The American Association of Petroleum Geologists Bulletin
V. 67, No. 1 (January 1983), P. 97-130, 25 Figs., 2 Tables.

# Petroleum Geology of Southern Iraq[1]

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## ABSTRACT

**Subsurface relations of the Albian rocks in southern Iraq are postulated from the study of lithofacies, electrical well logs, petroleum occurrences, geothermal source rocks maturation, and hydrogeologic mapping.**

**From these studies an evaluation of the commercial potential for oil in the Nahr Umr Formation became feasible.**

**It appears that a petroliferous belt exists in the marine-marginal facies of the lower Albian Nahr Umr sandstone. The oil in the Nahr Umr reservoirs has probably been generated in deep Lower Cretaceous source rocks, and may have started to generate as early as Paleocene time.**

**The upper shale beds of the Nahr Umr Formation supersedes the Ahmadi Shale Formation, which acts as a cap rock to the Albian reservoirs in Kuwait and Neutral Zone. Hitherto, no economic oil trap has been discovered in the upper Albian Mauddud Formation that overlies the Nahr Umr and underlies the Ahmadi in southern Iraq.**

## INTRODUCTION

The Albian rocks of southern Iraq are composed of the siliciclastic Nahr Umr Formation and the calcareous Mauddud Formation (Dunnington et al, 1959). The Rutbah Sandstone Formation is considered to be in physical and probably chronologic continuity with the Nahr Umr (Ibrahim, 1981b).

This study is a geologic analysis of the subsurface environments of the Mauddud and Nahr Umr Formations, using final well reports, lithologic logs, and wireline logs of exploration wells and a selection of development boreholes drilled in southern Iraq and surrounding areas (Fig. 1).

The Albian lithostratigraphic units are bounded by the post-Shu'aiba disconformity below and the post-Mauddud/pre-Ahmadi disconformity above (Fig. 2), with a regional dip toward the east-northeast of southern Iraq (Fig. 3).

The currently accepted stratigraphic picture of the Middle East tends to correlate the exposed Rutbah Sandstone Formation and the carbonates of the Cenomanian Wasia group of Iraq with that of the sandy and carbonate facies of the Wasia Formation of Saudi Arabia (Powers et al, 1966; Dunnington, 1967; Powers, 1968).

Apart from the Nahr Umr oil field, the Nahr Umr Formation is not exploited as an oil-producing zone in southern Iraq. This study is mainly focused on the petroleum geology of the Nahr Umr Formation.

## STRATIGRAPHY

### Nahr Umr Formation

The type section of the Nahr Umr was described from the Nahr Umr 2 well by Owen and Nasr (1958), between drilling depths of 8,688 and 9,321 ft (2,649 and 2,842 m). Lithologically, the type section consists of black shales interbedded with medium to fine-grained sands and sandstones, containing lignite, amber, and pyrite.

The upper contact of the Nahr Umr with the overlying Mauddud Formation is conformable and gradational, and is placed at the base of the limestone of the Mauddud Limestone Formation and the top of the black shale of the Nahr Umr Formation (Naqib, 1967).

The lower contact of the Nahr Umr Formation at the type section is with the Shu'aiba Limestone Formation, where a disconformity was established on regional evidence (Dunnington, 1967), though Owen and Nasr (1958) had accepted conformable relations between these two formations. Fossils included benthonic foraminifers, pelecypods, algae, amber, and plant remains. An Albian age was accepted on the basis of fossil contents, and early Albian age is now widely accepted (Table 1).

### Rutbah Sandstone Formation

The type section of the Rutbah was described by Dunnington et al (1959). The locality of the type section is between Wadi Ubeila and Rutbah. The base of the formation lies approximately at lat. 33°04'20", long. 40°12'50". The Rutbah is 75 ft (23 m) thick, varicolored or white, ferruginous, coarse to fine-grained sands and sandstones, locally cemented to quartzites. Dunnington et al (1958) considered the basal parts as possibly of continental origin and the upper parts as marine.

No fossils were reported from the Rutbah Formation. The type section is underlain unconformably by the Mulussa Formation (Late Triassic?), with an obvious erosional discordance. The Rutbah Formation is overlain by the Ms'ad Formation in what was described by Dunnington et al (1958) as a transitional, gradational contact "taken at the base of the first definite limestone bed above the continuous sandstones of the Rutbah Sandstone."

The age of the Rutbah sandstone could range from post-Triassic or Late Triassic to pre-Cenomanian or early Cenomanian, according to Dunnington et al (1959).

Barber (1948, p. 61) stated that the Rutbah sand is equiva-

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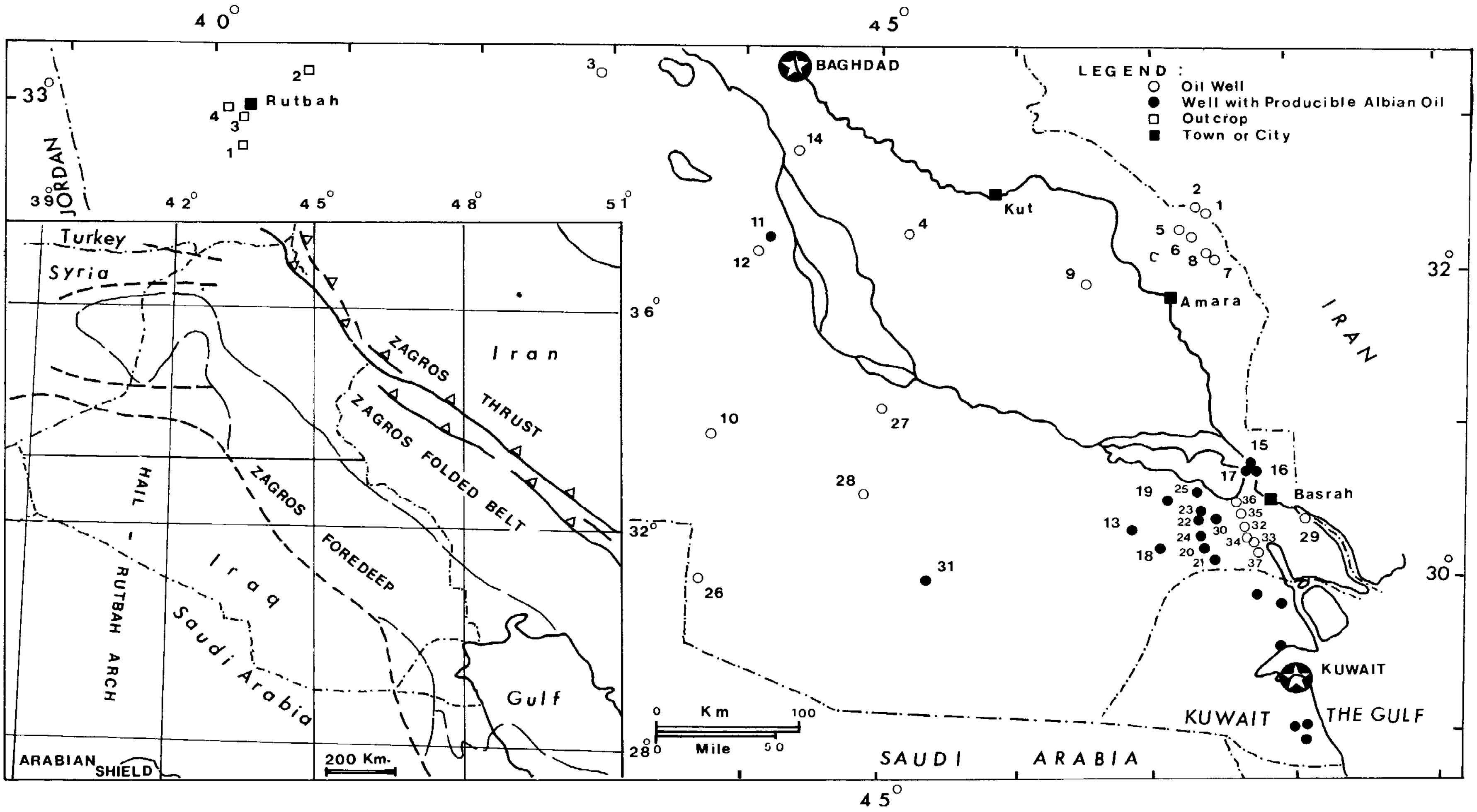

FIG. 1—Location map showing wells with producible Albian oil. Wells and exposures on other illustrations are shown as W or E with numbers corresponding to the following. Outcrop exposures: (1) Jabal Tayarat; (2) Wadi Husainiya; (3) Wadi Ms'ad; (4) Wadi Ubeilah. Wells: (1) Abu Ghirab 1; (2) Abu Ghirab 2; (3) Abu Jir 1; (4) Afaq 1; (5) Buzurgan 1; (6) Buzurgan 2; (7) Buzurgan 3; (8) Buzurgan 4; (9) Dujaila 1; (10) Ghalaisan 1; (11) Kifl 1; (12) Kifl 2; (13) Luhais 1; (14) Musaiyib 1; (15) Nahr Umr 1; (16) Nahr Umr 2; (17) Nahr Umr 3; (18) Rachi 1; (19) Ratawi 1; (20) Rumaila 1; (21) Rumaila 15; (22) Rumaila 20; (23) Rumaila 21; (24) Rumaila 32; (25) Rumaila 35; (26) Safawi 1; (27) Samawa 1; (28) Shawiya 1; (29) Siba 1; (30) Tuba 1; (31) Ubaid 1; (32) Zubair 1; (33) Zubair 2; (34) Zubair 15; (35) Zubair 30; (36) Zubair 31; (37) Zubair 39.

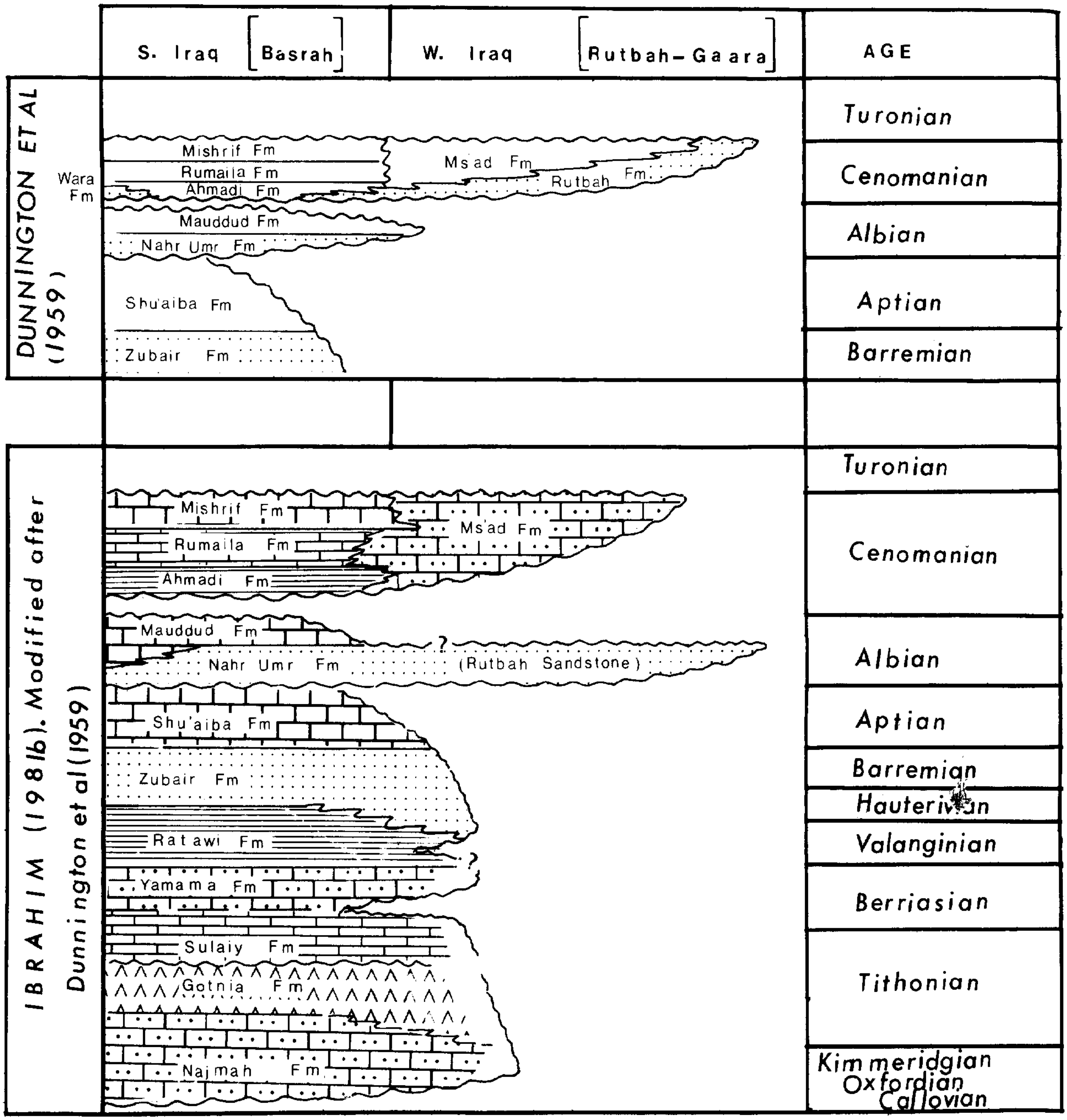

**FIG. 2—Stratigraphic relationship of Callovain-Cenomanian rock units in southern Iraq.**

lent to the Nahr Umr Formation and proposed an Albian age for both. This was later disputed by Dunnington et al (1959, p. 206), basing their argument on the field evidence of R. Wetzel and others that the Rutbah sandstone is in gradational contact with the upper Cenomanian Ms'ad Formation. Ibrahim (1981b) argued that Wetzel's continuity and intergradation can be explained by the reworking of loose sand into the base of the high-energy sediments of the transgressive Ms'ad Limestone Formation.

On the basis of subsurface mapping, Ibrahim (1981b) concluded that "the probabilities of physical correlation between the Nahr Umr and the Rutbah Formation are rather convincing." Figure 4 shows the proposed relationship of the Nahr Umr to the Rutbah Formation in a cross-sectional diagram. This relationship consequently implies an Albian age with possibly a reworking of the upper parts during the Cenomanian (Table 1).

### Mauddud Formation

The Mauddud reference section was reported from the Zubair 3 well, between drilling depths of 8,457 and 8,910 ft (2,578 and 2,716 m), and was described as an "organic, detrital, locally pseudo-oolitic, cream-colored limestone broken by occasional green or bluish shale layers" (Owen and Nasr, 1958). A late Albian age is currently accepted for the Mauddud Formation (Table 1).

In southern Iraq, the upper contact of the Mauddud with

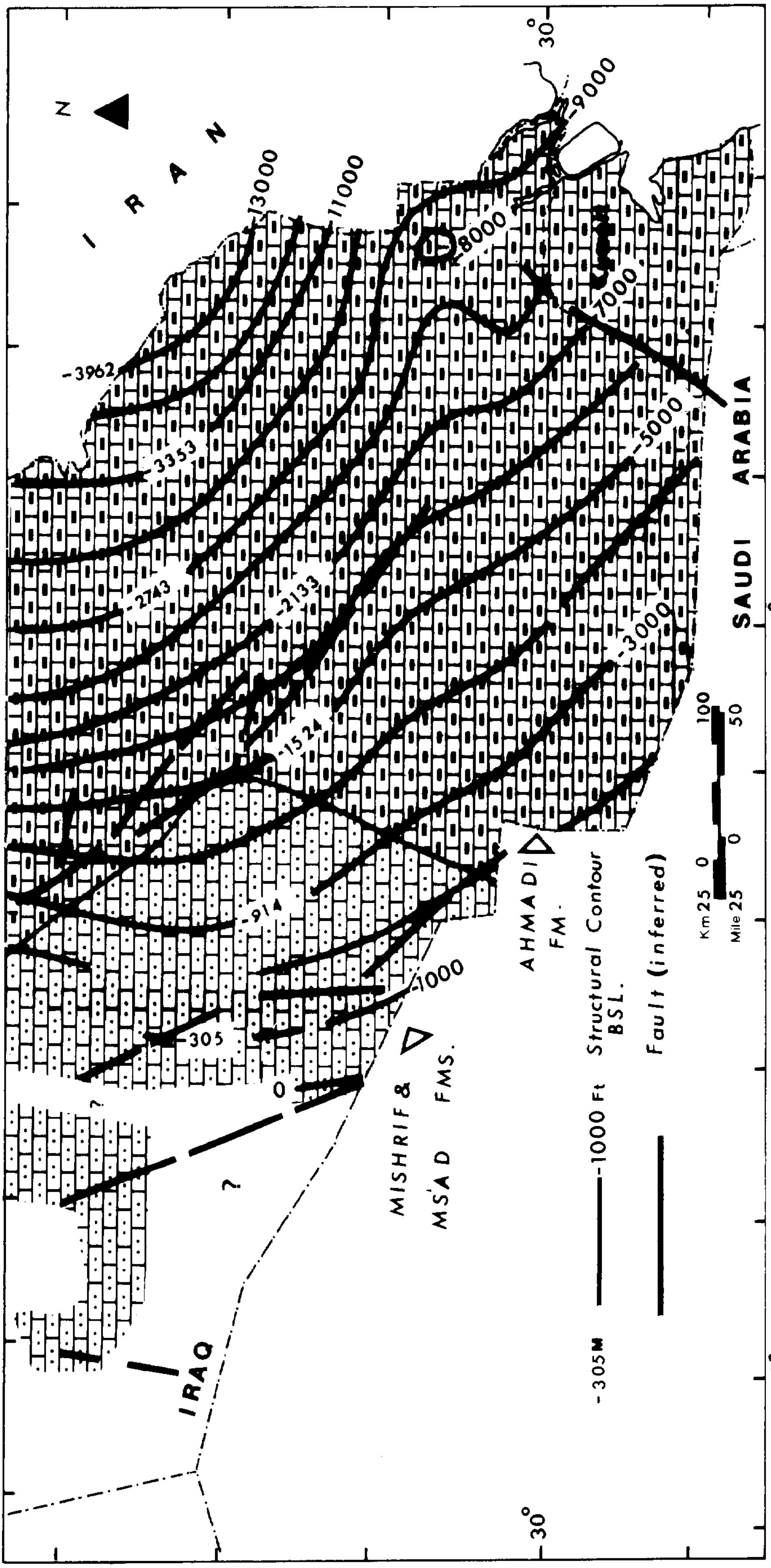

FIG. 3—Structural contour and lap-out map of top of Albian rocks of southern Iraq.

Table 1. List of Previously Published Datings of Rock Units Studied in This Work

| Author(s) | Age Interpretation | Formation |
|---|---|---|
| Smout (1965) | Cenomanian or possibly Albian | Mauddud Formation |
| Owen and Nasr (1958) | Cenomanian | |
| Dunnington et al (1959) | Albian | |
| James and Wynd (1965) | Cenomanian | |
| Sayyab (1966) | Albian | |
| Naqib (1967) | Albian | |
| Al-Shamlan (1975) | Albian | |
| Sugden and Standring (1975) | Albian | |
| Al-Khersan and Hassan (1978) | Cenomanian | |
| Al-Siddiki (1978) | Early to mid-Cenomanian | |
| Riché and Prestat (1980) | Late Albian | |
| Ibrahim (1981b) | Late Albian | |
| Barber (1948) | Albian | Rutbah Sandstone Formation |
| Dunnington et al (1959) | Post-Triassic or Upper Triassic to pre-Cenomanian or early Cenomanian | |
| Naqib (1967) | Cenomanian | |
| Ibrahim (1981b) | Albian | |
| Owen and Nasr (1958) | Albian | Nahr Umr Formation |
| Dunnington et al (1959) | Albian | |
| Naqib (1967) | Albian | |
| Al-Siddiki (1978) | Albian | |
| Venkatachala and Rawat (1980) | Cenomanian | |
| Riché and Prestat (1980) | Early Albian | |
| Ibrahim (1981b) | Early Albian | |

the Ahmadi Formation is disconformable. This contact is taken at the top of orbitolinal limestones of the Mauddud Formation and below the shaly lower beds of the Ahmadi Formation. Marly or chalky limestones are present at the base of the Ahmadi Formation in a few localities, such as in the Buzurgan 2, Dujaila 1, and Kifl 1 wells, but they are more shaly in character than the underlying limestones. The Mauddud Formation pinches out on the eastern flank of the Hail-Rutbah arch (Figs. 1, 2, 5); it also vanishes between Wara and Nahr Umr in westen Kuwait.

### Regional Stratigraphy

The Albian rocks of southern Iraq are correlatable with the upper Qamchuqa and Jawan formations in northern Iraq (Dunnington et al, 1959; Dunnington, 1967), and a diachronous lithologic relationship could exist between the Nahr Umr Formation and the upper parts of the Sarmord Formation in the Kirkuk area (Naqib, 1959).

The Burgan and Mauddud Formations are the Kuwaiti lithologic correlatives of the Albian rocks of southern Iraq (Owen and Nasr, 1958). The Khafji, Safaniya, and Mauddud members of the supposedly Albian-Turonian Wasia Formation are probable lithologic correlatives of the Albian rocks in northern Saudi Arabia (Powers, 1968).

In Khuzestan (southwest Iran), the Kazhdumi Formation and the Mauddud member of the Albian-Turonian Sarvak Formation are in lithologic continuity with the Albian rocks of southern Iraq (James and Wynd, 1965; Setudehnia, 1972, 1978).

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### Lithofacies

The Mauddud and Nahr Umr formations are intertongued. The Mauddud-Nahr Umr biostratigraphic contact is shown on Figure 4. The rocks generally increase in thickness northeastward until they begin to thin in the northeastern corner of southern Iraq. The depoaxis (more than 1,250 ft, 281 m) lies along a northwest-trending subsident tract extending from east of Basrah toward Amara city (Fig. 5). Rocks of these formations pinch out over the eastern flank of the Hail-Rutbah arch. Quantitatively, the rocks can be divided into four lithologic associations, as shown by Figure 5 (local lithologic variations at the top of structural oil fields were omitted).

The area is dominated by sandstone in the west and southwest, reflecting an influx of siliciclastics from the southwest and the west while calcareous equivalents were being deposited synchronously in the northeast (revealed by the discordance of the clastic ratios with the isopachs, which keep an oblique, but constant, spacing). The central part of the area is dominated by siliciclastics, occupying a northwest-trending central strip in southern Iraq, which includes the location of the Rumaila and Zubair oil fields. This strip partly coincides with the area inferred to be dominated by marginal marine to inner neritic environments of the Nahr Umr Formation (Figs. 5, 6).

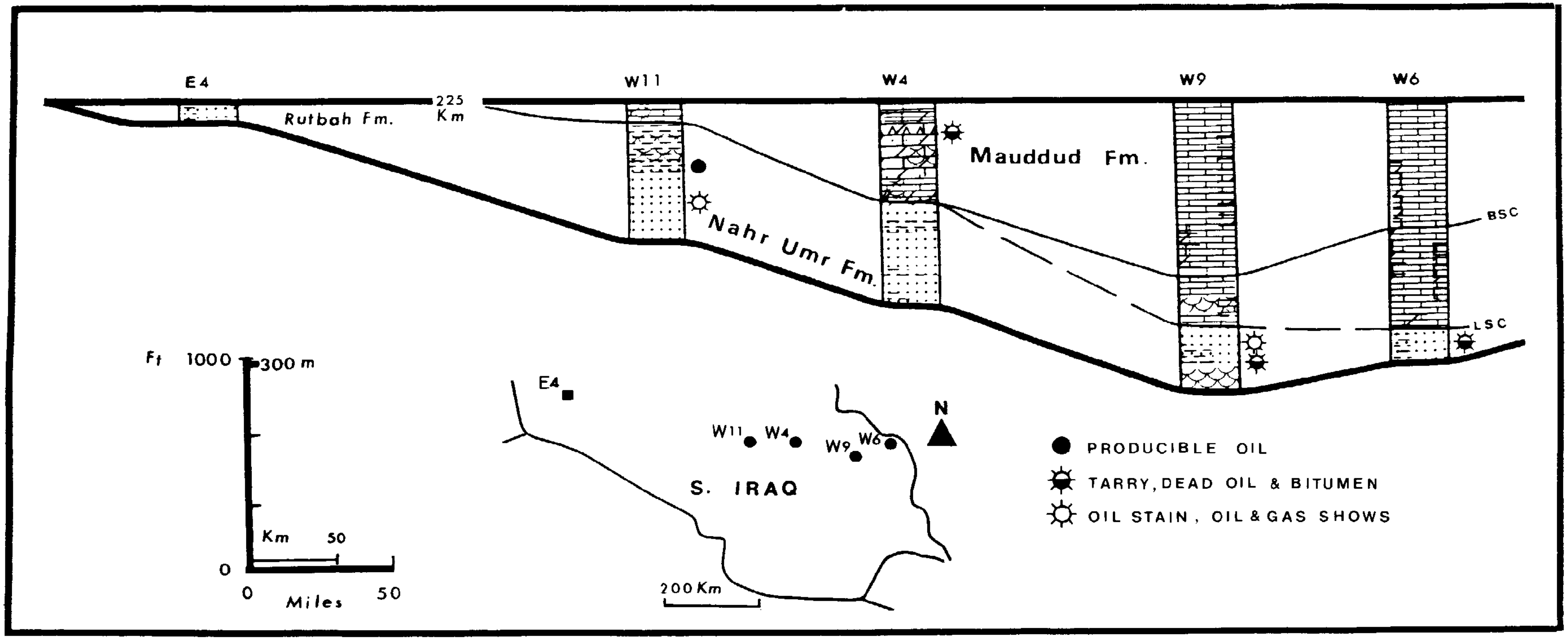


**FIG. 4**—Stratigraphic correlation diagram of Albian rocks in southern Iraq. Solid thick line is unconformable contact and thin line is biostratigraphic contact. Broken line is lithostratigraphic contact between Nahr Umr and Mauddud (after Ibrahim, 198ab).

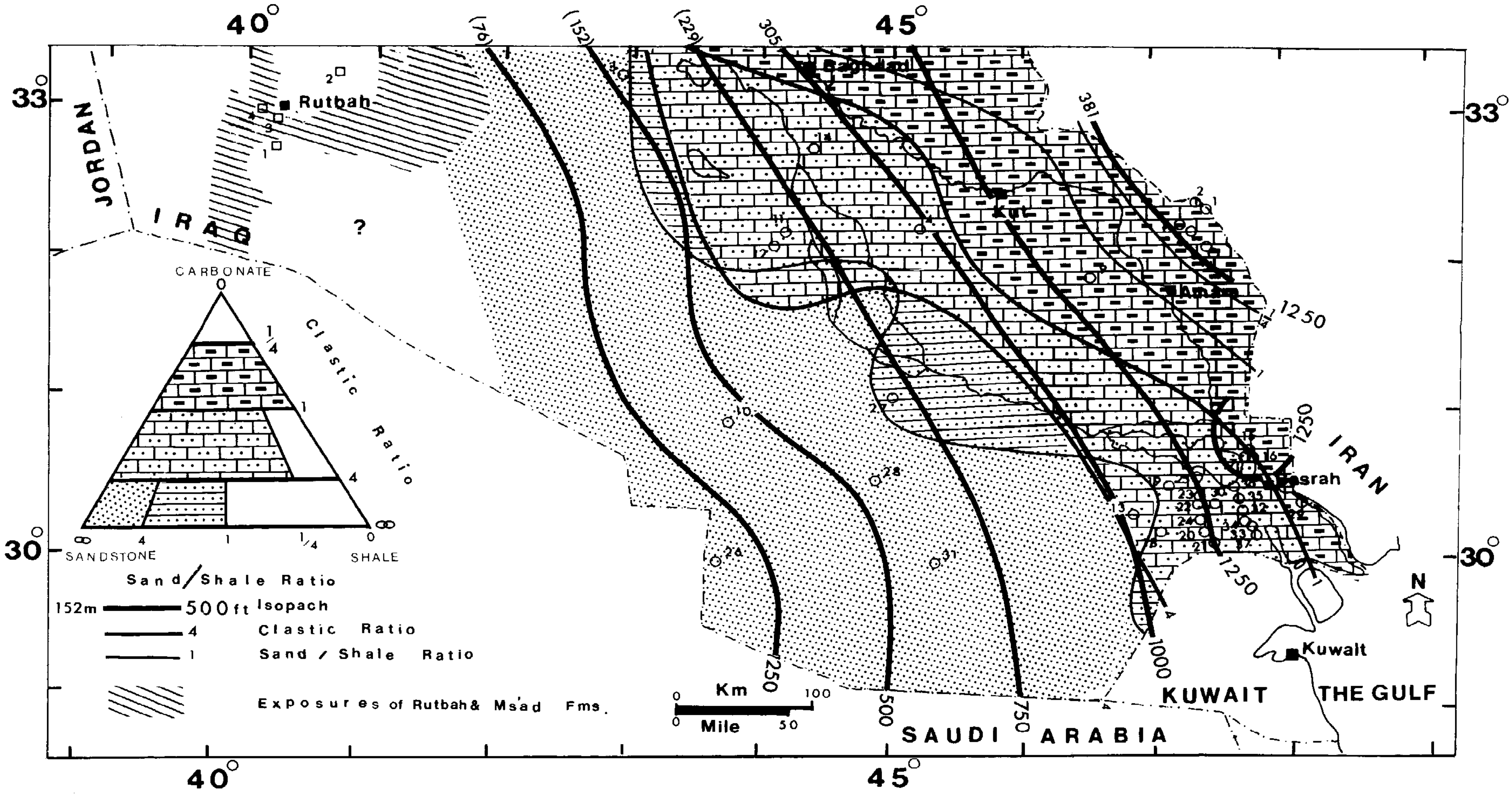


FIG. 5—Isopach and lithofacies map of Nahr Umr and Mauddud Formations. Rutbah Formation is assumed to be equivalent to Nahr Umr Formation (after Ibrahim, 198ab).

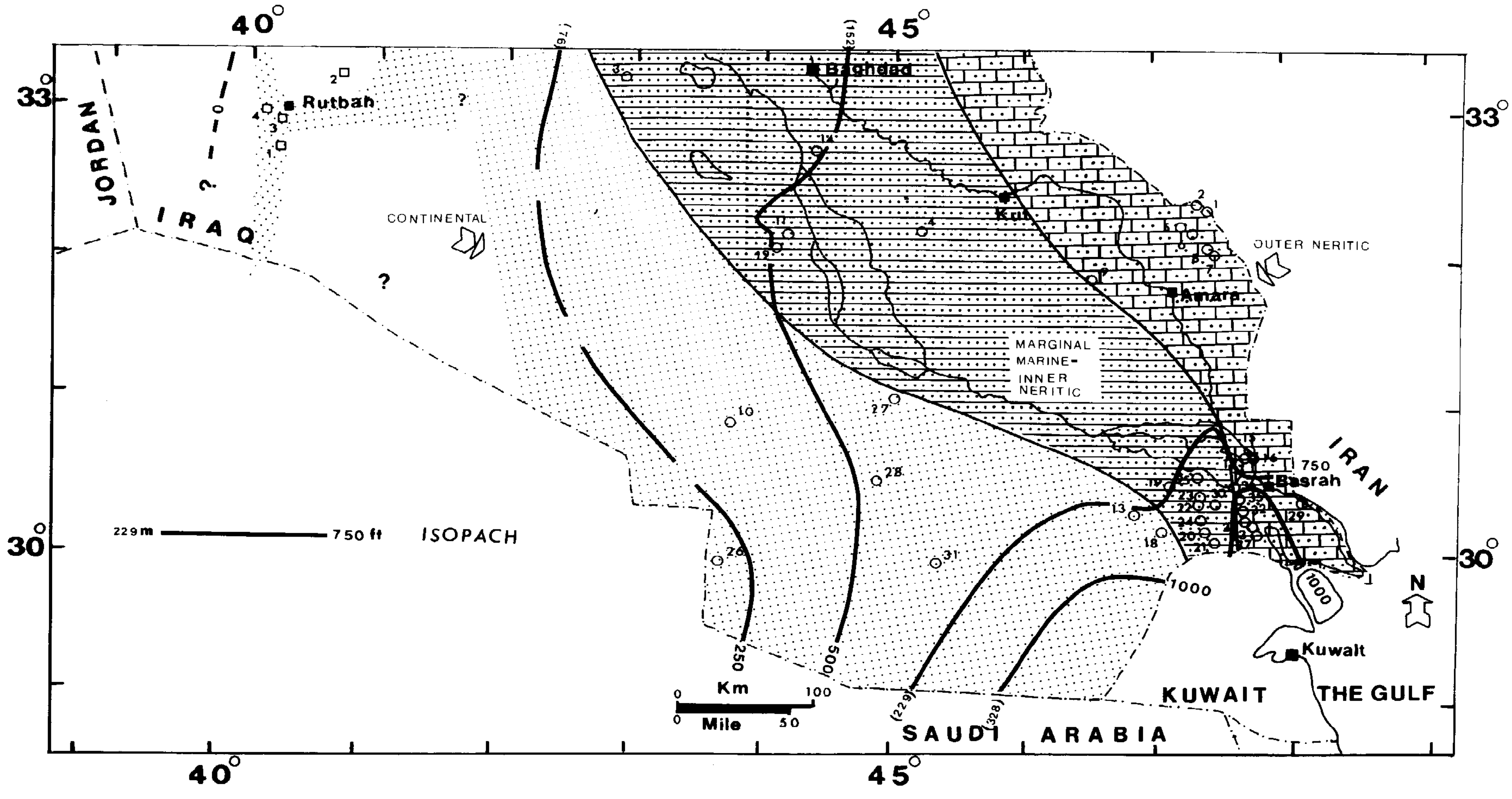


FIG. 6—Isopach map and inferred environments of deposition of Mauddud Formation.

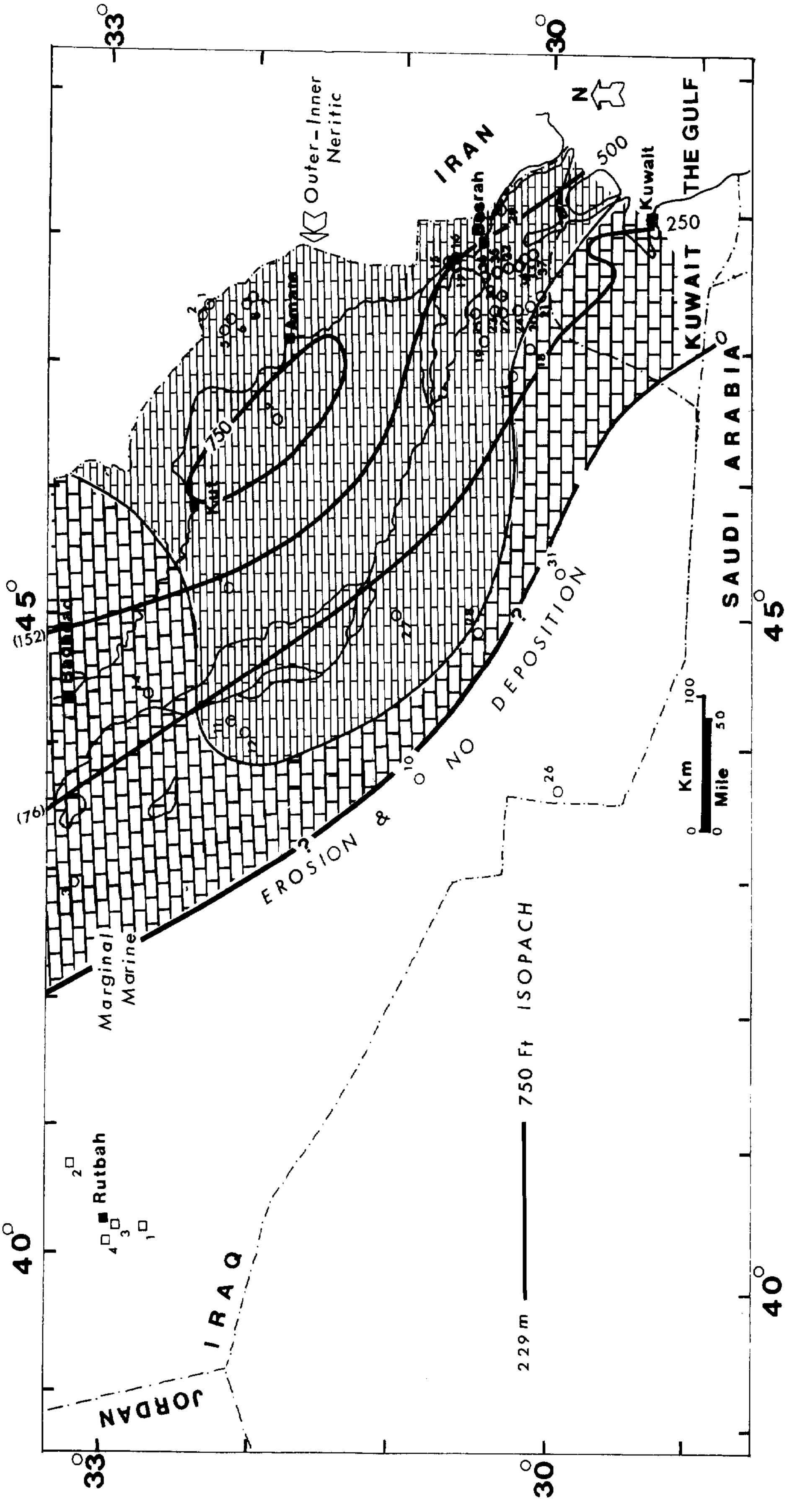
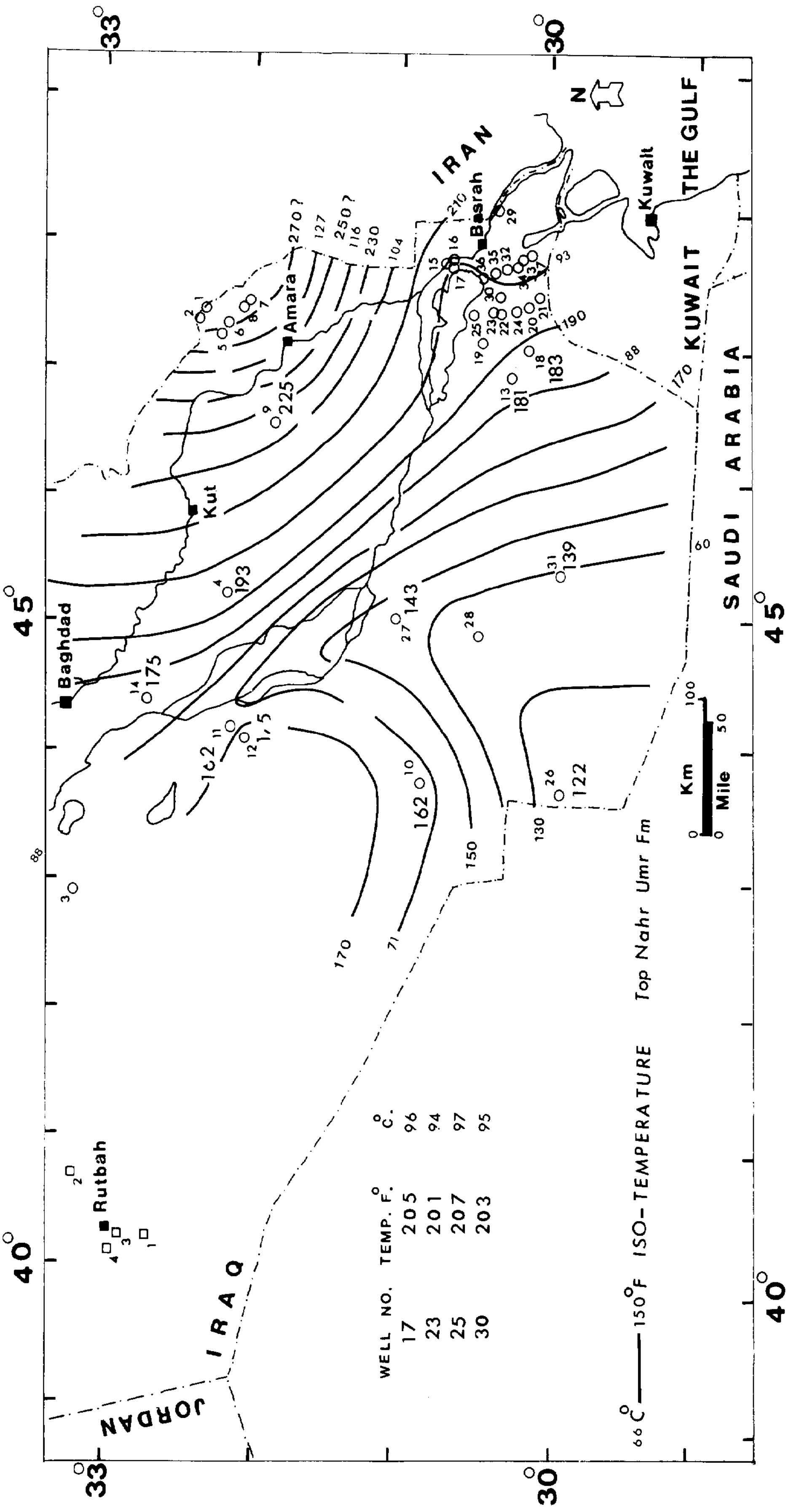


FIG. 7—Isopach map and inferred environments of deposition of Nahr Umr Formation.



| WELL NO. | TEMP. °F. | °C. |
|---|---|---|
| 17 | 205 | 96 |
| 23 | 201 | 94 |
| 25 | 207 | 97 |
| 30 | 203 | 95 |

FIG. 8—Iso-geothermal contour map of top of Nahr Umr Formation.

## Environments of Deposition

The dominant environments of deposition of the Albian rocks (inferred from the lithologic documentation of the well logs) are shown in Figures 6 and 7.

An area dominated by continental environments in the southwestern part of southern Iraq lies to the west of a line between the Rachi 1 well (18) and Samawa 1 well (27; see Fig. 6). The continental environment is best represented by the Nahr Umr section of the Safawi 1 well, where the Nahr Umr was described as fine-grained sandstone with clear frosted grain surfaces, rounded to subrounded grains, and some fissile shales and siltstone; no fossils were reported. The roundness and frosting of the fine uncemented sands, the diversity of the dip of the bedding planes, and the absence of fossils attest to a continental environment of deposition (possibly with an eolian element).

Another type of continental environment can be inferred from the lower part of the Nahr Umr Formation at well Rachi 1. The medium to coarse-grained, angular to subangular, poorly sorted, loose, argillaceous and carbonaceous sandstone, with black fissile noncalcareous and, in places, carbonaceous shale, indicates a unidirectional subaqueous transportation with quiet areas of abundant vegetation, typical of flood-plain or delta-plain environments.

The exposed Rutbah Formation was inferred to indicate continental environments of deposition by Naqib (1967), Kukal and Saadallah (1970), and in part by Dunnington et al (1959).

A marginal marine-inner neritic environment is inferred to have occupied a central northwest-trending area of southern Iraq during Nahr Umr deposition, as shown in Figure 6. A typical section (in well Kifl 1) consists of a lower medium to fine-grained subangular to rounded, partly consolidated sandstone, which grades upward into orbitolinal limestones, through a glauconitic silt and ostracodal shale interval. All this section indicates an influx of sand under a subaqueous environment of marine and nonmarine character. Hence, a marginal marine-inner neritic environment is deduced. A margin of marine carbonate rocks is inferred to fringe the Mauddud shelf facies (Fig. 7).

An outer neritic type of environment dominated the east-northeastern part of southern Iraq during the deposition of the Nahr Umr Formation, and an outer, inner-neritic type is inferred to have dominated that of the Mauddud Formation in the central and southeastern parts of southern Iraq (Figs. 4, 7).

The latter environment can be typified by the Mauddud section in the Siba 1 well, where a light-gray, chalky limestone is interbedded with dark-gray to brown, micritic and pyritic limestone with ostracods,echinoids, gastropods, and *Orbitolina* sp. These are generally indicative of an outer, inner-neritic environment.

The environments of deposition presented in this study are compatible with those indicated by Murris (1980, Figs. 17, 18), where similar trends were shown under a different terminology.

## Geothermal Maturation

The time-temperature index of thermal maturation (TTI) was calculated using Lopatin's method (1971), as modified by Waples (1980). In the calculation, the average geothermal gradient from maximum recorded bottom-hole temperatures was used after applying the empirical correction of Kehle (1972), the stratigraphic units as dated by Dunnington et al (1959), and the geologic time scale compiled by Van Eysinga (1978). The geothermal level at the top of the Nahr Umr Formation ranges from 122°F (50°C) in southwestern Iraq to about 270°F (132.2°C) in eastern Iraq (Fig. 8).

The TTI calculation was applied to the contact at the base of the Lower Cretaceous and top of the regionally distributed Gotnia evaporitic formation, to the base of the Ratawi Formation, and to the base and top of the Nahr Umr Formation. Examples of this calculation are shown in Table 2 and samples of the graphic model are shown in Figures 9 to 11.

Waples (1980) reviewed Lopatin's TTI limits (1971). He suggested 15$\tau$ as the lower TTI limit for oil generation, and set 75$\tau$ as the TTI value for the peak of oil generation. The calculated 15$\tau$ limit was checked by the writer against measured vitrinite reflectance ($R_o$%) data from an anticline in the same region and was found to correlate to $R_o$% values of 0.58. Although this correlation is satisfactory (Waples, 1981, p. 104), it must be emphasized that the calculated 15$\tau$ has proved to be higher than the minimum level of oil generation (Tissot and Welte, 1978).

By contouring the TTI values (Fig. 12), it appears that the base of the Nahr Umr in the eastern and southeastern parts is within the minimum limit of oil generation, whereas in the rest of southern Iraq that phase has not been reached yet.

The base of the Ratawi Formation was found to be within the 15$\tau$ limit over the central and eastern parts of southern Iraq (Fig. 13), and the base of Sulaiy-Chia Gara extends even beyond that limit (Fig. 14).

## Hydrogeology

The NaCl concentrations (in ppm) in water of the Nahr Umr Formation were calculated by converting formation-water resistivity (Rw) values derived from quantitative spontaneous potential (SP) log analysis (Schlumberger, 1969a, b). Figure 15 is an isosalinity contour map of Nahr Umr Formation water. It shows an increase in NaCl concentration in the formation water toward the northeast, and a decrease in salinity toward the west and southwest parts of southern Iraq. The isosalinity contour map (Fig. 15) suggests a meteoric or less saline water at the eastern flank of the topographically high Hail-Rutbah arch, but higher salinity contours persisted in, and in front of, the tectonically younger Zagros foothills.

However, because ions other than $Na^+$ and $Cl^-$ are present in considerable concentrations in the Cretaceous reservoirs of southern Iraq (Jamil, 1975, 1978), the calculated concentrations are "equivalent" NaCl concentrations (Schlumberger, 1969a, b). Hence, in the absence of detailed chemical analysis of formation waters, the contoured values of Figure 15 must engulf some approximation.

Except in development wells 23, 25, and 35, formation pressure measurements derived from drilling-mud pressures of exploration wells are optimally higher than the actual reservoir pressures. The writer used the following modified

**Table 2. Calculation of Present TTI Values of Geologic Models***

| Stratigraphic Level | Temperature Interval (°C) | $r^n$ | ΔTime (m.y.) | Interval TTI | Total TTI |
|---|---|---|---|---|---|
| | | | Safawi 1 Well | | |
| Base of Sulaiy Fm. (146 m.y.) | 20-30 | $2^{-8}$ | 14.0 | 0.0547 | 0.0547 |
| | 30-40 | $2^{-7}$ | 42.5 | 0.3320 | 0.3867 |
| | 40-50 | $2^{-6}$ | 15.5 | 0.2422 | 0.6289 |
| | 50-60 | $2^{-5}$ | 14.0 | 0.4375 | 1.0664 |
| | 60-70 | $2^{-4}$ | 60.0 | 3.7500 | 4.8164 |
| Base of Ratawi Fm. (125 m.y.) | 20-30 | $2^{-8}$ | 6.0 | 0.0234 | 0.0234 |
| | 30-40 | $2^{-7}$ | 34.0 | 0.2656 | 0.2891 |
| | 40-50 | $2^{-6}$ | 15.0 | 0.2344 | 0.5234 |
| | 50-60 | $2^{-5}$ | 38.0 | 1.1875 | 1.7109 |
| | 60-70 | $2^{-4}$ | 32.0 | 2.0000 | 3.7109 |
| Base of Nahr Umr Fm. (105 m.y.) | 20-30 | $2^{-8}$ | 9.0 | 0.0352 | 0.0352 |
| | 30-40 | $2^{-7}$ | 19.0 | 0.1484 | 0.1836 |
| | 40-50 | $2^{-6}$ | 15.0 | 0.2344 | 0.4180 |
| | 50-60 | $2^{-5}$ | 62.0 | 1.9375 | 2.3555 |
| Base of Ahmadi Fm. (100 m.y.) | 20-30 | $2^{-8}$ | 8.5 | 0.0332 | 0.0332 |
| | 30-40 | $2^{-7}$ | 16.5 | 0.1289 | 0.1621 |
| | 40-50 | $2^{-6}$ | 14.0 | 0.2188 | 0.3809 |
| | 50-60 | $2^{-5}$ | 61.0 | 1.9063 | 2.2871 |
| | | | Tuba 1 Well | | |
| Base of Ratawi Fm. (125 m.y.) | 30-40 | $2^{-7}$ | 11.0 | 0.0859 | 0.0859 |
| | 40-50 | $2^{-6}$ | 12.0 | 0.1875 | 0.2703 |
| | 50-60 | $2^{-5}$ | 9.5 | 0.2969 | 0.5703 |
| | 60-70 | $2^{-4}$ | 12.5 | 0.7813 | 1.3516 |
| | 70-80 | $2^{-3}$ | 12.0 | 1.5000 | 2.8516 |
| | 80-90 | $2^{-2}$ | 11.0 | 2.7500 | 5.6016 |
| | 90-100 | $2^{-1}$ | 16.0 | 8.0000 | 13.6016 |
| | 100-110 | 1 | 33.0 | 33.3000 | 46.6016 |
| | 110-120 | 2 | 8.0 | 16.000 | 62.6016 |
| Base of Nahr Umr Fm. (105 m.y.) | 30-40 | $2^{-7}$ | 3.0 | 0.0234 | 0.0234 |
| | 40-50 | $2^{-6}$ | 10.5 | 0.1641 | 0.1875 |
| | 50-60 | $2^{-5}$ | 12.5 | 0.3906 | 0.5781 |
| | 60-70 | $2^{-4}$ | 12.0 | 0.7500 | 1.3281 |
| | 70-80 | $2^{-3}$ | 11.0 | 1.3750 | 2.7031 |
| | 80-90 | $2^{-2}$ | 18.0 | 4.5000 | 7.2031 |
| | 90-100 | $2^{-1}$ | 32.0 | 16.000 | 23.2031 |
| | 100-110 | 1 | 6.0 | 6.0000 | 29.2031 |
| Base of Ahmadi Fm. (100 m.y.) | 30-40 | $2^{-7}$ | 8.0 | 0.0625 | 0.0625 |
| | 40-50 | $2^{-6}$ | 12.0 | 0.1875 | 0.2500 |
| | 50-60 | $2^{-5}$ | 12.0 | 0.3750 | 0.6250 |
| | 60-70 | $2^{-4}$ | 11.0 | 0.6875 | 1.3125 |
| | 70-80 | $2^{-3}$ | 17.0 | 2.1250 | 3.4375 |
| | 80-90 | $2^{-2}$ | 32.5 | 8.1250 | 11.5625 |
| | 90-100 | $2^{-1}$ | 7.5 | 3.7500 | 15.3125 |

Table 2. (Continued)

| Stratigraphic Level | Temperature Interval (°C) | $r^n$ | ΔTime (m.y.) | Interval TTI | Total TTI |
|---|---|---|---|---|---|
| | | | Dujaila 1 Well | | |
| Base of Ratawi Fm. | 30-40 | $2^{-7}$ | 2.75 | 0.0215 | 0.0215 |
| (125 m.y.) | 40-50 | $2^{-6}$ | 17.5 | 0.2734 | 0.2949 |
| | 50-60 | $2^{-5}$ | 8.0 | 0.2500 | 0.5449 |
| | 60-70 | $2^{-4}$ | 18.75 | 1.1719 | 1.7168 |
| | 70-80 | $2^{-3}$ | 22.0 | 2.7500 | 4.4668 |
| | 80-90 | $2^{-2}$ | 41.5 | 10.3750 | 14.8418 |
| | 90-100 | $2^{-1}$ | 4 | 2.0000 | 16.8418 |
| | 100-110 | 1 | 2.5 | 2.5000 | 19.3418 |
| | 110-120 | 2 | 3.0 | 6.0000 | 25.3418 |
| | 120-130 | 4 | 5.0 | 20.0000 | 45.3418 |
| Base of Nahr Umr Fm. | 30-40 | $2^{-7}$ | 1.0 | 0.0078 | 0.0078 |
| (105 m.y.) | 40-50 | $2^{-6}$ | 9.0 | 0.1406 | 0.1484 |
| | 50-60 | $2^{-5}$ | 19.0 | 0.5938 | 0.7422 |
| | 60-70 | $2^{-4}$ | 22.0 | 1.3750 | 2.1178 |
| | 70-80 | $2^{-3}$ | 40.0 | 5.000 | 7.1172 |
| | 80-90 | $2^{-2}$ | 4.0 | 1.000 | 8.1172 |
| | 90-100 | $2^{-1}$ | 2.5 | 1.2500 | 9.3672 |
| | 100-110 | 1 | 6.5 | 6.5000 | 15.8672 |
| | 110-120 | 2 | 1.0 | 2.000 | 17.8672 |
| Base of Ahmadi Fm. | 30-40 | $2^{-7}$ | 2.5 | 0.0195 | 0.0195 |
| (100 m.y.) | 40-50 | $2^{-6}$ | 17.0 | 0.2656 | 0.2852 |
| | 50-60 | $2^{-5}$ | 22.5 | 0.7031 | 0.9883 |
| | 60-70 | $2^{-4}$ | 33.0 | 2.0625 | 3.0508 |
| | 70-80 | $2^{-3}$ | 14.0 | 1.7500 | 4.8008 |
| | 80-90 | $2^{-2}$ | 2.75 | 0.6875 | 5.4883 |
| | 90-100 | $2^{-1}$ | 2.5 | 1.2500 | 6.7383 |
| | 100-110 | 1 | 5.75 | 5.7500 | 12.4883 |

*Models given in Figures 9 to 11.

$$TT = \sum_{n\,max}^{n\,max} (\Delta Tn)(r^n).$$

mud-pressure formula (Kumar, 1977):

$$P = Wt \times 0.052 \times D \qquad (1)$$

where P = hydrostatic pressure, Wt = mud weight in lb/gal, and D = depth in feet.

The approximate dynamic heads were calculated using the following formula (Dickey, 1979):

$$H = \frac{P}{W} \qquad (2)$$

where H = hydrodynamic head (BHP expressed as feet of water), P = bottom-hole pressure (in psi), and W = weight of water in psi/ft (0.433 psi/ft for fresh water).

By substituting calculated P values of equation (1) for P in equation (2), the head can be converted into a potentiometric head (F), as in the following:

$$F = \frac{P}{W} - (D\text{-}E) \qquad (3)$$

where F = elevation of potentiometric surface (in feet with reference to sea level), D = depth of producing formation (in feet below Kelly bushing), and E = elevation of Kelly bushing (in feet above sea level).

By substituting (0.433 psi/ft) for the fresh-water gradient in equation (3), the resultant map (Fig. 16) displays a general slope in the approximated potentiometric surface from the northeast toward the west and southwest of southern Iraq.

### Availability of Traps

According to Ibrahim (1978, p. 270), southern Iraq is divisible into nine subsurface structural style zones, simplified here into four basic zones.

1. The Basrah tectonic zone, which is located roughly within the Zagros foredeep south of lat. 31°E (Fig. 1), is characterized by north-south trending, nearly symmetrical, gently deformed anticlines.
2. The Amara-Baghdad tectonic zone, which is delineated by the Zagros foredeep north of lat. 31°E, is characterized by northwest-southeast-trending, asymmetric, elongated folds.
3. The Shabicha-Abu Jir zone, which lies at the eastern

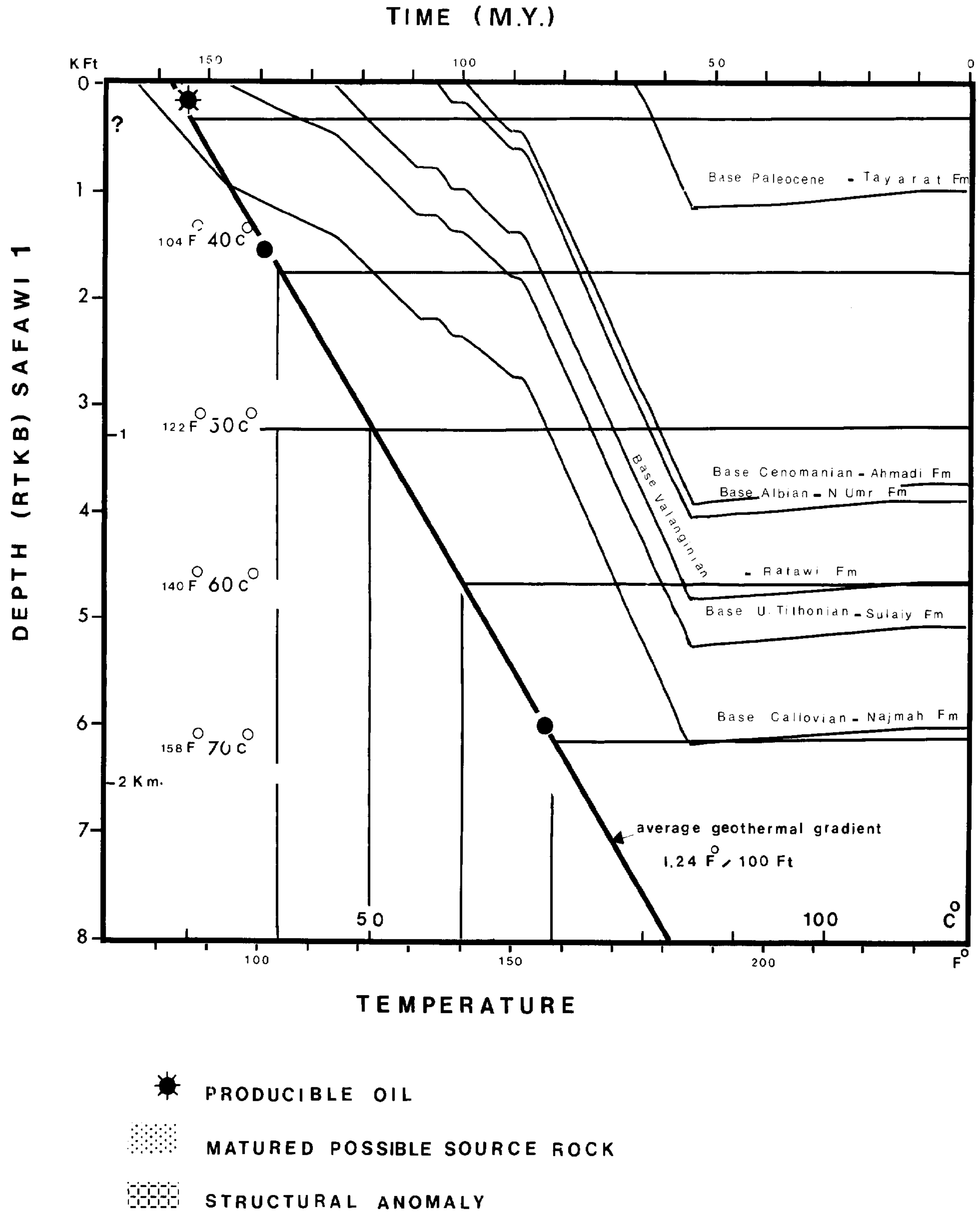


FIG. 9—Geothermal gradient and time-temperature maturation model of geologic sequence of Safawi 1 well (W26).

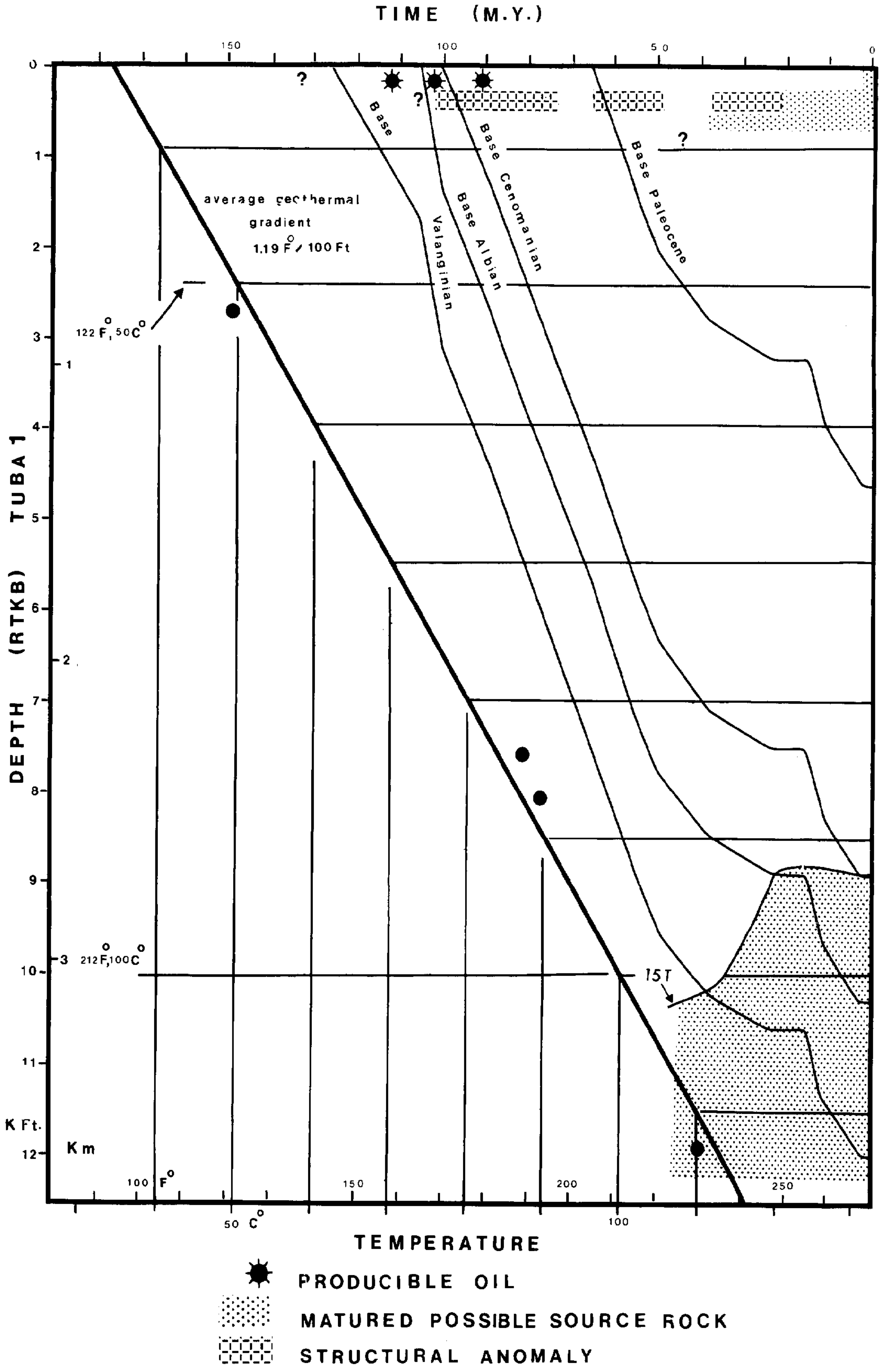


FIG. 10—Geothermal gradient and time-temperature maturation model of geologic sequence of Tuba 1 well (W30).

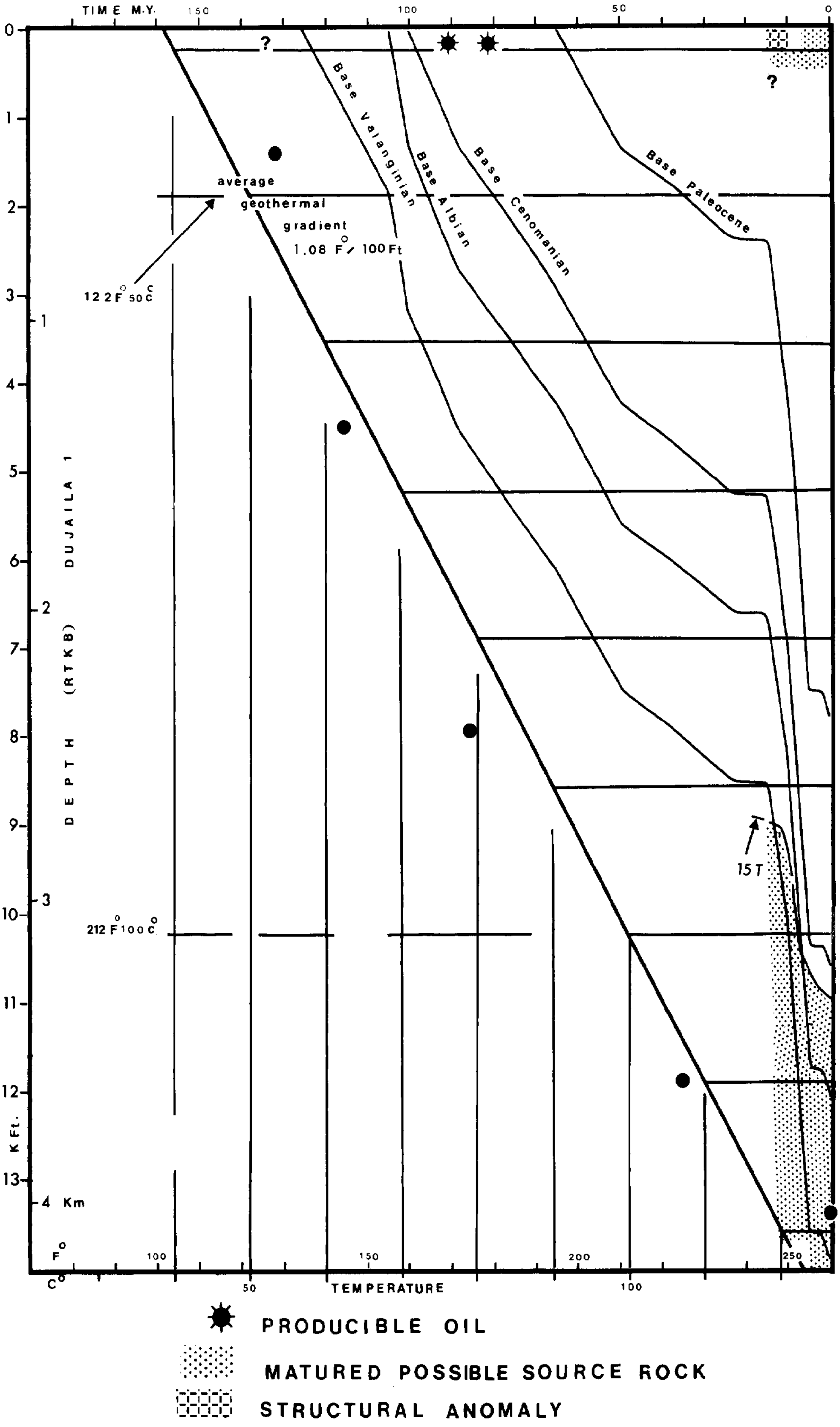


FIG. 11—Geothermal gradient and time-temperature maturation model of geologic sequence of Dujaila 1 well (W9).

flank of the Hail-Rutbah arch, engulfs north-south, northeast-northwest, and northwest-southeast-trending structures (Fig. 1).

4. The crest of the Hail-Rutbah arch is a subsurface extension of the Arabian shield (Fig. 1).

The Basrah tectonic zone in southeastern Iraq includes most of the Albian traps and extends into Kuwait and the Neutral Zone.

The possibilities of stratigraphic trapping in the Nahr Umr and the Mauddud Formations were mentioned by Sayyab (1966) and Ibrahim (1978). However, no proven stratigraphic trap has been reported, though the trap at the Ubaid 1 well may have a stratigraphic element, as the Ahmadi Formation (Fig. 3) may disconformably overlie the Nahr Umr there (Figs. 6, 7).

## HYDROCARBON PROSPECTS

The available data controlled the number of variables included in determining prospects. These variables include petroleum occurrences, lithofacies, calculated geothermal source-rock maturity, hydrogeology, and availability of structural traps in relation to times and directions of petroleum migrations.

### Lithofacies and Petroleum Occurrences

A contour denoting a sandstone to shale ratio of more than one and less than eight roughly bounds the area of producible oil occurrences in the Nahr Umr Formation (Figs. 1, 5). Proper ratios of reservoir and carrier rocks to cap and source rocks are found to delineate areas of producing oil fields (Dicker and Rohn, 1955). Such ratios probably indicate the optimum combination of source, reservoir, and cap rocks in an oil-producing province. However, it is possible that the Zubair and/or deeper source rocks contributed to the entrapped oil in the Nahr Umr Formation, because almost all the discovered producible oil traps in the Nahr Umr Formation are above economic Zubair reservoir oil fields (see Fig. 1). The exceptions are the Nahr Umr oil field where the Zubair reservoir contains producible gas, and the Ubaid 1 well where no deeper petroleum deposit was found. In both places, the lack of deeper oil production was caused by the ineffectiveness of the Zubair as cap rocks. The ineffective cap rock is reflected by the high sandstone to shale ratio of the Zubair, Ratawi, and Shu'aiba Formations in the Ubaid area, and by the faulted Zubair shale in the Nahr Umr oil field.

The Lower Cretaceous shale and carbonate sequence in southern Iraq, southwestern Iran, and Kuwait have been geochemically identified as potential source rocks (Gill, 1978; Ibrahim, 1978, 1981c; Ala et al, 1980; Murris, 1980, Ayres et al, 1982). In fact, the potentiality of the Lower Cretaceous source rocks has been recognized since the early days of exploration (Dunnington, 1958). It is also anticipated that no significant vertical migration of petroleum across the thick, regionally distributed Gotnia Anhydrite Formation has occurred, hence all pre-Gotnian source rocks were excluded from the present assessment (Ibrahim, 1981a).

The Ahmadi Shale Formation provides an effective cap rock to the Albian reservoirs in Kuwait, but in southern Iraq the upper shale beds of the Nahr Umr Formation provide a superseding alternative (Figs. 3,4). The effectiveness of the Ahmadi as a cap rock is questionable, as no economic oil deposits have been discovered in the Mauddud Formation of southern Iraq.

The Nahr Umr sands, like the Rutbah sandstones, can be classified as quartzarenites. The Nahr Umr has an average geothermal gradient of 1,126°F/100 ft (2,053°C/100 m), and a depth of burial of the Albian from zero at Rutbah to 13,500 ft (4,114.6 m) at Buzurgan in the east-northeast of southern Iraq. Therefore, according to Schmidt and McDonald's (1979) depth-diagenesis scheme, the quartzarenites of the Nahr Umr may grade from diagenetically immature, as in the loosely cemented Rutbah sands in western Iraq, to diagenetically semi-mature in central and southeastern parts of southern Iraq, to probably a diagenetically mature sandstone in the east-northeastern part of southern Iraq (Schmidt and McDonald, 1979, Fig. 11, p. 188).

The environment of deposition of the Nahr Umr Formation may have influenced its primary reservoir characteristics, therefore, following Schmidt and McDonald (1979), the sandstones can still retain a reduced, but essentially primary, porosity in the western, central, and southeastern parts of southern Iraq. Figure 6 shows a general coincidence of the marginal marine environments of deposition with the producible oil traps of the Nahr Umr Formation.

### Thermal Maturation of Petroleum Source Rocks

Assuming that the ancient average geothermal gradient of wells in southern Iraq did not differ significantly from the present gradient, as determined from present thermal well-log measurements, it is calculated that, in the Safawi 1 well, the base of Sulaiy, base of Ratawi, and the Nahr Umr have not attained the 15$\tau$ level (Waples, 1980). Therefore, in the presence of an immature Cretaceous sediment and the existence of an effective Gotnia barrier, there is little chance of vertical migration of oil into the Albian at Safawi 1 (Figs. 9, 12, 13, 14), as migration is assumed to follow maturation of source rocks (Waples, 1981).

In the Tuba 1 well in southeastern Iraq, the top of the Mauddud Formation attained the 15$\tau$ level during the Pleistocene. However, the base of the Nahr Umr reached that level during the Miocene ($\simeq$ 22 m.y. ago). The base of the Ratawi attained the 15$\tau$ level during the Eocene (about 39 m.y. ago), and the base of the Sulaiy probably reached the same level during late Paleocene to early Eocene time (Figs. 10, 12, 13, 14).

At the Dujaila 1 well, in the east-northeastern part of southern Iraq, the top of the Mauddud Formation is still thermally immature, but the base of the Nahr Umr attained the 15$\tau$ level during the late Miocene ($\simeq$ 7 m.y. ago). The base of the Ratawi reached the 15$\tau$ level during the mid-Miocene ($\simeq$ 14 m.y. ago), and the base of the Chia Gara could have attained that level during an earlier Miocene time (Figs. 11 to 14).

### Hydrogeology

By applying statistical regression analysis to the graphic plotting of the calculated formation-water salinity against the depth of burial of the Nahr Umr Formation in southern Iraq, a

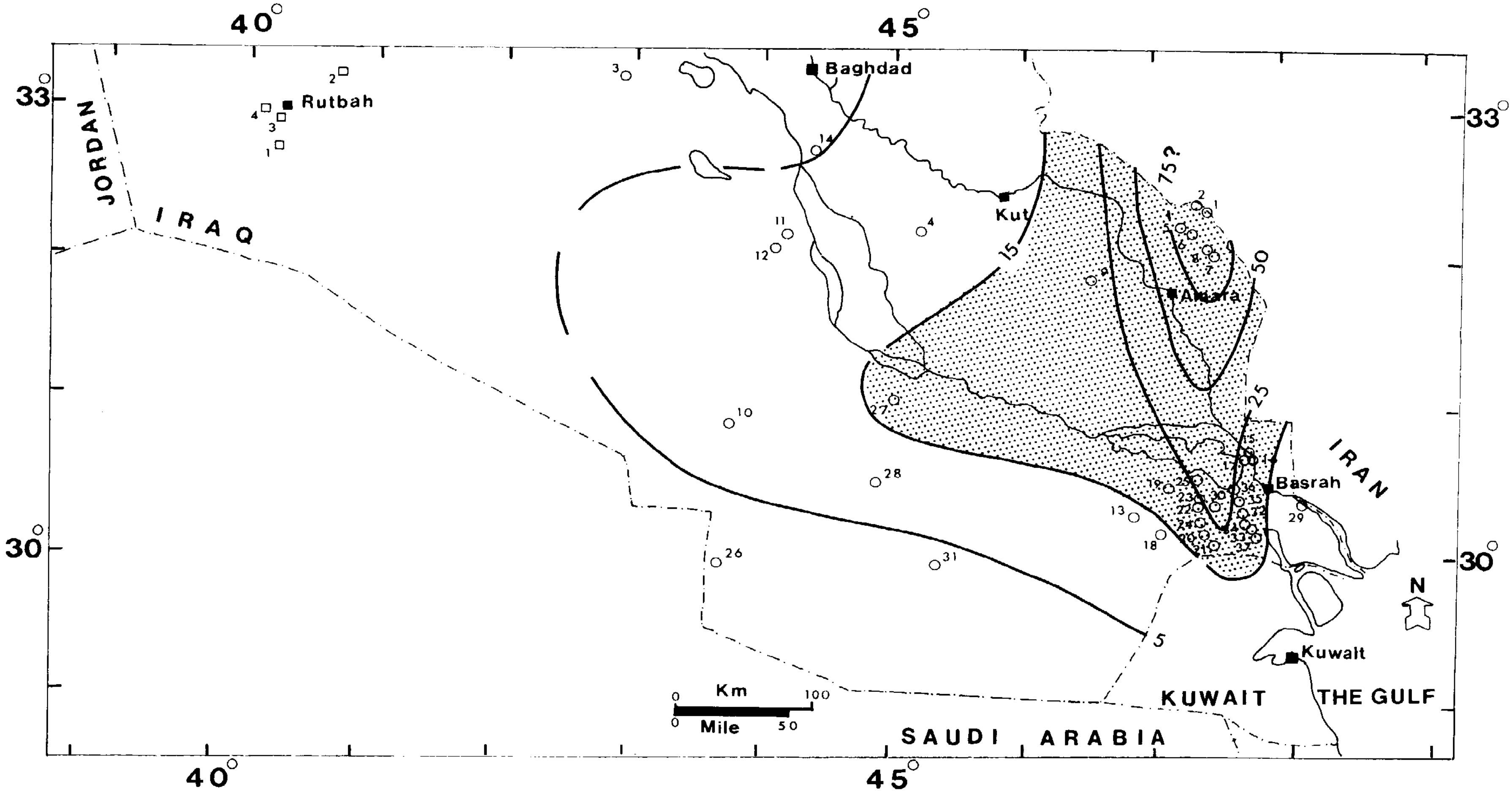


FIG. 12—Iso-TTI contour map of base of Nahr Umr Formation in southern Iraq.

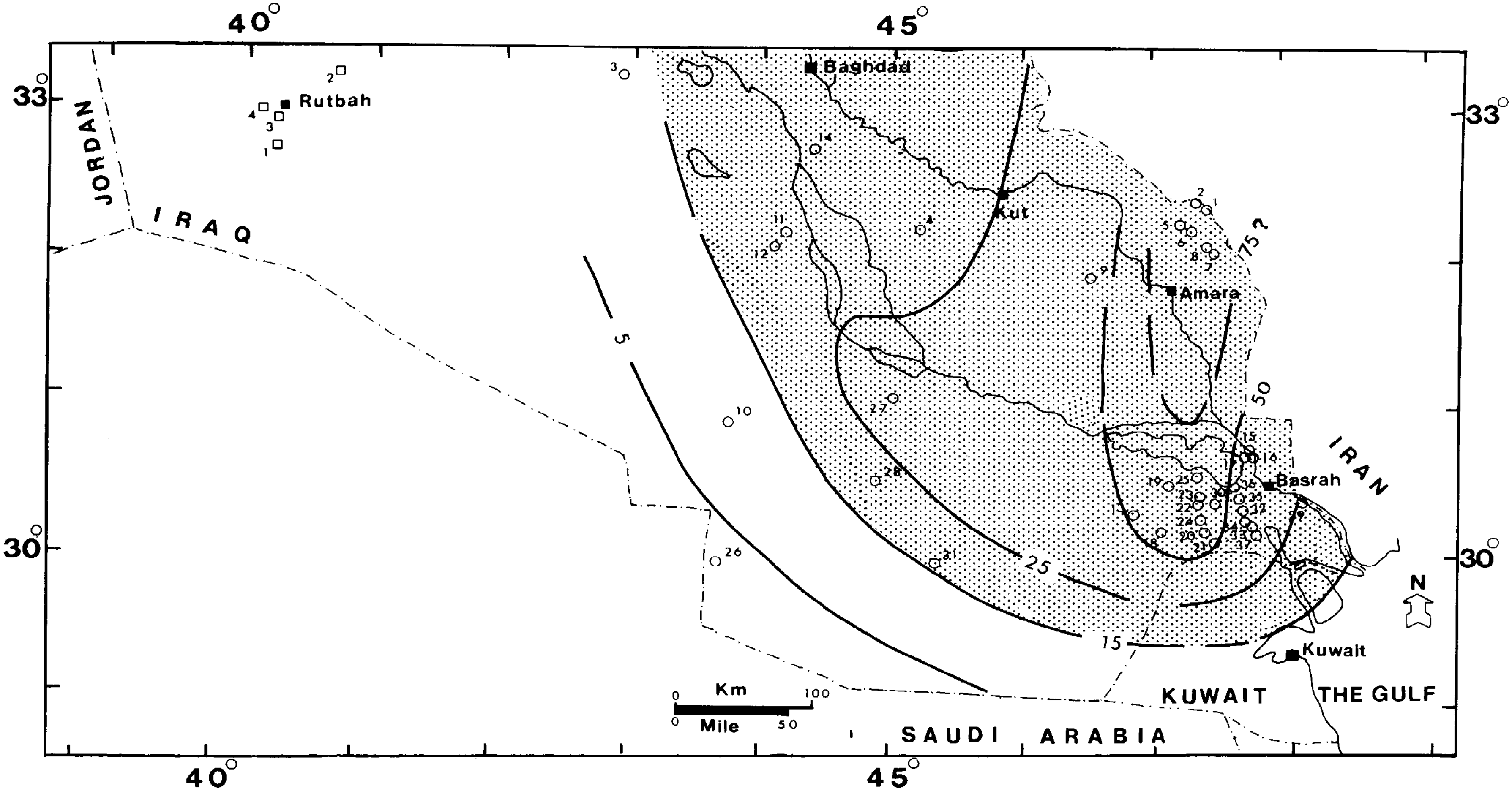


FIG. 13—Iso-TTI contour map of base of Ratawi Formation in southern Iraq.

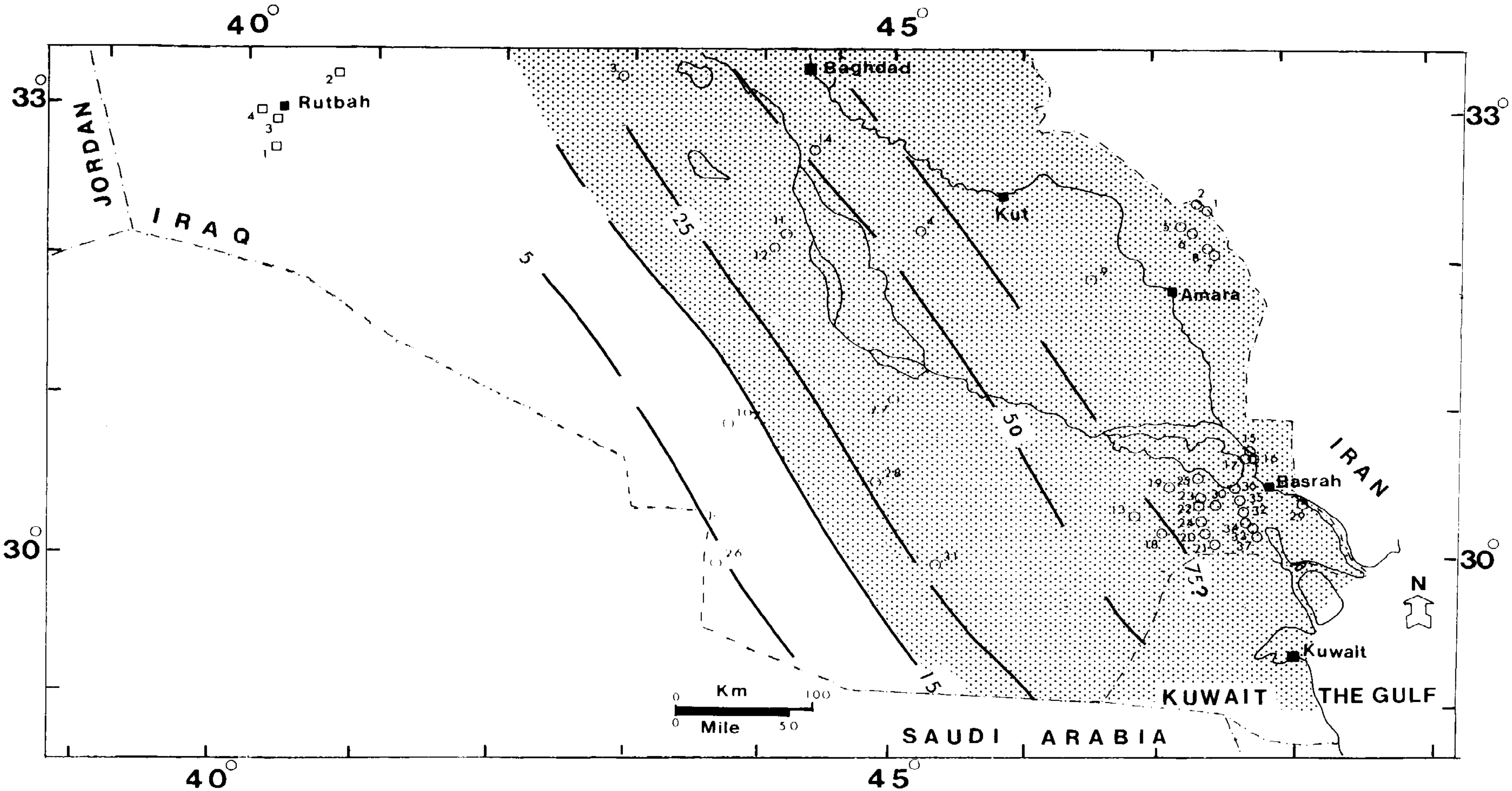
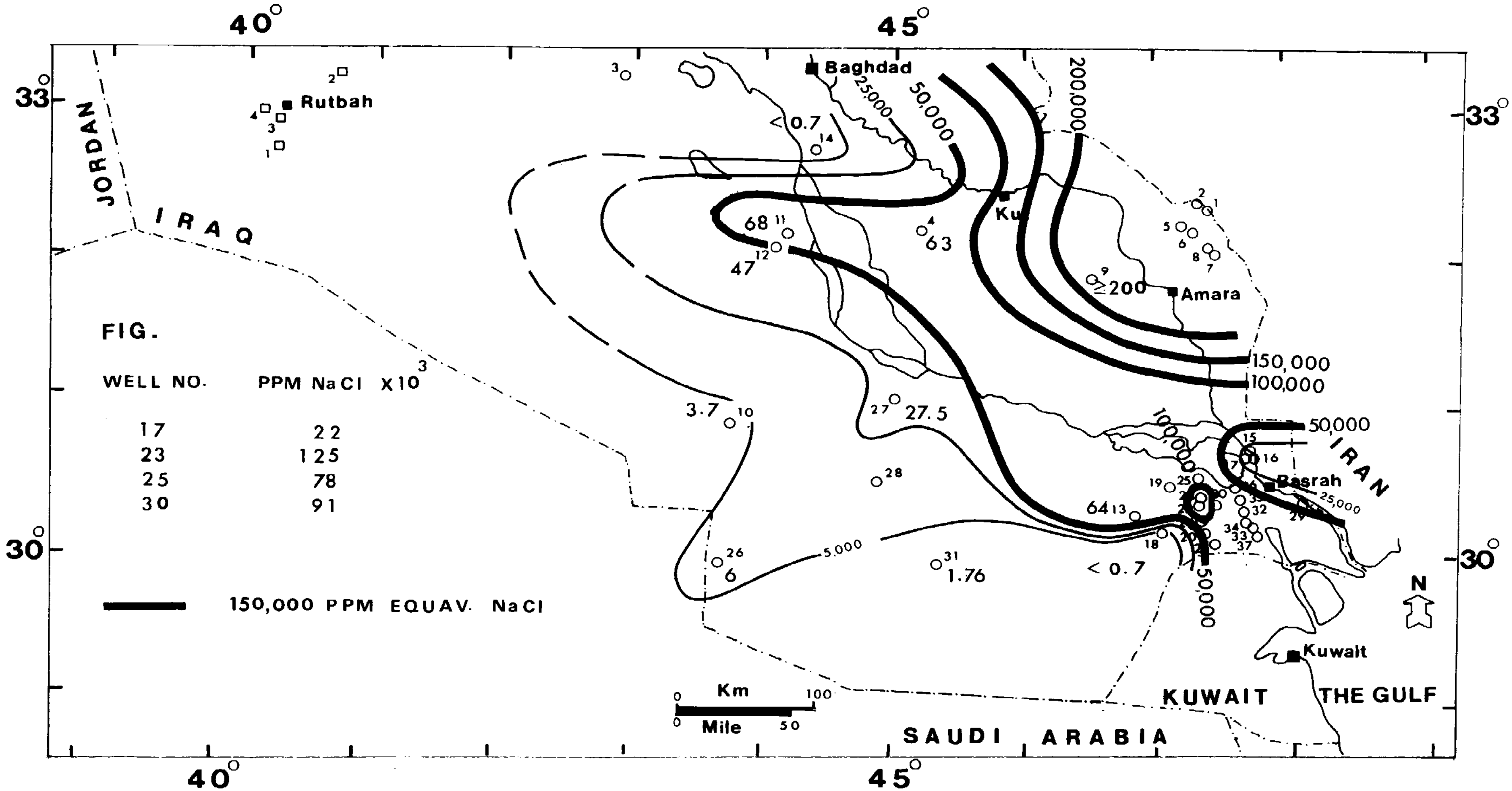
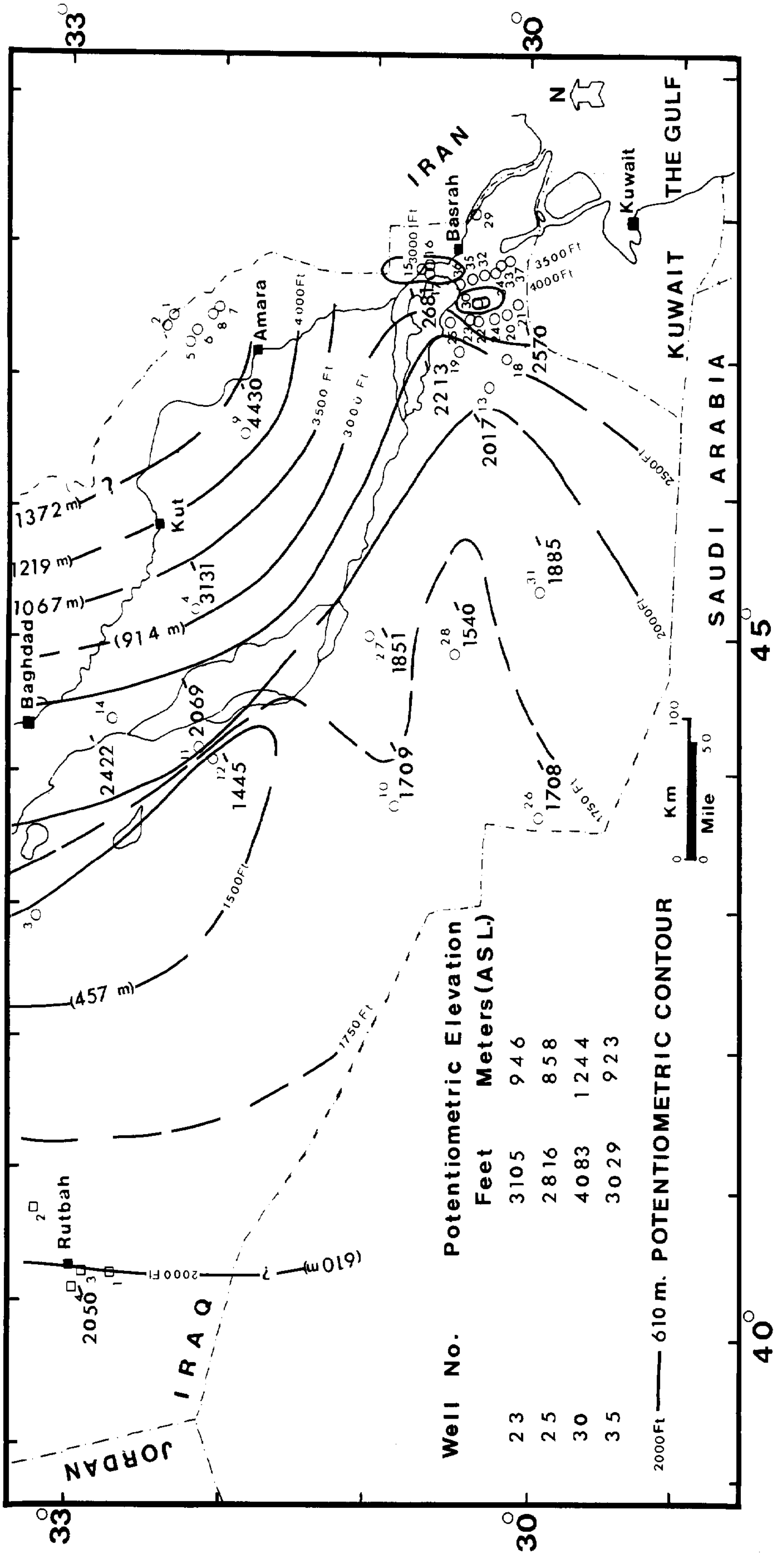


FIG. 14—Iso-TTI contour map of base of Sulaiy-Chia Gara Formations in southern Iraq.



| WELL NO. | PPM NaCl X10$^3$ |
|---|---|
| 17 | 22 |
| 23 | 125 |
| 25 | 78 |
| 30 | 91 |

FIG. 15—Iso-salinity contour map of formation water of Nahr Umr aquifers. Contours are in "equivalent" NaCl concentrations in ppm.



| Well No. | Potentiometric Elevation Feet | Meters (ASL) |
|---|---|---|
| 23 | 3105 | 946 |
| 25 | 2816 | 858 |
| 30 | 4083 | 1244 |
| 35 | 3029 | 923 |

FIG. 16—Equipotentiometric surface contours (in feet above sea level) of Nahr Umr aquifers in southern Iraq. Pressure gradient of fresh water (0.433 psi/ft) was used for each locality.

significant and positive correlation was calculated to exist between the two variables (Fig. 17). However, there was a clear clustering into two groups of wells, divided by an inferred fault trend (possibly a hinge line) that extends from Abu Jir to Kifl and Samawa and lies northeast of the spring belt (Figs. 3, 18). Each of the two groups was subjected to further statistical regression analysis, which revealed a very significant correlation in wells in the east-northeast of southern Iraq, but a very weak correlation in wells located in the west-southwest (Fig. 17). Also, by plotting the calculated formational pressures against depths of burial, the pressures were found to cluster into two groups separated by the same trend (Fig. 19). However, a very significant and positive relationship was found between pressures and depths of burial on both sides of the postulated fault trend, but with a higher gradient on the east-northeast side (Fig. 19). A very significant and positive correlation was calculated between formational temperatures and the depths of burial of the Nahr Umr Formation (Fig. 20). Although there is a cluster into two groups along the same dividing line of the water salinity and hydraulic pressure, the correlation proved insignificant in west-southwest Iraq and only significant in the east-northeast of southern Iraq (Fig. 20).

The above analysis has proven the existence of two hydraulic regimes in southern Iraq. The west-southwest regime has an erratic temperature-depth graph, which contrasts with a similar graph for the east-northeast.

It has been shown earlier that there is a general increase in NaCl concentration in the Nahr Umr aquifer toward the northeastern part of southern Iraq (Fig. 15). Therefore, by comparing isosalinity contours with the topographic map of South Iraq (Fig. 18) there seems to have been a probable fresh-water recharge at the exposed section in Rutbah and/or northern Saudi Arabia.

An association of normal fresh-water hydrostatic or artesian pressure, lower salinity, and lower temperature than corresponding regional averages, may point to a probable contemporary meteoric invasion. Conversely, higher salinity, pressure, and temperature may distinguish areas of discharge. Hence, plottings of hydrostatic pressure versus water salinity (Fig. 21), temperature versus salinity (Fig. 22), and temperature versus hydrostatic pressure (Fig. 23) were constructed to detect such common associations.

Statistical regression analysis of these graphic plottings proved the existence of a very significant and positive correlation between formational pressure and salinity of the Nahr Umr Formation in southern Iraq. However, by treating each of the west-southwest and east-northeast wells separately, a very significant correlation was found in the east-northeast wells and a very weak correlation was calculated in west-southwest wells of southern Iraq (Fig. 21). Also, a significant and positive correlation was calculated to exist between formational temperature and water salinity of the Nahr Umr in southern Iraq. However, the same variables are only significantly correlative in east-northeast southern Iraq and have no correlation in west-southwest Iraq (Fig. 22). The temperature proved to have a very significant and positive correlation with the formational pressure of the Nahr Umr Formation over southern Iraq, but only in east-northeast southern Iraq was there significant correlation, and no correlation was found in west-southwest of southern Iraq (Fig. 23).

The statistical analysis of the graphs shown in Figures 21 to 23 proved no significant common association of lower temperature, salinity, and pressure in west-southwest southern Iraq. However, it can be seen that with the exception of well 11, the P-T plotting in Figure 23 shows a subnormal trend that groups wells 26, 27, and 31, and an abnormal trend that contained wells 10 and 12. This may be inferred as a west-southwest hydrologic regime with a possible recharge and discharge outlet.

A single, intermediate (centripetal) drainage basin was drawn by Chiarelli (1973) for the "Cretaceous aquifer" of the southern Middle East. It has a salinity increase toward the center of the Arabian Gulf, and an equipotentiometric surface that dips toward the center of the gulf as well.

The present investigation, although not planned as a detailed hydrogeologic study, indicates the presence of a more complex situation than the one envisaged by Chiarelli in this part of the Middle East.

Knowing that the "potentiometric surface will slope in the direction which the water is moving" (Dickey, 1979), the presence of a low and closed equipotentiometric contour in the Abu Jir-Kifl 2 area (Figs. 16, 24a) that coincides with a line of springs (possibly fault controlled) and salt lakes (Fig. 18) may be inferred as a possible flow and discharge of formation waters within the area bounded by the lowest closed contour (Toth, 1980). Therefore, an extremely slow flow of meteoric water (or possibly fossil fresh water) can be inferred in west-southwest southern Iraq. The potentiometric surface slopes from the east-northeast and west-southwest toward the Abu Jir-Kifl 2 area, delineating a possible aquitard separating the two salinity regimes (Figs. 24b, 25), which is manifested at ground level as a line of saline springs and lakes (Unesco, 1976, p. 161; Jamil, 1977).

Abrupt variations in water salinity and pressure are noticeable over the anticlinal oil field area in southeast Iraq (Figs. 15, 16). Similar variations in salinity were measured in water samples from the Zubair Formation in the same area, and were attributed to lateral westward flow (Jamil, 1977, 1978). However, vertical water seepage over anticlinal areas was believed by Magara (1980) to occur in Kuwait. Other causes of these salinity variations may be found, but certainly the pattern of isosalinity and the equipotentiometric contours in the vicinity of wells 13 and 18 are different. This dilution of formation water is speared by Wadi Al-Batin, a known fault and drainage wadi along the Iraqi-Kuwait border.

## Trap Availability

The abundance of Albian oil traps in the southeastern corner of southern Iraq and Kuwait is due to the occurrence of what is generally accepted as salt tectonic structures that exhibit a Cretaceous or Paleocene to Holocene semicontinuous structural growth (Fig. 10) (Brown, 1972; Ibrahim, 1979). The rest of southern Iraq exhibits intermittent structural growth pulses with different starting times (Ibrahim, 1978).

All wells in the central, eastern, and southeastern parts of southern Iraq (Fig. 1) were drilled on structural prospects.

Continuous structural growth is a positive factor in oil fields all over the world (Law, 1957; Scholton, 1959), and southern Iraq presents no exception. Fields exhibiting such

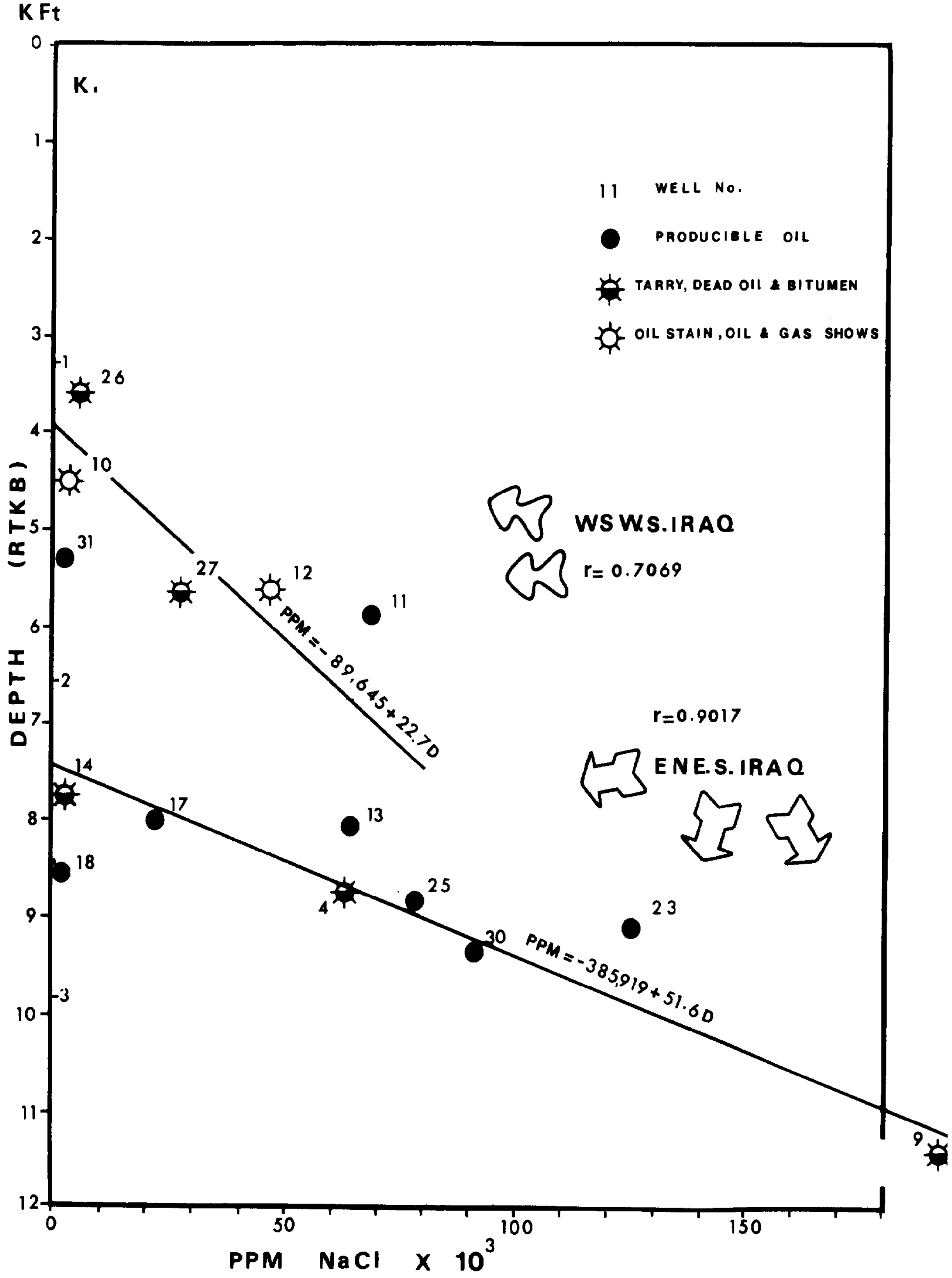


FIG. 17—Graphic plotting of calculated "equivalent" NaCl concentration (ppm) versus depth of burial of Nahr Umr reservoirs in southern Iraq; r is the coefficient of correlation. Equation on graph is linear regression equation.

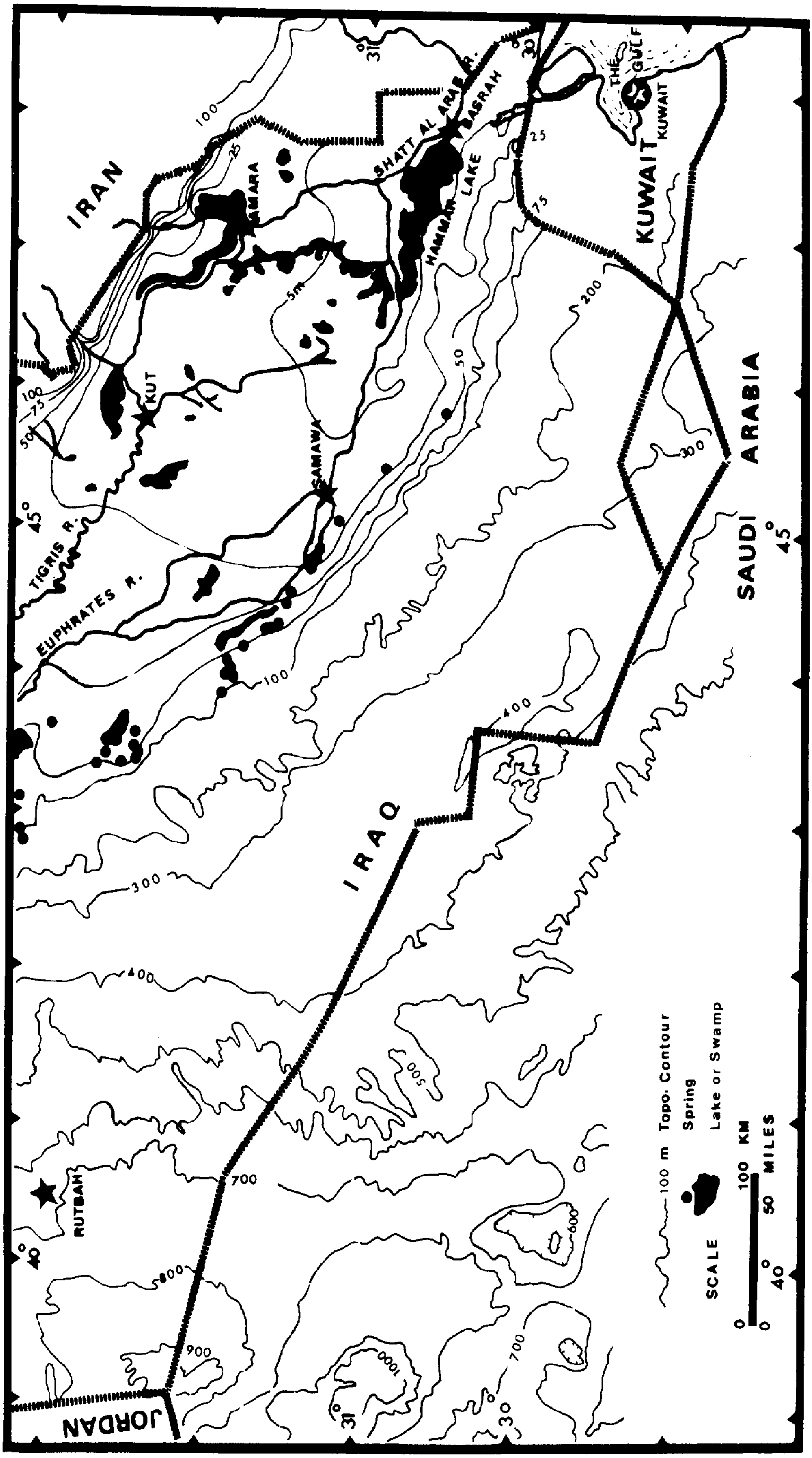


FIG. 18—Topographic contour map of southern Iraq (after Ibrahim, 1978) from several sources.

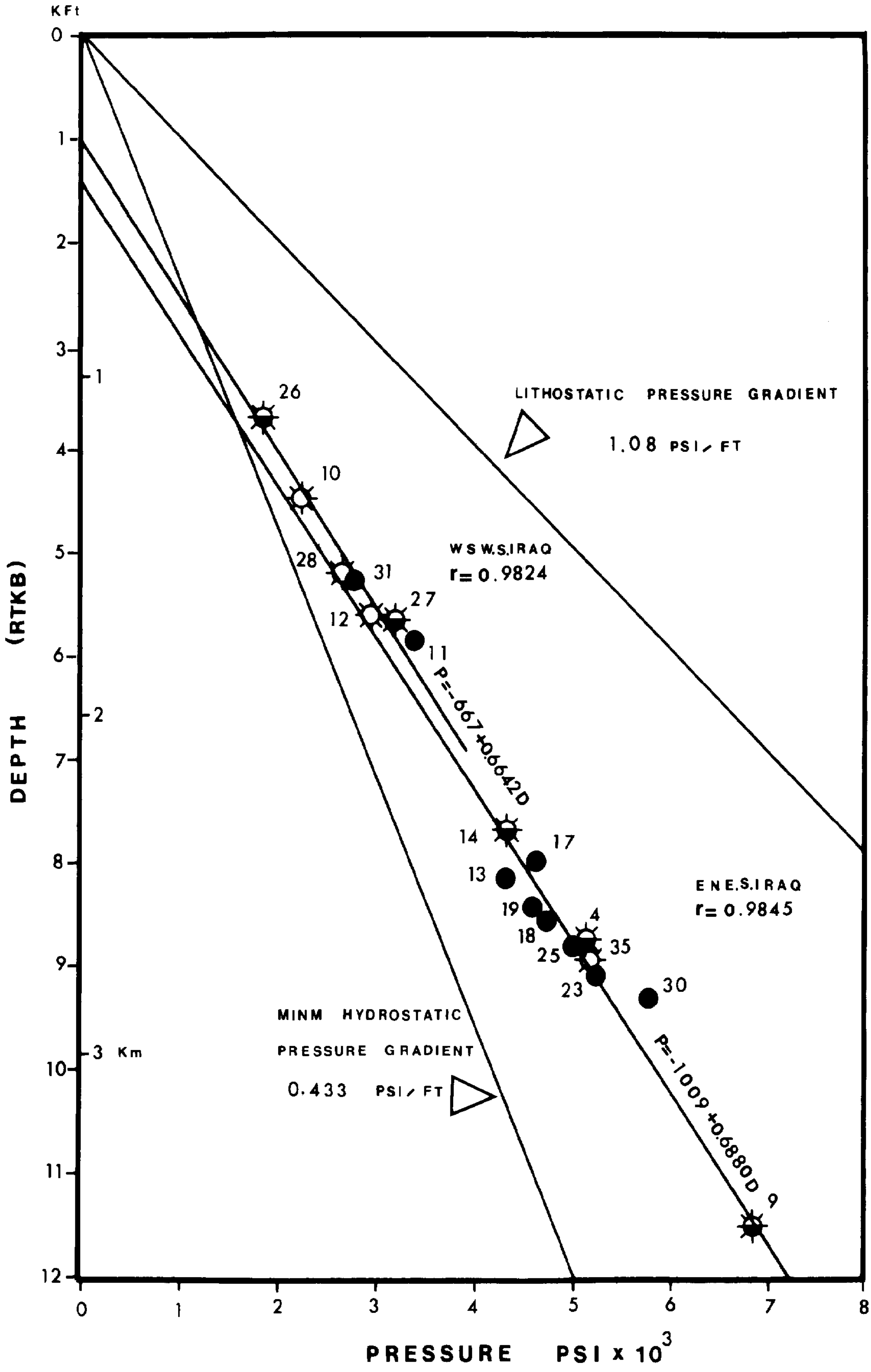


FIG. 19—Graphic plotting of calculated mud pressure (≃ hydrostatic pressure) versus depth of burial of Nahr Umr Formation.

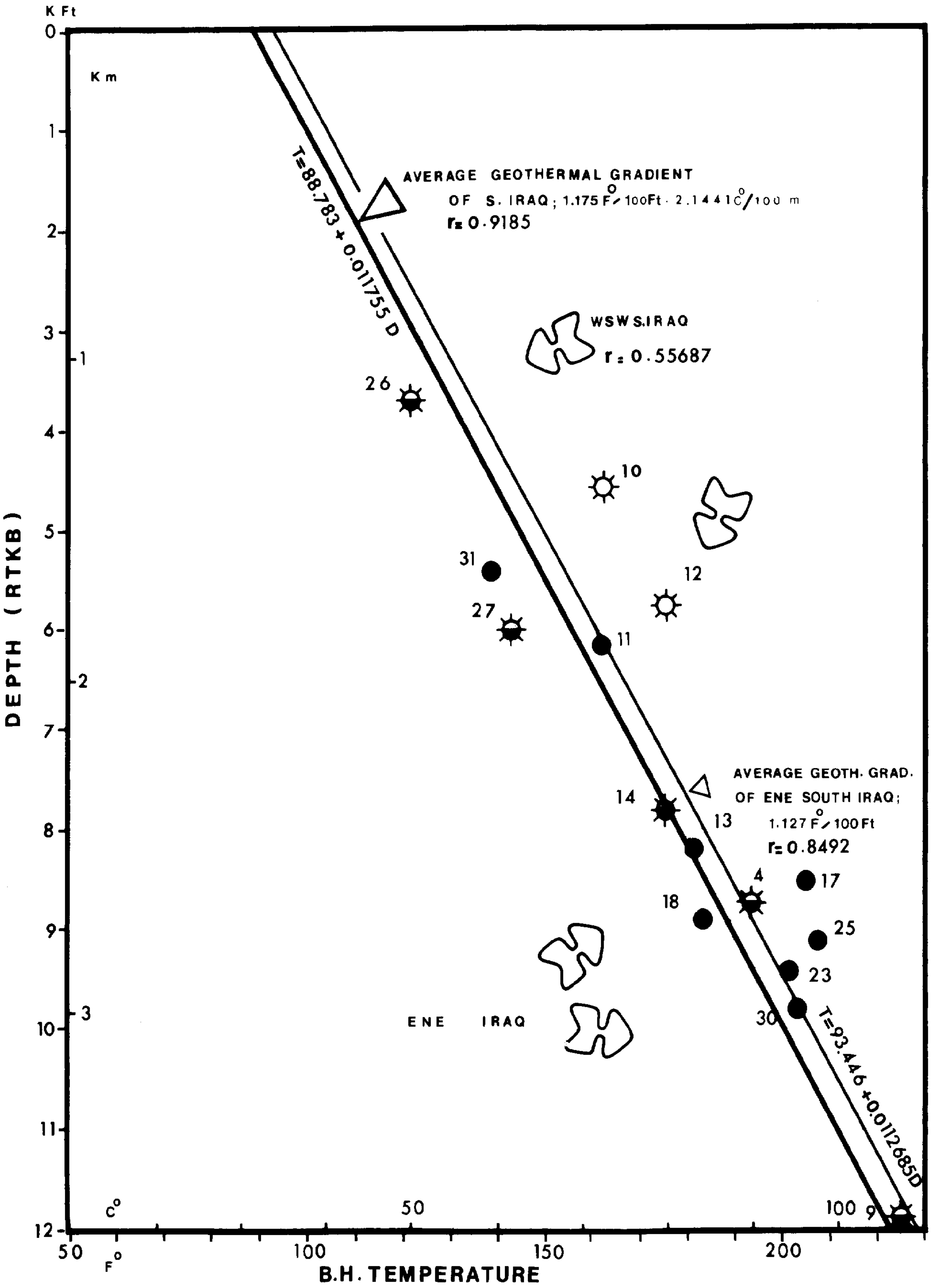


FIG. 20—Graphic plotting of corrected temperature recordings against depths of Nahr Umr Formation.

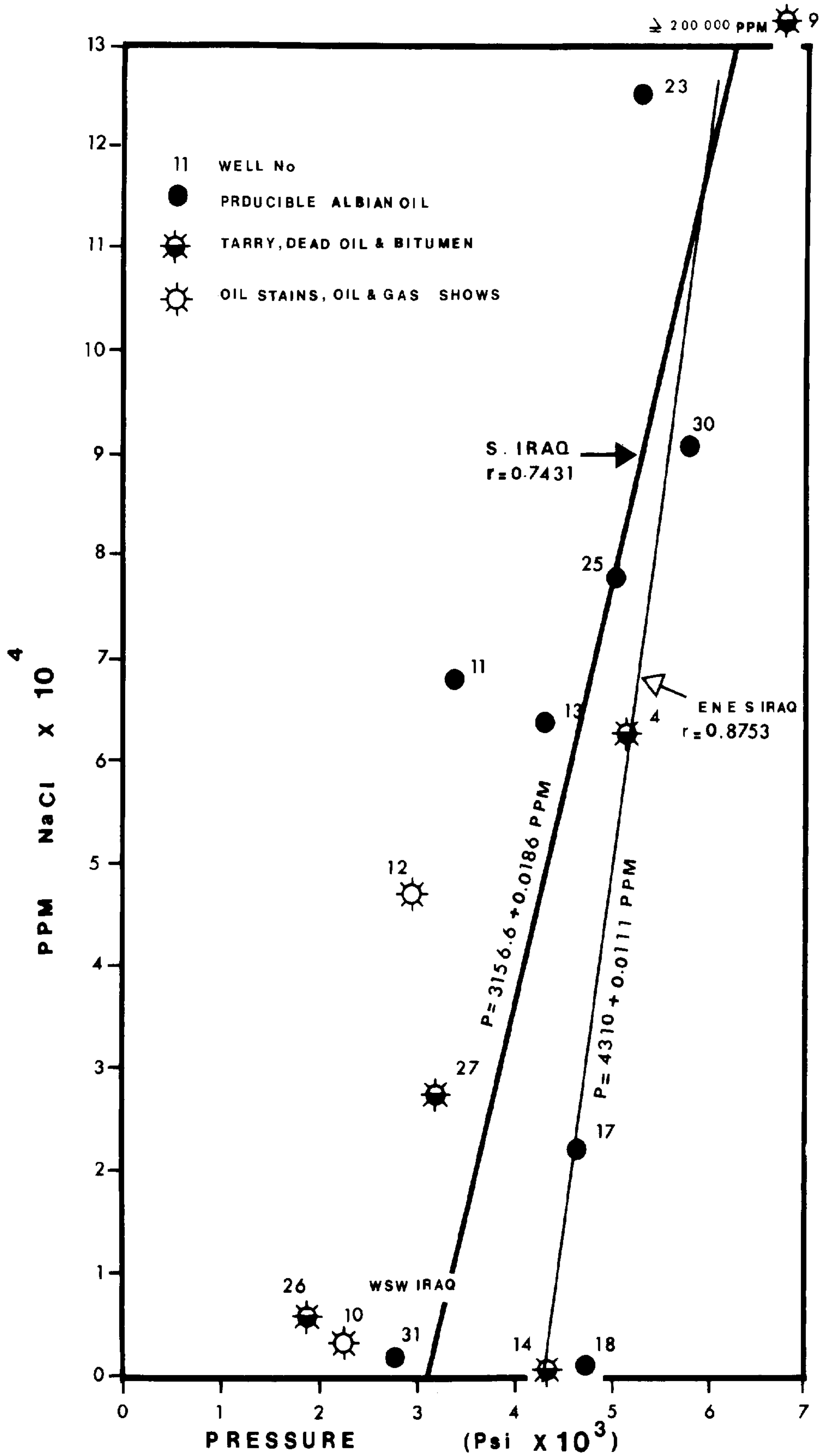


FIG. 21—Graphic plotting of calculated mud pressure (≃ hydrostatic pressure) versus calculated salinity of Nahr Umr Formation waters in southern Iraq; r is coefficient of correlation.

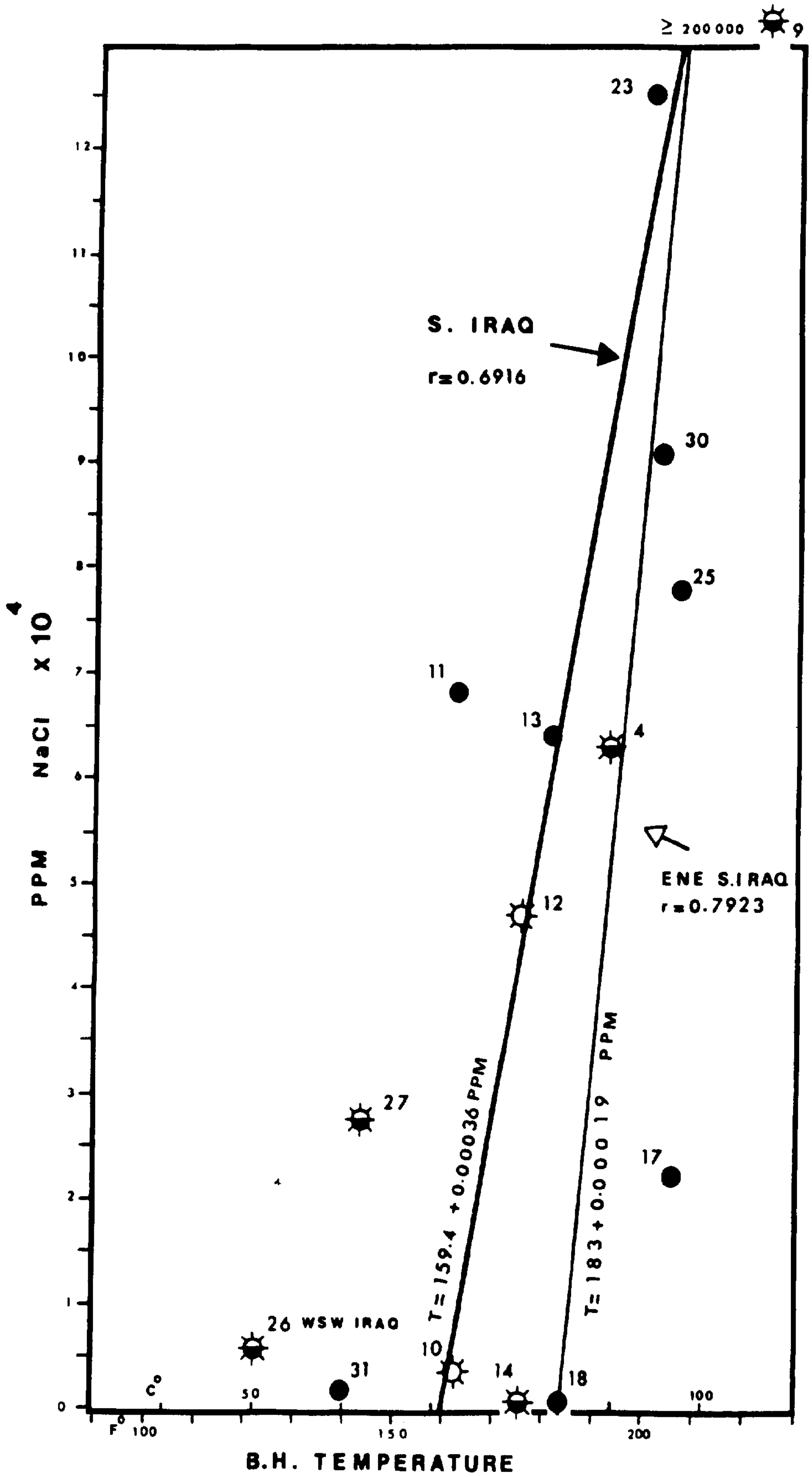


FIG. 22—Graphic plotting of corrected temperature measurements versus calculated salinities of Nahr Umr Formation waters.

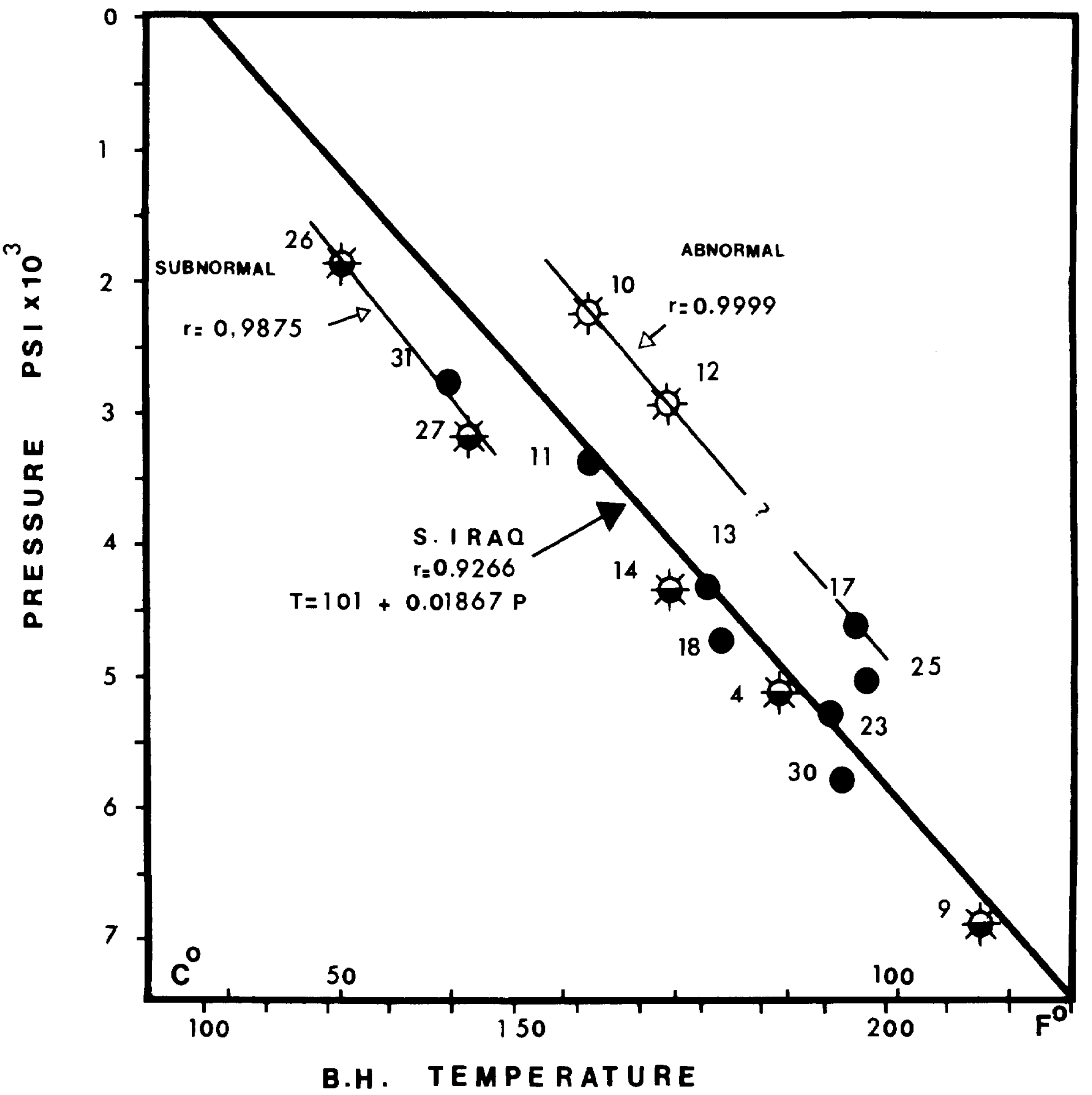


FIG. 23—Graphic plotting of calculated mud pressure (≃ hydrostatic pressure) versus corrected temperature measurements of Nahr Umr Formation waters.

structural growth behavior are considered to have a relatively high petroleum-trapping potential (Ibrahim, 1978).

Evidence of Oligocene-Miocene structural growth is present in the east-northeast of southern Iraq (Fig. 11). This growth is inferred to have been induced by the lateral stresses of the Alpine orogeny of ancient Zagros (Ibrahim, 1979).

### Petroleum Entrapment

Vertical hydrocarbon migration from Cretaceous formations deeper than the Zubair may have contributed to the oil accumulation in the Nahr Umr reservoirs in southeastern Iraq and Kuwait (Dunnington, 1967; Al-Shahristani and Al-Atyia, 1972; Magara, 1980). Such migration could have started at an earlier time (late Paleocene to Eocene) than any lateral migration from the deep-water Albian facies (Kazhdumi Formation), which could only have reached the threshold of thermal maturation during Oligocene time (Fig. 10).

Long-distance lateral petroleum migration may have been from the east-northeast toward the west-southwest (i.e., updip and perpendicular to the axes of basinal subsidence) and the post-Paleocene axes were no exception (Ibrahim, 1979).

Vertical migration of petroleum from source rocks as deep as the Chia Gara may have begun in the northeast of southern Iraq as early as Miocene time. However, the possibility of such migration occurring is handicapped by the presence of shale beds hundreds of feet thick. The base of the Nahr Umr reached the 15τ level in the late Miocene, and it is still near

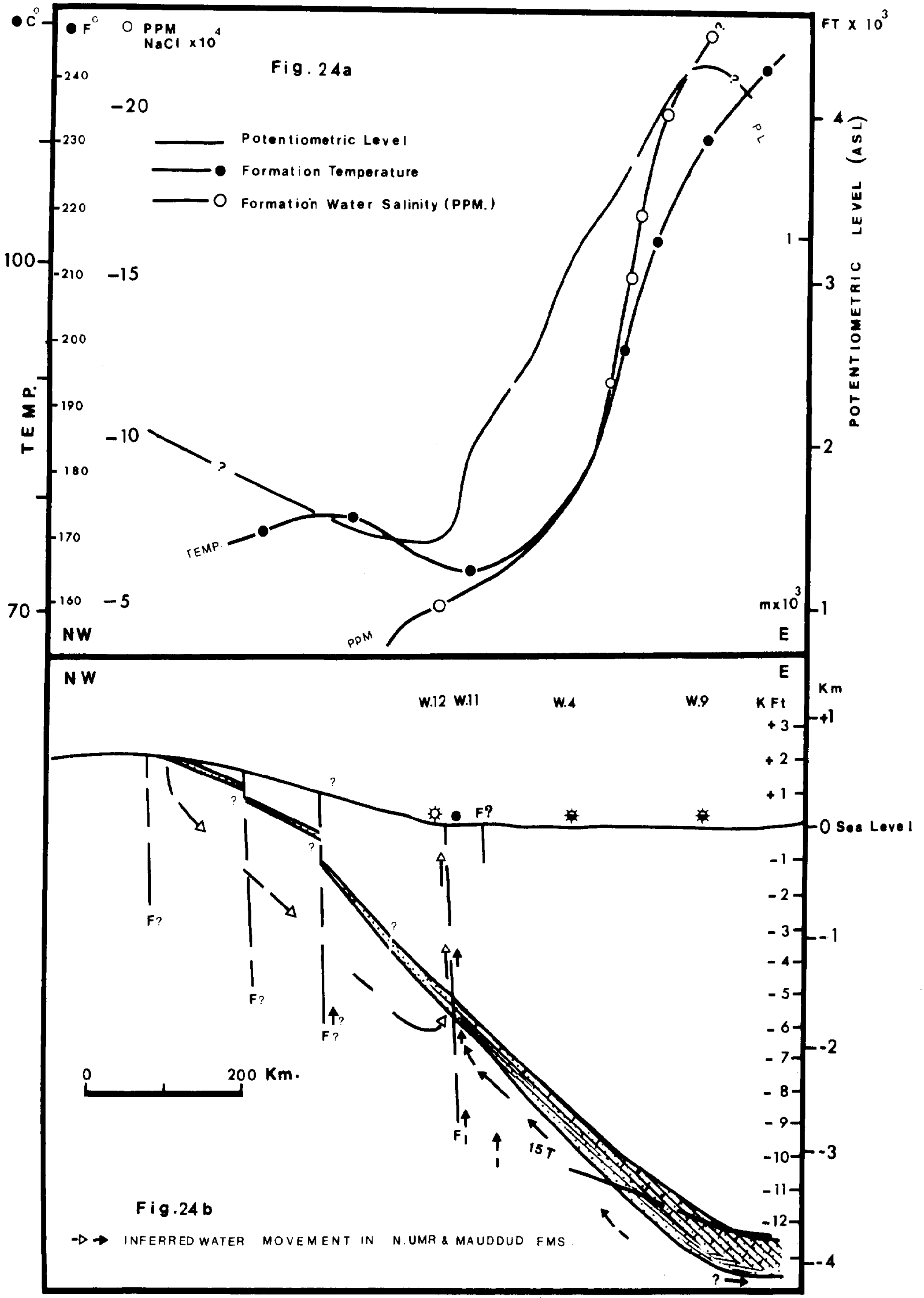


FIG. 24—Diagrammatic illustration of some inferred geologic and hydrogeologic variables controlling petroleum occurrences in Albian rocks of southern Iraq: (a) hydrologic controls: TEMP. = formation temperature of Nahr Umr; ppm = Nahr Umr water salinity in equivalent NaCl; PL = equipotentiometric level of fresh water at 77°F. (b) Inferred water movement of fossil(?) meteoric (white arrows) and original brines (black arrows) in Albian rocks.

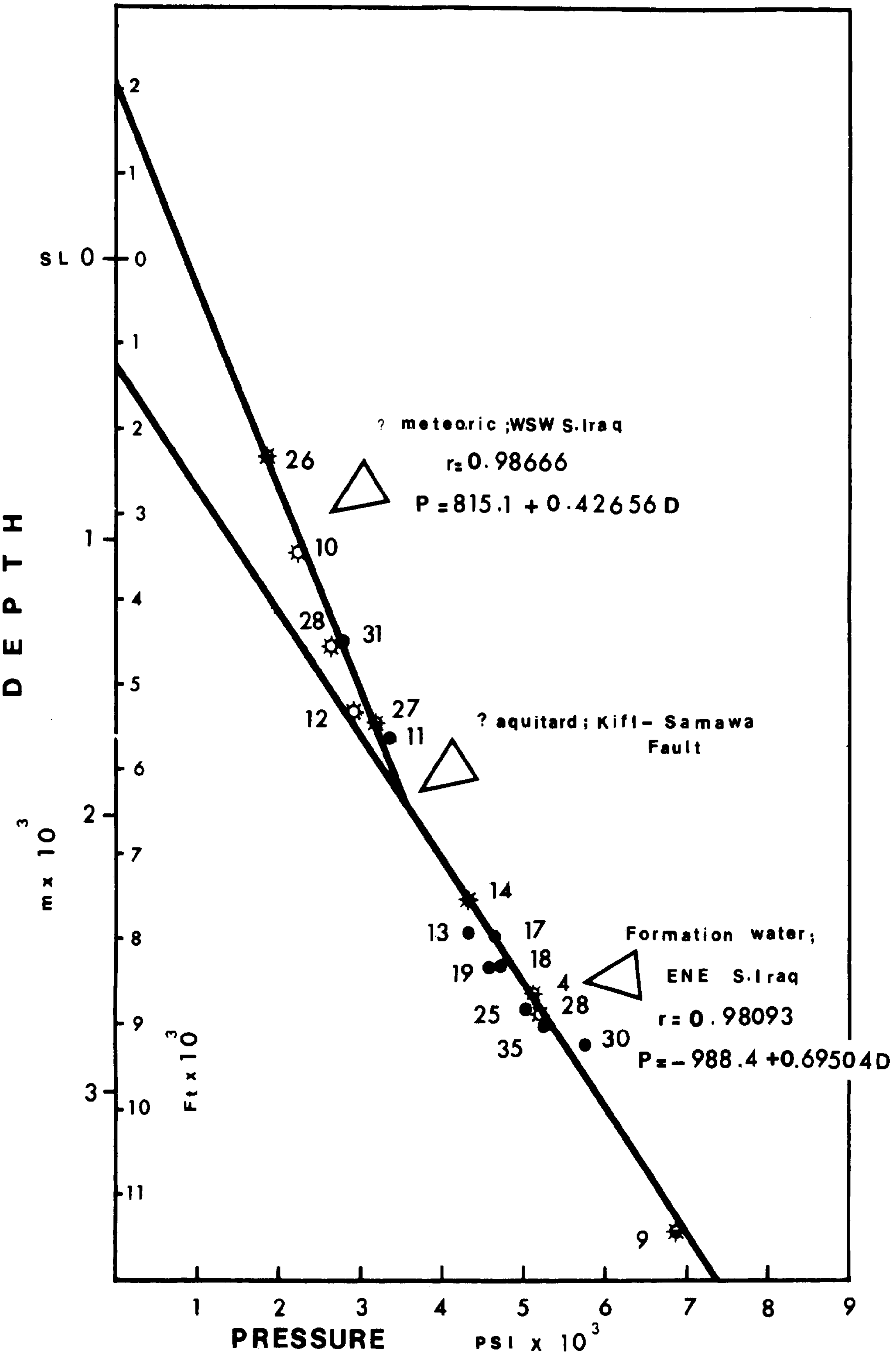


FIG. 25—Graphic plotting of hydraulic pressure of Nahr Umr Formation against depth below sea level, showing effect of difference in water salinity on pressure gradients across inferred fault system; r is coefficient of correlation.

that level. The petroleum that may have been generated within the Nahr Umr (Kazhdumi source rocks) could only be of a heavy, immature nature; this is generally similar to the noncommercial oils found in the Albian reservoirs in northeast southern Iraq (Figs. 2, 11 to 14).

The producible oil in the Nahr Umr reservoir in the Kifl 1 (W. 11) well is probably derived from vertical migration as the Albian rocks are calculated to be thermally immature (Figs. 12 to 14).

Possible source rocks at the Safawi 1 (W. 26) and Ghalaisan 1 (W. 10) wells have not reached the threshold of petroleum generation even at the deepest feasible formation (Sulaiy) and the Nahr Umr shale beds are missing there, hence no economic oil was encountered (Figs. 9, 12 to 14). A thermal threshold has been attained in deeper Cretaceous rocks at Shawiya 1 (W. 28), but evidence of an effective cap was not encountered and no trap was found (Ibrahim, 1978).

In southeastern Iraq, Lower Cretaceous source rocks have retained the $15\tau$ level since possibly late Paleocene to Eocene times, structural traps started to develop during the Cretaceous, and there is an effective reservoir and cap rocks. Therefore, trapping conditions are satisfied in this part of southern Iraq. Hence almost every trap in southeast southern Iraq and Kuwait contains producible oil in the Nahr Umr reservoirs. The exceptions at the Zubair and Siba fields are due to the effectiveness of the Zubair shale as a cap rock there. In this area the shales were not fractured by the mild structural deformation, hence they were not charged from below. Ancient (and possibly present day) meteoric water washing (Bailey et al, 1973) of oil in west-southwest Iraq is possible.

## CONCLUSION

The combined effect of lithofacies, structural development, geothermal maturation of source rocks, hydrogeology, and environments of deposition on petroleum generation, migration, and entrapment in the Nahr Umr Formation in southern Iraq has been interpreted in terms of petroleum prospects.

The presence of producible oil in both the Lower Cretaceous Zubair and Nahr Umr Formations in the same fields was noticed, hence common source rock and vertical migration from deeper Lower Cretaceous sources are favored for the oil in these Albian reservoirs. As both are commonly associated with a calculated time-temperature maturation of the top of the Yamama-Chia Gara Formations, it is assumed that these are possible source rocks for the oil in the Albian reservoirs.

Petroleum could have begun its generation in Lower Cretaceous source rocks and migrated into the Albian reservoir rocks during the late Paleocene to early Eocene in southeastern Iraq, and during the Miocene in the northeastern part of southern Iraq. The direction of migration was probably dominantly vertical, and to a lesser extent lateral, up the present regional dip and at right angles to the late Tertiary deposition axes (i.e., from the east-northeast toward the west-southwest of southern Iraq).

Oil traps of the Nahr Umr Sandstone Formation are located mainly within a belt of marginal marine environments of deposition. No producible oil was encountered in the Mauddud Formation in southern Iraq, although it is an important reservoir in the Middle East. This is perhaps due to the inefficiency of the Ahmadi shale as a cap rock in southern Iraq and the presence of shale beds in the upper parts of the Nahr Umr Formation, which generally act as cap rocks in southern Iraq and which may prevent vertical charging.

Producible oil in the Nahr Umr Formation is dominantly in traps that started their structural growth during Cretaceous or Paleocene time. The Albian rocks of southern Iraq are inferred to be influenced by two hydrogeological regimes separated by the Abu Jir-Kifl 2 lineament.

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