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* شرکت نفتی کونکو، هوستون، آمریکا

** دپارتمان علوم زمین، دانشگاه تنسی

* Conco Inc., Geoscience, P. O. Box 2197, Houston, TX. U. S. A.

** Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996- 1410, U. S. A.

Figure 5d. Folded Asmari Fm. carbonates overlain by Gachsaran Fm. evaporites (white). The Miocene Gachsaran Fm. was the initial deposit in the developing foredeep associated with the late Tertiary Zagros orogeny. The Gachsaran Fm. evaporites at this locality are now folded along with the Asmari Fm. This is the result of progressive northeast to southwest deformation, as the foreward development of the fold-thrust belt gradually deforms its own foredeep. The photograph was taken from the main highway southeast of Pol-e-Dokhtar.

the Zagros oils. Furthermore, imbrication and overthrusting of Arabian Platform rocks within the FFTB is not restricted to the late Tertiary Zagros event; contraction began in the Late Cretaceous and continues to the Present Day. This led to progressive trap formation, multi- stage hydrocarbon generation, and complex migration, re- migration and accumulation of hydrocarbons. The Oman Mountains may provide a pre- collision snapshot of the Zagros. By comparison with Oman, compressional traps probably formed on the Arabian platform in advance of the obducted ophiolite allochthons. Source rocks on the platform margin which became buried under the Amiran Foredeep, would have been forced to depths adequate to initiate hydrocarbon generation. The extent to which these early formed hydrocarbons would have been preserved, remigrated, or thermally cracked during subsequent burial, is a subject for future study.

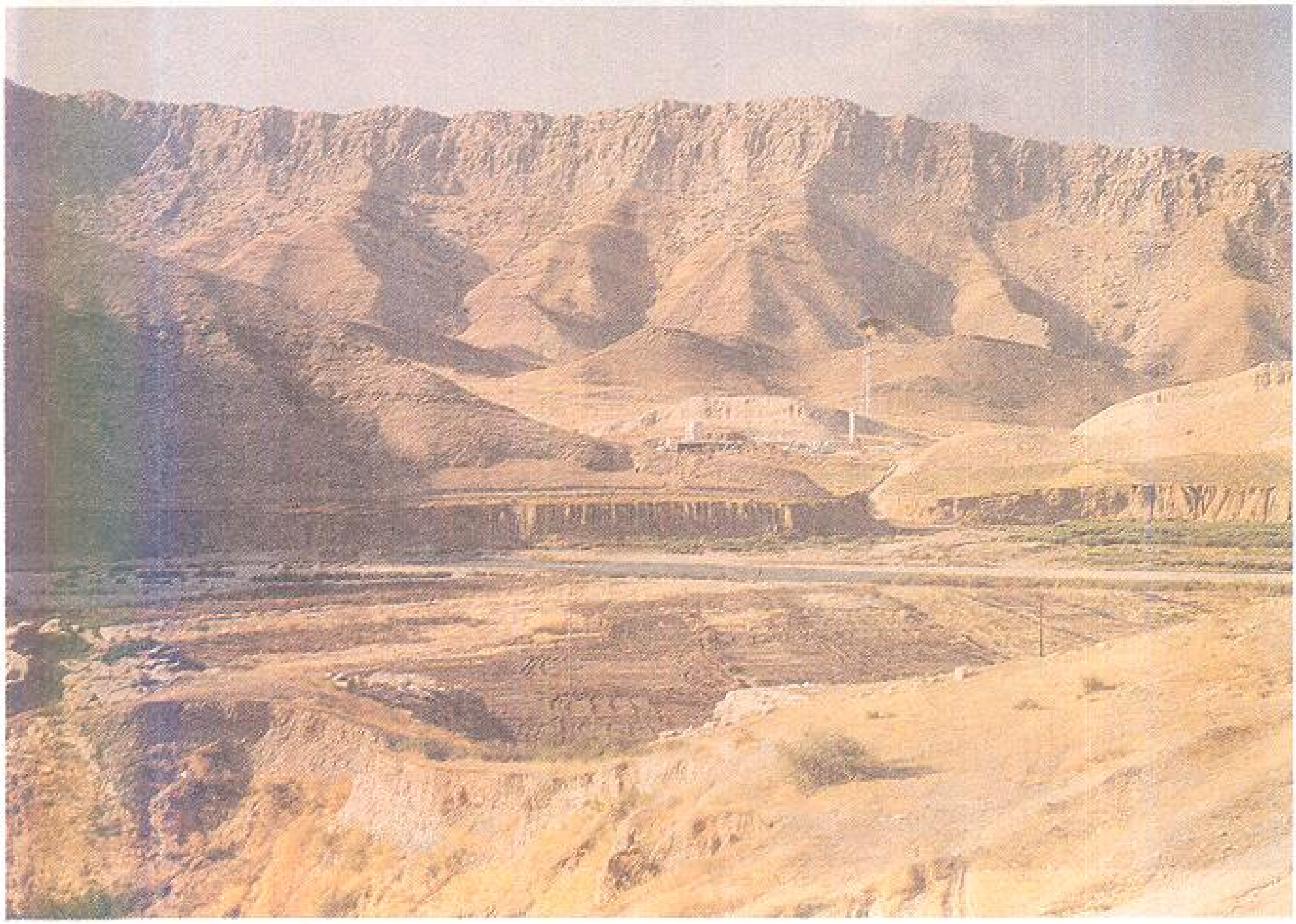

Figure 5c. Early Tertiary rocks are exposed in the core of Maleh Kuh, a large NE-SW trending asymmetric anticline in the Simply Folded Belt of the Zagros fold-thrust belt. The rocks exposed in the cliff are, from the top down, the Asmari Fm., Eocene red beds, and Amiran flysch. The Amiran flysch was originally deposited in a Cretaceous foredeep related to ophiolite emplacement. This early foredeep was subsequently deformed by the late Tertiary Zagros orogeny. The flare from Maleh Kuh field, which produces primarily from the Upper Cretaceous Sarvak and Ilam Fms., can be seen in the centre of the photograph. The photograph was taken from the main highway northeast of Pol-e-Dokhtar

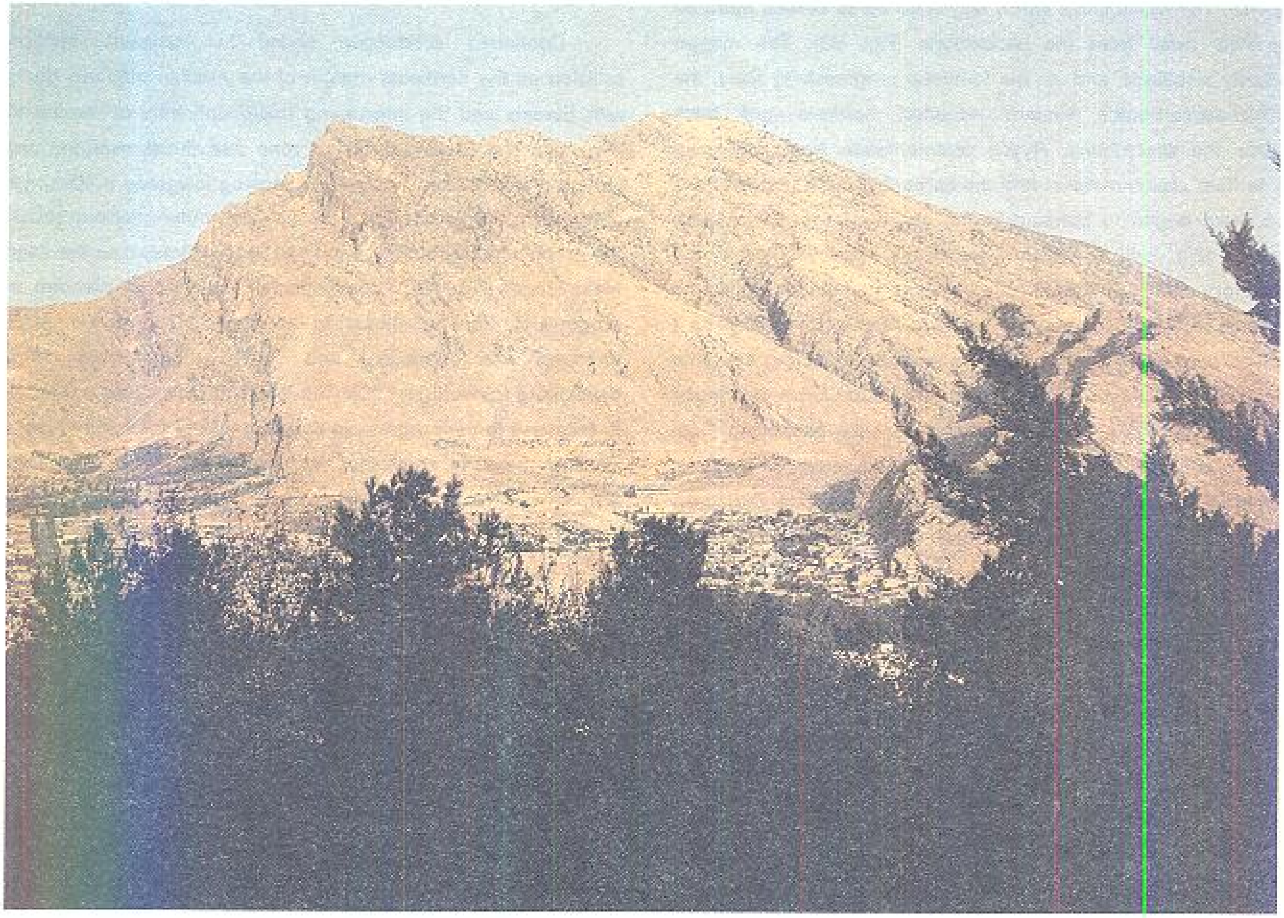

Figure 5b. Middle Cretaceous limestones of the Bangestan Group within the Simply Folded Belt of the Zagros fold-thrust belt. The limestones are folded by a large doubly-plunging anticline trending NW-SE. This photograph, looking northwest, views the northeast-limb of the fold where bedding now dips at ca. 25° to the northeast. The rocks are carried in a thrust sheet within the fold belt and may have been transported many kilometres from their original site of deposition. The town of Khurramabad lies at the foot of the mountain.

encroaching from the northeast (Fig. 5D). These eventually gave way to northeast derived clastic sedimentation (e.g. Agha Jari) shed from the upwelling orogen (Fig. 4G).

Implications

The hydrocarbon system in the Zagros FFTB is probably more complicated that generally recognized. Proprietary industry studies in the 1970's provide evidence of hydrocarbon accumulation as early as the Middle Cretaceous, based on outcrop data around diapiric extrusions. Beydoun (1992) also refers to evidence of oil accumulation and seepage in the Late Cretaceous This early formed oil was probably generated from a Paleozoic source; Mesozoic source rocks were likely immature at this time. Mesozoic source rocks, however, are believed to be the source for most of the oil in Iran (Bordenave et al 1989). This oil is generally interpreted to have migrated into Mesozoic reservoirs and subsequently remigrated into the Asmari reservoirs when the early traps were breached during the Zagros orogeny (Ala 1982).

Recent industry studies reveal, however, that while in a gross sense this is hypothesis is reasonable, the full story is somewhat more complex and other intervals have contributed to erosion, sediment loading and a general widening of the foredeep (Fig. 4D). The flysch/shale apron aggraded up to several hundred kilometers away from the allochthons (Fig. 3G). The margin gradually stabilized, and, as the foredeep progressively filled, the flysch/shale/carbonate system retracted northeastward back towards the allochthons. Flysch sedimentation eventually gave way to finer clastic material and the carbonate bank (Asmari Fm.) once more began to buildout to the northeast over the Amiran foredeep (Fig. 3H). The source for clastic sedimentation in the allochthon- derived flysch/shale system remained from the northeast. The Arabian margin must have been relatively high as it received comparatively little or no sedimentation during this time especially on the promontories (Fig. 4D). Subduction continued under the Sanandaj- Sirjan zone, progressively destroying Neo-Tethys and fueling igneous activity in the Sanandaj- Sirjan zone. Southern Neo- Tethys was all but closed by the Late Oligocene and the Sanandaj- Sirjan zone had docked with the Arabian platform (Figure 4e). The closing was diachronous, beginning earlier in the northwest and progressing to the southeast.

Early Miocene to Recent

Continued subduction ended in continent- continent collision as the northeast margin of the Arabian platform docked with Eurasia and the intervening microcontinents of Central Iran (Fig. 1B). The Sanandaj- Sirjan zone was thrust over the distal portion of the Arabian margin juxtaposing lowgrade metamorphic rocks of the Sanandaj- Sirjan zone against outer- platform rocks of the Arabian platform along what has become known as the Zagros Main Thrust (Fig. 1B). Deformation of the Arabian platform was progressive from northeast to southwest. The earlier Amiran foredeep was imbricated and carried piggy- back on the developing foldbelt (Fig. 5C). The resultant facies which developed in response to the progressive development of the foldbelt include from northeast to southwest, molasse of the Razak Fm. Asmari Fm. limestones, pabdeh shales and, proximal to the Arabian Shield, Ahwaz Sandstone (Fig. 4F). Subsequently, evaporitic sedimentation (e. g. Gachsaran) succeeded the Asmari in the new Zagros foredeep which developed in front of the orogen

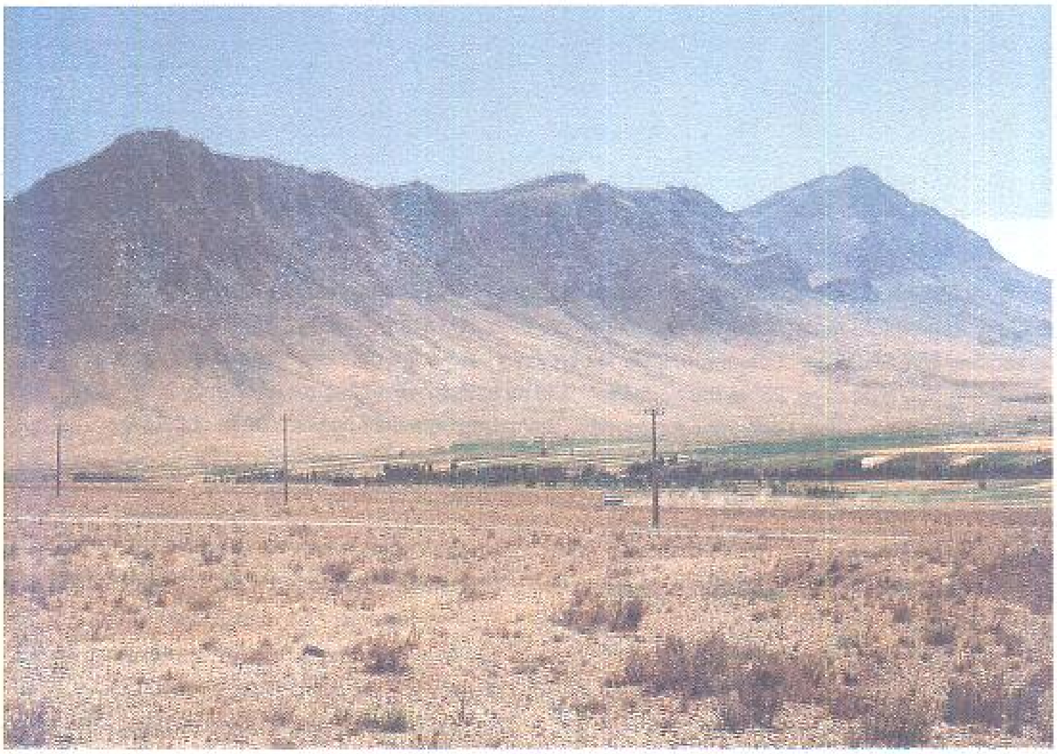

Figure 5a. Cretaceous rocks thrust over Hamadan phyllites within the Sanandaj-Sirjan zone. The reported presence of fossils in the Cretaceous carbonates with a Eurasian rather than Arabian affinity may require that the Sanandaj-Sirjan zone rifted away from Arabia and accreted to Eurasia. The photograph was taken from main highway just west of the town of Arak.

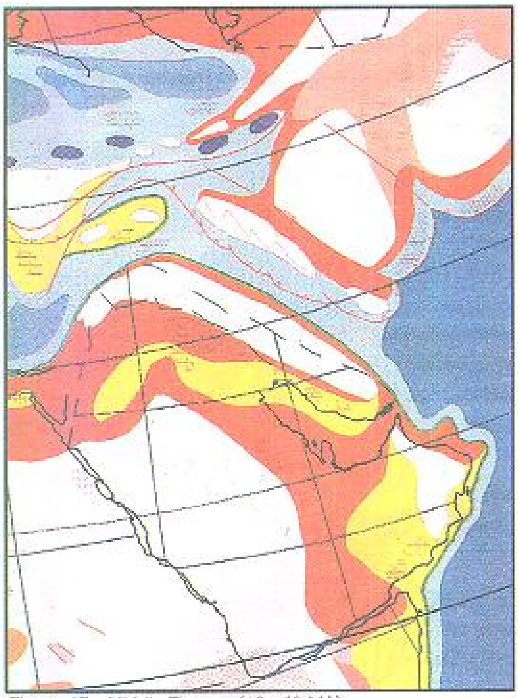

Figure 4D. Middle Eocene (46 - 40 MA)
Arabian margin rebounds following emplacement of ophiolitic allochthons into embayments; foredeep widens; flysch/shale apron aggrades up to several hundred kilometers away from allochthons

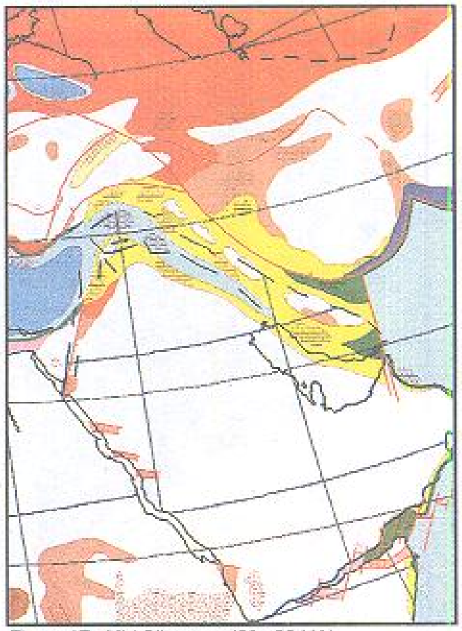

Figure 4E. Mid Oligocene (30 - 28 MA)
Margin gradually stabilizes; foredeep progressively fills and flysch/shale/carbonate system retracts northeastward back toward allochthons; Neo-Tethys all but closed; Sanandaj-Sirjan zone docks with Arabian platform; closing was diachronous, beginning earlier in northwest and progressing to southeast

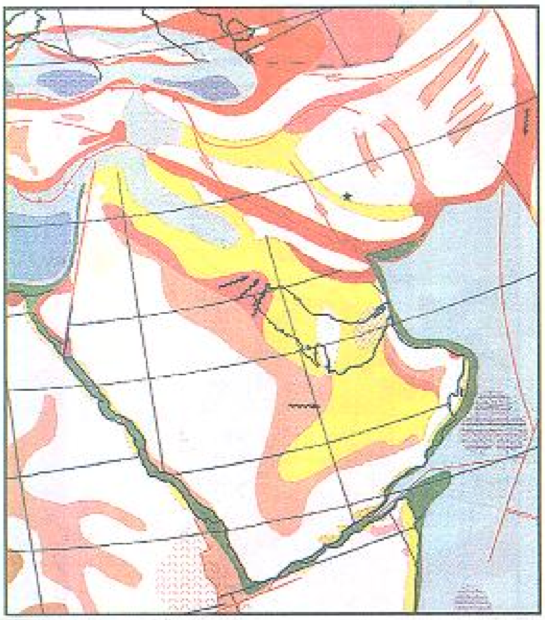

Figure 4F. Early Miocene (18 - 16.5 MA)
Continued subduction ends in continent-continent collision as northeast margin of Arabian platform docks with Eurasia and intervening microcontinents of Central Iran; Sanandaj-Sirjan zone thrust over distal portion of Arabian margin; earlier foredeep imbricated and carried piggy-back on developing foldbelt; resultant facies developed in response to progressive development of foldbelt are from northeast to southwest - molasse of the Razak Fm; Asmari Fm. limestones; Pabdeh shales; proximal to the Arabian Shield, southwest-derived Ahwaz Sandstone

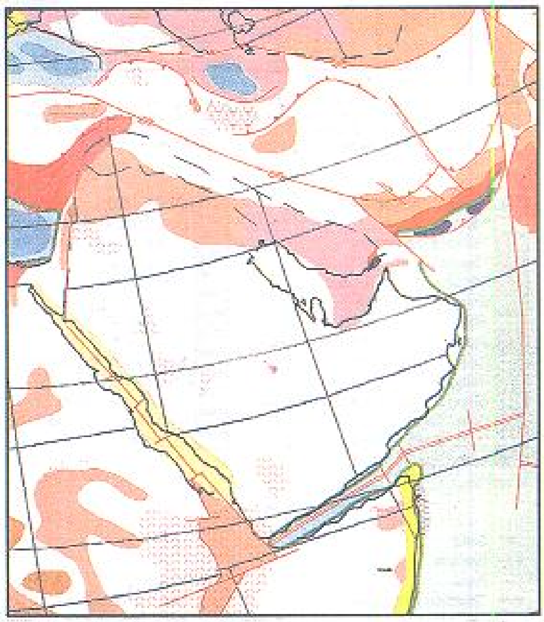

Figure 4G. Late Miocene (11.5 - 6 MA)
Evaporitic sedimentation (e.g. Gachsaran) succeeds the Asmari Fm. in the new Zagros foredeep developed in front of encroaching orogen; eventually gives way to northeast derived clastic sedimentation shed from upwelling orogen

Figure 4 *continued*

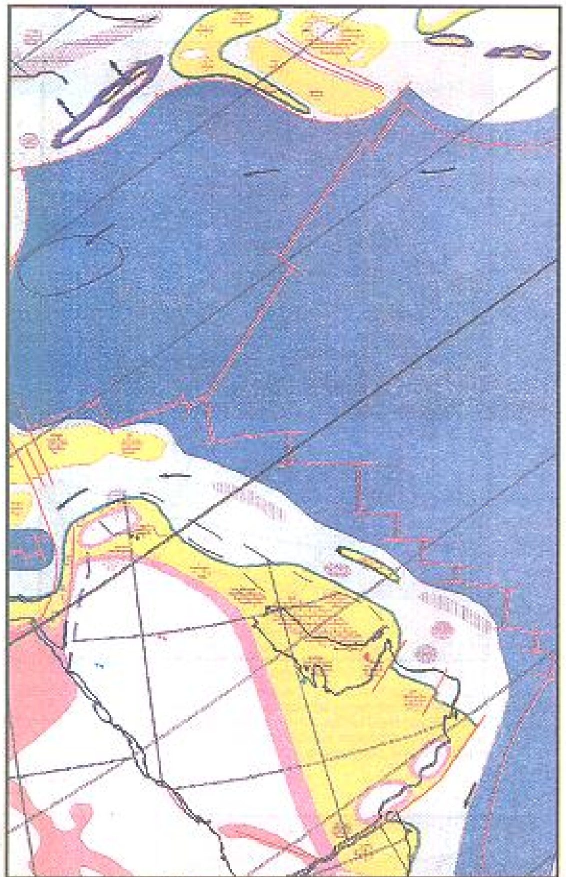

Figure 4A. Lower Aptian (114 - 112 MA)
Neo-Tethys at maximum extent; ? subduction under Sanandaj-Sirjan zone; complex spreading centers in Neo-Tethys; Sanandaj-Sirjan zone and Central Iranian microcontinents accreted to Eurasia; Arabian platform remains a broad, stable, shallow shelf dominated by carbonate deposition

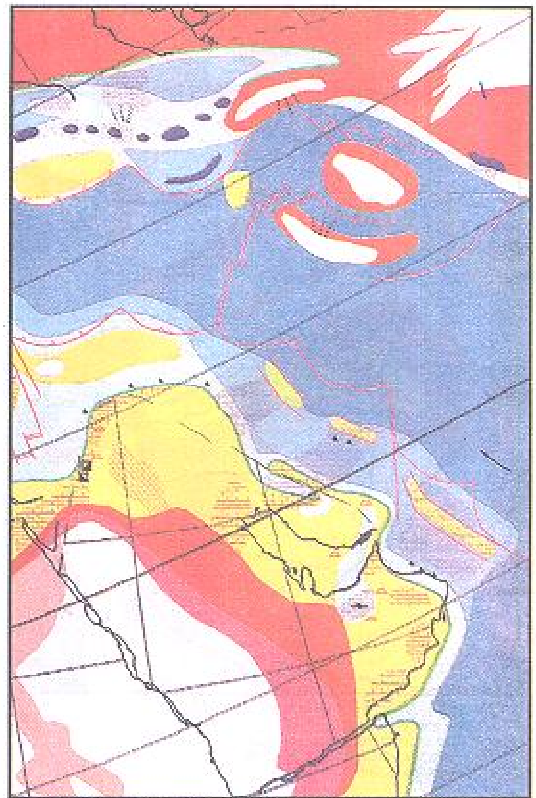

Figure 4B. Late Cenomanian (94 - 92 MA)
Southern margin of Eurasia breaks up; Sanandaj-Sirjan zone and Central Iranian microcontinents adrift in Neo-Tethys; spreading within Neo-Tethys ceases during the Albian; Neo-Tethys begins to close via northward-directed subduction zone off northern margin of Arabia

PALEOENVIRONMENTS
- Exposed Land
- Fluvial & Lacustrine
- Fluvialdeltaic
- Margino-Littoral & Lacustrine
- Evaporitic Platform
- Shallow Platform
- Terrigenous Shelf/Shallow Basin
- Slope or Shelf Edge Boundary
- Pelagic Rise
- Slope and Deep Basin above CCD
- Deep Basin Below CCD
- Deep Basin without any data
- Island Arc

LITHOLOGIES
- Non Deposition or Exposed Land
- Conglomerate, Sand, Silt, Clay
- Sand, Clay
- Clay, Shale
- Flysch
- Evaporite
- Dolomite
- Shallow Water Carbonate
- Radiolarite
- Submarine Hiatus
- Volcano-clastic Sediment
- Magmatism

SYMBOLS
- Gold
- Breccia
- Reef
- Direction of Supply
- Deep Sea Fan
- Surface Current
- Active Spreading Ridge
- Rift
- Fault
- Thrust
- Oceanic Subduction
- Accretionary Wedge
- Paleolatitude
- Present Day Coastline

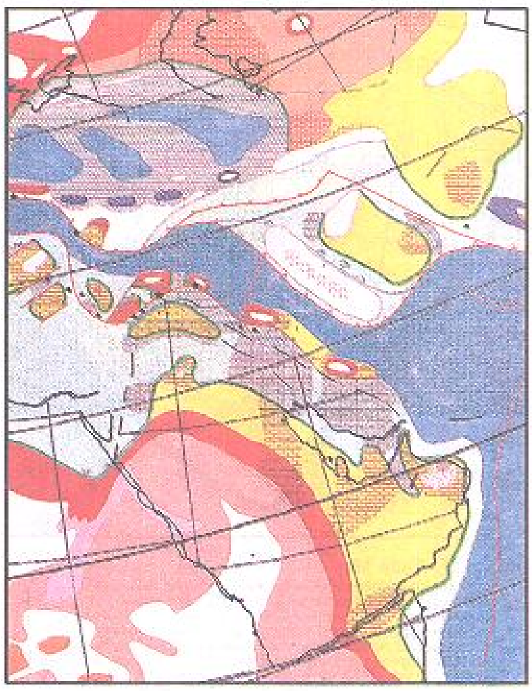

Figure 4C. Late Maastrichtian (69.5 - 65 MA)
Supra-subduction ophiolites emplaced into embayments; emplacement of ophiolites depresses margin and creates a foredeep; carbonate bank retreats rapidly to southwest; flysch/shale apron develops in front of advancing allochthons

Figure 4. Paleogeography and Paleoenvironments in the Tethyan Realm, from Lower Aptian to Upper Miocene (from Dercourt J. et al 1993).

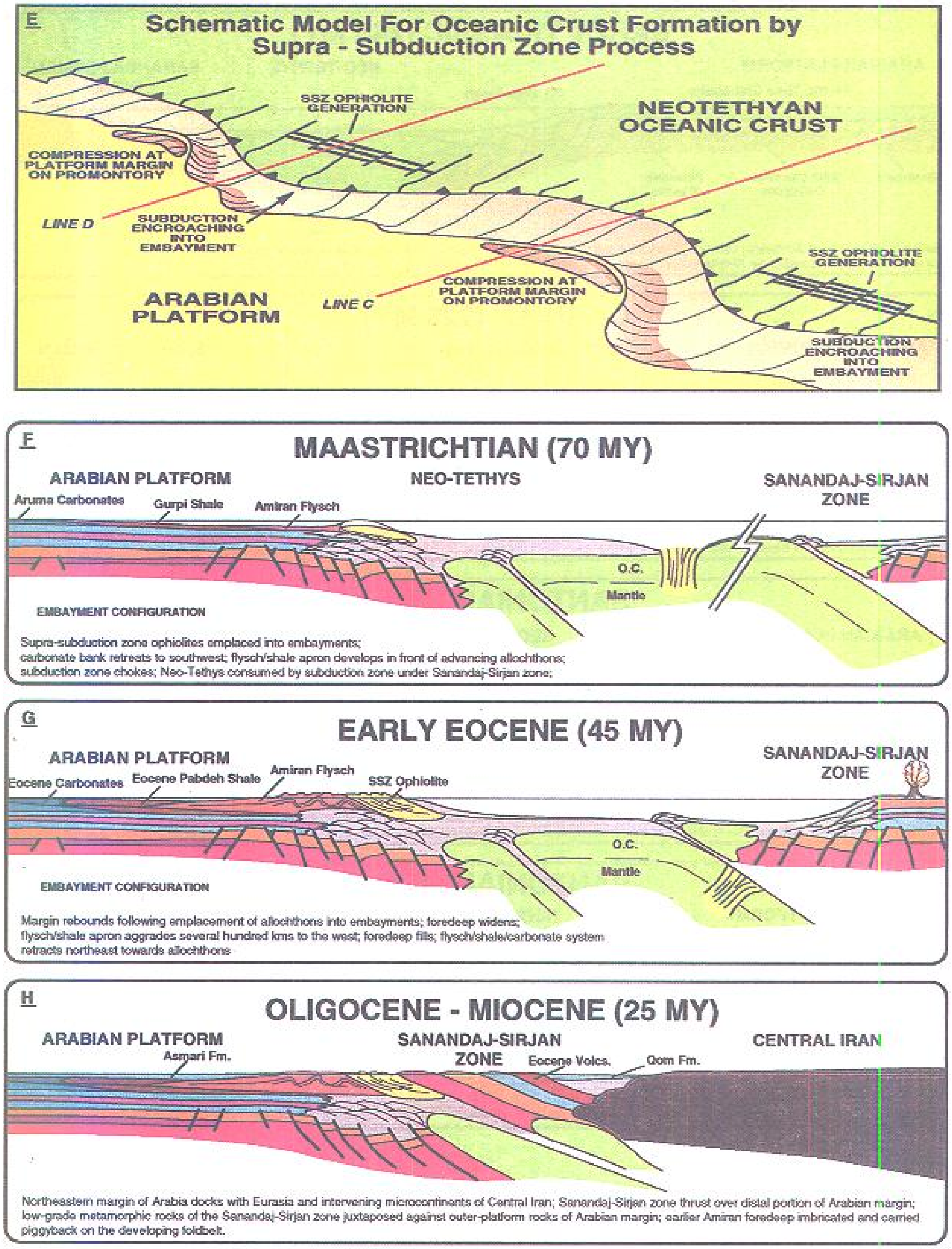

Figure 3. *continued*

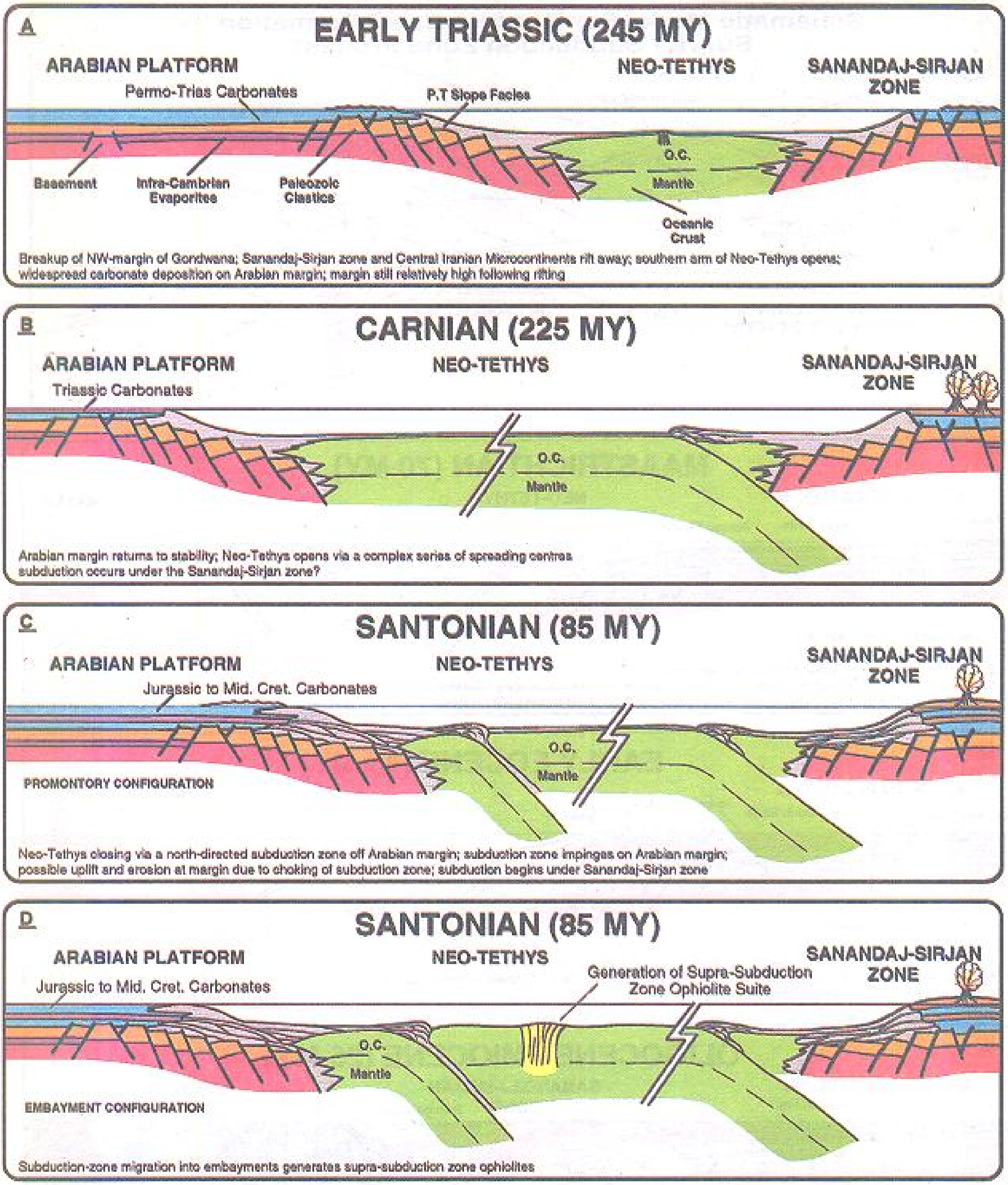

Figure 3. Schematic cross sections illustrating the tectonostratigraphic development of the southern Tethyan Margin from Early Triassic to Olig-Miocene.

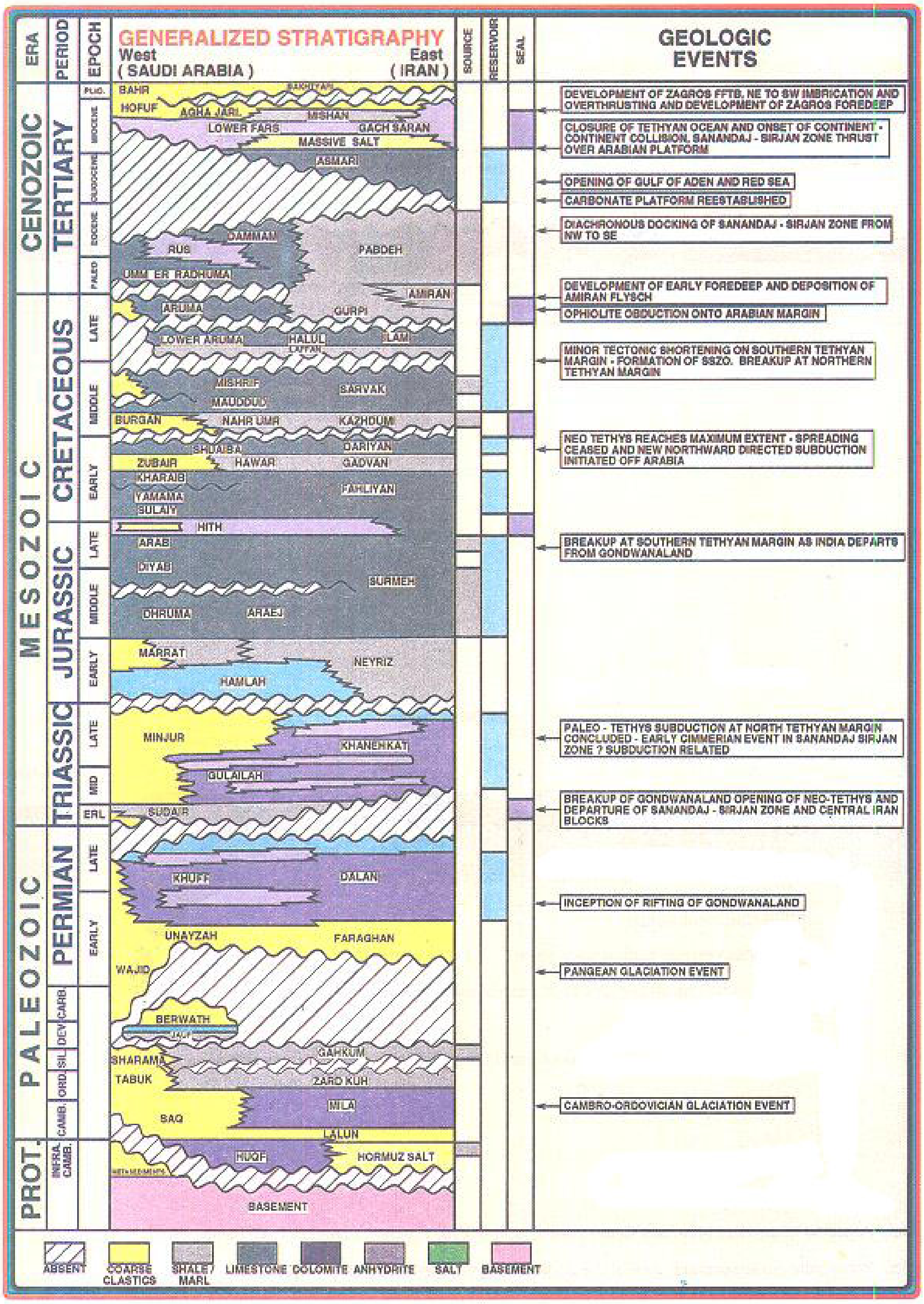

Figure 2   Tectonostratigraphic correlation chart for the Arabian Platform

Figure 1a

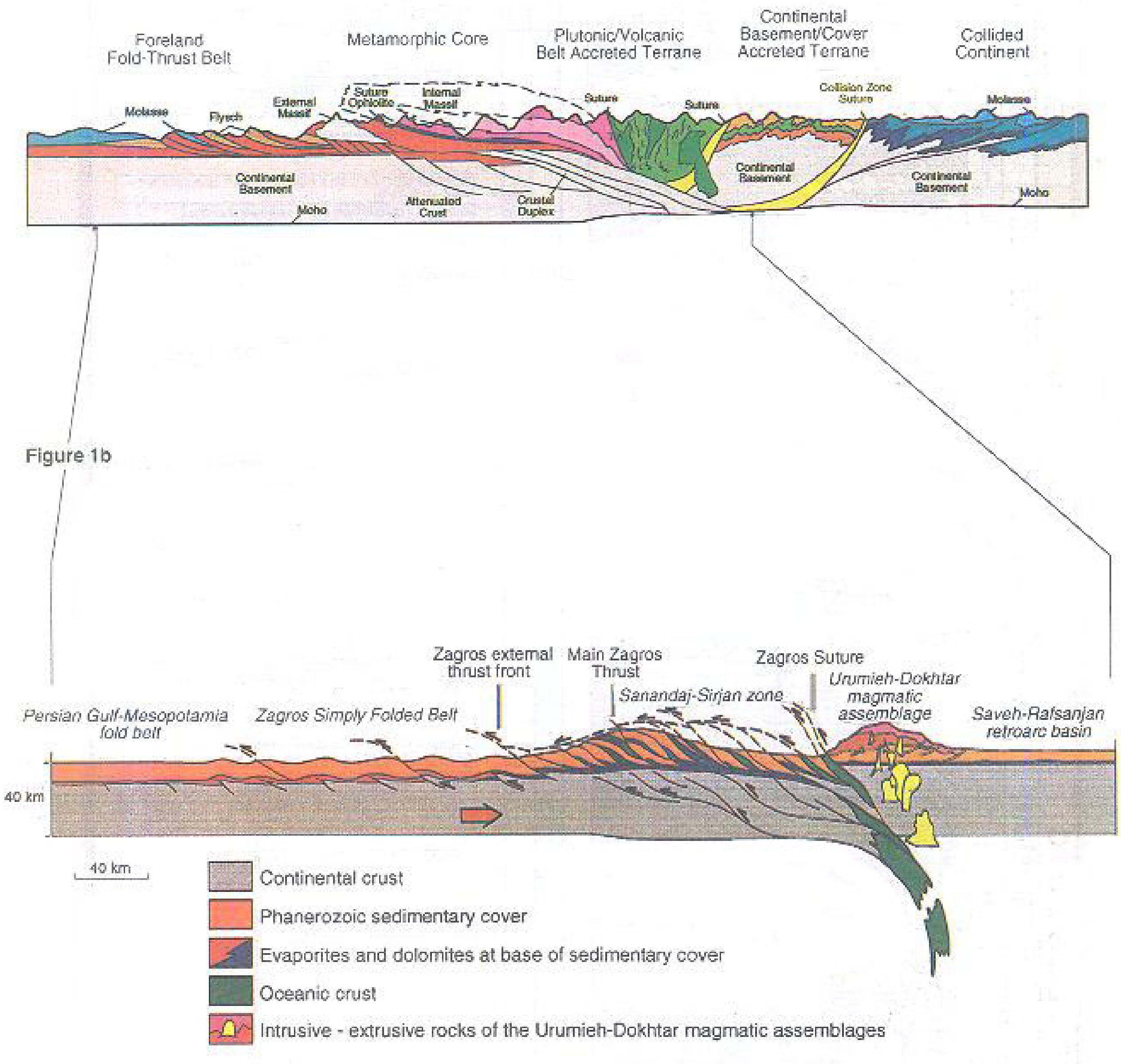

Figure 1a. Anatomy of an Ideal Mountain Chain (modified from R.D. Hatcher Jr. and R.T. Williams, 1986)

Figure 1b. Schematic cross-sectional view of the Zagros Orogenic Belt from Alavi (1994) and Central Iranian microcontinents (Lut, Tabas, etc.) rifted away and the southern arm of Neo- Tethys began to open (Fig. 3A). The margin at that time was defined by a series of major promontories and embayments. Widespread carbonate deposition continued over much of the Arabian platform, though the platform margins were likely still relatively high following rifting (Fig. 3A). By the Carnian, the Arabian platform had returned to stability, and carbonate deposition once again persisted over the whole platform (Fig. 3B). Neo- Tethys continued to open via a complex network of spreading centers. An Early Cimmerian (Carnian) metamorphic event, recorded in the southeast Sanandaj- Sirjan zone, may require concurrent destruction of southern Neo-Tethyan crust under part of the Sanandaj- Sirjan zone (Fig. 3B). The generally accepted model describes northward- directed subduction below the Sanandaj- Sirjan zone, and, although we accommodate this event in our model, convincing evidence to this effect is lacking. This postulated subduction zone may have persisted through the Lower Aptian by which time Neo- Tethys was likely at its maximum extent (Fig. 4A).

Subduction of Paleo- Tethys under Eurasia ultimately accreted the Sanandaj- Sirjan zone and Central Iranian microcontinents to Eurasia. It must be noted, however, that there is some question as to whether the Sanandaj- Sirjan zone actually rifted from Gondwana. Our current model accepts the reported presence of Cretaceous carbonates within the Sanandaj- Sirjan zone with a Eurasian rather than Arabian affinity (Fig. 5A). This observation supports the idea that the central Iranian microcontinents and the Sanandaj- Sirjan zone had rifted from the northern margin of Arabia and were accreted to the northern margin of Neo- Tethys. Throughout most of the Jurassic and Early Cretaceous, the Arabian platform remained a broad, stable, shallow shelf dominated by carbonate deposition (Figs. 4A and 5B). Evaporites (Gotnia; Hith) and source facies (Hanifa; Shilaif; Kazhdumi) developed in relatively shallow intraplatform depressions (Droste, 1990; Harris and Frost, 1984). By the late Cenomanian, break- up of the southern margin of Eurasia had once more set the Sanandaj- Sirjan zone and Central Iranian microcontinents adrift in Neo- Tethys (Fig. 4B). Spreading within Neo- Tethys probably ceased during the Albian, and Neo- Tethys began to close via a northward- directed subduction zone, developed off the northern margin of Arabia (Fig. 4B).

Late Cretaceous- Cenomanian

Stable platform conditions persisted over the Arabian platform until the middle Cretaceous, resulting in predominantly carbonate deposition over a large area. The principal controls on sedimentation were eustacy and continuing post- rift subsidence of the platform. The tectonic regime since the Hercynian event had been primarily extensional, resulting in the periodic development of intra- platformal basins (Fig. 4B). Local halokinesis occured in the Infra-Cambrian salt basins. Hints of imminent change are possibly noted at the Tethyan margin in Oman, where large areas experienced uplift and sub- aerial erosion (eg. Jebel Akhdar).

Late Cretaceous- Santonian

The configuration of the Arabian platform changed irrevocably in the early Santonian (85 Ma). The northward- directed subduction zone within Neo- Tethys began to impinge upon promontories on the Arabian margin (Figs 3C and 3E). Partial choking of the subduction zone at the promontories, led to uplift and erosion, or non- deposition (at the promontories). Concurrent subduction zone migration into the embayments, resulted in supra- subduction zone spreading (as described by Harris, R. A., 1992), and the formation of new oceanic crust (Figs 3D and 3E). This young, hot crust was destined to become the ophiolites of Kermanshah, Neyriz, and the Oman Mountains. Neo- Tethys continued to close via a new, northward- directed subduction zone developed on the northern margin of Neo- Tethys under the Sanandaj- Sirjan zone.

Late Cretaceous- Maastrichtian

Contraction resulting from the continued subduction of the northern margin of Arabia under Neo- Tethys ultimately caused the emplacement of the supra- subduction ophiolites into the embayments (Fig. 3F). The process was relatively rapid. The ophiolites overrode a melange apron and were emplaced, still hot, onto imbricated slope and deeper- water facies of the Arabian platform. The subduction zone ultimately choked, and consumption of the remaining fragments of southern arm of Neo-Tethys was thenceforth accomplished solely via the northward-directed subduction zone under the Sanandaj- Sirjan zone (Fig. 4C). Emplacement of the ophiolites depressed the margin and created a foredeep, the effects of which, were widely felt over the platform. The carbonate bank retreated repidly to the southwest, and a flysch/shale apron (Amiran- Gurpi) developed in front of the advancing allochthons (Fig. 4F). For the first time since the breakup of Gondwana, the dominant source for clastic deposition on the northern margin of the Arabian platform was from the northeast; this situation would predominate to the present day.

Early Eocene to Oligo- Miocene

Rebound of the Arabian margin following emplacement of the ophiolitic allochthons in the embayments, lead to accelerated

پیدایش کناره جنوبی تتیس در ایران در پی پاشیدگی گندوانا- پیامدهایی برای ایالت هیدروکربنی زاگرس

نوشته: دکتر رابرت هوبر *، ایان بارون *، دکتر رابرت هاچر ** و مهندس سیامک آگاه *

Introduction

Most previous analyses of the hydrocarbon system on the northeast margin of the Arabian plate (excluding those of Alavi (1980; 1994) have focussed primarily on the Zagros foreland fold thrust belt (FFTB). This is perhaps not surprising because the principal traps in the extremely prolific Zagros hydrocarbon province are young anticlines related to the late Tertiary Zagros orogeny.

FFTB's are, however, only one component of orogenic belts (Fig. 1a). FFTB's sit outboard of the orogenic core and separate relatively undeformed rocks of the platform from crystalline thrust sheets of the orogenic interior (Hatcher and Williams, 1986). The present day configuration of the Zagros orogen as depicted by Alavi (1994, Fig. 19) is shown in Figure 1b and can be compared to the ideal orogen of Hatcher and Williams (1986) in Figure 1a. The model of Alavi (1994) clearly shows the thin- skinned nature of the Zagros FFTB and also illustrates how the FFTB is linked to other components of the Zagros orogen. There is clearly more to the orogenic belt that arose from the destruction of the southern Tethyan margin than the Zagros FFTB. Our understanding of the fold belt and its prolific hydrocarbon system should be improved by analysis of the orogen as a whole.

In this paper we explore a developmental model to explain the Cenomanian to Recent geology of the northeast margin of the Arabian plate. A simplified regional stratigraphy and a summary of important geologic events which have affected that margin is presented in Figure 2. For the purpose of this paper, we do not dwell on the older, pre- Permian, history. Little is actually known of this time period with respect to the Zagros FFTB, because there is minimal exposure and an absence of key well penetrations. We therefore begin our developmental history in the late Paleozoic as the northeastern margin of Gondwana begins to break up.

Our model, which is based largely upon our synthesis of published data, comparisons to other orogenic belts worldwide, and our own field observations, has many similarities to those previously proposed by Alavi (1980; 1994). In particular, both models recognize the thin- skinned character of the Zagros FFTB and both models appreciate the importance of viewing the Zagros FFTB in the context of the orogen as a whole. Our model recognizes the influence of promontories and embayments on the Tethyan margin, provides a mechanism for the generation and emplacement of the ophiolites, identifies the presence of two foredeeps and appreciates the affect they have on maturation and migration, and requires that the Sanandaj- Sirjan zone is an allochthon, thrust over the old Arabian margin. Our developmental model is discussed below through a series of conceptual cross-sections (Fig. 3) and paleogeographic maps modified from Dercourt J., et al (1993) (Fig. 4).

Developmental History

Permian to Early Cretaceous

Rifting along the northeast margin of Gondwana began in the Early to mid Permian. The breakup occurred in the Early Triassic as blocks destined to become the Sanandaj- Sirjan zone

The Development of the Southern Tethyan Margin in Iran After the Break- up of Gondwana - Implications for the Zagros Hydrocarbon Province

Dr. Hooper, R. J., * Baron, I * ., Dr. Hatcher, Jr. R. D ** and Eng. Agah, S. *

چکیده

کمربندهای پیش کرانه‌ای که چین‌خوردگی و راندگی دارند در همه جای دنیا بخش مکمل کمربندهای کوه‌زایی هستند. این پیش‌کرانه‌ها در بیرون یک هسته کوه‌زایی جای دارند و توالی‌های نادگریخت کراتنی مربوط به خود را از بخش‌های درونی که دارای ورقه‌های رانده شده و بلورین می‌باشند جدا می‌سازند. با این وجود بایستی توجه داشت که این کمربندها تنها یکی از متشکلین کمربندهای کوه‌زایی هستند. برای درک پیدایش و تحول یک سیستم هیدروکربنی در کمربند چین‌خورده- مانند ایالت هیدروکربنی زاگرس- نبایستی آن را به تنهایی به دید آورد بلکه بایستی آن را با کوه‌زایی مربوطه بطور یک‌جا مورد توجه قرار داد. وقتی که کمربند چین‌دار و راندگی‌دار زاگرس بطور یک‌جا یا کوه‌زاد زاگرس مورد نظر قرار گیرد دریافته می‌شود که سیستم هیدروکربن آن به مراتب بیش از آنچه که عموماً از آن دستگیر شده است پیچیده‌تر است. فلوراری و راندگی درون کمربند زاگرس که در کرتاسه پسین آغاز گردید به تدریج به تشکیل تله زایش و مهاجرت پیچیده‌ی چند مرحله‌ای هیدروکربن، مهاجرت دوباره، انباشتگی و انباشتگی دوباره هیدروکربن منجر گردید.

Abstract

Foreland fold- thrust belts are an integral component of orogenic belts worldwide. They form outboard of an orogenic core and separate undeformed cratonic sequences of the foreland from more inboard crystalline thrust sheets of the orogenic interior. Foreland fold thrust belts are, however, only one component of orogenic belts. When trying to understand the development of a fold- belt hydrocarbon- system, such as the Zagros hydrocarbon province, care must be taken not to view it in isolation; it needs to be considered from the standpoint of the orogen as a whole. When the Zagros FFTB is viewed in the context of the Zagros orogen as a whole, it becomes apparent that the hydrocarbon system is considerably more complicated than generally recognized. Imbrication and overthrusting within the FFTB, beginning in the late Cretaceous, led to progressive trap formation, multi- stage hydrocarbon generation, and complex migration, remigration, accumulation, and reaccumulation of hydrocarbons.