The American Association of Petroleum Geologists Bulletin
V. 65, No. 11 (November 1981), P. 2403-2416, 9 Figs.

Structural Evolution of Harmaliyah Oil Field, Eastern Saudi Arabia[1]

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ABSTRACT

The history of structural growth of the Harmaliyah oil field in eastern Saudi Arabia was studied by means of a series of paleostructural maps to determine if early entrapment of hydrocarbons played an important role in preserving the high porosity of the Kimmeridgian (Upper Jurassic) Arab D reservoir. The Arab D has been affected by shallow or preburial diagenesis—a common feature in Arabian Upper Jurassic calcarenitic reservoirs. Closure forming the structural trap in the Arab D at Harmaliyah oil field developed principally during the late Turonian (Late Cretaceous). During Kimmeridgian (Late Jurassic)-early Turonian (Late Cretaceous) time, shallow or preburial diagenesis of the calcarenitic Arab D reservoir rocks seems to have played a major part in preservation of porosity before the porosity was filled with hydrocarbons.

INTRODUCTION

The Arab D reservoir of the Harmaliyah oil field of Saudi Arabia (Fig. 1) is characterized by relatively high primary porosity. The rock exhibits, in addition to facies changes and dolomitization, many preburial diagenetic fabrics identical with those discussed by Purser (1978, p. 92, Fig. 6).

Primary porosity can be preserved by early migration of oil into a relatively uncompacted reservoir rock, thus forming an inert insulating medium which impedes ion exchange and stops further plugging of pores by cementation (Dunnington, 1967a; Fuchtbauer, 1967; Kamen-Kaye, 1970; Purser, 1978). Purser (1978), however, suggested that calcarenites with "preburial," early diagenetic fabrics retain most of their primary porosities; he reported examples of calcarenitic rocks, which, without such early diagenetic features, have been compacted under surface, reservoir, and nonreservoir conditions, and vice versa. He concluded that the preburial, early diagenetic features are the cause of porosity preservation.

The aim of the present study was to find out exactly when the oil-bearing structure was formed, that is, whether it developed before, after, or during the deposition of this highly porous reservoir.

Five cumulative isopach triangles were used, modified from the one suggested by Bakerov et al (1975) to trace the history of structural growth of the Harmaliyah oil field in an attempt to define the time that a trap formed (presumably predating oil entrapment). The cumulative isopach triangle method is explained in the Appendix. Only formation thicknesses were used in making the isopach maps; no contour summation was used in the construction of the cumulative isopach maps.

GENERAL GEOLOGY OF HARMALIYAH OIL FIELD

The Harmaliyah oil field is an asymmetric, NNE-SSW-striking anticline, 40 km long and 15 km wide with its steeper flank dipping at 1.5° to 2.5° to the southeast. It has no significant surface expression (Halbouty, 1980). The anticline is broken by at least five transverse faults (Fig. 1). Lateral movement along some of them is more than 2 km. The field is located on the western shelf of the Middle East geosyncline where sedimentation has continued with little interruption since the Infracambrian (Ibrahim, 1979). Figure 2 is a generalized stratigraphic column of eastern Saudi Arabia.

Oil was discovered in the Arab D reservoir at Harmaliyah by Aramco in December 1971. The field went on production in 1973 and was shut down in early 1980. It produced, under its own pressure, crude oil of about 35° API gravity, 740 gas/oil ratio, and 1.65% sulfur content. Because the Arab D/Jubaila Formation contact is a well-recorded marker (Fig. 2), this study is primarily concerned with the history of the structural growth at the base of the Arab D reservoir (Fig. 3A). The Arab D reservoir is capped by the Arab D evaporites, or what are locally known as the "C-D evaporites" (Fig. 3B); the Arab D member is used here to group both units. Aramco's stratigraphic dating is used in this work. No faults are shown on the structural maps (except Fig. 1) in this study to permit direct comparison with the isopach maps which are used as paleostructural maps.

[1]Manuscript received, October 1, 1980; accepted, March 10, 1981; revised, July 13, 1981.

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We thank the Ministry of Petroleum and Mineral Resources of Saudi Arabia and the Faculty of Earth Sciences (FES), King Abdulaziz University, for their support in acquiring the basic data for this work. The research was made possible by the contribution of many working hours by Aramco geologists and technicians.

We thank R. Murris of Shell International Petroleum Co.; P. Binda, G. Coorey, and C. Groen of FES; M. Ala of Imperial College for reviewing the manuscript; H. V. Dunnington and M. Barazangi of Cornell University; and S. Al-Khatieb of Imperial College and M. Al-Rawi of University of Kuwait for useful discussions.

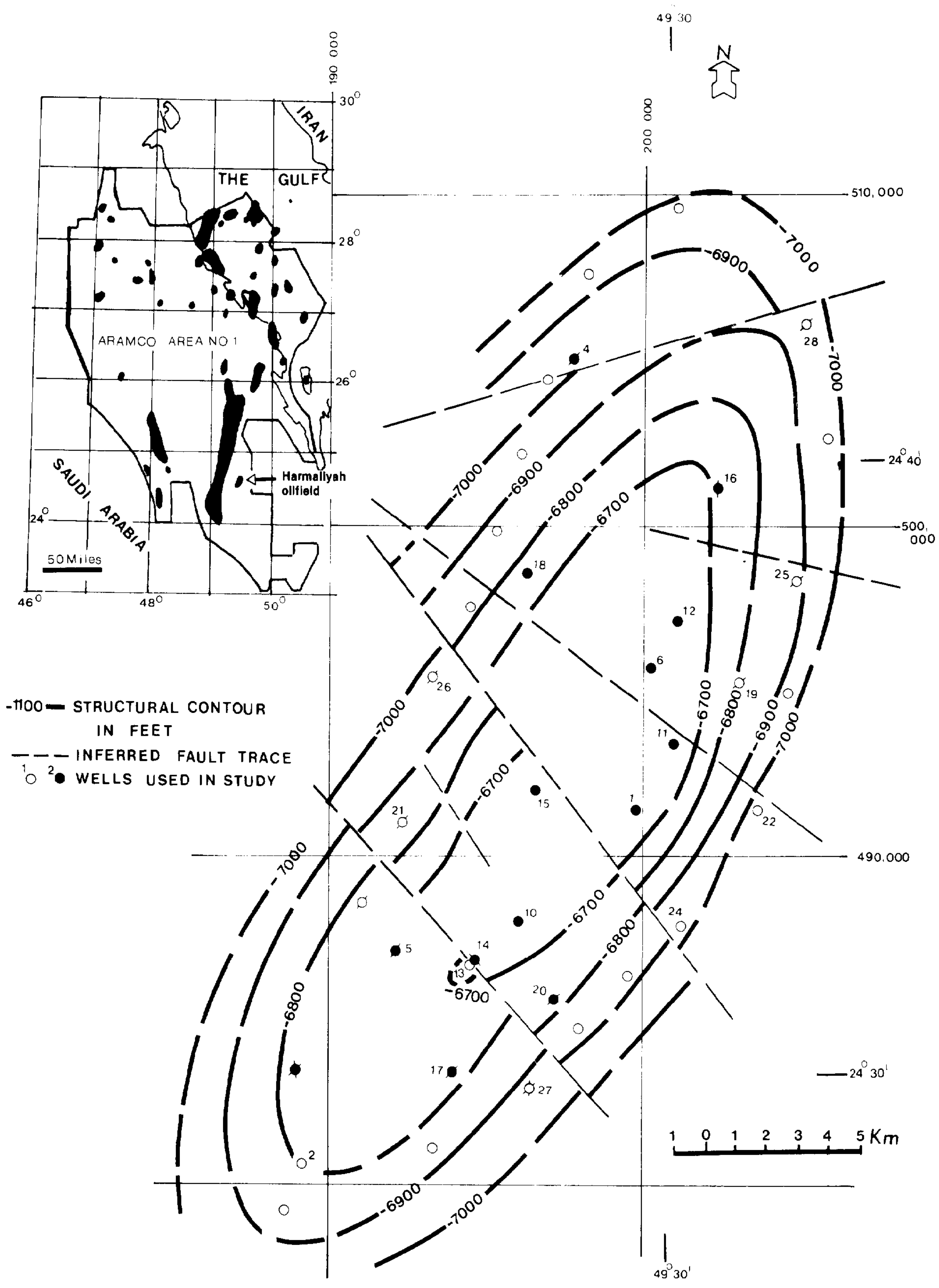

FIG. 1—Harmaliyah oil field, eastern Saudi Arabia. Structural contours are on top of Hith Anhydrite.

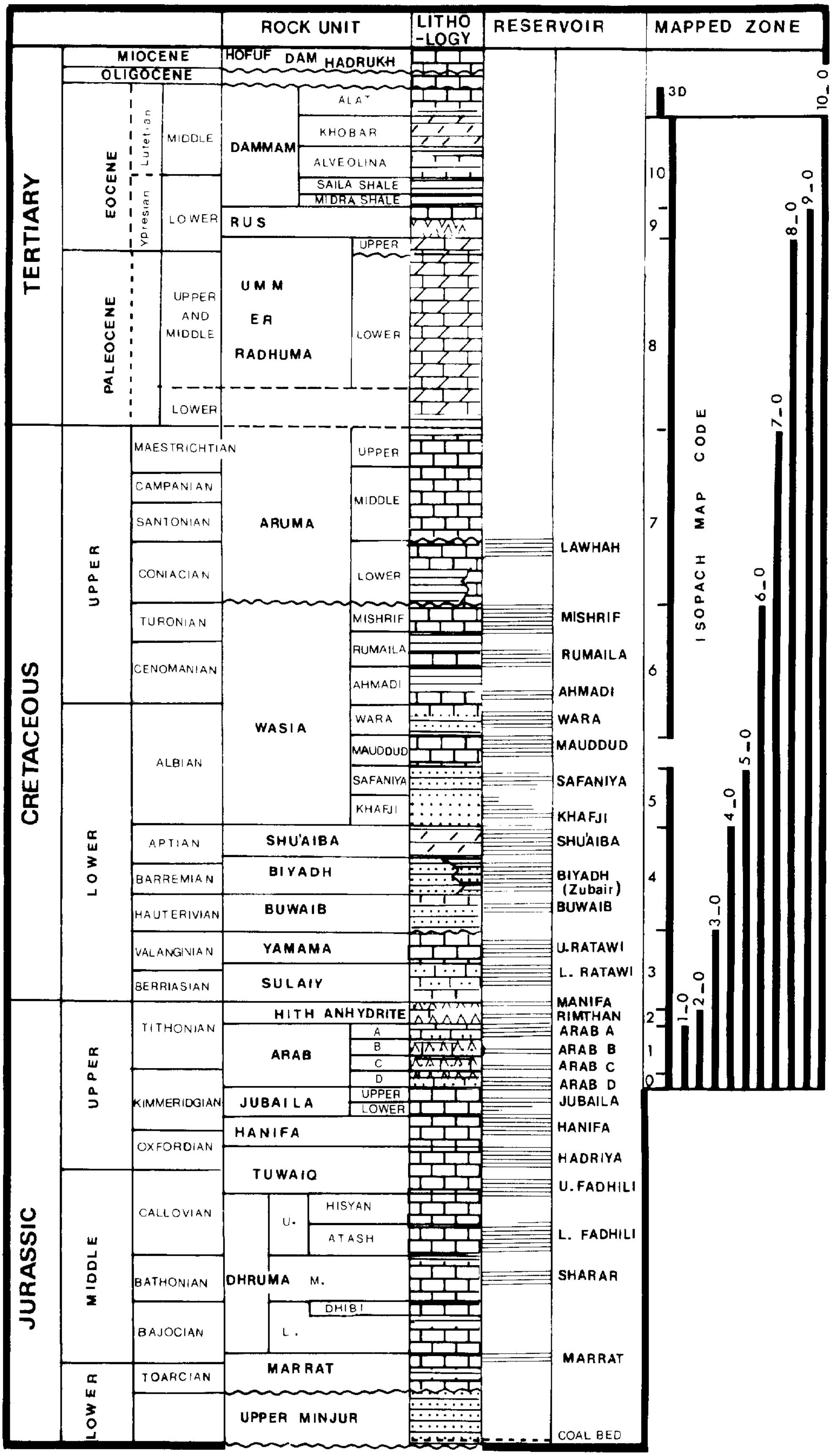

FIG. 2—Generalized post-Triassic Saudi Arabian stratigraphic section showing mapped and producing zones.

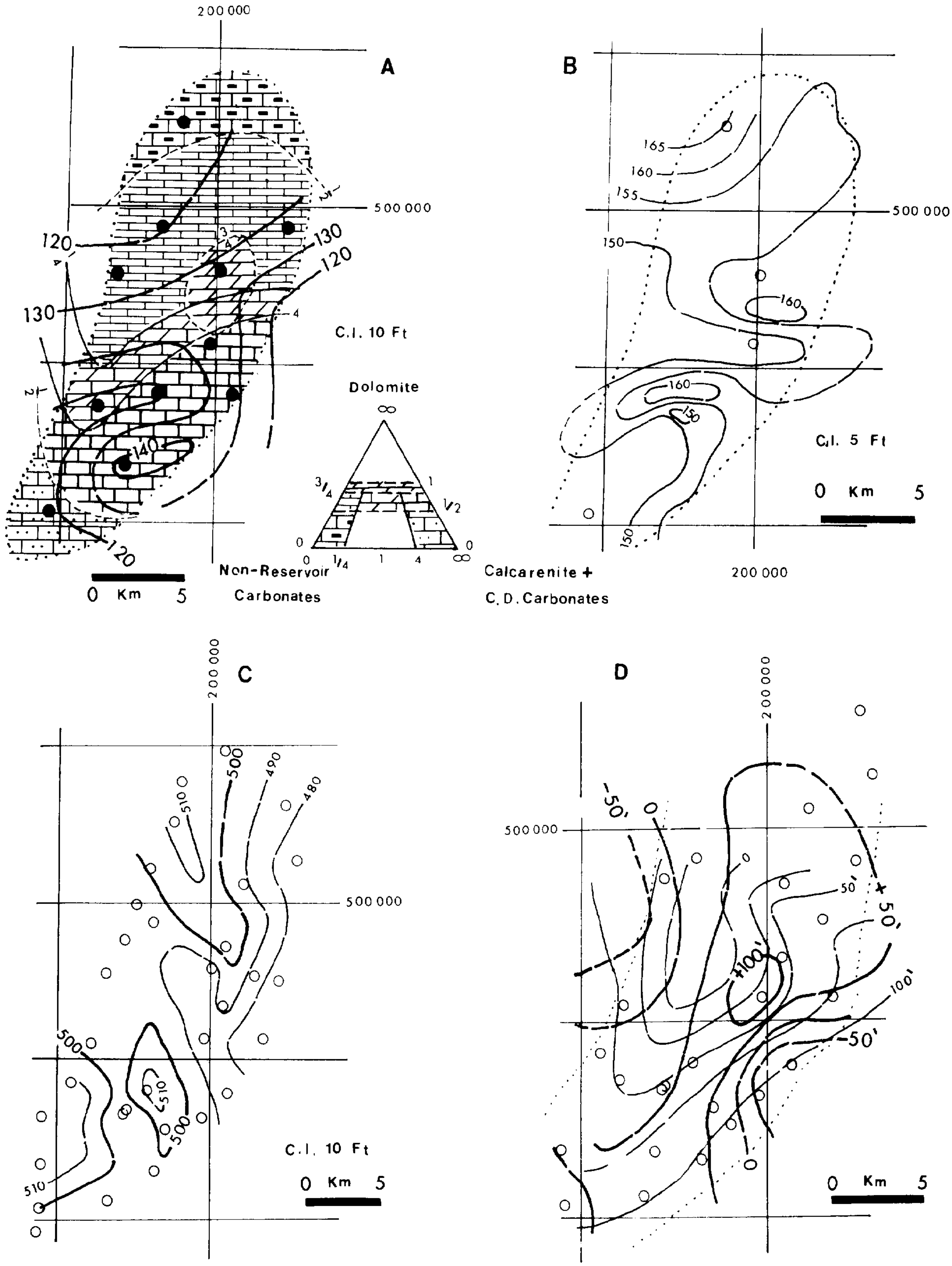

FIG. 3—A, isopach-lithofacies map of Arab D reservoir. B, isopach map of Arab C-D anhydrite. C, isopach map, top of Arab A to top of Arab D reservoirs. D, structural contour map of Dammam Formation with respect to sea level (thick contours) and isopach map of Alat Member of Dammam Formation (thin contours), outlined against present structural position of top of Hith Anhydrite (dotted line). All contours are in feet. Addition of formation thickness and structural contours was used to construct map D.

STRUCTURAL HISTORY OF HARMALIYAH OIL FIELD

Kimmeridgian-Tithonian

The paleostructural map at the base of the Arab D reservoir at the beginning of deposition of the Arab C reservoir (early Tithonian) shows no arching, but rather what seems to be a northeast-southwest-trending axis of deposition (Fig. 4, map 0). This could be attributed to preferential grainstone deposition over a paleohigh. However, this axis of deposition does not correlate with the distribution of the calcarenitic facies of Arab D reservoir (Fig. 3A). On the contrary, the axis correlates with finer grained facies, which indicate a possible axis of subsidence. Nor was there a structural closure at the beginning of deposition of the Hith Formation (Tithonian) as shown by the structural map of the base of Arab D reservoir during earliest late Tithonian (Fig. 4, map 1-0). The more marked variations in local thickness at this time indicate stable shelf conditions that exerted a strong influence on the environment of deposition, possibly aided by syndepositional fault movements. Compaction and diagenetic deformation of evaporites of later times may have amplified syndepositional variations and can be detected across fault lines on the basis of strong local thickening of downthrown blocks and relative thinning of upthrown blocks. This feature is present in every Upper Jurassic evaporite (see Fig. 3B for the underlying Arab D anhydrite, and Fig. 4, map 2, for the isopachs of the overlying Hith Formation).

At the end of the Tithonian and the beginning of Berriasian, two small local structural closures can be seen at the base of the Arab D member (Fig. 4, map 2-0). Later diagenetic deformation of anhydrite is shown by an increase in the vertical relief of the overlying anticline, as compared with the structure at the base of the Arab D member (Fig. 4, compare maps 2 and 2-1 with 2-0). However, the paleostructural map above the Arab D reservoir at this time shows no structural closure (Fig. 3C).

The two small closures on the base of the Arab D member are the only positive structural features that appear at the end of the Jurassic. They indicate a differential elevation of 3 to 10 ft (1 to 3 m) at an approximate depth of burial of 1,000 ft (305 m). Retention of hydrocarbons by impermeable rocks seems possible but improbable in this location at the end of the Jurassic because the more porous facies are updip (Fig. 3A). Furthermore, hydrocarbon generation and migration at this depth on the Arabian shelf seem unlikely (Tissot and Welte, 1978), as does vertical migration from deeper Upper Jurassic reservoirs, as the entrapped oils of the Arab D reservoirs in the Arabian shelf are of slightly older age (Young et al, 1977).

Berriasian-Early Albian

During the deposition of the Sulaiy-Yamama Formations (?Berriasian-?Valanginian) and more definitely at the beginning of deposition of the Buwaib Formation (?Hauterivian), a southwest-plunging, gentle structural nose appeared on the lower surface of the Arab D member as well as in overlying formations. The nose seems to be asymmetric, with a northwesterly dipping steeper flank (Fig. 5, map 3-0). There was no definable closure in the oil field, but the contour spacing suggests a closure northeast of the mapped area.

This anticlinal nose at the base of Arab D reservoir became more pronounced during the deposition of the Buwaib, Biyadh, and Shuaiba Formations (?Hauterivian-?Aptian), as shown by the paleostructural map at the beginning of deposition of the Khafji Member of the basal Albian (Fig. 5, map 4-0).

The structural nose at the base of the Arab Formation became even sharper during or at the end of deposition of the Safaniya Member (early Albian) and the beginning of deposition of Wara Member (late Albian; Fig. 5, map 5-0). The Mauddud Limestone Member is missing, as the Mauddud shoreline was east of the Harmaliyah area, the Wara Member being deposited directly over the Safaniya Member, with a probable hiatus between them.

Unlike the Upper Jurassic, the Lower Cretaceous sequence shows structural dissimilarities between deeper horizons, there being a general shift of the traces of the axes of folds in younger strata northwestward (Fig. 5, compare maps 4-0 with 4, and 5-0 with 5). This may be explained by the changes in thickness of these strata across the anticline, with a westward increase in overburden thickness (Fig. 5, compare map 4 with 4-0). Such a northwesterly shift in crestal axes was somewhat masked by an influx of clastic sediments from the northeast during the early Albian as shown by maps 5 and 5-0 of Figure 5. At this stage the Arab-Hith anhydrites started to show signs of anomalous diagenetic deformation, as displayed by Figure 5, maps 3 and 4-3 and clearly by map 5-3. This explains the great variations in thickness of the Hith Formation across faults (Fig. 4, map 2).

Late Albian-Maestrichtian

The upper Wasia is marked by a regional (erosional) unconformity. This Turonian-Coniacian Wasia-Aruma unconformity was well documented all over the Middle East by Dunnington (1967b).

At the beginning of deposition of the lower Aruma Group (Coniacian), a north-northeast-south-southwest-trending, closed, asymmetric anticline with about 200 ft (60 m) of closure appears at the base of the Arab D member (Fig. 6, map 6-0), at a position slightly east of the present anticline, whereas the Lower Cretaceous south-southwest-plunging anticlinal nose suddenly disappeared.

Evidence of early Late Cretaceous structural growth was reported by Steineke et al (1958) from oil fields in eastern Saudi Arabia, but they reported no prior structural development.

The late Albian-Turonian base of Arab D anticline became domelike by the end of the Maestrichtian, when a strong (?diapiric) structure developed at the base of the Arab D member during or shortly after the deposi-

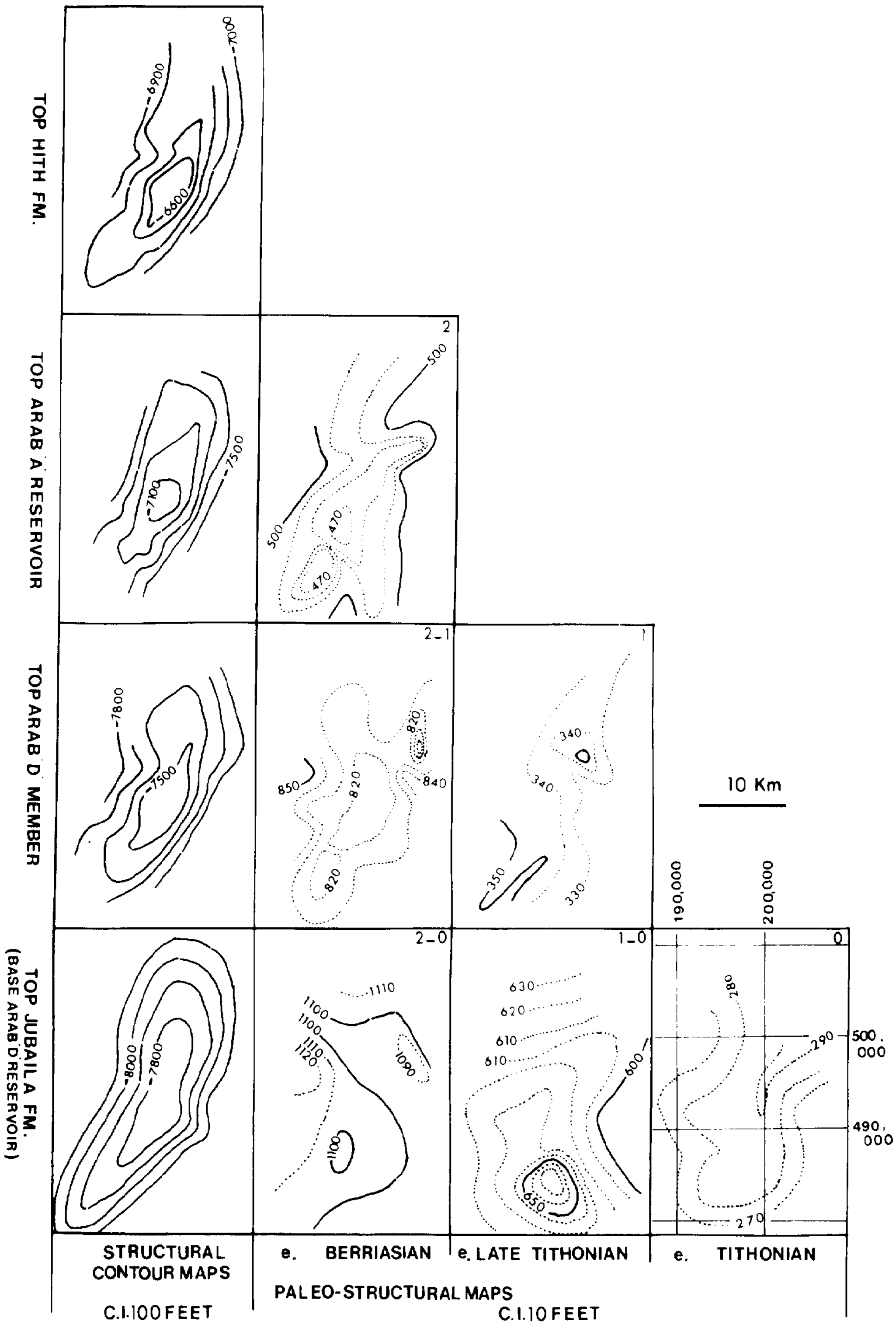

FIG. 4—Paleostructural maps of Harmaliyah oil field during earliest Tithonian to earliest Berriasian. 0, paleostructural map of base of Arab C member during earliest Tithonian (isopach map of Arab D member). 1-0, paleostructural map of base of Arab D member during earliest late Tithonian (isopach map of Arab Formation). 2-0, paleostructural map of base of Arab D member during earliest Berriasian (isopach map of Arab and Hith formations). 1, paleostructural map of top of Arab D member during earliest late Tithonian (isopach map of Arab A reservoir, Arab B and Arab C members). 2-1, paleostructural map of top of Arab D member during earliest Berriasian (isopach map, top of Hith to base of Arab C). 2, paleostructural map of top of Arab Formation during earliest Berriasian (isopach map of Hith).

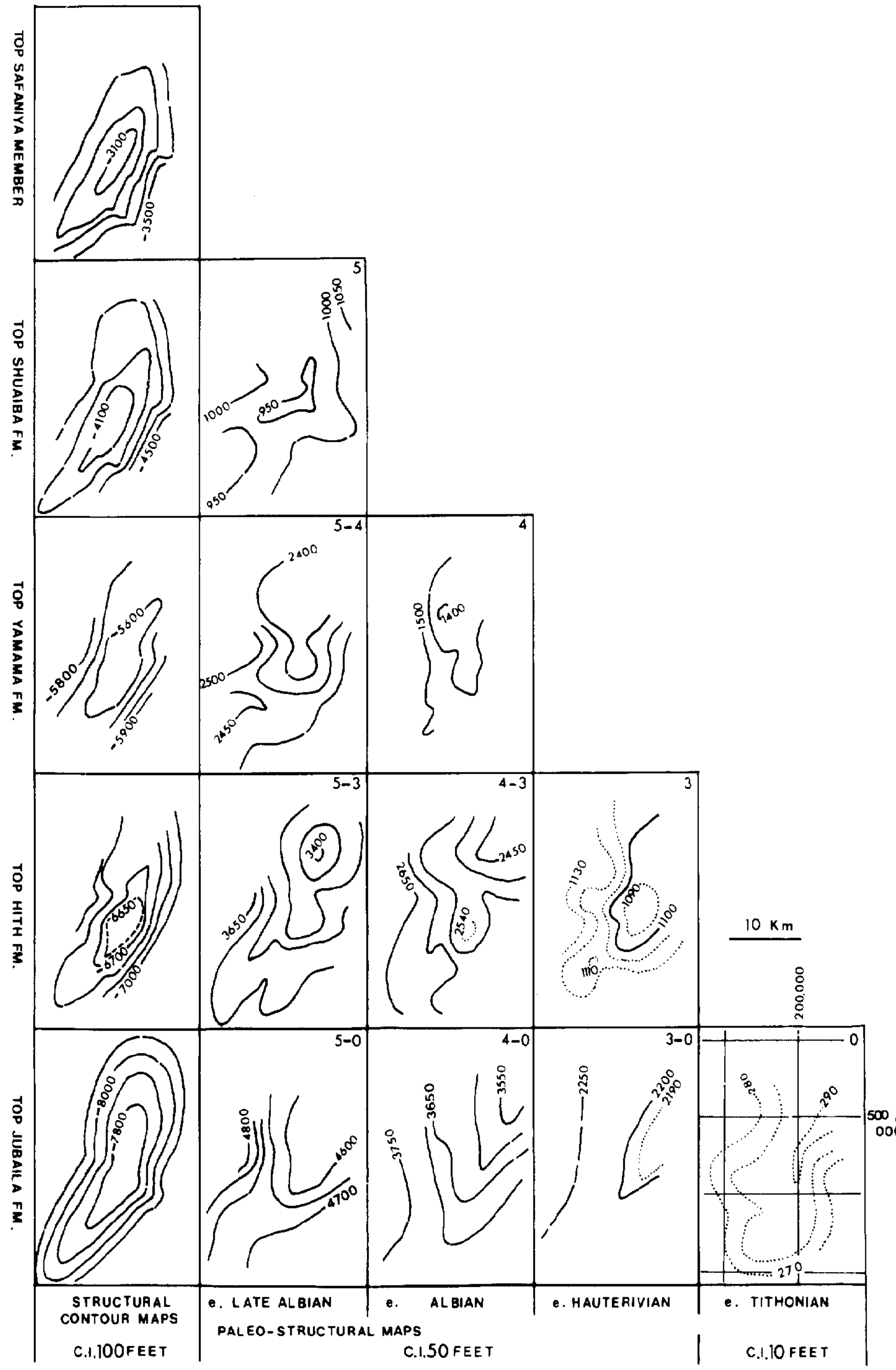

FIG. 5—Paleostructural maps of Harmaliyah oil field during earliest Tithonian to earliest late Albian. 0, Paleostructural map of base of Arab D member during earliest Tithonian (isopach map of Arab D member). 3-0, paleostructural map of base of Arab D member during earliest Hauterivian (isopach, top of Sulaiy to base of Arab Formations). 4-0, paleostructural map of base of Arab D member during earliest Albian (isopach map, top of Shuaiba to base of Arab Formation). 5-0, paleostructural map of base of Arab D member during earliest late Albian (isopach map, top of Safaniya Member to base of Arab Formation). 3, paleostructural map of top of Hith during earliest Hauterivian (isopach map of Yamama and Sulaiy Formations). 4-3, paleostructural map of top of Hith during earliest Albian (isopach map, top of Shuaiba to base of Sulaiy). 5-3, paleostructural map of top of Hith during earliest late Albian (isopach map, top of Safaniya to base of Sulaiy). 4, paleostructural map of top of Yamama during earliest Albian (isopach map, top of Shuaiba to base of Buwaib). 5-4, paleostructural map of top of Yamama during earliest late Albian (isopach map, top of Safaniya to base of Buwaib). 5, paleostructural map of top of Shuaiba Formation during earliest late Albian (isopach map of Safaniya and Khafji Members).

tion of the Aruma Group (Coniacian-Maestrichtian; Fig. 6, map 7-0). Halokinetic salt that provides such diapirism is present in the Triassic Jilh Formation and the Infracambrian Hormuz series.

The Turonian transformation led to the creation of a structure capable of holding migrating hydrocarbons in the position of the present Harmaliyah anticline. A correlation possibly exists between this phase of structural growth and the Late Cretaceous (Turonian–early Coniacian) plate collision along the Late Cretaceous Zagros suture on the east, which was accompanied by deepening of the geosynclinal axis east of the area under study (Ibrahim, 1979).

Tertiary

During the Paleocene, the deformation of the Arab D member led to the development of an anticline with about 300 ft (90 m) of closure and a slightly convex-westward axis. This deformation was reflected as crestal thinning in the Paleocene Umm er Radhuma Formation as shown by comparison of the paleostructural map of the top of the Aruma Group with that of the base of Arab D reservoir during the early Ypresian (Fig. 7, maps 8, 8-0). By the end of deposition of the overlying anhydritic Rus Formation (early Eocene), the anticlinal structure at the base of Arab D reservoir came closer to the present shape and trend of the base of Arab D structure than at any previous stage (Fig. 7, map 9-0).

The early Eocene structure of the Arab D member was less clearly transmitted to the Rus Formation (that was being deposited), than to the Umm er Radhuma Formation, and there was an apparent decrease in the rate of anticlinal growth at this time as shown by comparison of the paleostructural map of the Umm er Radhuma Formation with that of the top of the Aruma (Fig. 7, compare maps 9 and 8 with maps 9-0 and 8-0).

True tectonic quiescence probably obtained during late Ypresian to Lutetian times when deeper structural expressions failed to register any significant effect on the contemporaneously deposited sediments of the lower Dammam Formation (on Fig. 7, compare the paleostructural map on base of Arab D reservoir—map 10-0—with that of top of Rus Formation during earliest late Lutetian—map 10).

Structural growth seems to have been resumed after the deposition of the Khobar Member, as the isopach map of the Alat Member (upper Lutetian) of the Dammam Formation reveals thinning similar to that on the base of the Arab D anticlinal form. Furthermore, the present-day structural contour map above the pre-Neogene unconformity shows a semianticlinal form that could well be considered as Neogene-?Holocene anticlinal growth (Fig. 3D).

DISCUSSION

Structural Evolution

The history of structural development indicates no significant structural closures either at the base or at the top of the Arab D member in the area of the present Harmaliyah oil field during Jurassic time. The Berriasian-Valanginian gently plunging structural nose probably had a closure of about 50 ft (15 m) somewhere northeast of the present oil field; it increased during the Albian, exhibiting a similarity to the present-day structural motif of the Arab D member.

The structural nose disappeared rather suddenly and was replaced by a north-northeast–south-southwest-trending, closed anticline during ?late Albian–early Coniacian time. This can be attributed to: (1) the growth of an anticline near the site of the earlier nose; or (2) a southwest shift of the Early Cretaceous nose, bringing its central closure into the locus of the present-day oil field; or (3) a regional tilt to the northeast, thereby bringing the anticlinal crest of the nose below the mapped area; or (4) a gravity slide along a pre-Upper Jurassic bedding-plane toward the east-northeast (Cloos, 1968).

There is no evidence to prove or disprove the first two possible causes; the third requires a regional dip far above the present one, but many indications in the area are in favor of the fourth. These include (1) the existence of many pre-Upper Jurassic incompetent sediments such as evaporites and salts; (2) the similarity of the structural shape of the nose to the southwest plunge of the present anticline; (3) the appearance of Cenomanian-Turonian deep-water facies associated with deepening of sediments in front of the ancient Zagros on the northeast, possibly indicating an increase in the eastward regional slope of the ancient Arabian Shelf; (4) the above normal thickening of sediments in the southern part during Aruma deposition (an uncommon event in this region) probably caused by tectonism at the Wadi Nisah fault area (Fig. 6, map 7); and (5) the juxtaposition of the east-west-trending Wadi Nisah and the Dhruma fault systems. The latter is a north-south graben system west and northwest of Riyadh. The system is concave basinward, thus suggesting that the feature was caused by gravity sliding (Cloos, 1968) as shown by the tectonic map of Saudi Arabia (Brown, 1972).

To ascertain as closely as possible the time that the Harmaliyah anticline became a closed feature, the upper Wasia was subdivided into three lithostratigraphic units: the Wara, Rumaila-Ahmadi, and the Mishrif Formation. To each of these, the isopach triangle method (Fig. 6, map 6) was applied. The Turonian was identified as the time of structural closure; on Figure 8, maps 62-0 and 63-0 show the development of the earliest Turonian and earliest Coniacian paleostructural configurations of the base of Arab D reservoir and the transformation of the structure from a nose to a closed anticline.

The Harmaliyah anticline at the base of Arab D reservoir was modified into a (?diapiric) domelike structure during Coniacian-Maestrichtian time. After the Maestrichtian, the domal form gradually changed into the present-day anticline, after a series of growth pulses that occurred intermittently during the Paleocene, Ypresian, late Lutetian, and Neogene-?Holocene (Fig. 7, maps 8-0, 9-0; Fig. 3D).

From the preceding discussion it seems probable that

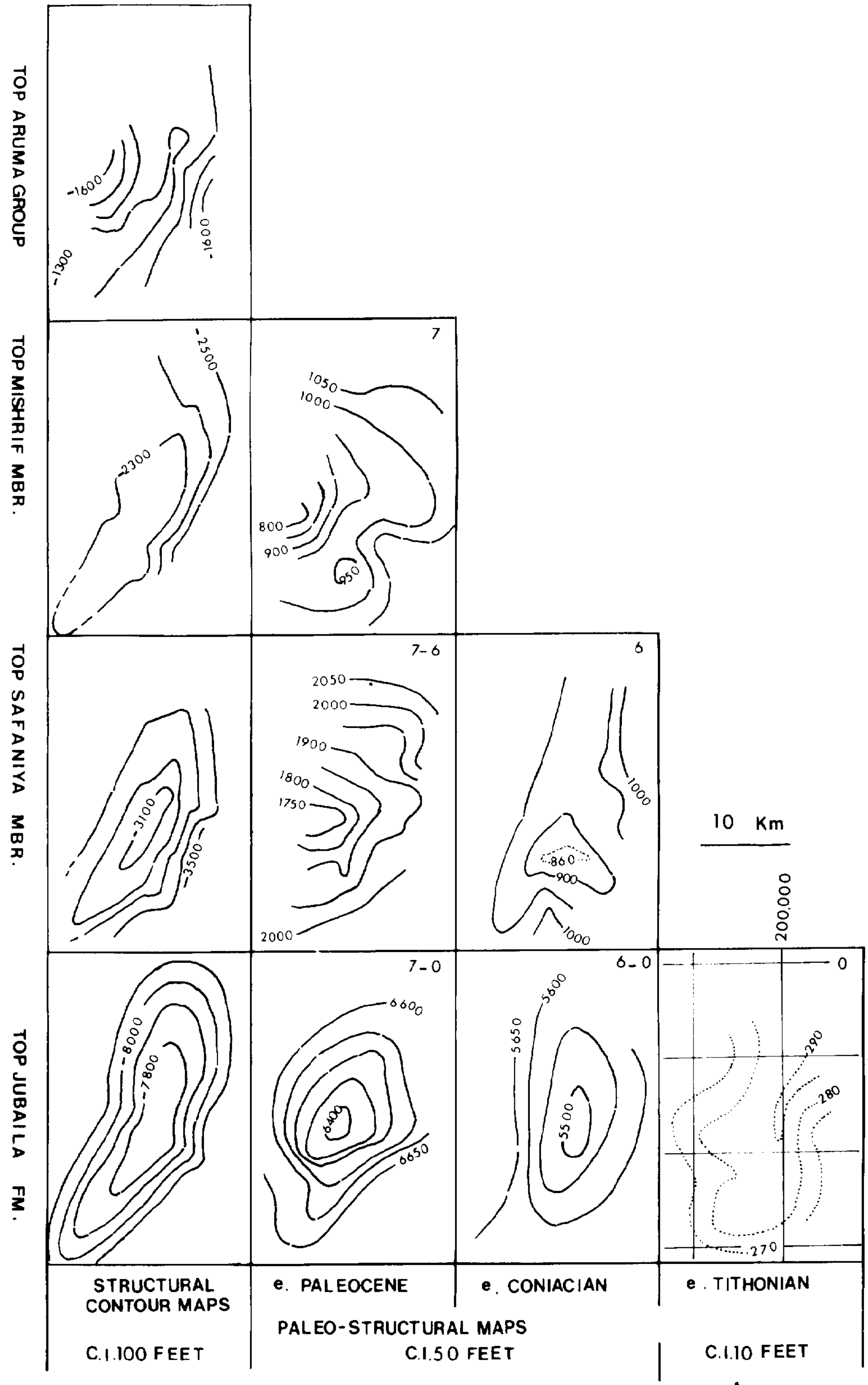

FIG. 6—Paleostructural maps of Harmaliyah oil field during earliest Tithonian to earliest Paleocene. 0, paleostructural map of base of Arab D member during earliest Tithonian (isopach map of Arab D member). 6-0, paleostructural map of base of Arab D member during earliest Coniacian (isopach map, top of Mishrif to base of Arab Formation). 7-0, paleostructural map of base of Arab D member during earliest Paleocene (isopach map, top of Aruma to base of Arab Formation). 6, paleostructural map of top of Safaniya Member during earliest Coniacian (isopach map, top of Mishrif to base of Wara Member). 7-6, paleostructural map of top of Safaniya Member during earliest Paleocene (isopach map, top of Aruma to base of Wara Member). 7, paleostructural map of top of Mishrif Member during earliest Paleocene (isopach map of Aruma Group).

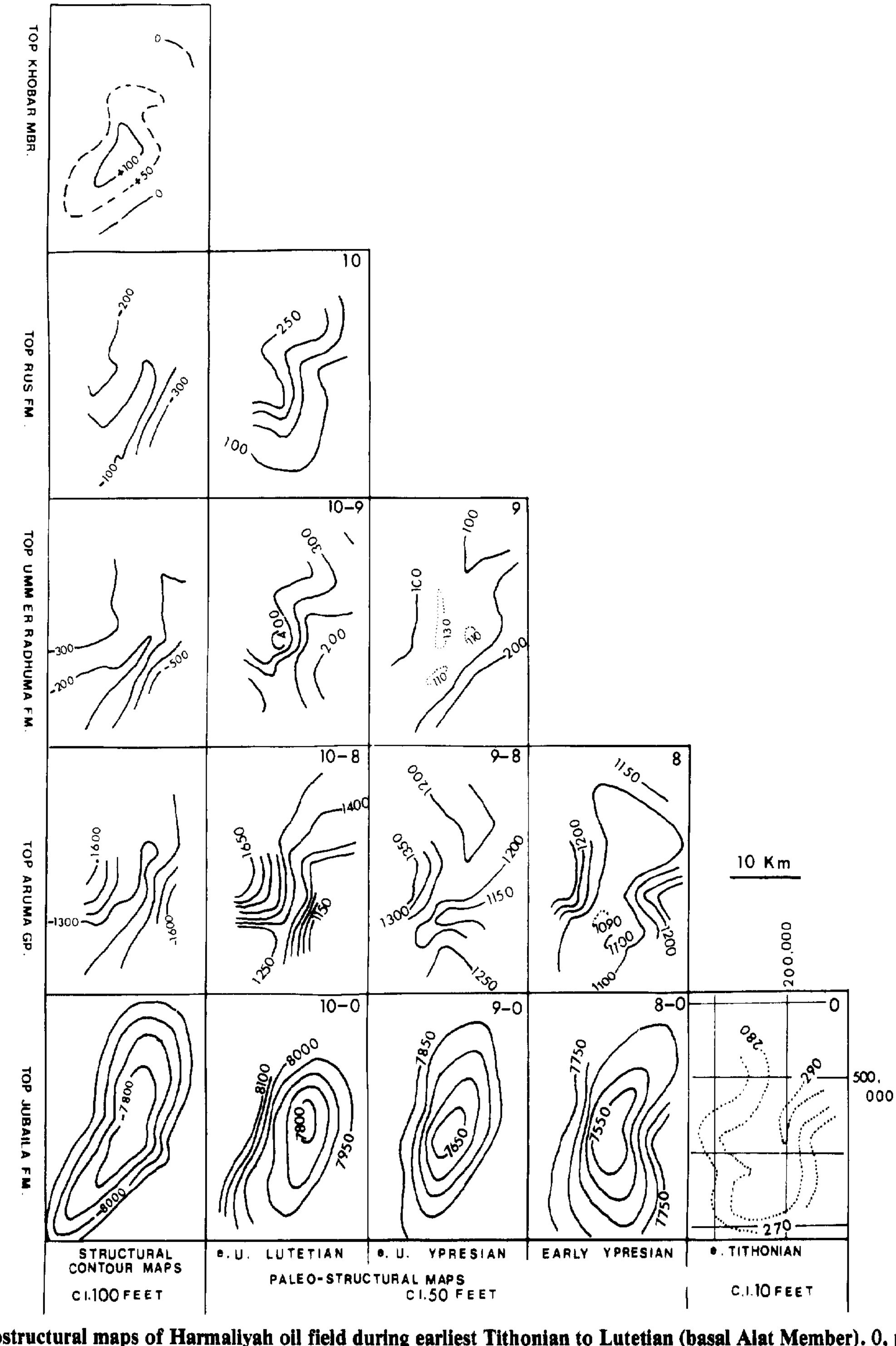

FIG. 7—Paleostructural maps of Harmaliyah oil field during earliest Tithonian to Lutetian (basal Alat Member). 0, paleostructural map of base of Arab D member during earliest Tithonian (isopach map of Arab D member). 8-0, paleostructural map of base of Arab D member during early Ypresian (i.e., basal Rus Formation; isopach map, top Umm er Radhuma to base of Arab Formation). 9-0, paleostructural map of base of Arab D member during early Eocene (isopach map, top of Rus to base of Arab Formation). 10-0, paleostructural map of base of Arab D member during middle Eocene (isopach map, top of Khobar Member to base of Arab Formation). 8, paleostructural map of top of Aruma Group during middle early Eocene (isopach map of Umm er Radhuma Formation). 9-8, paleostructural map of top of Aruma Group during late early Eocene (isopach map of Rus and Umm er Radhuma Formation). 10-8, paleostructural map of top of Aruma Group during middle Eocene (isopach map, top of Khobar to base of Umm er Radhuma). 9, paleostructural map of top of Umm er Radhuma Formation during early Eocene (isopach map of Rus Formation). 10-9, paleostructural map of top of Umm er Radhuma Formation during middle Eocene (isopach map, top of Khobar to base of Rus Formation). 10, paleostructural map of top of Rus Formation during middle Eocene (isopach map of pre-Alat Dammam Formation).

a structural closure may have existed outside the Harmaliyah oil field during the Early Cretaceous, but that definite closure in the present location of the oil field dates from the late Turonian.

The Harmaliyah is not the only oil field in the region with such history of structural growth; Hassan et al (1979) stated:

> Isopach maps for the Zakum Field show that a feature of the growth of the structure—of the Thamama Zone IV, Basal Cretaceous—was that the crest was situated to the NNE of the present crestal area during the Cretaceous. It was during the Paleocene that the crest started to migrate to the south and became established in its present position during the Lower Eocene. Structural growth continued to the Recent as indicated by the occurrence of a topographic high on the sea bed to the SE of the Zakum Cretaceous culmination.

Pelissier et al (1980) studied the paleo-oil/water contact of the Mishrif fields (Sirri "C" and "D") in offshore Iran and showed that in the Mishrif reservoir the contact was even steeper than the present north-northwest-dipping oil/water contact. Hence, if a horizontal paleo-oil/water contact is assumed, the ancient structural crest should be located on the northeast. Pelissier et al (1980) explained the present north-northwest inclination of the Mishrif oil/water contact as a response to a northwestward flow of formation water. Such inclination of the oil/water contact could be explained as an off-structure "frozen in" or diagenetic oil trap (Wilson, 1977; Al-Rawi, 1981).

The documentation of both Hassan et al (1979) and Pelissier (1980) can be improved by the use of isopach triangles in the study of the structural growth histories of the Mishrif and the Zakum fields.

Time of Hydrocarbon Entrapment

The minimum depth of burial required for sediments to be within the principal zone of oil formation (PZOF), that is, for hydrocarbon generation to occur, is roughly 5,000 ft (1,500 m). This depth varies according to the geothermal gradient and type of source rocks according to Tissot and Welte (1978, p. 164-169), who stated further (p. 287): "Primary migration occurring during the main phase of hydrocarbon generation, generally at depths between 1500 and 3000 m to 3500 m, is documented by the majority of oil accumulations of Cenozoic, Mesozoic and Paleozoic age around the world and should be accepted as a fact."

Assuming marine source rocks, provided by the Jubaila and/or the Hanifa Formations (Steineke et al, 1958; Powers, 1961; Kamen-Kaye, 1970; Young et al, 1977; Murris, 1980), and a geothermal gradient of 3 to 4.5°C/100 m (Murris, 1981, personal commun.), the upper limits of the PZOF in this region would be in the shallower part of the depth ranges stated previously. If the oil was the result of vertical and/or lateral migration from the surrounding deeper synclines, then, judging by the paleostructural depths, the Arab D reservoir rock and its source rocks in the area were not deep enough at the close of the Jurassic for such migration to occur; nor was it possibly deep enough during the Albian and Cenomanian, where there was no closure in the locus of the present oil field. The source rocks were possibly well within the oil generation and maturation level of the PZOF and trapping conditions were satisfied during the late Turonian-Maestrichtian. However, a trap probably existed—or possibly still exists as a "frozen in" or diagenetic trap (Wilson, 1977)—in the paleostructural closure of the crestal part of the pre-Turonian nose, somewhere northeast of the present Harmaliyah anticline. Such hydrocarbons could have remigrated (at least in part) to the post-Turonian Harmaliyah anticline after its formation, but it is unlikely that the present-day structural closure of the Harmaliyah had trapped any significant hydrocarbon before the late Turonian structural transformation. The time-temperature index of maturation (TTi; Waples, 1980) was calculated and the result indicates that the base of the Arab Formation reached the upper PZOF limits during earliest Eocene, and during the Paleocene in the adjacent synclines. However, if vertical primary migration is contemplated, then a Maestrichtian (or earlier) time may be considered for deeper Jurassic source rocks.

The Late Cretaceous plate collisions produced rapid compaction and relative subsidence of the deeper eastern part of the basin. These factors could have created the suitable increases in depth and hydrodynamic head that probably accelerated the process of petroleum generation, migration, and maturation (Dickinson, 1974; Ibrahim, 1979).

The possibility of vertical hydrocarbon migration through the many fault planes that dissect the Harmaliyah anticline is not, however, excluded but all over the area such migration seems to be rather limited (Young et al, 1977). It is concluded that the earliest significant oil entrapment could not have occurred before the late Turonian, when a trap came into existence. The Turonian-early Coniacian tectonism seems to have caused the structural growth or the modification of previous structures over a large part of the Arabian Shelf (Steineke et al, 1958; Dunnington, 1967b; Hosoi and Murakami, 1971; Willoughby and Davies, 1979).

Illing et al (1967) stated that many of the Arabian oolitic reservoirs retained their primary porosities. Such calcarenitic reservoirs owe their high porosities to early migration of hydrocarbons (i.e., shortly after burial and early diagenesis); the chemically inert hydrocarbons would inhibit solution and cementation (Dunnington, 1967; Fuchtbauer, 1967; D. J. Shearman, Imperial College, personal commun., 1972).

To explain the phenomenal preservation of primary porosity of the Arab D reservoirs, Steineke et al (1958) suggested, "If oil was generated soon after the time of deposition of Jubaila and Arab rocks it seems possible that the great calcarenite lens or lenses of 'D member' of the Arab may have acted as a stratigraphic trap or traps to hold the oil in the general vicinity until the appearance of the structural traps as they are now." Kamen-Kay (1970) stated, "If the compaction of shale or of other muddy rocks is assumed to furnish energy for the migration of oil into the reservoir, the movement should take place almost immediately after—if not partly during—deposition of the reservoir. Such early move-

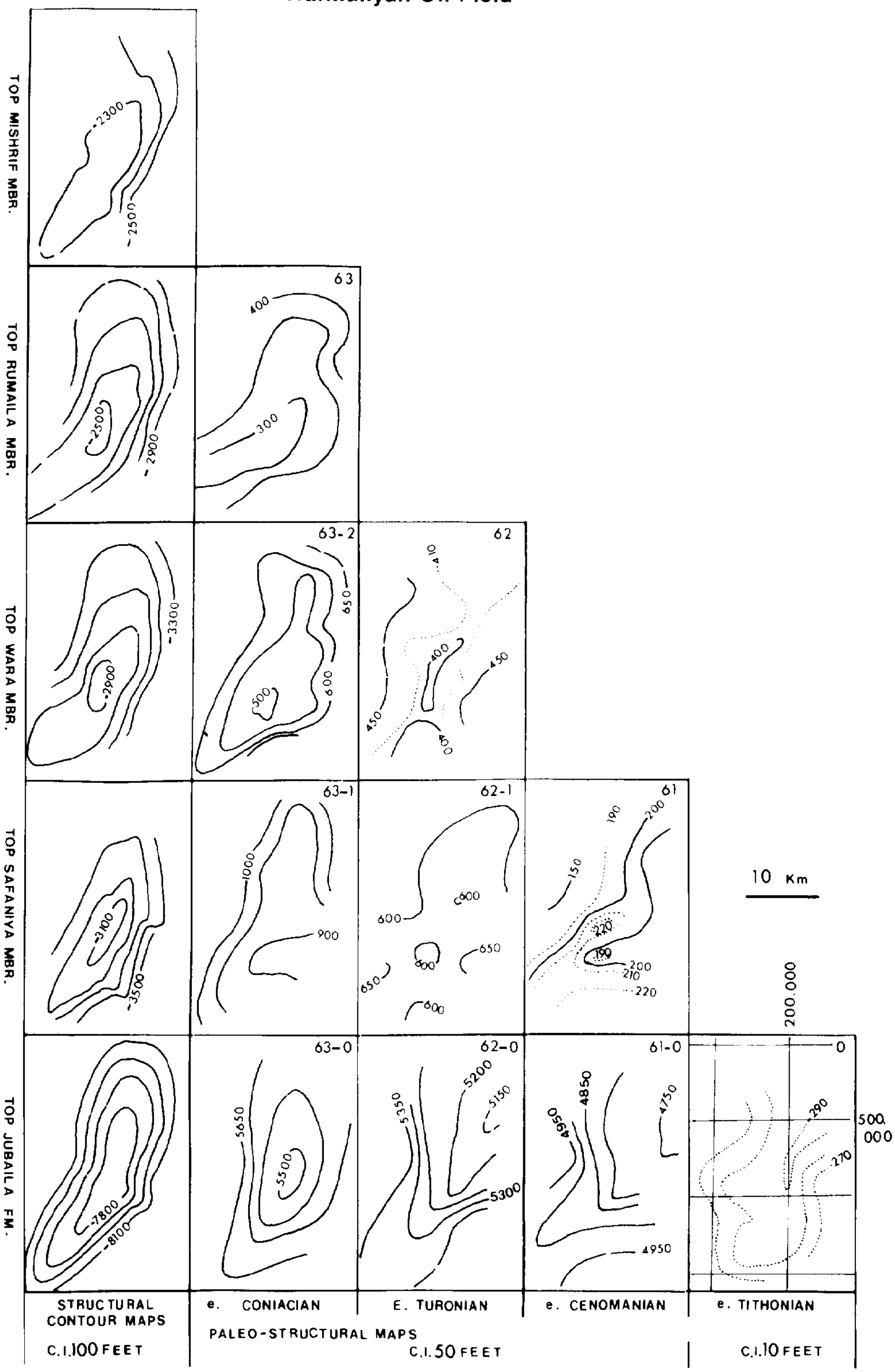

FIG. 8—Paleostructural maps of Harmaliyah oil field during earliest Tithonian to earliest Coniacian. 0, paleostructural map of base of Arab D member during earliest Tithonian (isopach map of Arab D member). 61-0, paleostructural map of base of Arab D member during earliest Cenomanian (isopach map, top of Wara to base of Arab Formation). 62-0, paleostructural map of base of Arab D member during early Turonian (isopach map of top of Rumaila to base of Arab Formation). 63-0, paleostructural map of base of Arab D member during earliest Coniacian (isopach map of top of Mishrif to base of Arab Formation). 61, paleostructural map of top of Safaniya Member during earliest Cenomanian (isopach map of Wara Member). 62-1, paleostructural map of top of Safaniya member during early Turonian (isopach map of top of Rumaila to base of Wara Member). 63-1, paleostructural map of top of Safaniya member during earliest Coniacian (isopach map of top of Mishrif to base of Wara Member). 62, paleostructural map of top of Wara Member during Turonian (isopach map of Rumaila and Ahmadi Members). 63-2, paleostructural map of top of Wara Member during earliest Coniacian (isopach map of top of Mishrif to base of Ahmadi Member). 63, paleostructural map of top of Rumaila Member during earliest Coniacian (isopach map of Mishrif Member).

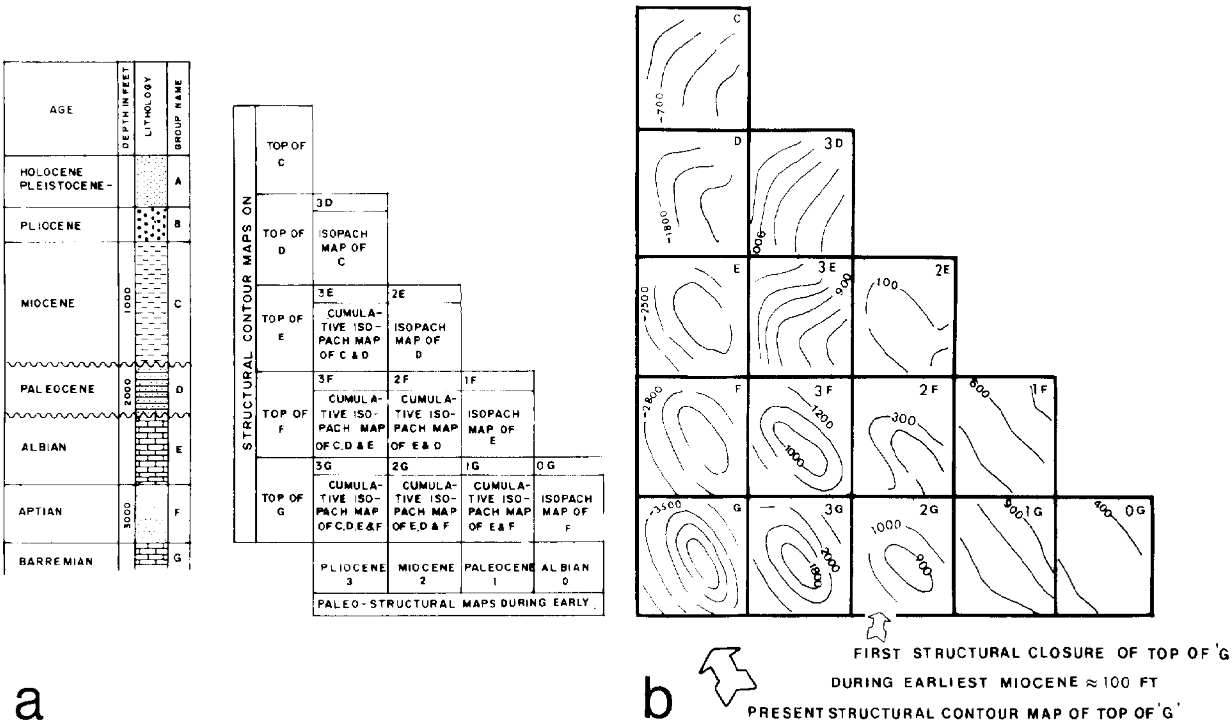

FIG. 9—a, Construction of isopach triangle system (after Bakerov et al, 1975, with modifications). b, Diagrammatic isopach triangle showing first appearance of structural closure on top of zone G during earliest Miocene.

Maps 0G, 1G, 2G, and 3G are paleostructural maps on top of Zone G; 1F, 2F, and 3F are paleostructural maps on top of zone F; 2E and 3E are paleostructural maps on top of Zone E; 3D is a paleostructural map on top of zone D.

Map 0G is a paleostructural map on top of zone G during earliest Albian; 1F and 1G are paleostructural maps on top of zones G and F during earliest Miocene; 2E, 2F, and 2G are paleostructural maps on top of zones E, F, and G during earliest Miocene; and 3D, 3E, 3F, and 3G are paleostructural maps on top of zones D, E, F, and G during earliest Pliocene.

ment could well have taken place on the platform because structures grew almost constantly after Jurassic time." Kamen-Kaye's statement seems to contradict Powers (1961) who stated, "The distribution of sand and mud without apparent regard for modern structures suggests that structural growth along these lines of folding had not yet taken place or that their relief during this time was subdued."

The present study supports Powers' (1961) finding. Furthermore, the Arab D member seems to have its more porous reservoir-prone facies located up the ancient regional slope. Hence, Steineke's suggested stratigraphic trapping of oil in the porous calcarenitic lenses of Arab D seems rather unlikely. Alternatively, Purser's (1978) suggestion that preburial diagenesis of Jurassic calcarenites preserves porosity and prevents later compaction with or without the presence of hydrocarbon presents a logical explanation of this phenomenon.

CONCLUSION

The data presented in the foregoing suggest that the earliest probable trapping of hydrocarbons occurred in late Turonian time. Thus it seems that the Arab D calcarenites retained most of their primary porosity during Kimmeridgian-Cenomanian time, before any possible hydrocarbon entrapment. Therefore, other mechanism(s) must have contributed to this phenomenal preservation of porosity; hence, Purser's (1978) thesis seems to supply a satisfactory explanation at present.

APPENDIX

The cumulative isopach triangle system is used to study local structural developments. It has an advantage over normal cumulative map analysis, because it enables the examiner to compare the structural developments of several stratigraphic levels at one or several geologic times (Bakerov et al, 1975). As shown in Figure 9, the study involves the construction of a series of present-day structural maps (left side of triangle), a series of simple paleostructural maps (cumulative isopach maps on the base and inside of triangle).

No paleodip or compaction corrections are applied, and the method is based on the assumption that the upper surface of deposition of each group is approximately horizontal. Hence on Figure 9a and b, an isopach map of unit F represents the paleostructural configuration of unit G during the time of deposition of the basal units of E, as shown by map 0G. Also, an isopach map of units F + E + D is the paleostructural map of the top of unit G at the beginning of deposition of unit C during earliest Miocene, as shown by map 2G of Figures 9a and b.

In the Arabic translation of Bakerov's text a cumulative isopaching was suggested for the maps at the base and the interior of the triangle. The procedure is

1. Construct isopach map 0G of the unit that overlies the zone of interest G (i.e., unit F, Fig. 9B). Then construct isopach maps 1F, 2E, and 3D for each of the overlying units up to the shallowest mappable unit (i.e., units E, D, and C). These maps will be situated on the

hypotenuse of the triangle system in order of their stratigraphic position. Each of these maps reflects the paleostructural configuration of their basal contacts.

2. Construct structural maps for the plane of interest (top of unit G, the base of each of the isopached overlying units, and the top of the uppermost mapped unit, C). These maps are situated on the left side of the triangle system in stratigraphic order.

3. By adding isopach values of map 1F to those of maps 0G the result will be the isopach values of maps 1G, and similarly 2E + 1F = 2F, and 3D + 2E = 3E. The resulting maps will be located in the first row of maps inside the triangle system and parallel with the hypotenuse row.

4. The second row of maps (inside the triangle and parallel with the hypotenuse) are constructed by adding the isopach values of maps 3E and 1F = 3F, and likewise 2F + 0G = 2F.

5. Similarly map 3G is constructed by contouring the cumulative isopach values of maps 3F and 0G.

In Figure 9A, the vertical rows are paleostructural maps at a fixed geologic time and each map corresponds to the stratigraphic level of the present structural contour map in the left column.

Horizontal rows of maps are a series of paleostructural maps that end with the map of the existing structures and enables us to follow the structural evolution of a fixed stratigraphic level throughout a discrete portion of geologic time. In this study, as suggested by Bakerov et al, we broke down the triangle (which otherwise would have been impracticably large) into four smaller triangles, in order to focus the work on the structural evolution of the zone of interest, the base of the Arab D member. In the Arabic translation of Bakerov's text, a cumulative isopach map was suggested for the maps at the base and the inside of the triangle. However, we contoured the true thickness values of each unit or group of rock units, and the term "cumulative isopach map" is used here to indicate mathematical summation of true thicknesses (e.g., thicknesses of 0G + thickness of 1F = thicknesses of 1G). In the maps of Figures 4 to 8 in this paper, the notation 1-0 means a summation of the true thickness values of maps (1) and (0), therefore 2-0 = 2 + 1 + 0, in Figure 4, and 10-0 = 10 + 9 + 8 + 7 + 6 + 5 + 4 + 3 + 2 + 1 + 0, in Figure 7.

The cumulative isopach triangle is an ideal method for determining the *time of trap closure*. Hence, coupled with the knowledge of the times of petroleum generation and migration (Waples, 1980) it can present a potential exploration tool.

Structural readjustment and modification can be fairly delineated by this method, thus locating any possible off-structure "frozen-in" and diagenetic traps hitherto usually unexplored (Wilson, 1977).

REFERENCES CITED

Al-Rawi, M. M., 1981, Geological interpretation of oil entrapment in the Zubair Formation, Raudhatain field: SPE paper 9591, p. 149-158.

Bakerov, A., et al, 1975, Theoretical principles of petroleum and gas exploration: Moscow, USSR, Meir Pub. Co., 368 p. (Arabic translation).

Brown, G. F., 1972, Tectonic map of the Arabian Peninsula, scale 1/4,000,000: Saudi Arabian Dir. Gen. Miner. Resour. Map AP-2.

Cloos, E., 1968, Experimental analysis of Gulf Coast fracture pattern: AAPG Bull., v. 52, p. 420-444.

Dickinson, W. R., 1974, Subduction and oil migration: Geology, v. 2, p. 421-424.

Dunnington, H. V., 1967a, Aspects of diagenesis and shape change in stylolitic limestone reservoirs: 7th World Petroleum Cong., Mexico, Proc., v. 2, p. 339-352.

——— 1967b, Stratigraphical distribution of oilfields in Iraq-Iran-Arabia basin: Inst. Petroleum Jour., v. 53, p. 129-161.

Fuchtbauer, H., 1967, Influence of different types of diagenesis on sandstone porosity: 7th World Petroleum Cong., Mexico, Proc., v. 2, p. 353-369.

Halbouty, M. T., 1980, Geologic significance of Landsat data for 15 giant oil fields: AAPG Bull., v. 64, p. 8-36.

Hassan, T. H., J. Wada, and J. Couroneau, 1979, The geology and development of the Thamuma zone IV of the Zakum field, Abu Dhabi: SPE Middle East Technical Conf., Bahrain, Proc., p. 231-246.

Hosoi, H., and R. Murakami, 1971, Radiated rupture-faults on the Arabian type oilfield (in Japanese): Japan, Assoc. Petroleum Technologists Jour., v. 36, no. 3, p. 10-17.

Ibrahim, M. W., 1979, Shifting depositional axes of Iraq; an outline of geosynclinal history: Jour. Petroleum Geology, v. 2, p. 181-197.

Illing, L. V., G. V. Wood, and J. Fuller, 1967, Reservoir rocks and stratigraphic traps in non-reef carbonate: 7th World Petroleum Cong., Mexico, Proc., v. 2, p. 487-499.

Kamen-Kaye, M., 1970, Geology and productivity of Persian Gulf synclinorium: AAPG Bull., v. 54, p. 2371-2394.

Murris, R. J., 1980, Middle East stratigraphic evolution and oil habitat: AAPG Bull., v. 64, p. 597-618.

Pelissier, J., et al, 1980, Study of hydrodynamic activity in the Mishrif fields offshore Iran: Jour. Petroleum Technology, v. 32, p. 1043-1052.

Powers, R. W., 1961, Arabian Upper Jurassic carbonate reservoir rocks, *in* Classification of carbonate rocks: AAPG Mem. 1, p. 122-192.

Purser, B. H., 1978, Early diagenesis and the preservation of porosity in Jurassic limestones: Jour. Petroleum Geology, v. 1, p. 83-94.

Steineke, M., R. A. Bramkamp, and N. J. Sander, 1958, Stratigraphic relations of Arabian Jurassic oil, *in* L. Weeks, ed., Habitat of oil: AAPG, p. 1294-1329.

Tissot, B. P., and D. H. Welte, 1978, Petroleum formation and occurrence (a new approach to oil and gas exploration): New York, Springer-Verlag, 538 p.

Waples, D. W., 1980, Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration: AAPG Bull., v. 64, p. 916-926.

Willoughby, W., and J. Davies, 1979, Dubai's Fateh field—Mishrif reservoir—history of sea water injection project: SPE Middle East Tech. Conf., Bahrain, Proc., p. 247-256.

Wilson, H. H., 1977, "Frozen in" hydrocarbon accumulations or diagenetic traps—exploration targets: AAPG Bull., v. 61, p. 483-491.

Young, A., et al, 1977, Calculation of ages of hydrocarbons in oils—physical chemistry applied to petroleum geochemistry: AAPG Bull., v. 61, p. 573-600.