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Paleozoic Stratigraphy and Hydrocarbon Habitat of the Arabian Plate

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This paper summarizes the efforts of many geoscientists from Shell, Saudi Aramco and Petroleum Development Oman.

ABSTRACT

The Paleozoic section became prospective during the early seventies when the enormous gas reserves in the Permian Khuff reservoirs were delineated in the Gulf and Zagros regions, and oil was discovered in Oman. Since then, frontier exploration has targeted the Paleozoic System throughout the Middle East, driven by the need to replace oil production from maturing fields, the need to add gas reserves to meet local energy requirements, and other economic considerations.

The Paleozoic sequences were essentially deposited in continental to deep marine clastic environments at the Gondwana continental margin. Carbonates only became dominant in the Late Permian. The sediments were deposited in arid to glacial settings, reflecting the drift of the region from equatorial to high southern latitudes and back.

Following Late Precambrian rifting that formed salt basins in Oman and the Arabian Gulf region, the Cambro-Ordovician sequences were deposited on a peneplained continental platform. However, by the Late Ordovician this margin probably differentiated into two terranes along the Zagros fault zone, as indicated by the Silurian paleogeography.

The entire region was affected by the Hercynian Orogeny during the Carboniferous, which caused long wave-length plate buckling in the north, block uplifts in the central region and regional uplift in the south and tectonism along the Zagros fault zone. This deformation caused widespread erosion of the Devono-Carboniferous section, and was probably caused by collision along the northern margin of Gondwana. The Paleozoic tectonic super cycle ended with the onset of break up tectonics in the Permian, and the deposition of Khuff carbonates over the eastern passive margin.

A major Paleozoic petroleum system embraces reservoir seal pairs spanning the Silurian to Permian sequences. Hydrocarbons occur in a variety of traps, and are sourced by the Silurian hot shale. A second petroleum system occurs in areas charged from Upper Precambrian source rocks in the salt basins. Hydrocarbon expulsion estimates and taking into account secondary migration losses, suggest that some 1 trillion BOE may have been trapped from the Silurian hot shale alone.

However, problems with deep seismic imaging and relatively tight and heterogeneous reservoirs combined with hostile subsurface environments pose significant challenges to exploration and development. The critical success factor is the continuous innovative effort of earth scientists and subsurface engineers to find integrated technology solutions, which render the Paleozoic plays economically viable even in a low oil price environment.

INTRODUCTION

The Middle East holds estimated proven reserves of some 625 billion bbls crude and 1,720 trillion (st)cf natural gas, circa 64% and 34% of world reserves respectively, which led Murris (1980) to describe the area as the world's richest hydrocarbon habitat. These reserves are found mainly in Mesozoic and Tertiary reservoirs in a northwest trending zone from Oman to Turkey (Fig.1).

Crude/condensate production from these reserves has reported in 1997 to be circa 7.4 billion/year (World Oil, 1998). Known reserves have been only partly developed due to remoteness from infrastructure, and for strategic reasons, technical considerations or capacity restrictions. Reserve estimates vary with project lifetime, but following initial development generally improve with technical advances allowing higher ultimate recovery (UR). Maintaining an exploration effort of any magnitude in this environment may seem difficult to justify.

The oil industry, however, continues to sustain an active exploration effort for several reasons. First, exploration for non-associated gas is needed to meet local energy requirements to supply power utilities and petrochemical developments. Furthermore, additional income is derived from the exploitation of gas condensates, which are not regulated by production quotas. Second, exploration is required to replace produced reserves in order to guarantee future income and maintain production quotas. Third, exploration is needed to replace lower value crude reserves with better quality crudes. Fourth, some of the producing fields have reached a high level of maturity, and revitalizing producing fields is often more cost beneficial than developing remote resources. Enhanced recovery programs may therefore stimulate the search for cheap local gas to optimize UR. Finally, the growing market demand continues to offer an incentive to direct frontier exploration towards increasingly more complex geological settings and, during the last decade in the Middle East, towards deeper Paleozoic targets.

The Paleozoic section has been known to host significant reserves since the oil discoveries in Oman and the delineation of the giant Permian Khuff gas fields in the central Gulf and the Zagros fold belt during the early seventies. Activities, especially since the late eighties, have established the economic attractiveness of the Paleozoic petroleum systems throughout the Middle East. In particular, the highly successful campaign in Saudi Arabia for the Unayzah play established the presence of a hitherto unknown hydrocarbon province. Discoveries in Jordan in Ordovician reservoirs, in Carboniferous reservoirs in Syria, Silurian and Ordovician reservoirs in Iraq, and Devonian reservoirs in Turkey, all charged essentially by Silurian source rocks, indicate the widespread occurrence of the Paleozoic petroleum systems.

In this paper we describe our present understanding of the Paleozoic frontier of the Middle East as it is thought to offer the industry a major opportunity to delineate new reserves. The sequences are to date only lightly explored, except in Oman and Central Saudi Arabia. Therefore, a discussion of the basin evolution and the hydrocarbon habitat of the Paleozoic sequences at the scale of the Arabian plate and Interior Iran remains speculative.

REGIONAL SETTING

Main Tectonic Elements

The Arabian Plate boundaries embrace all types of plate boundary processes. They include rifting and seafloor spreading in the Red Sea and Gulf of Aden, collision and subduction along the Zagros, Bitlis suture and Makran respectively, and transform fault activity along the Dead Sea and Owen-Sheba fracture zones (Fig. 1). The Makran and Zagros convergence zones separate the Arabian plate from the Interior Iran plates.

The Middle East basins nest on Precambrian basement which is exposed in the Arabian Shield in the west and locally along the Arabian Sea and in Interior Iran. The Arabian platform stretches east of the shield toward the Oman and Zagros Mountains. Northward the Arabian platform is interrupted by the intra-plate Palmyra and Sinjar troughs, which were inverted during the Eocene - Miocene. The Aleppo and Mardin highs form stable blocks between this intra-plate deformation zone and the alpine collision zone in Turkey.

The Zagros fold belt, High Zagros Mountains and the Sanandaj ranges form the site of alpine orogenesis associated with the closure of Neo-Tethys, essentially starting during the Late Cretaceous (Alavi, 1994). Remnants of the Neo-Tethys Ocean are found in ophiolite complexes exposed all along the trend, including the Oman Mountains, which is a zone of Late Cretaceous ophiolite obduction. The Urumieh Dokhtar volcanic arc witnesses subduction related magmatic processes. The suture between the Arabian and Interior Iran Plates is thought to be located just southwest of the volcanic arc, and may be hidden under a linear belt of Tertiary intra-montane basins.

The Interior Iran micro-plates are thought to have been part of Gondwana during most of the Paleozoic era together with the Arabian plate (Beydoun, 1993). The Paleozoic continental margin of Gondwana probably extended along the Elborz-Kopeh Dagh sutures into Turkey (Fig. 1). They broke away from Gondwana during the Permian, and probably docked with Eurasia during the latest Permian (Ruttner, 1993). The tectonic history of Interior Iran is very complex, but the presence of large shear-zones in which tectonic lenses of oceanic crust are present indicate that the area is a mosaic of smaller terranes. Paleomagnetic modeling suggests that the tectonic history of individual micro-plates diverged through time, for instance involving major rotations of the Central Iran Microplate (Davoudzadeh et al., 1981) before they were assembled during the alpine orogeny.

The Precambrian basement, which underlies the Middle East Basin, consists of accreted island-arc and microcontinent terranes (Brown et al., 1989), overlain by post cratonic sediments and volcanics. Rift basins were formed during the latest Precambrian (Husseini, 1988). These rift basins were the site of salt deposition in the Arabian Gulf and Oman (Fig. 1).

The main structural elements in the platform indicate the existence of a number of inherited mechanical weak trends. They are defined by: i) northerly trending highs as exemplified by the Qatar Arch, ii) Northwesterly trending systems like the Azraq and Ma'rib grabens of Mesozoic age, and iii) northeasterly trending systems like the South Syrian Platform, Khleissia, and the Mosul trend. These trends are well expressed in the structural map of top basement (Fig. 2).

The parallelism between major structures in the Precambrian basement of the Arabian Shield and Phanerozoic structures is striking, and suggests that rejuvenation of mechanical discontinuities in the basement played an important role in the evolution of the plate.

Figure 2 highlights the overall asymmetric nature of the basin with basement at surface in the west. The basin deepens gently in an easterly direction with maximum depth reached in a foredeep setting in front of the Zagros convergence zone. No obvious foredeep is developed along the northern plate boundary reflecting the escape tectonics of the Anatolian Plate (Turkey). Shallow basement along the Arabian Sea reflects repeated episodes of uplift associated with the break-away and drift of the Indian sub-continent. Moreover, the north-easterly trending salt basins in Oman are well expressed. Basement trends in the Zagros follow essentially the surface structural grain.

Paleo Plate Positions

The Arabian plate is thought to originate in the Late Neoproterozoic due to accretion tectonics (Unrug, 1996). By the end of the Precambrian the plate was located close to the equator (Fig. 3), and had an east-west orientation with Iran in the north. The area translated gradually to southern latitudes during the early Paleozoic times, and was accompanied by a minor anti-clockwise rotation. The Levant formed the southernmost part of the area by Late Ordovician time; Oman was located in subtropical latitudes compared to present day climate zones. During the Silurian to Late Carboniferous the plate underwent a major clockwise rotation of some 100 degrees, and did not make significant north south translations. Oman was positioned in the south by the Late Carboniferous, and Turkey in the north. During these rotations the Hercynian Orogeny winded down to the northwest. These movements were followed by a rapid translation of Arabia to the north during the Permian. Turkey reached the equator shortly after the end of the Paleozoic.

The journey of the Arabian plate during the Paleozoic across the southern hemisphere may be summarized in three distinct episodes: 1) Precambrian to Late Ordovician southward translation, 2) Silurian to Carboniferous clockwise rotation without north-south translation, and 3) rapid Permian northward translation.

Stratigraphic Framework

Most knowledge pertinent to the stratigraphy of the Paleozoic of Arabia stems from wells drilled over structural highs and outcrops along the present basin margins. Large areas, especially in the deeper parts of the basin, contain sparse or no well data. Most of the basin is covered by older vintages of seismic data that do not adequately image the Paleozoic section due to low impedence contrast in the predominantly clastic section, high amplitude interbed multiples from Mesozoic and Cenozoic carbonates, and near surface statics.

The data available for Interior Iran is essentially derived from surface outcrops that were described during the seventies and earlier. A complex geological picture emerges. The stratigraphic resolution of the work and lithostratigraphic approach does not allow an unambiguous interpretation of the data in the context of a Middle East scale sequence stratigraphic model. Therefore, this data will only be used to stress key issues related to the basin evolution.

The Paleozoic sequences are dominated by clastics, essentially sourced from the exposed interior of Gondwana to the west and south. Figures 5a-c illustrate the generalized stratigraphic framework for the Paleozoic of the Middle East. Figure 5c includes a summary of the Precambrian section. Note that the Huqf sequences in Oman and their lateral equivalents are presently dated as Precambrian, following recent developments in chronostratigraphy (Gradstein and Ogg, 1996). They define the base of the Cambrian at 543 million year. This also implies that rifting which preceded basin formation is of latest Proterozoic age.

The base of the Paleozoic section is formed by a massive, continental sand unit of Early Cambrian age. The base of these sands is a diachronous horizon. The continental sands are followed in the north and east by the development of a shallow marine carbonate platform of Middle Cambrian age. A return to clastic, braid delta environments took place during the Late Cambrian. These are followed by a stack of prograding braid delta sequences in an overall transgressive setting, culminating in a primary maximum flooding surface in the Middle Ordovician. The maximum flooding surface is followed by two prograding, clastic cycles during the Middle to Late Ordovician, interrupted by a second maximum flooding event. The close of the Ordovician is represented by a major regional unconformity caused by a large drop in sea-level associated with the Ordovician glacial event. Glacial and periglacial, continental to subaquatic deposits and their lateral equivalents testify to two major phases of ice advance and retreat, predominantly from the west (McClure, 1978; Vaslet, 1990).

The deglaciation phase resulted in a primary, plate wide, maximum flooding surface of Llandoverian age, during which the prolific source rocks of the “hot shale” were deposited. A second younger Silurian source rock was deposited in the deepest parts of the basin. The remainder of the Silurian witnesses the evolution of a prograding deltaic complex.

The latest Silurian to the latest Carboniferous period is poorly represented in the rock record. This is primarily due to Hercynian tectonism, and possibly also to the increased maturity of the basin, resulting in a deceleration in subsidence rates with loss of preservation potential.

The preserved Devonian is fluviatile, deltaic and shallow marine in origin. The latter include shallow carbonate platform environments of Early Devonian age probably deposited during maximum flooding, which are uncomformably overlain by continental clastics. The Hercynian Orogeny affected the basin from latest Devonian time, but appears to have climaxed in the Early Carboniferous. The Carboniferous, syn-orogenic sequences were deposited in continental to shallow marine environments, embracing shallow marine, carbonates of Visean age. The Carboniferous clastics were mainly derived from the erosion of older clastics in uplifted areas.

The latest Carboniferous witnessed the establishment of ice-house conditions in southern Arabia, again resulting in a major drop in sea-level and coeval erosion. Glacial and glacio-lacustrine deposits are preserved in Oman and southern parts of Saudi Arabia.

Permian deposits are present throughout the basin, reflecting increased accommodation space related to stretching of the crust, which gave rise to the formation of the Neo-Tethys Ocean. The Lower Permian comprises clastics of fluvial and eolian origin. These clastics were partly deposited coeval with rift tectonics along the eastern and northern margins of the Arabian Plate. They are unconformably followed by the plate wide, syn-drift deposition of carbonate/evaporite platform sequences of Late Permian age.

PALEOZOIC BASIN EVOLUTION

Lower to Middle Cambrian

The Paleozoic depositional cycle starts with the deposition of continental clastics of Early Cambrian age. These sequences unconformably overlie a peneplained, stable platform, and they were essentially derived from interior sources in Gondwana. They can be traced over the northern part of the Arabian platform, and time equivalents in similar facies are observed throughout the Iranian micro-plates. They are missing in the south-western part of the platform probably due to emergence.

The sediments consist of reddish to white, variably sorted arkosic sandstones, conglomerates, and subordinate red shale. They were deposited in a system of alluvial fans grading into braid plains and braid deltas. The braid plains may include playa lake type deposits in Oman. The distribution of these sediments in the salt basins indicates that accommodation space was generated by halokinesis.

During the latest Early Cambrian to early Middle Cambrian the platform became inundated from the north (Fig. 6). Siliciclastic tidal flats were established in marginal settings, which basinwards grade into low-energy carbonate and clastic carbonate mixed tidal flats, followed by subtidal carbonates (Amireh et al., 1994). The latter develop into a vast shallow marine, stable carbonate platform covering most of northern Arabia and Interior Iran. Locally, oolites and stromatolites have been described. Salt pseudomorphs, and anhydritic dolomites indicate the temporal establishment of evaporitic conditions. These carbonates form a key seismic marker in northern Arabia. Carbonate platform environments persist throughout the Middle Cambrian on the deeper parts of the platform, but along the basin margin deposition returns to alluvial-fluvial environments, interrupted by subordinate marginal marine deposits.

Continental deposits replace the marginal, marine environments southward. In the salt basin province, an angular unconformity separates the upper Lower Cambrian from the underlying sequences. This unconformity is thought to mark the onset of subsidence driven by thermal relaxation. The age of this unconformity is still controversional; it may also reflect the base of the Paleozoic.

The continental deposits are interpreted as proximal alluvial fan deposits sourced from local uplifted basin margin highs. Basinward these deposits interfinger with alluvial and aeolian sandstones. All relict topography appears to have been leveled by Middle Cambrian time and relatively uniform depositional conditions persisted over large areas, which include Central Saudi Arabia for the first time.

Regional facies trends indicate a southwest to northeast transport direction suggesting that the sediments were derived from the southwestern and southern margins. Fluvial fan conglomerates and sandstones pass northeastward into fluvial-eolian sandstones and inland Sabkka deposits.

Upper Cambrian to Lower Ordovician

Increased clastic influx in the Late Cambrian terminated carbonate deposition in northern Arabia and the Zagros, and a prograding clastic apron was deposited conformably over the Middle Cambrian sequences (Fig. 7). In interior Iran, however, carbonate deposition persisted into Late Cambrian time. In the northern and central area of the plate, fluvial to fluvio-deltaic to shallow marine clastic environment were established, sourced from exposed areas in the west. They grade eastward into distal shale dominated marine environments in the Zagros.

In the south, the base of the Upper Cambrian is a regional unconformity. In south Oman continental conditions persisted, whilst in the Ghaba and Fahud Salt Basins a marine influenced environment of deposition became established. The base of these sections is made up of a stack of shallow marine to inter-tidal shallowing upward cycles, consisting of alternating carbonates, sands and shales. These are followed by shallow marine mudstones deposited during maximum flooding. The section concludes with stacked braid delta lobes separated by marine mudstones.

The Cambro-Ordovician boundary is poorly defined in the rock record, and Upper Cambrian deposition continues uninterrupted into the earliest Ordovician.

During the later Tremadocian to Arenigian the platform became inundated again, and deeper marine environments become established over the basinward parts of the platform in the north, including Interior Iran. Mixed clastic /carbonate settings are found on the Central Iran Micro Plates (Rickards et al., 1994). The sea invaded the basin margin and braid-plain to braid delta environments are overlain by coastal plain to inner neritic clastic environments. The transgression involved multiple eustatic cycles as indicated in marginal settings further south. Here initially shallow, open marine mudstones were deposited which are followed by a shoaling sequence before returning to mudstones. These latter are topped by an unconformity of Late Tremadocian age which is overlain by coastal sands, followed by sediments deposited during a transgression giving rise to maximum flooding in the earliest Arenigian. This is followed by a regression in the remainder of the Arenigian during which a prograding braid delta system was deposited, consisting of massive quartz sand/siltstones, and subordinate shales.

Middle/Upper Ordovician

A major unconformity separates the Middle from the Lower Ordovician in the south, which extends into central Arabia. A thin sandy unit locally overlies this unconformity, but generally the rapid transgression resulted in deposition of middle to outer neritic shales. This primary maximum flooding surface is of Llanvrinian age, and can be traced basin wide (Fig. 8). Locally the shale may be rich in organic material, indicating restricted water circulation in the basin for the first time.

Prograding clastic aprons overlie the maximum flooding deposits near the basin margins. These Middle Ordovician sediments were deposited in inner neritic to estuarine or deltaic environments. Point sources can be recognized in Oman and northern Saudi Arabia (Fig. 8).

The Middle Ordovician cycle is followed by a transgressive regressive cycle of Caradocian age. Sediments were deposited in similar environments, and the basin geometry remained apparently unchanged. Basinwards, the cycles are difficult to recognize as the section consists of an undifferentiated package of essentially middle to outer neritic graptolitic shales.

Time equivalent deposits are absent in most of Interior Iran, only locally remnants have been preserved (Reitz and Davoudzadeh, 1995), possibly due to Late Ordovician and younger erosion events. They are also absent in the Mardin area of southeastern Turkey, where the entire Ordovician section has progressively been removed by pre-Silurian erosion (Fig. 5c). Whether this is due to tectonic processes or shelf edge erosion associated with the fall in sea-level during the close of the Ordovician remains to be resolved.

Late Ordovician Glaciation

The base of the latest Ashgillian deposits is an important unconformity, which formed during the Late Ordovician glaciation of Gondwana. The polar icecap covered sub-Saharan Africa, and advanced into western Arabia in two major pulses, depositing two sequences of tillite and pro-glacial clastics, mostly sandstones within incised valleys adjacent to the Arabian Shield and southern Jordan (Fig. 9; McClure, 1978; Vaslet, 1987, 1990).

The deep valley systems were incised to depths exceeding 500 m by glacial and fluvial processes, and have been traced into the subsurface of northern Saudi Arabia with seismic data (McGillivary and Husseini, 1992, Aoudeh and Al-Hajri, 1995). The associated major fall in relative sea-level is witnessed away from the glaciated areas by a sudden influx of significant amounts of fluvial to deltaic sands on top of deeper marine sediments in parts of the basin.

Silurian

The Llandoverian saw a major phase of global warming, which resulted in the retreat of the glaciers. Sea-level rapidly started to rise and recaptured the Arabian platform (Fig. 9). Shallow to open marine environments were established in marginal areas, whilst deeper marine environments covered the inundated platform, and extended southward along the narrow subsiding intrashelf trough located in central Saudi Arabia (Jones and Stump, 1999). Anoxic bottom waters in the sediment starved basin resulted in the preservation of organic rich shales, the prolific Silurian hot shale, one of the principal source rocks for Paleozoic hydrocarbons (Abu-Ali et al., 1991; Mahmoud et al., 1992). A second, younger source rock of possibly Wenlockian age occurs in the northern parts of the basin. The initial transgression is followed by a thick (>1000m) coarsening-upward mega-sequence of shales and sandstone of Llandoverian to Peridolian age, which prograded basin inward. However, middle to outer neritic environments persist in the north and east during the remainder of the Silurian.

In Interior Iran, Lower Silurian sediments rest directly on Lower Ordovician sediments, and the entire Middle to Upper Ordovician interval is not represented, except for local remnants.

Initially coarse continental clastics were deposited, which laterally appear to grade into and are followed by shallow marine carbonates. Volcanic rocks have been described from various parts of the basin, indicating tectono-magmatic activity. Note that these sequences may represent the margin of PaleoTethys in the Kopet Dagh area and eastward, taking into account the alpine rotations carried out by the Central Iran microplate (Davoudzadeh et al., 1981). In the Elborz Mountains the Silurian has not been preserved or deposited, and uppermost Devonian rests unconformably on Cambrian / Lower Ordovician deposits, indicating uplift of the continental margin during the Devonian at the latest.

The dramatically different paleogeography of the Central Iran basin indicates that Interior Iran had been uplifted by Early Silurian time and possibly had started to follow its own tectono-magmatic evolution separate from Gondwana. In contrast, similarities in the Cambrian to Lower Ordovician stratigraphy suggest that Central Iran may have been an integral part of Gondwana. It follows that the Zagros fault zone may have been rejuvenated during the latest Ordovician.

Siluro-Devonian

The base of the Upper Silurian - Devonian mega-sequence is a regional disconformity. The section is not present over large areas probably due to Hercynian erosion (Fig. 10). The most complete section has been preserved in Saudi Arabia (Al-Hajri et al., 1999). There, the cycle starts with continental clastics of latest Silurian age (Fig. 5a), followed by marine deposition during the Pragian (reaching into the Emsian). A large delta front became established in Saudi Arabia and Qatar, which in the north is replaced by mixed marine siliciclastics and carbonates.

The marine incursions of Emsian to Eifelian age also reached Oman and Iraq, Syria and Turkey. Continental environments became established in Central Arabia, Syria and Iraq, whilst marginal marine environments developed in Turkey and Oman. The latter include anoxic mudstones deposited in lower coastal plain environments.

Alternating marine and continental deposits characterize the close of the Devonian in Iraq and Turkey, which southward are replaced by continental sediments. The marine sequences embrace carbonate deposits.

The absence of Lower Devonian deposits in Turkey and Iraq suggest a structural high position with respect to the depo-center in Saudi Arabia. The return of marine environments especially during the latest Devonian in the northern region (or the preservation thereof), suggest differential down-warp of the northern margin of Gondwana. Similar relationships can be observed in Interior Iran. Uppermost Devonian strata rests directly on Cambrian / Lower Ordovician sequences in the Elborz mountains, whilst a more continuous Paleozoic section including older Devonian, is preserved in the basin south of the Elborz Mountains (Fig. 9, Wensink, 1991). These relationships suggest that the northern margin of Gondwana became tectonically unstable, and herald the onset of the Hercynian Orogeny.

Carboniferous

The Carboniferous is largely missing due to widespread uplift and erosion during the Hercynian Orogeny. However, in Syria Lower Carboniferous sequences were deposited and preserved in a northeast trending proto-Palmyra trough (Fig. 11). The base of the Carboniferous is a regional unconformity, becoming angular adjacent to Hercynian uplifts.

The basal part of the section in Syria comprises Tournasian to earliest Visean shallow marine shale with subordinate sand/silt-stones and bioclastic carbonates. Incomplete biozones are indicative of intra-formational depositional hiatuses. These are followed by fully marine carbonates of Visean age, reflecting the maximum extent of the transgression.

The overlying sequences are part of a regressive complex made up of near shore to deltaic clastics. These sediments range in age up to the Stephanian. Thinning and pinching out of the carbonates, and variations in sand/shale ratios of especially the Middle to Upper Carboniferous sequences suggest that deposition occurred in a shallow, land locked SW-NE trending depression. This implies a major change in basin geometry, which may be attributed to the Hercynian Orogeny (see below).

Isolated occurrences of Carboniferous siliciclastics have been penetrated in Saudi Arabia. They consist of poorly dated syn-Hercynian continental sandstones of the Berwath and Unayzah-C member, which were deposited in lows between Hercynian uplifts.

Upper Carboniferous deposits outside the proto Palmyra depression are known from the south. Here glacials and periglacial deposits of the Al Khlata (Helal, 1966; Braakman et al., 1982) and Juwayl Formation have been preserved of Moscovian to Late Carboniferous age (Fig. 5c). The glacial deposists are related to uplifted areas located southeast of Oman (Al-Belushi et al., 1996). Deposition in glacial environments in Oman continued during the Early Permian.

Lower Permian

The first extensive deposits following the Hercynian Orogeny are the Lower Permian clastics that rest with angular unconformity on older Paleozoic rocks and basement. These mainly continental clastics are widespread, but appear to be missing in the north, and in the Oman Mountains (Fig. 12). In the latter their absence can be explained by erosion or non-deposition associated with Permian rifting. In addition they are missing by onlap, and/or truncation over the ENE-trending Central Arabian arch.

Generally the section is made up of braided plain, channel fill, and eolian sandstones and siltstones, which were deposited under semi-arid conditions (Senalp and Al-Duaiji, 1995). They are replaced basinward by braid plain deposits overlain by shallow marine near shore sediments to essentially shallow marine sands in the Zagros (Szabo and Kheradpir, 1978). The thickness of these clastics is variable due to onlap on the Hercynian structures.

The Lower Permian section in Oman embraces shallow marine carbonates of Sakmarian age (Fig. 12). The intial transgression is witnessed in the deeper part of the basin by a transgressive lag and marine mudstones, which grade laterally into alluvial and fluvial deposits. They are followed by regressive marine carbonates and their clastic lateral equivalents, which in turn are overlain by shore face deposits followed by lower coastal plain sediments. The latter are developed in fines, which may include lacustrine and playa deposits, suggesting diminishing basin topography. The early part of the Artinskian documents a sudden increase in sand content brought in by rivers, probably in response to uplift in the source areas associated with incipient rifting, preceding the formation of the Neo-Tethys margin.

Upper Permian

The base of the overlying Upper Permian Khuff clastics and carbonates is an unconformity, which marks the opening of the Neo-Tehtys Ocean.

The base of this megasequence is formed by continental to marine sandstones and shales supplied from the west, and deposited during the Artinskian in the basin to Kazanian along the basin margin. Northward the continental deposits include economic coal deposits indicating more wet tropical environments. A regression during the Kungurian gave rise to evaporitic hypersaline lagoons grading into shallow marine carbonates (Fig. 13).

These were followed by extensive carbonates and anhydrites over the entire Arabian shelf in shallow marine to tidal flat environments (Al-Jallal, 1995). Restricted evaporitic environments became established on the western part of the platform protected by shoals from open marine in the east. Deep marine environments were established in the northeast as preserved in the High Zagros and Oman Mountains. The Khuff Formation includes at least four depositional cycles. During maximum transgression carbonates overstep the clastic realm and rest directly on basement over the Central Arabian Arch. The close of the Paleozoic and Scythian saw the deposition of anhydritic limestones and dolomites grading into oolitic shoals and shallow marine carbonates.

HERCYNIAN OROGENY

The stratigraphic relations indicate tectonic instability during 1) the latest Ordovician, 2) the latest Devonian - early Carboniferous, and 3) the Permian. The latter is clearly related to the opening of the Neo-Tethys Ocean. The Ordovician event suggests a first phase of disintegration of the northeastern margin of Gondwana.

The Carboniferous event resulted in a major change in basin geometry. The Hercynian subcrop map (Fig. 11) reveals the complex regional structure, which originated during the Carboniferous. This subcrop map shows a northeasterly basement high protruding into the basin in central Arabia, the Central Arabian Arch. Facies patterns and thickness variations in Devono-Silurian and older sequences suggest that the arch originated during the Hercynian, and persisted into the Mesozoic. This high is overprinted by northerly trending basement cored uplifts, which juxtapose various rock units. The northwesterly trending faults in the Azraq Graben were also active, and are associated with large uplifts accompanied by deep erosion (Fig. 14).

The proto-Palmyra and its northeasterly extension occur just south of a zone where uplift and erosion exposed Ordovician strata in the area of the Aleppo and Mardin Highs. Northward younger rock units have been preserved in the Diyarbakir Basin, stimulating an interpretation of the uplift zone in terms of a regional, ENE-trending foreland bulge. It is noteworthy that this bulge trends parallel to the Central Arabian Arch.

Additional evidence for Hercynian tectonism stems from structural observations. Figure 14 shows a geological cross-section illustrating the structural stratigraphic relationships in the northern Arabian Plate. The section shows that the Silurian to Cambrian sequences form one structural entity. The Devonian hiatus may be essentially due to vertical movements. A major angular unconformity occurs at the base of the Carboniferous. The Siluro-Ordovician sequences are truncated. Moreover, the sequences are folded at a regional scale prior to the deposition of the Carboniferous. The axial zone appears to coincide with the South Syrian Platform (Compare with Fig. 2). Folded Siluro-Ordovician can also be observed below the base Triassic and younger unconformities further south. Finally, the distribution of the Carboniferous sequences suggests that the area was affected by a phase of differential uplift prior to the deposition of the Triassic.

The cross-section shown in Figure 15 follows the trend of the Central Arabian Arch and extends from the Arabian Shield across several large structures in central and eastern Saudi Arabia to the Qatar arch. Pre-

Permian strata are clearly truncated by erosion below the Hercynian unconformity. This extensive erosion, particularly of the Devonian section demonstrates that the structures were uplifted by thousands of meters during the Carboniferous (Fig. 11).

The north-trending Hercynian uplifts such as Ghawar are bounded by reverse faults, indicating that the uplift was due to a regional compressive stress field.

In general, post-Hercynian pre-Permian erosion leveled the topography, but not completely, as indicated by thickness and facies variations in the Unayzah Formation. Many of the Hercynian faults bounding the major north-south uplifts were reactivated during Triassic extension and especially during Late Cretaceous compression, as indicated by the dramatic thickening of the Aruma Formation (Upper Cretaceous) on the flanks of these uplifts. It is noteworthy that not all structures shown on Figure 15 are Hercynian, the Ghawar and Qatar structures may have started to grow earlier. Furthermore, the Harmaliyah anticline, located immediately east of Ghawar, preserves the most complete Devonian section in Arabia and is clearly post-Hercynian in origin.

Figure 16 highlights the geological relationships in the south. The post Hercynian Carboniferous sequences in general rest on Ordovician or older deposits, leaving a large hiatus. Locally, some Devonian is preserved. No folding or reverse faulting is known from Oman, suggesting that Hercynian movements were essentially vertical in nature. Note that the main phase of halokinesis affected the Cambro-Ordovician sequences.

Fission track studies, combined with organo-chemical studies, carried out in Turkey to Oman, indicate overburden removal over the uplifted areas in the order of kilometers. The changes in basin geometry, regional uplift, basement-cored uplifts, evidence of folding and inversion tectonics suggests that the Arabian Plate underwent multiple phases of compression during the Hercynian Orogeny. The geometry of the structures cannot all be due to a singular stress regime. The structural observations are consistent with a northwest to southeast directed principle compressive stress vector.

Further evidence for Hercynian movements, though still highly speculative, is derived from the Sanandaj-Sirjan ranges and the Oman Mountains. In the former, intensely folded metamorphic Devonian complexes have been found (Fig. 10, Davoudzadeh and Weber-Diefenbach, 1987; Thiele et al., 1968). These are overlain by non metamorphic Permian. Although still sparse, radiometric age dating indicates an Early Carboniferous age for the metamorphism (Crawford, 1977). In the Oman Mountains the Permian rests unconformably on highly deformed and metamorphosed Lower Paleozoic rocks attributed to the Hercynian Orogeny (Mann and Hanna, 1990).

The deformation combined with the metamorphism indicates that the subsequent Zagros margin was possibly a zone of transpressional movements.

HYDROCARBON HABITAT

Hydrocarbon Availability

Understanding the Silurian petroleum system yields one of the keys to unlocking most Paleozoic resources. Our working definition of a petroleum system differs from published definitions (Magoon and Dow, 1994). A petroleum system is defined as the total space occupied by all hydrocarbons derived from one chemically distinguishable source rock interval. Emphasis in this definition is on establishing hydrocarbon availability.

Organic-rich shales exist throughout the basin at the base of the Silurian (Fig. 9). These source rocks are made up of dark grey to black shale, containing marine algae, acritarchs and abundant chitinozoans and graptolites (Jones and Stump, 1999). Source rock quality and thickness varies with depositional environment, as demonstrated by “source out” into a shallow marine bioturbated, sandy, micaceous claystone facies in basin margin settings. Source rock thickness varies from hundreds of meters in the Rub al Khali Basin, via some 50 meters in the northern basin, to a few meters in marginal settings.

In Jordan, Syria and Iraq a younger source rock level has been observed of probable Wenlockian age.

Oil to oil, and oil to source correlations indicate the presence of Silurian derived fluids over a wide geographical area from Turkey to Oman, from Saudi Arabia to Qatar (Fig. 17). They occur as mixtures or end member crude. The crudes have a distinct chemical fingerprint (Grantham et al., 1987; Abu-Ali et al., 1991; Mahmoud et al., 1992; Cole et al., 1994).

Estimating availability and quality of Silurian sourced hydrocarbons is often hindered by complex burial histories. Burial histories are complicated by cyclic burial interrupted by major phases of uplift, especially during the Hercynian. This may leave the interpretation of a Vitrinite Reflectance (VR) measurement difficult in terms of timing, especially considering the uncertainties in thermal history. Areas with deep Paleozoic burial may have generated their potential prior to the Carboniferous, and reservoired hydrocarbons may have been lost to surface during Hercynian deformation.

In other areas source rocks only reached the oil window prior to Hercynian uplift, leaving only potential for gas generation during the Alpine burial phase. Therefore, a key critical success factor forms the understanding of generation histories, which can only be successfully addressed through the application of inorganic paleo-thermometer tools.

The predicted cumulative volumes of oil and gas expelled from the Silurian “hot” shale contained within the present day oil window across the depocenter range between 430 to 760 billion bbls of oil and 1,540 to 2,575 TCF of gas. Cumulative volumes of oil and gas expelled from the Silurian within the present day gas window range between 3,000 to 3,600 billion bbls of oil and 21,595 to 39,200 TCF of gas. When we assume that approximately 90% of these predicted expelled volumes are lost either due to migration losses or are due to various model inaccuracies, then:

1) 48 to 83 billion bbls of oil and oil equivalents are predicted to be recoverable from the geographic area, where the source rock is within the oil window.

2) 380 to 439 billion bbls of oil and oil equivalent are predicted to be recoverable from the geographic area,

where the source rock is presently in the gas window. The Paleozoic exploration frontier may, therefore, offer a HIIP (Hydrocarbon Initially In Place) of 1 trillion BOE reservoired from the Silurian hot shale alone.

Although the Silurian hot shale is the principal hydrocarbon source, recent geochemical evidence from the Shamah gas field in Eastern Saudi Arabia indicates that the Unayzah condensates are derived from a different source rock, yet unidentified.

A second group of established petroleum systems involves upper Precambrian source rocks in Oman. They may also be present in the other Precambrian salt basins (Fig. 1). Hydrocarbons derived from these source rocks have been found in reservoirs spanning the entire Phanerozoic. The hydrocarbons have been linked to several source rock intervals deposited in the pre- to syn-rift sequences. They embrace carbonate source rocks, which contain mainly Type I(/II) organic matter with total organic carbon contents (TOC) up to 7%. Silicilyte source rocks are found in both pre salt and intra-salt settings. They have variable TOC's ranging up to10%, and may occur in massive sections up to 1750 meters thick. They are considered a world class source rock, which are characterized by anomalously low activation energies.

Finally, a group of hydrocarbons have been defined in Oman, the so-called 'Q"-oils, which have distinct geochemical characteristics (Grantham et al., 1987). The exact source of these hydrocarbons remains to be identified, though they appear to be Precambrian in character.

Reservoirs and Seals

The stratigraphic diagrams (Figs. 5 a-c) show the relationship between the main source rocks, seals, and reservoirs in the Paleozoic section. They are generalized schemes; local exceptions are to be expected.

The Permian sandstones and carbonates contain the main reservoirs in the Silurian petroleum system, sealed by intra-formational claystone/shale, or by tight carbonates and evaporites. The regional seal in Saudi Arabia are shales of the Triassic, which completely separate the Silurian hydrocarbon system from the Mesozoic systems above.

The lack of seals render little prospectivity to these sequences in northern Arabia. The Carboniferous to Devonian sequences may include excellent potential reservoirs, especially the Devonian of eastern Saudi Arabia. The presence of only local seals, combined with rapid lateral facies variations, render these sequences of limited regional prospectivity. Exceptions include structures where these reservoirs sub-crop below Permian seals, and are juxtaposed across faults against a sealing facies.

The Silurian section also includes possible reservoirs in the form of sand deposits within the shale dominated outer neritic environments. Generally these reservoirs are thin and their quality difficult to predict. This play was recently confirmed by discoveries in Saudi Arabia and Iraq.

The Silurian hot shale forms the ultimate seal to the pre-Silurian section. The latter embraces excellent reservoirs, which may be also charged from the hot shale. An example is the Abu Jifan field in eastern Saudi Arabia, in which sandstones of Ordovician Sarah / Qasim Formation are the main reservoir.

The pre-Silurian section becomes an important target in addition to the Permian in those regions underlain by Precambrian source rocks. The trapping potential in the Cambro-Ordovician basin margin sections, made up of massive coarse clastics, depends on truncation, which juxtaposes them against Permo-Carboniferous or younger seals. Seal potential increases basin inward in parallel with changes in environment of deposition towards more marine settings (lower sand/shale ratios). However, reservoir quality deteriorates especially due to increased burial, and the presence of reservoir becomes highly dependent on the diagenetic history.

ESTABLISHED PLAYS

The Paleozoic frontier offers a wealth of opportunities as testified by several established plays including the Khuff gas play, the Unayzah/Gharif play, the Devonian plays, and various other plays in the Middle East (Fig. 17). However, exploration and development of the deep Paleozoic presents several challenges including difficulties in seismic imaging, often poor reservoir characteristics, hostile (high temperature and pressure) drilling conditions, and high-cost operations. The critical success factor is the continuous innovative effort of earth scientists and subsurface engineers to find integrated technology solutions, which render projects economically viable, even in a low price environment.

Khuff Play

Gas was initially discovered in carbonates of the Permian Khuff Formation in the Awali dome of Bahrain in 1949. Subsequent gas discoveries were made in deeper pool tests of the major structures in Saudi Arabia, Abu Dhabi, Iran, Oman and particularly in the north Dome of Qatar (1971). These discoveries have made the Khuff the largest “reservoir” of non-associated gas in the world, with approximately 750 TCF of recoverable reserves. The Khuff is primarily a gas play due to cracking of oil in the deep Khuff reservoirs.

The Khuff contains separate gas accumulations in one to four reservoir units corresponding to four depositional cycles. Each cycle begins with transgressive carbonates and is capped by regressive anhydrite (Fig. 18). The four cycles become progressively thinner upwards, reflecting progressive decrease in accommodation space coupled with increasing frequency of eustacy.

The reservoirs consist of oolitic grainstones and intertidal dolo-mudstones deposited during periods of sea level highstands and regression respectively, and are capped by anhydrite seals deposited during sea level lowstands. The development of the Khuff reservoirs on this scale is related to several factors, such as the relative position on the carbonate shelf and the development of higher energy facies on shoals that may straddle structural highs and shelf margin reefs (Al-Jallal, 1995). The quality of the Khuff reservoirs varies from excellent to poor, depending primarily upon the extent of diagenetic dolomitization, leaching, fracturing, and cementation (particularly by anhydrite). Leached zones often form the better portion of the reservoir. Production may be both from the matrix and from fractures, but productivity generally improves with the presence of fractures. These factors suggest that the Khuff has considerable potential for stratigraphic traps, yet unexplored.

The Khuff play presents two major challenges: reservoir performance and gas quality.

The quality of Khuff gas is variable depending upon the amounts of non-hydrocarbon gases, mainly H_2S, CO_2, and N_2. The amount of H_2S in the Khuff correlates with temperature, and consequently depth of the reservoirs, reflecting in situ conversion of hydrocarbons to H_2S by thermochemical reduction of anhydrite sulfate. The amounts of other gases such as N_2 and CO_2 contaminants appear to increase with increasing depth and maturity of the source rocks.

The quality of the Khuff reservoirs presents the highest risk to development due to abrupt lateral and vertical variations in porosity and permeability. The Khuff reservoirs display a wide variety of porosity types, ranging from primary intergranular to secondary oomoldic. Reservoir permeability is equally variable, depending upon leaching of either matrix and cement components, or the extent of fracture development. For these reasons, petrophysical evaluation and geologic modeling of the Khuff reservoirs is hampered by uncertainties. 3-D seismic data has proven to be the best approach for delineating zones of Khuff porosity ahead of development drilling.

For example, Figure 20 shows inverted 3-D seismic volumes from the Khuff-C reservoir in the middle of the Ghawar structure. The Khuff C was divided into three 15 m thick layers for the purpose of illustration. The seismic impedance in this reservoir was calibrated with well data from nearby areas, which indicated an inverse correlation of impedance with porosity. The inverted seismic data was then used to position six development wells in the most porous zones, all of which proved successful, therefore minimizing the risk of drilling unproductive wells.

There is some uncertainty about the history and paths of hydrocarbon migration into the Khuff, particularly in areas where shales and tight carbonates at the base of the Khuff seal hydrocarbon accumulations in the underlying Paleozoic clastics. It is likely that reactivated Hercynian faults, such as those on the west flank of Ghawar (Fig. 22), provided direct pathways for vertical migration into the Khuff from hydrocarbon kitchens in flanking basins.

Unayzah/Gharif Play

Oil was initially discovered in 1972 in sandstones of the Permian Gharif Formation in the Ghaba North structure in Oman, and the subsequent campaign demonstrated the economic viability of the play throughout Oman. In Saudi Arabia, the potential of the Permian Unayzah Formation was confirmed in 1982 by a gas discovery in the southern part of the Ghawar structure. The Unayzah play became more significant in 1989, when super light oil was discovered in Central Saudi Arabia in the Hawtah structure. This was followed by an aggressive exploration campaign that resulted in the discovery of 18 oil and gas fields along the Hawtah and Nuayyim trends during the following 10 years. The fields are structural closures along Hercynian basement-cored uplifts, that may be transpressional in origin (Simms, 1995). Moreover, the stratigraphic variability of the Unayzah Formation, influenced by paleo-topography and the continental environments of deposition, lends a stratigraphic component to entrapment.

The Unayzah and overlying basal Khuff clastics are composed of alluvial, fluvial, and eolian deposits that display substantial variation in facies. The Unayzah includes three sandstone reservoirs, designated informally as A, B, and C, and separated by silt- and mudstone (McGillivary and Husseini, 1992; Senalp and Al-Duaiji, 1995).

The sandstone reservoirs are laterally discontinuous, and their quality varies depending on sorting and the amount of diagenetic quartz, kaolinite, illite/smectite cement. Intergranular porosity ranges up to 30% and permeability up over one darcy, particularly in the eolian sandstone facies. The top seal are transgressive shales at the base of the overlying Khuff Formation.

The Unayzah oils range from 48˚ to 53˚ API gravity and their gas/oil ratio is less than 90 m^3/m^3. The low GOR is attributed to solution of methane in waters in an active hydrodynamic system driven by influx of meteoric water from outcrops along the western edge of the basin (Fig. 15). The Silurian source rocks in central Saudi Arabia are immature, and the Unayzah oils were evidently generated in the deeper parts of the basin and migrated about 200 kms westwards towards the basin margin (Abu Ali et al., 1991).

The acquisition of 3D seismic surveys during field development has helped in mapping the distribution of the Unayzah reservoirs. Figure 21 shows the structural configuration of the Hawtah field. The present structure was formed by reactivation of Hercynian faults during the Triassic. Also shown is the variation of seismic amplitudes in the Unayzah-A reservoir in the field. The high seismic amplitudes correspond to eolian sandstone facies, and the low amplitudes correspond to non-reservoir silt- and mudstones. The seismic amplitudes and other attributes were used for locating wells, which improved the success ratio of development wells from 54% to 84%. The amplitudes also show that the north Hawtah area is a stratigraphic trap due to up-dip pinchout of the A reservoir. The 3D surveys were thus used to discover other stratigraphic and combination traps, as in the Usaylah field (Evans et al., 1998).

The Unayzah play was extended during the last decade to target gas in the deeper basin (3700+ m) near facilities in Eastern Saudi Arabia (Fig. 22). The gas exploration campaign has resulted in the discovery of six additional Unayzah gas/condensate fields near the Ghawar structure, such as Waqr and Tinat (Fig. 22). The Unayzah deep gas play presents additional challenges, which include poor seismic imaging of the Paleozoic section and abrupt variation in reservoir quality due both to stratigraphic and diagenetic reasons. The problems of deep seismic imaging and reservoir heterogeneity are both being addressed by the acquisition of high-effort (28,800 channel) 3-D seismic surveys to reduce reservoir and trap risks.

Devonian Play

Gas in the Devonian Jauf sandstone was initially discovered in 1980 by a deeper pool test on the north end of the Ghawar structure. Subsequent deep tests showed that the Devonian section was mostly eroded from the crest of the structure. The discovery in 1994 of Jauf gas in a combination structural-stratigraphic trap along the flank of Central Ghawar was a major exploration success, especially in light of the poor seismic imaging of the pre-Khuff section (Wender et al., 1998).

The Jauf consists of shallow marine sandstones with relatively high porosities (up to 25%), which is unusual given their burial to over 4,300 m. Although pre-Khuff siliciclastics have undergone extensive silica cementation, the Jauf reservoir is weakly cemented with authigenic illite that coats grain surfaces. This early illite has apparently inhibited quartz cementation and preserved porosity. The abundant illite also lowers resistivity values due to the excess bound water and the high cation exchange capacity of illite. This can cause pessimistic water saturation estimates and lead to potentially bypassed low-resistivity pay zones (Wender et al., 1998).

The cross section in Figure 22 shows the structural relationships of the Devonian Jauf play. On structures like Ghawar that were subjected to a large amount of Hercynian growth, the Jauf Formation is eroded from the crest and preserved along the flanks. The Jauf flank play is defined by the lateral truncation of the Jauf reservoir against sealing faults, or by top truncation of the reservoir by the Hercynian unconformity, with top seal provided by the basal shales of the Khuff Formation. The Jauf may also be preserved over the crest of low relief structures like Waqr, where it is a structural play.

Cambro-Ordovician Plays

Outside Oman, the thick Silurian shales form an effective regional seal to potential hydrocarbon accumulations in the Upper Ordovician sandstones. Several discoveries have been made in structural traps, including Dilam and Abu-Jifan in Central Saudi Arabia, Kahf in northern Saudi Arabia, and Wadi Sirhan 4 and Risha in Jordan (Fig. 17). The hydrocarbons, mainly gas, are sourced from the overlying Silurian shales, which also act as seals.

The main challenge to the Ordovician play is the poor reservoir quality, particularly in the deeper parts of the basin.

The deep Ordovician sandstones generally have low porosities and permeabilities due to compaction and extensive cementation by quartz overgrowths during burial. Petrographic studies have shown that any significant porosity is always secondary, due primarily to dissolution of early intergranular carbonate cement. The early carbonate cementation was localized in areas where Hercynian uplift and erosion had placed Permian Khuff carbonates unconformably above the Ordovician sandstones. The carbonate cement was probably derived from the Khuff carbonates, and occurred at shallow depths before the sandstones underwent significant compaction. The subsequent dissolution of carbonate cement preceded hydrocarbon migration into the reservoirs.

In Oman, major hydrocarbon discoveries have been made in the Cambro-Ordovician section despite the absence of the thick Silurian shales. These discoveries occur in a variety of plays. The following two examples illustrate the unconventional potential and challenges of exploring the deeper Paleozoic clastics.

Hasirah Mass Flow Play

The Caradocian Hasirah play has been defined in onshore Central Oman. The sediments form possibly part of a tide dominated sandy deltaic (or estuarine) system fed by braided rivers from an overall southerly source. These pass basin-ward into undifferentiated marine mud/clay-stones and interbedded, laterally discontinuous, sandy mass flows, which are deposited in outer shelf environments (Fig. 23). The latter have excellent reservoir qualities due to reworking and rapid deposition. Porosities reach up to 32%. The sediments were deposited in an active salt withdrawal basin in ponded geometries, and occur at an average depth of about 3,000 meters.

One of the critical success factors of these potential stratigraphic traps is predicting reservoir distribution and quality. The ponded nature of these sands combined with their potentially erratic vertical distribution introduces a high risk in predicting their presence using conventional technology.

Rock property modeling indicates that the interface between the marine fines, which are acoustically hard, and the underlying sandstones has a strong acoustic impedance contrast probably due to the highly porous nature of the sands. The event is expressed as a soft kick. Peak amplitudes probably reflect the presence of hydrocarbons, which is confirmed by amplitude versus offset (AVO) analysis. Mapping this event confirms its discontinuous nature. Acoustic impedance and coherency maps indicate the lateral extent of the mass flow system, and the lobate structure of the sands (Fig. 24). Amplitude maps show the potential presence of hydrocarbons.

Body checking was applied to visualize the reservoir in its proper structural configuration (Fig. 25). The result clearly shows the mass flow system to be limited to the axial zone of the basin southwest of the Qarat Kibrit salt diapir. The play clearly indicates the unconventional potential of the Paleozoic sequences, and may have a wide geographical extent.

Haima Deep Gas Play

The recent successful campaign for the Haima deep gas play in onshore Central Oman illustrates the challenges of exploring the Paleozoic sequences. The initial discovery of the Haima gas/condensate resources was made in 1989. To date some 17.6 TCF (expectation) of non-associated gas reserves have been booked. The emerged project involves the supply of natural gas to a liquefied natural gas (LNG) export scheme.

The gas resources occur in the Lower Ordovician Barik Sandstone at depths in excess of 4 kilometers (Fig. 26). The reservoirs are found in salt cored domes, which may be compartmentalized by faults (Fig. 27). Initial reservoir pressures are about 500 bar and temperatures are 125 to 140˚ (Celsius, providing a considerable challenge in terms of deep well engineering. The condensate-gas ratio varies from 0 to 950 $m^3/10^6m^3$ (std). Hydrocarbon columns are in the order of 100 to >200 m.

Key issues include: 1) Seismic imaging. Low acoustic contrasts within the objective section combined with a high level of multiple contamination due to strong overburden reflectors results in a seismic response with low signal to noise ratios, leaving reservoirs and faults difficult to image. In addition, high source energy absorption associated with surface conditions may negatively influence seismic quality. Modeling of the reservoir is therefore dependent on neighboring reflective packages.

2) Reservoir quality. The reservoirs represent a sandy braid delta interrupted by periodic flooding events. The latter result in the deposition of a non-reservoir heterolithic, shallow marine faces. Eustatic variations gave rise to eight stacked flow units. Reservoir characteristics vary with overall position within the depositional system; average porosity and permeability is in the order of 8 - 10% and 1 - 2 mD, respectively. Local variations in reservoir parameters also depend on diagenetic history, and especially on the presence of an early oil charge, which inhibited quartz overgrowth and dolomite cementation. The presence of higher quality thief zones complicates reservoir management through introducing a risk of early water breakthrough. In addition, reservoir performance is highly dependent on fractures.

A dedicated team of earth scientists and subsurface engineers was given the task to find integrated technology solutions to address the preceding challenges. This resulted in:

(1) The acquisition of a tailor-made 3D survey, shot in 1998 over the Barik field, the objective of which was to improve the structural definition. The survey utilized a new cost effective acquisition approach,

Orthogonal Wide-Line acquisition, specifically designed to improve multiplicity for deep targets (Hoetz and Duyndam, 1999). In addition, a recently developed processing sequence was applied to the data, which is specifically designed to preserve true amplitude and phase stability to allow deterministic interpretation (McGinn and Duyndam, 1998). The data quality is superior compared to the 1992 survey, and relates to an increased signal to noise ratio and reduced multiple contamination. The increased resolution allows more reliable fault mapping, and a far more confident mapping of top reservoir as such significantly reducing uncertainty (Fig. 27).

(2) An extensive effort targeted to increase well productivity through improved fracture performance, resulting in a reduction in the number of wells initially required for the contractual production capacity. This involved dynamic gas-condensate reservoir modeling combined with fracture geometry modeling in order to determine the preferred well configuration to drain the entire hydrocarbon column (Jones et al., 1998). The resulting design is vertical wells with single- or multiple-propped hydraulic fractures (dependent on local reservoir architecture) that cover the entire hydrocarbon column (all flow units). Development with horizontal wells is not further considered as for the overall mismatch with fracture orientation. Productivity increases are amongst other parameters dependent on fracture width and the length of the perforated interval connected to the fracture. The studies and the tests show that a productivity increase in the order of 20 to 35% may be expected. The development with fracture stimulated wells will result in significant savings in overall subsurface project cost. This dedicated effort, utilizing all available company experience and knowledge, secured the green light for the project even in a low oil price environment.

CONCLUDING REMARKS

The Paleozoic frontier in the Arabian plate offers major opportunities to discover and delineate new energy reserves. The system includes multiple reservoir objectives in Cambrian-Lower Permian continental and marine clastics, and in Upper Permian carbonates. Hydrocarbons were mainly derived from the prolific Silurian hot shales, which extend over most of the basin. In addition, the Precambrian rift basins include additional source rocks in Oman and possibly elsewhere.

The Paleozoic sequences were deposited on a vast platform along the northeastern margin of Gondwana. Tectono-stratigraphic relationships indicate that stable platform environments prevailed until the latest Ordovician, when the margin started to disintegrate probably along the proto-Zagros zone.

The Hercynian Orogeny was heralded by tectonic unrest at the plate margin starting during the latest Devonian, resulting in extensive intraplate deformation. This is manifested by ENE trending regional upwarps in Syria, Central Arabia and Oman, and sags in the Palmyra and Rub' al Khali basins. The second manifestation of Hercynian deformation is the narrow N-trending basement cored uplifts in Central Arabia and elsewhere. The Hercynian deformation climaxed during the Carboniferous, and was followed by rifting along the eastern margin during the Early Permian, which led to opening of the Neo-Tethys ocean during the Late Permian. Specifics about the pre- and syn-Hercynian tectonic history of the Arabian plate remain to be determined.

The prospectivity of the Paleozoic section is largely determined, in addition to the sedimentary facies patterns, by the pre- and post-Hercynian burial and thermal histories, which dramatically impact reservoir quality and availability of hydrocarbons. A non-traditional approach is required to constrain thermal histories due to the complex burial/uplift history. Although porosity was largely destroyed during the deep burial of the section, it was locally preserved due either to the presence of an early diagenetic phase, or to early emplacement of hydrocarbons. Moreover, secondary porosity was selectively created in thin carrier beds by leaching during fluid flow.

Exploration and development success will depend on significant innovations to meet the challenges posed by low acoustic contrasts between the target rock units, difficult surface conditions, tight reservoirs, and deep subsurface environments. The history of hydrocarbon exploration in the Arabian plate has yielded a wide variety of new and often unexpected hydrocarbon plays spanning the Tertiary to Precambrian section. Exploration success in these plays, driven by creative geologists, was often much to the surprise of the established views.

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List of Figures

References

Abu-Ali M. A., U. A. Franz, J. Shen, F. Monnier, M. D. Mahmoud and T. M. Chambers (1991). Hydrocarbon Generation and Migration in the Paleozoic Sequence of Saudi Arabia. SPE Middle East Oil Show Bahrain, paper 21376, pp 345-356.

Alavi M. (1994). Tectonics of the Zagros Orogenic Belt of Iran: New Data and Interpretations. Tectonophysics 229, pp.211-238.

Al-Belushi J., K. W. Glennie and B. P. J. Williams (1996). Permo-Carboniferous Glaciogenic Al Khlata Formation, Oman: A New Hypothesis for Origin of its Glaciation. GeoArabia, Vol. 1, No. 3, pp. 389-404.

Al-Hajri, S.A., Filatof, J., Wender, L.E., and A. K. Norton (1999). Stratigraphy and Operational Palynology of the Devonian System in Saudi Arabia: GeoArabia, v.4, pp. 53-68.

Al-Jallal I. A. (1995). The Khuff Formation: Its Reservoir Potentail in Saudi Arabia and Other Gulf Countries; Depositional and Stratigraphic Approach. in Husseini, M.I., Geo ‘94, The Middle East Petroleum Geosciences, Gulf Petrolink (Publ.), Bahrain, pp.103-119.

Alsharhan A. S. and A. E. M. Nairn (1994). Geology and Hydrocarbon Habitat in the Arabian Basin: the Mesozoic of the State of Qatar. Geologie en Mijnbouw 72, pp.265-294.

Amireh B. S., W. Schneider and A. M. Abed (1994). Evolving Fluvial-Transtional- Marine Deposition through the Cambrian Sequence of Jordan. Sed. Geol., 89, pp.65-90.

Aoudeh S. M. and S. A. Al-Hajri (1995). Regional Distribution and Chronostratigraphy of the Qusaiba Member of the Qalibah Formation in the Nafud Basin, Northwestern Saudi Arabia. in Husseini, M.I., Geo ‘94, The Middle East Petroleum Geosciences, Gulf Petrolink (Publ.), Bahrain, pp. 143-154.

Best J. A., M. Barazangi, D. Al-Saad, T. Sawaf and A. Gebran (1993). Continental Margin Evolution of the Northern Arabian Patform in Syria. AAPG Bull. V.77, No.2 , pp. 173-193.

Beydoun Z.R. (1993). Evolution of the Northeastern Arabian Plate Margin and Shelf: Hydrocarbon Habitat and Conceptual Future Potential. Revue de l’Institut Francais du Petrole, Vol. 48, pp. 311-345.

Buday T. and S. Z. Jassim (1987). The Regional Geology of Iraq. Vol.2. Tectonism, Magmatism and Metamorphism. I. I. M. Kassab and M. J. Abbas eds., State Establishment of Geological Survey and Mineral Investigation, Bagdad, Iraq.

Braakman J. H., B. K. Levell, J. H. Martin, T. L. Potter and A. van Vliet (1982). Late Palaeozoic Gondwana Glaciation in Oman. Nature, V. 299, pp. 48-50.

Brown G. F., Schmidt D. L., and A. C. Huffman Jr.(1989). Geology of the Arabian Peninsula. Shield Area of Western Saudi Arabia. U.S. Geological Survey Prof. Pap. 560-A.

Cole G. A., M. A. Abu-Ali, S. M. Aoudeh, W. J. Carrigan, H. H. Chen, E. L. Colling, W. J. Gwathney, A. A. Al-Hajji, H. I. Halpern, P. J. Jones, S. H. Al-Sharidi and M. H. Tobey (1994). Organic Geochemistry of the Paleozoic Petroleum System of Saudi Arabia. Energy and Fuels, 8, pp.1425-1442.

Crawford A. R. (1977). A summary of isotopic age data for Iran, Pakistan and India. Mem. Soc. Geol. France, ser.h, 8, pp.251-260.

Davoudzadeh M., H. Soffel and K. Schmidt (1981). On the Rotation of the Central-East-Iran Microplate. N. Jb. Geol. Palaont. Mh., pp.180-192.

Davoudzadeh M. and K. Weber-Diefenbach (1987). Contribution to the Paleogeography, Stratigraphy and Tectonics of the Upper Paleozoic of Iran. N. Jb. Geol. Palaont. Abh. 175, 2, pp. 121-146.

Evans, D.S., Bahabri, B.H., and A. M. Al-Otaibi (1997). Stratigraphic Trap in the Permian Unayzah Formation, Central Saudi Arabia. GeoArabia, v. 2, pp 259-278.

Gradstein F. M. and J. Ogg (1996). A Phanerozoic Time Scale. Episodes, Vol. 19, nos.1,2, pp. 3-5.

Grantham P. J., G. W. M. Lijmbach, J. Posthuma, M. W. Hughes Clarke and R. J. Willink (1987). Origin of Crude Oils in Oman. J. of Petr. Geol., 11(1), pp. 61-80.

Helal, A.H. (1966). On the Occurrence and Stratigraphic Position of Permo-Carboniferous Tillites in Saudi Arabia. Neus. Jahrbuch fur Geologie und Paleontologie Monatshefte, v. 7, p. 391-415.

Hoetz H. G. and B. P. M. Duyndam (1999). Barik 3D Reshoot: Tailormade Acquisition for Multiple Objectives. SPE Middle East Oil Show Bahrain, paper 53225.

Husseini M. I. (1988). The Arabian Infracambrian Extensional System. Tectonophysics, 148, pp. 93-103.

Jones A. T., M. S.Al Salhi, S. M. Shidi, M. England and R. Pongratz (1998). Multiple Hydraulic Fracturing of Deep Gas-Condensate wells in Oman. SPE Ann. Techn. Conf. and Exh. New Orleans, Louisiana, paper 49100.

Jones, P.J., and T. E. Stump(1999). Depositional and Tectonic Setting of the Lower Silurian Hydrocarbon Source Rock Facies, Central Saudi Arabia. AAPG Bull., v. 83, pp. 314-332.

Loosveld R. J. H., A. Bell and J. J. M. Terken (1996). The Tectonic Evolution of Interior Oman. GeoArabia, Vol. 1, No. 1, pp.28-51.

Magoon L. B. and W. G. Dow (1994). The Petroleum System. In: Magoon and Dow (eds): The Petroleum System from source to Trap. AAPG Memoir 60.

Mann A. and S. S. Hanna (1990). The Tectonic Evolution of Pre-Permian Rocks, Central and Southeastern Oman Mountains. In: Robertson A. H. F., M. P. Searle and A. C. Ries (eds): The Geology and Tectonics of the Oman Region. Geol. Soc. Spec. Publ. No. 49, pp 307-325.

Mahmoud, M.D., Vaslet, D., and M. I. Husseini (1992). The Lower Silurian Qalibah Formation of Saudi Arabia: An Important Hydrocarbon Source Rock. AAPG Bull., v.76, pp.1491-1506.

McGillivray, J.G., and M. I. Husseini (1992). The Paleozoic petroleum geology of central Arabia. AAPG Bull., v. 76, pp 1473-1490.

McClure, H.A. (1978). Early Paleozoic Glaciation in Arabia. Paleogeography, Paleoclimatology, Paleoecology, v.25, pp. 315-326.

McGinn A. and B. Duyndam (1998). Land Seismic Data Quality Improvements. The leading Edge, Nov, pp. 1570-1577.

Murris R. J. (1980). Middle East: Stratigraphic Evolution and Oil Habitat. AAPG Bull. V.64, No.5, pp. 597-618.

Reitz E. and M. Davoudzadeh (1995). Ordovician Acritarchs from the Banestan, Kerman Area, Central Iran; Paleobiogeographical Evidence for a Warm Water Environment. N. Jb. Geol. Palaont. Mh., H.8, pp. 488-500.

Rickards R. B., M. A. Hamedi and A. J. Wright (1994). A New Arenig (Ordovician) Graptolite Fauna from the Kerman District, East-Central Iran. Geol. Mag. 131, pp.35-42.

Ruttner A. W. (1993). Southern Borderland of Triassic Laurasia in North-East Iran. Geol. Rundsch 82, pp.110-120.

Senalp, M. and A. Al-Duaiji (1995). Stratigraphy and Sedimentation of the Unayzah Reservoir, central Saudi Arabia, in Husseini, M.I., Geo ‘94, The Middle East Petroleum Geosciences, Gulf Petrolink (Publ.), Bahrain, pp. 837-847.

Simms, S.C. (1995). Structural Style of Recently Discovered Oil Fields, Central Saudi Arabia, in Husseini, M.I., Geo ‘94, The Middle East Petroleum Geosciences, Gulf Petrolink (Publ.), Bahrain, pp. 861-866.

Szabo F. and A. Kheradpir (1978). Permian and Triassic Stratigraphy, Zagros Basin, South-West Iran. J. of Petr. Geol., 1, 2, pp. 57-82.

Thiele O. M., R. A. Assefi, A. Hushmand-Zadeh, K. Seyed-Emami and M. Zahedi (1968). Explanatory Text of the Golpaygan Quadrangle Map. Geological Survey of Iran, Geological Quadrangle No. E7, 24p.

Unrug R. (1996). The Assembly of Gondwanaland. Episodes, Vol. 19, nos 1,2, pp.11-20.

Vaslet D. (1987). Early Paleozoic glacial deposits in Saudi Arabia, a lithostratigraphic revision: Saudi Arabian Directorate General for Mineral Resources Technical Record BRGM-TR-07-1, 24p.

Vaslet D.(1990). Upper Ordovician glacial deposits in Saudi Arabia. Episodes 13, pp.147-161.

Wender, L.El, Bryant, J.W., Dickens, M.F., Neville, A.S., and A. M. Al-Moqbel (1998). Paleozoic (Pre-Khuff) Hydrocarbon Geology of the Ghawar Area, Eastern Saudi Arabia. GeoArabia, v.3, no. 2, p. 273-302.

Wensink H. (1991). Late Precambrian and Paleozoic Rocks of Iran and Afghanistan. In: Moullade and Nairn (eds): The Phanerozoic Geology of the World I. The Paleozoic. Elsevier, pp.147-217.

World Oil (1998). World Trends. Exploration, Drilling, Production. Gulf Publishing Company. August 98, pp.25-29.

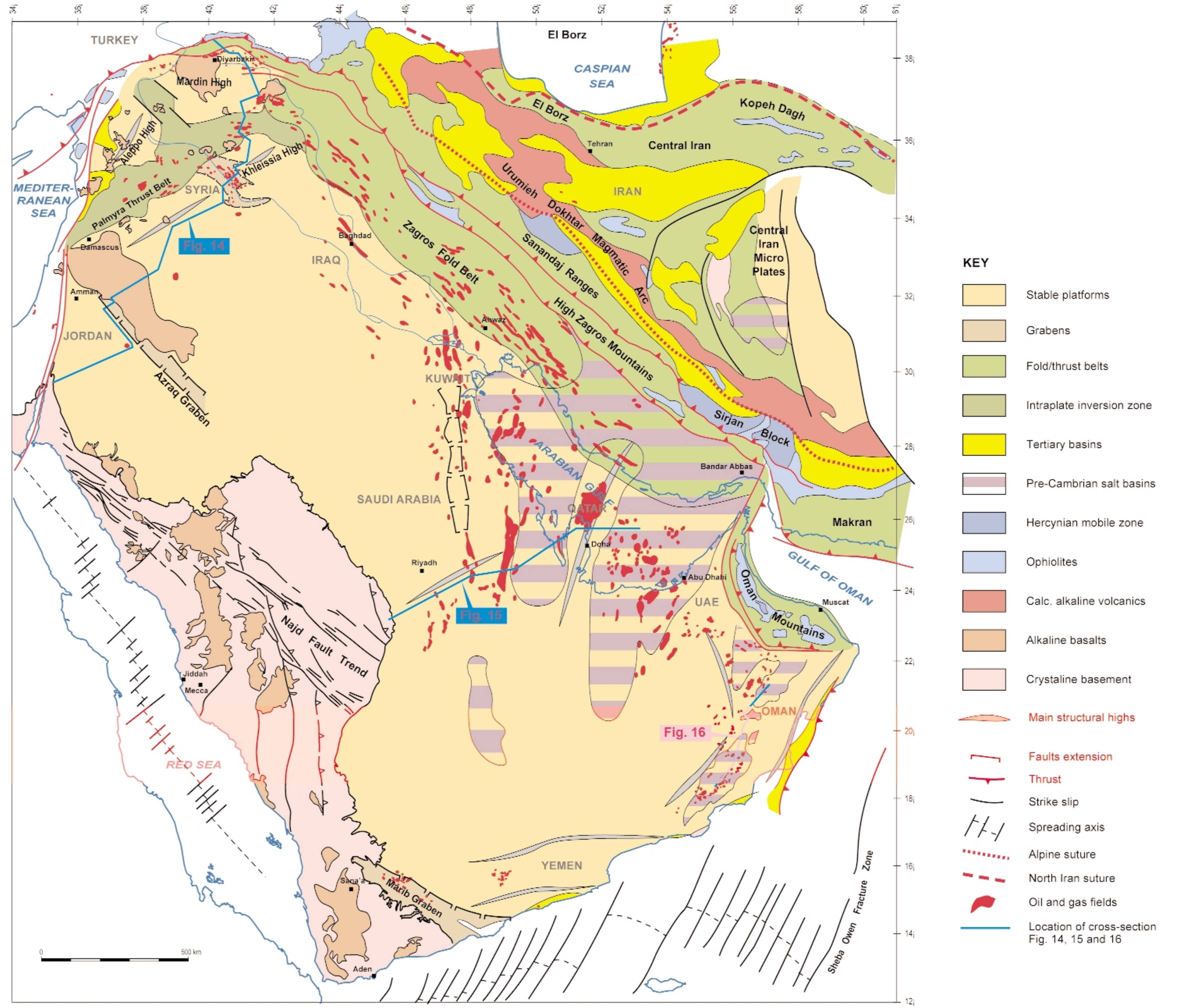


Figure 1. Location and major tectonic elements of the Arabian plate and Iran.

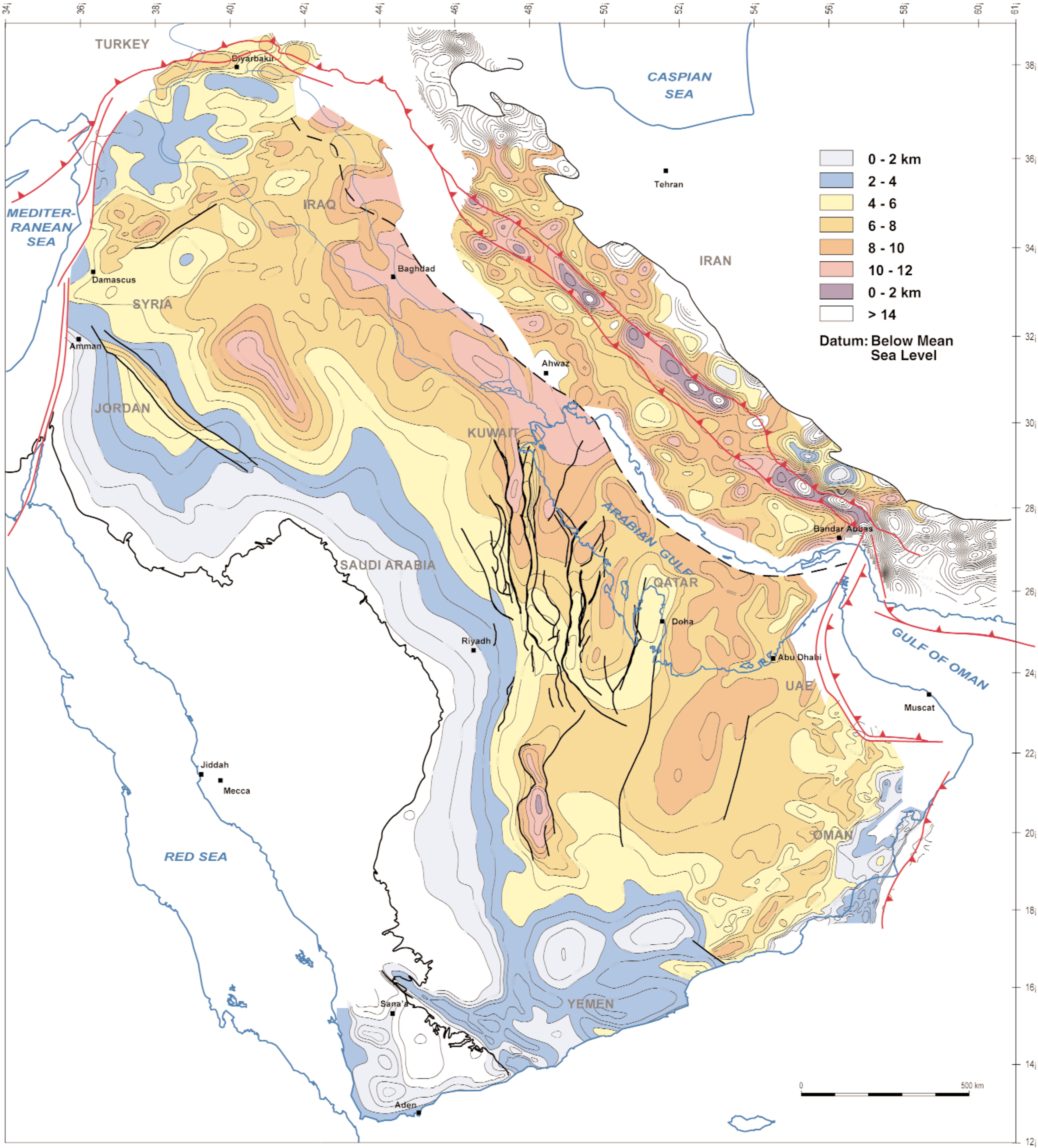


Figure 2. Tentative basement depth map. Contours in kilometers below mean sea-level (partly based on modified Best et al., 1993; Buday and Jassim, 1987; Loosveld et al., 1996).

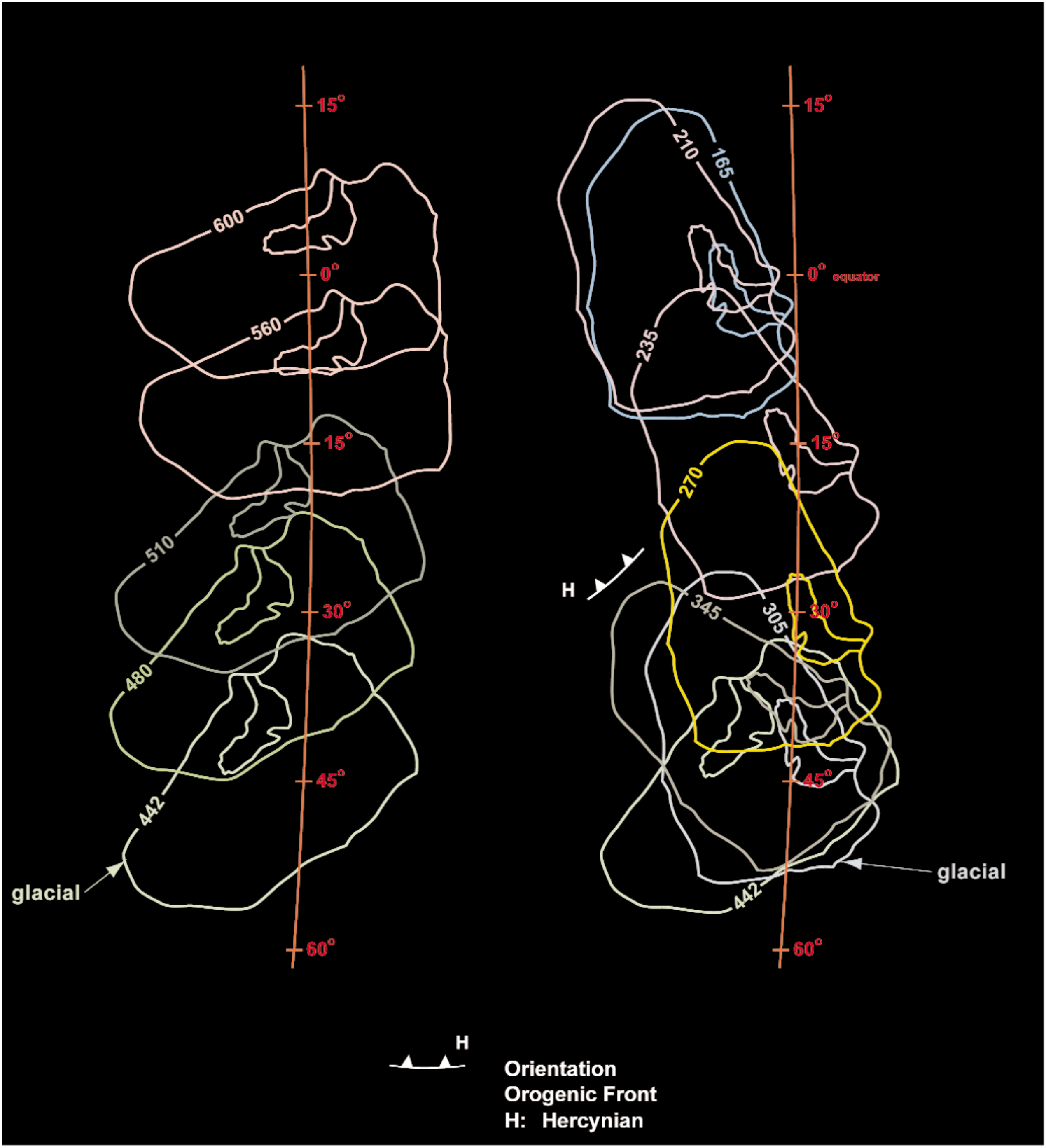


Figure 3. Paleo positions of the Arabian plate during the Paleozoic. Key for colors: see time scale Fig. 5.

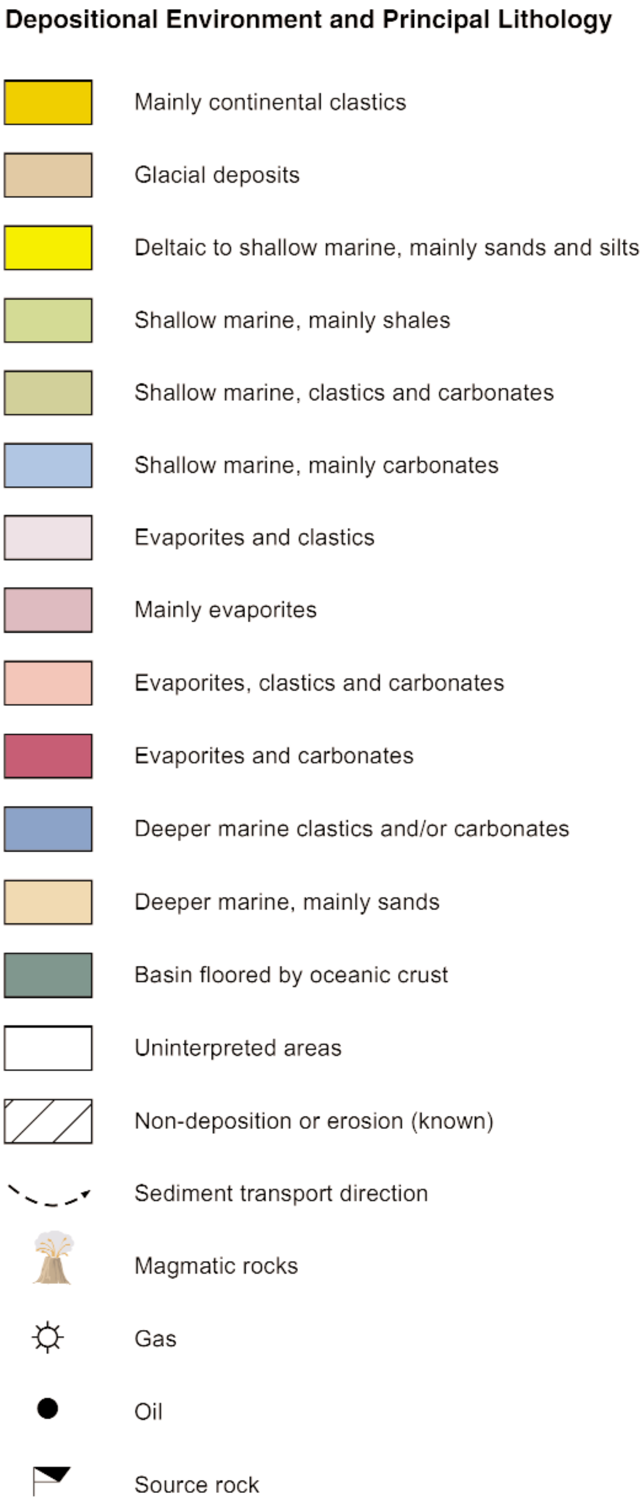


Figure 4. Key to stratigraphic diagrams and environmental maps (Figures 5 through 13).

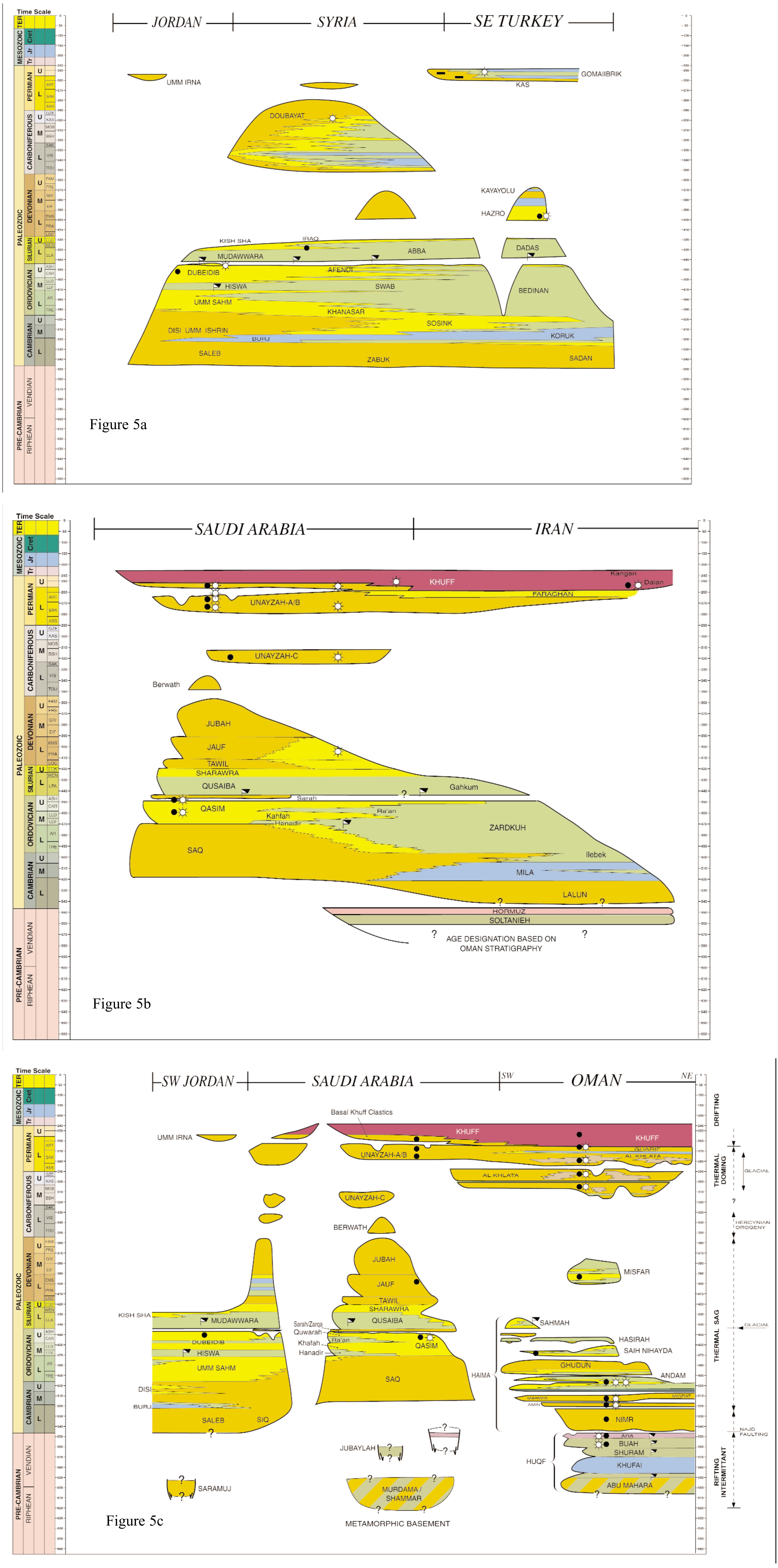


Figure 5. Stratigraphic summary diagrams. a) Jordan through Syria to southern Turkey, b) Saudi Arabia to Qatar, c) Jordan through central Saudi Arabia to Oman. See Figure 4 for key to environments of deposition.

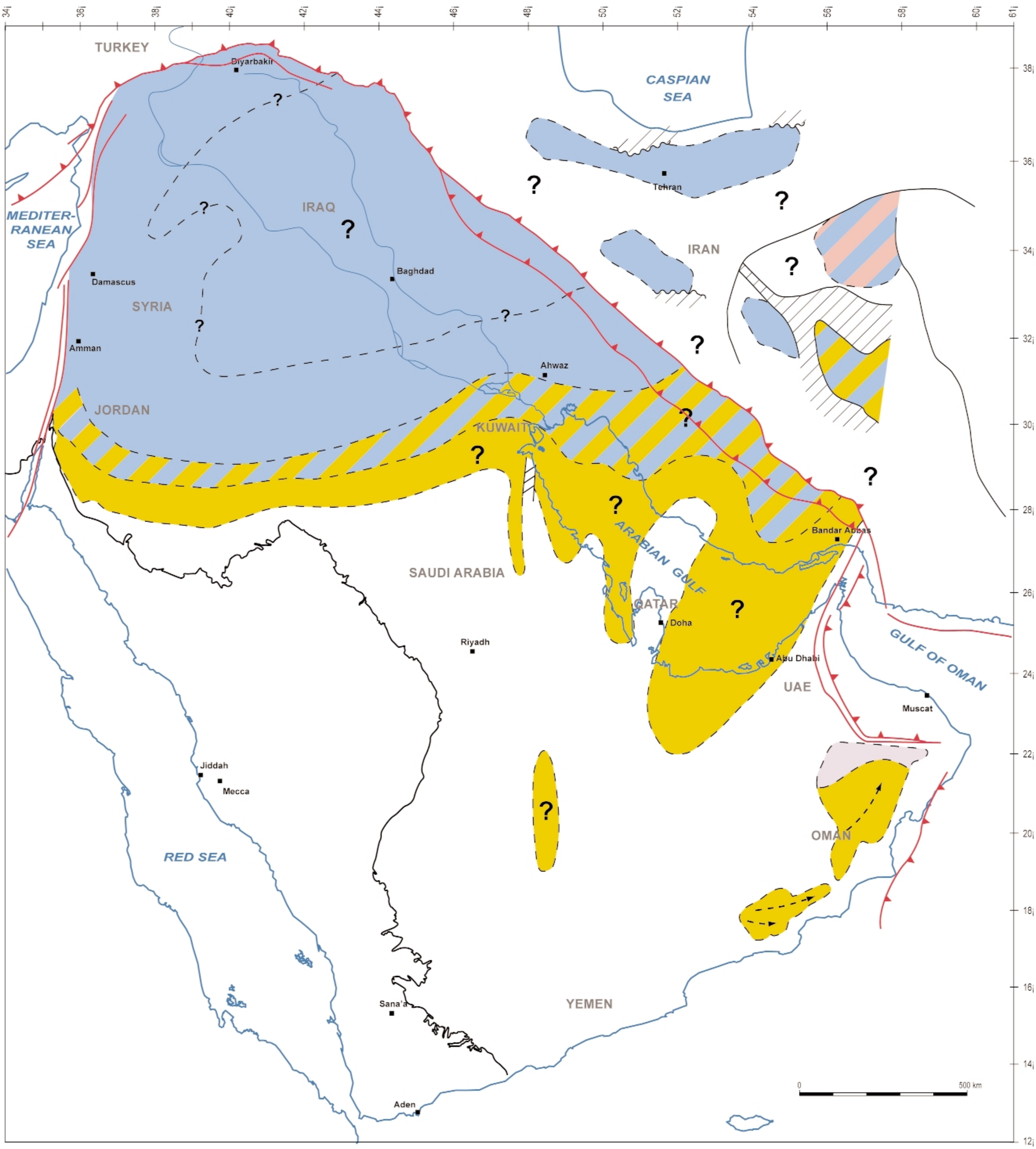


Figure 6. Middle Cambrian environments of deposition. See Figure 4 for key to environments of deposition.

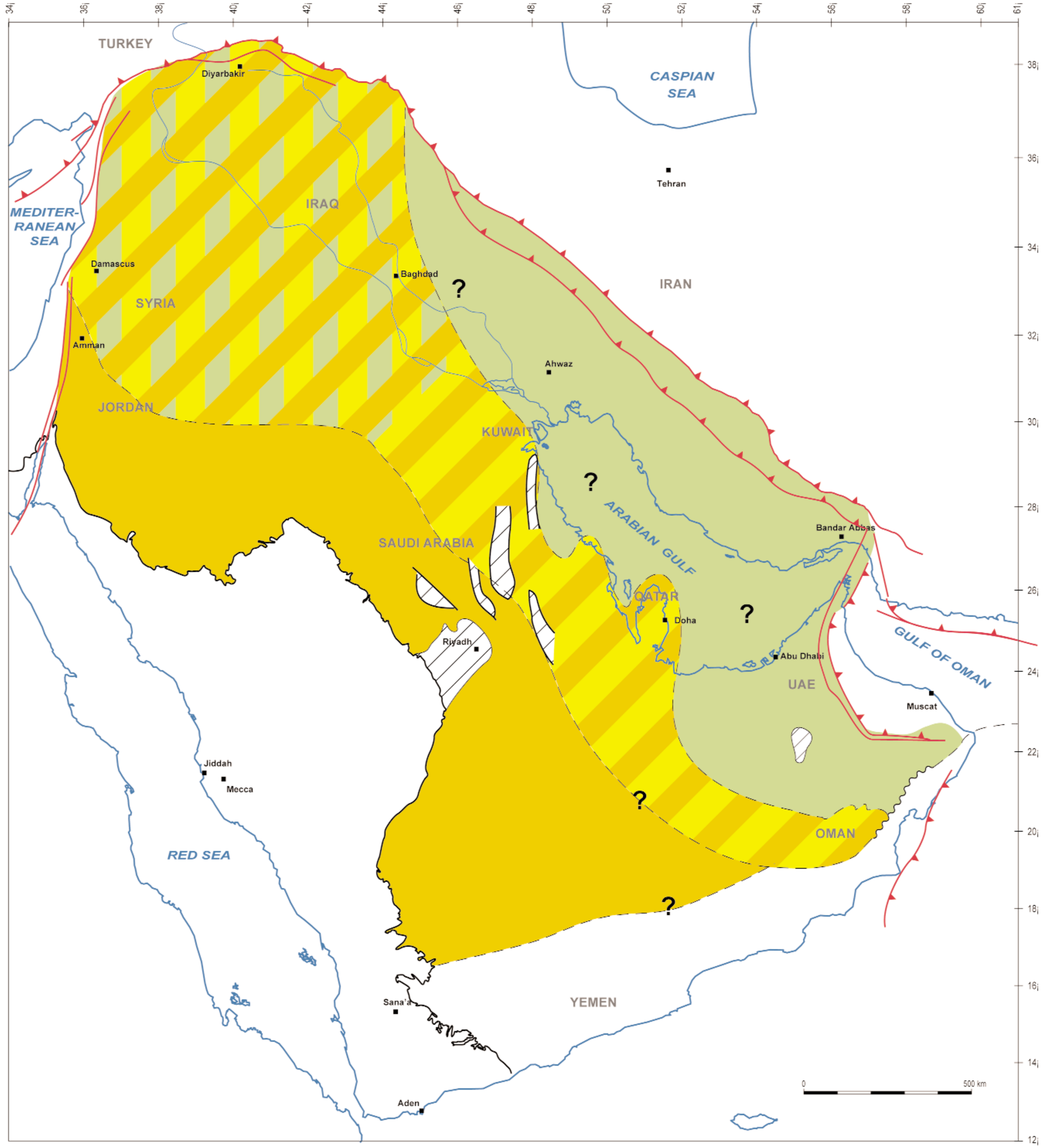


Figure 7. Late Cambrian environments of deposition. See Figure 4 for key to environments of deposition.

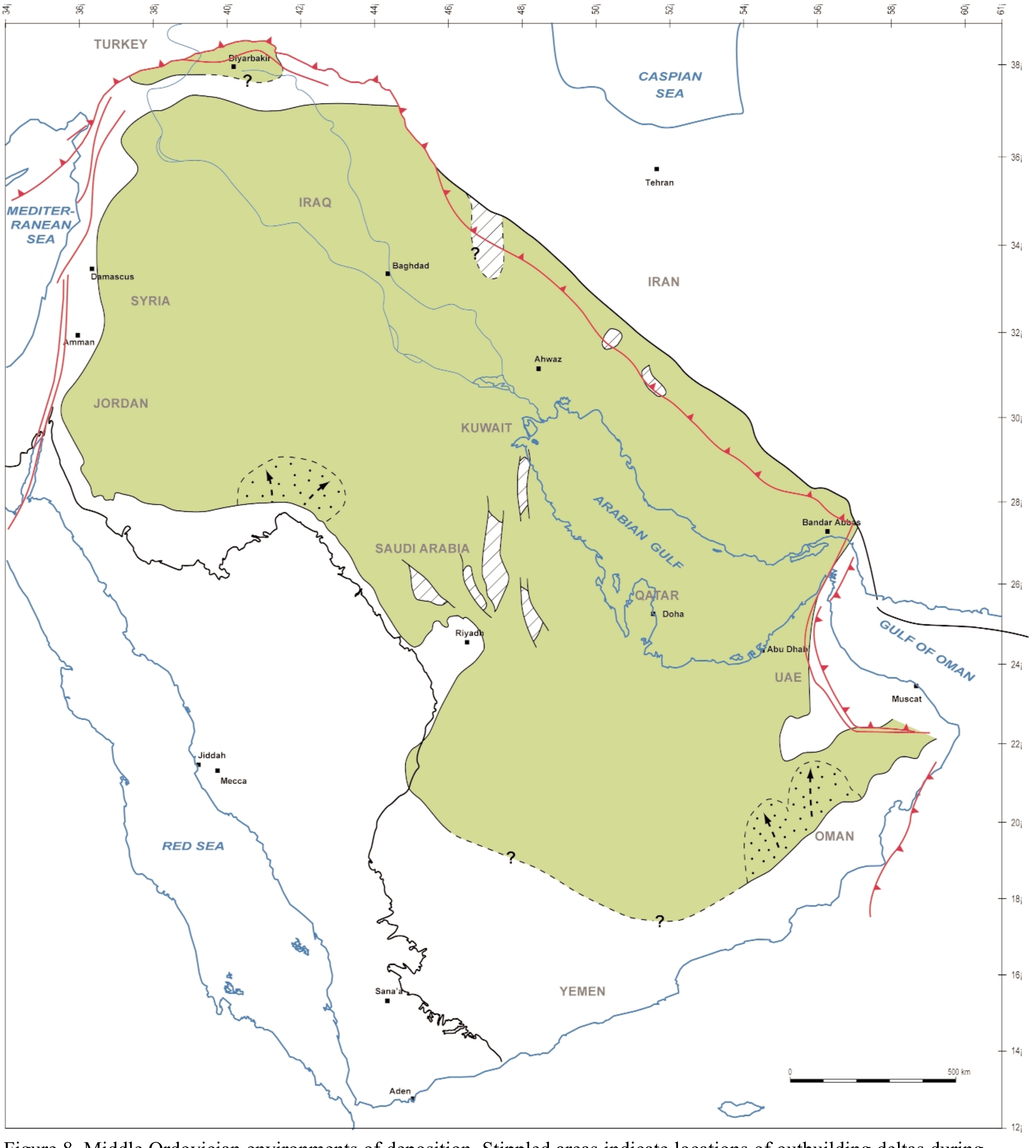


Figure 8. Middle Ordovician environments of deposition. Stippled areas indicate locations of outbuilding deltas during subsequent regressive stage. See Figure 4 for key to environments of deposition.

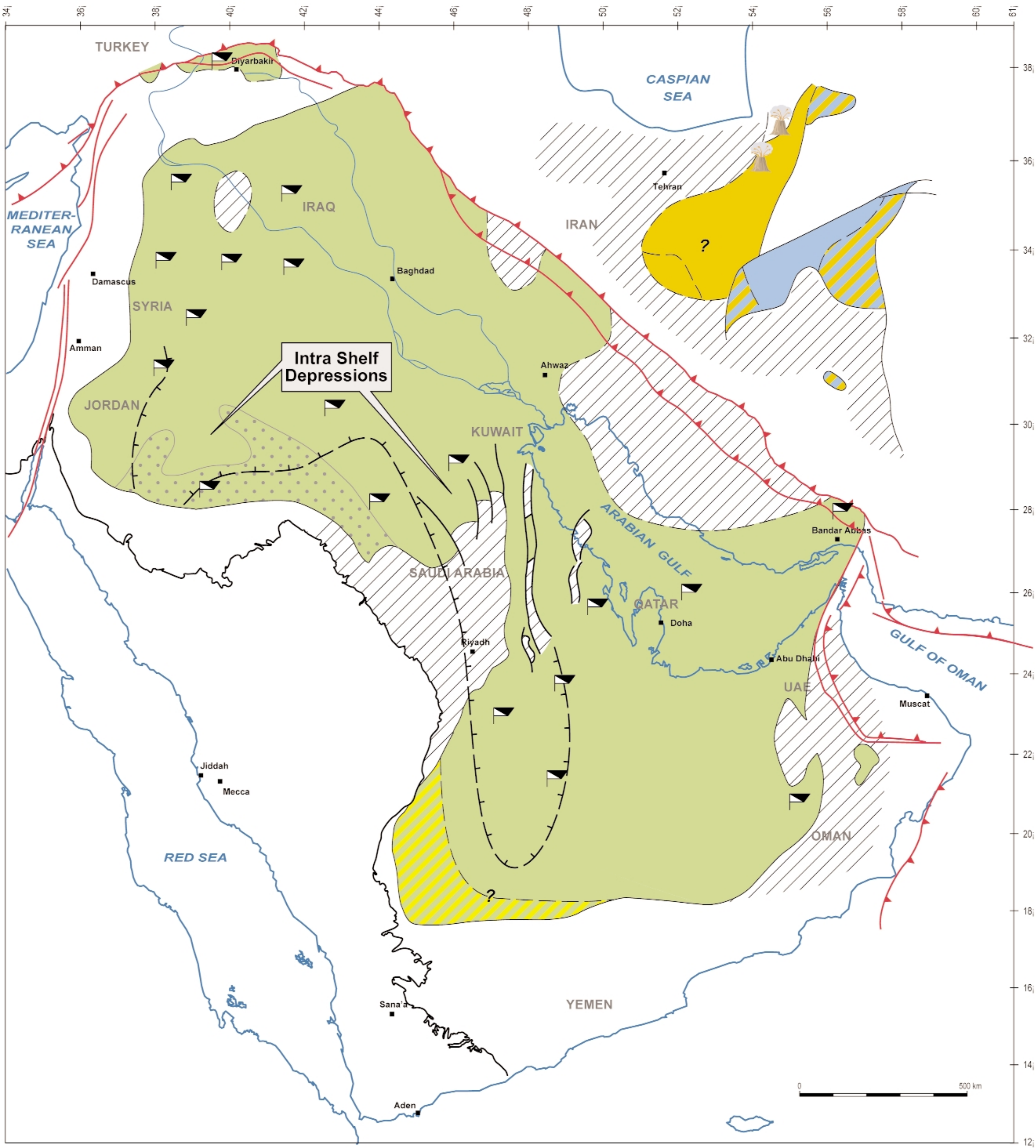


Figure 9. Early Silurian environments of deposition. Stippled area outlines area underlain by latest Ordovician glacial valleys. See Figure 4 for key to environments of deposition.

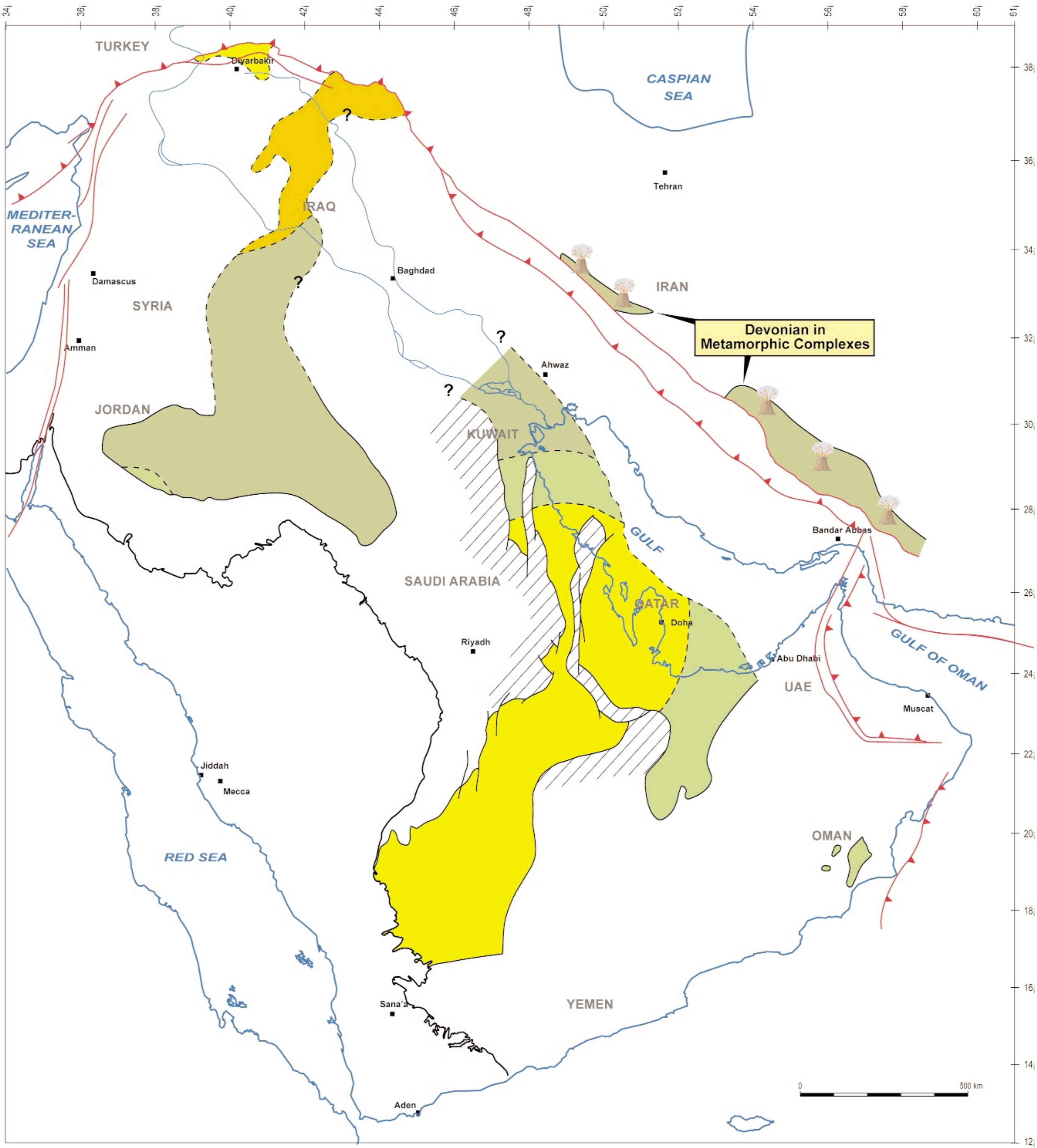


Figure 10. Devonian environments of deposition during the Emsian. See Figure 4 for key to environments of deposition.

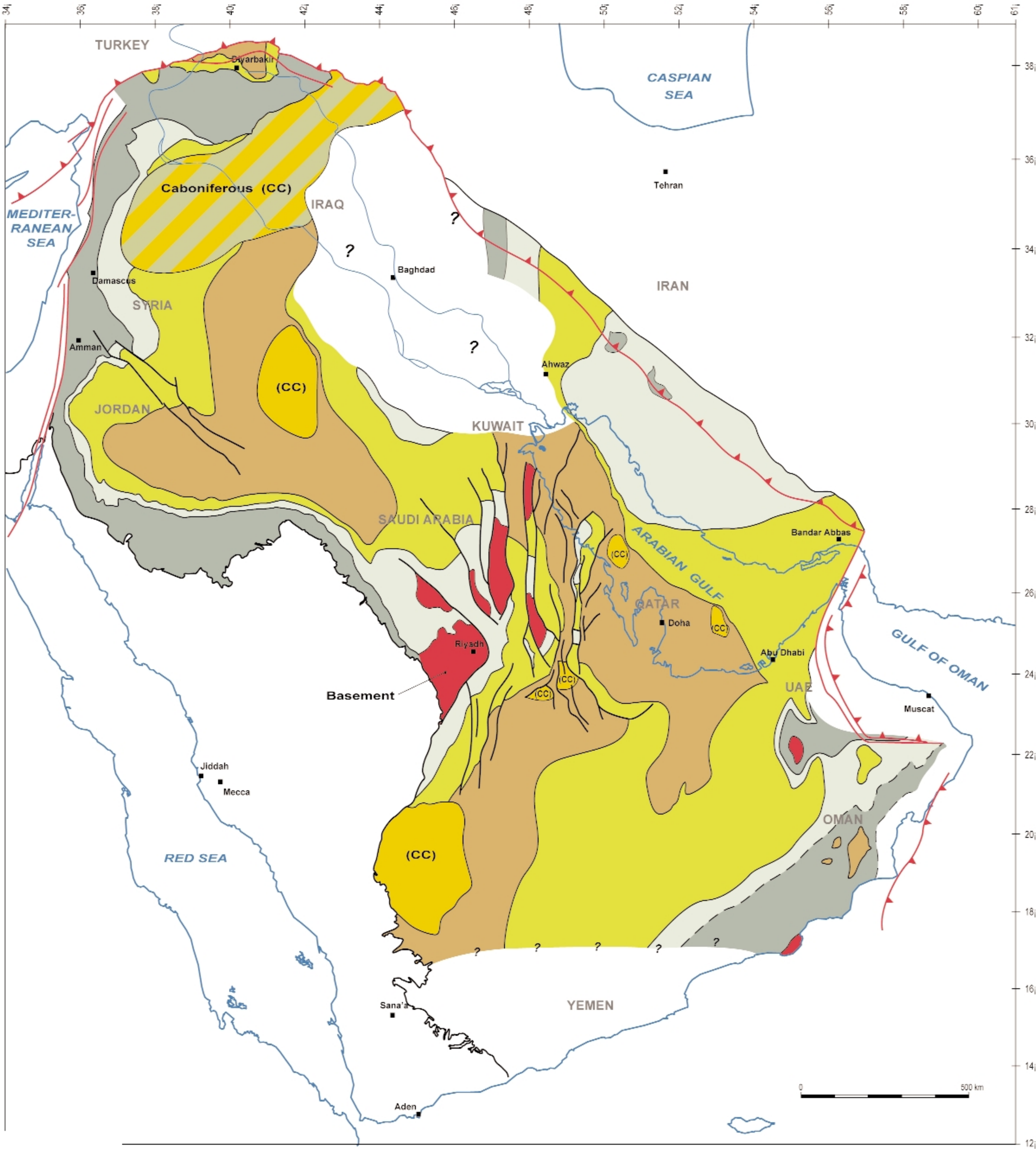


Figure 11. Carboniferous environments of deposition and Hercynian subcrop map. See Figure 4 for key to environments of deposition. Key for subcrop map: see time scale Fig. 5.

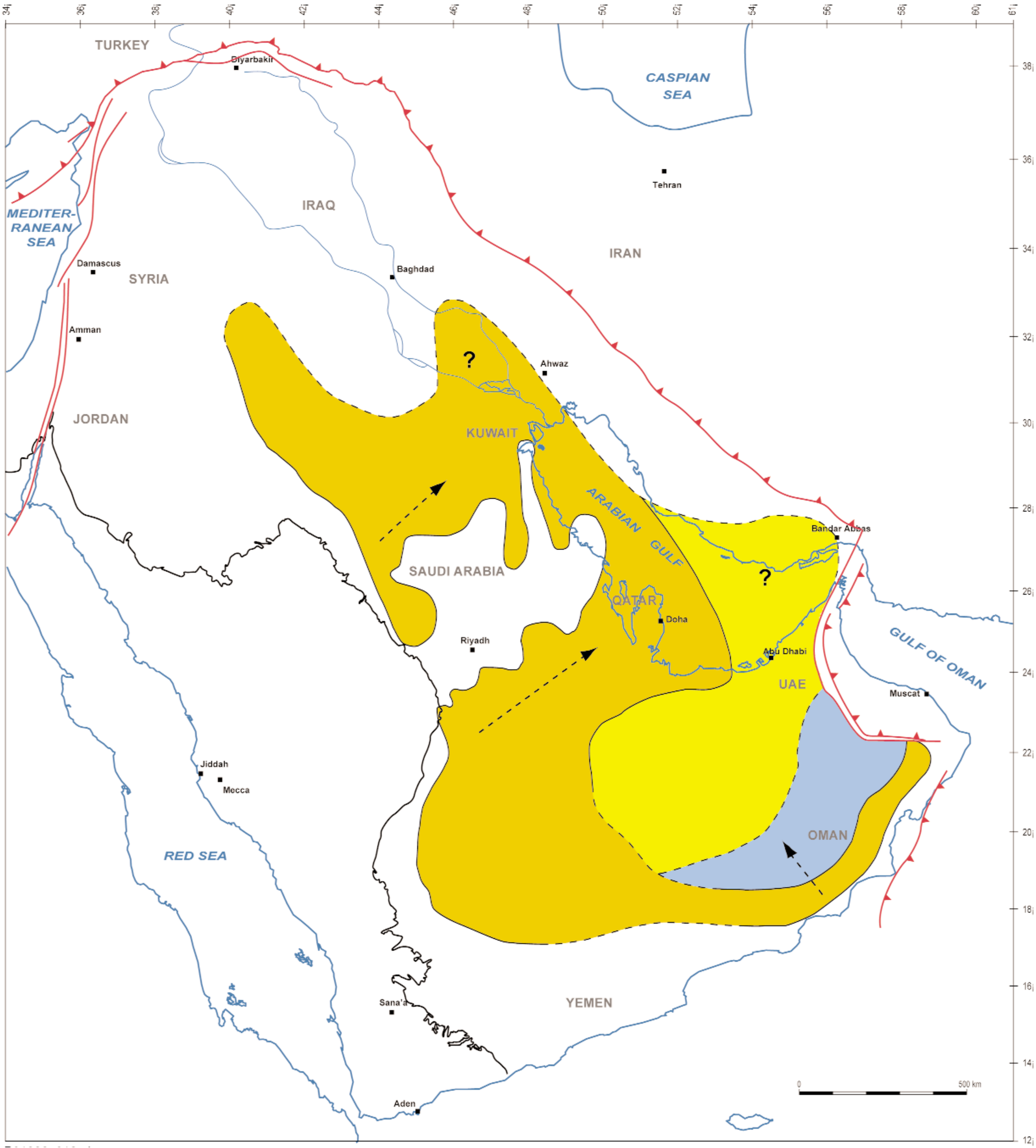


Figure 12. Early Permian environments of deposition at the close of the Sakmarian. Arrows in Saudi Arabia indicate the location of the main channel complexes in the overlying basal Khuff clastics. See Figure 4 for key to environments of deposition.

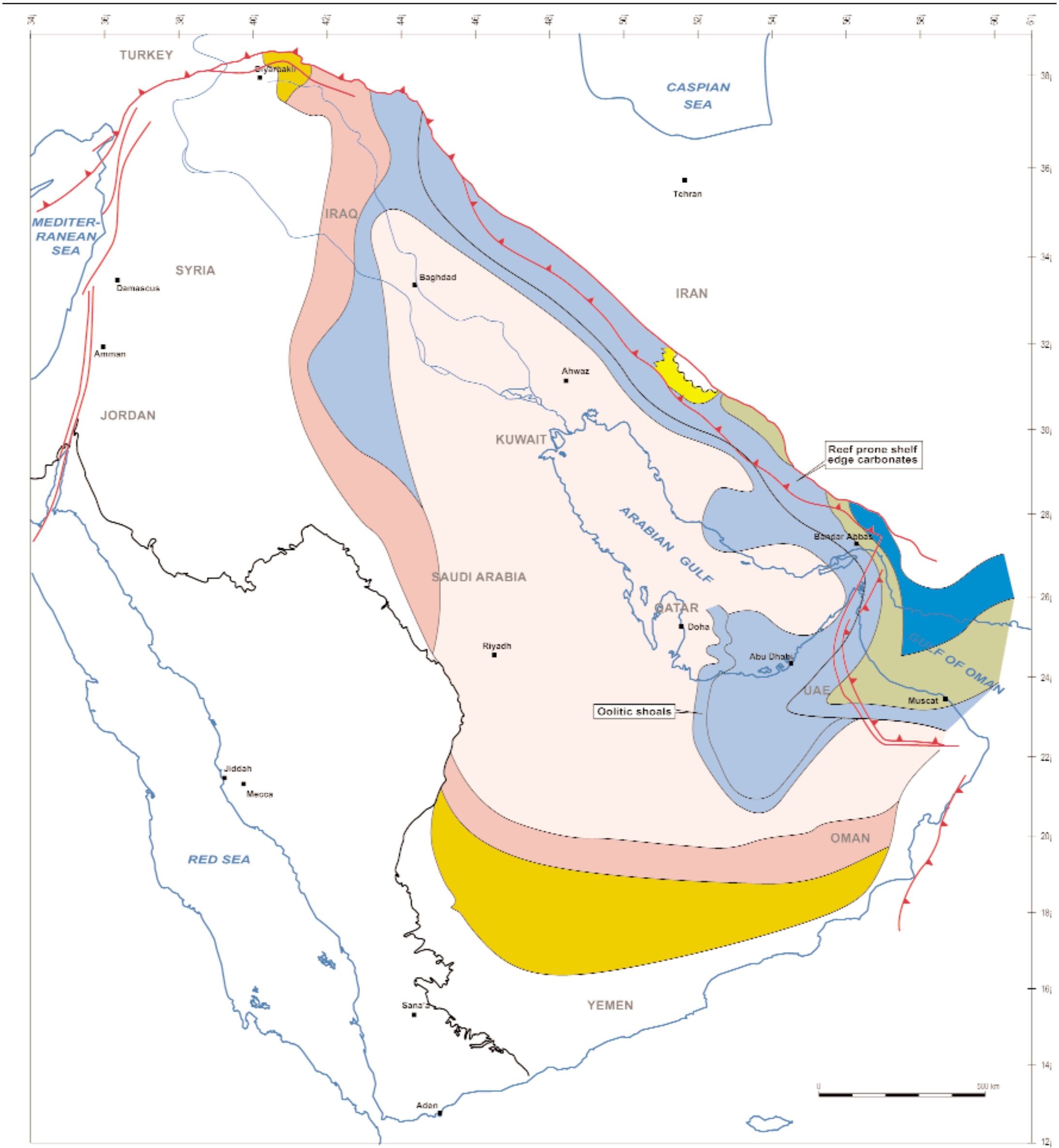


Figure 13. Late Permian environments of deposition during the Kungurian to Tartarian (modified from Al-Jallal, 1995). See Figure 4 for key to environments of deposition.

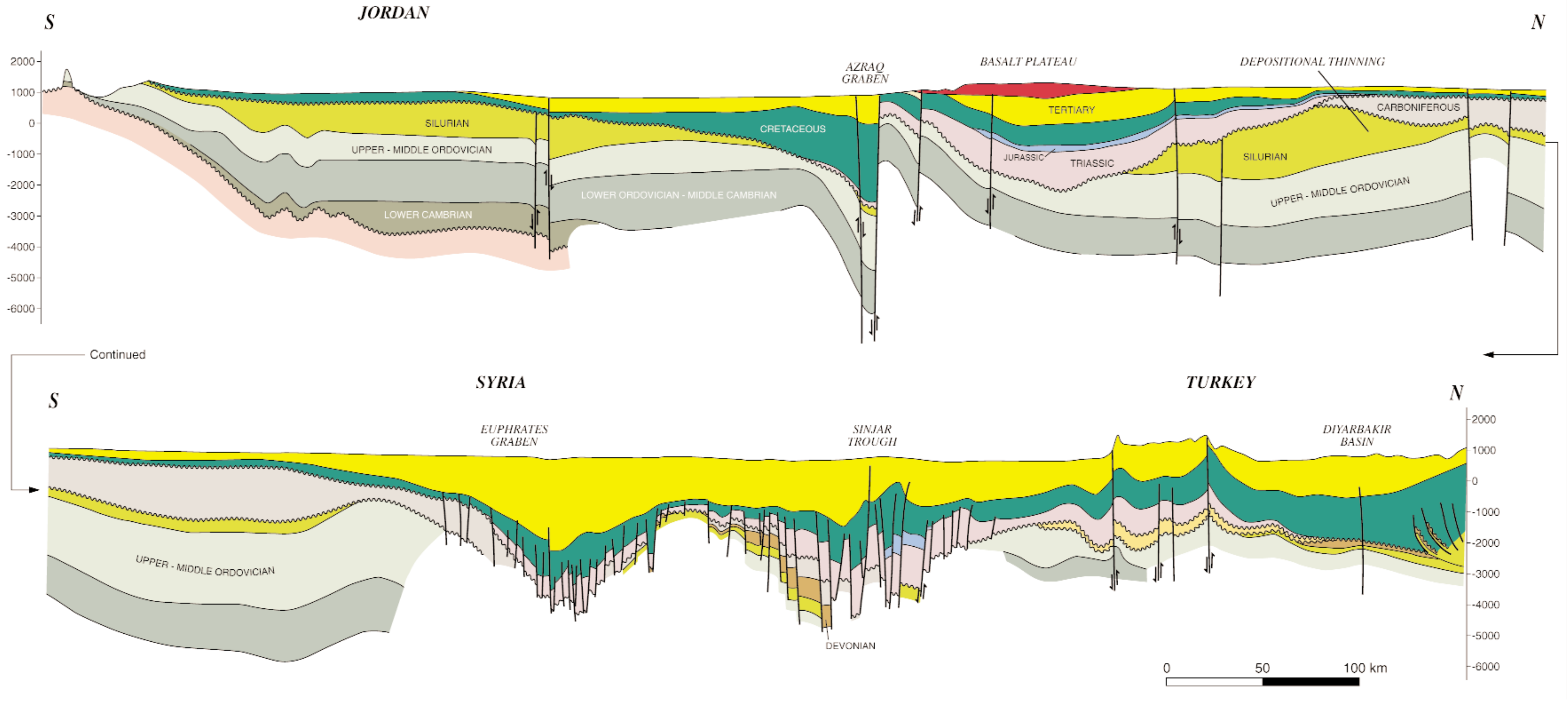


Figure 14. Geologic traverse through Jordan to Turkey. See time-scale Fig. 5 for key. For location see Fig. 1.

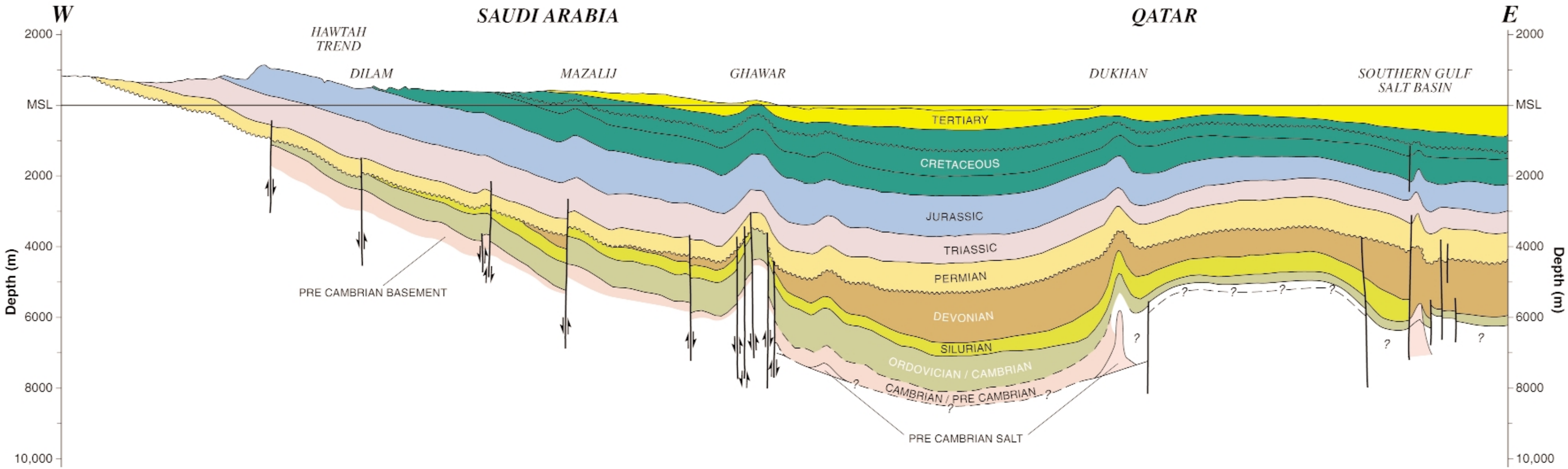
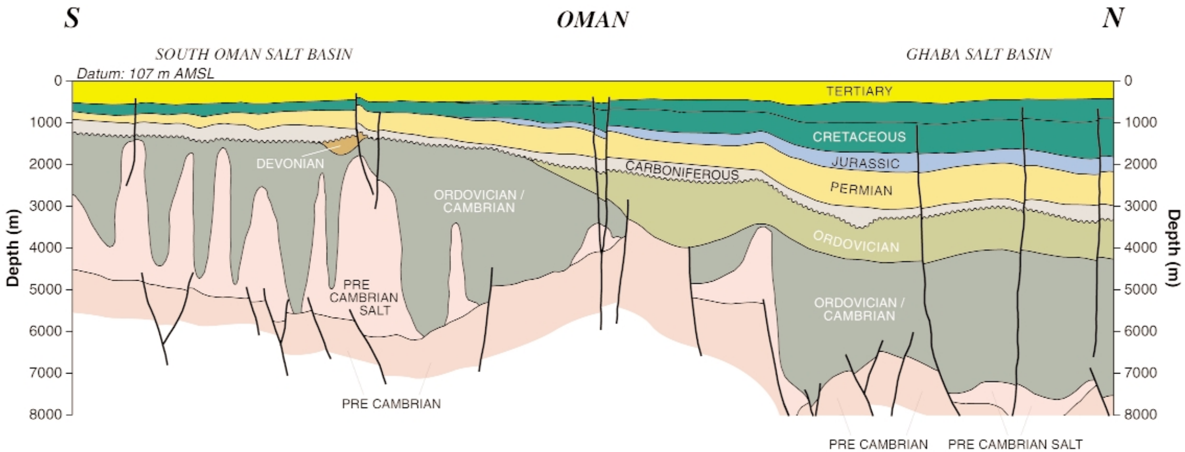


Figure 15. Geologic traverse through Saudi Arabia to Qatar (see also Alsharhan and Nairn, 1994). See time-scale Fig. 5 for key. For location see Fig. 1.



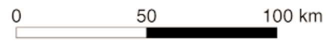


Figure 16. Geologic traverse through Oman. See time-scale Fig. 5 for key. For location see Fig. 1.

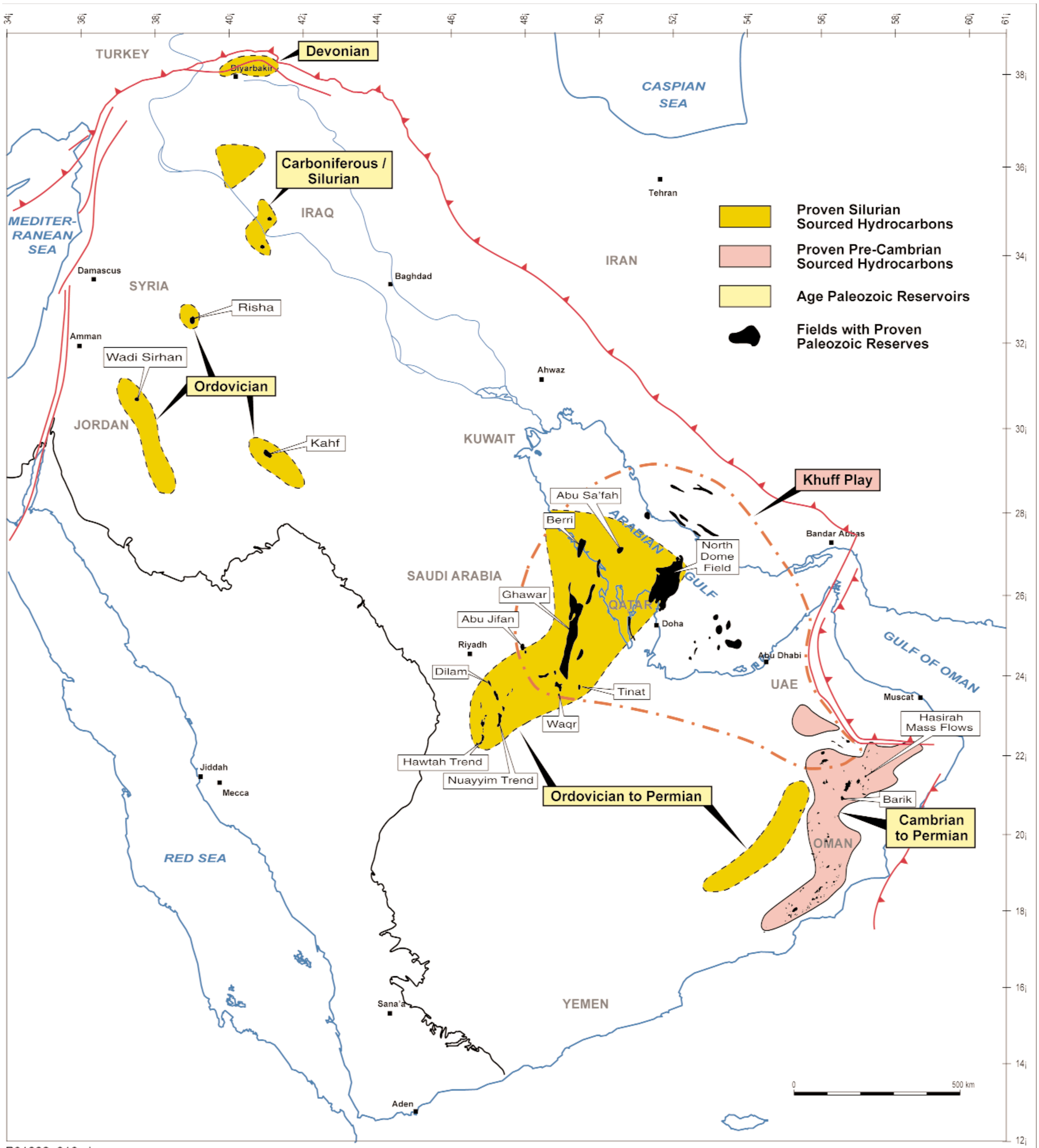


Figure 17. Map showing the proven extent of the Silurian and Precambrian petroleum systems.

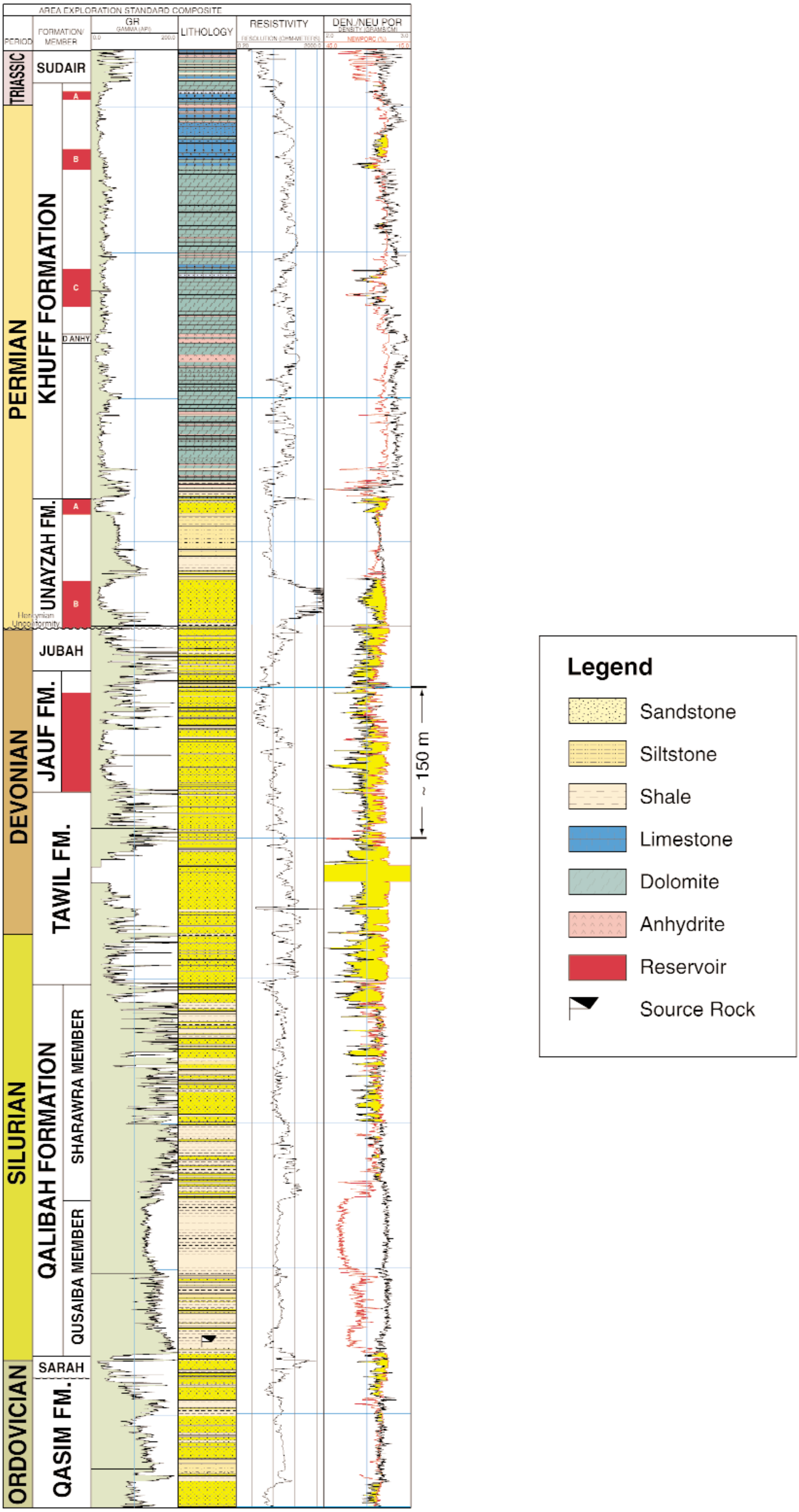


Figure 18. Composite log of the Paleozoic section in the Ghawar area in Eastern Saudi Arabia. See Figure 4 for key to environments of deposition.

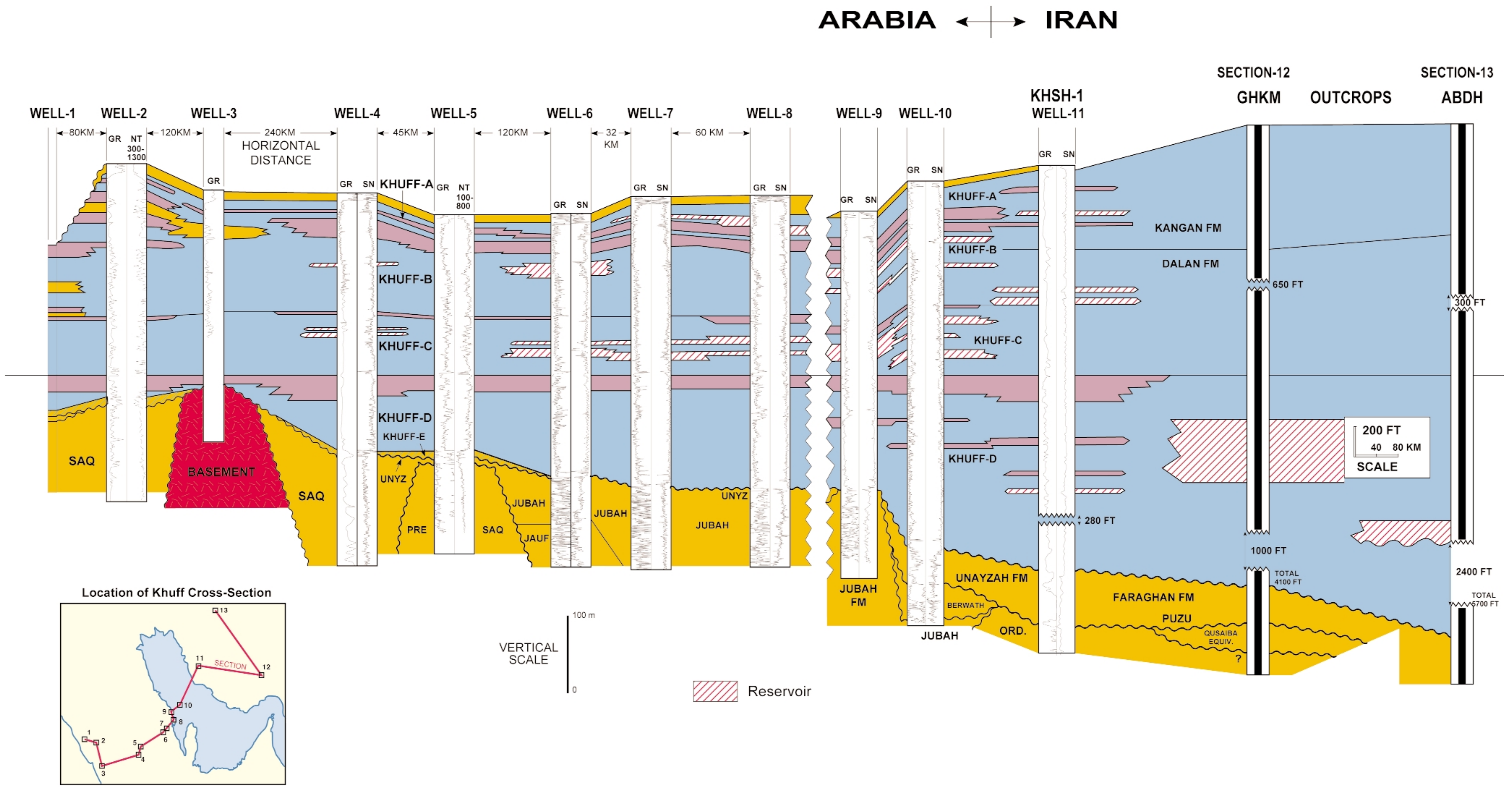


Figure 19. Stratigraphic cross section from Saudi Arabia to Iran, showing reservoir development in the Khuff A-D reservoirs. Datum is the Khuff D anhydrite.

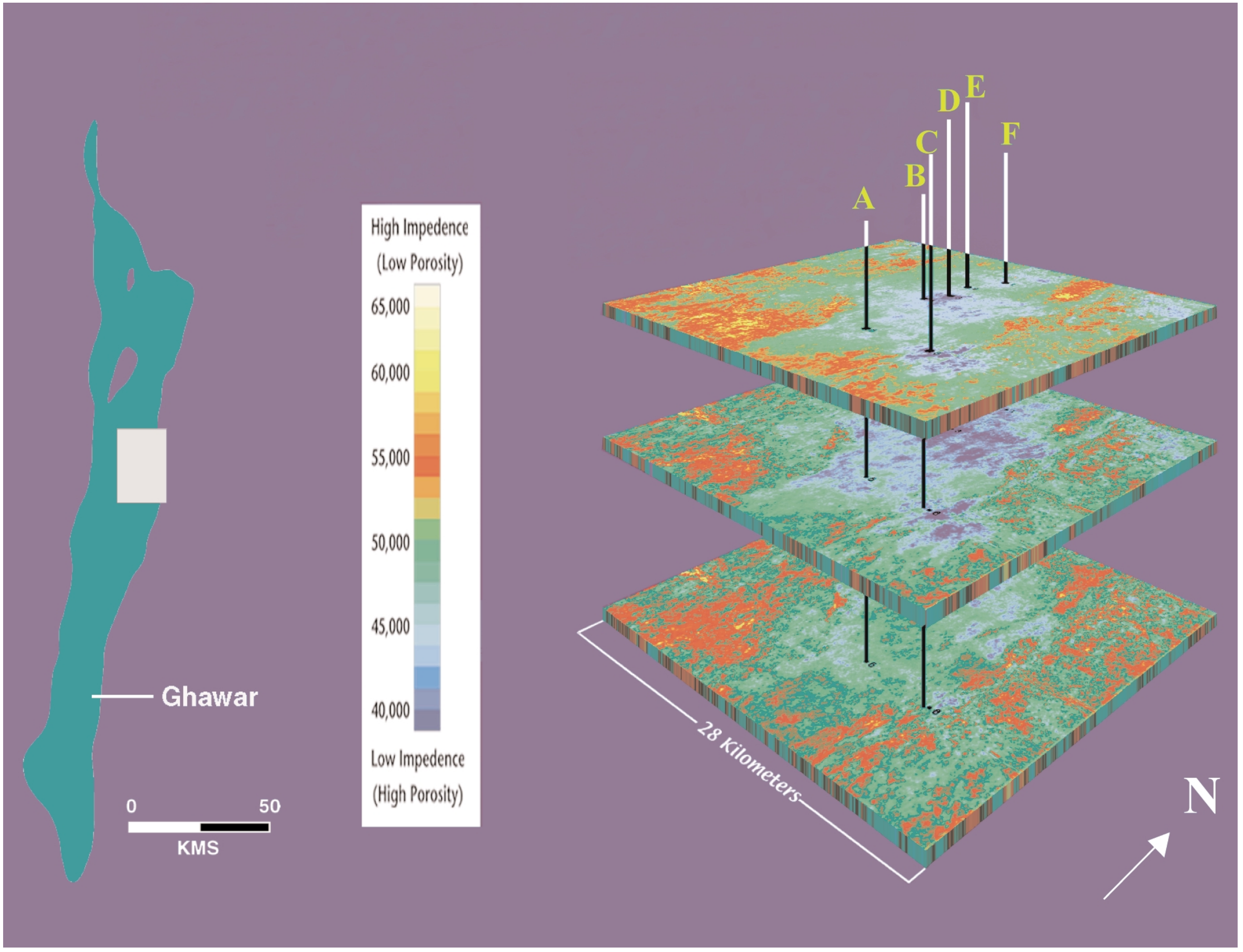


Figure 20. Perspective diagram showing 3D seismic impedance in the Khuff-C reservoir used to locate six development wells.

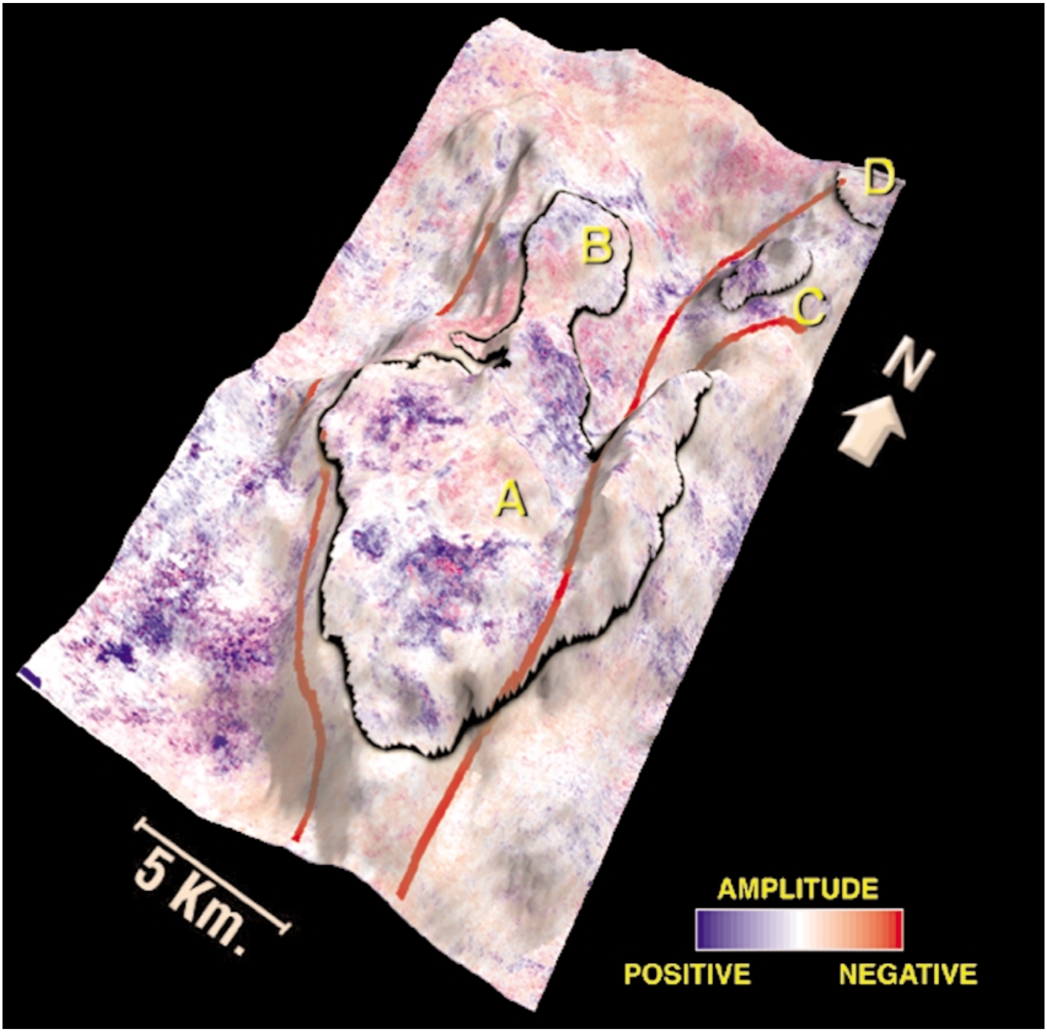


Figure 21. Perspective diagram of the Hawtah oil field, Central Saudi Arabia, from 3D seismic data, showing amplitude of the Unayzah reservoir draped over structure. The flanks of the structure are drape folds over deep Hercynian faults. The blue areas correspond to good reservoir development in eolian sandstone facies, whereas the red areas correspond to non-reservoir facies. A: Poor reservoir at the crest of the Hawtah structure; B: Stratigraphic trap in the north Hawtah area defined by the updip pinchout of the reservoir; C: Nisalah field.

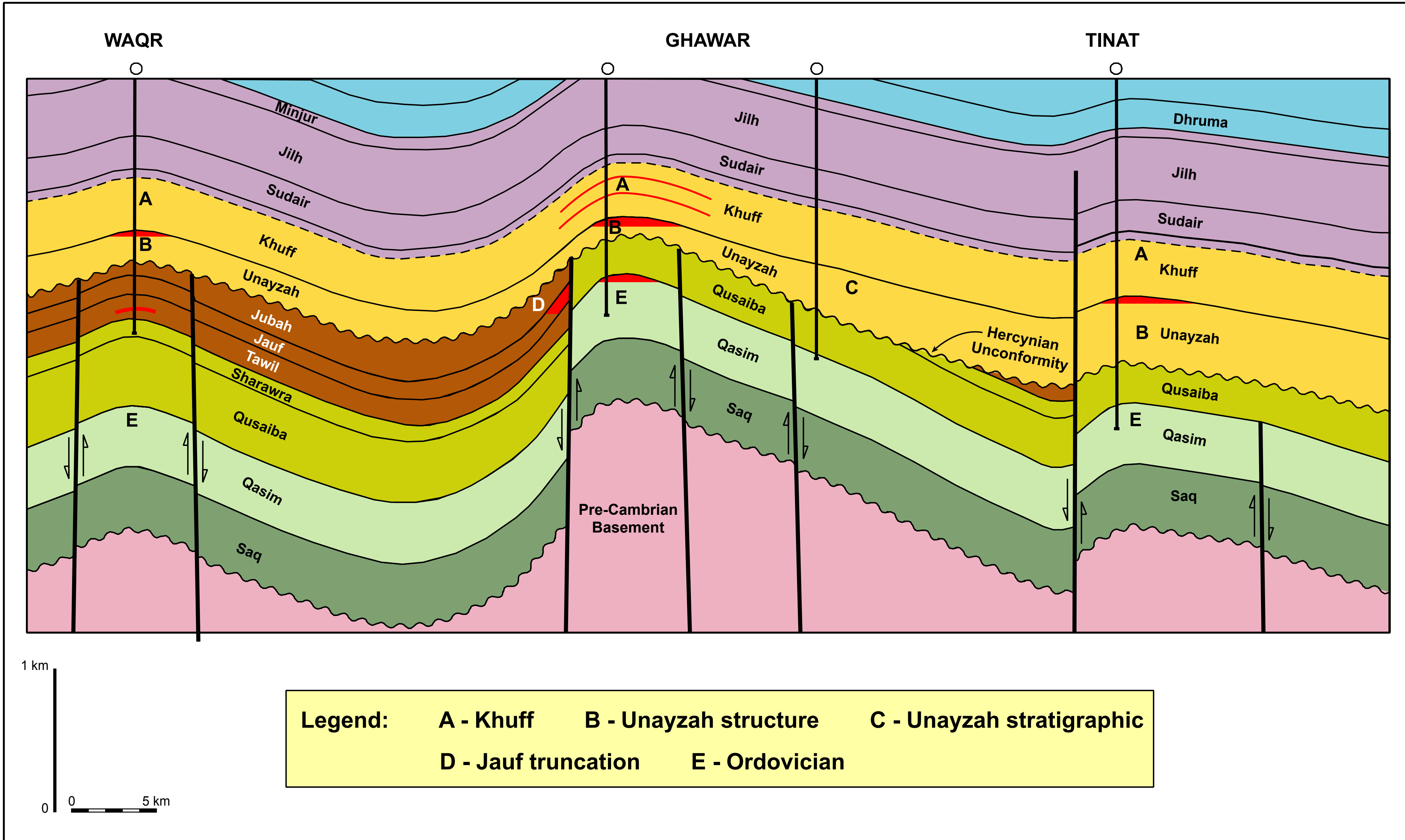


Figure 22. Schematic E-W structural cross section across the Waqr-Ghawar-Tinat fields, showing the major Paleozoic plays.

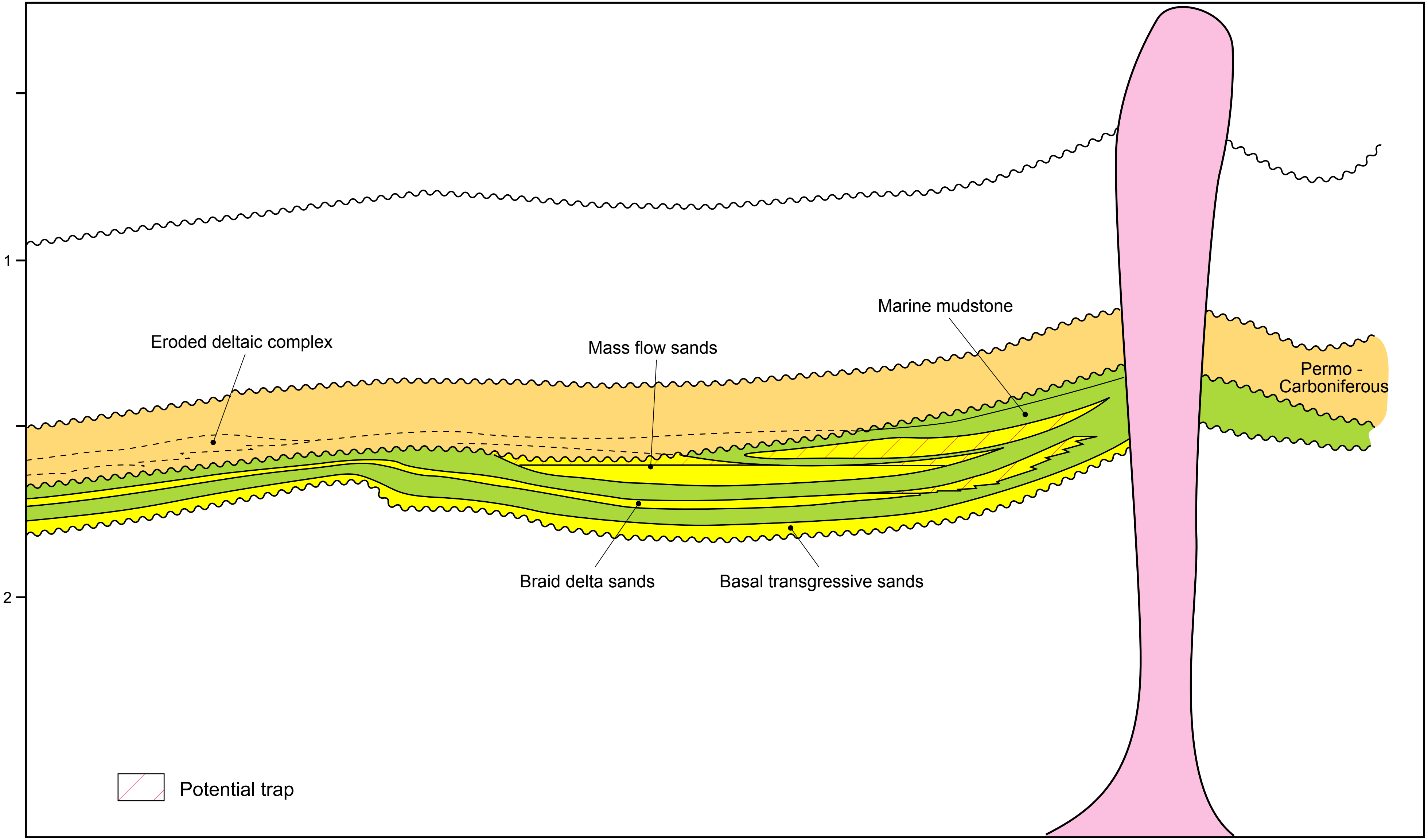


Figure 23. Conceptual diagram showing the Ordovician mass flow sand play.

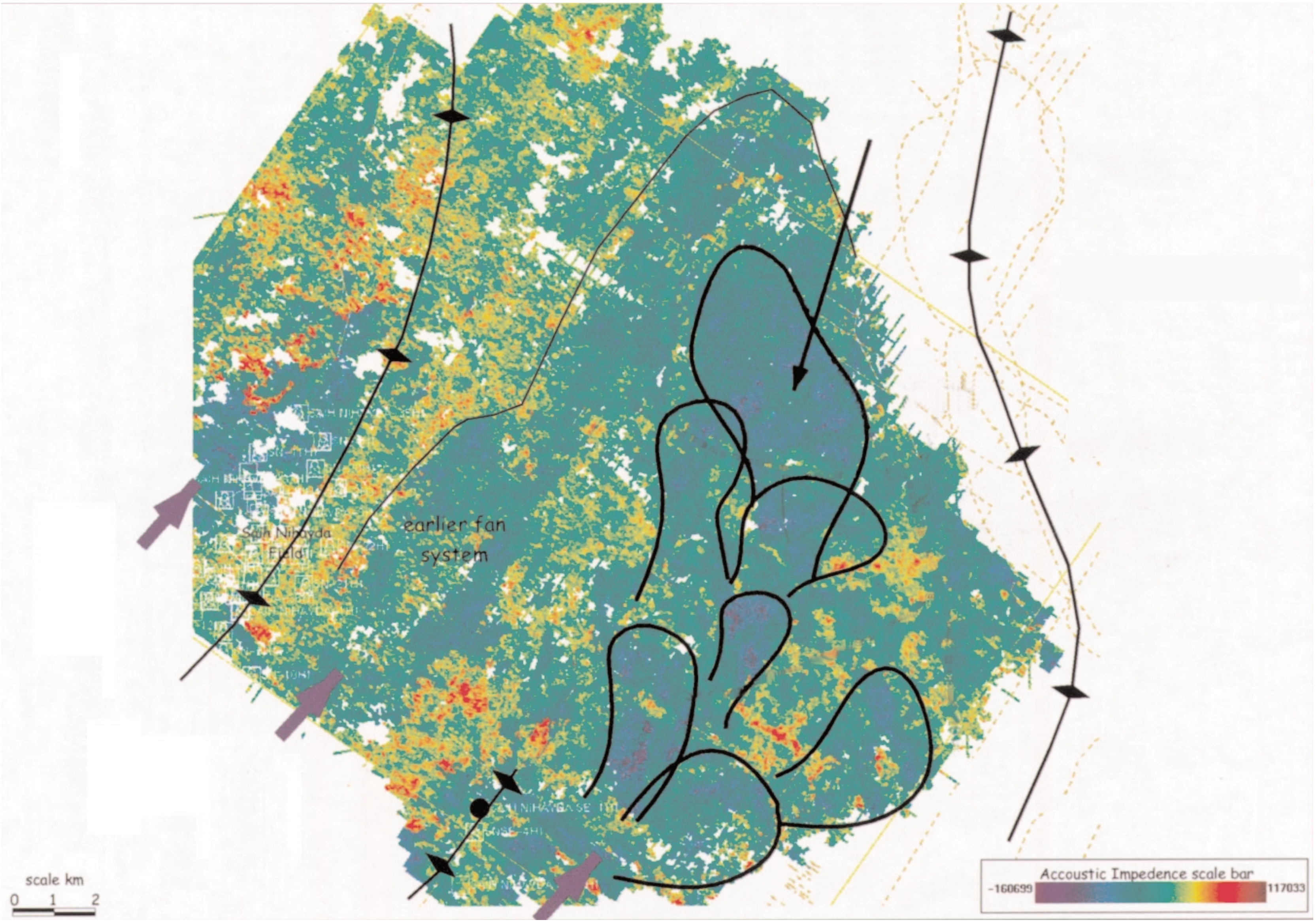


Figure 24. Acoustic Impedence on a time window around the mass flow sand loop highlights the sand-probe lobes. Sands are fed from the SSW via paleo-saddle points.

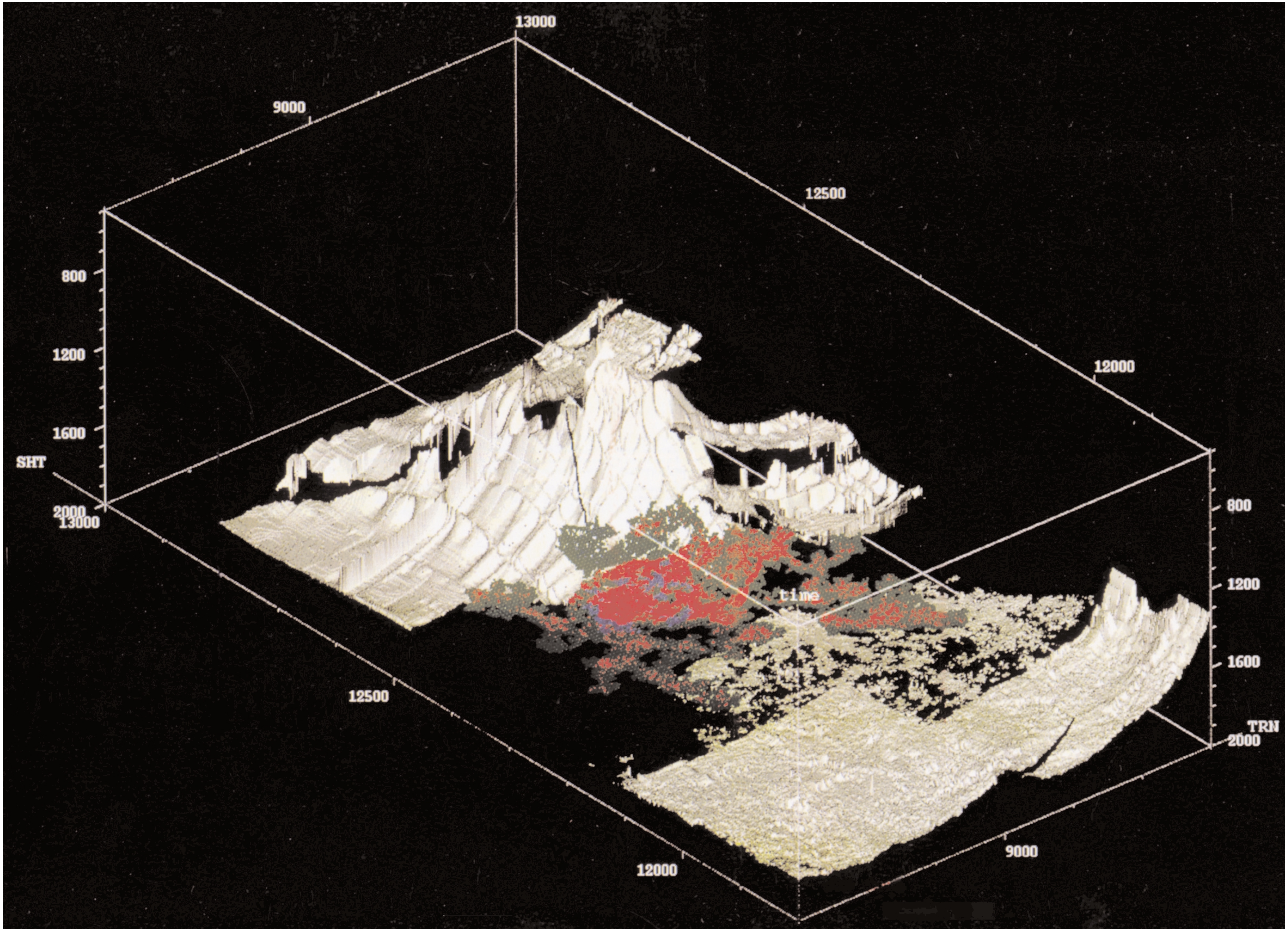


Figure 25. Body checked mass flows. Note that the dome structure to the north is cored by salt.

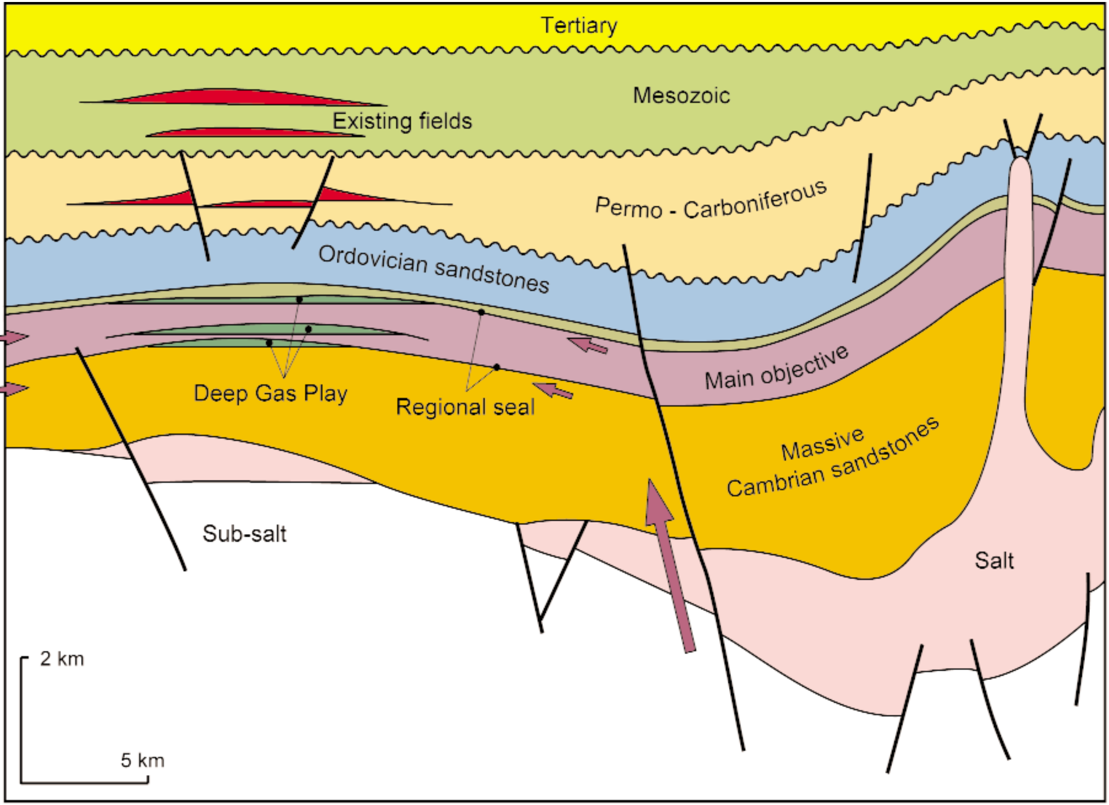


Figure 26. Conceptual diagram showing the Haima deep gas play.

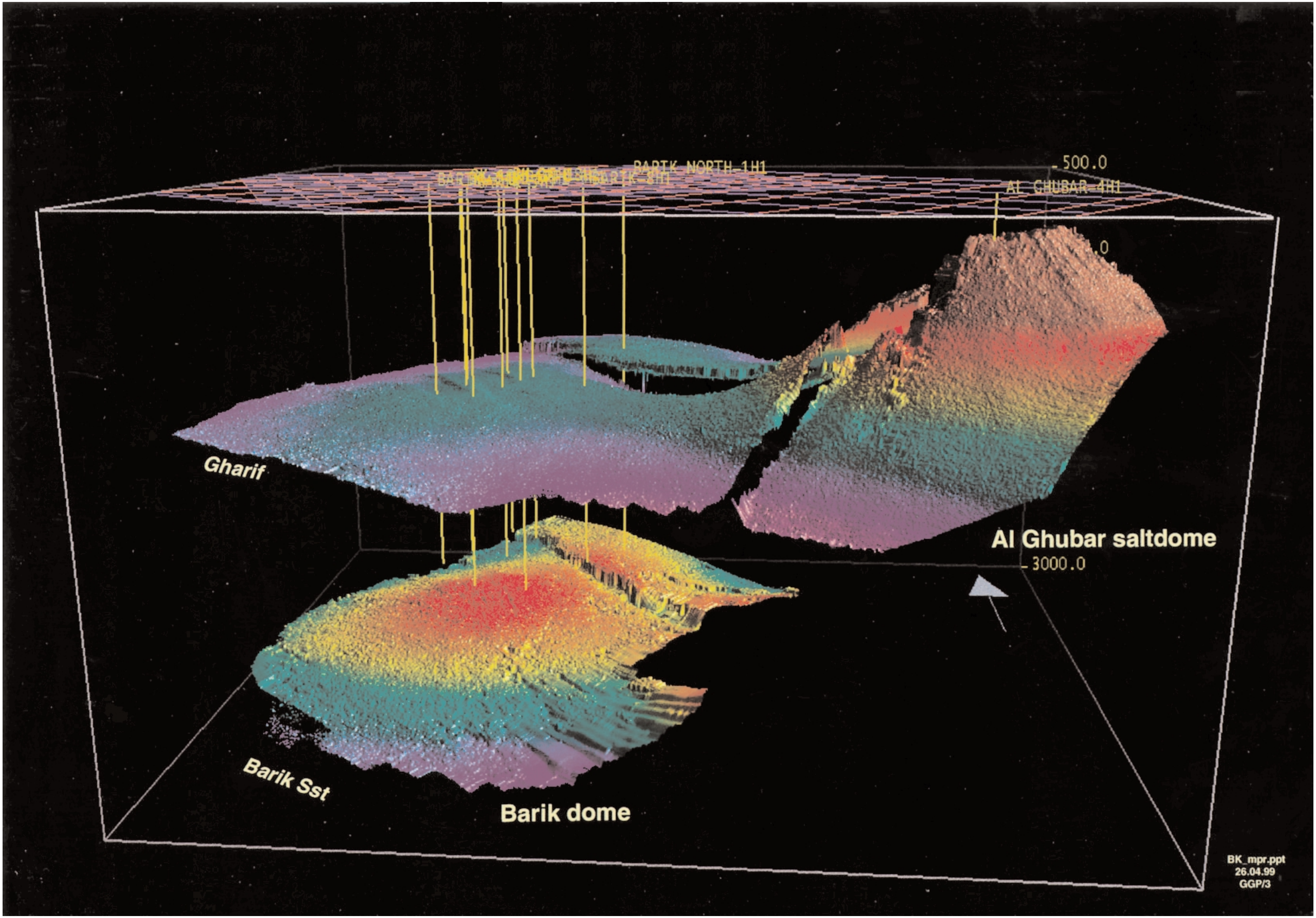


Figure 27. Structural presentation of the Barik structure and the Al Ghubar salt dome at Permian (Gharif) and Ordovician (Barik sandstone) level. The Gharif horizon represents the main reservoir in the Barik Field. The Barik sandstone horizon shows the structure at the deep Haima gas objective. Note that NW-trending faults compartmentalize the structure. Colors represent travel time.