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Origin of the Arabian Plate Structures: Amar Collision and Najd Rift

Moujahed I. Al-Husseini
Gulf PetroLink

ABSTRACT

The regularly spaced, N-trending Summan Platform, Khurais-Burgan Anticline, En Nala (Ghawar) Anticline and Qatar Arch in the eastern part of the Arabian Plate appear to have formed during the Precambrian Amar Collision between about 640 and 620 million years ago. This collision occurred along the N-trending Amar Suture (that bisects the Arabian Peninsula at about longitude 45°E) when the Rayn micro-plate in the east was fused to the western part of the Arabian Craton. The great anticlines are bounded by the NE-trending Wadi Batin Fault and NW-trending Abu Jifan Fault that converge on the Amar Suture. Deep wells drilled into these anticlines intersected deformed metasediments that are dated as syn-collisional. The Amar Collision was followed by a widespread extensional collapse of the Arabian-Nubian Shield between about 620 and 530 million years ago. During the final extensional stage, between about 570 and 530 million years ago, the NW-trending Najd Fault System dislocated the Arabian Shield left-laterally by about 250 to 300 kilometers. This dislocation appears to complement NE-oriented intra-continental rifts in Oman, Pakistan, Zagros Mountains and the Arabian Gulf. In these rift basins there accumulated thick sequences of clastic and carbonate rocks and salt, such as the Ara Group in Oman, Salt Range Formation in Pakistan, and Hormuz Series in the Arabian Gulf and Zagros Mountains. During the extensional collapse, the N-trending anticlines probably remained elevated as elongated horsts bounded by normal faults. The intervening subsiding grabens accumulated syn-rift sediments including the Hormuz Salt, and form an inter-fingering pattern between the great N-trending anticlines. The Precambrian anticlines, together with the syn-rift salt form the foundations of most of the hydrocarbon traps in the Arabian Plate.

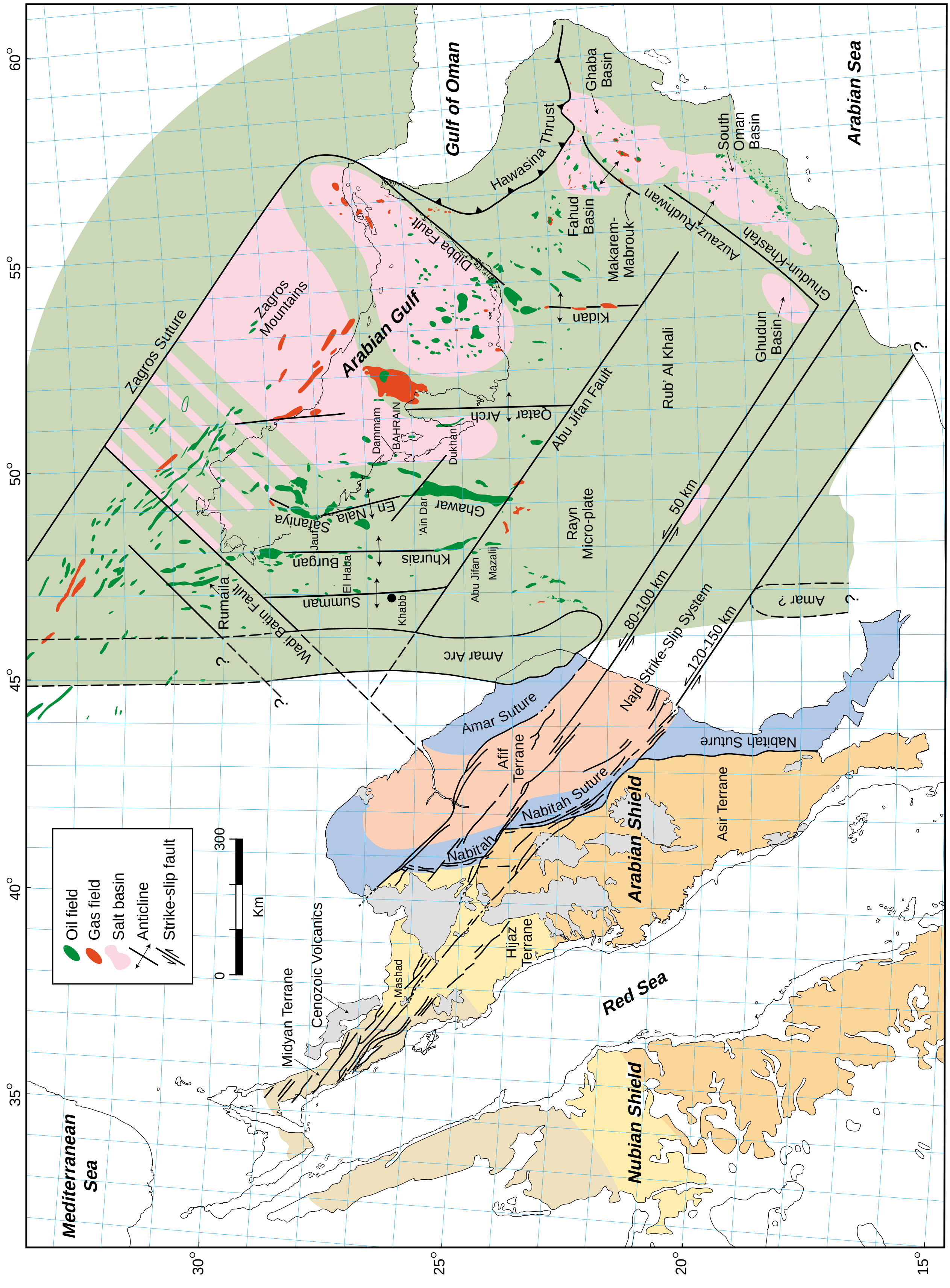
INTRODUCTION

The great hydrocarbon-bearing anticlinal traps of the Arabian Plate form a systematic and regular N-, NE- and NW-trending pattern (Figure 1). The N-trending En Nala Anticline, for example, is about 500 km long and houses the world's largest onshore and offshore petroleum traps: Saudi Arabia's Ghawar and Safaniya fields. Further west, another 500-km-long N-trending anticline extends from Saudi Arabia's Khurais field to Kuwait's Burgan field. Other northerly trends, such as the Summan Platform and Qatar Arch, are recognized throughout the Arabian Plate. Farther east, in the Arabian Gulf, Zagros Mountains and Oman, many circular and elliptical structural traps are mostly salt domes that occur within N- and NE-trending basins (Figure 1).

This striking geometric pattern appears to have formed in two tectonic stages: the Precambrian Amar Collision between about 640 and 620 million years ago (Ma), followed by the development of the Najd Rift System between about 570 to 530 Ma. This paper interprets the origin of the Arabian Plate structures in terms of these two fundamental stages. The paper also presents a late Precambrian-Cambrian chrono-stratigraphic scheme that adopts the Geological Time Scale of Gradstein and Ogg (1996), and consists of pre-, syn- and post-Najd Rift sequences.

PRECAMBRIAN AMAR COLLISION: 640-620 Ma

According to the plate tectonic model of Stoeser and Camp (1985), the Al Amar-Idsas Orogeny (hereafter the Amar Collision) was the collision between the Afif terrane (see Figures 1 and 2) and the Ar Rayn



Oil field
Gas field
Salt basin
Anticline
Strike-slip fault
0
300
Km
Mediterranean Sea
Red Sea
Arabian Gulf
Gulf of Oman
Arabian Sea
Nubian Shield
Arabian Shield
Zagros Suture
Zagros Mountains
Dibba Fault
Hawasina Thrust
Ghaba Basin
South Oman Basin
Fahud Basin
Makarem-Mabrouk
Auzaz-Rudhwan
Ghudun-Khasfah
Ghudun Basin
Kidan
Rub' Al Khali
Abu Jifan Fault
Qatar Arch
Dammam
BAHRAIN
Dukhan
Ghawar
'Ain Dar
En Nala
Safaniya
Jauf
Burgan
Khurais
El Haba
Summan
Khabb
Abu Jifan
Mazalij
Rumaila
Wadi Batin Fault
Rayn Micro-plate
Amar Arc
Amar ?
50 km
80-100 km
120-150 km
Najd Strike-Slip System
Amar Suture
Afif Terrane
Nabitah Suture
Nabitah
Asir Terrane
Hijaz Terrane
Mashad
Midyan Terrane
Cenozoic Volcanics
60°
55°
50°
45°
40°
35°
30°
25°
20°
15°

Figure 1: The Midyan, Hijaz, Asir and Afif terranes, and Amar Arc of the Rayn micro-plate form the Arabian Shield (Stoeser and Camp, 1985; Husseini 1989). The Rayn micro-plate (green) forms the eastern part of the Arabian Plate. The Amar Collision (about 640-620 Ma) fused the Rayn micro-plate and Afif terrane along the Amar Suture, and formed the N-trending, basement-controlled blocks (Summan Platform, Khurais-Burgan Anticline, En Nala-Ghawar Anticline and Qatar Arch). These giant anticlines are bounded by the orthogonal NE-trending Wadi Batin and NW-trending Abu Jifan strike-slip faults that appear to be syn-collisional. The much younger Najd Fault System (about 570-530 Ma) dislocated the older Nabitah Suture (about 680-640 Ma) by about 250-300 km.

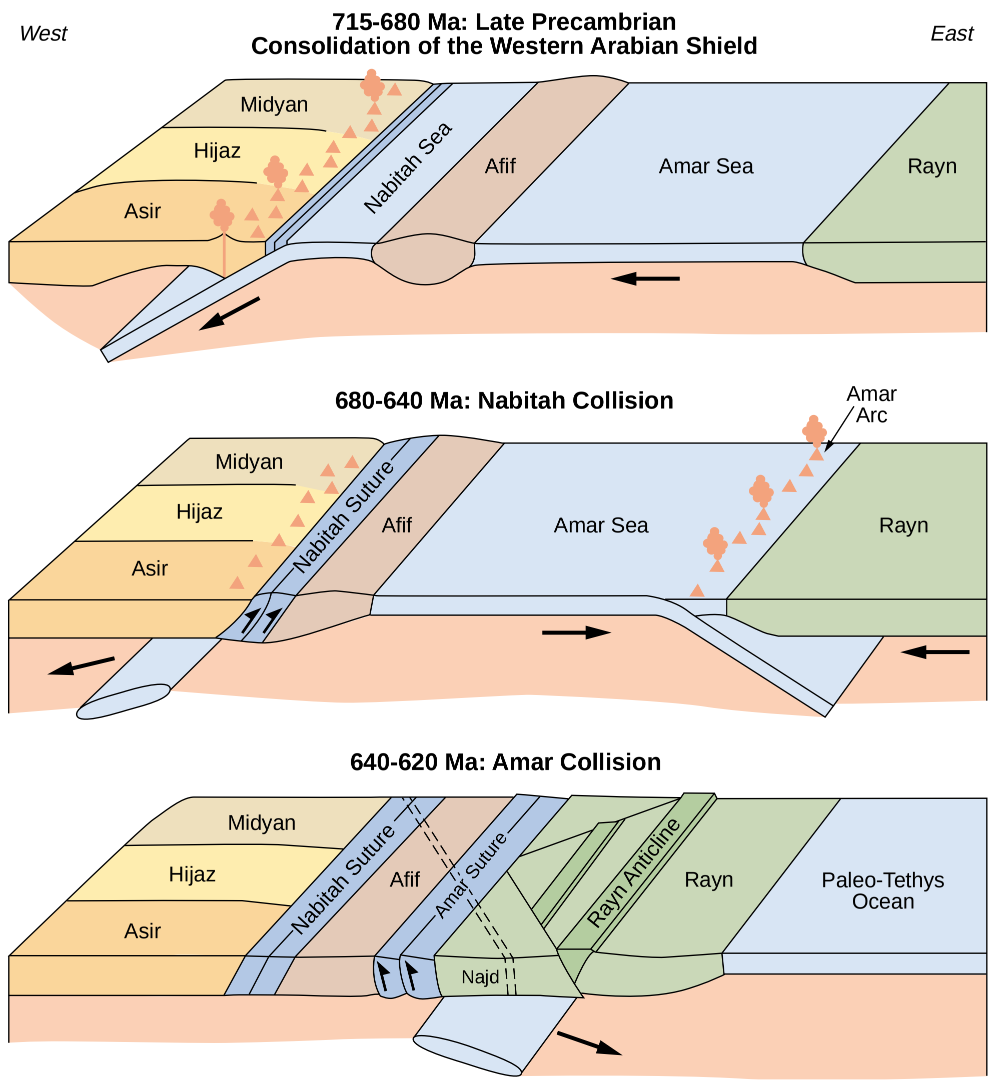


Figure 2: Schematic reconstruction of the accretionary evolution of the Arabian Plate. By 715 Ma, the Asir, Hijaz and Midyan terranes formed the western part of the Arabian Shield. Between about 680 and 640 Ma the Afif terrane collided with the western Shield along the Nabitah Suture. At about 670 Ma, a subduction complex formed west of the Amar Arc. The Amar Collision lasted from about 640 to 620 Ma when the Rayn micro-plate and Afif terrane collided along the Amar Suture. The N-trending Rayn anticlines and conjugate NW and NE fractures and faults may have formed at this time.

terrane (hereafter the 'Rayn micro-plate'). The collision took place along the N-trending Al Amar-Idsas Suture that is here referred to as the 'Amar Suture'. The Afif terrane formed the eastern edge of a series of terranes (Midyan, Hijaz, and Asir in Figures 1 and 2) that were successively accreted onto the northeastern margin of the African Plate before about 715 Ma (Stoeser and Camp, 1985). The Rayn micro-plate corresponds to central and eastern Arabia and is bounded to the west by the Al Amar Island Arc (Amar Arc) (Figures 1 and 2).

The exposed Rayn micro-plate on the eastern margin of the Arabian Shield is composed of the Amar Group. According to Vaslet et al. (1983), the Group consists of a tholeiitic to calc-alkaline suite of volcanics, related pyroclastic rocks, and subordinate calcareous sediments. It was intruded by arc-related intrusions older than 650 Ma, and syn-tectonic plutons dated at about 640 to 620 Ma.

The Amar Suture, which marks the collision zone between the Afif terrane and Rayn micro-plate, consists of westerly directed, N-trending thrust faults that contain slices of ophiolite of either oceanic or island-arc origin (Figure 3). The ophiolites consist of ultramafic rocks, serpentite, gabbro, sheeted dike complexes, theoleitic metabasaltic rocks, and ocean-floor metasedimentary rocks (Brown et al., 1989). This geometry indicates that prior to the Amar Collision an oceanic crust ("Amar Sea" in Figure 2) was consumed by easterly dipping subduction beneath the Amar Arc. The location of the Arc coincides with a distinct, elongated N-trending magnetic anomaly (Figure 4) that extends to at least latitude 29°N, and possibly as far as the Zagros Suture (Johnson and Stewart, 1994).

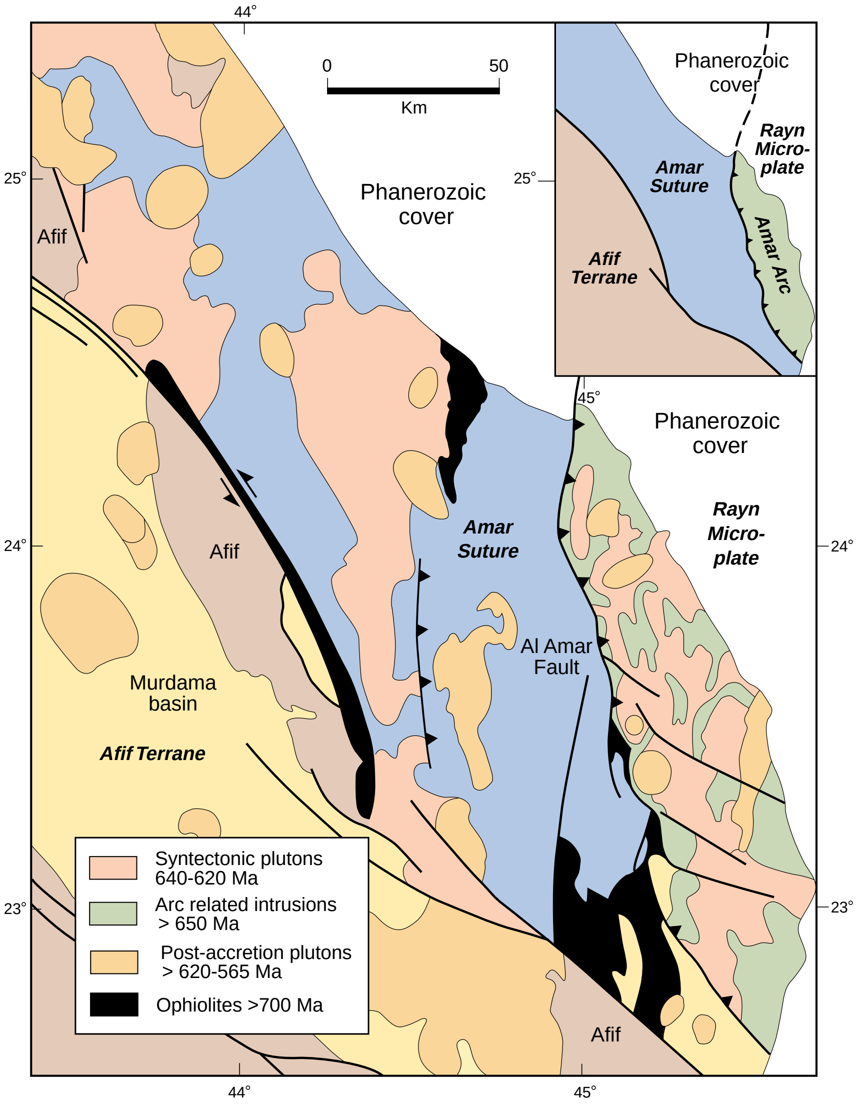


Figure 3: The Amar Arc is located along the eastern margin of the Arabian Shield (Figure 1). It consists of arc–related intrusions older than 650 Ma (green), and syn-tectonic plutons dated at 640 to 620 Ma (pink). The post-accretion plutons (orange) range in age from 620 to 565 Ma. The remains of the oceanic crust, between the Afif terrane and Rayn micro-plate, is recognized from the tectonized ophiolite belts (black) within the Amar Suture. Sketch modified from Johnson and Stewart (1994).

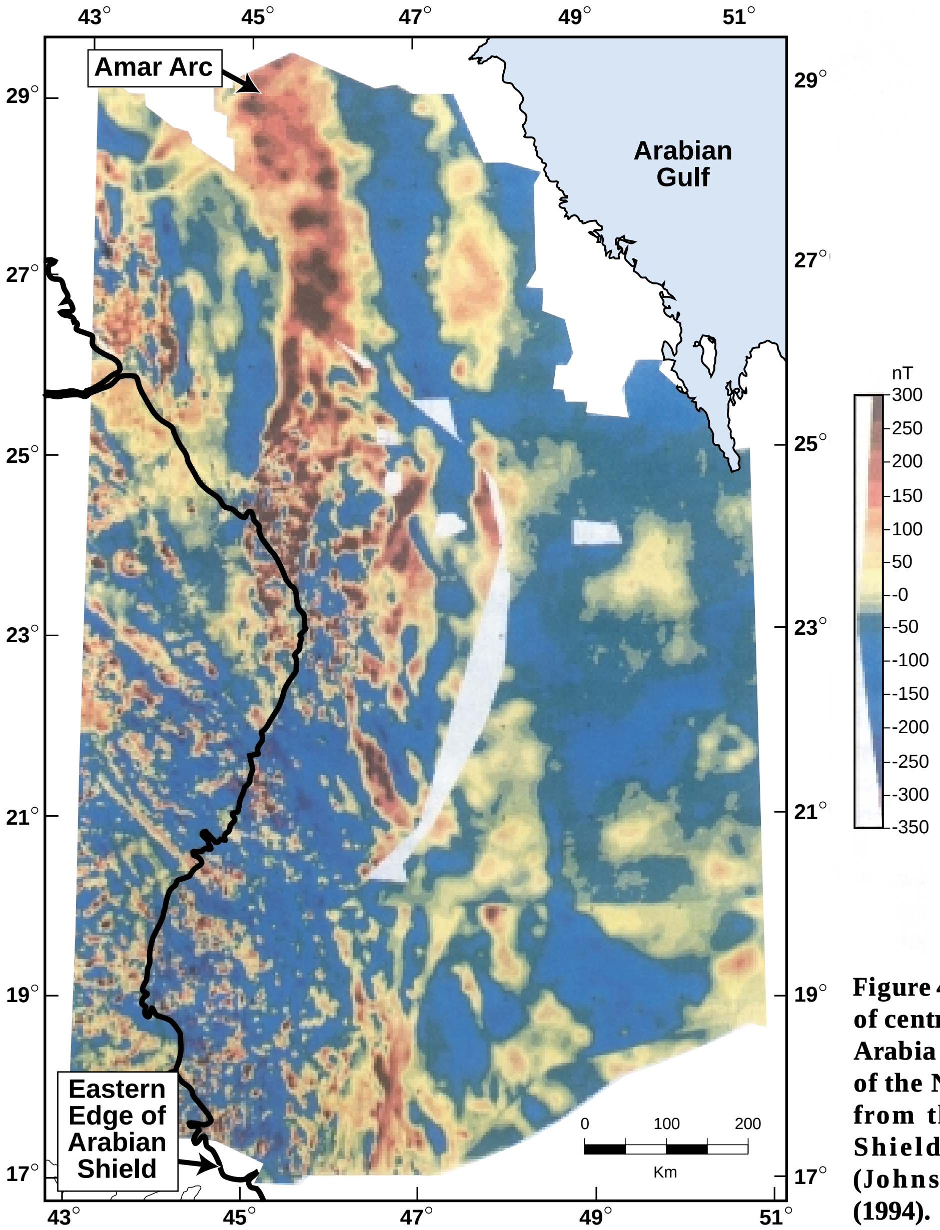


Figure 4: Aeromagnetic map of central and eastern Saudi Arabia shows the extension of the N-trending Amar Arc from the eastern Arabian Shield to at least 29° N (Johnson and Stewart, (1994).

Amar Collision Fractures Rayn Basement

The collision along the N-trending Amar Suture caused EW-directed compression that appears to have formed the regularly-spaced, N-trending Summan, Khurais-Burgan, En Nala-Ghawar and Qatar anticlines (Figures 1 and 2; hereafter the "Rayn anticlines"). During the collison the Rayn anticlines may have been folds belts with westerly-directed thrust faults (Figure 5). The collision may also have generated the NW- and NE-trending fracture pattern that is recognized at many scales throughout the basement of the Arabian Plate (S. Al-Husseini, written comm., 1977). Younger features such as the NW-trending Najd Fault System and Zagros Suture, and the NE-trending Oman Salt basins and Dibba Fault, may have formed as fracture zones during the Amar Collision.

The Precambrian Rayn anticlines are bounded by the NE-trending Wadi Batin Fault and NW-trending Abu Jifan Fault (Figure 1). These two faults appear orthogonal and intersect near the Amar Suture. They may therefore be strike-slip faults forming part of a more widespread collisional slip-line field For a discussion of the application of slip-line theory to collisional systems, see Tapponier and Molnar

(1976). Other slip-lines that are less extensive may run parallel to these two primary wrench faults (for example north of the Rumaila and Ghawar fields in Figure 1).

The Rayn anticlines were later strongly re-activated (Wender et al., 1998) during the following major regional tectonic episodes:

(1) the Najd Rift System (see following discussion);
(2) Late Paleozoic "Hercynian" Orogeny;
(3) Permo-Triassic Zagros Rift; and
(4) Late Cretaceous Cyprus-Taurus-Zagros-Oman obduction of the Neo-Tethys Ocean crust onto the Arabian Plate.

Deep exploration wells that penetrate the Rayn anticlines further support a direct relationship between their structural origin and the Amar Collision. In the Summan Platform (Figure 1), for example, the El-Haba-2 and Khabb-1 wells intersected steeply-dipping (up to 70°) metamorphozed shales directly below the Permian Khuff Formation. The metasediments in Khabb-1 were dated at 636 to 605 Ma (M.N. Bass, written comm., 1981). Along the Khurais-Burgan trend, a deep Burgan well (Khan, 1989) and the Jauf-10 well also penetrated steeply dipping metamorphozed shales directly below the Khuff. Along the Ghawar Anticline, well Ain Dar-196 intersected folded sandstones and shales dated at 671 to 604 Ma below the Upper Cambrian-Ordovician Saq Sandstone (T.H. Kiilsgaard and W.R. Greenwood, written comm., 1976).

EXTENSIONAL COLLAPSE: 620-530 Ma

Following the Amar Collision at about 620 Ma, the entire Arabian-Nubian Shield appears to have started collapsing in extension (Husseini, 1988; Blasband et al., 2000; Genna et al., 2000). In the Arabian Shield, from about 630 to 560 Ma (Stoeser, 1986), post-orogenic alkali-feldspar granites (A-type granites derived from the mantle) intruded a thinned and extending crust (Stern and Hedge, 1985; Brown et al., 1989; Blasband et al., 2000). Also from about 638 to 600 Ma (Brown et al., 1989) molassic deposits of the Murdama Group (Figure 5) filled basins between the orogenic mountains, the highest of which were raised next to the ophiolite belts on the margins of the Amar Suture.

The Shammar Rhyolite is younger than the Murdama and consists of alkalic and peralkalic extrusive rocks and associated gently folded sedimentary rocks. The Shammar has been variously dated: Brown and Jackson (1960) estimated the culmination of volcanism at about 570 Ma; Fleck et al. (1976) dated the Shammar at 567 and 581 Ma; and Brown et al. (1989) gave dates of about 560 Ma. The Shammar volcanism was interpreted by Genna et al. (2000) as accompanying extension of the Arabian Shield. A similar situation prevailed in the northern Nubian Shield of Egypt where post-tectonic granitic rocks mostly range in age from 620 to 575 Ma and the associated Dokhan Rhyolite has an age range of about 600 to 580 Ma (Stern and Hedge, 1985).

Blasband et al. (2000) review the igneous rocks that support the interpretation for a post-collisional collapse of the Arabian-Nubian Shield from about 600 to 530 Ma. They attribute the collapse to gravitational instability of the crust associated with lithospheric over-thickening during the collisional phases.

The extensional collapse of the Arabian-Nubian Shield culminated in the development of the regionally extensive Najd Fault System and its complimentary rift basins that make up the Najd Rift System.

NAJD RIFT SYSTEM: 570-530 Ma

The "Najd Rift System" as defined here consists of the Najd Fault System of the Arabian Shield (Figure 1), the Oman, Punjab and Dibba Rifts, the Zagros Fault, and the Sinai Triple Junction (Figure 6a) (Husseini, 1988, 1989; Husseini and Husseini, 1990). The three branches of the Sinai Triple Junction are the Najd Fault System, the Egypt Rift (Stern and Hedge, 1985), and the Jordan Valley (Bender, 1982; Andrews, 1991) and Derik Rift.

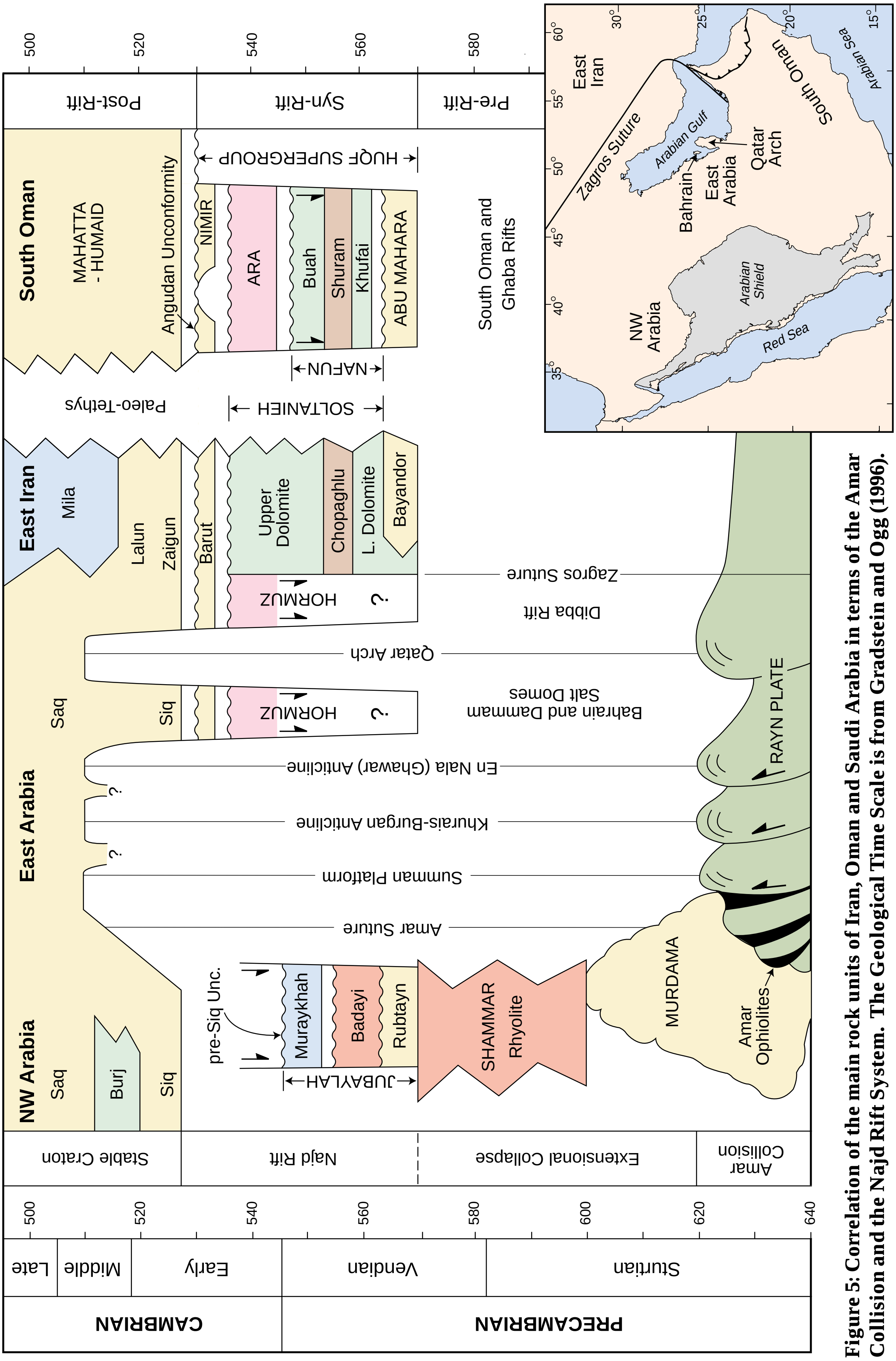


Figure 5: Correlation of the main rock units of Iran, Oman and Saudi Arabia in terms of the Amar Collision and the Najd Rift System. The Geological Time Scale is from Gradstein and Ogg (1996).

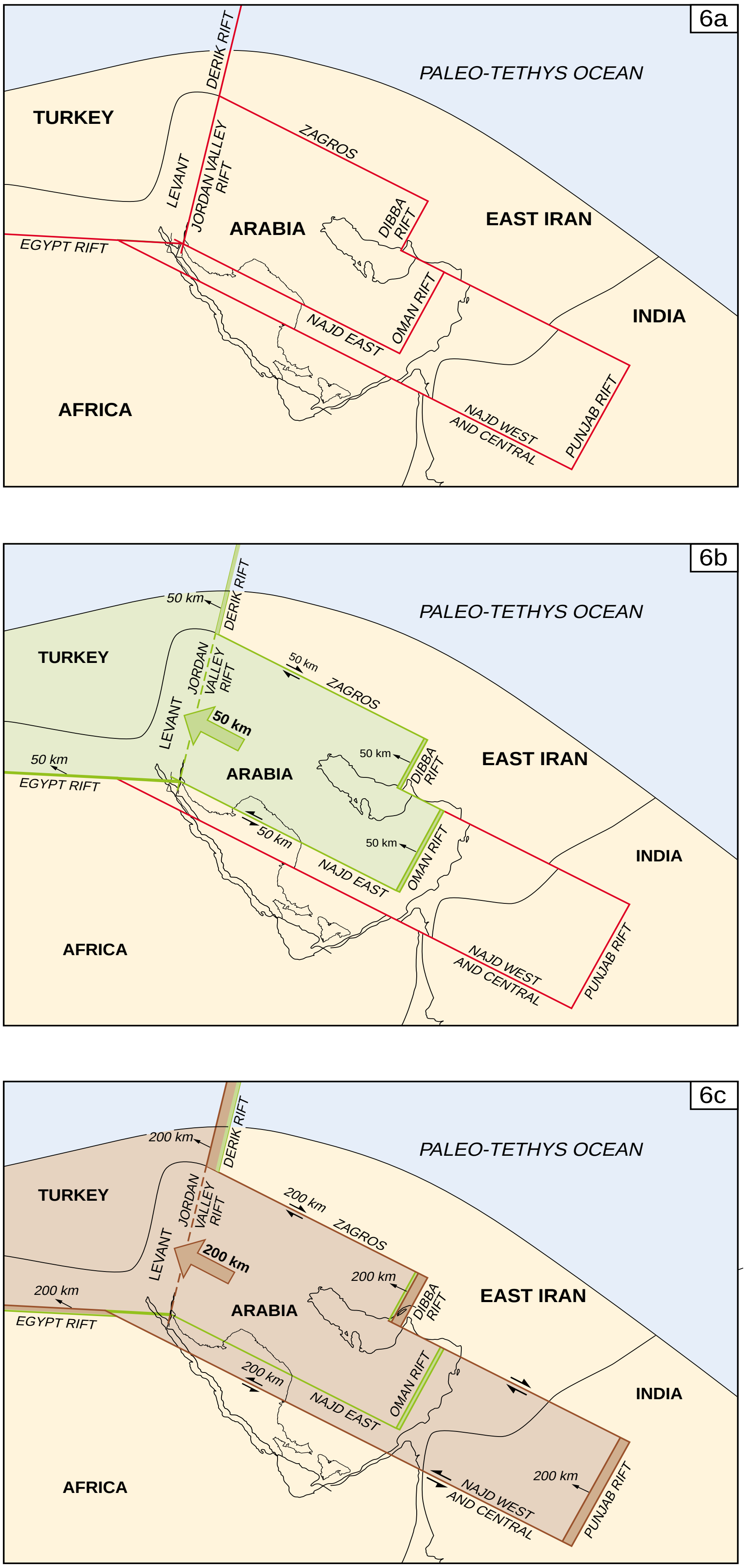


Figure 6:

(a) The Najd Rift System is restored to 570 Ma prior to the initiation of the Najd strike-slip system.

(b) A left-lateral dislocation of 50 km along the Najd East Fault corresponds to 50 km of rifting in the Oman and Dibba basins. This movement is accompanied by 50 km right-lateral movement along the Zagros Fault and a narrow rift along the Egypt and Derik branches of the Sinai Triple Junction.

(c) A left-lateral dislocation of 200 km along the combined Najd Central and West faults (shown as one fault here) results in the opening of the Punjab Rift, and further extension along the other rift centers by 200 km. The steps shown in (b) and (c) may have occurred at the same time.

In Figure 6b, the 50-km extensional contribution of the Najd East Fault is shown together with the associated Oman and Dibba rifts (Figure 1). Figure 6c shows the contributions from the combined Najd Central and Najd West faults of about 200 km, together with the Punjab and Dibba rifts. The reconstructions in Figure 6b and 6c are not intended to show two different times, but just that the Najd Rift System is kinematically self-compatible. The following discussion describes the main tectonic components of the Najd Rift System and the corresponding syn- and post-rift sequences.

Najd Fault System

The sinistral Najd Fault System (Figure 1) consists of three main parallel fault zones, each about 5 to 10 km wide, that dislocated the much older (about 680-640 Ma) N-trending Nabitah Suture by approximately 250 to 300 km (Brown and Jackson, 1960; Brown, 1972; Moore, 1979; Brown et al., 1989). The fault system has a width of about 300 km and an exposed length of 1,100 km. The dislocations on the Najd West, Central and East faults (Figure 1) are about 120 to 150, 80 to 100 and 50 km, respectively (Brown et al., 1989). The fault movement was brittle and the plate motion along the faults was kinematic (Moore, 1979; Howland, 1979).

The onset of the Najd movement can be estimated from a Najd fault that cuts off the Abu Aris Granite dated at 567 Ma (Fleck and Hadley, 1982). The duration of the Najd event can be inferred from felsic dikes that intruded the Najd faults between 577 and 529 Ma (Fleck et al., 1976). The age of the Najd faulting can also be inferred from the radiometric dating of the Badayi Volcanics of the Jubaylah Group (see below), and from the stratigraphic position of the group (Figure 5) that was deposited in elongated rift basins within the Najd Fault System.

Jubaylah Group

The Jubaylah Group (also spelled as Jibalah or J'balah) crops out in Najd fault-controlled, pull-apart basins in the Arabian Shield. It is up to 3.3 km thick (Hadley, 1974) and lies unconformably on the Shammar Rhyolite (Delfour, 1970). Fleck et al. (1976) place the Shammar Rhyolite, dated at between 581 Ma and 567 Ma, below the Jubaylah (by faulting). The Jubaylah lies disconformably on the granite of Jabal ar Rahadah dated at 577 Ma, which intrudes the Murdama Group (Baubron et al., 1976).

The Jubaylah consists of three units (Delfour, 1970; Hadley, 1974). The oldest is the Rubtayn conglomerates and clastics (Umm Al Aisah of Delfour, 1970). The second unit, the Badayi, is a calk-alkalic and strongly alkalic andesite that Brown et al. (1989) compare to "volcanism associated with large continental rifts." The Badayi has been variously dated between 558 and 528 Ma (Hadley 1974; Brown et al., 1989). The youngest unit of the Jubaylah Group is the Muraykhah limestone and shale (upper Jifn of Delfour, 1970). At Mashad (Figure 1), in the northern Arabian Shield, a basalt dike in the Jubaylah is dated 532 Ma and occurs beneath the Lower Cambrian Siq Sandstone (Brown et al., 1989).

The syn-rift Jubaylah Group is therefore younger than the Shammar Rhyolite (about 570 Ma) and older than the Early Cambrian Siq Sandstone. The undated Siq is overlain by the Burj Formation that includes the first age-diagnostic fossils. The Burj is dated as late Early Cambrian to early Middle Cambrian based on trilobites, brachiopods and hyolithids (Powell, 1989) and this would correspond to an age of about 520 Ma (Gradstein and Ogg, 1996). These stratigraphic considerations indicate that the Jubaylah's age and corresponding Najd sinistral movement occurred between about 570 and 530 Ma (Figure 5).

Pre-Siq and Pre-Saq Unconformities

The pre-Siq Unconformity separates the syn and post-rift sequences in Saudi Arabia. In regions that remained uplifted throughout the Amar Collision and Najd rifting, the Siq and Burj formations are absent by non-deposition. In these upland regions the post-rift sequence is the Late Cambrian-Early Ordovician Saq Sandstone. As indicated by Figure 5, the pre-Siq, pre-Saq and Oman's Angudan Unconformity (see below) define the base of the post-rift sequences.

Subsurface Najd and Syn-Rift Sequences

In the subsurface, the Najd Fault System extends across the western Rub' Al Khali as interpreted from seismic, gravity and magnetic data (Figure 1). Pull-apart basins that align with the Najd Fault System, show syn-rift, layered seismic reflections and salt structures (Dyer and Al-Husseini, 1991; Faqira and Al-Hauwaj, 1998). The Jubaylah Group of the Arabian Shield may not therefore represent a complete account of the syn-rift sequence as interpreted from seismic data. The unconformity between the Siq and Jubaylah could represent a substantial hiatus during which the seismically imaged salt and younger syn-rift clastics (like the Ara Salt and Nimr clastics of Oman in the following discussion) were deposited in the Najd pull-apart basins of the Rub' Al Khali (Figure 5). Erosion of the Arabian Shield may also have removed a substantial record of the syn-rift sequence in outcrop.

Oman Rift Basins

The 600-km-long NE-trending South Oman and Ghaba salt basins are located between the Najd Fault System and the Late Cretaceous Hawasina Thrust (Figure 1). The Ghudun-Khasfah, Anzauz-Rudhwan and Makarem-Mabrouk highs define the northern flank of the South Oman and Ghaba basins. The basins are about 100 km wide and bounded to the northwest by major normal faults with throws of as much as 5 km (Loosveld et al., 1996).

The Najd East Fault defines the southwest edge of the undrilled upper Proterozoic-lower Paleozoic Ghudun Basin in southwest Oman (Figure 1). Regional seismic, gravity (Ravaut and Warsi, 1997) and aeromagnetic data indicate the basin to be located immediately northwest of the Ghudun-Khasfah high (Blood, 2000). Seismic facies analysis and gravity modeling tentatively support the presence of salt swells in the basin that are equivalent to the Ara Salt (Blood, 2000).

Huqf Supergroup

In Oman, Loosveld et al. (1996) interpret the Huqf Supergroup and Nimr Group as syn-rift sequences. The Huqf (Figure 5) consists of the predominantly clastic Abu Mahara Group at the base, and the stratified clastic and carbonate deposits of the Nafun Group at the top (Gorin et al, 1982; Hughes Clarke 1988; Loosveld et al. 1996). The Nafun consists of the Khufai, Shuram and Buah formations. Above the Nafun the Ara Group consist of evaporites that include massive halite. The Ara Salt may account for up to 1,775 m of the Huqf's 3 km thickness (Hughes Clarke 1988). Clastics of the Nimr Group are conformable to unconformable above the Ara. The Nimr was recently assigned to the Huqf Supergroup (Hartkamp-Bakker et al., 1998) and it is separated by the Angudan Unconformity from the overlying Mahatta-Humaid Group (Loosveld et al., 1996; Oterdoom et al., 1999).

The age of the Abu Mahara varies considerably according to the radiometric techniques used. A K-Ar date from a trachyte at its base is 654 Ma (Gorin et al., 1982), but a rhyolite and an alkali granite, also at its base, yielded Rb-Sr ages of 562 Ma and 556 Ma, respectively (Dubreuilh et al., 1992; Platel et al., 1992). A zircon from the Abu Mahara basal glacial deposits was dated at 723 Ma (Brasier et al., 2000). Ignimbrites found within the Ara Formation are dated at 544.5 Ma by U-Pb radiometric techniques (Brasier et al., 2000).

In Figure 5 the Abu Mahara is correlated with the Rubtayn Formation of the Jubaylah Group. These conglomerates and coarse clastics could be the basal deposits generally found in newly formed, steep-sided rift basins. The age (about 556-562 Ma) and nature of the rhyolite and alkali granite (typical extensional igneous rocks) found in the Abu Mahara are consistent with the syn-rift model. Above the Angudan Unconformity, the post-rift sequence in Oman consists of the Mahatta Humaid Group.

Angudan Uplift in Western Oman

In western Oman, a compressional event is associated with the Angudan Unconformity (Figure 5) which separates the syn-rift Huqf Supergroup (inclusive of the Nimr Group) from the Mahatta Humaid Group (Loosveld et al., 1966; Immerz et al., 2000; Webster, 2000). Loosveld et al. (1996) report that in most wells in western Oman deformation features (folds, cleavages and steep to subvertical dips) are intersected; and N-trending folds and thrusts are observed in the field. Loosveld et al. (1996) suggested that these features may be kinematically compatible with sinistral movements on the Najd Fault System.

Immerz et al. (2000) interpret the formation of the salt basins of Oman (and the Arabian Gulf) as part of a series of basement arches and intervening synclines (salt basins) developed in a compressive tectonic regime during the deposition of the Ara and Nimr groups. Webster (2000) proposed a collisional tectonic model involving the escape of a small plate, located south of Oman, which involves mixed transtension and transpression.

These collisonal models are incompatible with the regional extensional collapse of the Arabian-Nubian Shield during the late Precambrian and Early Cambrian 620-530 Ma (Husseini, 1988; Blasband et al., 2000). They are inconsistent with the widespread deposition of carbonates and evaporites over most of the Arabian Plate during this period (Gorin et al., 1982; Husseini, 1989). With the exception of major uplands developed on the Rayn anticlines and Amar Suture, most of the region was a submerged marine platform. In contrast, a collision would presumably have uplifted the entire region well above sea level.

The steeply-dipping rocks (sometimes referred to as the "deformed Huqf") that are encountered in wells drilled in western Oman and northwest of the South Oman-Ghaba salt basins may be much older than the syn-rift Huqf Supergroup. These rocks may be equivalent to the steeply dipping clastics encountered in deep wells in Saudi Arabia and Kuwait that were deformed during the Amar Collision (640-620 Ma).

Punjab Salt Range Basin

In northern Pakistan the Salt Range Province is a large, fault-controlled, NE-trending salt basin that may extend beneath the Hindu-Kush fold belts of the Himalayan Suture. The basin is at least 250 km wide. Its SW flank appears to terminate near where the Najd West and Central Faults may have intercepted it (Figure 6).

The Salt Range Formation is considered to be a syn-rift sequence and the overlying Lower Cambrian Khewra Sandstone (also known as the Purple Sandstone Series) a post-rift sequence (Husseini, 1988, 1989; Husseini and Husseini, 1990). The Salt Range consists of the Punjab halite and gypsum, carbonates and clastics that overlie the Precambrian basement (Shah, 1977; Gorin et al., 1982; Wolfart, 1983). Wolfart (1983) reports that the Salt Range is more than 2,000 m thick, and that it is probably equivalent to the evaporites of the Ara Group and Hormuz Series.

Gulf-Zagros Hormuz Salt Basin

The Hormuz Series consists of halite, gypsum, fetid limestone, cherty dolomite, red sandstone and shale, and volcanic rocks that are probably syn-sedimentary (Kent, 1970). The thickness of the Hormuz is estimated to exceed 3 km. To the east of the Zagros Suture, the Soltanieh Formation is time equivalent to the Hormuz. The Soltanieh consists of a Lower Dolomite Member (123 m), Chopaghlu Shale Member (247 m) and an Upper Dolomite Member (790 m). In the Alborz Mountains of northern Iran, the Soltanieh overlies the Bayandor Formation consisting of nearly 500 m of fine-grained clastics intercalated with dolomite stringers (Stöcklin et al., 1964; Wolfart, 1983).

The Hormuz is interpreted as a syn-rift sequence (Husseini, 1988) and the Soltanieh and Bayandor as the time-equivalent platform sequences deposited on the Paleo-Tethys side of the Zagros Suture (Figure 5). This interpretation implies that the Hormuz evaporite basins were intra-continental.

The Zagros and Dibba faults sharply define the eastern side of the "Lower Gulf" Hormuz Salt Basin (Figure 1). The extent of the Hormuz Salt to the north and west is less well-defined. The salt is believed to be absent along the Qatar Arch and its NE-trending extension towards the Zagros Suture (Figure 1). To the west it thins out toward the Rub' Al Khali embayment between the Qatar and Kidan anticlines. In Figure 6. the Dibba Fault that bounds the southeastern margin of the Hormuz Salt Basin is interpreted as the main rift axis.

Many structures north of the Qatar Arch are interpreted as Hormuz Salt domes based on their oval shapes and corresponding negative gravity anomalies (Figure 1). The Dammam and Bahrain domes are typical examples and the Dukhan field of Qatar is interpreted as a Hormuz Salt wall.

As with the Qatar Arch, the Hormuz Salt is absent from the Ghawar Anticline (and other Rayn anticlines). This suggests that these anticlines, originally formed during the Amar Collision (about 640-620 Ma), remained uplifted horst blocks during the Najd Rift (about 570-530 Ma). The Rayn anticlines were probably surrounded by subsiding, normally faulted N-trending grabens. The resulting post-rift pattern consists of regularly spaced N-trending horsts and grabens, NE-trending intra-continental rift basins, and a system of NW-trending transform faults.

The extent of the Hormuz Salt in the Arabian Plate is not fully mapped. In the southern region of Arabia it extends as far west as the Najd Fault System (Faqira and Al-Hauwaj, 1998). How far it spreads into the deep grabens between the Rayn anticlines is unclear. Numerous circular, low-relief structures in the “Dibdibah Trough” located between the Summan Platform and Khurais-Burgan Anticline, could be salt cored. Nor is it clear how far north the Hormuz extends along the western side of the Zagros Suture (Figure 1).

Jordan Valley-Derik Rift

In Wadi Araba, Jordan Valley, felsic to mafic N- and NE-striking dikes are overlain by Cambrian clastics (Bender, 1982). Elongated N-trending volcanic belts consisting of rhyolites and andesites are dated at 560 Ma and 510 Ma. Bender (1982) interpreted the Jordan Valley Suture as a rift basin. In eastern Turkey, the Derik region lies along the strike of the Jordan geosuture and is interpreted as the continuation of the Jordan Valley Rift (Figure 6; Husseini, 1988).

Saramuj and Derik Groups

In the Jordan Valley the volcano-clastic Saramuj Formation consists of post-orogenic, molasse-type, poorly-sorted conglomerates and sandstones, which are intruded by felsic and mafic dikes (Mitchell, 1955; Gorin et al., 1982; Blasband et al., 2000). Sedimentary structures include alluvial fans, channel fills and debris flows. The Saramuj is dated at between 600 and 550 Ma (Jarrar and Zellmer, 1991; Jarrar et al, 1992) and is considered to be a syn-rift sequence. The Early Cambrian Salib Formation is a post-rift sequence correlated with the Siq Sandstone (Powers 1968; Powell, 1989). The Salib is overlain by the uppermost Lower Cambrian to lower Middle Cambrian Burj Formation (Powell, 1989).

In the Derik region the 500-m-thick Derik Formation consists of andesites, porphyries, spilites, volcanic breccia and tuffs that are interbedded with sandstone and shale (Wolfart, 1981, 1983). The Derik Formation is interpreted as a syn-rift sequence and the overlying Lower Cambrian Telbismi Formation as being of post-rift origin.

Egypt-Sinai Rift Branch

The basement in northeastern Egypt includes post-tectonic granites, most of which have been dated at between 620 and 575 Ma; the Dokhan rhyolites and andesites at 600 to 580 Ma; and E- to NE-trending dike swarms dated at 595 to 540 Ma (Stern and Hedge, 1985). Stern (1985) concluded that the region was an easterly trending rift basin that terminated in the Sinai Desert against a rift-related Najd transform system. Further east, in the Midyan region of Saudi Arabia, Clark (1985) dated the rift-related Minewah Volcanics at about 575 Ma, and an alkali-feldspar syenite at 553 Ma. Clark concluded that the northwest edge of the Arabian Peninsula was a rifted margin.

Hammamat Group

The Hammamat Group in northeast Egypt is interpreted as a syn-rift sequence by Stern (1985). It is up to 5 km thick and consists of thick sequences of unsorted to well-sorted conglomerates, sandstones and siltstones. Sedimentary structures include debris flow, alluvial fans and channel fills that Grothaus et al. (1979) believed were syn-sedimentary with normal faulting in an intra-montane landscape.

PETROLEUM HABITAT

The model presented here implies that the Najd syn-rift petroleum system of the Arabian Plate (for example the Huqf Supergroup of Oman) is more widespread than generally suspected. Two recently found examples of the system are the frontier undrilled salt basins in the western Rub' Al Khali of Saudi Arabia (Dyer and Husseini, 1991; Faqira and Al-Hauwaj, 1998), and the Phillips operated Ghudun Basin (Figure 1) in southwestern Oman (Blood, 2000). The extensional model also implies that the grabens between the great anticlines of eastern Arabia may have thick syn-rift sequences, including salt.

Another implication is that the foundations of the Arabian Plate structures (excluding the younger Zagros and Oman fold belts) consist of either rigid basement-controlled blocks or mobile salt cores. The basement does not have a plane surface, but rather it has substantial, fault-controlled vertical relief, consisting of horsts, grabens and salt basins. These factors imply an unstable foundation that adjusts itself vertically in response to overburden and lateral tectonic stresses.

These implications set the stage for stratigraphic trap exploration. For example, during the late Paleozoic Hercynian Orogeny the basement-controlled N-trending Rayn anticlines were uplifted and much of the overlying Paleozoic sediment cover was eroded. Salt domes, on the other hand, were not significantly mobilized during this orogeny which suggests that they were largely decoupled from the basement's stress system by the syn-rift Hormuz Salt. This implies that the pre-Khuff plays will generally be along the flanks of the basement-controlled structures, and crestal for the salt domes.

In contrast, the closing of the Neo-Tethys Ocean and the Zagros Collision, from the Late Cretacous to the present, preferentially mobilized the salt-cored structures. For example, the Dammam and Bahrain salt structures have a much greater vertical relief and fault intensity than the basement-controlled Ghawar field. This suggests that the salt domes may have greater Mesozoic stratigraphic trap potential along their flanks.

Finally, the model presented here implies that a complex and extensive network of N-, NW- and NE-trending faults intersect the entire Precambrian basement and affects the overlying Phanerozoic sequences. Movements along these basement fractures will readily propagate upward through the overlying strata causing subtle structural growth, hydrocarbons to migrate along deep-seated fractures, and basins to subside over mobile regions. Undoubtedly the detailed mapping of the Precambrian basement structure and its fault network will reveal many previously unnoticed and important patterns.

CONCLUSION

The collision along the N-trending Amar Suture at between about 640 to 620 Ma (Stoeser and Camp, 1985; Brown et al., 1989) appears to have formed the regularly-spaced, northerly-oriented Summan Platform, Khurais-Burgan Anticline, En Nala (Ghawar) Anticline and Qatar Arch (Rayn anticlines). This simple collisional model for the origin of these great anticlines is supported by coincident radiometric dating of compressional deformation on both sides of the Amar Suture. The anticlines increase in N-S extent eastwards, and are bounded by the apparently syn-collisional NW-trending Abu Jifan and NE-trending Wadi Batin strike-slip faults.

The pursuant crustal collapse of the Arabian-Nubian Shield between about 620 and 530 Ma, is based on the dating of widespread extensional plutonic and volcanic rocks (Husseini, 1988, 1989; Husseini and Husseini, 1990; Genna et al., 2000; Blasband et al., 2000). The final stage of the extensional model (about 570 to 530 Ma) interprets the dislocation of about 250 to 300 km as part of the Najd Rift System. This system is identified on the following basis:

(1) geometric relationships: for example, Najd strike-slip faults that cut off orthogonal salt basins; Najd faults that are parallel to the Zagros Suture;
(2) plate tectonic templates: for example, Sinai Triple Junction that matches three active Precambrian-Cambrian rift branches; elongated salt basins which are fault-bounded;

(3) kinematic considerations: for example, three parallel Najd fault brittle dislocations that match the widths and tectonic geometries of the Oman and Punjab salt basins; and
(4) spatial and temporal coincidence of the radiometrically dated extensional igneous rocks and corresponding syn-rift sequences.

During the period of rifting, the N-trending Rayn anticlines (originally formed during the Amar Collision) remained uplifted horst blocks surrounded by subsiding, normally faulted grabens. The resulting post-rift pattern consists of regularly spaced N-trending horsts and grabens and NE-trending intra-continental salt-filled rift basins.

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ABOUT THE AUTHOR

Moujahed I. Al-Husseini *founded Gulf PetroLink in 1993, a consultancy aimed at transferring technology to the Middle East petroleum industry. Moujahed was previously Exploration Manager for Saudi Aramco. He received his BSc in Engineering Science from King Fahd University of Petroleum and Minerals (1971), MSc in Operations Research from Stanford University (1972), PhD in Earth Sciences from Brown University (1975) and Program for Management Development from Harvard University (1987). In 1996, Gulf PetroLink launched the journal of Middle East Petroleum Geosciences, GeoArabia, for which Moujahed is Editor-in-Chief. Moujahed is a member of the AAPG, AGU, SEG, EAGE and Geological Society of London.*