PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Subsidence History of the Middle East Zagros Basin, Permian to Recent [and Discussion]

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Subsidence history of the Middle East Zagros Basin, Permian to Recent

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[Overlay]

The Zagros Basin is broadly defined as the palaeodepositional wedge of sediments along the present belt of the Zagros Mountains. A series of ten regional isopach maps trace the development of a portion of this basin from Permian to Recent. From the Permian to the middle Cretaceous the area occupied a position along the stable northeastern Atlantic-type shelf margin of the Afro-Arabian continent, bounded by a rift zone that evolved into a southern Tethys ocean. Late Cretaceous to Recent subsidence patterns are influenced by plate margin tectonics, obduction, and eventual continental collision along the Zagros Suture as this ocean closed. The late Alpine Zagros folding and faulting took place from the Miocene onwards.

1. Introduction

In this paper regional time–isopach and facies maps are used to demonstrate the post-Carboniferous evolution of the Zagros Basin. These maps represent a compilation of surface and subsurface studies made in Iran in 1977, supplemented by published regional information from adjacent areas.

Figure 1 shows the present regional tectonic and geographical setting of the area under consideration. The NE limit of the area is shown on this map as the Zagros Suture, which is interpreted as a former plate boundary separating the Zagros fold belt from the complex Hamadan–Sirjan zone of Central Iran. The NW–SE-striking Zagros mountain chain exposes the entire sequence down to the Palaeozoic. The narrow interior fold belt plunges SW along the 'mountain-front flexure' into a folded 'foothills' belt, which is the setting for the major oilfields of Iran and Iraq in the Dezful and Kirkuk embayments, respectively. Further SW the stable Arabian platform rises gently to the Arabian Shield and the Huqf–Dhofar of south Oman.

The chrono-stratigraphic intervals covered by the ten isopach–facies maps are shown on the table of formations (figure 2), which includes most of the more commonly used formation names of the region.

All thicknesses shown on the maps are preserved thicknesses and no attempt has been made to estimate how much might have been removed by erosion at unconformities, nor to allow for differential compaction. It has also not been possible to make a reliable palinspastic restoration of the localities to their original relative geographic positions in the Zagros orogenic belt. Because of repeated transgressions and regressions, the facies boundaries drawn on the maps should be regarded as average positions for the period.

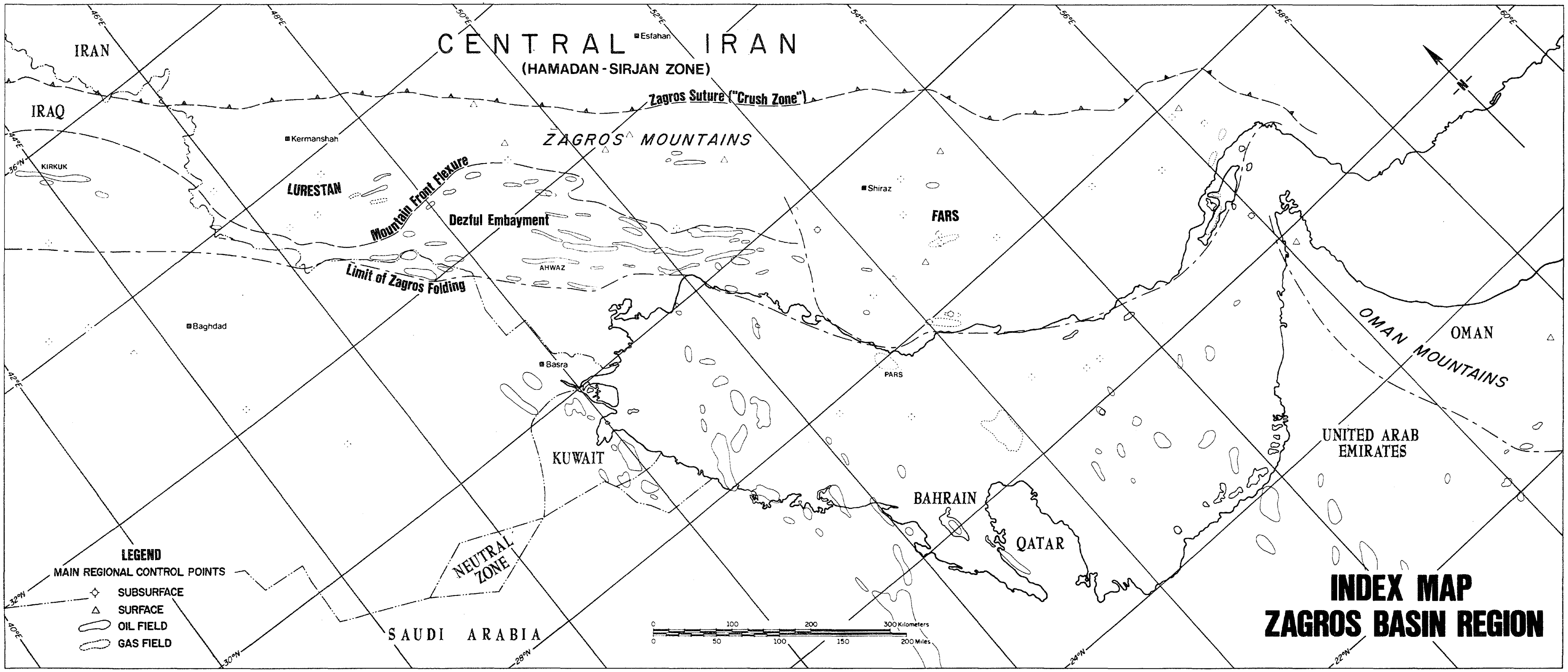


FIGURE 1. Index map. Regional geographic and tectonic setting of the Zagros Basin.

The isopach and facies maps are based on the work of a large number of geologists who have worked in Iran and adjacent countries, and on the results of many years of oil company drilling. Publications by Dunnington (1958, 1967), James & Wynd (1965), Glennie *et al.* (1973), Clarke (1975), Hassan *et al.* (1975), Szabo & Kheradpir (1978), Setudehnia (1978) and others have been particularly useful in extending the regional patterns into adjacent areas. Some of the maps were originally prepared by G. Orbell, who participated extensively in the study. Our dependence on him and other workers, and on the various exploration organizations, is gratefully acknowledged. R. Green drafted the illustrations.

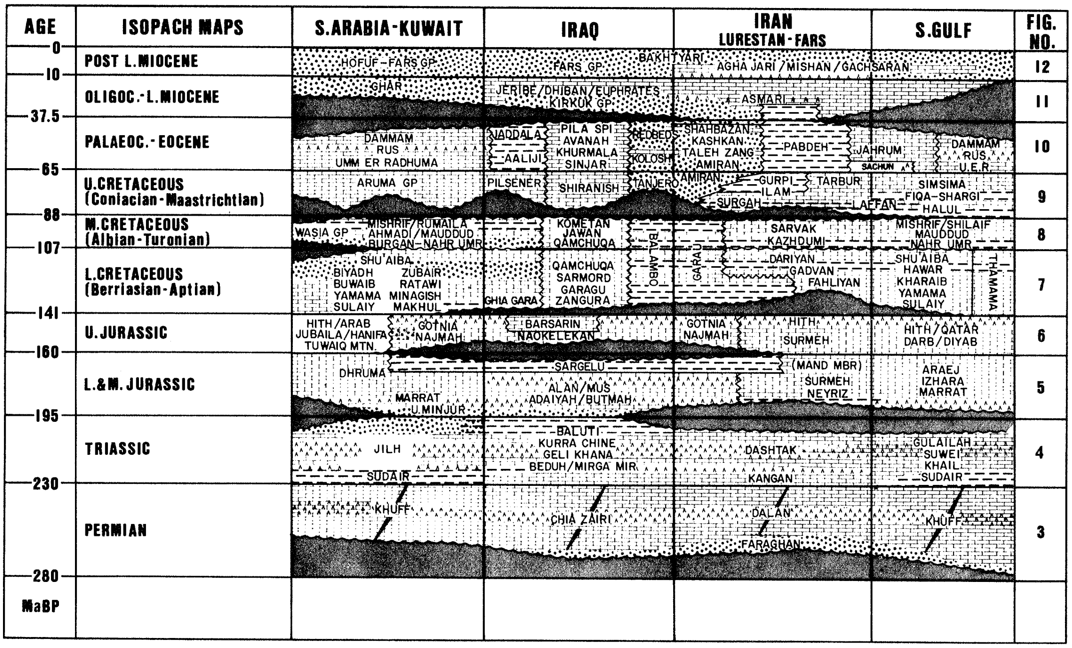


FIGURE 2. Simplified time–stratigraphic table of formation names, Zagros Basin and adjacent areas.

2. PRE-PERMIAN PATTERNS

Regional stratigraphic comparisons and palaeogeographic patterns suggest that during late Precambrian (Infra-Cambrian) and Palaeozoic time the entire area on both sides of the later Zagros Suture was an extension of the Afro-Arabian continental shelf and was the site of widespread platform, largely marine, sedimentation flanking a continental block (Gondwanaland) to the SW. Distinct intrashelf salt basins lay, during the Infra-Cambrian, on both sides of the Zagros Suture (Stöcklin 1974; Murris 1980). These 'Hormuz' salt layers play an important halokinetic role in subsequent basin evolution, both in growth and piercement structures in the shelf areas, as well as forming a detachment horizon during the Neogene Zagros folding and thrusting. This initial Infra-Cambrian carbonate–evaporite deposition was followed by a predominantly clastic régime that prevailed until the Permian.

The distribution of Cambrian to Carboniferous sediments is affected by several intervening regional unconformities and in particular by the late Carboniferous Hercynian unconformity, which cuts down to the Precambrian basement in some areas. In the Zagros Basin the sparse control points show that the mid(?)-Permian carbonates, with a thin basal sandstone, rest on a truncated Silurian to Infra-Cambrian surface (Szabo & Kheradpir 1978). The pattern of the pre-Permian subcrop shows a probable series of highs on both sides of the Zagros Suture (e.g. Zagros High, figure 3). This pattern is interpreted as suggesting thermal expansion of the lithosphere along an incipient rift within the Iranian portion of the Afro-Arabian continent along the later Zagros Suture.

3. Zagros Basin evolution

The Zagros Basin provides an excellent example of all the stages of evolution of a basin, from a passive continental shelf to a rift and drift phase and, finally, through various stages of deformation associated with plate collision. Figures 3–12 show the shifting axes of depocentres and the facies patterns resulting from these plate interactions. The post-Carboniferous subsidence patterns illustrated by the ten maps fall logically into three phases.

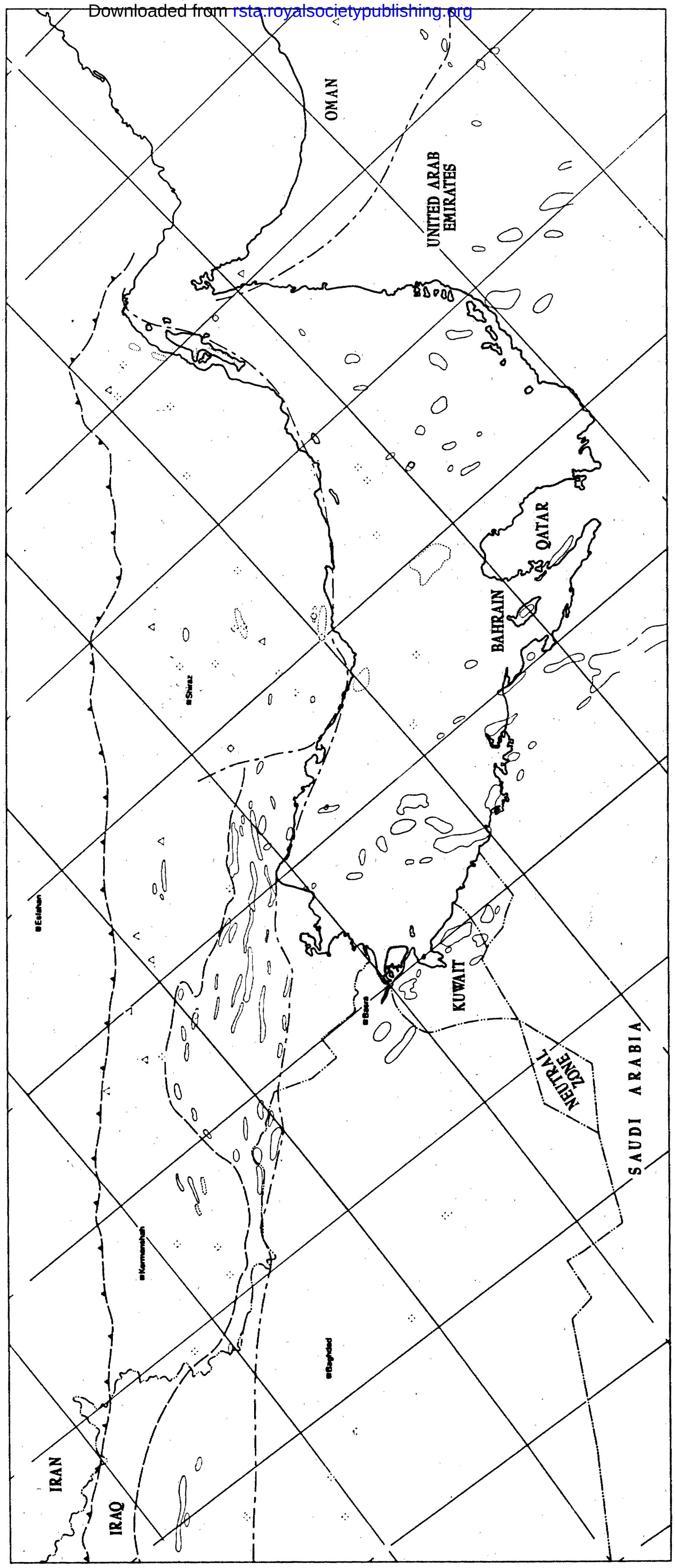
(*a*) *Rifted continental shelf phase: Permian and Triassic*

Traces of late Carboniferous to early Permian glacial deposits are reported from Oman and Saudi Arabia, but in the Zagros Mountains the first sedimentary rocks deposited on the Hercynian unconformity surface were thin basal sands overlain by fossiliferous Middle Permian limestone. During the middle and late Permian a facies pattern of inner shelf carbonates and evaporites bounded to the NE by partly reefal organic carbonates became established (figure 3). The earlier Zagros High (pre-Permian arching) remained positive, resulting in a local source of redbed terrigenous clastics. Thiele *et al.* (1968) described a clastic–basic volcanic Permian sequence at Ab-e Barik immediately NE of the Zagros Suture, which supports the suggestion of early rifting along this line. Other areas of adjacent Central Iran show a very thick open marine Permian carbonate section. The oceanic realm of the main Tethys may have lain much further to the NE at this time, in the vicinity of the present Alborz Range (Stöcklin 1974).

The pattern of inner shelf evaporitic facies rimmed by massive shelf carbonates in the High Zagros was repeated in the Triassic (figure 4). Evaporites became the dominant facies across the entire Gulf region. In contrast to the Permian, the entire High Zagros area was now affected by thinning due to uplift and pre-Jurassic truncation. This continued arching along the line of the Zagros Suture has not resulted in any recognized source of terrigenous clastics to the NE. A strong late Triassic sand source was developed at the Arabian Shield margin to the SW. A basin-wide late Triassic to early Jurassic unconformity extending across Central Iran is recognized as marking the onset of drift separation of the Arabian plate and the Central Iranian plate(s) along the present Zagros Suture, so that the post-late Triassic history of the area NE of the Zagros Suture was totally different from that of the Zagros Basin. The new ocean was referred to as the Neo-Tethys by Stöcklin (1974).

(*b*) *Passive miogeoclinal phase: Jurassic to end Middle Cretaceous*

After drift separation along the Zagros Suture, a significant change of isopach and facies patterns is seen on the Lower–Middle Jurassic map (figure 5). The Fars Platform appears as a positive area of thin carbonate deposition. Local domal uplifts on this platform are attributed to Infra-Cambrian salt movement (see below). A complementary negative element, the deeper water silled evaporite–carbonate–shale basin of the Basrah–Lurestan area, was initiated during this same interval. High energy carbonate grainstones on the Surmeh–Dhruma shelf extend



Overlay to figures 3–13.

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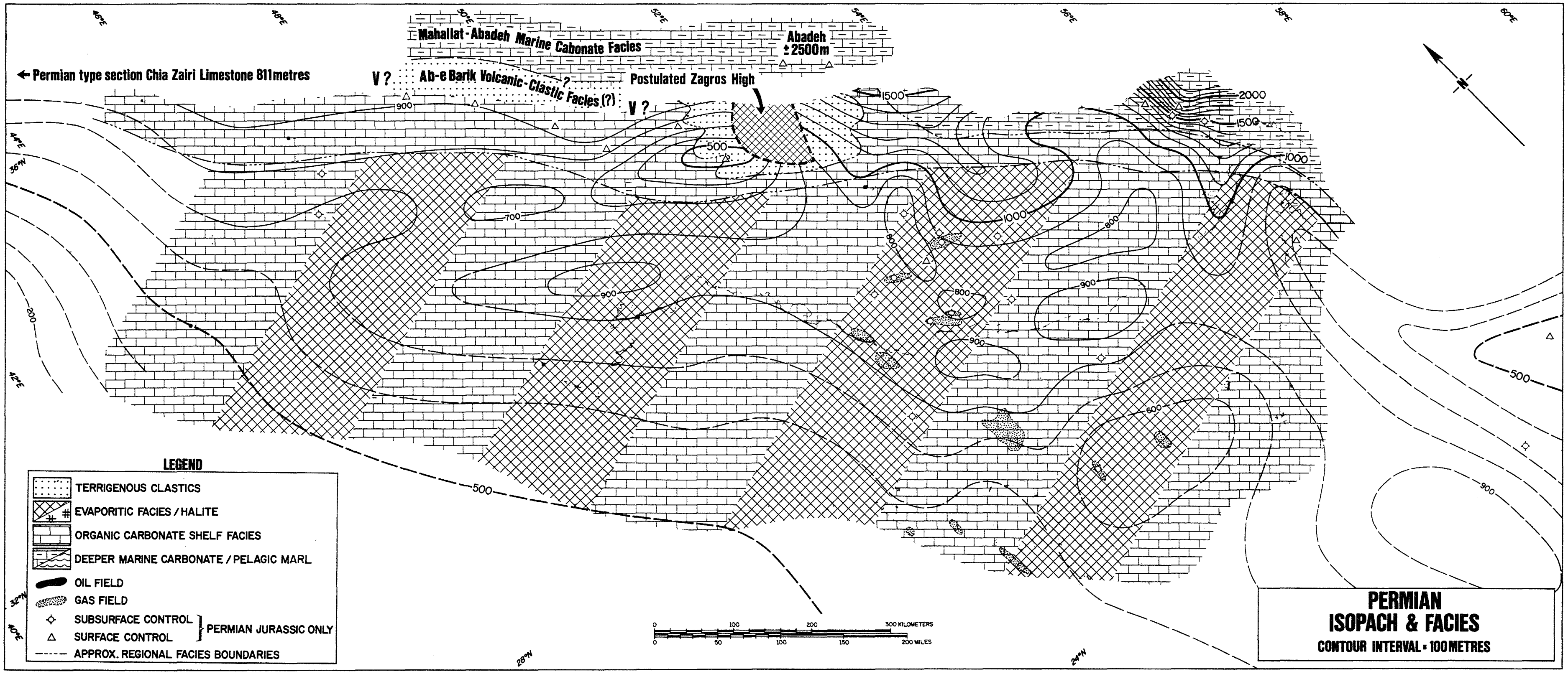

FIGURE 3. Permian isopach and facies distribution map. Facies boundaries on this and subsequent maps are extremely generalized and emphasize selected facies that are considered to be significant indicators of basin evolution. The legend applies to figures 3–12.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

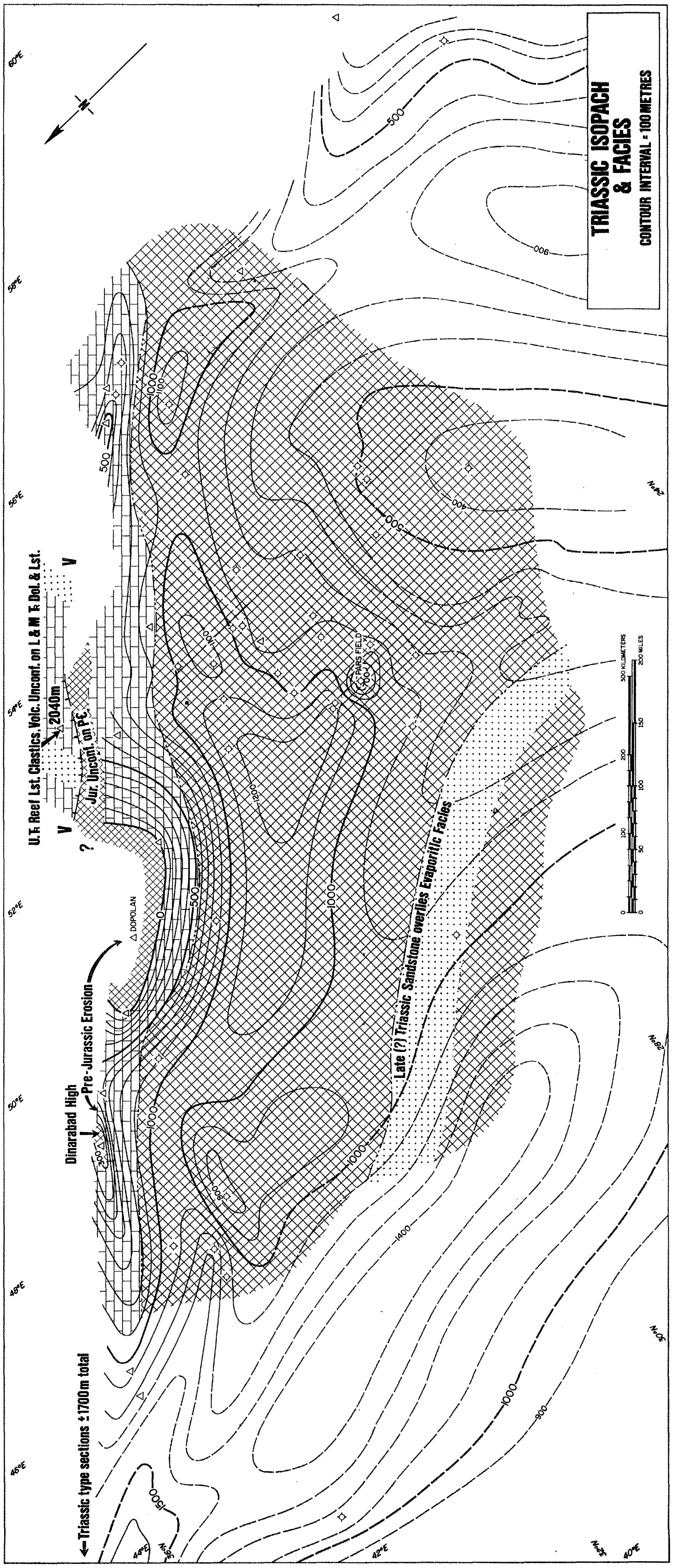

Figure 4. Triassic isopach and facies distribution map.

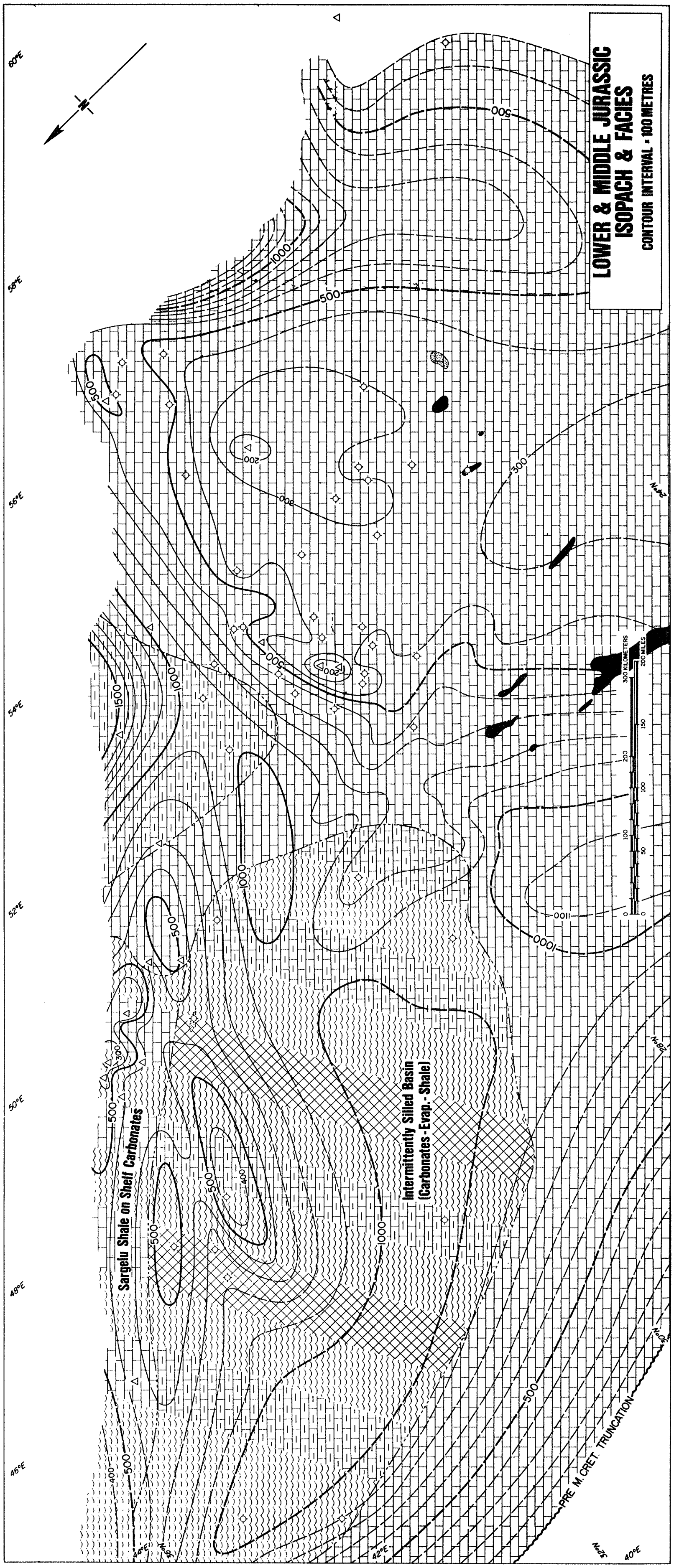

FIGURE 5. Lower and Middle Jurassic isopach and facies distribution map.

as sheets over large areas and locally constitute oil and gas reservoirs. A thickening section of outer shelf carbonates NE of Shiraz suggests proximity to the continental slope, but in general the inner Zagros remained a zone of thin sediment preservation separating the Zagros Basin from the newly opened Neo-Tethys ocean.

The overall patterns of the Upper Jurassic (figure 6) remained very similar to those of the Lower and Middle Jurassic. Basin tectonics, facies differentiation and arid climate conditions became more pronounced. The margin of the Surmeh carbonate platform rimming the Basrah–Lurestan basin remained in the same position but the basin became increasingly restricted with portions reaching the halite evaporite stage (Kuwait), while others were apparently sediment-starved (Dezful area) with a pronounced basal unconformity or depositional hiatus. The southern Gulf area was the site of intrashelf marls alternating with high-energy grainstones and finally anhydrite as the shelf depressions became infilled and more restricted. This sequence resulted in the ideal source–reservoir–seal juxtaposition responsible for the giant oilfields in the Arab–Qatar Formation underlying the Hith Anhydrite. The NE margin of the Zagros Basin received minimal deposition in Iraq–Lurestan, while the shelf margins of interior Fars were depressed and became the site of continental slope tintinnid-bearing carbonate facies at the Jurassic–Cretaceous boundary.

During the early Cretaceous (figure 7) subsidence patterns continued to reflect the Jurassic basin elements, but uplift of the Arabian Shield margin provided an abundant source of terrigenous clastics; evaporitic conditions ceased. Shelf carbonates persisted in the Fars and southern Gulf areas and now constitute hydrocarbon reservoirs. Along the southern margin of the former Basrah (Gotnia) Basin, a Neocomian oolitic facies and the overlying Barremian–Aptian sandstones resulted in multiple Lower Cretaceous reservoirs. The Basrah–Lurestan Basin was largely infilled and euxinic pelagic conditions retreated to a more distal shelf position in Lurestan–N. Iraq, the Garau Basin. The depressed shelf margin with open marine tintinnid facies persisted into the early Cretaceous in N. Fars and Oman. The early Cretaceous terminated with an extremely widespread Aptian carbonate transgression, which blanketed most of the earlier deposits. In the southern Gulf area local intrashelf basins were flanked by rudistid reefs that form the Shuaiba oil reservoirs.

The basin-wide Aptian marine transgression was abruptly terminated by a major pre-Albian regression that resulted in some erosion and another major clastic régime – the Burgan–Safaniya delta system – which pushed the carbonate–shale facies of the Dezful–Lurestan area further to the NE. The Albian Kazhdumi shales, which were deposited beyond the limits of the delta sands on the Aptian surface, are the major source rocks of the Iranian oilfilelds, and the overlying Cenomanian–Turonian limestones constitute important reservoir rocks. The Fars Platform remained a fairly stable positive element. The Middle Cretaceous isopachs (figure 8) are strongly affected by pre-late Cretaceous tectonism and erosion along conspicuous N–S linear trends of the northern Gulf as well as by more localized salt pillowing in the Fars – southern Gulf region. This tectonism marked the onset of collision phenomena along the outer continental shelf margin of the Arabian plate as the Neo-Tethys oceanic seaway began to close.

(*c*) *Collision phase: Upper Cretaceous to Recent*

The Upper Cretaceous map (figure 9) shows a significant change in thickness and facies patterns in response to the complex plate margin tectonics along the Zagros Suture line near the end of the Turonian. Intrashelf elements became more pronounced. Truncation and onlap

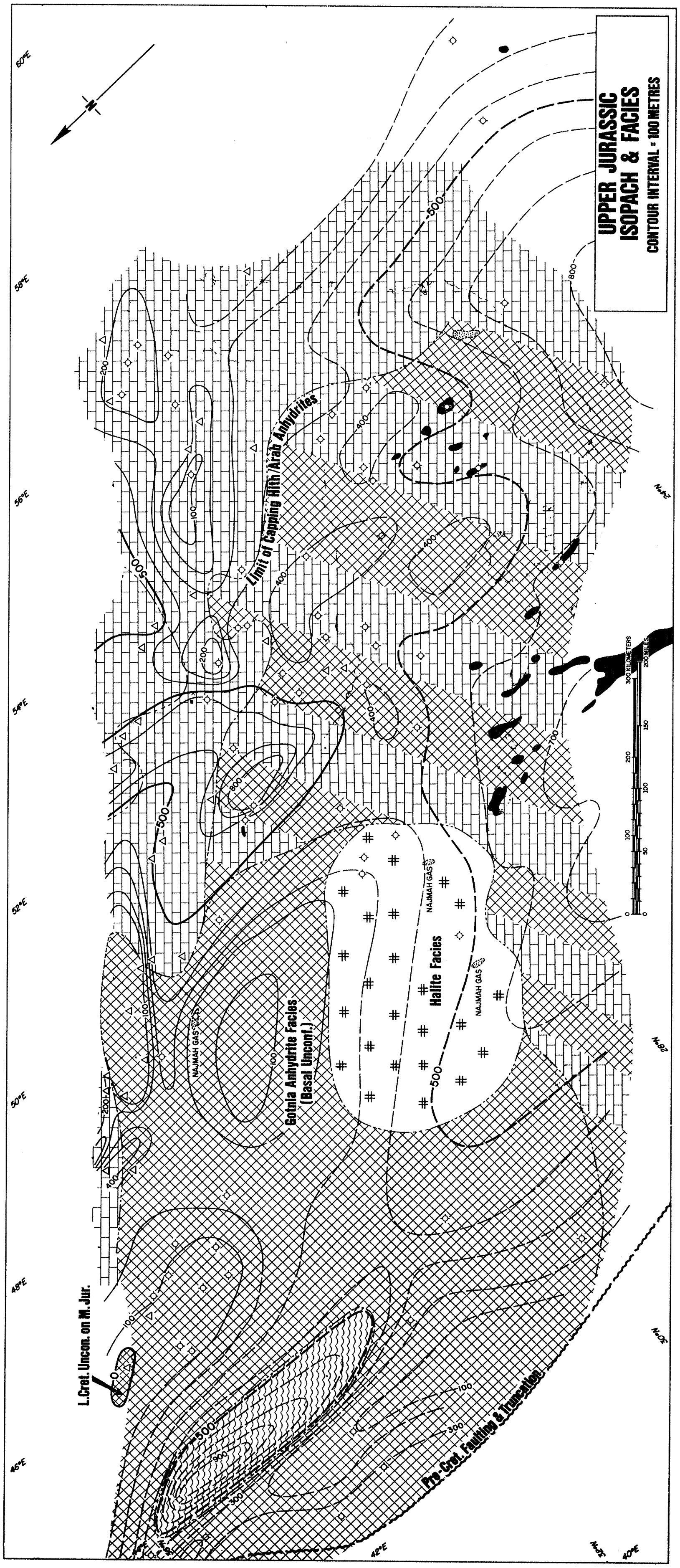

FIGURE 6. Upper Jurassic isopach and facies distribution map.

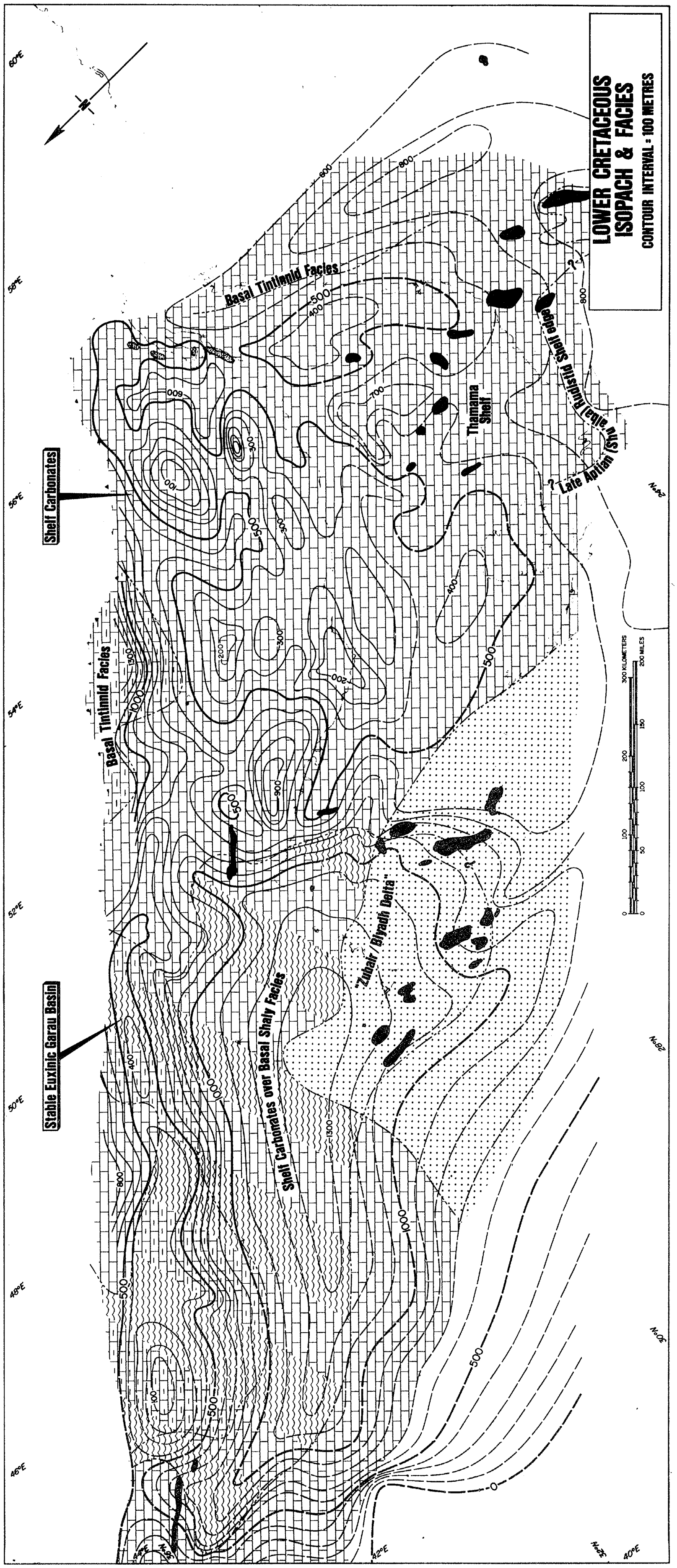

FIGURE 7. Lower Cretaceous isopach and facies distribution map.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

are strongly in evidence at this pre-late Cretaceous unconformity. Structural growth at this time formed the main elements of closure on many of the giant oilfields on the Arabian side of the Gulf and these ancient N–S trends have been traced through the Iranian oilfields area into the Zagros Mountains. Oceanic sediments and ophiolites were emplaced onto the continent margin during the late Cretaceous (probably Campanian). A series of linear foredeeps, developed to the SW of this orogene, were filled with detritus derived from the oceanic rocks. SW of this 'flysch' foredeep, deeper water marine conditions prevailed in the Gurpi basin, where a thin pelagic shale was deposited NE of the carbonate platform fringing the Arabian Shield to the SW. These linear subsidence and facies trends, paralleling the collision zone along the Zagros Suture, persisted into the Tertiary.

Regional uplift late in the Cretaceous resulted in an unconformity that affected most of the elongate basin, except in parts of Lurestan where pelagic sedimentation was continuous from late Cretaceous to early Miocene. The Palaeocene–Eocene isopach–facies map (figure 10) shows a thin veneer of pelagic marls along the central axis of the basin between the carbonate margin and the mountain front foredeep which had persisted from the Cretaceous. Shallow-water marine carbonates fringed the 'flysch' trough. A carbonate–evaporite régime was developed in interior Fars, where there is considerable evidence that movement of the deep Infra-Cambrian salt was influencing sedimentation. Terrigenous clastic supply diminished towards the end of the Eocene and shallow marine limestone frequently blanketed the 'flysch' deposits suggesting that the southern Tethys seaway was still not completely closed. Evidence for this is provided also by an oceanic mélange, with a matrix age of Maastrichtian to early Tertiary, adjacent to the suture (Stoneley 1981).

Before the Oligocene a minor phase of uplift appears to have rejuvenated the ancestral Inner Zagros Mountains, shifting the axis of the depocentre to the SW and then confining marine sedimentation to a shallow elongate basin in the Oligocene – early Miocene (figure 11). Oligocene marl deposition continued in the central part of the basin from Iraq to N. Fars (upper Pabdeh Formation) with neritic carbonates (Asmari Formation) at the margins. A delta centred on Kuwait extended towards the Dezful Embayment (Ahwaz Sandstone Member). In the early Miocene the shallow water carbonates, and locally evaporites, spread over the deeper marine marls and eventually over the Ahwaz delta sands. The Asmari Formation is the most prolific oil reservoir rock in the Zagros fold belt. (It is emphasized that, in this instance, the top of the isopach interval (figure 11) is not a precise time line owing to lateral facies changes between the upper Asmari and the overlying evaporitic Fars Group: in the Oman foredeep and the southern Gulf the thick lower Fars salt sequence may be in part equivalent to the Asmari, but scarcity of information has necessitated its inclusion in the overlying interval.)

Figure 12 is a highly generalized map of the total 'post-Asmari' sedimentary thicknesses, embracing the entire Fars Group and also in some synclinal areas the Bakhtyari syn-orogenic conglomerates. The Zagros folds were already forming so that a true isopach map should properly indicate some thinning over every rising fold. The map, however, emphasizes the major subsidence of the pre-Zagros foredeep in the Dezful Embayment, where in excess of 5 km of post-Asmari sediments accumulated. Salt deposited during the initial stages of this interval constitutes the all-important seal over the Asmari oil accumulations, and is also the incompetent layer that forms the upper detachment zone above the buried folds of the Dezful oil province. The Miocene evaporites and carbonates were succeeded by Upper Miocene–

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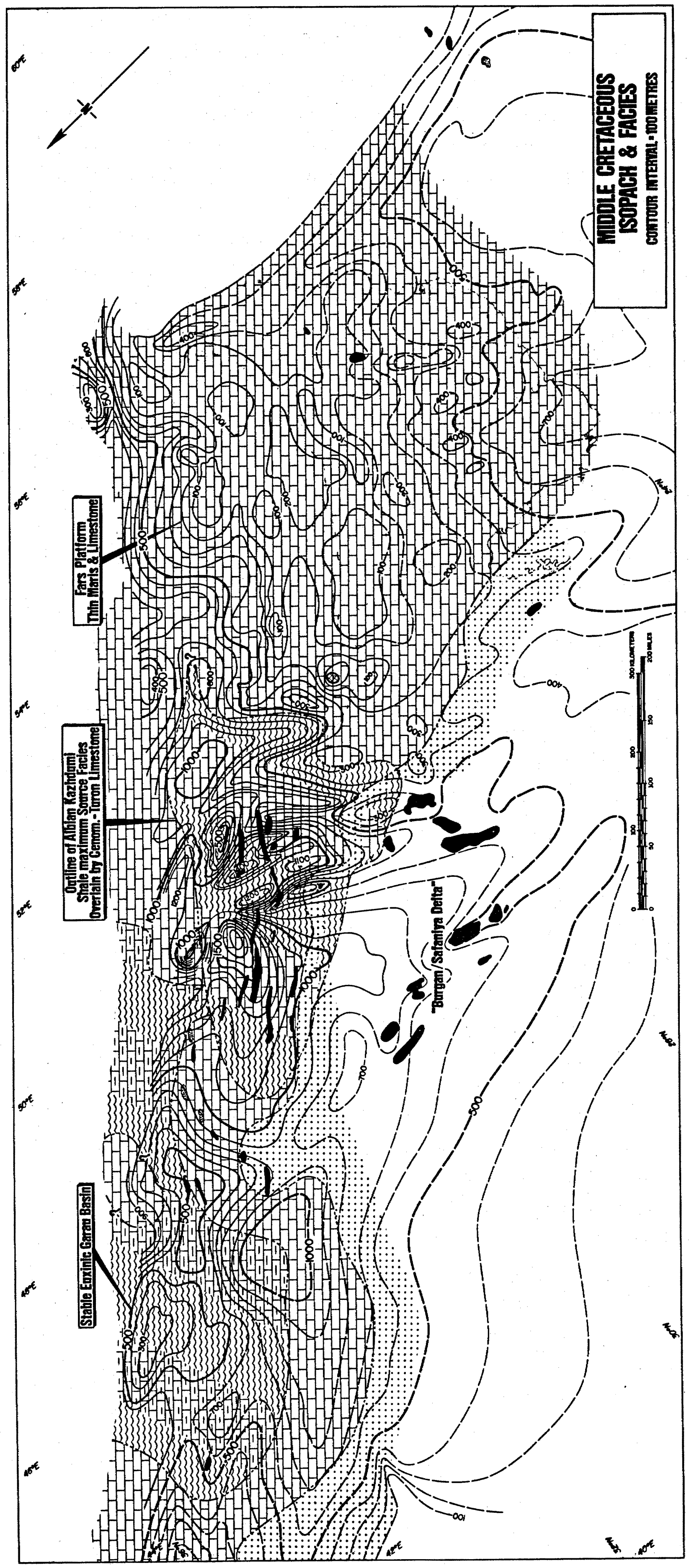

FIGURE 8. Middle Cretaceous isopach and facies distribution map.

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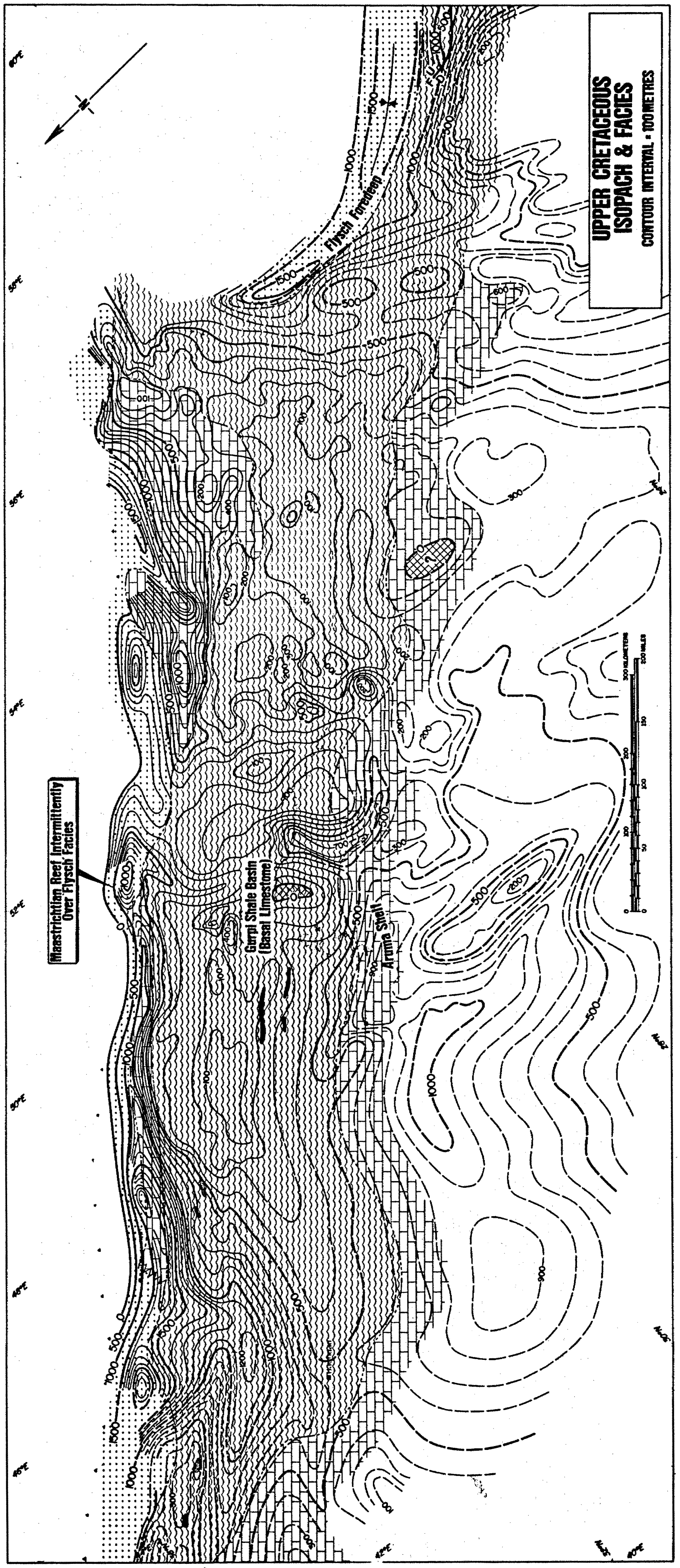

FIGURE 9. Upper Cretaceous isopach and facies distribution map.

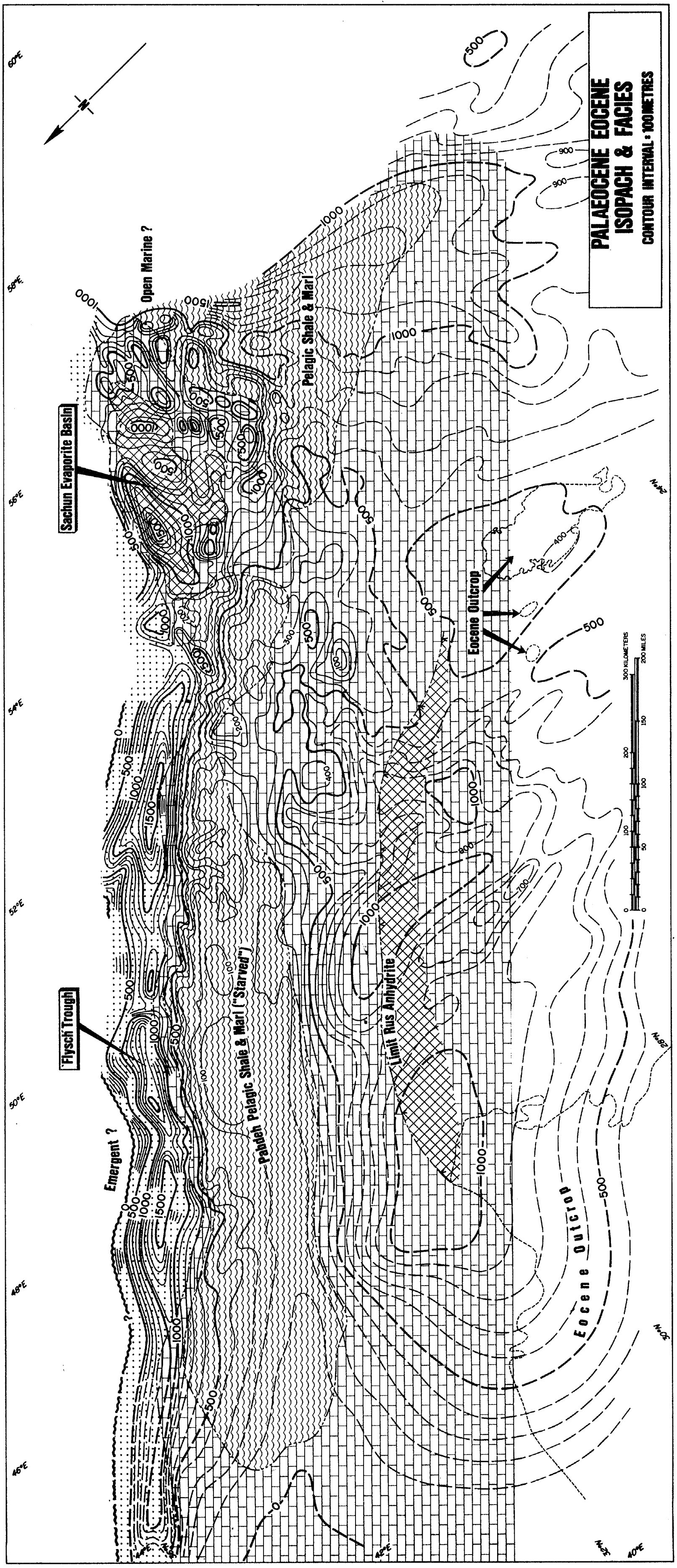

FIGURE 10. Palaeocene–Eocene isopach and facies distribution map.

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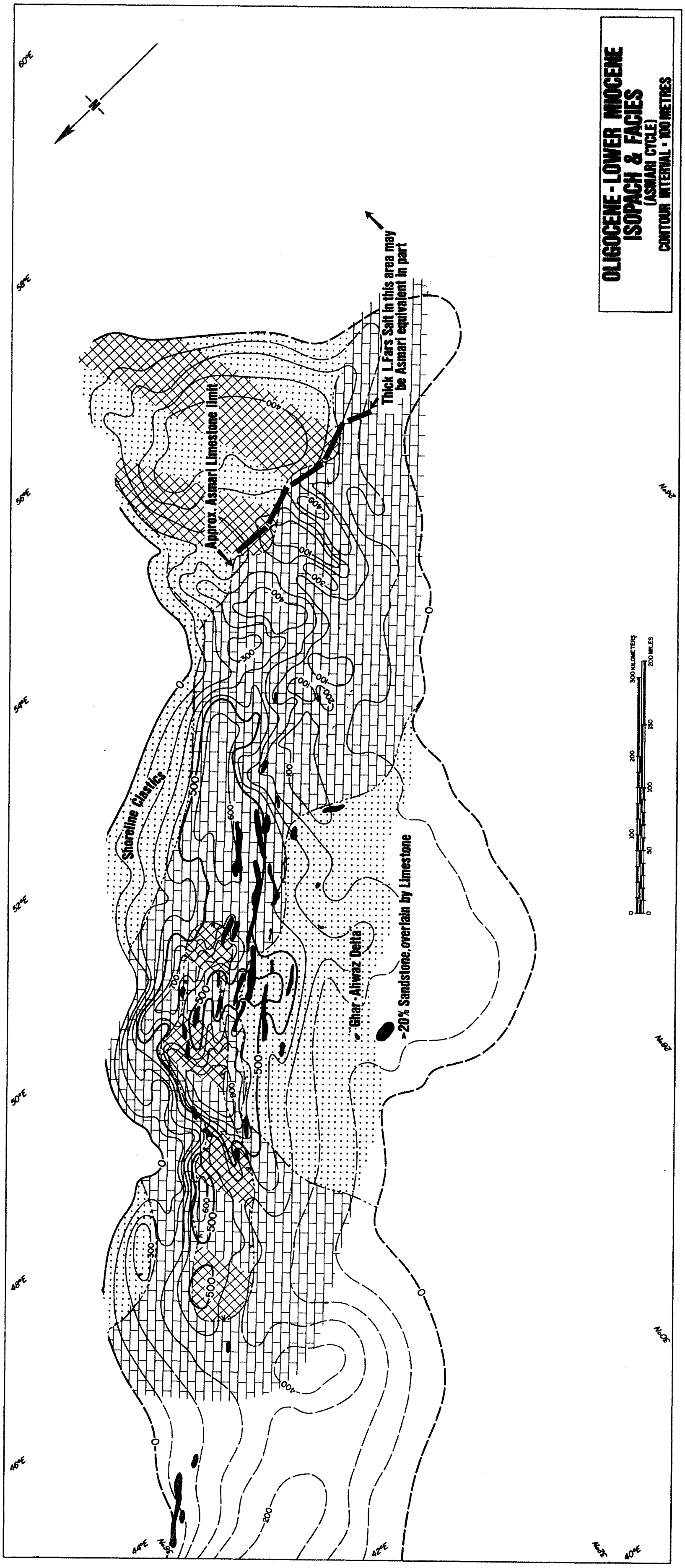

FIGURE 11. Oligocene – Lower Miocene isopach and facies distribution map: Asmari Cycle.

Pliocene 'molassic' redbed clastics as the deposition axis shifted westward towards the present Gulf.

The locations of Infra-Cambrian salt domes in the Gulf area are also shown on figure 12. Salt movement is inferred to have started as early as the Triassic, from thinning observed in the Pars gas field (figure 4). Several plugs reached the surface during the Cretaceous (Kent 1979) and the isopachs frequently reflect local salt movement.

4. Conclusions

The evolution of the Zagros Basin can be interpreted from the series of isopach–facies maps presented in this paper as having resulted from plate interactions marginal to the Afro-Arabian continent. The following stages are recognized (figure 13).

1. A major Hercynian tectonic phase of block-faulting and regional arching resulted in a complex palaeogeological surface that was unconformably blanketed by a marine carbonate–evaporite platform during the mid-Permian.

2. Permian and Triassic subsidence and facies patterns paralleled the Zagros Suture; thinning along this line is taken as evidence of thermal arching and rifting.

3. A regional late Triassic–early Jurassic unconformity marks the onset of drift separation along the Zagros Suture forming the southern or Neo-Tethys ocean. Oceanic sediments from this seaway, of Triassic to mid-Cretaceous age, were emplaced on the shelf margin in the late Cretaceous.

4. Subsidence and sedimentation patterns became more complex during the Jurassic to middle Cretaceous as the carbonate shelf evolved on the passive newly formed margin of the Arabian continent. The depocentres tended to remain SW of the present Gulf, while the shelf edge along the present Zagros Suture was alternately depressed (slope facies) or raised, resulting in widespread restricted sub-basins. The SW basin margin was spasmodically uplifted to supply large volumes of terrigenous clastics from the Arabian Shield.

5. A regional late Cretaceous (post-Turonian–pre-Coniacian) unconformity and the first evidence of terrigenous clastics derived from a source to the NE marked the beginning of plate margin tectonics along the Zagros Suture as the Neo-Tethys closed. A series of roughly N–S linear uplifts along pre-existing basement trends were strongly reactivated in response to this tectonism, affecting both Middle and Upper Cretaceous isopachs.

6. The Upper Cretaceous and Palaeocene–Eocene maps show a threefold subsidence and facies pattern paralleling the Zagros Suture: a 'flysch' foredeep in front of the complex 'collision' zone to the NE, a belt of thin 'starved' marly facies along the main Iranian oilfields trend, and a broad subsiding carbonate shelf depocentre roughly along the SW coast of the present Gulf.

7. Closure of the Neo-Tethys was probably complete by the Oligocene or early Miocene and the Zagros Basin was reduced to a single trough with marginal clastics flanking a central carbonate–evaporite seaway.

8. A final very pronounced subsidence during the Miocene to Plio-Pleistocene(?) preceded and was partly contemporaneous with the Zagros orogeny, creating an enclosed redbed–evaporite trough. The NE flank of this deep trough became the scene of southwestward thrusting and folding as the continent–continent collision continued along the complex Zagros Suture Zone and the Zagros Basin migrated to its present position in the Gulf.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

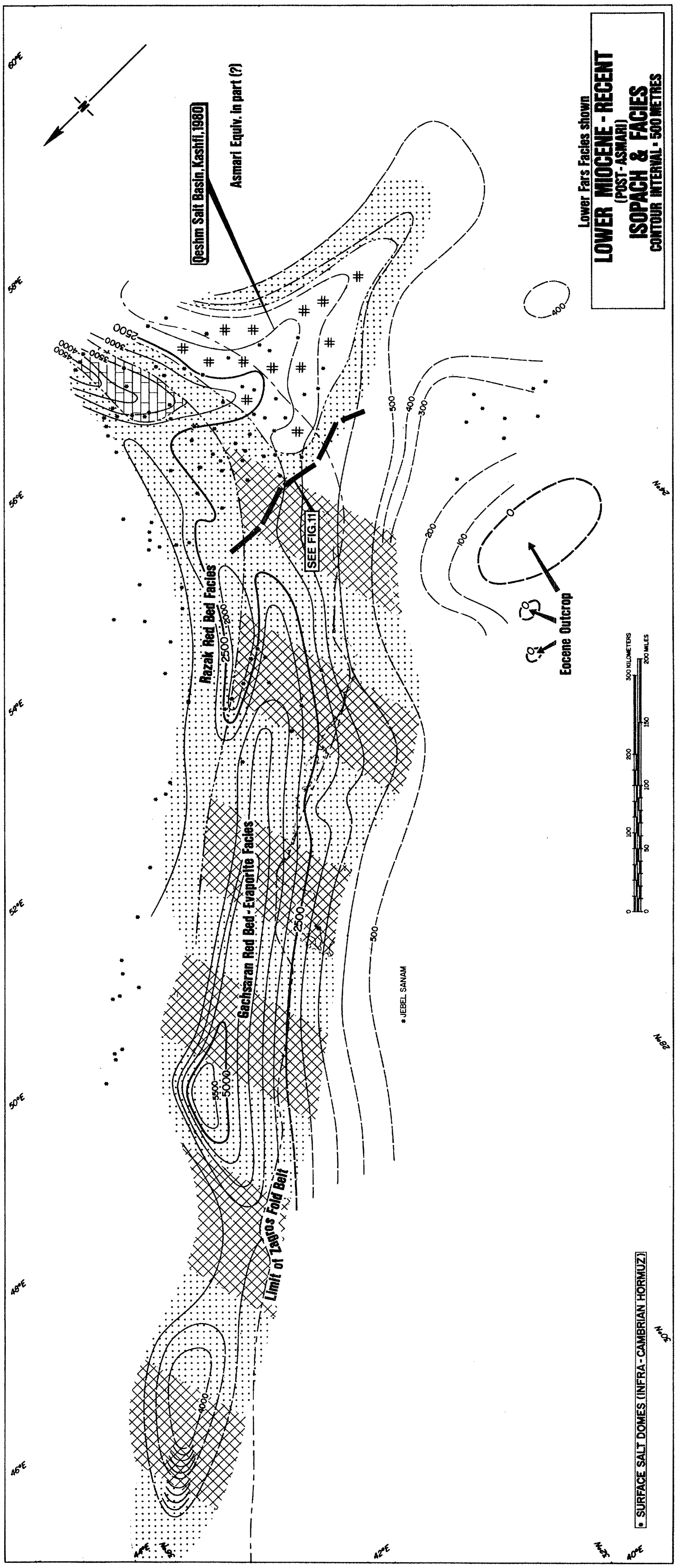

FIGURE 12. Miocene–Recent (Post-Asmari) isopach and facies distribution map, showing Infra-Cambrian surface salt plugs. Thicknesses in the fold-belt are highly interpretive as this stage was partly synchronous with Zagros folding.

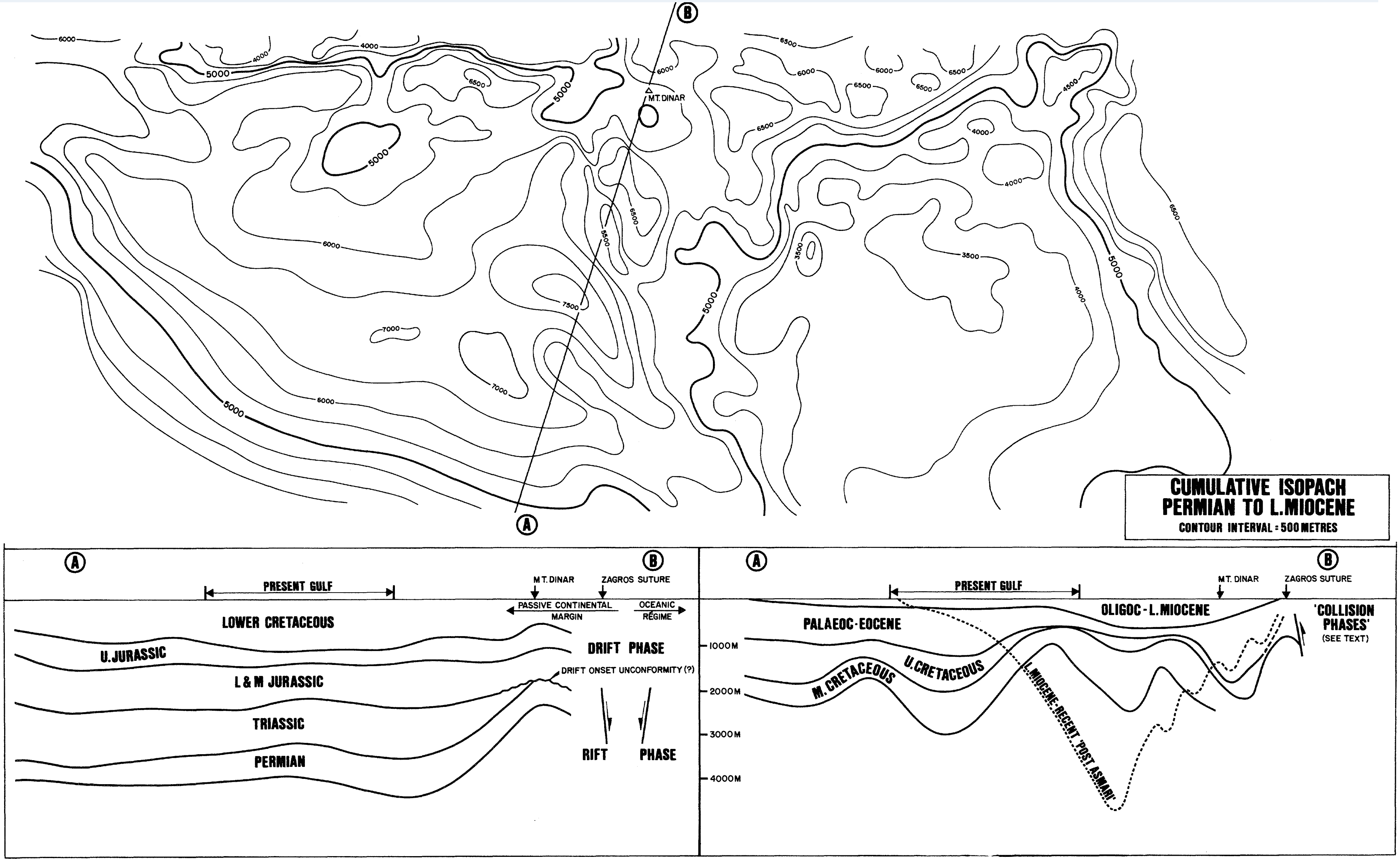

Figure 13. Isopach showing the cumulative thickness of post-Hercynian sediments in the Zagros Basin at early Miocene time (top Asmari Formation). Profiles A–B illustrate the nine time rock unit layers included in the isopach: left, Permian to Lower Cretaceous (figures 3–7); right, Middle Cretaceous to Lower Miocene (figures 8–11) with 'post-Asmari' (figure 12) superimposed. The final subsidence and tectonism (Zagros Orogeny) illustrated by the dotted profile (from figure 12) should be added to the isopach to obtain the total post-Hercynian basin subsidence.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Discussion

M. F. Ridd. Normally on opposite sides of a suture the pre-collision rocks are of different facies, since they were deposited in geographically different regions; only after the suturing has occurred do the facies on either side become similar. Yet in the Zagros the rock types that the authors describe on either side of the present suture were very similar even before the Triassic collision. How did this come about?

W. J. Koop. I believe that the pre-Triassic rocks that are now next to each other on either side of the present suture were originally deposited on the same continental margin. Part of this margin was then separated by rifting from the remainder of the Arabian plate during the Triassic. Thereafter the sediments deposited on the two parts of the margin were very different, since they lay far apart. On the Iranian side, there is a section of Lower Jurassic coals, suggesting that even the climates on the two parts were different. When the suture closed it did so by bringing back together the two pieces of the margin that had been separated by the rifting.

R. W. Murphy. The timing of events along the Alpine–Himalayan chain is of great interest in unravelling the tectonic history. Stöcklin (1977, 1980) has shown the importance of a late Triassic compressive phase along the southern margin of Eurasia. This suture, which has been dated locally as post-Carnian, pre-Norian, can be traced eastwards into the mountains of Yunnan and northern Vietnam. This appears to be the same age as the rifting along the axis of what later became the Zagros suture. It would be instructive to discover (*a*) if the late Triassic suturing can be traced into Iran, and (*b*) if the Zagros rifting precedes the suturing or postdates it.

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W. J. Koop. The Tethys was presumably near the Alborz mountains during Triassic and Permian times. Stöcklin (1974) suggests that the ophiolite slices at Rasht and Mashad may be evidence of late Triassic closing of this northern Palaeo-Tethys ocean at the same time that rifting and drifting opened up the southern Neo-Tethys along the Zagros zone.

R. Stoneley. A possible explanation is that the pre-Triassic Tethys lay entirely to the North of the present Iranian land mass. This is the ocean to which Murphy is referring, and which extended from Crimea through the Himalayan region. Then towards the end of the Triassic the piece of Gondwanaland which now forms central Iran broke away from the Arabian plate, and a new ocean opened up. The part of Tethys north of Iran closed, probably towards the end of the Jurassic or during the early Cretaceous. This disappearance of the Northern Tethys occurred as the new Southern Tethys was produced, along what is now the Zagros Suture. Finally the Southern Tethys closed during the mid-Tertiary.

R. W. Murphy. How does the timing of the closing of the Northern Tethys compare with that of the opening of the Southern ocean?

R. Stoneley. As far as the Iranian sector is concerned, both the location and the timing of the closure of Northern Tethys are uncertain. There is some evidence from northeastern Iran that it may finally have closed in the early Cretaceous.

M. F. Osmaston. What happened in the Zagros between the Maastrictian, when the Oman ophiolite was emplaced, and the middle Eocene when the first accretionary slice known in the Makran, containing Lower Eocene ooze, was emplaced. For instance, what was the Palaeocene palaeogeography?

R. Stoneley. Along the suture there is a mélange of oceanic sediments from which Maastrictian, Palaeocene and early Eocene ages have been obtained. The mélange also includes blocks of neritic shelf carbonates with ages from Maastrictian to early Miocene; however, the compressional folding in the Zagros itself did not start until the end of the Oligocene or the early Miocene.

M. M. Kholief. In the Zagros most of the oil production is confined to the Mesozoic sedimentary sequence of Jurassic or Cretaceous age. Is there also oil in the Tertiary sediments, especially those of Miocene age? If so, is there any resemblance between the structure and sedimentology of these rocks and those in the Gulf of Suez?

W. J. Koop. The bulk of the oil in the Zagros fold belt does in fact occur in Oligo-Miocene, mainly carbonate, reservoirs (the Asmari Formation and the Kirkuk Group), even though it is believed to have migrated upward from Cretaceous source rocks. These Tertiary limestones were deposited in a shallow marine trough between the Arabian platform and the Zagros Suture immediately preceding the main Zagros downwarp and folding. The oil-bearing section in the Gulf of Suez is in part the same age and has some lithological similarities, but the pull-apart régime is, I believe, completely different from the linear compressional setting of the Tertiary Zagros Basin.