuts up to cut 11; in cuts 12 to 15 oil P is not greatly different from oil A. The class S curve on figure 22 represents the average correlation indexes for three fields in Tps. 5 and 6 N., Rs. 54 to 56 W., Colorado. The correlation-index curve for this oil shows it is similar to oil P up to the 6th cut. From cut 6 to cut 15 the curve of this oil departs from all other curves, indicating that the oil is more paraffinic than all the others.

In summary, the occurrence of several classes of oil in the J and D sands probably reflects differences in the environment of accumulation of the source material for the oil. If the black shales and sandy shales that lie at the stratigraphic position of the reservoir sand lenses and interfinger with them contained the principal source material for the oils, as appears likely, slight local differences in the plant and animal life during time of deposition might account for the slight differences in the composition of the oils. It has been shown that the crude oils from the Burbank sand bodies in Kansas and Oklahoma are similar along an ancient shoreline nearly 150 miles long but that crude oils from different stratigraphic horizons in a single field or area are dissimilar (Neumann and others, 1947, p. 135-138). This dissimilarity in the Midcontinent region was attributed to possible differences in environment during sedimentation but it was admitted that concrete data to support the interpretation was unavailable. A similar situation exists in the Denver basin. The contrast between the heavy oil in the M sand and the light oils in the D and J sands seems most reasonably attributable to different depositional environments. The M sand is largely continental in origin; the D and J sands are marine. The close similarity of crudes from the several sandstone bodies that appear to form a shoreline system of bars such as the D sand bodies of the Badger Creek, Little Beaver, Bobcat, and Sand River fields, as contrasted with slightly different crudes in nearby fields whose sandstone bodies do not appear to have been a part of the shoreline system, doubtless is significant. A slightly different environment along the shoreline system from that at the sites of deposition of the other sandstone bodies might account for the differences in the crude oils. On the other hand, the fact that differences are only minor between the crudes in the J and D sands throughout the oil-fields area suggests that the general environment changed but little between the times of deposition of the J and D sands.

The distribution of the oil fields in the northern part of the oil-fields area having class A oil (fig. 6) might suggest that the reservoir sandstone bodies of these fields, and probably others whose oil type is not as yet known, were deposited simultaneously during a brief time when the position of the Cretaceous seashore remained fixed. The fact that the broad belt including these fields coincides roughly with the trend of thickness lines for the Dakota sandstone shown on figure 3 may or may not have significance. The grouping of the fields having oils of the several classes, however, suggests local environmental control for the source material of the oil.

LOCATION OF WILDCAT WELLS

For the Midcontinent shoestring sands, the location of wildcat wells is made by projecting the general trends of sandstone bodies into undrilled areas but offsetting a mile or so for the next sandstone body. Such a method should also be applicable to local areas in the Denver basin. The trends in the Denver basin are not as perfect as in the Midcontinent; the sandstone bodies may not represent systems of offshore bars, but they do appear to represent some type of sandstone lenses deposited in shallow marine waters. Projections of established trends accordingly will likely find more fields than haphazard locations. The fact that the wells with large initial daily yields are found in a narrow belt near the middle of many sandstone bodies where the thickest homogeneous portion of the sandstone bodies are present, can be put to practical use. If a line is drawn through the wells with large initial daily yield in a given field, it will represent the approximate middle of that sandstone body. Extensions of these lines, recognizing the existence of offsets in the trend, should guide the prospector in locating wildcat wells.

The presence of many dry holes in a given area should not necessarily condemn the entire area. Figure 23 shows an area 18 miles wide by 30 miles long in the southern part of the oil-fields area of the Denver basin, showing only dry holes. At first it would appear difficult to promote more drilling in this area if this map were shown, and yet figures 9 and 10 show that the area contains 31 oil fields; many hypothetical fields can be projected in the area between dry holes, and it is likely that several more fields are present here.

Inasmuch as structure contours on the "bentonite marker" bed are deflected sharply up dip at the north end of oil fields in the D sand zone (fig. 2), such a feature in an area containing no known fields might be used with caution and in conjunction with other data to locate wildcat wells.

The regional distribution of the marine sandstone members of the Dakota sandstone should be used as a general guide for selecting broad areas for prospecting. Some distance northeastward from the oil-fields area the J and D sandstones coalesce with the other sandstone members of the Dakota and become continental in origin. Hence the area in which oil fields will be discovered will probably be limited northeastward by this change of facies, the exact location of which was not determined in this investigation. A similar lithologic change may take place eastward. The general area in which such a change of facies occurs in the D sand zone is suggested by the occurrence of heavy oil (22° API gravity) in the D sand in sec. 25, T. 3 S., R. 51 W., Washington County, Colorado, because heavy oil is not uncommon in beds of continental origin. Waage (1955, p. 28) showed that on the outcrop the marine sequence of the Dakota group (which is equivalent to the J sand and associated beds) merges with continental beds several miles south of Denver. This would suggest that a marine environment, favorable for the generation of crude oil, probably persisted in a relatively broad area southwest for several miles from the oil-fields area as here used.

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