GeoArabia, Vol. 1, No. 1, 1996
Gulf PetroLink, Bahrain

The Tectonic Evolution of Interior Oman

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ABSTRACT

The evolution of Oman's onshore sedimentary basins from the Late Precambrian to the Present is reflected by six tectono-stratigraphic units. Unit I, the Precambrian basement, represents continental accretion. Units II and III, Infracambrian to Ordovician, may reflect two periods of rifting, possibly related to Najd movements in western Saudi Arabia. The northeast-southwest trending salt basins formed during this time interval. A classical "steer's head" basin geometry is developed in North Oman, whereas a less complete rift-sag sequence is preserved in South Oman. Of the entire time-span from Late Silurian to Mid-Carboniferous, only little Devonian (Emsian) sediment is preserved. Unit IV, Late Carboniferous to Mid-Cretaceous, reflects the break-up of Gondwana and the creation of the northeastern and southeastern passive margins of the Arabian Plate. Unit V documents intra-plate deformation related to Late Cretaceous continent-ocean obduction in the north and transpressional movements of the Indian Plate in the east. Unit VI, spanning the Tertiary, represents a return to quiet conditions followed by continent-continent collision in the north. Following Late Eocene uplift, the Gulf of Aden rift developed in the south in the early Oligocene, with sea-floor spreading from the Late Miocene onwards. Salt flow and dissolution, both playing a major role in the configuration of most intra- and post-salt hydrocarbon traps in Oman, are episodic and can be related to tectonic events.

INTRODUCTION

The Sultanate of Oman is situated on the southeastern margin of the Arabian Plate (Figures 1 and 2). It is bounded to the south by the Gulf of Aden spreading zone, to the east by the Masirah Transform Fault and Owen Fracture Zone, and to the north by the complex Zagros-Makran convergent plate margin, which in Oman has resulted in the building of the Oman Mountains. The Oman Mountains, in which the Semail Ophiolite is spectacularly exposed, have received considerable attention since the first comprehensive field study by Glennie et al. (1974). In contrast, relatively little has been published on the subsurface geology of Oman's flat desert interior, although more than 35 years of hydrocarbon exploration has yielded a detailed picture of its geological evolution (Tschopp, 1967; Al-Marjeby and Nash, 1986; Hughes-Clarke, 1988; Levell et al., 1988; Visser, 1991; papers in Robertson et al., 1990). A tectonic synthesis is still missing from the literature.

Here, we will briefly review the tectonic evolution of Oman, with emphasis on its desert interior, and within a framework of six discrete tectono-stratigraphic units. These units preserve a tectonic record that reveals a continental evolution comprising island-arc accretion (Unit I), followed by intra-plate rifting, wrenching and epeirogenic tectonics (Units II and III), continental break-up and the development of passive margins (Unit IV), active margin tectonics involving ophiolite obduction (Unit V), concluding with continent-continent collision in the north and the development of a new passive margin in the south (Unit VI).

TECTONO-STRATIGRAPHY

Unit I: Basement - Pan-African Accretion in the Arabian Peninsula

Five distinct Precambrian terranes in western Saudi Arabia were amalgamated during the Late Precambrian (Stoesser and Camp, 1985). These are: the Asir, Hijaz, Midyan, Afif and Ar Rayn terranes (Figure 1). The Asir, Hijaz and Midyan terranes are interpreted as island-arc terranes, fused together along the Bir Umq and the Yanbu sutures around 715 million years before the present (Ma). Both sutures contain strongly deformed and ophiolitic rocks and extend for several hundred kilometers into Sudan.

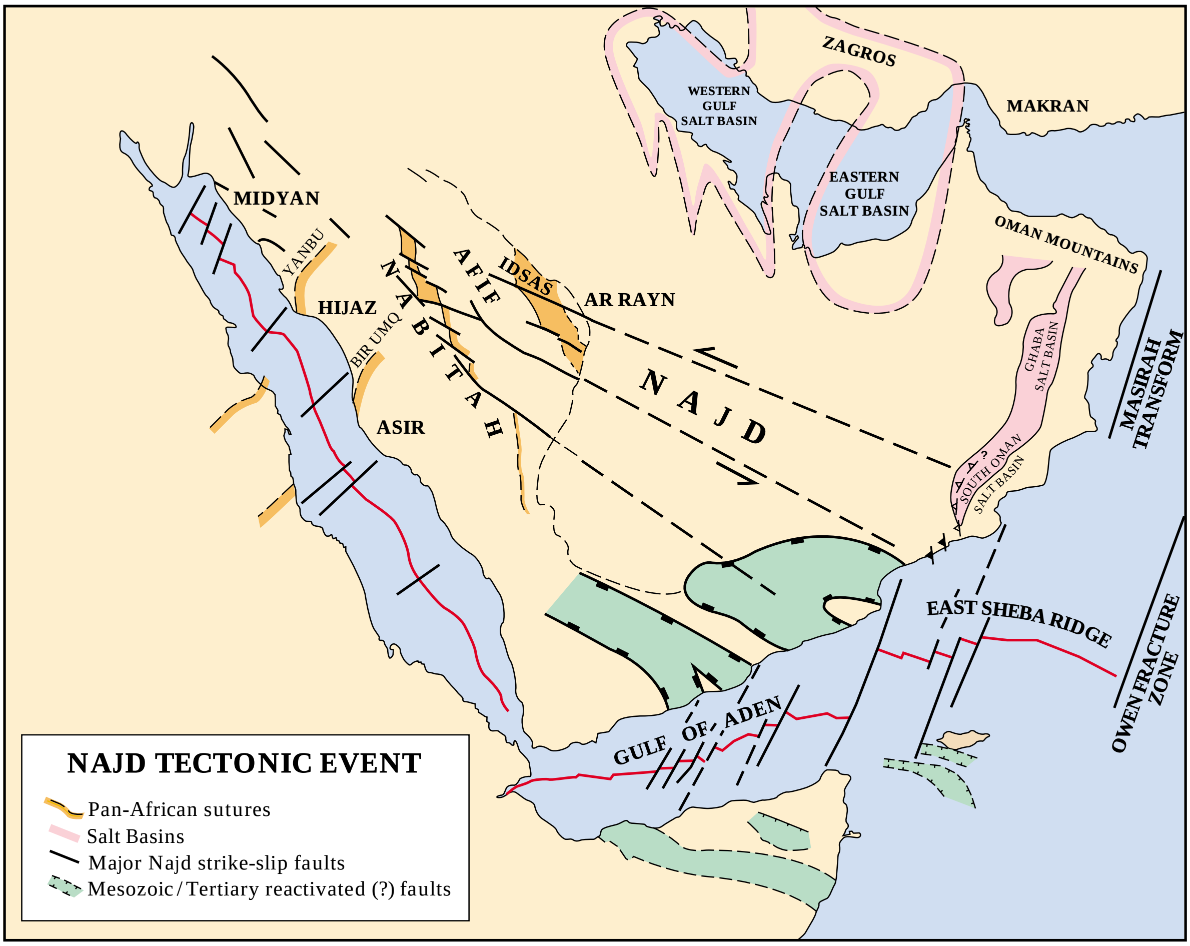


Figure 1: The Arabian Peninsula, with Precambrian terranes in the Arabian Shield area of western Saudi Arabia and the Infra-Cambrian sinistral Najd tectonic event (600-530 Ma) (Brown and Jackson, 1960; Moore, 1979) with its Mesozoic and Tertiary reactivations (Bott et al., 1992; Richardson et al., 1995). Microplate boundaries based on Stoesser and Camp (1985).

Pallister et al. (1988) dated the closure of these sutures at between 620 and 700 Ma. Between 680 and 640 Ma, the Afif gneissic terrane was accreted along the Nabitah suture. This suture is between 100 and 200 kilometers (km) wide and consists of broad, linear complexes of synorogenic plutonic and metamorphic rocks, as well as ophiolitic complexes. Finally, the Al Amar island arc and the Ar Rayn gneissic terrane were added along the Al Amar-Idsas suture, containing abundant syn-orogenic granites dated at around 640 Ma ("Idsas Orogeny"). It thus seems that island-arcs and micro-continents were added to the eastern side of the Arabian Shield, with eastwards-younging accretion ages.

In Oman, Precambrian metamorphic and igneous basement rocks, including metasediments of greenschist or amphibolite facies intruded by dolerites, granodiorites and granites, are known from outcrops in the eastern part of the country (Lees, 1928; Glennie, 1977; Gass et al., 1990; Le Métour et al., 1993; Hauser and Zurbriggen, 1994; Figure 2). In addition, the Precambrian basement has been penetrated by five wells. Radiometric age dates indicate that the outcrop rocks lie within the Pan-African age range from 830 to 730 Ma (Gass et al., 1990; Würsten et al., 1991; Béchennec et al., 1993). The Rb-Sr age of 662 ±13 Ma determined from migmatites penetrated by the well Zafer-1 represents the latest Precambrian metamorphic event in Oman (Hughes-Clarke, 1988). Older basement of the type recognized in western Saudi Arabia (Afif Terrane, 1770 Ma, Stacey and Agar, 1985) has not been recorded in Oman.

The calc-alkaline signature of many of the igneous basement rocks onshore eastern Oman and the apparently ophiolitic ultramafic rocks in the Al Halaaniyaat islands imply the presence of another continental suture along the present-day east coast of Oman. Platel et al. (1992) did not confirm this interpretation after mapping the islands.

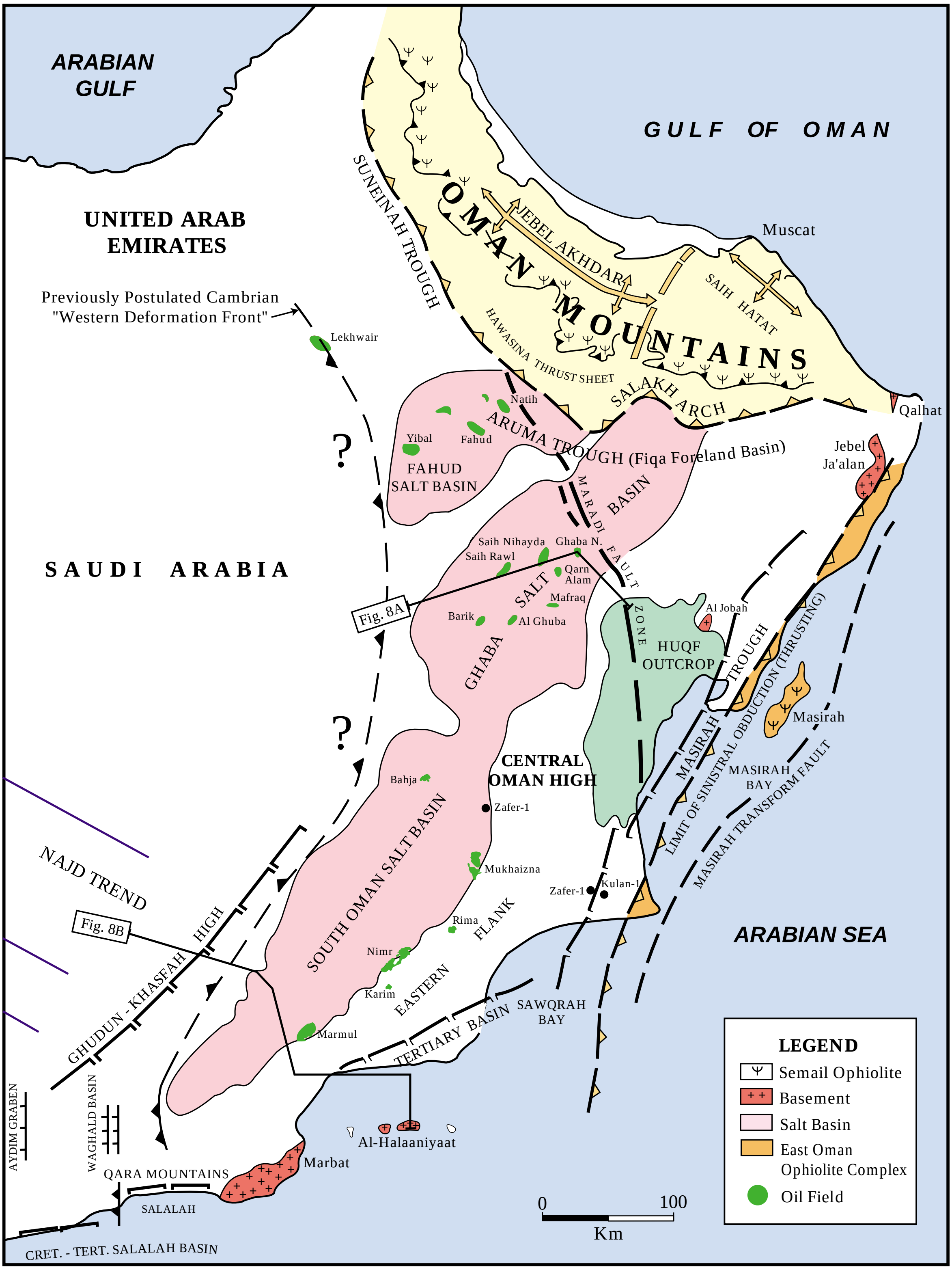


Figure 2: Tectonic map of Oman. Precambrian outcrops are from north to south Qalhat, Jebel Ja'alan, Al Jobah, Al Halaaniyaat Islands and Marbat.

Unit II: Vendian/Infracambrian - Rift Cycle 1

In Saudi Arabia around 630 Ma, collisional tectonics changed to intra-continental extensional tectonics, possibly associated with post-tectonic alkali-granites and rhyolites dating approximately between 620 and 580 Ma (Stoesser, 1986; Calvez and Kemp, 1986; Husseini, 1989; Husseini and Husseini, 1990). In Oman, Unit II unconformably overlies the deformed rocks of Unit I, passing from predominantly clastic

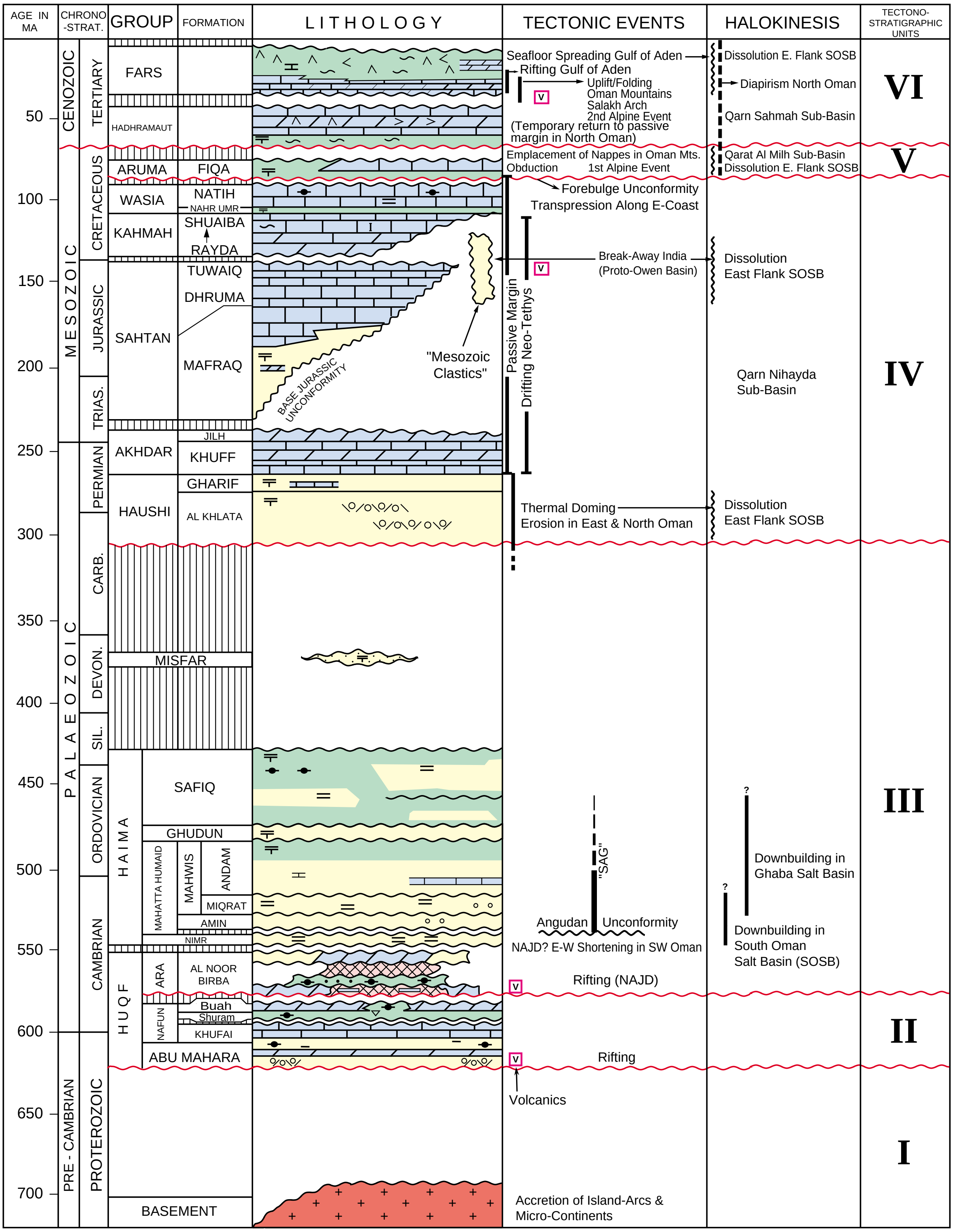
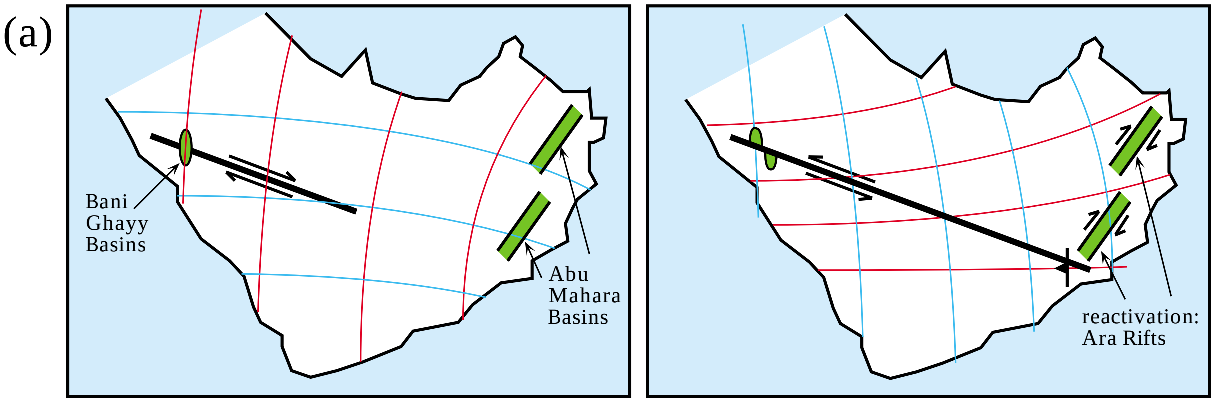


Figure 3: Tectono-stratigraphy of Oman. The stratigraphic column carries a revised PDO nomenclature which will be discussed in a separate study.

sediments of variable thickness (Abu Mahara Group) at the base to more uniformly stratified clastic deposits and platform carbonates (Nafun Group) at the top (Figure 3). An Infracambrian age is inferred from acritarchs of presumed Vendian age (Gorin et al., 1982; Rabu, 1988) and from regional correlations with the Robutain Formation of the J'Baylah (also Jubaylah, Powers et al., 1966; Powers, 1968;) Group and Bani Ghayy group (Agar, 1986) in Saudi Arabia and the Minhamir Formation of the Ghabar Group of southern Yemen (Beydoun, 1966; Husseini, 1989; Husseini and Husseini, 1990; Figure 4a).



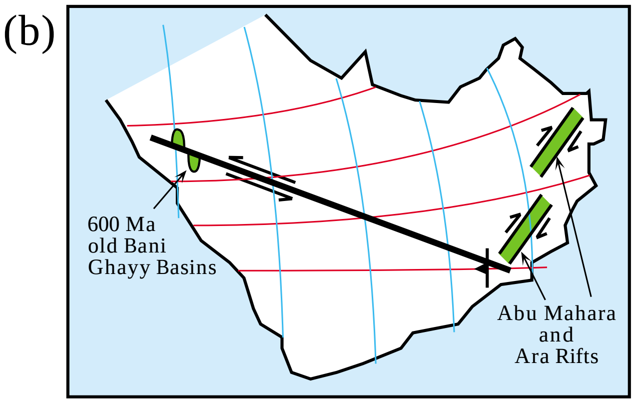


Figure 4: Possible relations between Abu Mahara and Ara Basins in Oman and the Najd strike-slip event and associated Bani Ghayy Basins in Saudi Arabia. In (a), two discrete rifting events occur with the first event involving a dextral Najd system accompanied by Bani Ghayy and Abu Mahara Basins around 600 Ma. The second event is a sinistral Najd System with Ara Salt Basins. In (b), a single rift event is associated with a sinistral Najd and both Abu Mahara and Ara rifting (580-530 Ma). Maximum and minimum principal stresses are parallel to red and blue trajectories, respectively.

In Oman, the Abu Mahara Group is poorly imaged on seismic but known from some 20 wells which partially penetrate it and from exposures in the Huqf area (Gorin et al., 1982; Hughes-Clarke, 1988). Stratigraphic equivalents are the Mistal Formation in Jebel Akhdar (Glennie et al., 1974; Rabu, 1988), the Hatat Formation in Saih Hatat (Le Métour, 1988), and probably the Wadi Ercohol outcrops of the Marbat Formation in the Marbat area (Qidwai et al., 1988; Platel et al., 1992).

Thickness variations in the limited penetrations of Abu Mahara Group suggest that, during deposition of its lower part, a northeast-southwest trending rift basin developed in eastern Oman. The existence of this basin, poorly recognizable on seismic, has been confirmed by subtracting the depth map of the top-Middle-Huqf Group from the depth map of the top-magnetic-basement. By assuming that the major thickness variations are in the Abu Mahara Group, rather than in the Nafun Group, this map shows an Abu Mahara basin extending for 200 km from Marbat to Dhahir-1 (Figure 5).

Abu Mahara rifting may have been widespread. Several references exist to Infracambrian sediments in other parts of the Arabian Plate. In Saudi Arabia, extensive and deep, north-south trending, fault-bounded basins developed between 620 and 608 Ma, filled with coarse clastics and volcanics of the Bani Ghayy Group (Agar, 1986), possibly synchronous with deposition of the early Abu Mahara Group (Figure 4a). Dyer and Husseini (1991) interpreted the presence of Infracambrian graben systems below the Rub Al Khali Basin, although on what appears very poor seismic data. Le Métour (1988) and Rabu (1988) also argue for northeast-southwest trending horst-and-graben structures during Abu Mahara times from (volcano-)sedimentary facies (variations) in the Oman Mountains.

In Oman, a series of north-south to northeast-southwest trending basement highs may have developed, from south to north, the Ghudun-Khasfah High, the Anzauz-Rudhwan Ridge and the Makarem-Mabrouk(-Semail) High (Figure 6), separating different basin segments. To date, this is still the dominant grain picked up by gravity surveys for example (Figure 7). The event is associated with igneous activity (Oman Mountains, Huqf area, wells in eastern Oman) and is followed by a thermal subsidence phase, possibly represented by siltstone, sandstone, stromatolitic carbonate and source rock of the upper Abu Mahara Group.

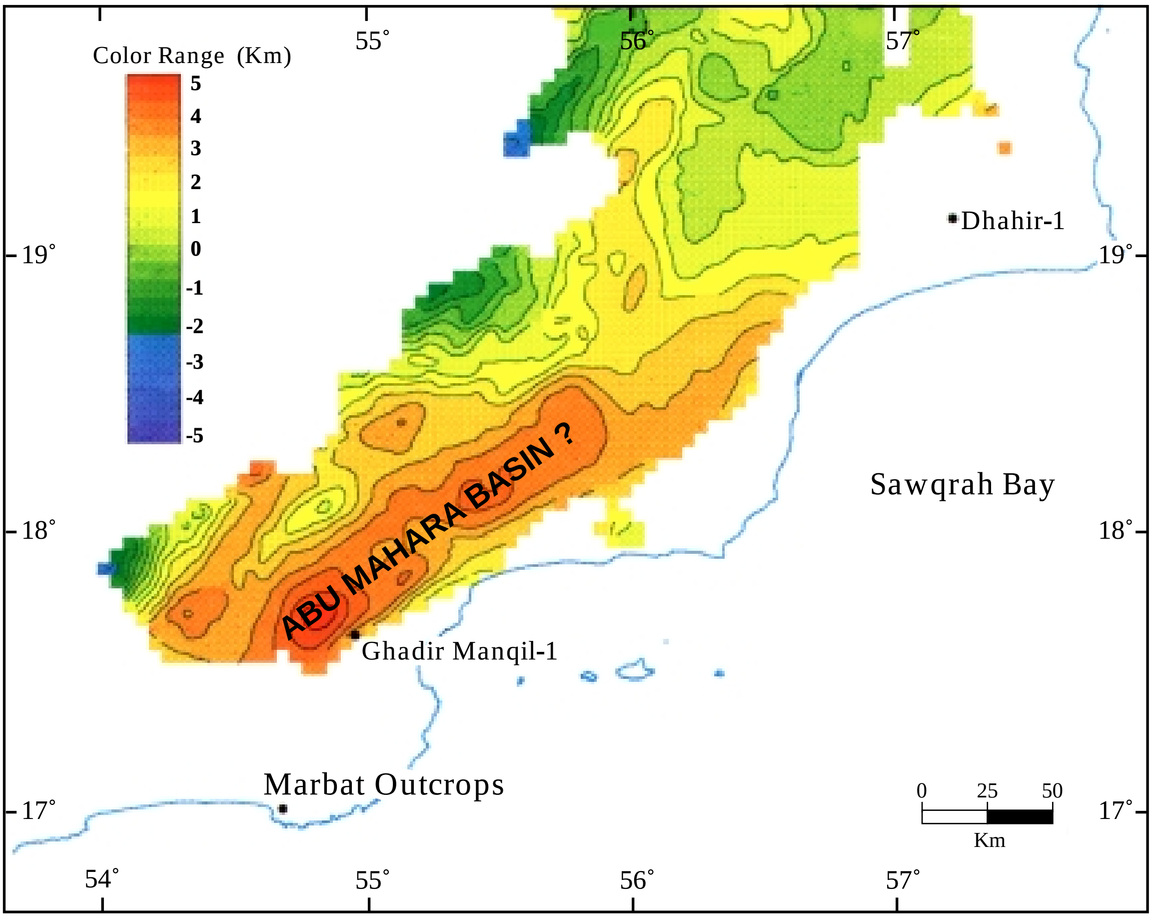


Figure 5: Isopach map of interval magnetic basement to top Middle Huqf, showing the Abu Mahara basin in southeast Oman.

The upper sequence of Unit II (Nafun Group consisting of Khufai, Shuram and Buah formations; Hughes-Clarke, 1988) is better known, both from outcrops (Huqf outcrop area and stratigraphic equivalents at Jebel Akhdar and Saih Hatat) and many well penetrations, particularly in South Oman. In some areas, a characteristic 'tramline' appearance on seismic data is caused by a 'layercake' sequence of two packages of platform carbonates (Khufai and Buah), separated by a sequence of mainly fine clastics (Shuram). Thickness and facies variations appear to be much less pronounced than in the underlying sequence. The absence of volcanics and coarse-grained clastics imply tectonic quiescence, although regional correlation is often difficult (Gorin et al., 1982). We suggest that the deposition of the Nafun Group may have been controlled by the later phases of thermal relaxation following the Abu Mahara rift event, epeirogenic movements and eustatic sea-level changes, and/or the onset of the second rifting event (Unit III).

The interpretation, presented above, of Unit II as a rift-sag cycle is based on circumstantial evidence and is still under discussion within Petroleum Development Oman. An alternative view (Bermingham et al., unpublished PDO report) is that Unit II was deposited during a period of relative tectonic quiescence, following the last phase of plate accretion. The earlier phase of clastic sedimentation is thought to have filled in a remnant relief of the preceding orogeny, in unspecified intra-cratonic basins. The later phase of mixed carbonate and clastic sedimentation followed complete peneplanation, and is presumed to result from epeirogenic movements and eustatic sea-level changes.

Unit III: Cambrian to mid-Carboniferous - Rift Cycle 2, followed by Epeirogenesis and Uplift

The Abu Mahara rift configuration was re-activated (or persisted) in early Upper Huqf times. Volcanics, penetrated in some widely spaced wells and outcropping in the Fara Formation in Jebel Akhdar (Rabu,

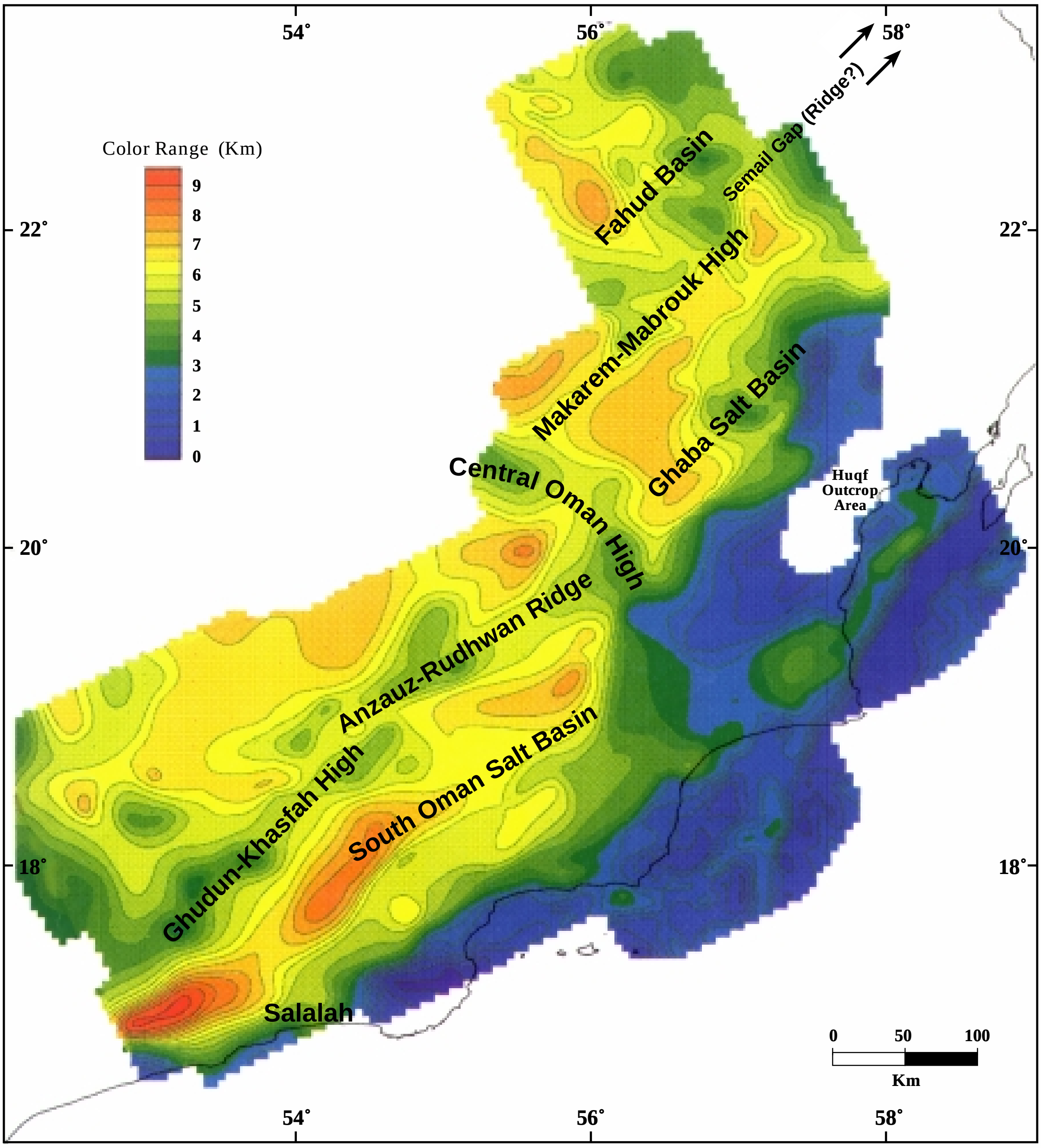


Figure 6: Depth map of magnetic basement.

1988), clastics near the Ghudun High and in the Oman Mountains and thick Ara salt (Hughes-Clarke, 1988; Matte et al., 1990) suggest rapid subsidence and renewed tectonic activity. The re-activated eastern low-angle bounding fault of the Ghudun-Khasfah High becomes the western margin of the asymmetrical South Oman Salt Basin (Figure 8b). In the north, the Ghaba Salt Basin develops as a narrower, deeper, and less asymmetrical feature with some asymmetry reversals (Figure 8a). Husseini and Husseini (1990) have argued that the South Oman and Ghaba Salt Basins are related to the Najd event of rifting and wrenching, which in Saudi Arabia is dated at between 600 and 540 Ma. The rift sequence is represented by the Upper Huqf and Lower Haima (Nimr) groups.

The Angudan Unconformity marks the end of this tectonic event with a clear angular unconformity in southwest Oman where Amin conglomerates with deformed pebbles overlie the unconformity (see “Discussion”), and a rift-sag unconformity on the flanks of the South Oman and Ghaba Salt Basins. The Middle, and possibly also the Upper, Haima represent the sag phase preserved over the Ghaba Salt Basin as the top of a classical “steer’s head” basin geometry (Figure 8a). Nonetheless, the Middle Haima

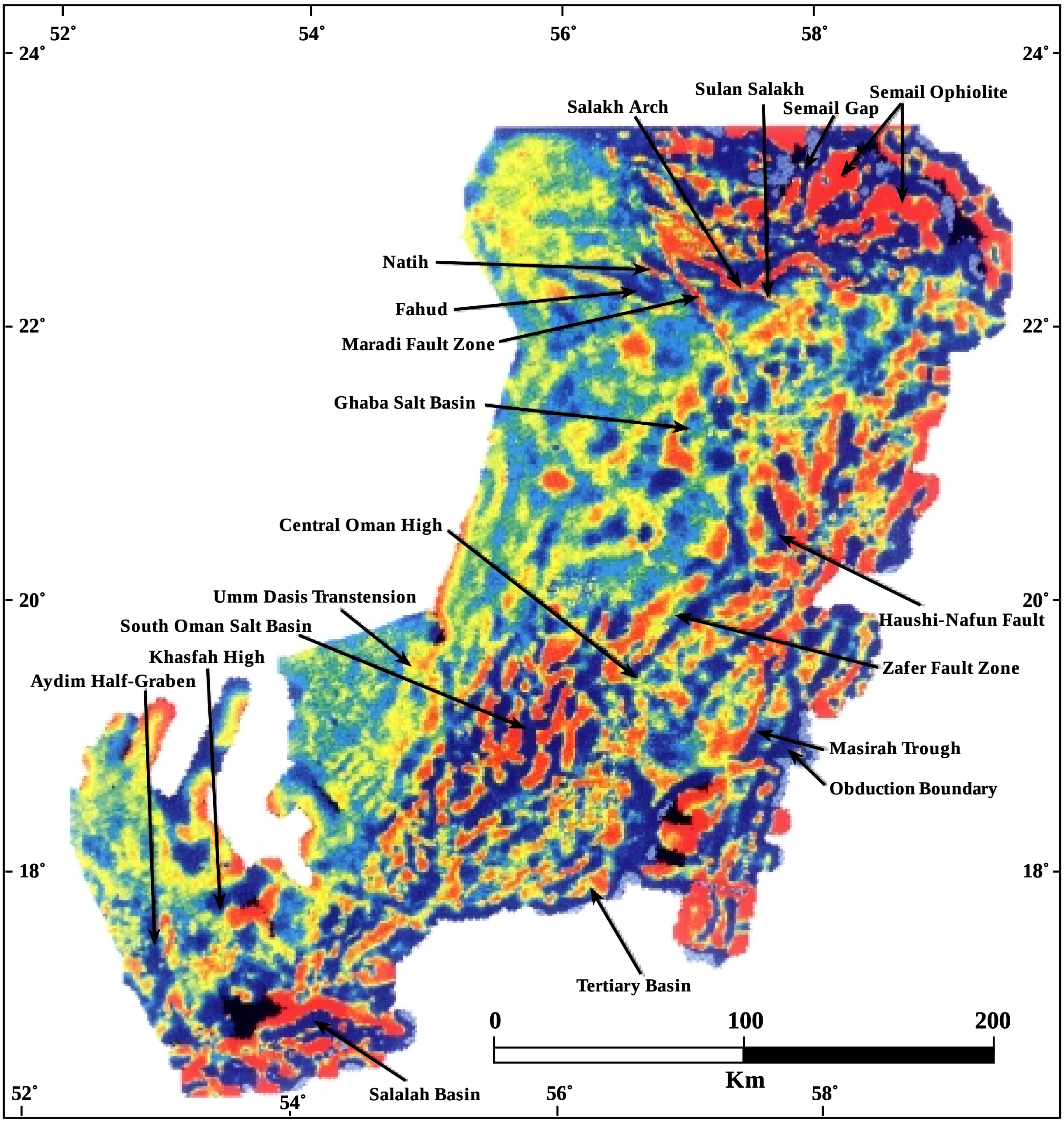


Figure 7: Residual gravity map. Blue color corresponds to residual gravity low (e.g. salt dome) while red to residual gravity high.

is affected by the last pulses of extension, which cause the downthrow of the Angudan Unconformity east of the Ghudun-Khasfah High, the creation of the Aydim and Waghald Basins and the widening of the Ghaba Salt Basin.

Deposition of the Ghudun Formation postdated Najd-related east-west shortening in southwest Oman (see "Discussion") and occurred in areas that previously were non-depositional. In the South Oman Salt Basin area, faulting on the western margin of the basin and a related westward tilting caused a shift of the depocentre towards the west. In North Oman, however, the depocenter was still located centrally over the Ghaba Salt Basin.

A regional unconformity separates the Ghudun Formation from the overlying Safiq Group. The Safiq group (Boserio et al., 1994) consists of open-marine to deltaic sediments stacked into three transgressive-regressive cycles, separated by erosion surfaces probably related to Ordovician glaciations. There is still a pronounced thickening of the Safiq Group over the central Ghaba Salt Basin (although thermal sagging should be in its final stages).

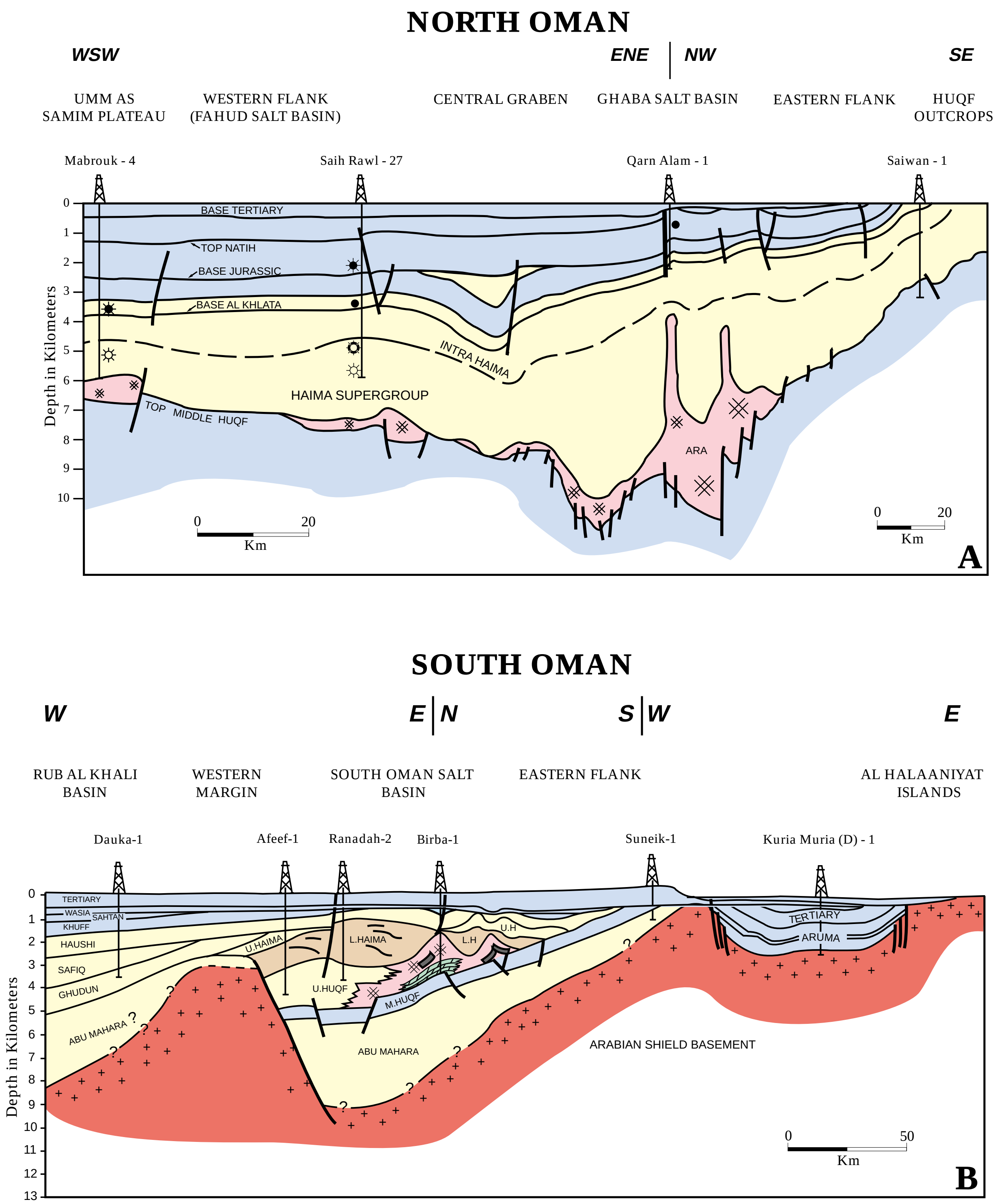


Figure 8: Schematic cross-sections. (See Figure 2 for location.)

Most of the Safiq Group and the overlying Silurian to Lower Devonian is no longer preserved. An important phase of erosion, caused by a very broad uplift before the deposition of the very locally preserved lacustrine or marginal marine Devonian Misfar sediments, may have removed significant amounts of sediment. The interval between mid-Devonian and Upper Carboniferous is also not preserved in the rock record of Oman. Both unconformities are associated with uplift of eastern Oman (Visser, 1991).

In conclusion, Unit III documents rifting, followed by a protracted period of thermal relaxation (better preserved in the north than in the south) and epeirogenic movements with regional northwestward tilting.

Age Uncertainty

Absolute ages of the Huqf and most of the Haima units are poorly constrained. Recent analyses of volcanics at the base of the Abu Mahara yield Rb-Sr dates of 556 ±11 and 562 ±42 Ma (Dubreuilh et al., 1992; Platel et al., 1992; Béchennec et al., 1993; Le Métour et al., in prep.). Preliminary Pb / Pb ages from stromatolitic Birba stringers (Upper Huqf) give ages of 513 ±75 Ma (unpublished Shell / PDO data). If correct, these ages imply that the Huqf Supergroup was deposited between approximately 560 and 510 Ma, as opposed to between 610 and 550 Ma as on the currently accepted chronostratigraphy (Figure 3). Using the modified Harland et al. (1990) time scale, this would place the Huqf in absolute age terms entirely within the Cambrian. However, the relative age, based on the presence of Vendian glacial sediments and palynomorphs, supports a Precambrian age, at least for the Abu Mahara Group. These data support the Odin and Odin (1990) age scale which places the Precambrian-Cambrian boundary at 530 Ma. If correct, the Abu Mahara Group may have been deposited during the sinistral regime of the Najd (Figure 4b).

K / Ar, Ar / Ar and apatite fission track ages suggest that a heating event, probably due to rifting, occurred around 530 to 500 Ma. This event corresponds to the Mahwis / Amin on the chronostratigraphy of figure 3, or the Ara Group if the Odin and Odin (1990) scheme is accepted. The absence of volcanics in the Amin and Mahwis, however, suggests low extension factors and a relatively minor disturbance of the thermal structure at this time. Widespread volcanism during Upper Huqf times and its general rift setting, on the other hand, could explain the observed cooling ages. Again, this implies a relatively young age for the Upper Huqf. The Middle Haima extensional faults would then represent the last pulses of an Upper Huqf / Lower Haima rift event rather than a new discrete rift event.

Unit IV: Late Carboniferous to Cenomanian - Gondwana Break-up, Passive Plate Margin and Intra-Plate Epeirogenic Tectonics

Tectono-stratigraphic Unit IV comprises the Permo-Carboniferous clastic Haushi Group with its lower mainly glaciogenic, continental Al Khlata Formation (Levell et al., 1988) and its upper fluvio-marine Gharif Formation (Hughes-Clarke, 1988). It follows a long period of erosion and non-deposition. The distribution of Haushi sediments, confined to interior Oman, reflects highs along the eastern and northern present-day coast lines of Oman. Sedimentary transport was mainly from south to north (increasing clastic maturity), with possibly some contribution from the eastern high. Scarcity of coarse clastics and thinning of the northerly onlapping Haushi sequence suggest that the high to the north as an area of clastic provenance must have been negligible. These highs were probably formed during thermal-doming which preceded the break-up of Gondwana (Figure 9; Le Métour et al., 1994).

Deep-water sedimentation (e.g. radiolarites of the Hawasina Ocean), and tholeiitic / alkaline volcanism began by early Late Permian north of the present-day Oman Mountains, suggesting the incipient development of oceanic crust of the Neo-Tethys (Blendinger et al., 1990). In the interior of Oman, at the same time, the Akhdar Group represents flooding of the Arabian Shield (Béchennec, 1988; Blendinger et al., 1990). The thickest development of Permian lower Khuff marine carbonates with evaporitic intercalations in west-central Oman is bounded by a belt of thinner, largely dolomitic sediments to the north, east and south. It appears, therefore, that highs, or areas of lesser subsidence, persisted in these directions. A similar pattern lasted until the Triassic. The northern high may have been a remnant rift shoulder, at a time when Neo-Tethyan spreading may already have started further north (Blendinger et al., 1990; Stampfli et al., 1991; Le Métour et al., 1994). Eastern Oman appears to remain a high. It is possible that the strata thinned over the northern reaches of this eastern high, which to the east gave way to more open marine sediments, now found as isolated blocks in the obducted Batain “Melange” (Shackleton et al., 1990; Lee, 1990). Further south, the high is likely to have become non-depositional, as it lay beyond a belt of redbeds which in the south forms a transition to areas of non-deposition.

During the Late Triassic to Early Jurassic the northern high collapsed - typical for the transition from rifting to oceanic spreading - and sedimentation was transitional from a carbonate platform in the present-day mountain area to the deeper facies of the Neo-Tethys to the north. Finally, in the latest Jurassic, the present-day mountain area subsided (relatively?) into a deeper marine domain. Shallow-water deposition was only restored by Aptian-Albian times, when carbonate platform sediments prograded northwards from interior Oman (Rabu et al., 1990).

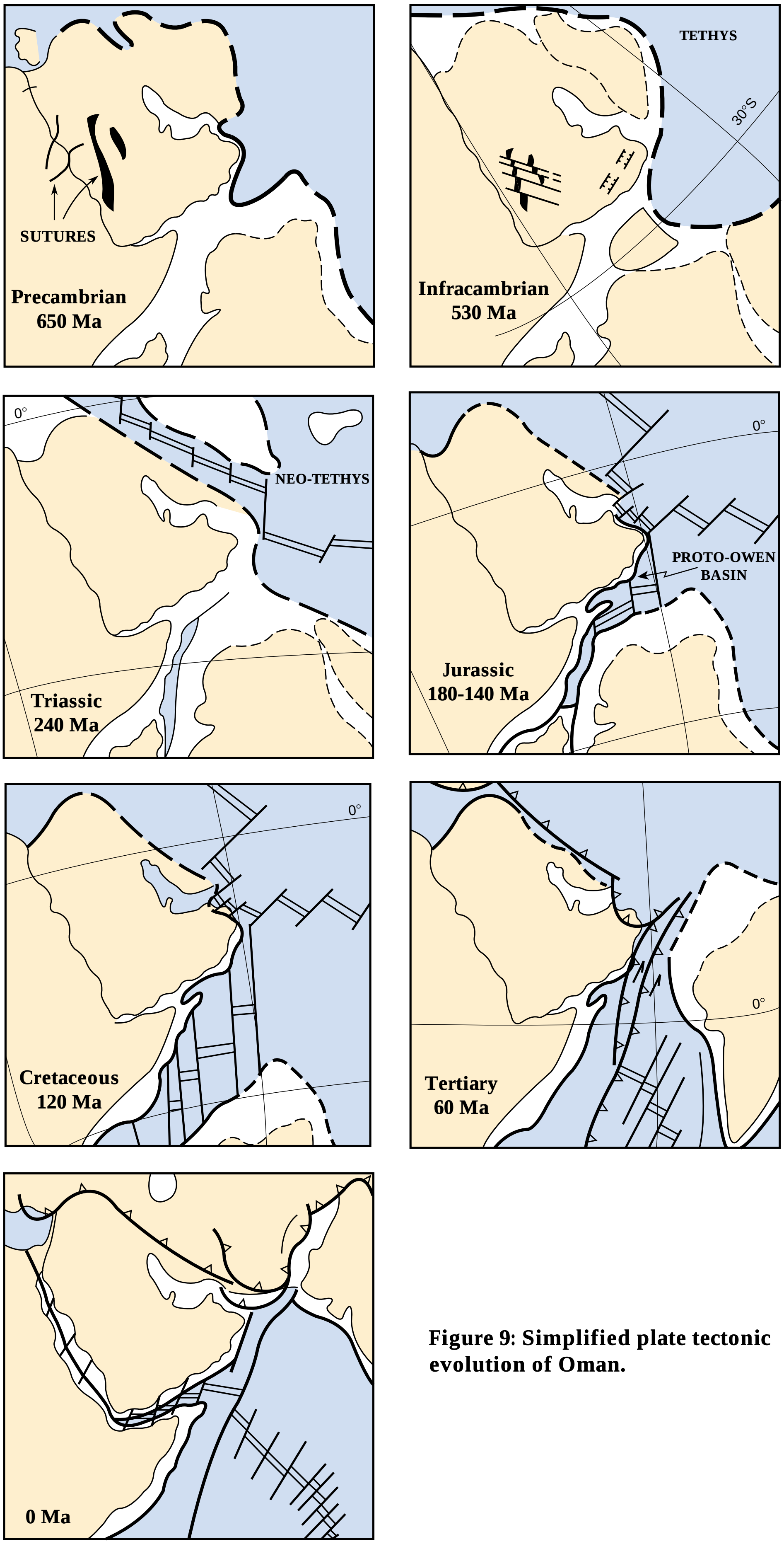


Figure 9: Simplified plate tectonic evolution of Oman.

The history of the eastern high, extending from Qalhat and Jebel Ja'alan in the northeast to Marbat in the south and comprising the present-day Huqf outcrop area, is different. Rifting and subsequent spreading was probably largely controlled by the pre-existing Huqf rifts, which formed the dominant "basement" grain. Precursors to break-up of Gondwana are the regional high at Haushi Group times in East Oman and, further south along the east coast of South Africa and Mozambique, the development of a large north northeast-south southwest trending rift system in which the primarily terrigenous Karoo Group was deposited between 300 and 205 Ma (Salman and Abdula, 1995).

In East Oman, regional westerly tilting is documented by a gradual eastward transgression of Early Jurassic marine sediments over an erosional surface below which Akhdar sediments are progressively truncated. We speculate that this "Base Jurassic" unconformity (Figure 3) may again be related to an early attempt at creating the proto-Owen basin (Figure 9; Mountain and Prell, 1990).

During the Late Jurassic-Early Cretaceous, a new phase of westerly tilt and uplift of the eastern high resulted in a similar, if less pronounced, eastward onlap of shallow marine sediments. This phase of uplift of eastern Oman may testify to the - now successful - separation of India-Madagascar-Antarctica from Africa-Arabia, and is related to the formation of the Masirah oceanic crust (= now the Eastern Ophiolite Belt of Oman), which has been dated at ~150 Ma both by U / Pb zircon radiometrics (Smewing et al., 1991; Peters et al., 1995) and by the biostratigraphy of radiolarian assemblages overlying basalts of MOR character (Beurrier, 1987; Le Métour et al., 1992; Immenhauser, 1995). This Tithonian age of early oceanic crust is possibly also corroborated by basic sills dated at 149 ±6Ma in Kulan-1 (unpublished PDO data).

Further south, in the Somalia and Mozambique Channel Basins, the break-up of Gondwana starts at the same time, at magnetic anomaly M25 (157 Ma; Salman and Abdula, 1995). Beauchamp et al. (1995) also suggested that rifting below and east of the Masirah Trough may have started during the Jurassic. Persistent shallow marine sedimentation over the eastern high is likely to have occurred only in the Albian, during deposition of the Wasia Group, coincident with a global rise in sea level.

In conclusion, Unit IV represents sedimentation near the developing northern and eastern passive margins of the Arabian Plate. The distribution of Haushi sediments documents incipient highs along the eastern and northern present-day coast lines of Oman. These highs were probably formed during the thermal-doming which preceded the break-up of Gondwana. Remnants of a northern rift dome disappear in the Late Triassic to Early Jurassic, from which time onwards a gradual, if geographically shifting, transition from intra-continental platform carbonates to Neo-Tethyan oceanic sediments occurs (Glennie et al., 1974; Béchennec et al., 1988). By contrast, the more pronounced eastern high underwent a history of intermittent uplift and was non-depositional well into the Cretaceous, long after spreading of the Indian Ocean had started. Apart from the described tectonic influences at the plate margin, carbonate sedimentation in the interior of Oman was greatly influenced by cyclic eustatic changes.

Unit V: Late Cretaceous - Foreland Basin Development in the North

Around 110 Ma, the Atlantic Ocean started to open, leading to closure of the Neo-Tethys between the Afro-Arabian and Eurasian plates (Dercourt et al., 1986). A northeasterly dipping intra-oceanic subduction zone developed, accompanied by back-arc spreading and the formation of the future Semail Ophiolite (Glennie, 1995). At ~93 Ma, this subduction complex collided with the continental crust of Oman (Lippard et al., 1986). Uplift and partial erosion of the Natih Formation during the earliest Turonian (Wasia-Aruma forebulge unconformity), and the development of a major hardground throughout the carbonate shelf area, signaled the onset of this first Alpine event (Béchennec et al., 1994). The initial uplift has been described as a mobile (Robertson, 1987) or stationary (Nolan et al., 1990) fore-bulge that preceded down-warping of the foreland ahead of the advancing thrust front. This is clearly demonstrated in the Suneinah Trough in the United Arab Emirates (Patton and O'Connor, 1988; Boote et al., 1990), along the Lekhwair High of northwest Oman (Warburton et al., 1990) and the Muti Basin on the southern edge of the Oman Mountains (Robertson, 1987; Le Métour, 1988; Rabu, 1988), but is less clearly expressed in the interior of Oman. Earliest Turonian emergence in Oman south of the thrust front is confined to the Natih-Fahud fault blocks and the northernmost parts of the Maradi Fault Zone, and is caused by (salt-assisted) footwall uplift (Figure 10a).

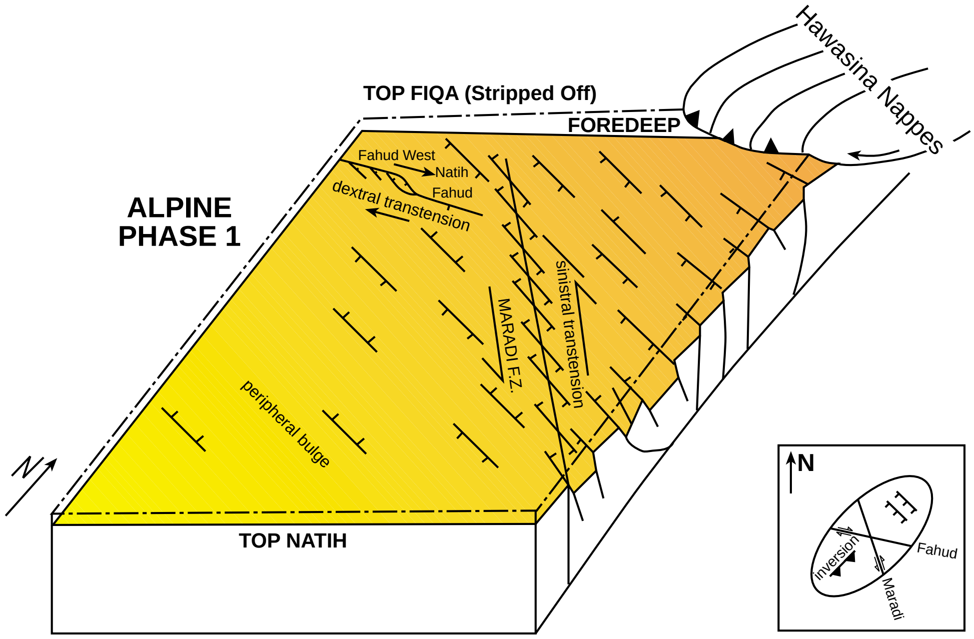


Figure 10 (a): During the Late Cretaceous First Alpine Phase (Turonian-Lower Maastrichtian) the region south of present-day Salakh Arch (see Figure 2) was in an extensional regime as the dominating strain is due to downbending. During this phase (1) the Hawasima and Samail Nappes are emplaced; (2) the region south of the nappes is downwarped with local footwall uplift; (3) the Aruma foredeep develops; (4) dextral transtension along the Fahud Fault Zone; and (5) sinistral transtension along the Maradi Fault Zone occur.

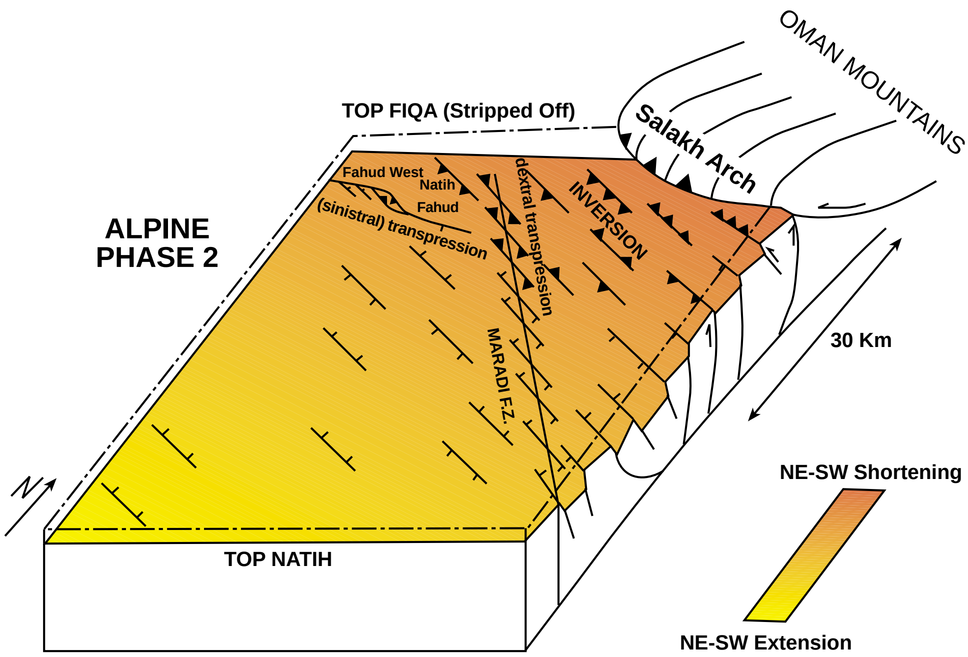


Figure 10 (b): In the Eocene-Pliocene Second Alpine Phase, folding commences in the Oman Mountains and shortening overprints extension in the area around Natih, Fahud, and the northern Maradi Fault Zone. During this stage (1) the Salakh Arch develops; (2) reverse faulting occurs in foredeep (e.g. Natih Field); (3) the northern part of the Maradi Fault Zone (close to the Salakh Arch) is inverted in dextral transpression; and (4) the Fahud main fault is reactivated with a small sinistral component.

Around 80 Ma, the relatively hot oceanic crust of the Semail was emplaced over the deep-water Hawasina sediments and Arabian continental margin (Lippard et al., 1986). This phase of northeast-southwest compression and loading led to southwestward stacking of thrust sheets in the area of the future Oman Mountains and the generation of a Campanian to Maastrichtian foredeep. This foredeep formed the depositional site of the Fiqa Formation (Glennie et al., 1974). The depocentre of this unit, which represents tectono-stratigraphic Unit V in the interior of Oman, fringes the southern edge of the Oman Mountains and consists of a dominantly deeper-marine pelagic facies in the north, derived from the advancing thrust front and thinning / onlapping southwards, and passing to shallow marine carbonates further south (Hughes-Clarke, 1988).

The deep-water environment of the Lower Fiqa Formation clearly illustrates the underfilled character of the foreland basin: sedimentation was subordinate to subsidence during the Coniacian to Santonian (Platel et al., 1994). Sediments, derived from the thrust sheets that advanced into the foredeep on the sea bed by gravity glide (Warburton et al., 1990), were partially cannibalised and thrusted. Thrusting continued until the Late Santonian, but the foredeep continued to subside into the Late Campanian as it was partly supplied by sediment derived from the emerging Hawasina and Semail ophiolite thrust sheets. Loading of thrust sheets resulted in the downwarping of the continental crust and its flexural extension, analogous to extension in e.g. the Molasse Basin north of the Alps (Nachtmann and Wagner, 1987; cf. Bradley and Kidd, 1991). The extension south of the Oman Mountains is largely accommodated by a set of evenly distributed northwest-southeast trending normal faults, all with minor throws.

Around 84 Ma, at magnetic anomaly 34, greater India, including the Seychelles micro-continent and the oceanic crust of present-day Masirah Island (and minor outcrops at Ras Jibsch and Ras Madrakah), separated from Madagascar and drifted northwards (Salman and Abdula, 1995). Associated with this drift was a component of compression along the eastern continental margin of Oman. Thus, simultaneous to the northeast-southwest extension south of the thrust sheets of the Oman Mountains, the eastern continental margin of Oman suffered from sinistral transpression (Figure 9; Mountain and Prell, 1990; Ries and Shackleton, 1990; Peters et al., 1995). The western margin of the Ghaba Salt Basin suffers minor inversion as a result (Figure 8a).

The combined effect of these two plate margin processes was the initiation and / or reactivation in north Oman of a conjugate set of strike-slip faults: north northwest-south southeast trending faults, such as the Maradi Fault Zone, had both a sinistral and a normal component, whereas west northwest-east southeast trending fault zones, such as the main Fahud Fault Zone, had both a dextral and a normal component (Figure 10). The Maradi trend is more dominant than the Fahud trend, implying anti-clockwise rotational strain. The Maradi trend, however, may be an inherited trend, possibly initiated locally during the Permo-Triassic. This conjugate set is bisected by the above-mentioned northwest-southeast trending normal faults.

The Late Cretaceous was a period of pronounced salt movement in the Fahud and Ghaba Salt Basins (see “Discussion”).

Unit VI: Tertiary - Gulf of Aden in South and Oman Mountains in North

In North Oman, the Late Cretaceous phase of deformation stopped abruptly when a new subduction zone developed towards the north near the Makran. The northeastern margin of Oman remained quiescent during the next 40 Ma (Glennie, 1995). By early Maastrichtian times, northern Oman’s continental margin entered this quiet phase with deep marine basins persisting in the Suneinah and Aruma troughs. North Oman returned to a stable passive margin which continued in the Late Maastrichtian with the submergence of the North Oman Mountains (Skelton et al., 1990).

Due to a global eustatic fall in sea level at the end of the Cretaceous, North Oman became emergent again leading to the Base Tertiary regional unconformity (Skelton et al., 1990). Early to mid-Tertiary sedimentation over a stable shallow marine platform produced a uniform sequence of clastic and carbonate-evaporite deposition.

Completion of the mountain building process was in the second (Oligocene-Pliocene) Alpine event (Figure 10b). The Oman Mountains were broadly uplifted, subsequent to which their culminations collapsed and large extensional structures developed (Mann et al., 1990). In a narrow zone south of the Salakh Arch, many normal faults were inverted, including the main Natih Field fault and the northern parts of the Maradi Fault Zone. It is for these northern parts of the Maradi Fault Zone that Hanna and Nolan (1989) argued for a Late Neogene dextral component associated with en echelon folds slightly anti-clockwise from the fault trend. We interpret this as a reactivation in a dextral transpressional manner.

East Oman remained strongly influenced by tectonics in the proto-Indian Ocean. In the late Campanian-early Maastrichtian, a rift developed between the Seychelles and India. This rifting culminated in the Deccan volcanic event at approximately 64 Ma, when a new oceanic spreading zone, the present-day Carlsberg Ridge, developed. This in turn resulted in continued northwards drift and anti-clockwise rotation of India (Royer et al., 1992; Plummer and Belle, 1995). At the Cretaceous/Tertiary boundary, intra-oceanic north-over-south thrusting between the lower and upper ophiolitic nappes of Masirah Island occurred, immediately followed in the Paleocene by the oblique obduction of the Masirah Ophiolite complex onto the Arabian continent (Peters et al., 1995). Seismic and well data suggest that obduction has been active from Late Cretaceous to at least Eocene (PDO, unpublished data). Even Miocene rocks are folded, along north northeast-south southwest trending axes, near Jebel Ja'alan. Along the east coast of Oman, i.e. largely offshore under Masirah Bay and Sawqrah Bay, a narrow, gently folded, Late Cretaceous to Miocene foreland basin, the Masirah Trough, developed. The western margin is bounded by normal faults reactivating Mesozoic rift-related faults. On its eastern margin, a wedge of ophiolitic and probably continental slope sediments is largely underthrusted below the eastern and uplifted part of this foredeep basin. Even Eocene sediments are tilted above this wedge. This eastern basin margin thus appears to overlie a passive roof thrust (cf. Lawton et al., 1994).

The stress field in Oman remained strongly influenced by the rapid northward movement of the Indian Plate, with continuous sinistral transtensional movement along the central and southern parts of the Maradi Fault Zone, and, often fault-initiated, (ongoing) halokinesis: some twenty forceful salt intrusions, six of which break to surface, have developed in the Ghaba Salt Basin.

Southern Oman has experienced an entirely different Tertiary history. Along the south coast of Oman and Yemen, the Gulf of Aden rift developed in the early Oligocene following Late Eocene uplift (Bott et al., 1992; Platel et al., 1992). Sea-floor spreading began in the Late Miocene. This rift extends eastwards and affects Al Halaaniyaat Bay. Rift-shoulder uplift resulted in a fresh-water flow towards the north (northwest) and salt dissolution along the eastern margin of the South Oman Salt Basin. Also along the eastern margin of the South Oman Salt Basin, some of the northeast-southwest trending Precambrian to early Paleozoic faults were reactivated in a dextral transtensional manner. A further zone of extension can be traced northeastwards along the coast to the east of Jebel Ja'alan with north-south to northeast-southwest trending normal faults and, occasionally, associated volcanics (37 to 44 Ma; Béchennec et al., 1992a). The interior of Oman was last submerged in the Miocene and since then has developed into a desert deflation surface. The Miocene cover dips gently westwards.

DISCUSSION

Strong East-West Shortening in Southwest Oman

In the late eighties and early nineties, a model was proposed in which the western margin of prospective areas in Oman was loosely delineated by an Early Cambrian (Upper Huqf to Lower Haima) collision zone, the "Western Deformation Front", developed between two Precambrian continental blocks (Boserio et al., 1994; unpublished PDO reports; Figure 2). This model explained the deformation (folds, cleavages, or just steep to sub-vertical dips) in most wells in western Oman, specifically in southwest Oman where also north-south trending folds and thrusts can be observed in the field in the Al Hota-Ain Sarit Formation (Roger et al., 1992), as opposed to the relative lack of deformation in eastern Oman even in the Marbat area (Figure 2). It also significantly downgraded the prospectivity of the area around and west of the Western Deformation Front because of the assumed widespread horizontal shortening and associated overmaturity of the Huqf source rocks.

However, as elements of the Huqf Supergroup have been recognized on the Arabian Peninsula west of Oman, the Western Deformation Front is more likely to be an intra- rather than inter-continental feature. Also, as the only clear evidence for strong regional deformation comes from southwest Oman, we question

IN GENERAL

SALT DEPOSITION

SALT STABLE
- First sediments deposited on salt are uncompacted and therefore gravitationally stable

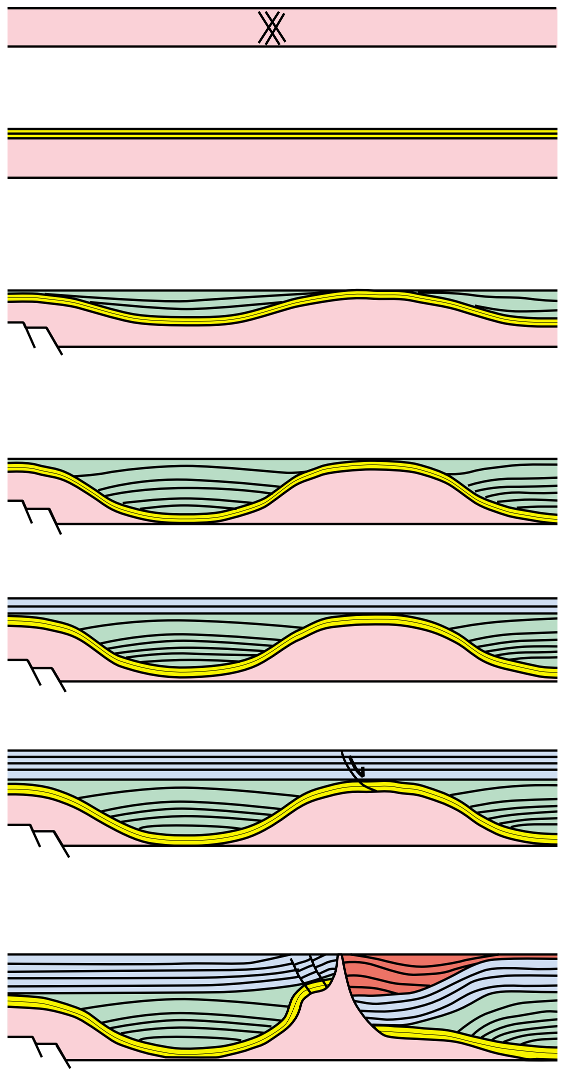
DOMING/DOWNBUILDING
- More sedimentation;
- Integrated density of sediments > density salt;→salt gravitationally not stable anymore.
- Sediments are still relatively weak and will fold/drape easily.

OVERBURDEN GROUNDED
- Sediments become grounded on substratum.
- Salt is redistributed in isolated pods → "feeding" of the salt dome stops.
- Sediments also being compacted and becoming stronger.

SALT STABLE AGAIN
- Salt pods are being buried.
- Possibly some steepening of flanks, otherwise overburden is too strong for deformation.

REACTIVE DIAPIRISM
- Faults on top of salt dome are necessary to initiate further halokinesis.
- Overburden is broken, losing its strength and its capacity to resist salt piercement.

ACTIVE DIAPIRISM
- Salt is injected forcefully through overburden;
- Creation of salt withdrawal sub-basins.



IN THE GHABA SALT BASIN

Ara Salt

First Haima sediments.

Haima deposition
salt moves preferentially to rift margins.

Haima is grounded
and salt is in isolated pods.

Silurian to Permo-Triassic sedimentation
and erosion periods.
Relatively stable epeirogenic period.

Mesozoic faulting.

20 diapirs along dilational sites of faults (e.g. pull-aparts).
Salt sourced from withdrawal sub-basins, which can be
dated as (1) Triassic-Jurassic, (2) Late Cretaceous and
(3) Tertiary. Main diapirism Late-Cretaceous and Tertiary.

Figure 11: Simplified history of halokinesis in the Ghaba Salt Basin.

the northwards continuation of the Western Deformation Front. As an alternative, or possibly complementary model, the deformed Huqf rocks in southwest Oman may form part of the northwest-southeast trending, sinistral Najd Fault System (Figure 1). This upgrades the prospectivity of western Central and North Oman. We offer the following arguments:

1. The north-south trending folds and thrusts in southwest Oman are kinematically compatible with the sinistral movement along the Najd Trend in Saudi Arabia.

2. The large displacements along the Najd shear zones suggest that these shear zones extend for long distances under the Rub Al Khali towards Oman. Based on the offsets of the Nabitah suture (Figure 1), Schmidt et al. (1979) estimate the cumulative sinistral displacement to be in excess of 300 km, while one of the four primary shear zones offsets the Nabitah suture by 165 km. In the absence of major deformation (pull-apart basins or thrust-and-fold belts) in the areas adjacent to the shear zone, the total length of the Najd Shear System may then be up to several thousands of kilometers. Straight extrapolation would bring the Najd Shear System under southwest Oman (Figure 1).

3. Magnetic trends suggest that the Najd indeed extends under the Rub Al Khali (Moore, 1979). Recently re-processed gravity and magnetic data clearly show the "Najd" trend in southwestern Oman. The west northwest-east southeast trending Mesozoic basins of Yemen and Somalia and the easternmost segments of the Gulf of Aden, the Sheba Ridge, could be reactivations of this trend (Figure 1; Richardson et al., 1995). The virtual absence of this west northwest-east southeast fault trend elsewhere in Oman (Figure 7) suggests it is related to an event mainly affecting the southern parts of Oman (Figure 1).

4. Four 5-15 milliGal negative Bouguer anomalies in southwest Oman have been interpreted as low-density granites (unpublished PDO report), similar to the post-tectonic, Najd-related, alkali-feldspar granites in the northern part of the Arabian Shield (Stoesser, 1986). Such anomalies are not known elsewhere in Oman.

5. The timing may well fit. The compressional event in southwest Oman postdates deposition of the Middle Huqf and predates deposition of the Amin Formation. This age bracket straddles the development of the Najd event (sinistral from 600 to 540 Ma; Stern, 1985; Husseini and Husseini, 1990). However, if the Najd event stops at 540 Ma and the Middle Huqf postdates this (see "Age uncertainty" above), then the compressional features in southwest Oman cannot be related to the Najd.

The synchronous extension accommodated by the northeast-southwest trending bounding faults of the Ghaba and South Oman Salt Basins can also be kinematically compatible with this stress field (possibly an additional dextral strike-slip component acted on these bounding faults; Figure 4a). The Angudan Unconformity marks the end of this tectonic event.

Halokinesis

Salt dissolution, salt doming and the three types of diapirism, i.e. passive (downbuilding), reactive (to normal faults) and active (forceful intrusion), all play a major role in the configuration of most intra- and post-salt traps in Oman. Halokinesis is episodic and is related to tectonic events.

Earliest salt movements and possibly minor local dissolution are documented from the syn-rift Lower Haima sequence in the South Oman Salt Basin. Here passive diapirism, (i.e. downbuilding, the accumulation of sediments around a salt dome / diapir with the top of the dome remaining at or near the surface), is the dominant mechanism. At each locality, halokinesis stopped when the Lower Haima grounded on the Upper Huqf. Sedimentation then shifted to a new (northeastward?) depocentre. Since then, the resulting elongate domes and salt walls have not changed much in the central South Oman Salt Basin.

In the Ghaba Salt Basin, early growth of salt domes was concentrated on the margins of the Ghaba Salt Basin. Fault-initiated downbuilding was the dominant mechanism (Figure 11). This growth can be dated from unconformities, onlap and rapid thickness variations of the Haima sediments. It continues up to Middle Haima and Safiq times, i.e. when halokinesis in the South Oman Salt Basin had already come to an end. It is probably related to normal faulting at the end of the second rift cycle.

Thus, by the end of Haima deposition, Ara salt had been redistributed in isolated salt bodies. These bodies are much more resistant to halokinesis than their sheet-like predecessors. This is because the driving force for halokinesis, i.e. the pressure of the salt on its surroundings generally due to overburden loading, is resisted by the strength of the overburden. To trigger further halokinesis, it is generally necessary that faults transect the overburden directly above the salt pod. Thus, the fairly stable conditions from Silurian to Permo-Triassic times prevented further halokinesis.

In North Oman, renewed halokinesis was triggered by various phases of Mesozoic and Cenozoic deformation (Figure 11). About 20 diapirs and some non-piercing domes were formed, most of them initiated by transtensional faulting along Maradi-parallel fault zones, and subsequently forcefully injected in the faulted overburden. It appears that salt has flowed towards sites of low mean stress, as e.g. in pull-aparts, and, as the overburden was broken, forced its way up in these sites. Pull-aparts are, paradoxically, therefore, often not lows but highs. These diapirs rim salt-withdrawal sub-basins. The three main ones can be dated as immediately pre-Jurassic-Unconformity (Jilh?), Late Cretaceous, and Tertiary. Most diapirs were active until the second Alpine event. Some of the salt diapirs are capped by the base of the Fars Group. Flow to surface in several other diapirs continues to the present day.

Several phases of tilting and uplift of eastern Oman have been accompanied by hydrological activity. The resulting intermittent dissolution of salt on the Eastern Flank of the South Oman Salt Basin resulted in pronounced local thickening and preservation of respectively Al Khlata (thermal doming but aborted rift?), Jurassic to Lower Cretaceous (alluvial “Mesozoic Clastics” in the pre-Nahr-Umr syncline, possibly related to the 150 Ma old separation of India-Madagascar from Arabia-Africa), Late Cretaceous (related to transpressional obduction?) and Oligocene-Recent sediments (related to the formation of the Gulf of Aden). Uplift of the Eastern Flank and the northwestwards retreat of the salt edge has thus caused a string of northwestwards younging elongate synclines in which sediments have been preferentially preserved (Heward, 1990).

CONCLUDING REMARK

We have made an attempt to describe the tectonic evolution of Oman’s interior in the context of six tectono-stratigraphic units. Clearly, there is scope for refinements and improvements. Further subdivision of the six tectono-stratigraphic units may well emerge, especially for the Late Proterozoic and the middle Paleozoic. The geological significance of many unconformities is not yet clear. Specifically, the boundary between Middle Huqf (Unit II) and Upper Huqf (Unit III) is not well understood. No doubt, the quest to explore ever deeper will in the coming years lead to a better definition of the architecture of the Abu Mahara and Ara rifts, both in terms of structure and fill.

An improved tectono-stratigraphy should lead to a better understanding of almost all aspects of exploration: the distribution of source rocks, reservoirs and seals, maturity and hydrocarbon generation, paleodips and hydrocarbon migration, trap configuration and their timing relative to migration, and reservoir characteristics.

ACKNOWLEDGEMENTS

This synthesis is the result of a great number of Petroleum Development Oman (PDO) and Shell geologists who cannot all be mentioned here. The basis for this paper was laid by a manuscript by Patrick Bermingham, Werner Bolliger and Guy Loftus entitled “The Geotectonic Evolution of Oman’s Onshore Sedimentary Basins” for presentation at a Kuwait conference which was subsequently cancelled because of the 1991 Gulf War. We have also drawn heavily on unpublished PDO and Shell reports. Special mention must go to Gavin Graham, Stuart Lake, Ian Boserio, Gordon Knox, Peter Nederlof, Govert van Beusekom, Saleh Al Anboori, Mark Doyle, Peter Diebold, Henk Droste, Urs Eichenberger, Christos Kapellos, Recep Kazdal, Hans van Marle, Angus McCoss, Ide van der Molen, Mike Naylor, Dietmar Neuhaus, Herman Priebe, Graeme Smith, Andy Spriggs, Marietta Vroon-ten Hove, Bob van Wees and Steve Whyte (all PDO), Adrian Immenhauser (Berne University) and Moujahed I. Al-Husseini (Gulf PetroLink) and two anonymous reviewers. We thank Petroleum Development Oman LLC and the Oman Ministry of Petroleum and Minerals for permission to publish this paper.

REFERENCES

Agar, R.A. 1986. *The Bani-Ghayy Group: Sedimentation and Volcanism in Pull-apart Grabens of the Najd Strike-slip Orogen, Saudi Arabian Shield.* Precambrian Research, v. 31, p. 259-274.

Al-Marjeby, A. and D. Nash 1986. *A Summary of the Geology and Oil Habitat of the Eastern Flank Hydrocarbon Province of South Oman.* Marine and Petroleum Geology, v. 3, p. 306-314.

Beauchamp, W.H., A.C. Ries, M.P. Coward and J.A. Miles 1995. *Masirah Graben: A Hidden Cretaceous Rift Basin?* The American Association of Petroleum Geologists Bulletin, v. 79, p. 864-879.

Béchennec, F. 1987. *Géologie des Nappes Hawasina dans les Parties Orientale et Centrale des Montagnes d'Oman.* Thesis, Docteur es-Sciences, Pierre and Marie Curie University, Paris 6; Bureau de Recherches Géologiques and Minières, Document No. 127, Orléans, France, 474 p.

Béchennec, F., J. Le Métour, D. Rabu, M. Villey and M. Beurrier 1988. *The Hawasina Basin: A Fragment of Starved, Passive, Continental Margin Thrust over the Arabian Platform during Obduction of the Samail Nappe.* Tectonophysics, v. 151, p. 232-343.

Béchennec, F., J. Le Métour, J-P. Platel and J. Roger 1995. *Doming and Downwarping of the Arabian Platform in Oman in Relation to EoAlpine Tectonics.* In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 167-178.

Béchennec, F., J. Roger, S. Chevrel and J. Le Métour 1992a. *Explanatory notes, Geological map of Al Ashkarah, 1:250.000.* Ministry of Petroleum and Minerals, Oman.

Béchennec, F., J. Roger, J. Le Métour and R. Wyns 1992b. *Explanatory notes, Geological Map of Seeb, 1:250.000.* Ministry of Petroleum and Minerals, Oman.

Beydoun, Z.R., 1966. *Eastern Aden Protectorate and Part of Dhufar.* In Geology of the Arabian Peninsula. Geological Survey Professional Paper 560-H, U.S. Geological Survey, 49 p.

Beurrier, M. 1987. *Géologie de la Nappe Ophiolitique de Samail dans les Parties Orientale et Centrale des Montagnes d'Oman.* D. Sc. Thesis Pierre et Marie Curie University, Paris. BRGM Document 128, 412 p.

Blendinger, W., A. Van Vliet and M.W. Hughes-Clarke 1990. *Updoming, Rifting and Continental Margin Development During the Late Palaeozoic in Northern Oman.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 27-37.

Boote, D.R.D., D. Mou and R.I. Waite 1990. *Structural Evolution of the Suneinah Foreland, Central Oman Mountains.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 397-418.

Boserio, I.M., C. Kapellos and H. Priebe 1995. *Cambro-Ordovician Tectonostratigraphy and Plays in the South Oman Salt Basin.* In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 203-213.

Bott, W.F., B.A. Smith, G. Oakes, A.H. Sikander and A.I. Ibraham 1992. *The Tectonic Framework and Regional Hydrocarbon Prospectivity of the Gulf of Aden.* Journal of Petroleum Geology, v. 15, p. 211-243.

Bradley, D.C. and W.S.F. Kidd 1991. *Flexural Extension of the Upper Continental Crust in Collisional Foredeeps.* Geological Society of America Bulletin, v. 103, p. 1416-1438.

Brown, G.F. and R.O. Jackson 1960. *The Arabian Shield.* 21st International Geological Congress Report, Copenhagen, section 9, p. 69 - 77.

Calvez, J.Y. and J. Kemp 1989. *Rb-Sr Geochronology of the Shammar Group in the Hulayfah Area, Northern Arabian Shield.* Saudi Arabian Deputy Ministry for Mineral Resources, Professional Papers, p. 1-12.

Dercourt, J., L.P. Zonenshain, L.E. Ricou, V.G. Kazmin, X. Le Pichon, A.L. Knipper, C. Grandjacquet, J.M. Sbortshikov, J. Geyssant, C. Lepvrier, D.H. Pechersky, J. Boulin, J.C. Sibuet, L.A. Savostin, O. Sorokhtin, M. Westphal, M.L. Bazhenov, J.P. Lauer and B. Biju-Duval 1986. *Geological Evolution of the Tethys from the Atlantic to the Pamirs Since the Lias.* Tectonophysics, v. 123, p. 241-315.

Dubreuilh, J., J.P. Platel, J. Le Métour, J. Roger, R. Wyns, F. Béchennec and A. Berthiaux 1992. *Geological Map of Khaluf, Sheet NF 40-15, 1:250 000 with explanatory notes.* Directorate General of Minerals, Oman Ministry of Petroleum and Minerals.

Duyerman, H.J., N.B.W. Harris and C. Hawksworth 1982. *Crustal Accretion in the Pan-African: Nd and Sr Isotope Evidence from the Arabian Shield.* Earth Planetary Science Letters, 59, p. 315-326.

Dyer, R.A. and M. Husseini 1991. *The Western Rub Al'Khali Infracambrian Graben System.* Society of Petroleum Engineers Paper 21396.

Gass, I.G., A.C. Ries, R.M. Shackleton and J.D. Smewing 1990. *Tectonics, Geochronology and Geochemistry of the Precambrian Rocks of Oman.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 585-599.

Glennie, K.W., 1977. *Outline of the Geology of Oman.* Memoire h. ser. Société Géologique France, v. 8, p. 25-31.

Glennie, K.W. 1995. *The Geology of the Oman Mountains, An Outline of their Origin.* Scientific Press Ltd. UK.

Glennie, K.W., M.G.A. Boeuf, M.W. Hughes-Clarke, M. Moody-Stuart, W.F.H. Pilaar and B.M. Reinhart 1974. *Geology of the Oman Mountains.* Verhandelingen Koninklijke Nederland Geologisch Mijnbouwkundig Genootschap, 31.

Gorin, G.E., L.G. Racz and M.R. Walter 1982. *Late Precambrian - Cambrian Sediments of Huqf Group, Sultanate of Oman.* The American Association of Petroleum Geologists Bulletin, v. 66, p. 2609-2627.

Hanna, S.S. and S.C. Nolan 1989. *The Maradi Fault Zone: Evidence of Late Neogene Tectonics in the Oman Mountains.* Journal of the Geological Society of London, v. 146, p. 867-871.

Harland W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith and D.G. Smith 1990. *A Geologic Time Scale, 1989.* Cambridge University Press.

Hauser, A. and R. Zurbriggen 1994. *Geology of the Crystalline Basement of the Hadbin Area (Salalah area, Dhofar, Sultanate of Oman).* Schweiz. Mineral. Petrogr. Mitt., v. 74, p. 213-226.

Heward, A.P. 1990. *Salt Removal and Sedimentation in Southern Oman.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 637-651.

Hughes-Clarke, M.W. 1988. *Stratigraphy and Rock Unit Nomenclature in the Oil-producing Area of Interior Oman.* Journal of Petroleum Geology, v. 11, p. 5-60.

Husseini, M.I. 1989. *The Arabian Infracambrian Extensional System.* Tectonophysics, v. 148, p. 93-103.

Husseini, M.I. and S.I. Husseini 1990. Orig*in of the Infracambrian Salt Basins of the Middle East.* In J. Brooks (Ed.), Classic Petroleum Provinces. Geological Society Special Publication 50, p. 279-292.

Immenhauser, A. 1995. *145 Ma to Present, Unbroken Bathymetric Record in Autochthonous Sediments on the Masirah Island Ophiolite (Sultanate of Oman).* Abstract, International Ophiolite Symposium, Pavia, September, 1995.

Lawton, D.C., D.A. Spratt and J.C. Hopkins 1994. *Tectonic Wedging Beneath the Rocky Mountain Foreland Basin, Alberta, Canada.* Geology, v. 22, p. 519-522.

Lee, C.W. 1990. *A Review of Platform Sedimentation in the Early and Late Permian of Oman, with Particular Reference to the Oman Mountains.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 39-47.

Lees, G.M., 1928. *The Geology and Tectonics of Oman and Parts of South Eastern Arabia.* Quarterly Journal of The Geologic Society London, v. 84, p. 585-670.

Le Métour, J. 1988. *Géologie del'Autochtone des Montagnes d'Oman: la Fenêtre du Saih Hatat.* Thesis, Docteur es-Sciences, Pierre and Marie Curie University, Paris 6; Bureau de Recherches Géologiques et Minières, Document No. 129, 420 p.

Le Métour, J., F. Béchennec, J. Roger, J.P. Platel and R. Wyns 1992b. *Geological Map of Al Masirah, Sheet NF 40-16, scale: 1:250,000, with Explanatory Notes.* Directorate General of Minerals, Oman Ministry of Petroleum and Minerals.

Le Métour, J., J.P. Platel, F. Béchennec, A. Berthiaux, S. Chevrel, J. Dubreuilh, J. Roger and R. Wyns 1993. *Geological Map of Oman, scale: 1:1,000,000.* Directorate General of Minerals, Oman Ministry of Petroleum and Minerals.

Le Métour, J., R. Frei, J.D. Kramers, I. Mercolli, R. Wyns, J. Dubreuilh and T.J. Peters, in prep. *Radiometric Dating of the Beginning of Sedimentation on the Proteozoic Crystalline Basement in Oman.*

Le Métour, J., F. Béchennec, J.P. Platel and J. Roger 1995. *Late Permian Birth of Neo-Thetys and Development of its Southern Continental Margin in Oman.* In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94. Gulf PetroLink, Bahrain, v. 2, p. 643-654.

Le Métour, J., J.L.M. Kramers and R. Frei, in prep. *Radiometric Dating of the Beginning of Sedimentation on the Crystalline Basement of the Dhofar and Huqf Areas, Oman.*

Levell, B.K., J.H. Braakman and K.W. Rutten 1988. *Oil-bearing Sediments of the Gondwana Glaciation in Oman.* The American Association of Petroleum Geologists Bulletin, v. 72, p. 775-96.

Lippard, S.J., A.W. Shelton and I.G. Gass 1986. *The Ophiolite of Northern Oman.* Geological Society Memoir, 11, 178 p.

Mann, A., S.S. Hanna and S.C. Nolan 1990. *The post-Campanian Tectonic Evolution of the Central Oman Mountains: Tertiary Extension of the Eastern Arabian Margin.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 549-563.

Mattes, B.W. and S. Conway-Morris 1990. *Carbonate/evaporite deposition in the Late Precambrian-Early Cambrian Ara Formation of Southern Oman.* In A.H.F. Robertson, Searle, M.P. and Ries, A.C. (eds), The Geology and Tectonics of the Oman Region. Geological Society of London, Special Publication 49, p. 617-636.

Moore, McM. J. 1979. *Tectonics of the Najd Transcurrent Fault System, Saudi-Arabia.* Journal of the Geological Society of London, v. 136, p. 441-454.

Mountain, G.S. and W.L. Prell 1990. *A Multiphase Plate Tectonic History of the Southeast Continental Margin of Oman.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 725-743.

Nachtmann, W. and L. Wagner 1987. *Mesozoic and Early Tertiary Evolution of the Alpine Foreland in Upper Austria and Salzburg, Austria.* Tectonophysics, v. 137, p. 61-76.

Nolan, S.C., P.W. Skelton, B.P. Clissold and J.D. Smewing 1990. *Maastrichtian to Early Tertiary Stratigraphy and Palaeogeography of the Central and Northern Oman Mountains.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 495-519.

Odin G.S. and C. Odin 1990. *Échelle Numérique des Temps Géologiques.* Géochronique, v. 35, p. 12-21.

Pallister, J.S., J.S. Stacey, L.B. Fischer and W.R. Premo 1988. *Precambrian Ophiolites of Arabia: Geologic Settings, U-Pb Geochronology, Pb-isotope Characteristics and Implications for Continental Accretion.* Precambrian Research, v. 38, no. 1, p.1-54.

Patton, T.L. and S.J. O'Connor 1988. *Cretaceous Flexural History of the Northern Oman Mountain Foredeep, United Arab Emirates.* The American Association of Petroleum Geologists Bulletin, v. 2, p. 797-810

Peters, Tj., A. Immenhauser and E. Gnos 1995. *Mesozoic Evolution of the Western Indian Ocean - Evidence from the Masirah Ophiolite (Sultanate of Oman).* Abstract, International Ophiolite Symposium, Pavia, September, 1995.

Platel, J.P., J. Philip, C. Bourdillon-de Grissac, J.F. Babinot, J. Roger and C. Mercadier 1995. *Geodynamic Setting, Stratigraphy and Paleoenvironments of the Aruma Group in Eastern Oman: the Campanian Platform around Haushi-Huqf.* In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94. Gulf PetroLink, Bahrain, v. 2, p. 771-783.

Platel, J.P., J. Roger, Tj. Peters, I. Mercolli, J.D. Kramers and J. Le Métour 1992. *Geological Map of Salalah, Sheet NE 40-09, 1:250 000 with explanatory notes.* Directorate General of Minerals, Oman Ministry of Petroleum and Minerals.

Plummer, Ph.S. and E.R. Belle 1995. *Mesozoic Tectono-stratigraphic Evolution of the Seychelles Microcontinent.* Sedimentary Geology, v. 96, p. 73-91.

Powers, R.W. 1968. *Arabie Seoudite.* In L. Dubertret (Ed.), Lexique Stratigraphique International, Vol. III Asie. CNRS Paris, fasc. 10bl, 177 p.

Powers, R.W., L.F. Ramirez, C.D. Redmond, and E.L. Elberg 1966. *Sedimentary Geology of Saudi Arabia.* In Geology of the Arabian Peninsula, Geological Survey Professional Paper 560-D, U.S. Geological Survey 147 p.

Qidwai, H.A., M.I. Khalifa and Khalid A. Ba-mkhalif 1988. *Evidence of Permo-Carboniferous Glaciation in the Basal Murbat Sandstone Formation, Southern Region Sultanate of Oman.* Journal of Petroleum Geology 11, p. 81-88.

Rabu, D., J. Le Métour, F.Béchennec, M. Beurrier, M. Villey and C.H. Bourdillon-De-Grissac 1990. *Sedimentary Aspects of the Eo-Alpine Cycle on the Northeast Edge of the Arabian Platform (Oman Mountains).* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 49-68.

Rabu, D. 1988. *Geologie de l'autochtone des Montagnes d'Oman: la Fenêtre du Jabal Akhdar.* Thesis BRGM Document Nº.130, 582 p.

Richardson, S.M., W.F. Bott, B.A. Smith, W.D. Hollar and P.M. Bermingham 1995. *A New Hydrocarbon 'Play' Area Offshore Socotra Island, Republic of Yemen.* Journal of Petroleum Geology, v. 18, p. 5-28.

Ries, A.C. and R.M. Shackleton 1990. *Structures in the Huqf - Haushi Uplift, East Central Oman.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 653-663.

Robertson, A.H.F. 1987. *Upper Cretaceous Muti Formation: Transition of a Mesozoic Carbonate Platform to a Foreland Basin in the Oman Mountains.* Sedimentology, v. 34, p. 1123-1142

Robertson, A.H.F., M.P. Searle and A.C. Ries (Eds.) 1990. *The Geology and Tectonics of the Oman Region.* Geological Society London Special Publication 49.

Roger, J., J.P. Platel, A. Berthiaux and J. Le Métour 1992. *1:250.000 Geological Map of Hawf, with explanatory notes.* Ministry of Petroleum and Minerals, Oman.

Royer, J.Y., J.G. Sclater, D.T. Sandwell, S. Cande, R. Schlich, M. Munschy, J. Dyment, M.F. Coffin, P. Patriat and H.W. Bergh 1992. *Indian Ocean Plate Reconstructions Since the Late Jurassic.* In R.A. Duncan, D.K. Rea, R.B. Kidd, U. von Rad and J.K. Weissel (Eds.), Synthesis of Results from Scientific Drilling in the Indian Ocean. American Geophysical Union, Geophysics Monogram 70, p. 471-475.

Salman, G. and I. Abdula 1995. *Development of the Mozambique and Ruvuma Sedimentary Basins, Offshore Mozambique.* Sedimentary Geology, v. 96, p. 7-41.

Schmidt, D.L., D.G. Hadley and D.B. Stoesser 1979. *Late Proterozoic Crustal History of the Arabian Shield, Southern Najd Province, Kingdom of Saudi Arabia.* In Evolution and Mineralisation of the Arabian-Nubian Shield. Institute of Applied Geology, Jeddah, v. 2, p. 41-58.

Shackleton, R.M., A.C. Ries, P.R. Bird, J.B. Filbrandt, C.W. Lee and G.C. Cunningham 1990. *The Batain Melange of NE Oman.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 673-696.

Skelton, P.W., S.C. Nolan and R.W. Scott 1990. *The Maastrichtian Transgression onto the Northwestern Flank of the Proto-Oman Mountains: Sequences of Rudist-bearing Beach to Open Shelf Facies.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 521-548.

Smewing, J.D., I.L. Abbotts, L.A. Dunne and D.C. Rex 1991. *Formation and Emplacement Ages of the Masirah Ophiolite, Sultanate of Oman.* Geology, v. 19, p. 453-456.

Stacey, J.S. and R.A. Agar 1985. *U - Pb Isotopic Evidence for Early Proterozoic Crust in the Eastern Arabian Shield.* Journal of the Geological Society of London, v. 142, p. 1189-1203.

Stampfli, G.M., J. Marcoux and A. Baud 1991. *Tethyan Margins in Space and Time.* Paleogeography, Paleoclimatology, Paleoecology, v. 87, p. 373-409.

Stern, R.J. 1985. *The Najd Fault System, Saudi Arabia and Egypt: A Late Precambrian Rift-related Transform System?* Tectonics, v. 4, p. 497-511.

Stoesser, D.B and V.E. Camp, 1985. *Pan African Microplate Accretion of the Arabian Shield.* Geological Society of America Bulletin, v. 96, p. 817-826.

Stoesser, D.B. 1986. *Distribution and Tectonic Setting of Plutonic Rocks of the Arabian Shield.* Journal of African Earth Sciences, v. 4, p. 21-46.

Tschopp, R.H. 1967. *The General Geology of Oman.* Proceedings of the 7th World Petroleum Congress, Mexico, v. 2, p. 231-242.

Visser, W. 1991. *Burial and Thermal History of Proterozoic Source Rocks in Oman.* Precambrian Research, v. 54, p. 15-36.

Warburton, J., T.J. Burnhill, R.H. Graham and K.P. Isaac 1990. *The Evolution of the Oman Mountains Foreland Basin.* In A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society London Special Publication 49, p. 419-427.

Würsten, F., M. Flisch, I. Michalski, J. Le Métour, I. Mercolli, U. Matthaeus and Tj. Peters 1991. *The Uplift History of the Precambrian Crystalline Basement of the Jabal J'alan (Sur area).* In Tj. Peters, A. Nicolas and R.G. Coleman (Eds.), Ophiolite Genesis and Evolution of the Oceanic Lithosphere. Kluwer Academic Press, p. 613-626.

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Manuscript Received 25 November, 1995

Revised 29 January 1996

Accepted 4 February 1996