Sarir Oil Field, Libya—Desert Surprise[1]

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Abstract The Bunker Hunt–British Petroleum Sarir oil field of Libya appears to be one of the 10 to 12 supergiants of the world. Credited with 11–13 billion bbl of oil in place, it is a water-drive field that could, and probably will, recover nearly 50 percent of its total oil. The maximum oil column is 300 ft and the area of surface closure is 155 mi². The field was discovered in November 1961 on a seismically defined structure. Development drilling was continuous through the next 4 years; a pipeline and loading terminal were completed and production was begun in late 1966. The oil reservoir is Cretaceous sandstone on basement, the probable oil source being the several hundred feet of overlying Cretaceous marine shale. Structurally, the field is a combination anticline and high fault-block complex within a broad structural low.

There appears to be good fluid communication throughout the reservoir. Average porosity values are 18–19 percent, and permeability values average several hundred millidarcys, with a few 2–3-darcy streaks. All production is water free. The oil is sweet and sulfur free, though of high paraffin content.

More than 100 wells have been drilled, of which about 60 are on production and 12–14 are awaiting gathering lines; most of the others are observation wells for pressure or fluid control. There was a decline of reservoir pressure during the first year of production; however, in most of the field a sustained water drive is developing. Producing capacities of individual wells range from a few thousand barrels daily to maximum estimated open flow of 28,000–30,000 bbl/day. The field went on production at 100,000 bbl/day, which rose to 300,000 bbl within the first year. Additional field facilities, when installed, will permit even greater increases.

Prologue

The Sarir oil field, owned jointly by Bunker Hunt and British Petroleum Company, is on concession 65 in the Sirte basin of east-central Libya (Fig. 1)—more specifically, in the sand-sea area of the central Cyrenaica district. The exploration of concession 65 and the development of Sarir field complex involved seemingly insurmountable problems and hardships, and many surprises, both good and bad.

Problems included (a) access, transport, and living conditions; (b) the sand-sea cover, which ruled out surface geologic mapping and necessitated the use of geophysical methods; (c) a several-hundred-foot lost-circulation zone (d) pipeline-transport problems caused by the high-pour-point, waxy crude; and (e) the construction of a marine loading terminal off a limestone hillside, rather than off a flat sand beach.

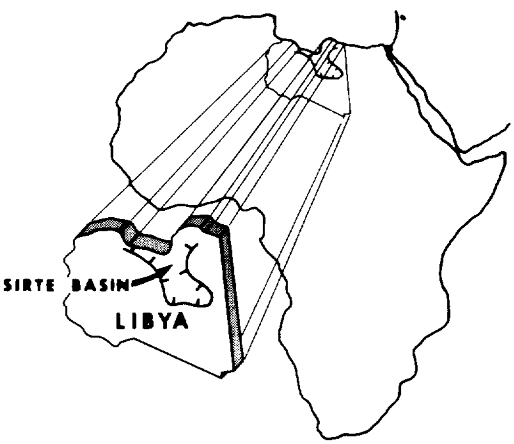

FIG. 1.—Location of Sirte basin, Libya.

During development of the field there were such unpleasant surprises as (a) the dynamiting sabotage of five field wells, (b) a long string of consecutive dry wildcats on the concession after the field discovery, and (c) several weeks of complete production shutdown after the Middle East war of June 1967.

These difficulties were offset somewhat by at least two pleasant surprises. First, the rapid increase in the number of square miles of developing field area and the mounting of reserves into the billions of barrels were certainly continually pleasing. Second, the prolonged closure of Suez Canal after the Middle East war increased demand for crude oil west of Suez, thus establishing an unexpectedly favorable market which has continued.

Introduction

The Sarir field is a water-drive reservoir of low gas-oil ratio producing average 37°, paraffin base, sulfur-free oil. Oil in place is estimated to be between 11 and 13 billion bbl. A 25-percent primary-recovery factor will give 3 billion bbl of oil. Secondary-recovery methods

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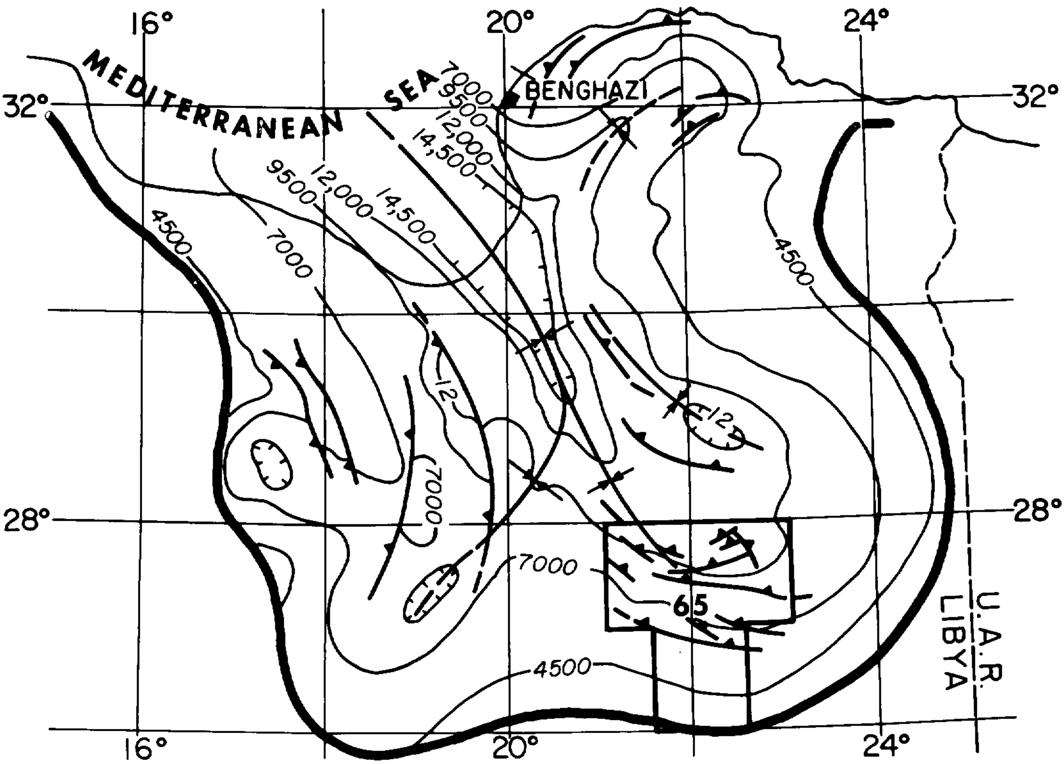


FIG. 2.—Sirte basin, Libya and original concession 65. Heavy black line shows basin outline. Datum for structural contours is unconformity surface at about mid-Cretaceous. CI = 2,500 ft.

in parts of the field, together with improved primary-recovery methods in other parts, could provide another 18–25 percent, or 2–3 billion bbl. Thus the field could have an ultimate oil recovery of 5–6 billion bbl.

The Sirte basin (Fig. 2) is mainly an upper Mesozoic and Tertiary feature developed on an old basement and eroded Paleozoic surface (Conant and Goudarzi, 1967). The main NW-SE synclinal trough underwent repeated subsidence, with accompanying fault adjustments. Several regional horst-and-graben trends which began to develop in Cenomanian (mid-Cretaceous) time remained active during Tertiary time as the basin continued to subside.

In many parts of Africa a great hiatus in mid-Cretaceous rocks is characterized mostly by sandstone of Early to middle Cretaceous age called "Continentale Intercalaire" (Intercalary Continental) deposits (for discussion of "Continentale Intercalaire" and general "Nubian Sandstone" problem, *see* Pomeyrol, 1968). Probably part of the more than 2,000 ft of sandstone in the Sarir field is of this age. Marine Late Cretaceous seas reworked these sands as they transgressed the old surface. Consequently, the drill penetrates a "sandstone-on-sandstone" sequence whose age and local unconformities are difficult to decipher. The reworked sands are at least earliest Late Cretaceous, and more likely are late Early Cretaceous. A basal sandstone of Early Cretaceous age is recognized by some geologists working in the area.

Oil is from this near-middle Cretaceous sandstone, in contact with basement and overlain by thick Cretaceous and Tertiary marine shale and limestone. The oil is at a depth of about 9,000 ft in a broad structure and in combined anticlinal and fault-trap accumulations. The drilled field area is about 160 mi^2 and has a maximum oil column of 300 ft; the area within the oil-water contact ring of the field is probably more than 330 mi^2.

Almost 100 wells have been drilled. About 90 are connected with flow lines, but generally fewer than 55 produce during a particular month. Many of the other wells are being utilized during this early stage of production as fluid-pressure and fluid-level observation holes. Day-to-day operating well potentials range up to 10,000 bbl/day; individual well potentials would range as high as 28,000–30,000 bbl/day, as observed during wild open flow at the time of the 1965 sabotage.

There are four main gathering centers in the field, and individual wells are connected by 6- and 8-in. gathering lines. Twelve-inch trunk lines connect the centers to the main 34-in. pipeline which runs north to the Tobruk marine terminal.

The field went on production in December 1966 at 100,000 bbl/day. Production gradually was increased to its present rate of about 330,000 bbl/day. The field's production capabilities are unknown; however, with ultimate pressure stabilizations, it could possibly sustain more than 700,000 bbl/day.

Concession 65, which originally contained 20,459 mi², has been reduced by three relinquishments (Fig. 3) and is now at its final size of 5,113 mi².

Sirte basin contains all of the major oil fields of Libya (Fig. 4). The fields are on the horst ridges or high fault edges of the regional tectonic features of the basin. Local oil accumulation generally is associated with sedimentary drape and cross-faulting of these main trends. The original 20,000+ mi² of concession 65, in the southern part of the basin, previously was thought to be outside the principal oil-prospect area, which was considered to be mainly the west flank of the basin. Sarir is now the southernmost oil field in the basin.

Exploration History

The original concession was about 120 mi north-south and 120 mi east-west at its widest part (Fig. 3). It was granted to Nelson Bunker Hunt in December 1957 as his second concession in Libya; he had taken concession 2 in the north in 1955. No oil had been discovered in the Sirte basin, although work was well underway on many concessions. Exploration was carried on by Hunt between 1957 and 1960, and the discoveries of 1958 and 1959 indicated major oil fields in the basin. In September 1960

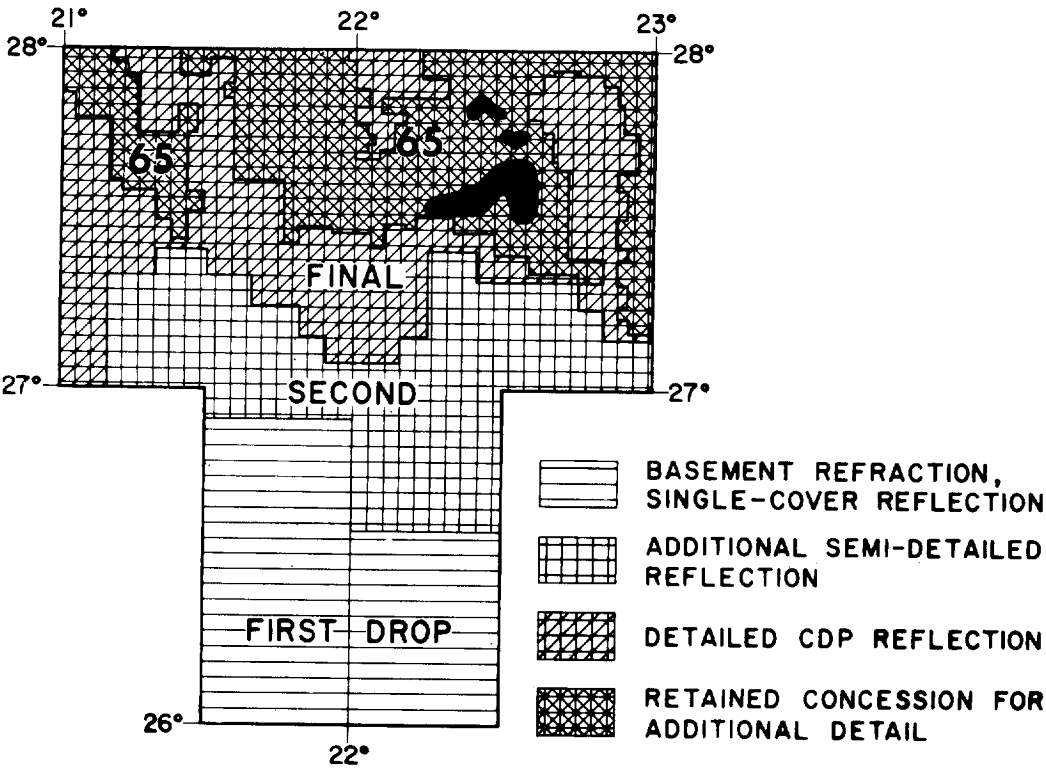


Fig. 3.—Original concession 65, Sirte basin, Libya, and parts relinquished as a result of geophysical surveys and test drilling.

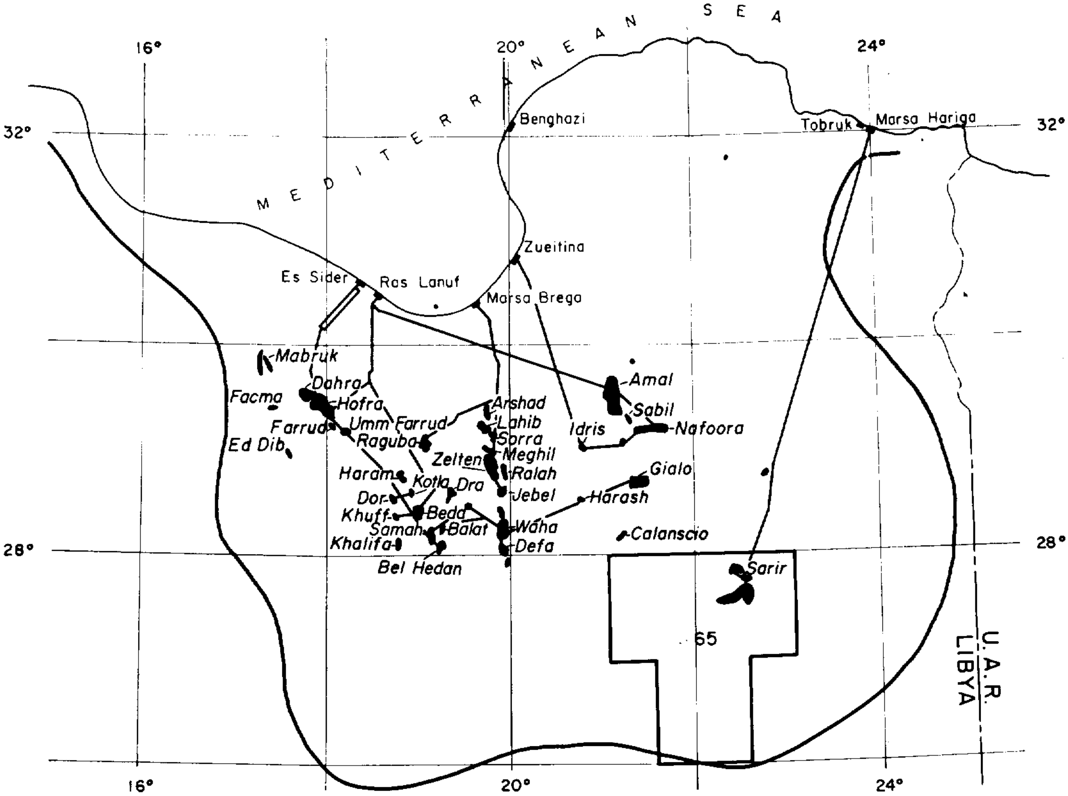


FIG. 4.—Oil fields in Sirte basin, and pipelines to shipping terminals.

Hunt turned over a half interest to British Petroleum (BP Exploration Co., Libya), which became the operator.

Air-magnetometer and gravity surveys were made over most of the original concession, and a refraction and reflection seismic reconnaissance grid was started. These surveys and a few rather discouraging wildcat holes led to the decision to relinquish the southern area (Fig. 3) in December 1962. Sizable structures were noted mostly in the northern part of the concession (Fig. 5).

Additional semidetailed reflection work and a few more wildcat holes led to the second relinquishment in December 1965. From 1965 to date seismic coverage has been by the CDP or six-fold stack technique. This enhancement of seismic data produced positive information which greatly assisted in the selection of acreage for the final land drop in December 1967. Stacked data also led to the discovery of the "L" producing area north of the main field. Figure 5 shows the principal faults and tectonic trends in concession 65, as well as all wildcats drilled to date. Figures 6–9 and 11–13 show the present concession area after the three drops and semidetailed information on the structure and stratigraphy.

Sarir unquestionably is a discovery based entirely on geophysical methods (Fig. 6). The major highs (stippled) and lows of the concession and their relief at different stratigraphic levels were determined originally by various methods of geophysics. The stratigraphic-marker tops from wildcat wells were introduced later into the mapping. The air magnetometer revealed the presence of the large southwestern area **A** structure and its southeastern prolongation, which subsequently was found to be a buried major fault line. Sarir field, superimposed on this map, was not detectable as an anomaly on the basis of this magnetic survey.

Gravity coverage (Fig. 7) followed the magnetic survey; it also outlined the major features. The Sarir feature shows only as a nose and is definitely overshadowed by the two features on the west. Hence, the latter became the **A** struc-

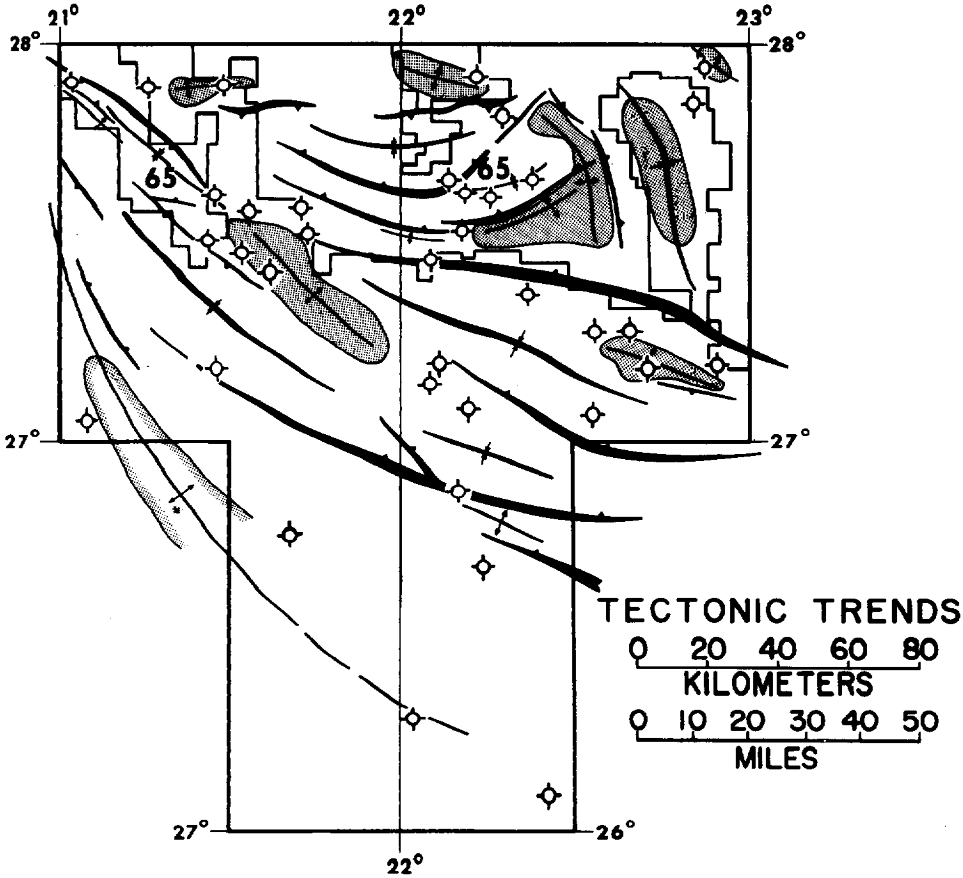


FIG. 5.—Tectonic trends in concession 65, found by geophysical surveys.

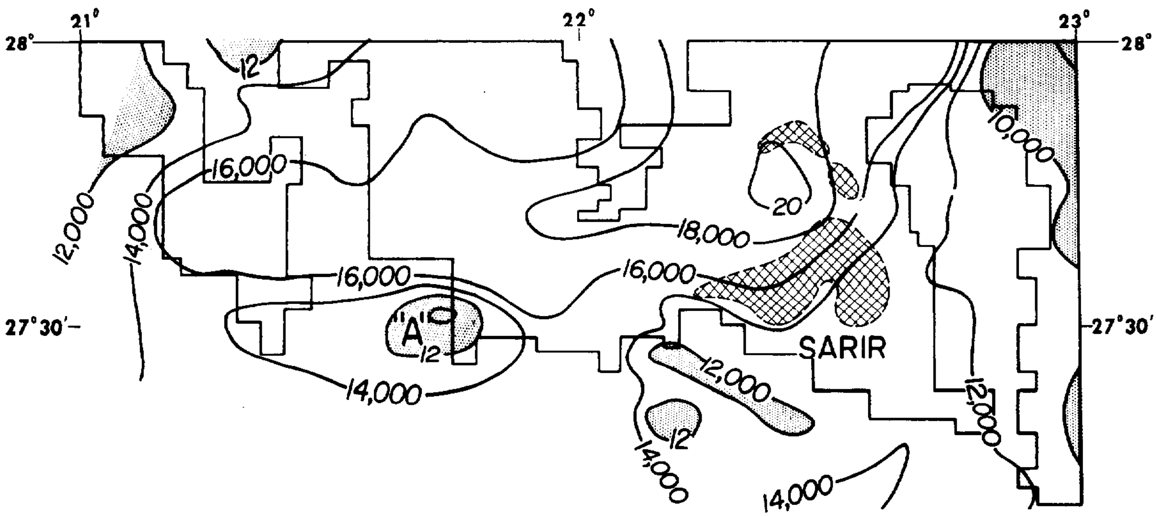


FIG. 6.—Aeromagnetometer basement-depth map of retained area. Depth in feet. CI = 2,000 ft.

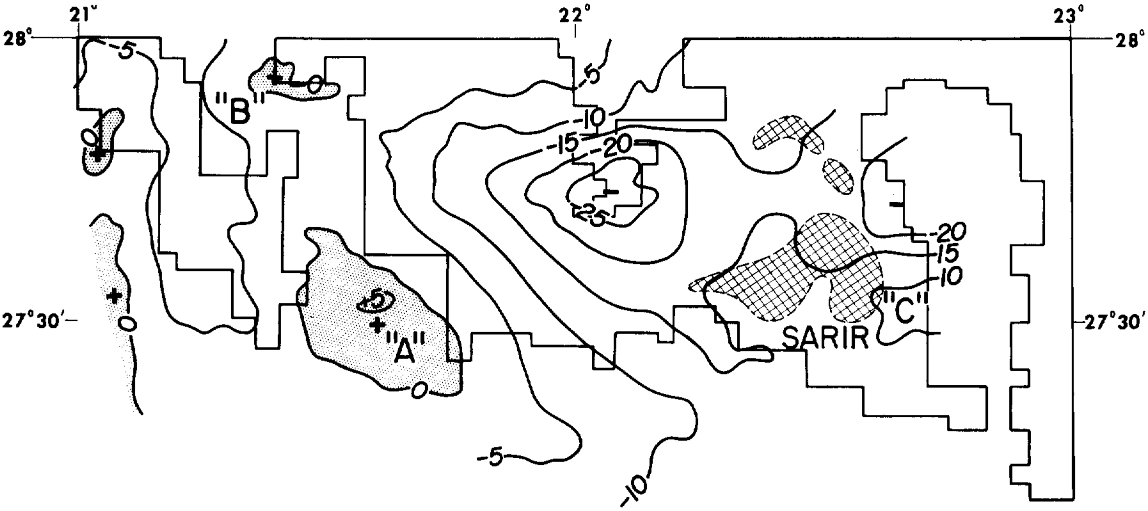


FIG. 7.—Bouguer gravity map of retained area. CI = 5 mgal.

ture at the +5-mgal contour line and **B** structure at the zero-miligal contour line. The then questionable and unnamed, eastern nosing feature was called the **C** structure; it later proved to contain the Sarir field.

Seismic reflection and refraction surveys were made in late 1960 and early 1961. The basement-depth map in Figure 8, constructed in depth from the two-way refraction time from granite and/or Precambrian metamorphic basement, also shows the major structural features. The **C** structure, comprising the Sarir producing complex (crosshatched), shows up as a pronounced basement feature. A shallow, 3,000-ft Eocene seismic-reflection horizon was mapped at the same time as the basement was mapped by refraction. The Eocene map showed only a few hundred feet of relief over the Sarir complex, in contrast to the basement refraction map which showed up to 2,000 ft of

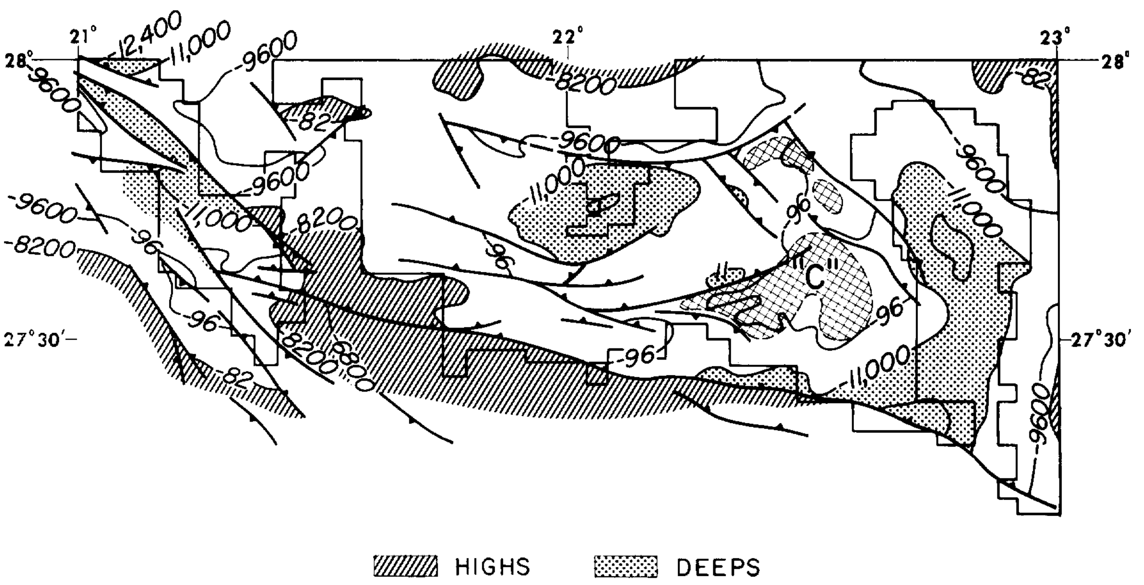


FIG. 8.—Seismic basement refraction map of retained area. CI = 1,400 ft. Cross-hatched area is **C** structure, comprising Sarir producing area.

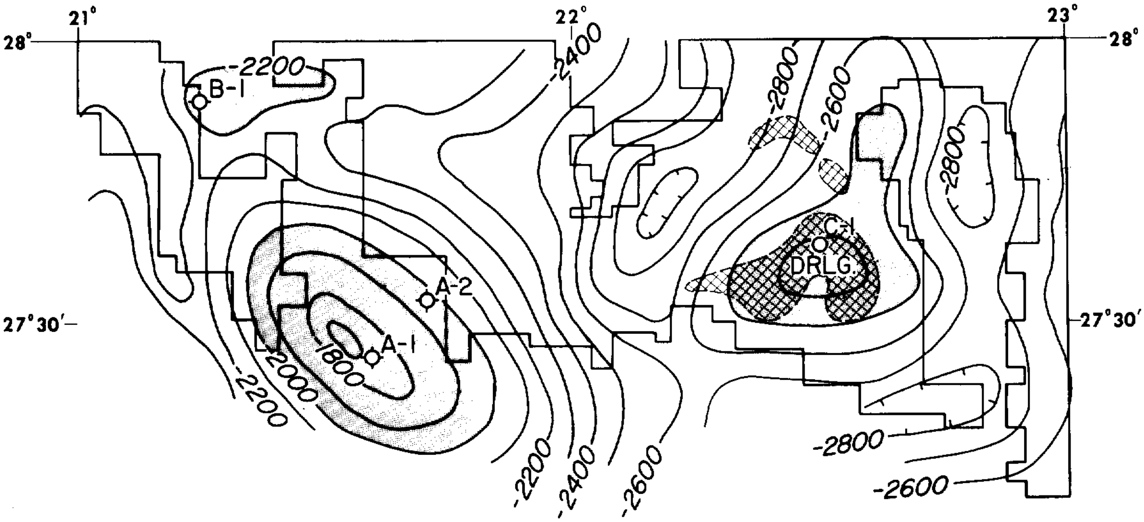


Fig. 9.—Geologic subsurface, top Eocene, November 1961 (discovery date December 1961). A-1, B-1, and C-1 are test wells drilled on **A**, **B**, and **C** structures.

relief. Thus, the need for one or two deeper reflecting horizons on which to map became apparent and they were developed later.

By early 1962 mapping of the shallow Tertiary reflector and the deep basement refractor was completed. Reflection and refraction highs generally coincide. The first wildcat (A-1-65), completed in March 1961, was high and dry at 7,437 ft in a section composed mainly of carbonate. No one knew yet of the "basal sand." The second wildcat (B-1-2) was low and dry at 10,193 ft. By combination of the seismic data with the tops penetrated in these two wells, a "top-of-Eocene" map was constructed (Fig. 9) which showed **C** as a very large structure with 300 ft of closure. It was a deeper structure than either **A** or **B**; if neither **A** nor **B** had shows or sandstone reservoirs, what chance could **C** have? The answer was provided by the C-1 well, which came in as a several thousand barrel per day discovery, producing from the upper 250 ft of a 500-ft or thicker sandstone reservoir previously unknown on the concession.

The great increase of closure with depth led to the belief that the structures had been growing with geologic time as a result of both rejuvenated fault uplift and continued sinking and compaction of the lows. With two dry wildcats and a discovery well completed, a better picture of field stratigraphy and lithology began to emerge (Fig. 10).

Stratigraphy

The stratigraphic successions penetrated by the wells are generally similar, the difference being only the relatively slight thickness variations of individual units (Fig. 10).

Holocene to Oligocene.—This interval consists of an upper zone (about 800 ft thick) of unconsolidated, slightly felspathic sand; a middle zone (about 1,000 ft thick) of gray-green and red-brown shale and claystone with dolomite and sandstone partings; and a lower zone (about 1,000 ft thick) of fine- to coarse-grained sandstone with some claystone partings and dolomitic beds. These beds are almost unfossiliferous but overlie well-dated late Eocene beds. In general the interval is thinnest over the crest of the Sarir structure and thickens away from it.

Upper Eocene.—The upper Eocene consists of 250–330 ft of interbedded limestone, dolomite, marl, and shale, which show marked lateral change in both lithologic character and thickness. There is a general change across the field from thinner, predominantly calcareous shale beds in the west to thicker, predominant limestone beds in the east. This variable sequence is somewhat transitional between the middle Eocene limestone below and the epicontinental, detrital, post-Eocene beds above. Dating of the sequence is based on the presence of

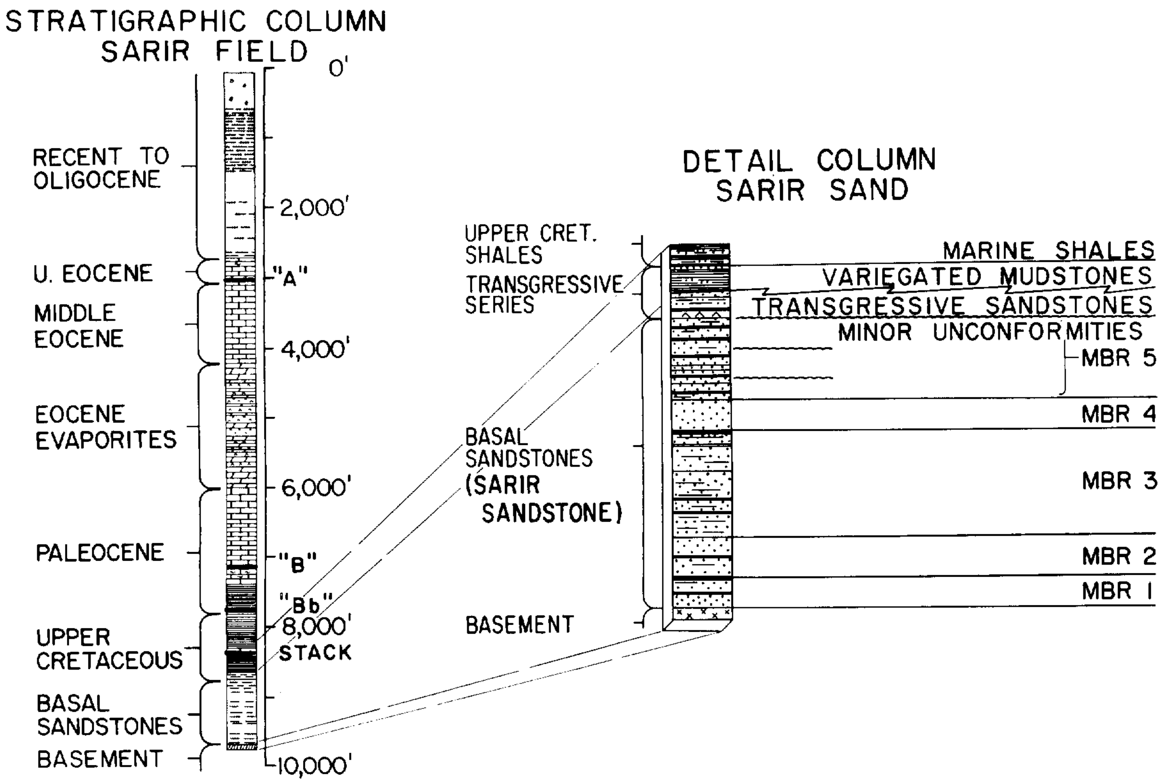


FIG. 10.—Stratigraphy of Sarir field, Libya.

the late Eocene *Nummulites fabianii* and *N. striatus*.

Middle Eocene.—This subdivision is approximately 1,200 ft of nummulitic limestone, argillaceous limestone, and marl with local beds of calcareous sandstone. The beds are very fossiliferous, containing such middle Eocene forms as *Nummulites subbeaumonti, N. curvispira, N. perforatus, N. bactchisariensis, Dictyoconus aegyptiensis,* and *Lockhartia tipperi*. Thickness of the unit is relatively constant across the large area of the field.

Eocene evaporites.—This sequence of evaporites consists of about 1,600–1,850 ft of interbedded dolomite and anhydrite. It is unfossiliferous and probably ranges in age from late Paleocene to early Eocene. It also is fairly uniform in thickness.

Paleocene.—The Paleocene is 1,600–1,900 ft thick and consists of an upper carbonate unit and a lower shale unit. The carbonate is mainly very porous dolomite with some limestone, shale, and a few stringers of anhydrite. The dolomite is mostly secondary. During the early drilling circulation losses in the dolomite caused delays.

The limestone intercalations carry a Paleocene fauna, including such forms as *Miscellanea miscella, Alveolina ovoidea,* and *Operculina patelensis*. The lower shale is dark gray to black, marine, and carries a fauna which includes *Globorotalia pseudobulloides* and *G. trinidadensis*.

The Paleocene-Upper Cretaceous contact, in the middle of a shale sequence, was cored in one well. It coincided with a gamma-ray log peak. There is believed to be a disconformity between the Upper Cretaceous and Paleocene, apparently marked by a high level of gamma radiation; thus the boundary now is picked on this readily discernible gamma-ray log peak. The thickness variation in the Paleocene is complex. There is a general thickening from the southeast to the north and west, and also local thickening on the flanks of the structure.

Upper Cretaceous.—The Upper Cretaceous consists principally of an upper marine shale unit which unconformably overlies a lower sandstone unit; this lower unit—the Sarir Sandstone—forms the reservoir of the field and lies directly on basement. Between the two units is a third unit consisting of several hundred feet of transitional beds (Fig. 10).

The upper unit consists mainly of 750–1,000 ft of dark-gray to black marine shale with some limestone and sandstone mainly in the lower part. The interbedded limestone generally is buff, glauconitic, finely crystalline, and dense, and the sandstone generally is fine grained, glauconitic, and impervious.

The associated fauna contains such Late Cretaceous forms as *Rugoglobigerina macrocephala, Pseudogümbelina costulata, Reussella aegyptica,* and *Globotruncana* spp. The youngest forms identified are of Maestrichtian age.

The middle or transitional unit includes several hundred feet of red, green, purple, and variegated anhydritic shales with some sandstone. The shales are very different from the gray-black shale of the upper unit. The sandstone is poorly sorted, fine to coarse grained, and generally is anhydritic and impermeable. Locally some porous beds are present which yield hydrocarbons.

The transitional unit overlies the lower unit —the Sarir Sandstone—unconformably. Evidence for the unconformable relation with the Sarir consists of shale colors, presence of numerous transgressive-regressive sequences, evaporite beds, and gradational sandstone-siltstone-shale sequences.

The lower unit—the Sarir Sandstone—is the field reservoir and is divisible into five members.

Seismic and Subsurface Control

Once the stratigraphy and lithology of the shallow section and the general geologic history of the Sarir area were known, a deeper mapping horizon or control level was needed and attainable. The geophysicists reworked all seismic data. They established what is called the "B" horizon and a phantomed "Bb" horizon, both at about 7,000–7,500 ft (*see* Fig. 10), in the Paleocene and Upper Cretaceous, respectively.

Figure 11 shows why the operators were very optimistic concerning the field during its early development stages. By March 1962, wells 1, 2, and 3 had been completed as good producers, rated at 7,500, 7,500, and 8,500 bbl/day, respectively. Number 4 was being drilled, and 5–8 were extension locations. The disappointment was great when four of the five outposts came in as marginal to nonproducing wells. Each had 100–200 ft of oil column, but the sandstone was silty to shaly and tight. The general lack of knowledge concerning the Sarir Sandstone thus became apparent.

Wildcat drilling continued in 1963 and 1964 while field development progressed. Figure 12 shows several hundred feet of structural relief at the top of the Sarir Sandstone. The bald highs surrounding the deep Sarir field area are confirmed by dry wildcats. Continued wildcat drilling also proved that the reservoir properties

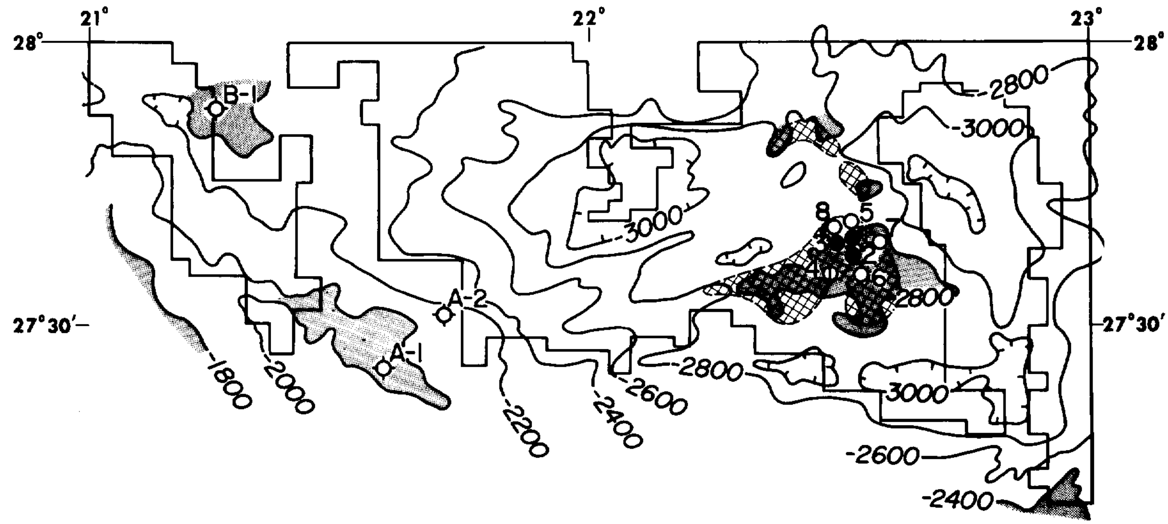


Fig. 11.—Structure as known in March 1962 with 3 wells completed and No. 4 being drilled; 5-8 are extension locations. Contour datum is seismic "A" horizon (top mid-Eocene; *see* Fig. 10).

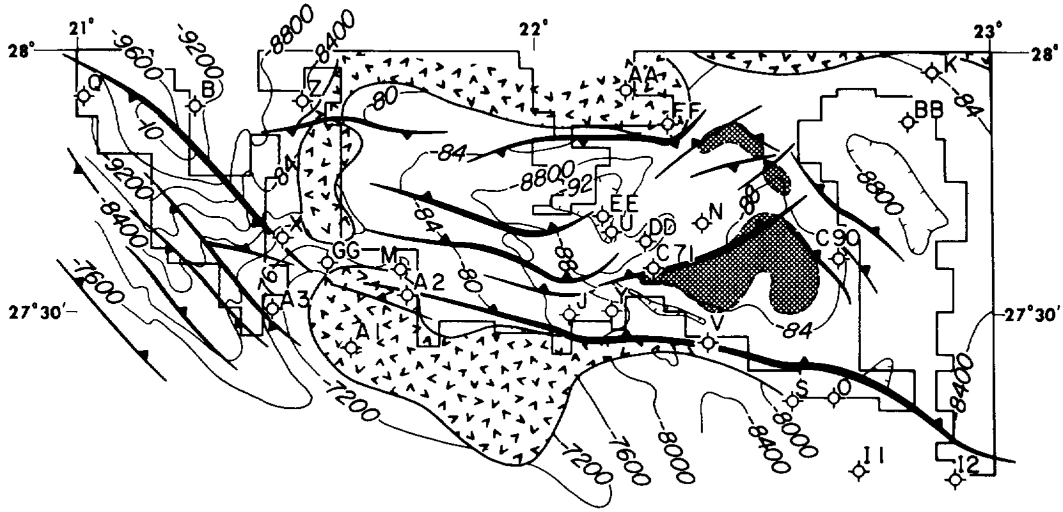


FIG. 12.—Structure contours with top of Sarir Sandstone as datum. Checked areas are basement subcrop. CI = 400 ft.

of the sandstone diminish off the west flank of the central (A-1 well) bald area. On the south the sandstone is mainly in the transition zone, and is of a poorer quality than that in the field.

Figure 13 shows the thickness of the reservoir-sandstone distribution over the present concession area. The greatest preservation of sand was in the deep trough where Sarir was discovered.

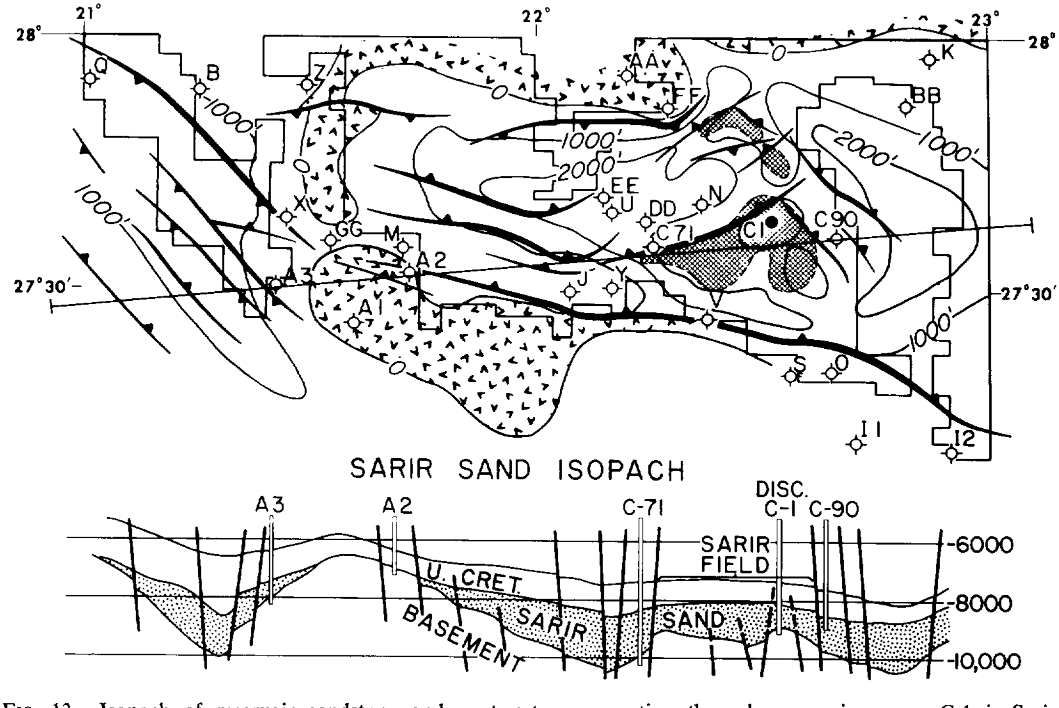


FIG. 13.—Isopach of reservoir sandstone and west-east cross section through concession area. C-1 is Sarir discovery well. Checked areas are basement subcrop. CI = 1,000 ft.

The post-Sarir uplift of the structure and subsequent erosion and reworking of the sandstone caused it to thin over the top of the structure. Sandstone is absent over the crest of the bald A structure, probably by erosion of Sarir Sandstone and nondeposition of younger transitional sandstone.

Normal or block faulting is apparent in the Sarir Sandstone (Fig. 13, cross section; Fig. 14). All high blocks seem to have been eroded to some degree.

As shown on Figure 10, Sarir Sandstone is divided into members. Although these divisions may be subject to later revision, they have proved to be adequate in development of the field.

Figure 14 shows the probable depositional sequence and transition from the basal (Sarir) sandstone into the overlying regressive and transgressive transitional sandstones. The main Sarir Sandstone ("Nubian," "Continentale Intercalaire," *etc.*) probably is a remnant sandstone from earlier sedimentation in the Sirte basin. It has been identified only in deep basin lows which remained below base level during the Late Cretaceous unconformable transgression. On this erosion surface, whether basement, Paleozoic rocks, or basal sandstone, the Late Cretaceous transitional sand, silt, and mud that graded upward into the Late Cretaceous marine mud were laid down.

Local faulting accompanied deposition; thus, the upthrown high edge of the Sarir field block was subjected to recurrent erosion. The eroded material was deposited downflank as a sequence of interbedded sand and mud (Fig. 14, middle panel). In time, these deposits lapped against and over the structural high and were themselves buried by the earliest deposits of the Late Cretaceous marine transgression (Fig. 14,

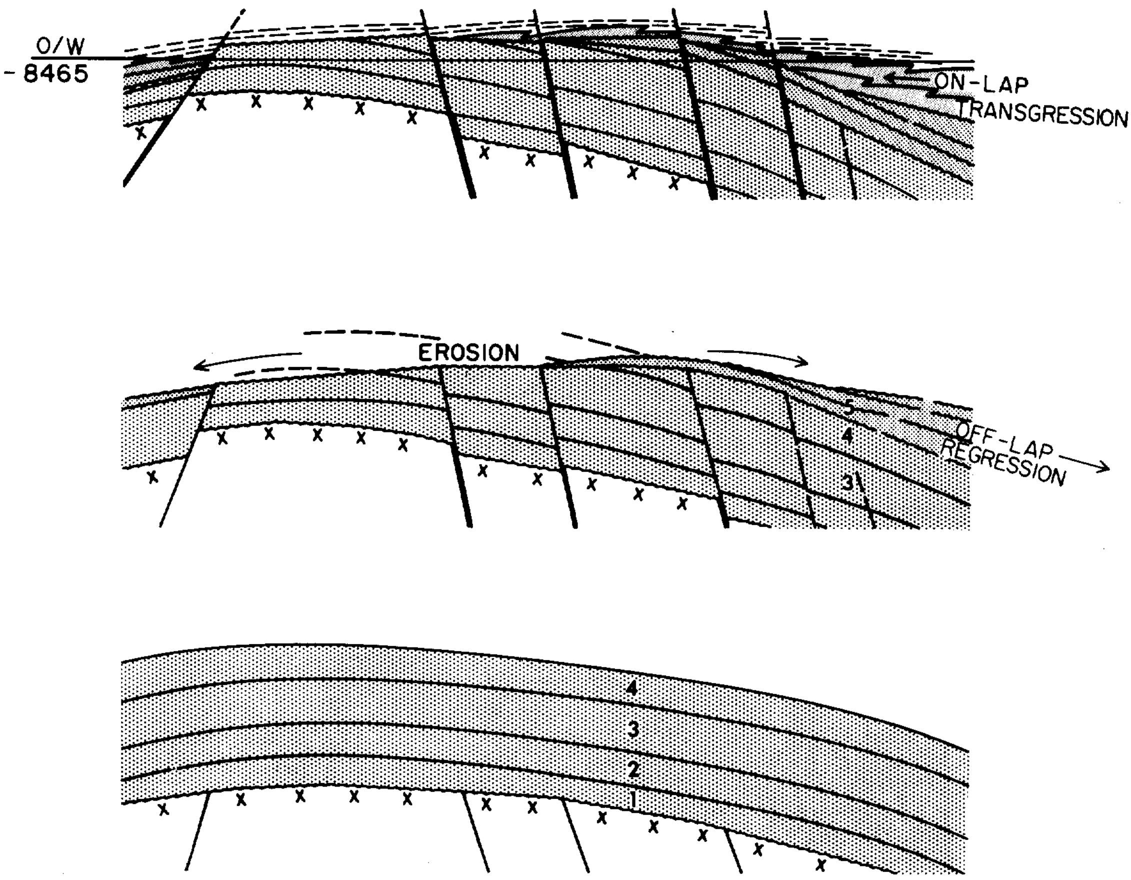


FIG. 14.—Sarir Sandstone sequence; probable transition of deposition from basal sandstone into overlying regressive and transitional sandstones.

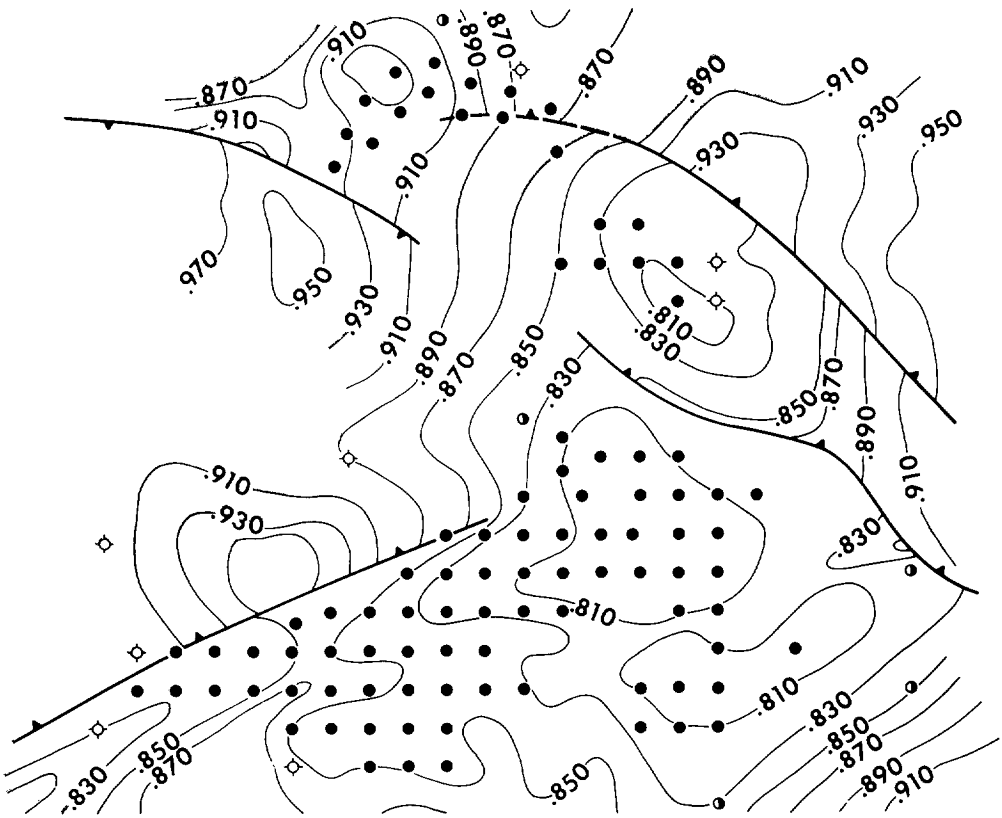


FIG. 15.—Basement refractor mapped before Sarir field discovery; 0.810 sec one-way time = approx. 9,000 ft. CI = 0.02 sec. The well pattern has been superimposed.

top panel). The oil-water contact is shown in Figure 14 to illustrate that the oil column cuts across the sandstone body and is partly in members 2–5 of the Sarir Sandstone, and in the transitional sandstone above.

In Figure 8, basement depths in the area surrounding Sarir are seen to be greater than 11,000 ft, whereas the perimeter of the structure is outlined within the 9,600-ft contour. In Figure 15 the 9,600-ft level is seen as about 0.850 sec; the crest of the closure on basement is 0.810 sec or about 9,000 ft; the deeps of 0.950 sec in the northwest part of the map are in excess of 11,500 ft.

The superimposed field wells are on a spacing of 2 km or 1.2 mi, which makes the oil-field area about 35 mi long by 25 mi wide.

Figure 16 shows the seismic "A" horizon (Fig. 10), top of the middle Eocene, as interpreted across the oil field. It is more detailed than Figure 11, which is a map of the entire concession. The basic grid was shot and the "A" horizon interpretation was made over the field area before the wells were drilled; very few changes were needed as the field was developed.

Early in the field development, the most critical problem to resolve was the fact that 100 ft of closure at the 3,000-ft "A" horizon increases to several hundred feet at the top of the reservoir. This accentuation of structure with depth became apparent as the first 15–20 wells were drilled. The dry wildcat at the far north (L-1, Fig. 16) was drilled in 1963 on the basis of structure seen on the "A" horizon and the basement refractor; in 1966, as a result of more precise CDP methods, the south offset (L-2) became the discovery well in this north extension.

Mapping of the "B" horizon, near the base of Paleocene, generally accentuated and shifted slightly the three high areas which later proved to be the three main lobes of the oil field. However, the "B" horizon map still was not suffi-

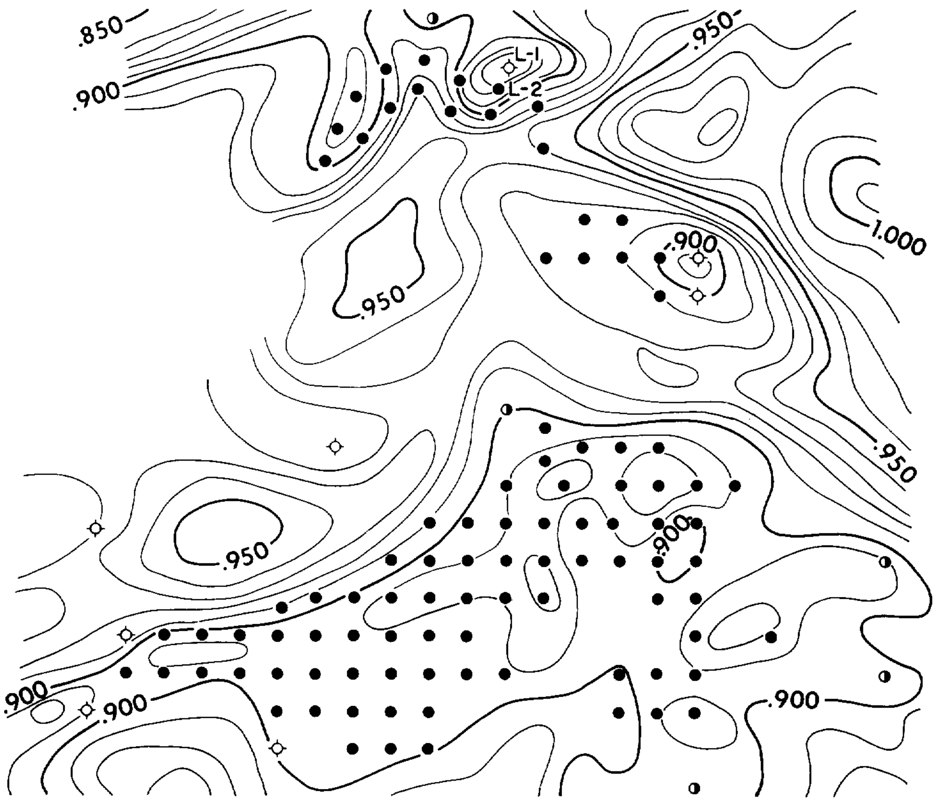


FIG. 16.—Reflection seismic "A" horizon, about top middle Eocene; 0.900 sec two-way time = approx. 3,000 ft. CI = 0.01 sec.

ciently accurate to prevent the drilling of many dry holes, and it was little used.

Detailed Field Structure

It was imperative that a control horizon be mapped on or near the top-of-sandstone level. Toward this end an experimental sixfold, multicover, reflection seismic survey was conducted over a part of the field where reliable, known subsurface tops had been determined. After considerable playback-center experimentation, a reliable reflector was found to be mappable just a few hundred feet above the sandstone-top unconformity; Figure 17 is a reconnaissance view. The interval from this so-called "stack" horizon down to the top of sandstone can vary by a hundred feet or more, but it was the most accurate deep horizon yet mapped. Most of the true structure of the reservoir began to be revealed, although pre-unconformity faults in the Sarir Sandstone that were not rejuvenated could not be mapped at the stack-horizon level.

CDP lines were shot from the unknown parts of the concession into the known field area where the reflecting horizons could be identified. Development drilling, extension drilling, and concession wildcat drilling continued with the combined help of edge CDP coverage and normal subsurface well tops. Figure 17 shows closures of 250 ft or more, compared with only 100 ft on the "A" horizon map (Fig. 16).

Figure 18 is a south-north seismic CDP line through the west end of the field—the first line of wells east of the south-central dry hole. Here the faults in the deeper beds show up well on the 600-percent stack section. Such results as this proved beyond doubt that the actual reservoir is faulted considerably. The large fault just north, or on the right, of well 23 is the bordering field fault. It has about 300 ft of throw at the top of the Sarir and nearly 1,000 ft at the depth of the basement. On Figure 17 the two southwestern-edge dry holes are in segments that are downfaulted from the main field. Figure 19 shows the manner in which one of these

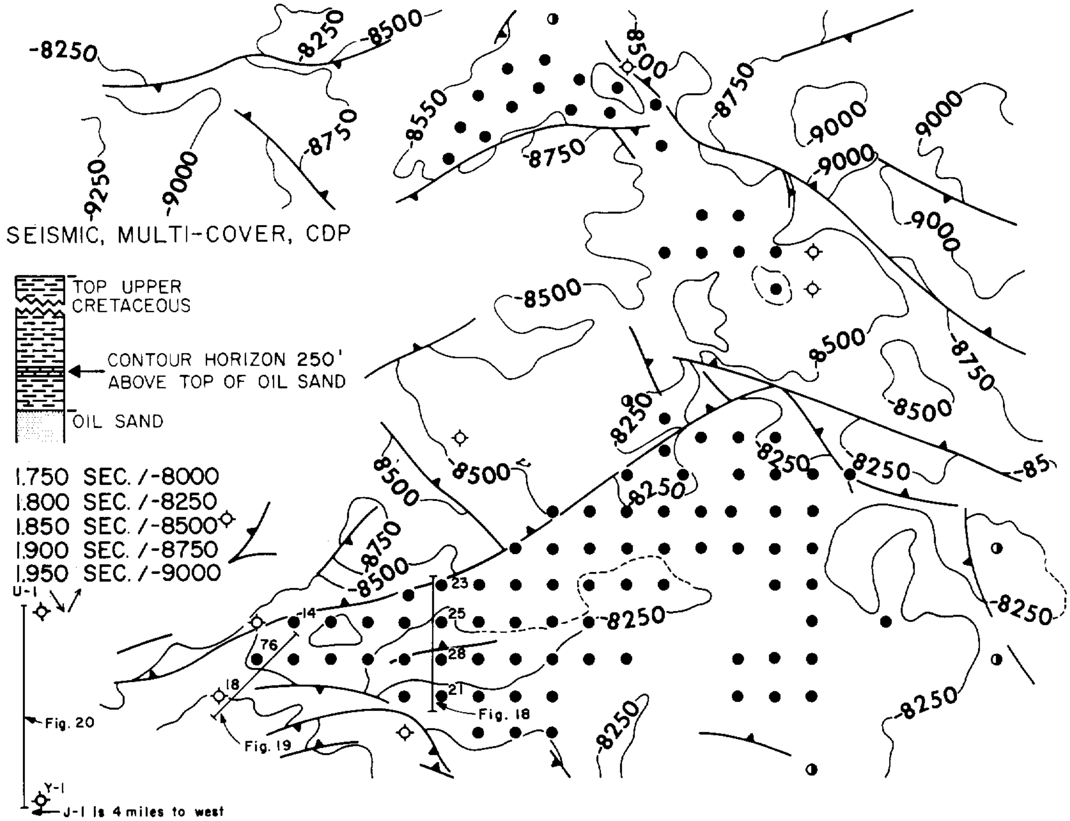


FIG. 17.—Reconnaissance map based on reflection seismic survey. Structural datum is 250 ft above top of Sarir Sandstone. CI = 250 ft. Locations of Figures 18-20 are shown.

faults grew by periodic rejuvenation, and the present measured throw at various levels. This fault has the characteristics of synsedimentary (Barakat, 1960), contemporaneous (Hardin and Hardin, 1961), or growth faults (Ocamb, 1961).

Figure 20 is a south-north multicover seismic line just west of the main field, extending from Y-1 to U-1, both basement wildcats. The stacking technique brings out basement and top-of-sandstone structure very well. What appears to be depositional thinning of the sandstone from right to left actually is caused by erosion of the sandstone at the unconformity at the top of the Sarir, as well as by truncation at the approximate stack-horizon level by the transgressive marine shales. It is not possible, seismically, to identify the individual sandstone members, but in Figure 20, member 1 probably would be subcropping beneath Cretaceous shale on the left, and members 2–5 would subcrop progressively northward.

Figure 21, a south-north CDP section in the western part of the concession, may be compared with the section between wildcats Y-1 and U-1 of Figure 20. The several down-to-the-north faults appear to have combined into two large faults. Erosion and truncation are extreme at the southern or left end of Figure 21. The sandstone thickness increases from a few hundred feet to more than 2,000 ft in about 2 mi. The sandstone is preserved in the low areas and generally is eroded from the high areas. Exceptions would be in places where the transitional sandstones above the Sarir and at the base of the overlapping transgressive sequence might lap directly onto the denuded basement. Only drilling would determine whether the thin sandstone over the high is part of the post-Sarir transitional unit or the uppermost unit (member 1) of the Sarir. Wildcats J-1 and Y-1, 4 mi west of the field area (not shown in the illustrations), penetrated several hundred feet of shaly, silty sandstone. It is still unknown

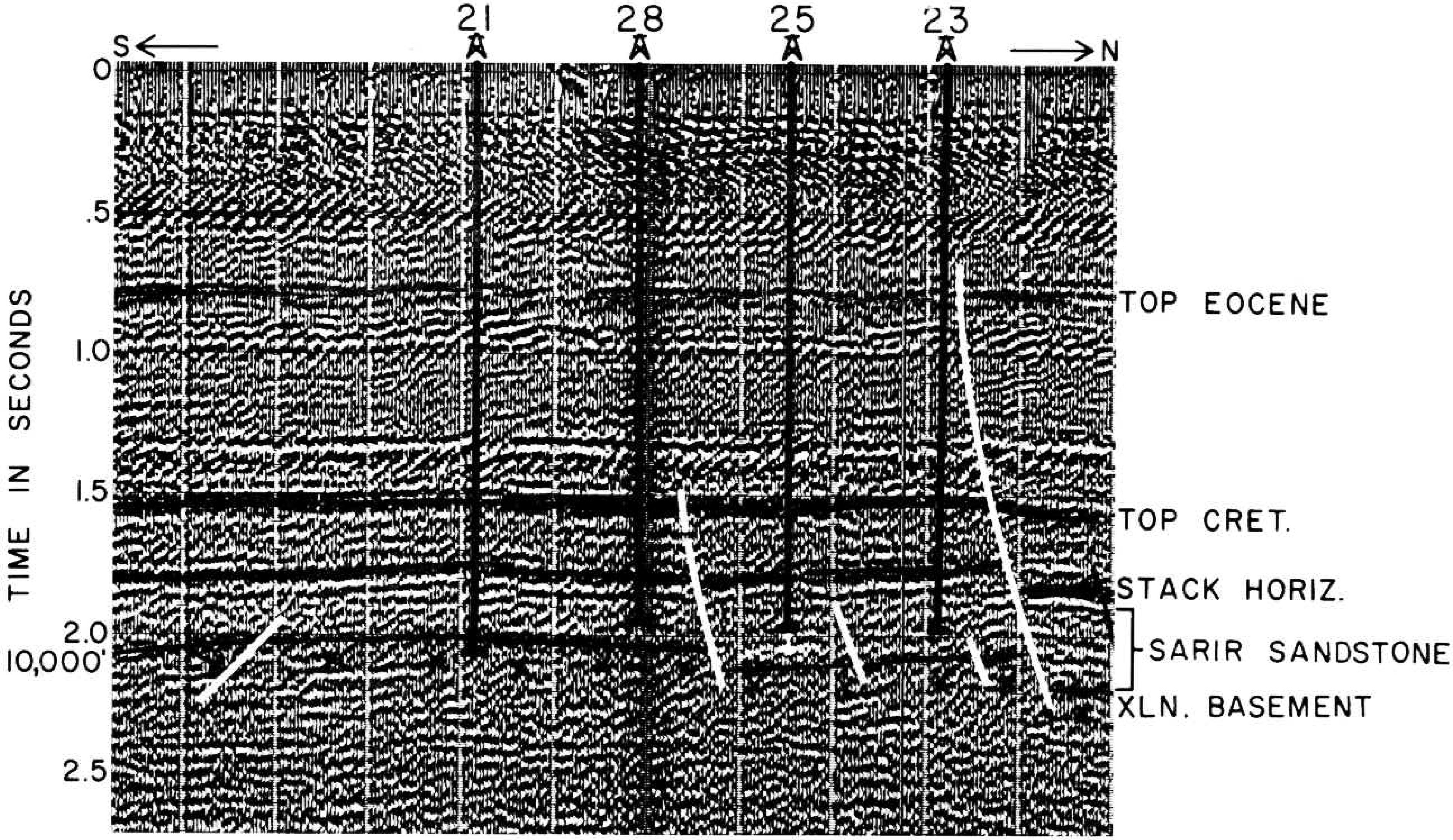


FIG. 18.—South-north seismic CPD line through west end of Sarir field. Location is shown on Figure 17. Faults are shown in white.

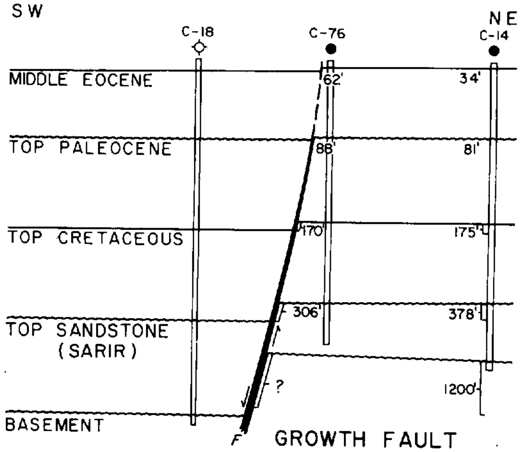


FIG. 19.—SW-NE section, southwest end of Sarir field. Fault growth is by periodic rejuvenation. Increments of growth are shown in feet. C-18 is westernmost dry hole and C-76 and C-14 are adjacent west-end field wells. Location is shown on Figure 17.

whether this section belongs to the onlapping transitional sandstones, or to member 1 of the Sarir Sandstone, or to both.

A sandstone-member subcrop (Fig. 22) shows the truncation from east to west across Sarir field. An interpretation of the structure at the top of pay sandstone, considerably simplified and without many minor faults, is given in two electric-log correlation sections (Figs. 23, 24). Figure 23, together with Figure 22, shows that the main Sarir structure is the flat crest of an upthrown block, bounded on the northwest and northeast by faults generally downthrown toward the north. The area of closure of the main field is roughly triangular, with an east-west base about 25 mi long and a north-south perpendicular distance of about 12 mi. Within the closed area dips are south and generally less than 1°. However, as an indication of the deep-seated nature of this structure, the depth to the basement between the crest of Sarir structure and the deep low just south of well 20 changes by 270 msec, or about 3,300 ft. This depth change is within a distance of 14 mi and is equivalent to an overall dip of 2.5°. The steepest dip recorded is 4.5°.

North of the main triangular structure, on the ridge separating the northwestern and northeastern basement lows, there are additional areas of closure—the Sarir North and L-area—which also are fault-bounded on the northwest and northeast. The full sequence of sandstone units is present in all three producing areas, as seen in Figure 23. This section also illustrates the three distinct water levels of the three producing lobes. Field production has shown that faults apparently do not act as fluid barriers. Thus, the different water levels must be explained by fault displacements of impermeable against permeable beds. Between the main field and the Sarir North area of well C-19, a low block brings shale down to water level. The same may or may not be true between Sarir North and the L-area.

On Figure 24, the angularity of the unconformity from east to west is most evident. It also is seen in the subcrops in Figure 22. With the depth of basement increasing from wells 1 to 11 to 14, a true depositional thickening of the sandstone members is demonstrated, even though subsequent truncation has occurred at the sandstone-shale contact. The main part of Sarir field has a uniform oil-water level of about −8,460 ft. The sandstone is greatly thickened in dry hole 18 because it is in a downthrown, noneroded block in an off-structure position. Figure 19 shows the 1,200 ft of basement throw and 378 ft of sandstone-top throw between wells 18 and 14.

SARIR SANDSTONE (BASAL SANDSTONES)

A study of the sandstone members in Figures 23 and 24 shows that thickness ranges from about 450 ft to more than 2,000 ft throughout the field. The sandstone beds are overlain unconformably by the transgressive sequence and directly overlie a basement complex of granite and metamorphic rocks. Angiosperm pollen has been recorded at a low level in the sandstones. Thus they are dated as no older than latest Early Cretaceous (Albian), and probably are of early Late Cretaceous age.

The basal sandstones are very nonhomogeneous and several attempts at subdivision were made during the field's developmental stages. A most obvious division of the entire sandstone interval is into three parts—a lower shaly sandstone, a middle clean sandstone, and an upper shaly, silty sandstone. This division is apparent on all lithologic sections and electric logs of the area. In a further breakdown the lowest unit is called member 1, the middle unit is subdivided into members 2, 3, and 4, and the upper unit is member 5 and transition beds. The members are described in descending order.

Member 5.—Member 5 is absent in much of the field and ranges in thickness from 0 to about 450 ft. It forms an outward-thickening fringe around the margins of the main structure.

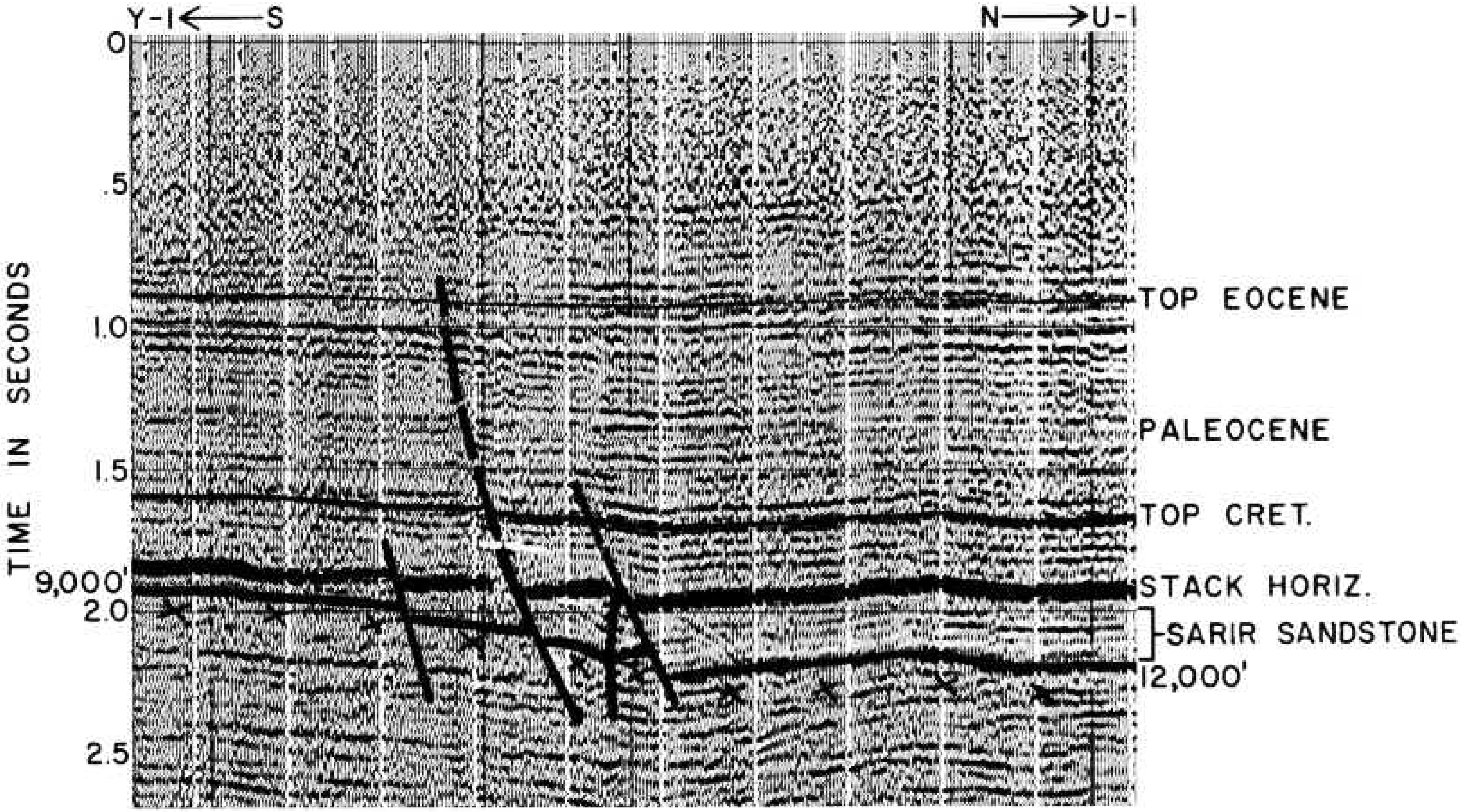


FIG. 20.—South-north multicover reflection seismic line, just west of main field, between wildcat wells Y-1 and and U-1. Location is shown on Figure 17.

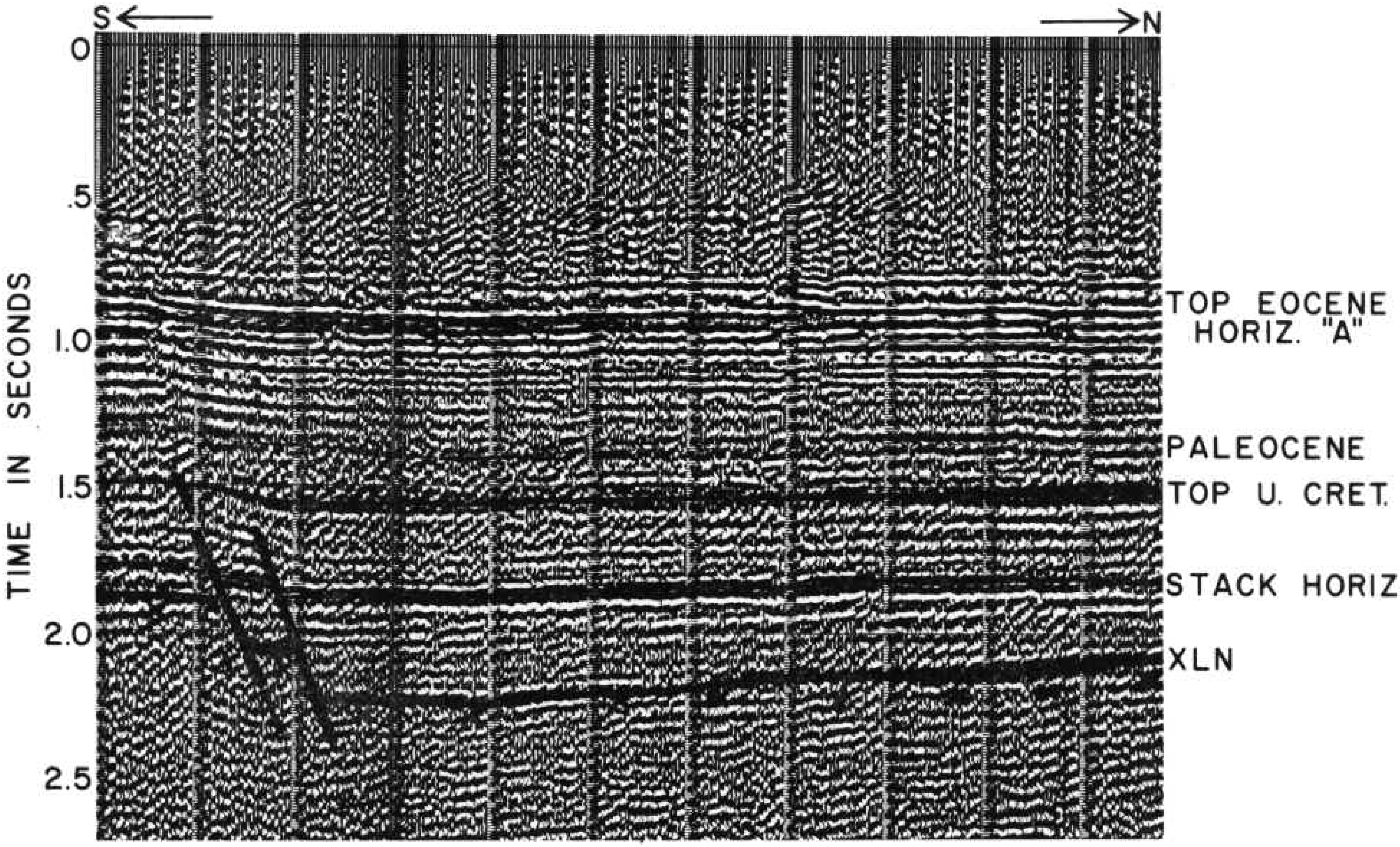


FIG. 21.—CDP section in western part of concession. Compare with Figure 20. Location is 4 mi west of Figure 20 (*see* Fig. 17).

The partial absence of the member is considered to be due to postdepositional erosion and/or nondeposition over high areas of the field. Detailed studies are still underway involving stratigraphy, lithology, and geologic history of member 5 and the overlying transitional sandstone beds.

Lithologically, member 5 is extremely variable, consisting of white to red-brown, poorly cemented, fine- to coarse-grained sandstone and shaly sandstone, with interbedded red and green shale and sandy mudstone. Although it is generally tight, several porous and permeable beds within it have almost the quality of the sandstone of member 4. Where porous and permeable beds are above the oil-water contact, they yield prolific production.

Member 4.—The 100–200-ft member 4 is the cleanest and most permeable sandstone unit. It separates the tighter sandstone of member 3 and the shalier sandstone of member 5. It is a white to buff, clean, medium- to coarse-grained, poorly sorted, poorly cemented, friable, blanket sandstone with good porosity (17–20 percent) and good permeability (several hundred millidarcys to 2- or 3-darcy streaks). Member 4 is the main reservoir of the basal sandstone sequence.

Member 3.—Member 3, 230–820 ft thick, consists of alternating porous and tight sandstones, with some shale. The nonporous sandstone beds are cemented tightly with a clay matrix.

The porous intervals in member 3 form good reservoirs. They are generally 20–40 ft thick, with porosity and permeability characteristics similar to those of the excellent member 4 sandstones.

Member 3 is present in the entire field and was eroded only partly at the unconformity over the crest of the structure.

Member 2.—This is a fairly uniform, clean sandstone, also similar in character to member 4; however, it becomes somewhat shaly in the lower part. It ranges in thickness from 100 to 270 ft.

The member is present in its entirety across the whole field and thickens from east to west, as did member 3 before it was eroded at the top. Only in the westernmost part of the field is member 2 found above the oil-water level.

Member 1.—This basal unit of the sedimentary succession consists of an alternation of sandstone, shaly sandstone, mudstone, and siltstone. Generally it is much more shaly than the upper members. It is present on the entire structure but is greatly varied in thickness. Like members 3 and 2, it thickens from about 50 ft on the east to more than 1,000 ft on the west. The great thickness variation of this member, as well as of members 2 and 3, probably is due partly to the infilling of an irregular basement topography, and partly to proximity to a source of abundant sediment in a nearby high area on the southwest. The faulting and structural uplifts of concession 65 might not have started during the time when member 1 was deposited. Nowhere in the field is this member above the oil-water level.

Oil Reservoir

Although seismic basement control proved to be fairly accurate throughout the concession, the need for structural, stratigraphic, and reservoir data necessitated the drilling of certain selected wells to basement. Figure 25 is a structure-contour map of basement. Just within this field area the basement surface has 1,000 ft or more of relief. Subsurface control of block faulting within basement is only fair, and is somewhat less clear within the sandstone members. There are very few, if any, reliable correlation markers within the individual sandstone bodies. Locally there may be unconformable or disconformable relations between members, or within a member, as there is thought to be between members 4 and 5 and between member 5 and the transitional sandstone beds.

Figure 26 shows that, at the 2-contour line, the water-bearing sandstone is only about twice as thick as the oil-bearing sandstone around the crest of the structure (roughly at the 9,000-ft contour on Fig. 25). Discovery well C-1 on the crest had 250 ft of oil-bearing and 250 ft of water-bearing sandstone—the thinnest total sandstone sequence on the entire structure. Outward from the crest, the water-bearing sandstone thickens markedly beneath the oil column. This great increase is a most significant feature of the reservoir and is part of the key to its water-drive energy source. There is no gas cap in the reservoir, and Sarir crude has a low gas-oil ratio of between 60 and 225 scf/bbl. Except on the crestal area of thinner sandstone, the entire field has developed into a water-drive reservoir.

Figure 27 is a thickness map of the gross oil-bearing sandstone above water level. During development drilling of the field certain wells were designated to be cored, some through the entire pay section and some through only selected parts. These wells are shown by the triangle symbols in Figure 27.

In the western part of the main field, the five wells marked by squares were blown up by unknown saboteurs on May 14, 1965. The christmas trees were dynamited, and wells 48, 24, 28, and 21 went out of control and caught fire. Well 23 blew wild but did not catch fire.

Engineers, production men, and the professional fire fighters at the time estimated for well 24 a free flow of 25,000–30,000 bbl/day. The wild flow of well 48 was estimated at 30,000–40,000 bbl/day through casing and tubing during the last 4 days before it was controlled. All wild wells finally were capped, recompleted, and found to have had no actual reservoir damage. The wild flow lowered the measured bottom-hole pressures from about 3,904 psi to about 3,895 psi, or a drop in that area of the field of less than 10 psi for the more than 1 million bbl produced by the five wells in the 6–15-day period. Nineteen months later, when the field was ready to go on pipeline production, reservoir pressure recovery had been complete. Well 24 has been producing at an average of 2,900 bbl/day and well 48 at an average of 7,000 bbl/day for 1½ years. Wellhead flowing pressures that originally were near 1,000 psi are now down about 100 psi in this part of the field, but sustained water drive is halting the decline. Flowing pressures in most of the field are still well above the 650-psi level used for potential estimates, but some sections, specifically the central, thin-sandstone area, show somewhat greater pressure drops of about 400 psi, or to about 600 psi, and pressure maintenance by water injection is being undertaken.

A structure map with the top of the pay sandstone (Sarir) as datum, contoured to accommodate the main faults known or believed to be present at this top-of-sandstone level, is shown in Figure 22. Somewhat fewer faults are shown here than are known on basement. The different oil-water contacts are marked around the three producing lobes. Drilling eventually may be done on the eastern and southern sides of the main field, as well as in the areas between the field segments; the decision to drill probably will depend on performance of the southeast-area wells when they are tied into the system.

In the center of the main field and just under the 8,200-contour elevation is well 54, one of

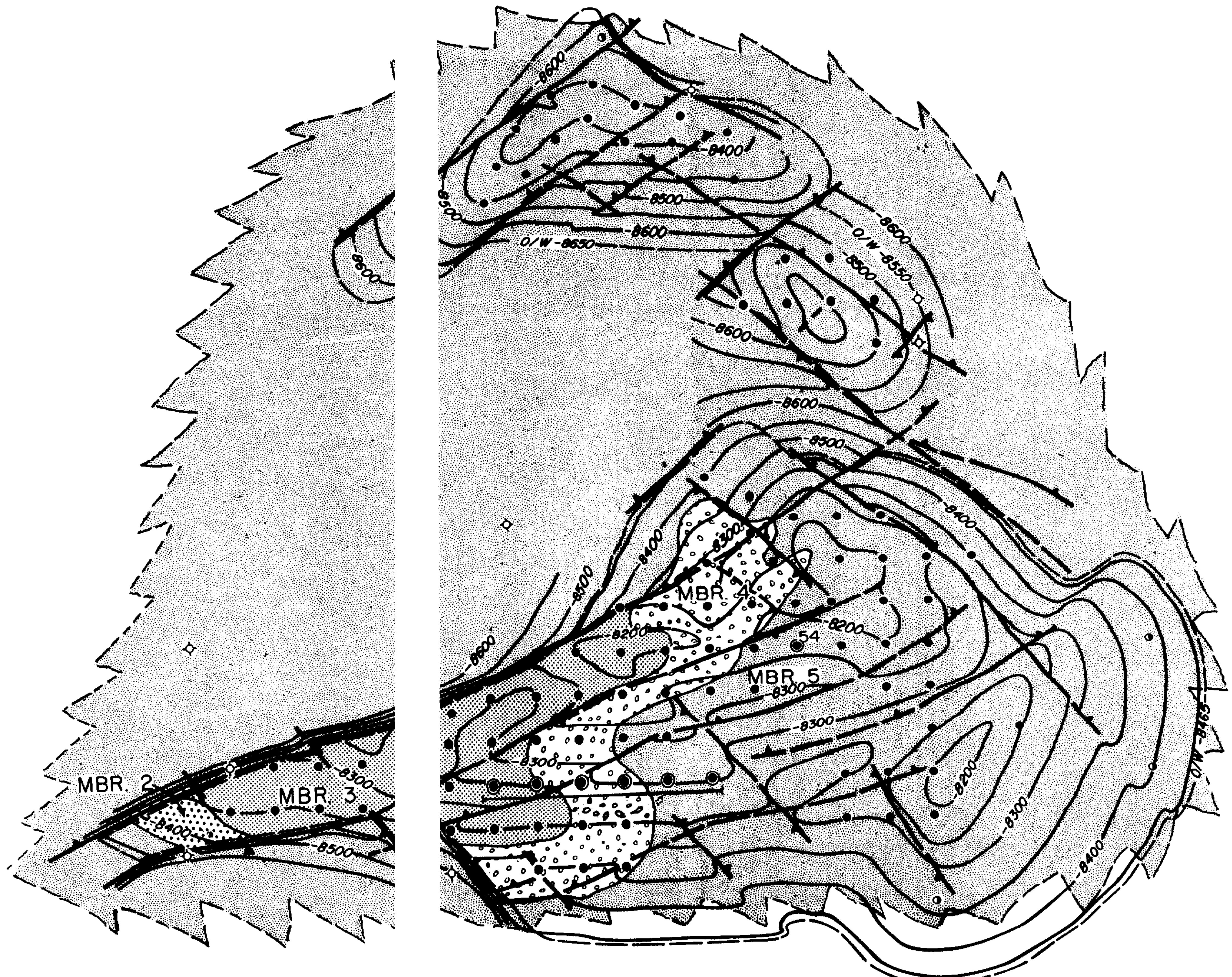


Fig. 22. Structure on base of shale or top of pay sandstone, with subcrop of sandstone members of Sarir Sandstone superimposed. CI = 50 ft. Very fine dot pattern is member 5; fine dot pattern is member 3; coarse dots are member 2; circles are member 4.

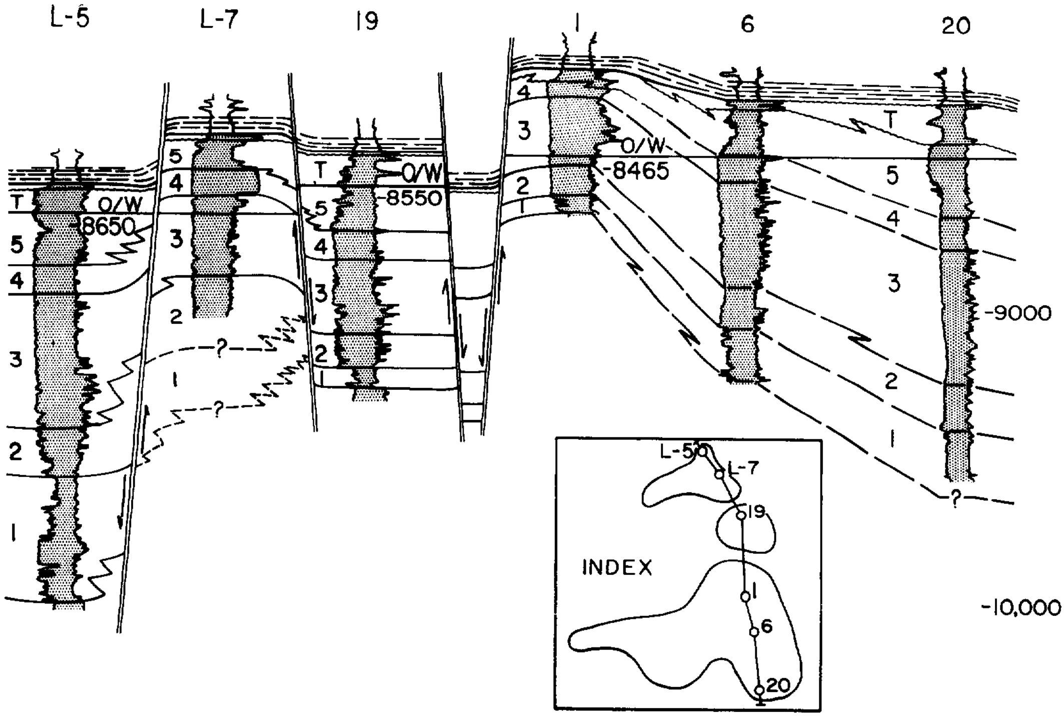


FIG. 23.—North-south section of Sarir pay.

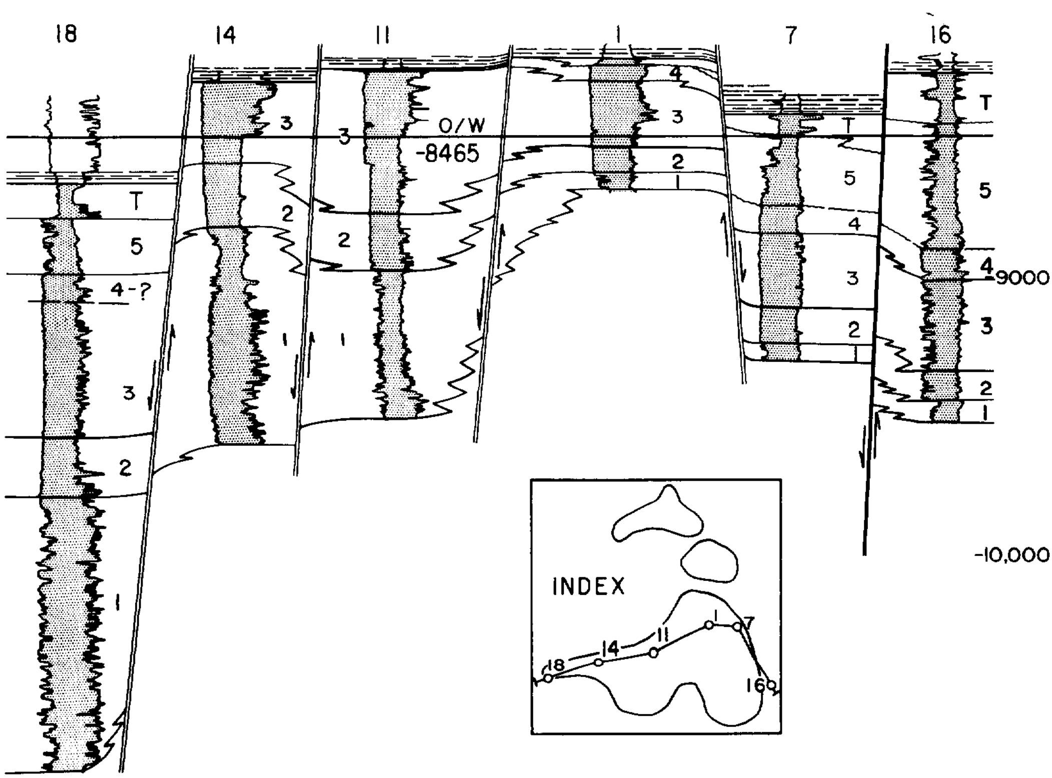


FIG. 24.—West-east section of Sarir pay.

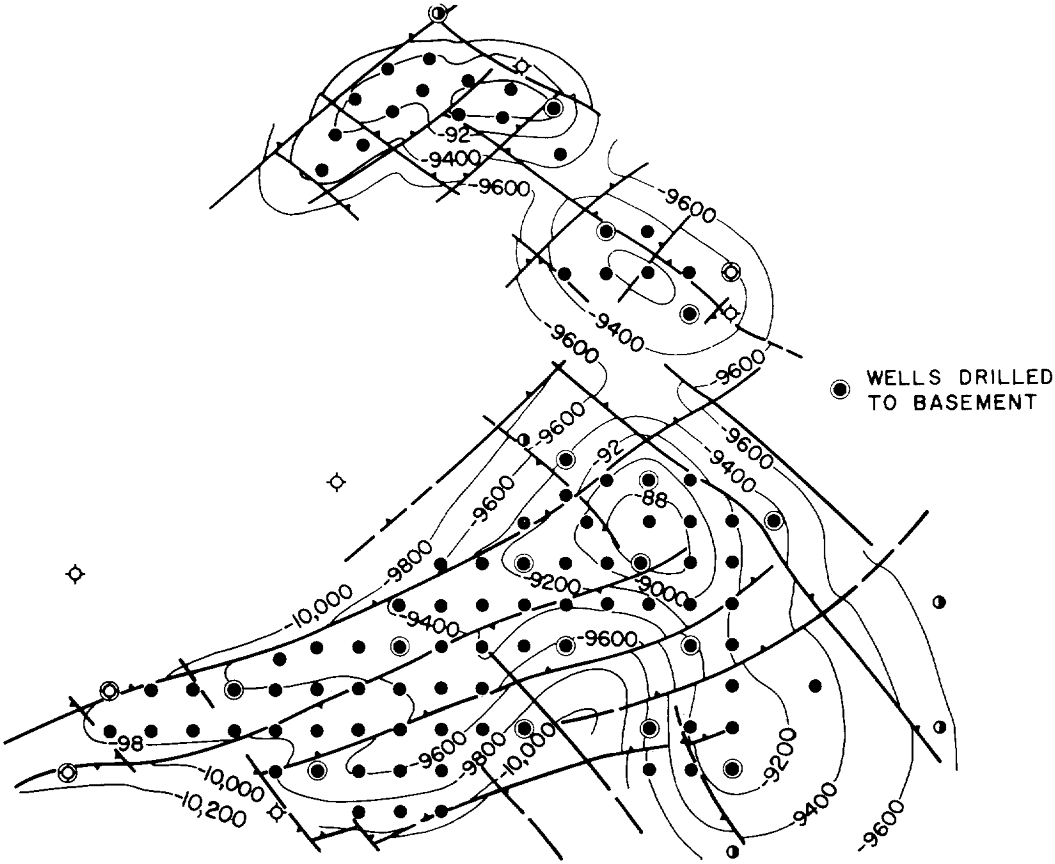


FIG. 25.—Basement contours, based on information from wells drilled to basement, incorporated with seismic refraction data. Wells with double circles were drilled to basement. CI = 200 ft.

the holes in which the entire pay section was cored. Figure 28 is a representative segment of about 85 ft of the coregraph of this well. The average reservoir porosity is about 19 percent, the permeability several hundred millidarcys, and the oil saturation 18–20 percent.

This 85-ft coregraph section was selected out of the total 240-ft pay section to show basal member 5 sandstone and upper member 4 sandstone; member 4 is the most prolific producer. Porosity and permeability values are somewhat reduced in members 3 and 5, although the clean sandstone streaks in the upper part of member 5 have all the best properties of the member 4 sandstone.

Production and Reserves

During field development no location was drilled intentionally in which less than 100 ft of gross oil column was expected. No wells, except fluid- or pressure-observation wells, were perforated and opened to production any deeper than 50 ft above the oil-water contact. However, deeper perforations in some wells were being considered in early 1968. The −8,460-ft oil-water contact is common throughout the main segment of the field.

Figure 29 shows gathering lines, trunk lines, and main pipeline. The southeastern area wells, with the dashed gathering-line symbols, were not tied into a gathering center during the first 1½ years of production, but now are being connected. The oil column in this southeast section is mainly in member 5 sandstone and therefore is not of the high production quality of the rest of the field. These wells and undrilled locations are not uneconomic, but during the early days better wells were supplying the necessary oil volume. Some of the southeast area wells yield 3,000–7,000 bbl/day, and others produce less. They are expected to be in the good water-drive area.

FIG. 27.—Isopach of gross oil-bearing sandstone above water. CI = 50 ft.

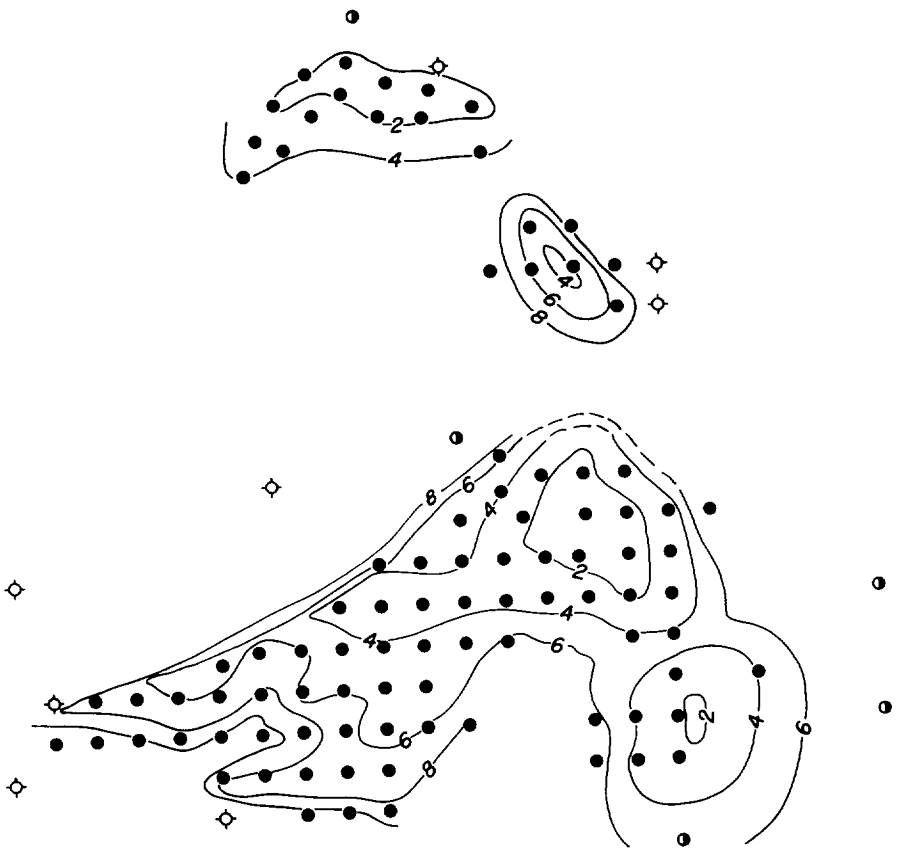
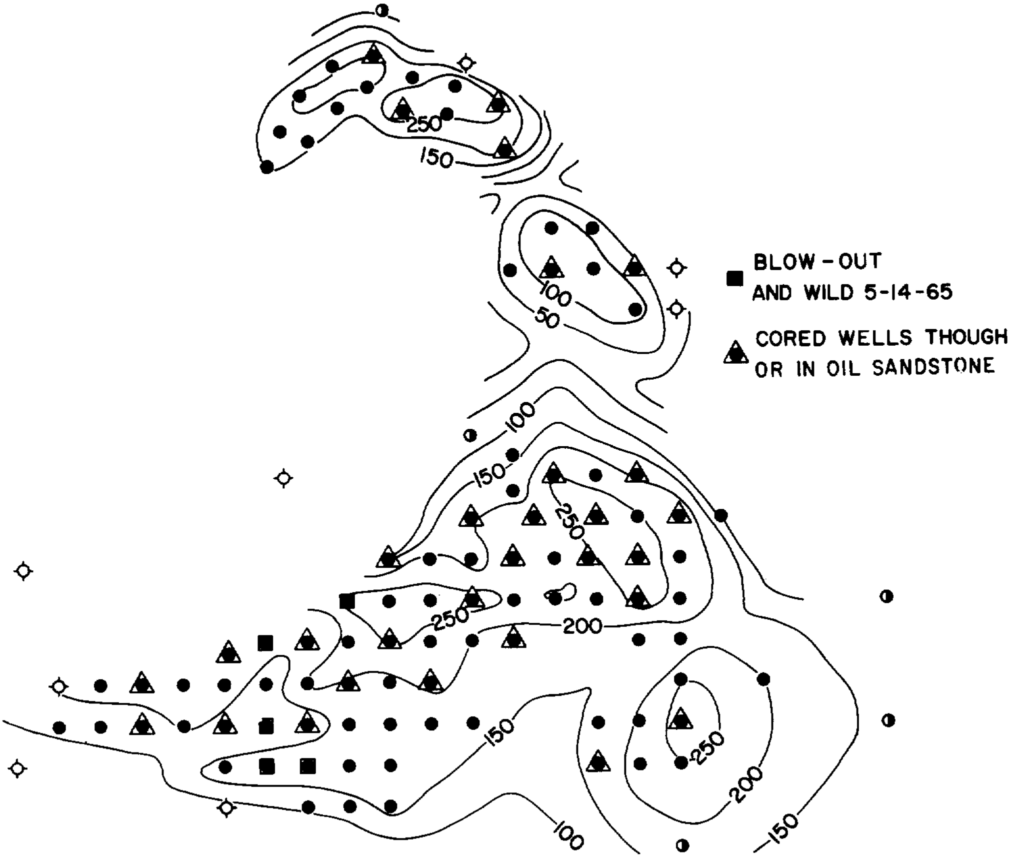


FIG. 26.—Ratio of water-bearing sandstone to oil-bearing sandstone. Strongest water drive, *i.e.* least pressure decline is in areas of highest ratio. CI = 2.

FIG. 28.—Coregraph of 85 ft of well C-54 (*see* Fig. 22), Sarir field. Shows properties of member 4, Sarir Sandstone.


BLOW - OUT
AND WILD 5-14-65
CORED WELLS THOUGH
OR IN OIL SANDSTONE
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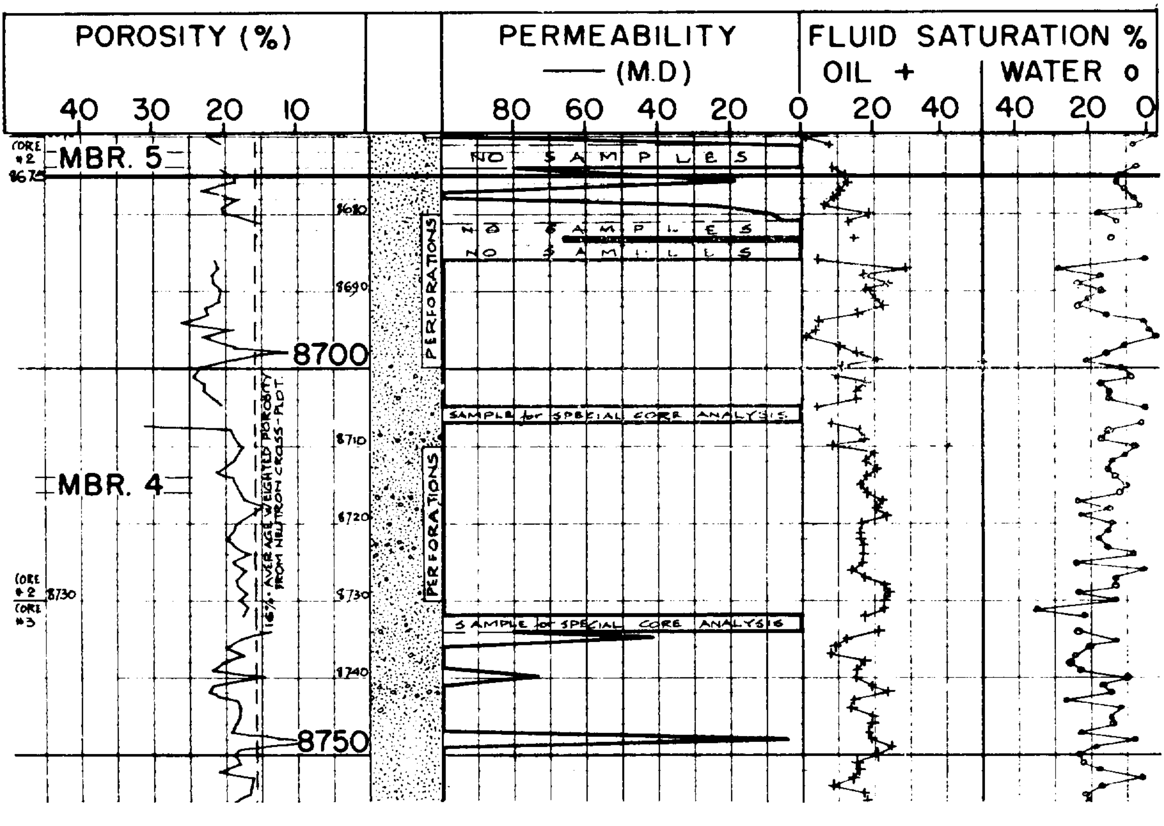
POROSITY (%)
40 30 20 10
PERMEABILITY
(M.D)
80 60 40 20 0
FLUID SATURATION %
OIL +
WATER o
0 20 40
40 20 0
CORE #2 8675
MBR. 5
NO SAMPLES
NO SAMPLES
NO SAMPLES
PERFORATIONS
8700
SAMPLE for SPECIAL CORE ANALYSIS
MBR. 4
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CORE #2 8730 CORE #3
SAMPLE for SPECIAL CORE ANALYSIS
8750

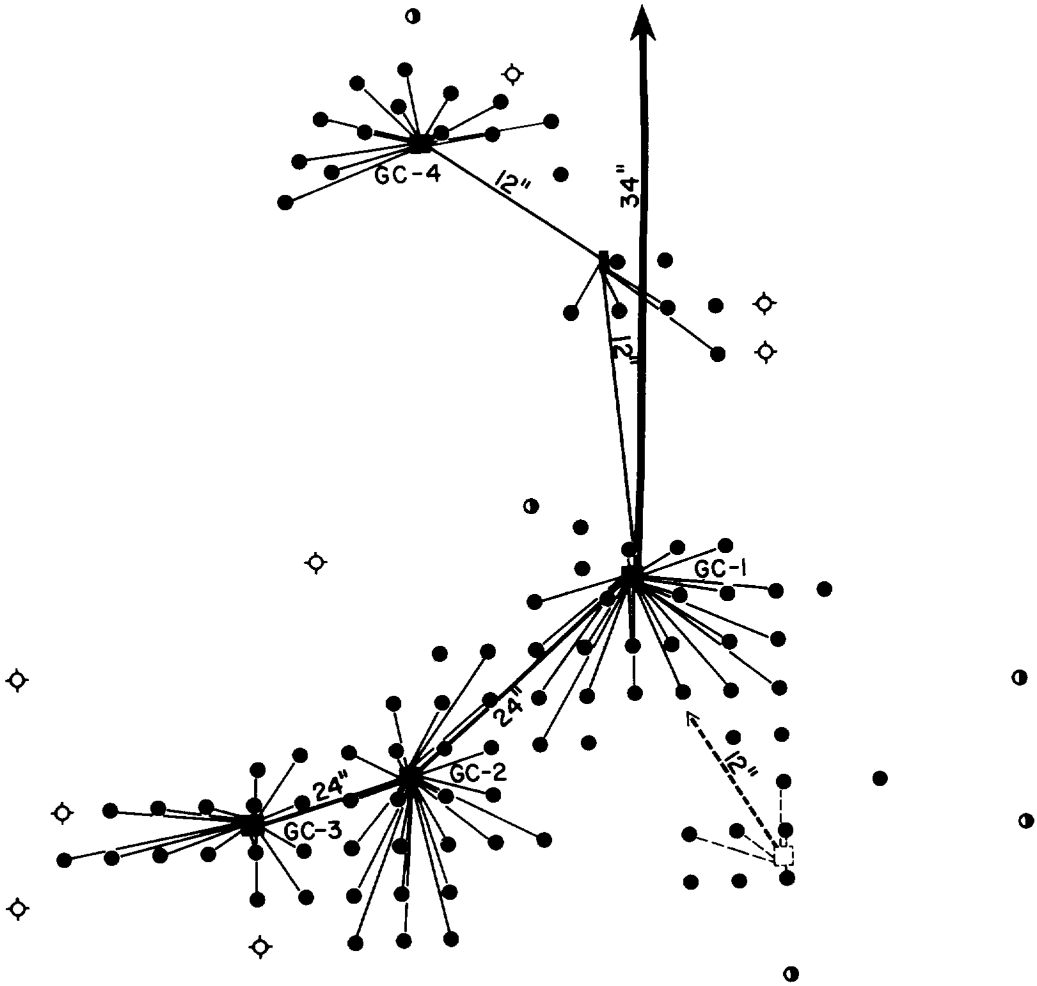

FIG. 29.—Gathering lines, center, and pipelines, Sarir field, Libya. Dashed lines are systems under construction.

For comparison of individual well potentials across the field, all Sarir wells were gauged on chokes of various sizes and thus registered various wellhead flowing pressures and volumes. Individual graphs were plotted for each well to show its producing capacity pulled down to a steady 650-psi wellhead flowing pressure. Average wellhead shut-in pressures were 970–1,000 psi before the field went on production. A total of 36 wells in the field produces 7,000–15,000 bbl/day at 650 psi, 33 produce 1,000–7,000 bbl/day, and 31 have less than the 1,000 bbl/day capability. Only 5 of 105 wells drilled—less than 5 percent—were dry holes without any oil column. Overall, the oil is a fairly light, waxy crude with a mean API gravity of 37°, wax content of 19 percent, and a uniformly low sulfur content of less than 0.25 percent. The pour point is high and ranges from 55 to 75°F.

Possibly because of two-stage migration of oils into the structure, there are also two different gravity oils present within the formation. A low-gravity zone of tar mat is present at the base of the reservoir near the oil-water level. The tar mat is variable in thickness, but averages about 10–30 ft where present on the east side. The properties of the tar mat have not been investigated fully but samples of very viscous oil obtained from drill-stem tests at the top of the zone show it to have a mean gravity of 24.5° API, a pour point of about 160°F, a

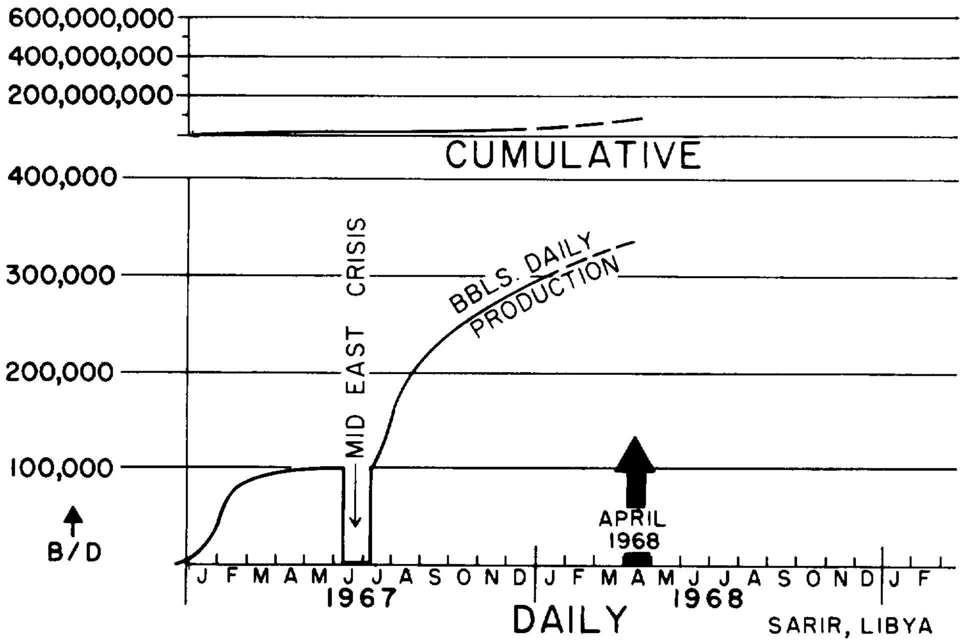

FIG. 30.—Daily production rate of Sarir field, 1967 and 1968.

wax content of about 15 percent, and an asphaltene content of 14–22 percent.

Most of the marginally economic wells have been completed as reservoir-observation wells. The field production engineers are observing daily, weekly, or monthly, water-level rise or fall in off-structure nonproducers, bottom-hole shut-in and flowing pressures, wellhead shut-in and flowing pressures, and other factors.

After testing of the gathering lines, centers,

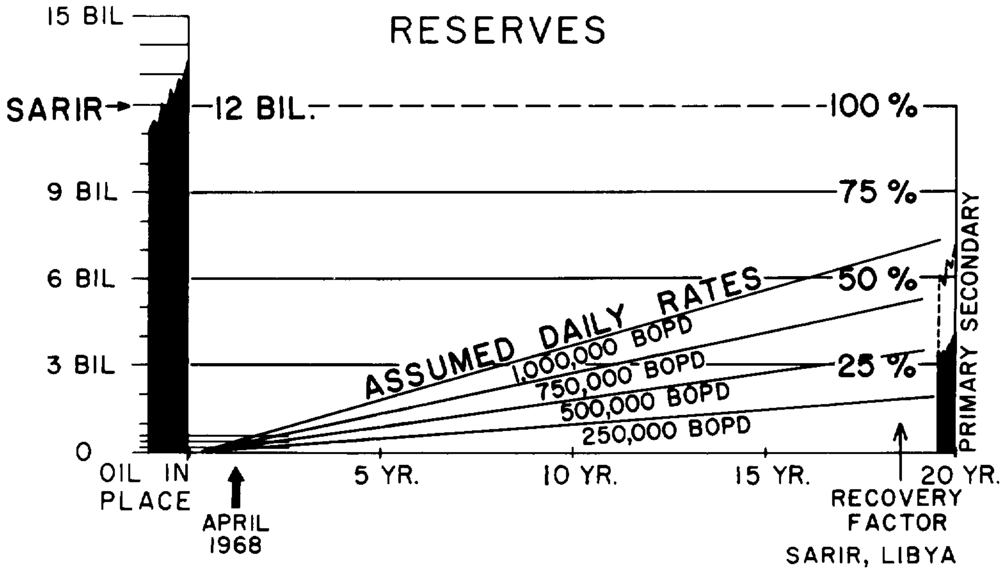

FIG. 31.—Reserves of Sarir field estimated at different percentages of recovery

Table 1. Estimated Total Potential of Completed Wells, Sarir Field

Part of Field	*No. Wells*	*Potential BOPD*	
Main Sarir			
GC-1	21	132,750	
GC-2	22	148,450	
GC-3	15	55,950	
Subtotal			337,150
Sarir North	6		9,550
"L-area"	12		83,900
Total			430,600

and main pipelines, the system went on production in December 1966. At that time, under calculated 650-psi flowing pressures, the total possible potential of the completed wells was estimated to be 430,600 bbl/day, divided as shown in Table 1.

The field installations, centers, and 34-in. pipeline actually went on production at 100,000 bbl/day; however the system had a capability at that time of about 350,000 bbl/day. The installation of additional booster stations along the line, plus separator capacity in the field, could increase the system capacity to nearly 1 million bbl daily.

Field production climbed steadily during 1967 to the 320,000-bbl/day level. Figure 30 shows the daily production rate from initiation through February 1968, with March and April estimated at about 325,000 bbl/day.[3] The June and early July 1967 Middle East war period is reflected in total shutdown. The upper graph shows cumulative production to April 1968 of 100 million bbl. This amount is the ultimate recovery of what is called a giant field in the United States.

Oil reserves and oil recoveries as they now are estimated are shown in Figure 31. The four small, closely spaced lines in the lower left corner are the 0, 2, 4, and 6 hundred million increments of Figure 30.

Oil in place at Sarir is estimated to be 11–13 billion bbl. Primary-recovery methods should produce an estimated 25–27 percent of 12 billion, or slightly more than 3 billion bbl. Improved primary-recovery methods, coupled with secondary recovery, could push the total recovery to about 54 percent, or more than 6 billion bbl. This amount is about comparable with, or perhaps a few hundred million barrels more than, the estimated ultimate recovery of the East Texas field.

In Figure 31 some assumed recovery rates are traced. A production rate of 500,000 bbl/day would recover the estimated 27 percent or 3 billion bbl of oil in about 18½ years. Increased production rates would recover the oil sooner, and decreased production rates would extend the time.

[3] Field production in January 1970 is 410,000 bbl/day.

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