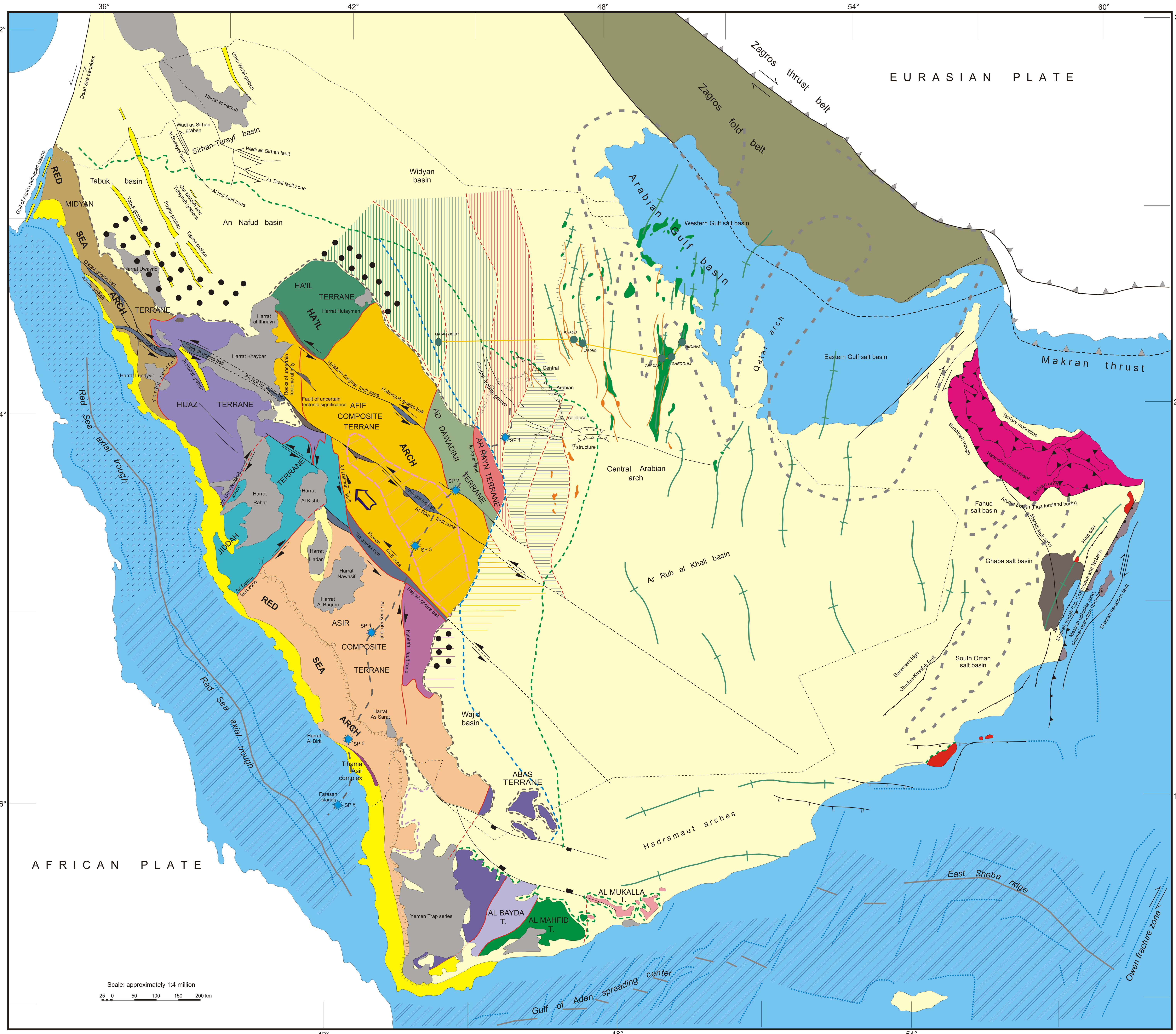
Ministry of Petroleum and Mineral Resources
Deputy Ministry for Mineral Resources

Technical Report USGS-TR-98-3
(IR 948)

Tectonic map of Saudi Arabia and adjacent areas

Compiled by Peter R. Johnson

1419 A.H   1998 A.D.



National boundary approximate

Lambert conformal conic projection, standard parallels 17° and 33°

Phanerozoic features

- Red Sea and Gulf of Aden axial trough (spreading center)
- Steep bathymetric gradient (probable fault)
- Possible mixed oceanic and continental crust of northern Red Sea
- Oceanic crust of southern Red Sea and Gulf of Aden, partly covered by Cenozoic sediments; boundaries approximate
- Proto-oceanic crust exposed on the Saudi Arabian coastal plain (Tihama Asir complex)
- Exposed Cretaceous, Paleogene, and Neogene sedimentary deposits of the Red Sea basin; local paleohighs and horst blocks of Pre-cambrian rocks not shown
- Paleogene and Neogene pull-apart basins and grabens associated with Red Sea extension
- Cenozoic flood-basalt associated with Red Sea extension
- Paleogene-Neogene sedimentary rocks exposed in the central Arabian shield and partly concealed by Cenozoic flood basalt
- Normal faults of the Sa'dah graben
- High, continuous Red Sea escarpment (Oligocene to present) south of Ad Damm fault; equivalent Gulf of Aden escarpment not shown
- Central Arabian collapse structure caused by dissolution of near-surface evaporites
- Faults of the Central Arabian graben system (Late Tertiary to Holocene)
- Gulf of Aden collapse structures associated with Gulf of Aden extension
- Normal faults associated with Cretaceous and Tertiary basins flanking the Gulf of Aden
- Post-collisional Zagros fold belt (Miocene-Pliocene)
- Zagros thrust belt (Eocene-Miocene): collisional suture between the Eurasian and Arabian plates; dashed where submerged
- Mesozoic anticlinal highs
- Hawasina and Semail thrust sheets in Oman: Cretaceous obduction of oceanic crust and associated rocks
- East Oman (Masirah) ophiolite complex
- Phanerozoic sedimentary rocks of the Arabian platform, unconformable on Precambrian basement
- Oil fields in Mesozoic reservoirs
- Oil fields in Paleozoic reservoirs
- Outcrop trace of pre-Upper Cretaceous disconformity
- Outcrop trace of pre-Jurassic disconformity
- Outcrop trace of pre-Upper Permian pre-Khuff) disconformity
- Outcrop trace of pre-Cambrian-Ordovician disconformity
- Concealed, pre-Unayzah (Hercynian) faults; locally reactivated during the Triassic
- Pre-Unayzah basement subcrop (subsurface); Lower Paleozoic high
- Region showing effects of Lower Paleozoic glaciation
- Concealed salt deposits in end-Precambrian -Cambrian pull-apart basins (failed rifts)
- End-Precambrian-Cambrian volcano-sedimentary rocks in failed rifts on the Arabian shield (Jibalah group) and in Oman (Huqf group)
- Transform fault; arrows show sense of movement
- QASIM DEEP — Line of section and bore holes showing Devonian "Hercynian" structure in central Saudi Arabia

Precambrian features

- Schist and gneiss in brittle-ductile trans-current shear zones and terrane sutures
- Transcurrent brittle-ductile shear zone (in part reactivated terrane suture); dashed where inferred beneath Phanerozoic cover
- Region of Group III evolved lead-isotopes in Afif terrane; possibly reflecting continental microplate
- Suspect terrane boundary, dashed where inferred; locally reactivated by northwest-trending strike-slip faults
- Sense of horizontal movement on Precambrian sutures and faults
- Sense of displacement of the Afif terrane relative to the Asir terrane

Precambrian suspect terranes

Surface extent / Possible extension beneath Phanerozoic cover:

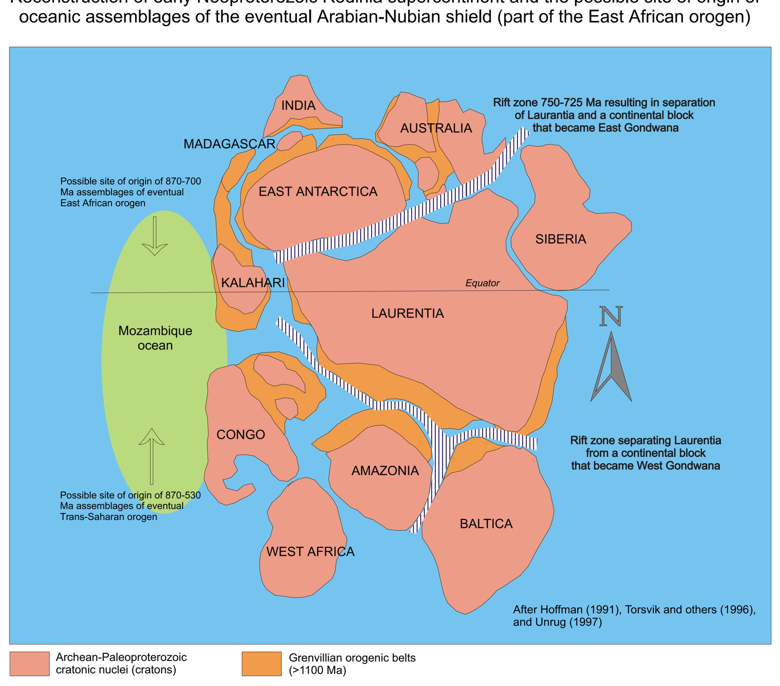
- Midyan terrane
- Hijaz terrane
- Ha'il terrane
- Afif composite terrane
- Ad Dawadimi terrane
- Ar Rayn terrane
- Unnamed suspect terranes in central Arabia
- Suspect terrane east of the Nabitah fault zone

Surface extent:

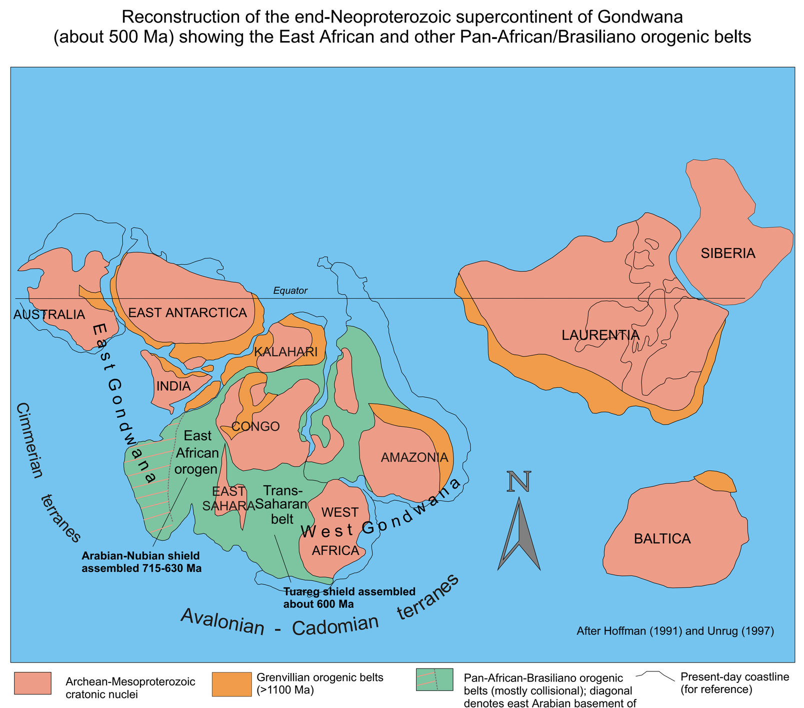
- Jiddah terrane
- Asir composite terrane
- Abas terrane
- Al Bayda terrane
- Al Mahfid terrane
- Al Mukalla terrane
- Metamorphic and igneous rocks of possible Neoproterozoic provenance in Oman

SP 3 — Location of shot points and seismic-refraction survey in western Saudi Arabia

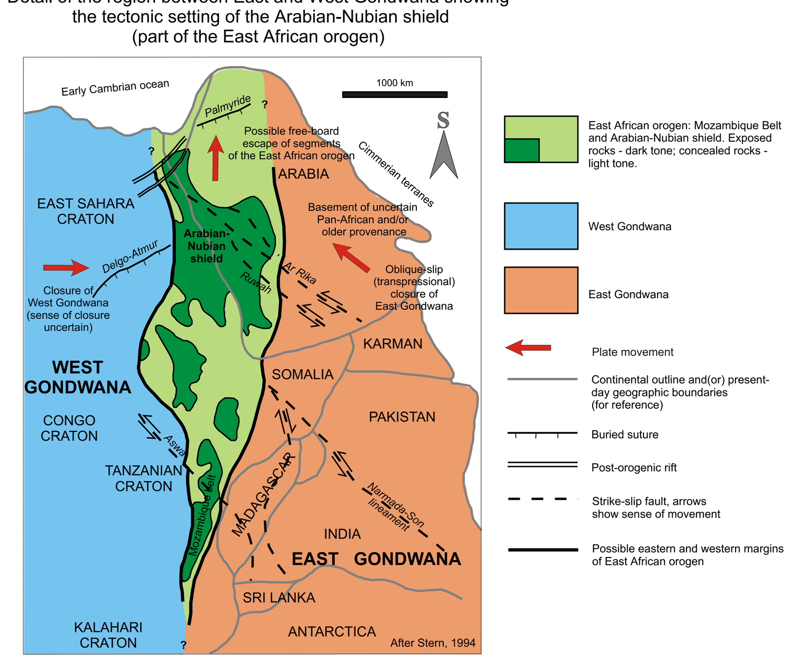
Reconstruction of early Neoproterozoic Rodinia supercontinent and the possible site of origin of oceanic assemblages of the eventual Arabian-Nubian shield (part of the East African orogen)



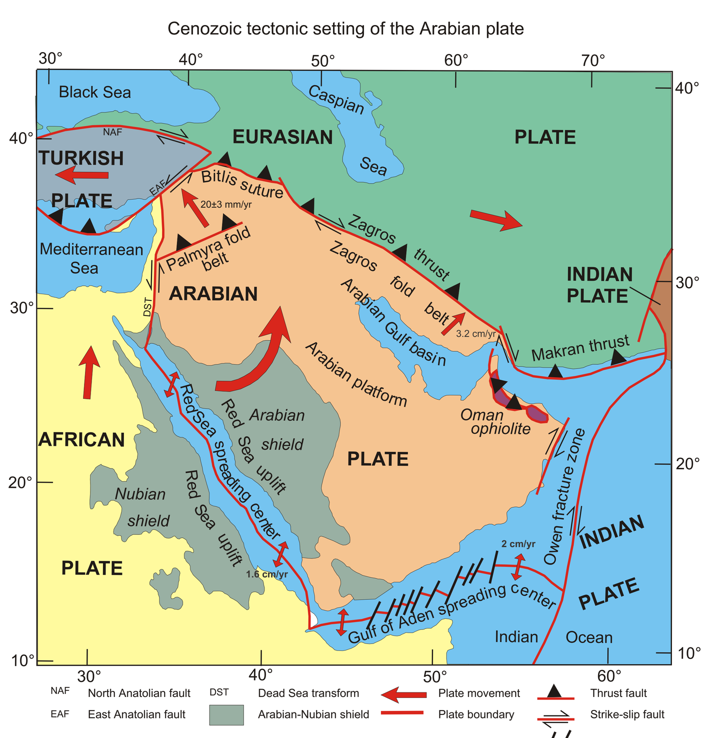
Reconstruction of the end-Neoproterozoic supercontinent of Gondwana (about 500 Ma) showing the East African and other Pan-African/Brasiliano orogenic belts

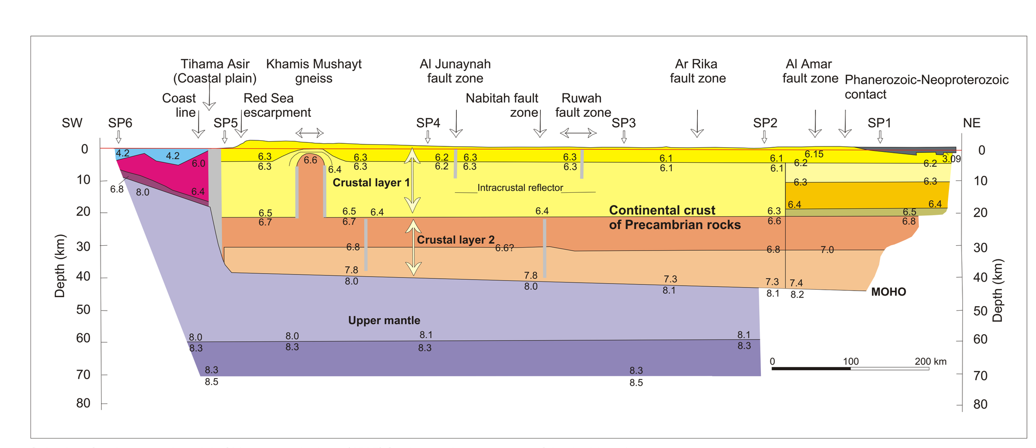


Detail of the region between East and West Gondwana showing the tectonic setting of the Arabian-Nubian shield (part of the East African orogen)

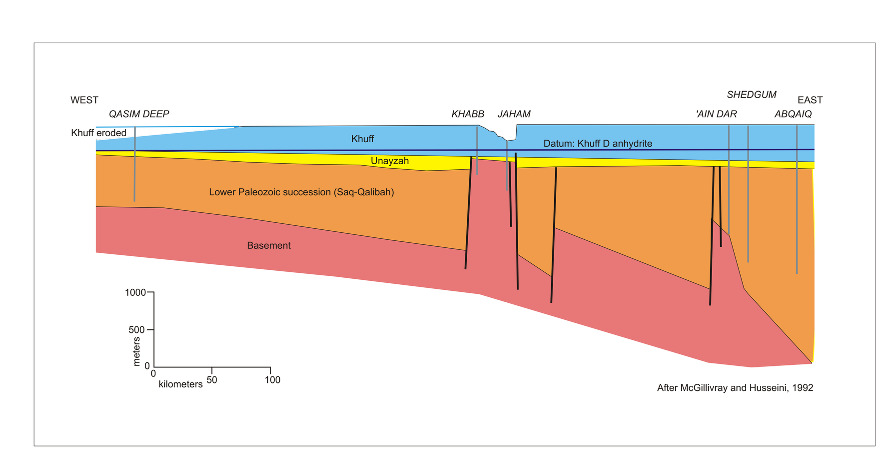


Cenozoic tectonic setting of the Arabian plate





Seismic-refraction crustal model of Mooney and others (1985) for the southwestern part of the Arabian plate showing a principal twofold division of the crust and rapid thinning of the crust beneath the coastal plain. Alternative models for the entire section or part of the section given by Prodehl (1985), Milkereit and Fluh (1985), and Badri (1991). Seismic-refraction data reported by Healy and others (1982); compressional-wave velocities in km/sec. For location of profile and shot points, see main map.



Section in central Saudi Arabia showing "Hercynian" structures in the Lower Paleozoic succession and basement caused by pre-Unayzah Devonian extension. The Lower Paleozoic strata are eroded over structural highs and preserved in structural basins. For location of section and bore holes see main map.

Coreldraw6 File: tectonic map final PRJ.cdr
August 2, 1997

Prepared as PDF File by A. Serano, October 2000

Ministry of Petroleum and Mineral Resources

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TECTONIC MAP OF SAUDI ARABIA AND ADJACENT AREAS

Compiled by: Peter R. Johnson

1419 A.H. 1998 A.D.

وزارة البترول والثروة المعدنية

وكالة الوزارة للثروة المعدنية

الخريطة الحركية للمملكة العربية السعودية والمناطق المجاورة

إعداد : بيتر جونسون

Summary

Tectonically, Saudi Arabia is part of the Arabian plate, one of over ten lithospheric plates that make up the Earth's surface. It consists of crystalline Precambrian basement overlain by low-dipping Phanerozoic sedimentary and volcanic rocks, and originated 25-30 million years ago as a consequence of rifting along the line of the eventual Red Sea and Gulf of Aden. The plate moved north and collided with the Eurasian plate. Prior to rifting, the rocks of Saudi Arabia were contiguous with those of Northeast Africa and the Horn of Africa, and shared the geologic history of those regions. Precambrian rocks that crop out in the western third of Saudi Arabia and in adjacent parts of Yemen and Jordan comprise an area referred to as the Arabian shield. Precambrian rocks also crop out locally in Oman and, on the basis of geophysical measurements, borehole intersections, and the character of deep crustal material ejected from Cenozoic volcanoes are inferred to exist as crystalline basement beneath the Phanerozoic sedimentary rocks that occupy central and eastern Arabia.

Judging from available isotopic ages, the basement is mainly Neoproterozoic (850-550 Ma), but locally older. It consists of deformed and metamorphosed volcanic and sedimentary rocks, which were deposited in volcanic arcs, sedimentary basins, half-grabens and other types of complex oceanic environments, and vast amount of granitic, dioritic and other igneous rock. These rocks were formed during a process of crustal accretion that, starting with juvenile oceanic crust and possible continental microplates, resulted in the creation of new continental lithosphere about 40–45 km thick. By the end of the Precambrian, this crustal layer, which is subdivided into an upper section of volcanic, sedimentary, and igneous, mainly granitic, rocks, and a lower section of mainly mafic rocks, each about 20 km thick, was sutured between the cratons of West and East Gondwana.

The Phanerozoic geologic history of Saudi Arabia is marked by a moderate degree of tectonism in the Precambrian basement and the formation of a succession of arches, basins, and fault blocks. Coupled with the rise and fall of sea level in the flanking Tethys ocean and the epeirogenic effect of, often distant, plate movements, these structures controlled sedimentation of the Phanerozoic rocks, resulting in the development of the unconformities, systematic sequence thickenings and thinning, and facies migrations that characterize much of the Phanerozoic succession in Arabia.

Younger tectonic events in Saudi Arabia reflect Cenozoic rifting, plate movement, and associated geologic phenomena. These include the eruption of large fields of flood basalt in western Arabia, uplift of the basement areas flanking the rift zones, and the development of juvenile oceanic floor in the Red Sea and Gulf of Aden basins. Collision with Eurasia caused folding and thrusting in the Zagros and Bitlis zones along the northeastern and northern margins of the Arabian plate, and concurrent strike-slip faulting on the Dead Sea transform caused the development of pull-apart basins and en echelon folds.

موجز

تُعتبر المملكة العربية السعودية من الناحية الجيوحركية جزءاً من الصفيحة العربية التي تمثل واحدة من أكثر من عشر صفائح من القشرة الأرضية المكونة لسطح الأرض. وتحتوي هذه الصفيحة على صخور القاعدة المتبلورة من دهر ما قبل الكمبري تعلوها صخور بركانية منخفضة الميل تابعة لدهر الحياة الظاهرة ، وقد نشأت هذه الصفيحة قبل ٢٥ إلى ٣٠ مليون سنة نتيجة للتصدّع الصفيحي الذي حدث على طول الأخدود الذي أحدث البحر الأحمر وخليج عدن في وقت لاحق. وقد تحركت الصفيحة بإتجاه الشمال وتصادمت مع الصفيحة الأوراسيوية. وقبل حدوث التصدّع كانت صخور المملكة العربية السعودية في وضع تلامس مع صخور منطقتي شمال شرق أفريقيا والقرن الأفريقي ، وكذلك تشاركهما التاريخ الجيولوجي . إن صخور ما قبل الكمبري المتكشفة في الثلث الغربي من المملكة العربية السعودية وفي الأجزاء المجاورة لها في كل من اليمن والأردن تكوّن ما يعرف بمنطقة الدرع العربي ، كما تتكشّف هذه الصخور موضعياً في عمان. وكذلك وفقاً للمعطيات الجيوفيزيائية وتقاطعات الحفر وخصائص المواد القشرية العميقة التي قذفتها براكين عصر الحياة الحديثة فإنها تدل على وجود هذه الصخور كقاعدة متبلورة تحت الصخور الرسوبية لدهر الحياة الظاهرة التي تشغل المنطقتين الوسطى والشرقية من شبه الجزيرة العربية.

وإستناداً إلى أعمار النظائر الإشعاعية المتوفرة فإن صخور القاعدة هي أساساً من دهر طلائع الحياة الحديثة (٨٥٠ – ٥٥٠ مليون سنة) ولكنها وضعياً أقدم عمراً ، وتتكون من صخور بركانية ورسوبية متشوهة ومتحولة ترسبت داخل أقواس بركانية وأحواض رسوبية وأنصاف أخاديد وأنواع أخرى من البيئات المحيطية المعقدة ، إضافة إلى كميات كبيرة من صخور الجرانيت والديوريت وصخور نارية أخرى. وقد تكوّنت هذه الصخور عملية تراكم قشري بدأت بالقشرة المحيطية حديثة النشأة مع إحتمال ظهور صفائح قارية صغيرة نشأت منها فيما بعد قشرة أرضية قارية جديدة بلغ سمكها مابين ٤٠ إلى ٤٥ كيلومتراً. وبنهاية دهر ماقبل الكمبري ، فإن هذه الطبقة القشرية ، التي تنقسم إلى جزء علوي من صخور بركانية ورسوبية ونارية معظمها جرانيتية ، وجزء سفلي يتكون أساساً من صخور قاعدية ، ويبلغ سمك كل جزء حوالي ٢٠ كيلومتراً ، قد إلتأمت بين الرسيخات في غرب وشرق جوندوانا.

إن التاريخ الجيولوجي لدهر الحياة الظاهرة في المملكة العربية السعودية يتميز بدرجة معتدلة من الحركية في صخر القاعدة التابع لدهر ماقبل الكمبري ، كما يتميز بنشأة تتابع من الأقواس والأحواض والكتل الصدعية. وقد تحكمت هذه التراكيب في ترسب صخور دهر الحياة الظاهرة ، مقترنة بإرتفاع وإنخفاض مستوى البحر في جوانب محيط التثيس وتأثير النشوء القاري المتعلق بتحرك الصفائح البعيدة غالباً ، مما أدى إلى حدوث عدم التوافق والتعاقب المنتظم من زيادة السماكة والترقيق وتغير السحنات التي تميز معظم التتابعات الصخرية لدهر الحياة الظاهرة في شبه الجزيرة العربية.

تعكس التطورات الجيوحركية الأحدث عمراً في المملكة العربية السعودية التصدع الصفيحي خلال عصر الحياة الحديثة وتحرك الصفائح والظواهر الجيولوجية المرتبطة بهما. ويشمل ذلك تدفق حمم بازلتية كبيرة في الجزء الغربي من شبه الجزيرة العربية ، وإرتفاع مناطق صخر القاعدة المحيطة بنطق الأخدود ، وتكوين قاع محيط حديث في حوضي البحر الأحمر وخليج عدن . وقد أدى تصادم الصفيحة العربية مع صفيحة أوراسيا إلى بروز طي ودفع دسري في نطاقي زاغروس وبتليس على طول الحافتين الشمالية الشرقية والشمالية للصفيحة العربية ، كما تسبب الصدع الإنزلاقي الأفقي المتزامن على البحر الميت في تكوين أحواض متباعدة وطيات درجية النسق.

INTRODUCTION

The study of tectonics deals with the broad architecture of the outer part of the Earth, and the age, relationship, and evolution of regional structural, deformational, and crustal features. This map shows selected tectonic elements of Saudi Arabia and, in lesser detail, elements in adjacent parts of the Arabian Peninsula. The map is modeled on the pioneering publication by Brown (1972), but itself is a new map incorporating geologic and geophysical information and plate-tectonic and terrane-agglomeration concepts acquired and developed since 1972, including those based on the author's own field work in the western part of Saudi Arabia. It depicts tectonic relations that began to evolve in the Archean, but continue to evolve because of ongoing deformational activity at the margins of, and within, the confines of the region shown.

Acknowledgements

This map was compiled under Subproject 4.1.1.2 (Compilation of small-scale geologic maps) of the Saudi Arabian Deputy Ministry for Mineral Resources Work Program for 1417-1418 (1997). The author is thankful for the continued support of the Deputy Minister, H.E. Ibrahim bin Ahmed Khaberi, and the Assistant Deputy Minister for Survey and Exploration, H.E. Dr. Mohammed bin Assad Tawfiq. The compiler acknowledges the work of earlier geologists who worked in the region, including Glen Brown, Richard Powers, Jaques Delfour, Mohammed Al-Shanti, Robert Stern, Robert Bohannon, William Greenwood, Douglas Stoeser, Victor Camp, John Stacey, Robert Agar, Moujahed Husseini, and Ramon Loosveld and his colleagues. The present map draws on the results of these authors, but incorporates them with the compiler's own interpretation, so that the final content of the map is the author's own. Victor Yuga and Marco Marasigan are thanked for help and advice about the digital format and presentation of this map, and Timothy Hayes (USGS) is thanked for his technical review.

ARABIAN PLATE

Saudi Arabia is part of the Arabian plate, one of over ten rigid lithospheric plates that make up the surface of the earth. The Arabian plate came into existence 25-30 million years ago (25-30 Ma), when the rocks that comprise what is now the Arabian Peninsula, Syria, Jordan, Iraq, and westernmost Iran began to separate from the African continent because of rifting along the margin of northeast Africa and the opening up of the Red Sea and Gulf of Aden. Although relatively young as a tectonic unit, the plate incorporates rocks that have evolved over a considerable span of geologic history. These rocks range in age from the Archean to the most recent and make up a layer of continental crust as much as 45 km thick. The Precambrian rocks are extensively exposed in the southwest of the plate, and locally in the southeast, because of Mesozoic and Cenozoic uplift. Elsewhere the Precambrian rocks are concealed by a low-dipping sequence of Phanerozoic (Infracambrian-Tertiary) deposits that, in the Arabian Gulf, for example, reach a thickness of more than 10 km. The presence of Precambrian basement, where concealed, is attested by the extension of magnetic anomalies from areas of exposure into areas of concealment, by gravity data, by seismic surveys, and by widely scattered borehole intersections.

The Precambrian rocks contain most of Saudi Arabia's known metal deposits, such as gold, silver, copper, zinc, iron, and magnesium. The Phanerozoic rocks contain the oil resources and deposits of bauxite (the source of aluminum), phosphate, clay, limestone, silica sand, light weight aggregate, and other mineral commodities that are of increasing importance to the industrial development of the Kingdom.

Since its creation, the Arabian plate moved northeast away from Egypt and Sudan, north away from Somalia, and rotated counterclockwise about a point in the vicinity of the Gulf of Suez. Such movement is accommodated by compression and strike-slip faulting along the Bitlis and Zagros zones, where the Arabian plate collides with and subducts beneath the Eurasian plate, and by strike-slip displacement along the Dead Sea transform. At the present time, the northern part of the Arabian plate moves northwest, with respect to the Eurasian plate, at a rate of 20±3 mm/yr. Because they are regions of extension, the southern, south-western, and southeastern margins of the Arabian plate have weak to moderate earthquake activity; the compressive northerly and northeasterly margins, conversely, are regions of strong earthquake activity. Overall, the plate has moved as much as 350 km away from Africa, depending on where the margins of the initial rift are placed with respect to present-day exposure of Precambrian basement, depending on how much stretched continental crust is believed to remain in the Red Sea basin, and depending on how much hybrid continental-oceanic and true oceanic crust is inferred beneath the Red Sea shelves and axial trough. Displacement along the Dead Sea transform separating the northeastern-most part of the African plate from the Arabian plate and linking extension in the Red Sea with compression in the Bitlis zone, is believed to be about 110 km.

A seismic-refraction survey in southwestern Saudi Arabia indicates that the Arabian-plate lithosphere broadly consists of two layers, each about 20 km thick. The MOHO, at the base of the lower layer separating the continental crust from upper mantle is 40-45 km below the surface over most of the survey area, shallowing rapidly beneath the coastal plain in the transition zone between continental and oceanic crust at the southeastern and southern margins of the plate. The uppermost layer is characterized by an average compressional-wave velocity of 6.3 km/s and probably consists of the types of deformed Precambrian rocks exposed at the present-day surface together with vast amounts of granitic rock. If the structure of these deformed rocks resembles that of orogenic belts elsewhere in the world, the exposed Precambrian volcanic and sedimentary rocks possibly extend only 5-15 km below the surface, bottoming in deeper intrusions or at subhorizontal faults, and constituting roof pendants or thrust sheets. The deeper layer has an average velocity of 7.0 km/s, suggesting that it is mafic in composition, consistent with the composition of fragments of deep crustal material brought to the surface by Cenozoic volcanic eruptions in several places in the western part of the Arabian plate.

PRECAMBRIAN BASEMENT

The southwestern outcropping Precambrian rocks constitute a region of exposed basement called the Arabian shield (the term shield meaning an exposed area of crystalline, stable to moderately stable basement). Most of the rocks are between 870 and 550 million years old, although some contain material as much as 2000 million years old. The older material consists of zircon grains, eroded from even older continental crust and incorporated as detrital grains into younger sedimentary and plutonic rocks, and rare intact old rock. Terranes in Yemen locally contain 2300 Ma Archean gneiss. The Afif composite terrane in Saudi Arabia contains inherited zircons, possible intact Paleoproterozoic-Archean rock, and feldspar and galena crystals that contain lead isotopes indicating derivation from an evolved continental source, types of data that all suggest the terrane incorporates a continental microplate (now largely destroyed by later intrusion).

The 870-550 Ma rocks of the shield represent one of the best exposed and largest assemblages of Neoproterozoic rocks in the world. Following current ideas about the evolution of orogenic belts worldwide, these rocks are divided into separate crustal units, or suspect terranes, believed to have distinct, unique geologic histories. Many of the Neoproterozoic rocks accumulated in oceanic environments as island arcs, ocean plateaux, and mid-ocean ridges. Reconstructions of Precambrian geography suggest that this ocean lay on the margins of Rodinia, the global supercontinent that existed during the early Neoproterozoic. Rodinia began to break up about 750 Ma, and rifted segments of the supercontinent reassembled by the end of the Neoproterozoic forming a new supercontinent of Gondwana. In this process, the basement rocks of Saudi Arabia, together with those of northeast Africa and those along strike in the Mozambique belt, were caught between western and eastern segments of Gondwana as the segments came together, forming a belt of folded, thrusted, and metamorphosed agglomerated terranes and reworked older rocks (the East African orogen) sutured to Africa (on the west, in present-day directions) and East Gondwana (on the east). Toward the end of this process, additional volcanic and sedimentary rocks were deposited in marine and continental environments, and a vast amount of plutonic rock was intruded into and beneath the deformed volcanic and sedimentary rocks. Sutures between the constituent terranes of the Arabian shield and its counterpart in northeast Africa are marked by serpentinite-decorated faults, thrusts, and brittle-ductile shear zones. These faults and shear zones coincide with zones of significant changes in gravity, magnetic, structural, isotopic, and geochronologic characteristics from one side to the other. Free-board segments of the newly formed crust partly escaped collision during the end Proterozoic and early Cambrian by displacement along transcurrent faults and by extension across normal faults. These faults have a range of ages and histories, but together represent a period of failed rifting or dismemberment of the newly formed Arabian crust. Neoproterozoic rocks crop out in Oman, and on the basis of their magnetic signature and rare bore-hole intersections, appear to extend some distance from the margins of the shield beneath Phanerozoic cover. The exact age and provenance of the concealed basement rocks, however, are uncertain.

PHANEROZOIC COVER

Despite being referred to, where exposed, as a shield, the crystalline basement of Saudi Arabia has not been completely stable since the end of crust-forming events in the Precambrian. It has been affected, in response to plate movements during the ongoing history of Gondwana and other parts of the world, by strike-slip faulting and rifting, forming grabens, and by uplift and subsidence, forming domes, basins, arches, and troughs. The effects of such deformation are considerable. The crest of the Ha'il arch is about 4 km above the trough of the An Nafud basin; crystalline rocks in the easternmost part of the Arabian plate are depressed beneath more than 10 km of sedimentary rocks; crystalline rocks in the western part of the plate are elevated by as much as 3 km along the Red Sea escarpment; basement rocks are vertically displaced as much as 3 km on buried faults beneath central Arabia; and the southeastern margin of the plate has been overthust by slices of ocean floor. The present-day Arabian shield is exposed because of uplift along the Ha'il arch and Red Sea arch, and the shield is partly concealed, between the arches, by Lower Paleozoic and Upper Cretaceous-Paleogene sedimentary rocks and Cenozoic volcanic rocks preserved in a north-south structural low.

The Infracambrian-Phanerozoic sedimentary history of Arabia began with the deposition, in grabens or pull-apart basins formed by the end Proterozoic faulting mentioned above, of clastic rocks and later evaporites (Huqf and Haima groups) in Oman and eastern Arabia and of clastic rocks, limestone, basalt, and rhyolite (Jibalah group) on the exposed shield, and the formation of the Dokhan Volcanics and associated dike swarms in the Egyptian Eastern Desert. The resulting large Infracambrian-Cambrian salt basins are a conspicuous feature of the eastern part of the Arabian plate and structures formed by later halokinesis, locally in conjunction with basement horst blocks, make extremely valuable oil traps. The South Gulf basin contains piercements rimmed by Cretaceous-Tertiary synclines. Farther north, the North Gulf basin contains large pillows and swells. The South Oman and Ghaba basins were affected by Lower Paleozoic halokinesis and the Ghaba basin by renewed diapirism in the Mesozoic, particularly during the Late Cretaceous and Tertiary concurrent with the second Alpine event in Eurasia.

During the Early Paleozoic, central Arabia was a stable subsiding passive margin flanking Gondwana. Shallow-marine, littoral, and fluvial sandstone, siltstone, and shale were deposited on the low-relief erosion surface formed on the Precambrian basement at the end of the Neoproterozoic, a depositional cycle interrupted during the Late Ordovician-Early Silurian by polar glaciation (Arabia at this time was within 30° of the South Pole). Sea-level rise and fall caused regression and transgression of the ocean flanking Gondwana and a corresponding migration of sedimentary facies on the stable shelf.

Because of "Hercynian" orogenic activity that originated beyond the confines of Gondwana, the passive margin of Gondwana in Arabia during the Devonian became active and central Arabia underwent uplift and tilting. A regional structural high that lacks Devonian sedimentary rocks marks the early development of the Central Arabian arch. Earlier deposits were depressed in fault basins or eroded across generally north-trending horst blocks resulting in an irregular topography preserved beneath the Unayzah-Khuff unconformity and resulting in the initiation of structures that eventually controlled the location of Paleozoic-hosted oil fields in central Arabia. Unayzah Formation clastic rocks, which constitute major oil reservoirs where they overlie appropriate Hercynian structures, mark a resumption of sedimentation in the Late Carboniferous. Deposition of the Khuff Formation, representing the earliest major carbonate unit in Arabia, followed, concurrent with rifting and Gondwana breakup in the Zagros region. Deep-water sedimentary(radiolarites) and tholeiitic/alkaline volcanic rocks, now cropping out in the Hawasina thrust sheets in Oman, indicate the onset of Late Permian ocean-crust formation in Neo-Tethys. Structural highs developed in Oman as a possible effect of thermal-doming prior to Gondwana breakup. During this period, a second episode of glaciation deposited Permo-Carboniferous glaciogenic clastic rocks in southwestern Ar Rub al Khali and in interior Oman

The Mesozoic geologic history of the Arabian plate is marked by the formation of structural highs and lows. In central Arabia, regional extension caused by continued breakup of Gondwana and rifting along the Zagros belt resulted in the Triassic reactivation of Hercynian structures and synsedimentary thinning of Triassic deposits over growth faults. Reactivated basement structures, shown in Saudi Arabia as N-S Mesozoic anticlinal highs, affected younger sedimentation, particularly during the Late Cretaceous, causing anticlinal drape folds and helping to create the Mesozoic oil fields of Saudi Arabia. The reservoir rocks are Jurassic and Cretaceous, into which Jurassic hydrocarbons migrated during the Tertiary. The axial region of the Central Arabian arch underwent Middle Jurassic and Early Cretaceous inversion and became a basin, followed by reformation of the arch during the Late Cretaceous as a consequence of uplift in southern Arabia and continued subsidence to the north. Similarly labeled Mesozoic anticlinal highs are important tectonic elements in the Hadramaut region of Yemen and Oman; they trend E-W and reperesent broad arches that were initiated in the Mesozoic, even possibly in the Paleozoic, and were active into the Tertiary. Farther southeast, the precursor of the Gulf of Aden, the proto-Owen basin, opened in the Jurassic, and tilting and uplift affected coastal Oman during the onset of separation of India-Madagascar-Antarctica from Africa-Arabia and formation of the Masirah oceanic crust. These oceanic rocks were later obducted in the Masirah ophiolite zone. During the Middle Cretaceous, concurrent with the opening of the Atlantic, Neo-Tethys closed, and the African-Arabian and Eurasian plates converged. The Semail ophiolite, created by back-arc spreading at a subduction zone between the approaching plates, began to thrust over eastern Oman. Obduction of the ophiolite and loading of the Arabian plate caused an initial bulge and a later downwarp in the foreland in advance of the thrust. The resulting Aruma trough (Fiqa foreland basin) flanked the southwestern margin of the Hawasina and Semail thrust sheets. The Semail ophiolite was in place by the Late Cretaceous at which time the southeastern coast of Oman was affected by sinistral transpression

TERTIARY SPREADING, UPLIFT, AND VOLCANISM

The present-day boundary between the Arabian and African plates is a series of troughs 2,000-4,500 m deep along the Red Sea, Gulf of Aden, and Gulf of Aqaba reflecting spreading along the Red Sea and Gulf of Aden and pull-apart basins along the Dead Sea transform fault. Seafloor spreading in the Red Sea began 5-6 m.y. ago, although an earlier episode of spreading may have occurred 15-25 m.y. ago. Intrusion of magma along the spreading axes created the oceanic crust of the southern Red Sea and formed pools of metal-laden brine and hot springs in particular deeps. The floor of the northern Red Sea may be a mixture of rifted continental crust and newly formed oceanic crust. Syn- and post-rift sedimentary rocks, including evaporites, flank the spreading axis in the Red Sea and underlie the Red Sea coastal plain (Tihama). In most localities, the contact between Precambrian rocks of the shield and Cenozoic rocks of the Red Sea basin is faulted. The Gulf of Aqaba pull-apart basins contain sedimentary rocks. Ocean crust in the Gulf of Aden began to form 11 million years ago (Middle Miocene) by westward propagation from the Carlsbad ridge in the Indian Ocean. The ocean crust is progressively younger toward to west, and is about 2 million years old where propagating west in Djibouti toward the Afar hot spot.

Processes related to spreading caused uplift of the southwestern and southeastern margin of the Arabian plate forming mountains in western Saudi Arabia and Hadramaut that crest at the erosional escarpment (2500-3300 m above sea level) inland from the Red Sea and Gulf of Aden. According to fission-track data, the Red Sea margin of southern Saudi Arabia has undergone 2.5-4 km uplift in the last 13.8 million years. East of the Red Sea escarpment and north of the Hadramaut escarpment the land surface slopes to a broad plateau 900-1,000 m above sea level, and farther east slopes gently to the Gulf. End-Cretaceous-Tertiary events in the southeastern part of the Arabian plate include oblique obduction of the Masirah ophiolite (Paleocene) onto the Arabian continent and rift-shoulder uplift and normal faulting of coastal southern Oman and eastern Yemen. This episode of uplift caused development of the Gulf of Aden collapse structures, fractures parallel and oblique to the general trend of the gulf that deform the edge of the uplifted plateau and the southern flanks of the Mesozoic Hadramaut arches.

Flood basalt erupted in western Arabia as a result of the spreading process forming large fields of subaerial volcanic rock (harrats) that cover parts of the shield and some Phanerozoic sedimentary rocks. The volcanic rocks are mainly alkali-olivine basalt and form lava fields that were extruded from numerous vents and volcanic cones. The northerly alignment of cones and faults in the volcanic fields possibly reflects a northerly alignment of fractures in the underlying crystalline basement along which magma rose from great depth. The oldest flood basalts are in Yemen and southern Saudi Arabia (30 Ma); the youngest are in parts of Harrat Rahat and Khaybar (erupted as recently as 700 years ago).

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