OMAN: an obduction orogen

Two major systems may develop in convergent oceanic/continental plate boundaries:

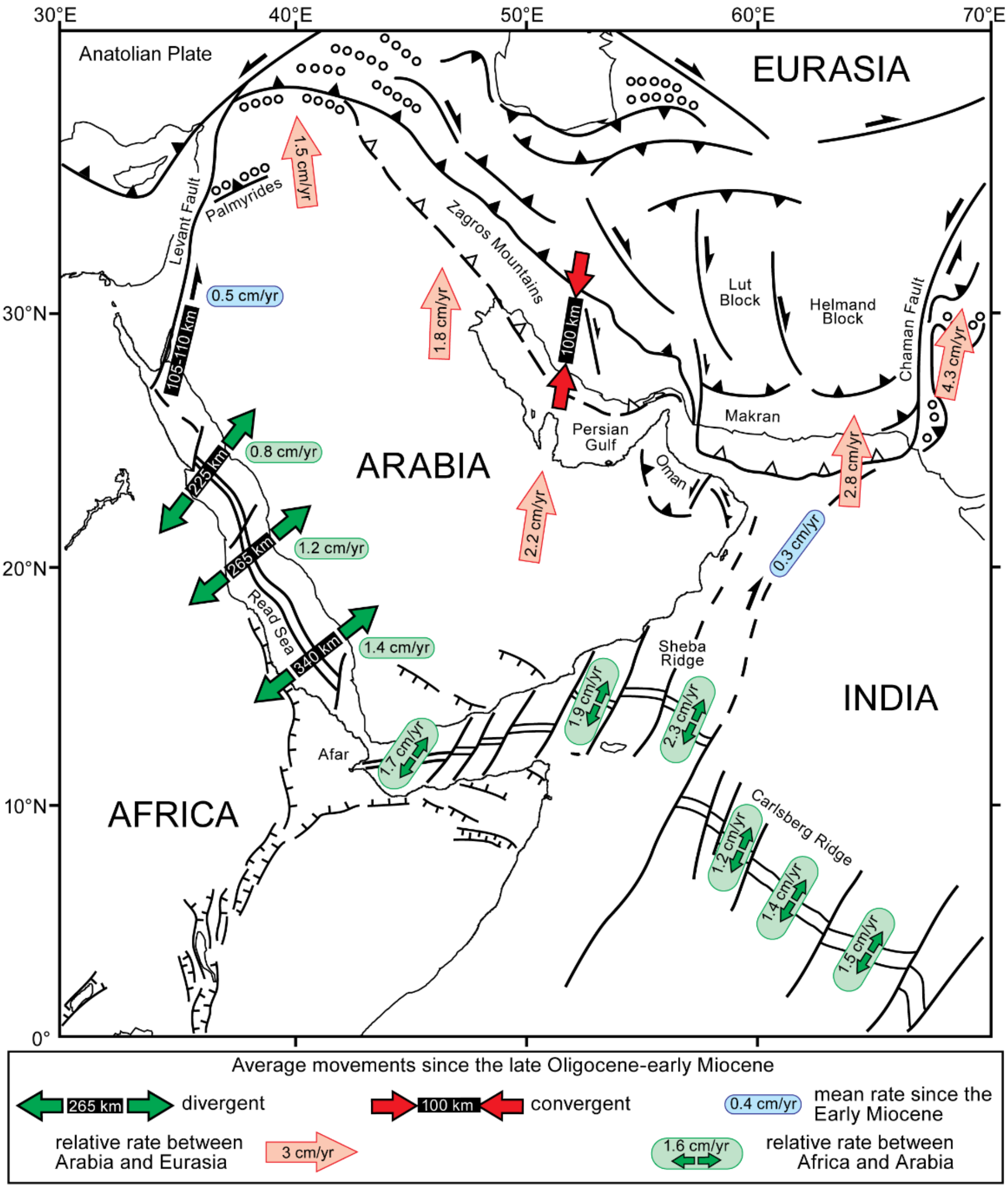
- (1) the oceanic lithosphere may sink into the mantle, developing a **Benioff-Wadati plane** and a **subduction system** beneath the opposed continental plate. This system is stable and permanent as long as there is oceanic lithosphere available for subduction.

- (2) The oceanic lithosphere may be thrust over the continental lithosphere: this is called **obduction,** an **accretionary** mechanism that involves thickening of the continental lithosphere due to the superposition of oceanic lithosphere onto a continental margin. The transported oceanic rocks are identified as an **ophiolite**. Obduction is particularly well documented in Oman where the convergence between Arabia and Eurasia resulted in the late-Cretaceous thrusting of Tethys oceanic lithosphere onto the Arabian continental margin.

The Oman Mountains

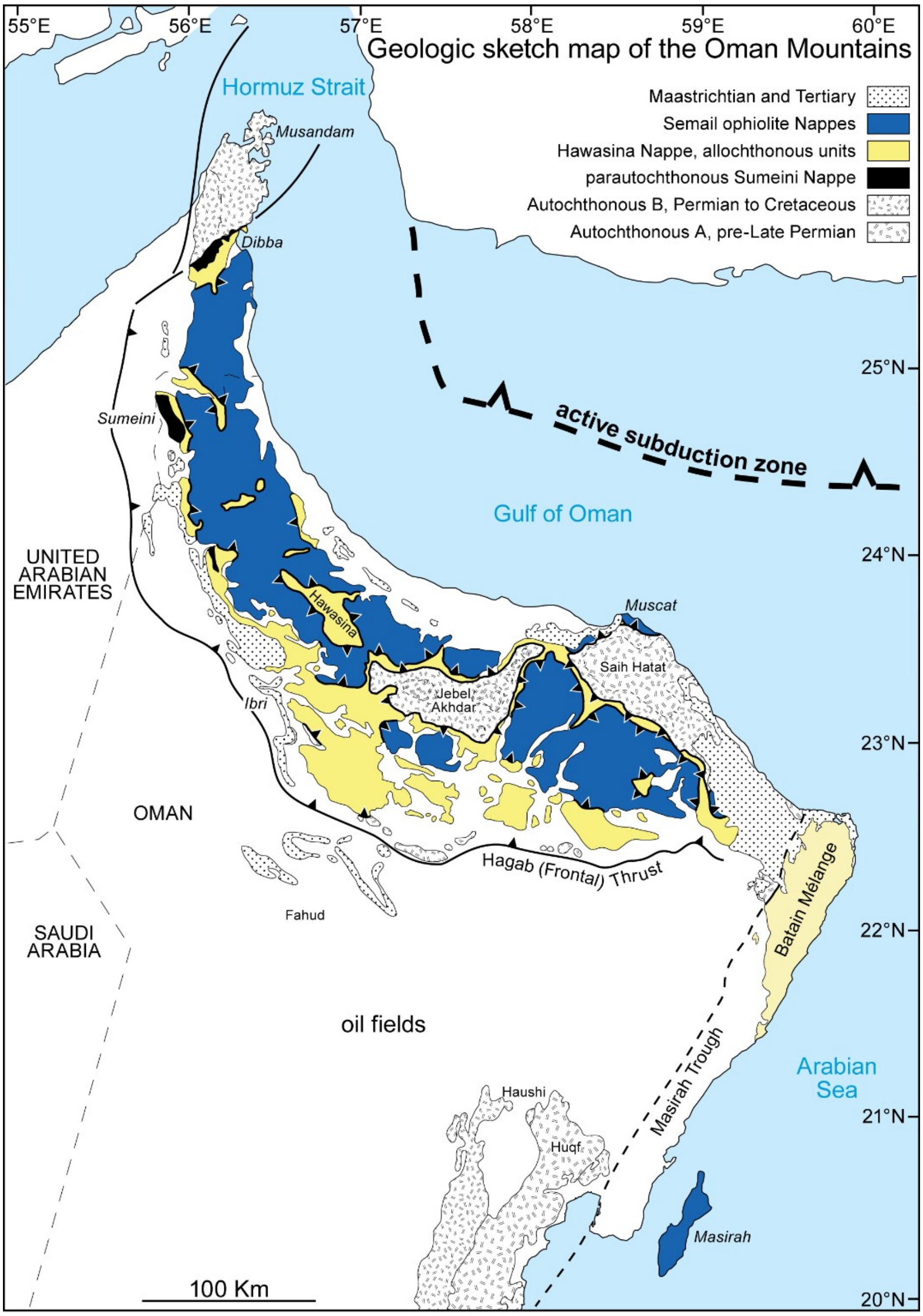
Location

The approximately 700 km long and 40-120 km wide Oman Mountains form an arcuate chain stretching from the Strait of Hormuz to the northwest, to the Arabian Sea in the southeast.



Structural sketch and situation of the Oman Mountains on the Arabic Plate in the frame of present-day plate tectonics

The boundaries of the Arabian continental plate, carrying the Oman Mountains, are:
- The Red Sea and the Gulf of Aden spreading centers to the southwest and the south.
- The Owen transform-fault in the Arabian Sea along the SE coast.
- The sinistral Levant Transform Fault to the west,
- The major Tethyan suture zones (Bitlis-Zagros-Makran) exposed in Turkey and Iran, along the northeastern margins.
- To the north, the Cretaceous oceanic of the Gulf of Oman is currently subducting northward beneath the Makran active margin of the Eurasian continental lithosphere.

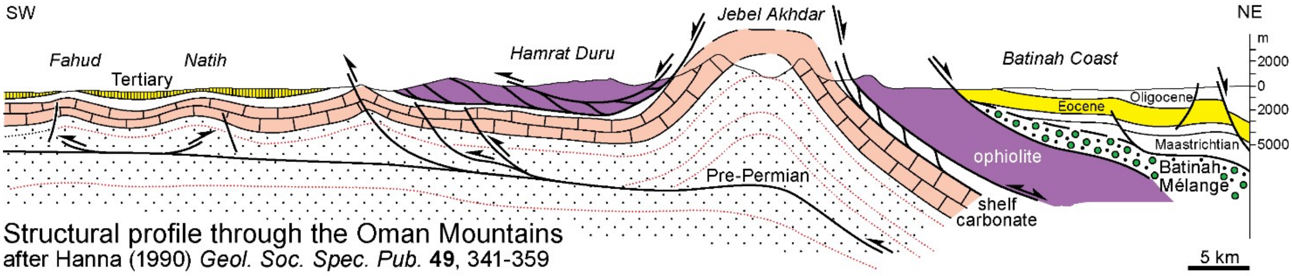


Geological Setting

The Oman Mountains define a continent-ocean collision boundary of dominantly Late-Cretaceous age, affected by further but minor compression and uplift during the Tertiary. In contrast with the remainder of the Alpine-Himalayan collisional system, continent-continent collision did not occur. Instead, convergence has shifted to the north into the active Makran subduction system, thus preserving much of the obduction system. Therefore, the Oman Mountains display a deformed passive margin ideal to study fundamental processes such as rifting, passive margin development, later thrusting, etc.

The Oman Mountains comprise three major tectonostratigraphic units. From the structural bottom upward they are:

- The pre-Permian basement unconformably overlain by mid-Permian to Cenomanian platform carbonates.
- Permian to Cenomanian rocks composing the relative autochthonous and allochthonous units.
- The upper unit, which is a neo-autochthonous sedimentary cover of Late-Campanian to Tertiary age.



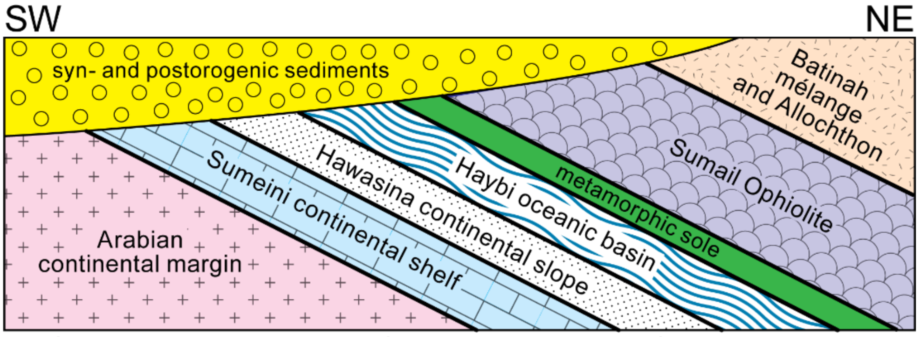
Structural profile through the Oman Mountains
after Hanna (1990) *Geol. Soc. Spec. Pub.* **49**, 341-359

Autochthonous and para-autochthonous units

These units include:
* Remnants of Pre-Permian basement (the Arabian shield) exposed in windows (Hatat Schists) and further south, where the basement is autochthonous.
* Remnants of mid-Permian to Cenomanian continental shelf carbonates of the former Arabian margin (Hajar Supergroup).
* The leading edge of the continental margin that has been subducted to depths where eclogite-facies metamorphism took place (Saih Hatat window).

Allochthonous units

Three main types of allochthonous complexes were thrust onto the Arabian platform:
* Remnants of the continental shelf: The **Sumeini Nappe**, which comprises Permian to Cretaceous carbonate slope deposits.
* Remnants of ocean basin sediments: The **Hawasina** and **Haybi Complexes**, a complicated assemblage of thrust sheets of proximal to distal deep-sea, Permian to Late Cretaceous sediments, volcanic and mélange units tectonically underlying the ophiolite thrust sheets. The Hawasina mélange units (Haybi) are particularly known for the exotic blocks they contain.
* Remnants of oceanic lithosphere: The **Sumail Ophiolite**, the world's largest and best-exposed section of oceanic lithosphere. It is the structurally highest thrust sheet of the thrust stack of former Tethys Ocean relics.



Schematic arrangement of thrust sheets in the Oman Mountains

Post-orogenic cover

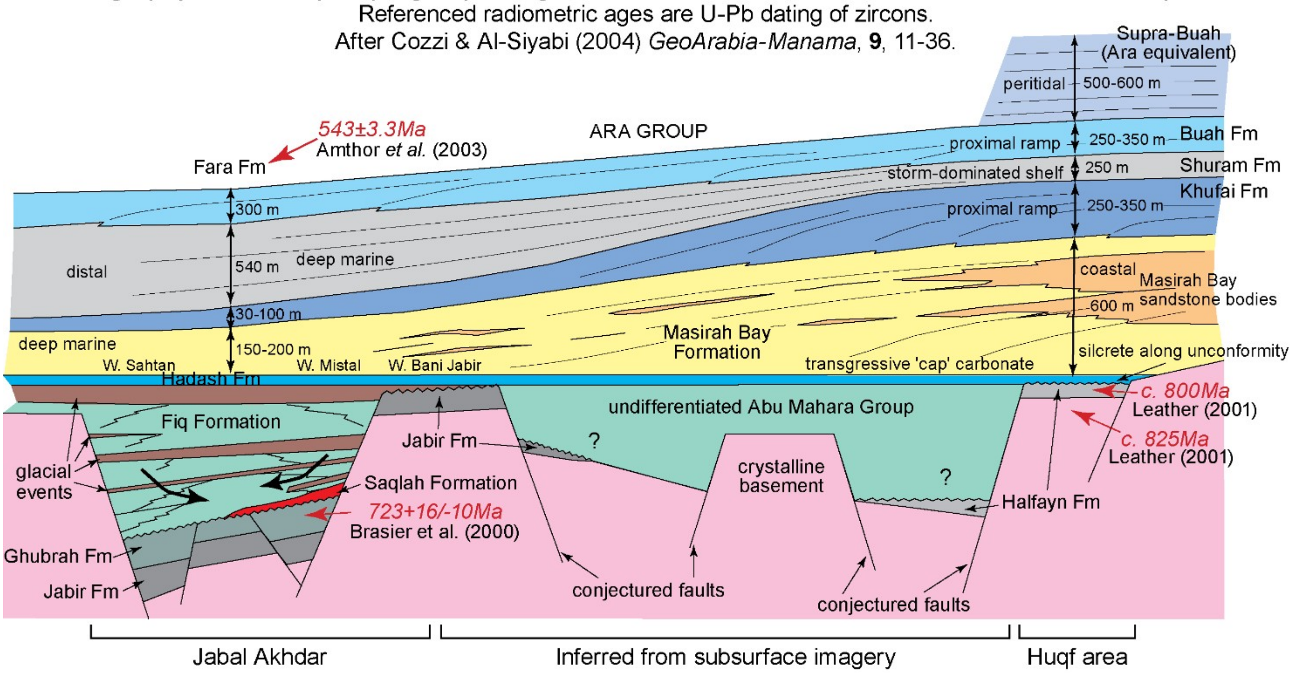
On-lapping Maastrichtian to Miocene sediments dominated by shallow-water carbonates, locally conglomeratic at the base, rest over the thrust stack.

The Afro-Arabian Shield

Craton

The structurally lowest units represent the autochthonous continent.
The Precambrian comprises metasediments of greenschist to amphibolite facies intruded by dolerites and large volumes of calc-alkaline granodiorites and granites. Geochronological data specify the rocks as of Late Proterozoic (ca. 850-600 Ma). Therefore, they are similar to Pan-African rocks of the Afro-Arabian shield and represent accretion of island arcs and microcontinents to Early Gondwana.
The oldest non-metamorphic rocks (**Huqf-Haushi**, in southern Oman) are Vendian to Early Cambrian (they span the Cambrian-Precambrian-boundary). Two periods of glaciation are identified. The first one took place between ca 725 and ca 715 Ma, the second one between ca 660 and 635 Ma. Glaciogenic sediments alternate with shallow- and open-marine clastic sediments deposited in grabens and half grabens and overlain by a cap carbonate formation, which marks the abrupt termination of the glacial epoch.

Stratigraphy of the Huqf Supergroup along a cross-section between the Jabal Akhdar and Huqf area.
Referenced radiometric ages are U-Pb dating of zircons.
After Cozzi & Al-Siyabi (2004) *GeoArabia-Manama*, **9**, 11-36.



A transgressive-regressive evaporitic–carbonate-shale (Ara and **Fahud**) formation and its time-equivalent (ca 545 Ma) carbonate volcaniclastics (Fara) Formation in Jebel Akhdar covered the Neo-Proterozoic (Huqf) sequence. These evaporitic red sequences are a geological rarity because they contain hydrocarbon-rich source rocks and large accumulation of oil. The cyclic sequences of carbonates and evaporites were deposited in a restricted basin whereas the source rocks were deposited in relatively deep anoxic parts of the basin. The reservoir rocks, most of them dolomitic, were deposited in shallow water on the adjacent shelf area. These rocks have never been buried deep and the thick evaporites provide the regional seal.
Possibly late Paleozoic (so-called Hercynian) structures in Neo-Proterozoic rocks are controversial because the lack of time markers such as dikes of different generations does not allow to convincingly differentiating them from late Cretaceous deformation events.

Continental margin

In the Oman Mountains, the structurally deepest units occur in the Jebel Akhdar and Saih Hatat dome-shaped culminations.

Proterozoic and Lower Paleozoic sediments constitute the autochthonous basement of the Oman Mountains. There is principally a sedimentation gap from the Late Silurian to the Carboniferous. Basement rocks have been subjected to NW-SE trending folding and very low-grade metamorphism before the Permian deposition of unconformable shallow-water carbonates. The Permian to Cenomanian rocks are composed of platform carbonates followed in the Turonian by deeper marine sediments (foredeep of the orogen, the Turonian-Campanian Muti Formation).

In the Saih Hatat Dome, intense deformation and High-Pressure/Low-Temperature metamorphism (blueschist-facies to eclogite-facies) that affect the Permian to Mesozoic cover have overprinted the pre-Permian structures.

From rifting to ocean spreading

Lithologies contained in the few centimeters to hundred meters big exotic blocks represent different paleogeographic units of the Oman continental margin redeposited on the northern edge of the Arabian shield. The sedimentary history of the Oman passive margin compares with that of present-day passive margins such as the Atlantic ones. It documents the continental break-up of Pangea.

The opening of the Hawasina (**Neo-Tethys**) Ocean was underway by Late Permian. Pulsed rifting in the Arabian craton in Early and Late Permian times was followed by mid to Late Triassic seafloor spreading in the (Neo-)Tethys Ocean. Thermal subsidence of the passive margin continued along with oceanic expansion throughout the Jurassic and Early Cretaceous until the Mid-Cretaceous, perhaps with a pulse of crustal extension in the Late Jurassic. The geological record shows that:

1) Early Permian: “non-volcanic” rifting was dominated by block faulting.
2) Late Permian: rifting was accompanied by volcanism. The development of a carbonate platform began along the margin of the developing Tethys.
3) Mid-Triassic to Early Jurassic alkaline volcanism records the final continental breakup.
4) Up to Late Cretaceous, there was thermal subsidence with the growth of a carbonate platform on the proximal continental margin and a deep marine basin on the distal passive margin.
5) In the Late Cretaceous, a foreland basin was created.

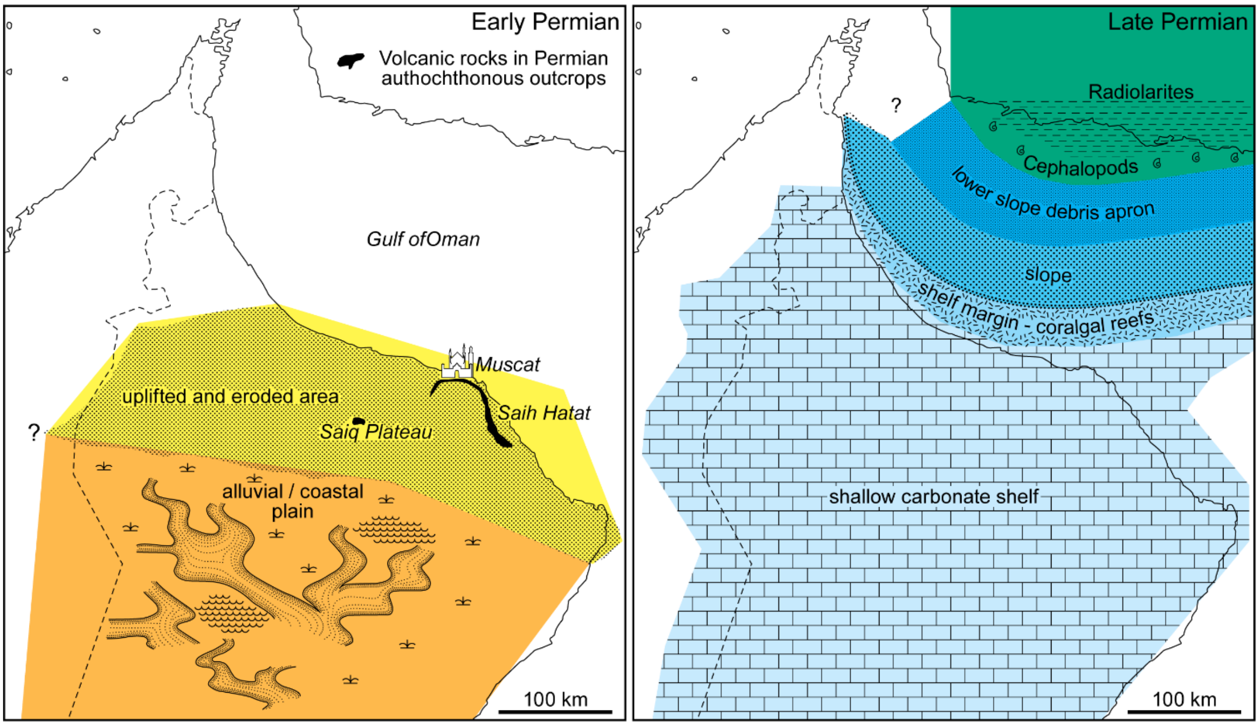
Rifting

The north Oman passive margin fully developed in the Permian. Low-angle normal faults and associated tilted blocks indicate asymmetric rifting. Oman would represent the hanging wall margin.

Late Carboniferous - Permian: northward thinning of continental clastic rocks indicates the updoming of an area roughly overlaying the Oman Mountains. Internal unconformities indicate contemporary uplift.

Early Permian: Bioturbated limestones and stromatolitic mudstones covered alluvial and shallow marine deposits with ubiquitous cross-bedded sandstones. Currents were dominantly flowing southward. The sediments have a glacial affinity and correspond to the Dwyka glaciogenic deposits of Gondwanaland. They are syn-rift deposits locally associated with bimodal (basalts and rhyolitic tuffs), mildly alkaline volcanism, which indicates that the margin was established at the expense of the continental crust now seen in the autochthonous parts of Oman. Early breakaway faults were dipping towards the oceanic basin, to the north (in the present-day orientation). This attitude of the main extensional lithospheric fault favored later re-activation as thrust faults for some of them. Their asymmetry is consistent with a lithospheric shear model and an upper plate passive margin.

Late Permian: Deep-water sediments off north Oman commenced in the early Late Permian. They are reef-derived sediments representing gravity flow deposits that have ammonoid fauna and record northward currents. Their substratum is tholeiitic pillows that may represent the oldest oceanic crust in the area (Neo-Tethys floor).



Paleogeographic maps of North-Oman
after Blendinger *et al.* 1990 *Geol.Soc.Spec.Pub.* **49** 27-37

Platform and slope

By the Late Permian, a vast stable shelf carbonate platform had completely covered the northeast Arabian plate margin extending along the entire Zagros and Oman mountain region. This stable carbonate platform lasted for over 160 million years until the Cenomanian. The Hawasina, Sumeini and Haybi sequences are age-equivalent continental rise, continental slope, and proximal oceanic basins, respectively.

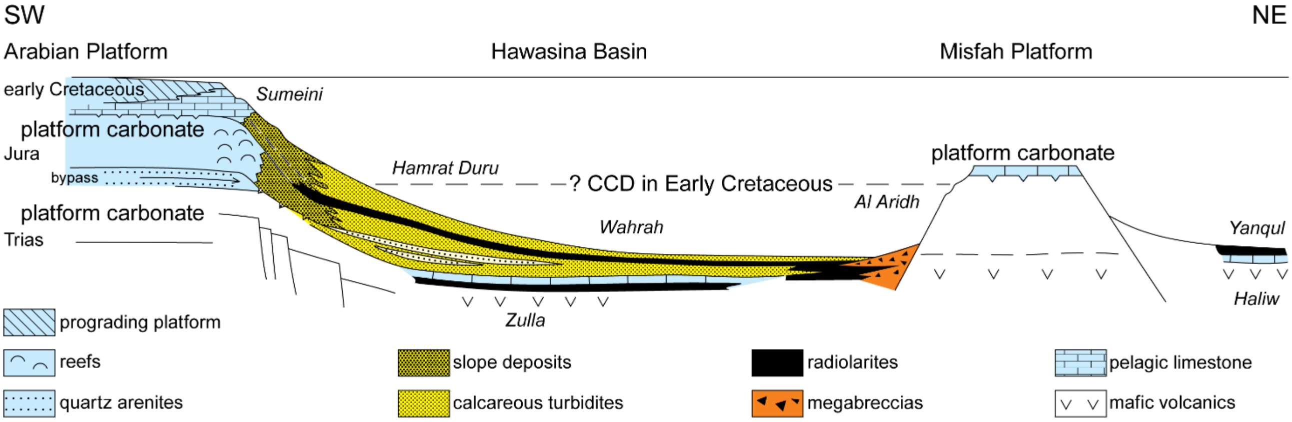
Late Permian: Late Permian, transgressive shallow-water carbonates and reef limestones covered the autochthonous area and the rift shoulders. The collapse of the Upper Permian rift zone and the beginning of thermal subsidence enhanced the change of climate from sub-glacial in late Carboniferous times to intertropical in late Permian and the eustatic rise of the sea level. The paleoclimatic change is attributed to the northward drift of Arabia from ca 50°S to 30°S.

Triassic-Early Jurassic: The sedimentary sequence of the Oman margin records thermal subsidence of both the thinned continental lithosphere and the attached, young oceanic lithosphere. During sedimentation of platform carbonates on the subsiding proximal margin (Jebel Akhdar), proximal to distal turbidites were deposited in the Hawasina (Tethys) basin. Turbidite facies changes reflect fluctuations of the oceanic environment (radiolaritic cherts below the CCD in the Middle Trias) and oscillations of the sea level (siliciclastic turbidites under lower sea level: the Rhetian-Early Liasic Guwayza sandstones). Further offshore, the Misfah platform of the Haybi Complex developed in the Late Triassic on a volcanic seamount forming atolls that were the sedimentary source of large breccias (Al Aridh, Ibra) intercalated in pelagic sediments of the Hawasina basin throughout nearly all the Mesozoic. The Haybi seamount became a Guyot in the Early Jurassic: a hard ground separates the sunken carbonate platform from overlying Middle Jurassic to Cenomanian pelagic sediments.

Late-Jurassic-Cenomanian: During the Tithonian-Berriasian (150-130 Ma), drowning of the northern margin (radiolaritic cherts, on-lap of pelagic sediments onto the platform under higher sea level in the Late Jurassic) and doming of the interior zones of the platform is associated with tilting of the Arabian margin. Normal faulting and a marked unconformity in the shallow marine carbonate of the Jurassic platform also reflect this flexure event.

All was reorganized from the late Turonian onwards, which signs the building of the Oman Mountains. Platform deposition halted abruptly at the end of the Cenomanian, 90 Ma ago when the passive margin was flexed down to form the "Aruma" foreland basin. Upward flexure and erosion, then subsidence and slumping into the syntectonic foredeep ended in the Campanian (70 Ma) with the formation of the obduction-type mountain range.

Palinspastic reconstruction of the Hawasina basin of the central Oman Mountains for the Early Cretaceous
after Bernoulli, Weissert & Blome 1990 *Geol.Soc.Spec.Pub.* **49** 189-202



Deep-sea basin

The Hawasina oceanic basin can be restored as a nearly 300 km wide outer continental margin basin. Pelagic rocks were deposited in a Late Permian to Late Cretaceous distal passive margin and ocean basin northeast of the Arabian craton.

Ophiolite

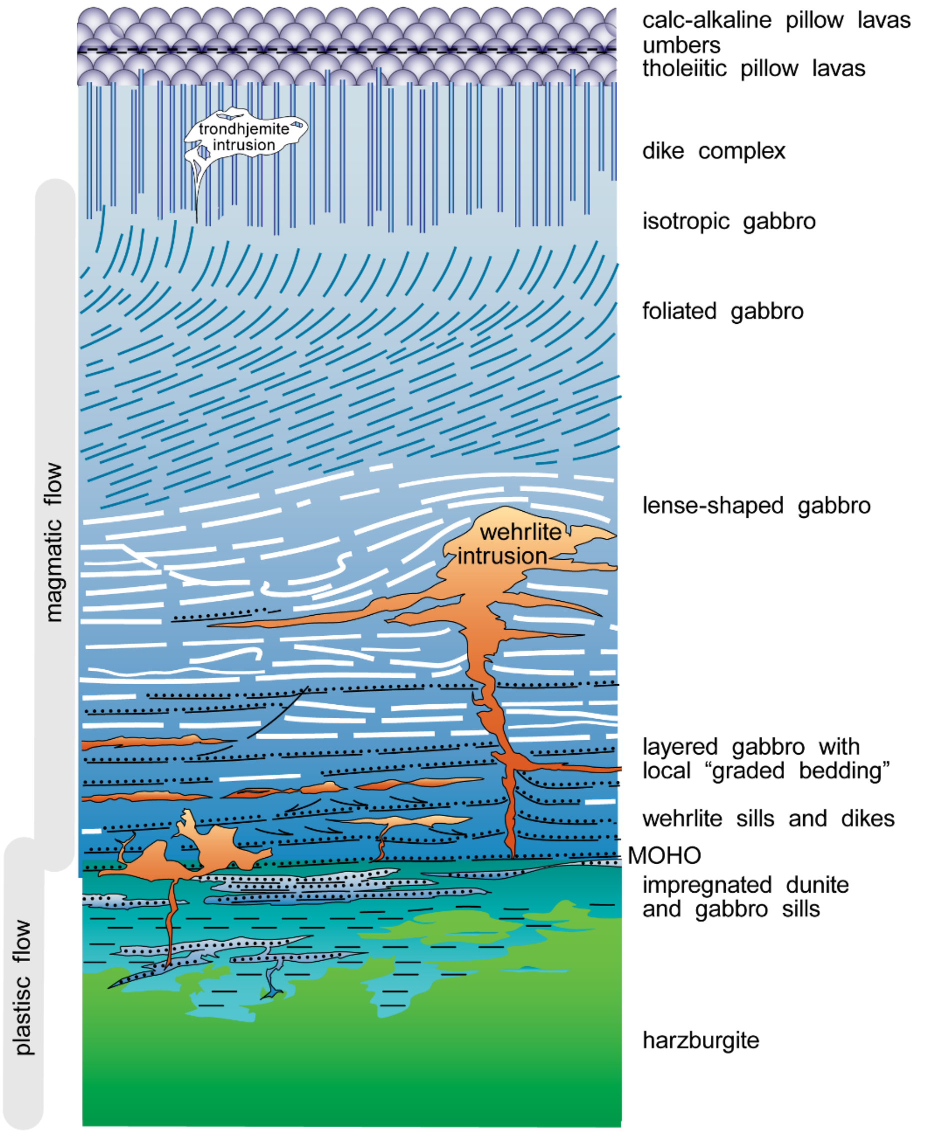
The Sumail Ophiolite was generated during the Cenomanian (there are 98-95 Ma plagiogranites, trondhjemites, and gabbros). It is one of the best-preserved and most complete sequences of oceanic crust and upper mantle at the Earth's surface, exposed as a ca. 550 km long, 50-100km wide and >10 km thick crescent-shaped nappe. Post-obduction tectonic events have disrupted the ophiolite nappe into twelve main, relatively intact massifs.
Petrology, structures, and geochemistry of Sumail Ophiolites indicate formation at a fast-spreading ridge whose tectonic setting as mid-ocean-ridge versus arc-related basin is still debated. Paleo-ridge segments have been identified from structural and petrological characteristics of the sheeted dikes, gabbros, and underlying peridotites. Plutonic and volcanic rocks with calc-alkaline geochemistry are attributed to incipient island-arc magmatism that intruded the Sumail Ophiolites once they became a supra-subduction lithosphere.

Crustal rocks

The crustal sequence is 4 to 9 km thick and comprises two magmatic sequences. The oldest, ophiolitic sequence includes, from top to bottom, deep-sea sediments and basalts, sheeted dikes, and isotropic onto layered gabbros. The MORB-type geochemistry typifies generation at an oceanic spreading center. Intrusions of pyroxenites, gabbronorites, olivine gabbros, and wehrlites with hydrous geochemistry represent younger island-arc type magmatism. Magmatic ages of these two sequences overlap between ~96.5 and 94.5 Ma.

Sediments

The uppermost sedimentary layer consists of pelagic, deep-sea sediments, e.g., radiolarian chert, calcilutite, red argillites, and minor volcano-clastic material.



out of scale, synthetic structural log of the Sumail Ophiolite
summarized after
Nicolas, Boudier & Ildefonse 1996 *Journal of Geophysical Research* **101**, 17941-17950

Lavas

The ophiolitic lava unit consists predominantly of pillowed and massive MORB-type lavas with interstitial **palagonite** and/or pelagic sediment; dikes, sills, lava tubes, and massive flows are present. Hydrothermal fluids have often pervasively altered the basalts metamorphosed in the greenschist facies where paleo- "black smokers" have precipitated ore deposits.
The top lava units include trace element depleted, low-Ti tholeiitic volcanites (in particular boninites) covering the ophiolitic upper crustal lavas and sediments. Their sporadic occurrence discloses incipient and short-lived (between about 97 and 92 Ma) island arc magmatism emplaced near the former spreading ridge on the hanging plate of intra-oceanic subduction.

Sheeted dike complex

The sheeted dike complex grades at its upper boundary into the lava unit. Along the base of this complex, the sheeted dikes either intrude or are intruded by gabbros and subsidiary plagiogranites, implying continuing magmatic activity. The mostly doleritic, with minor gabbro, albitite, and rodingite dikes regionally strike NW-SE, which is assumed the present-day orientation of the paleo-ridge axis.

Gabbros

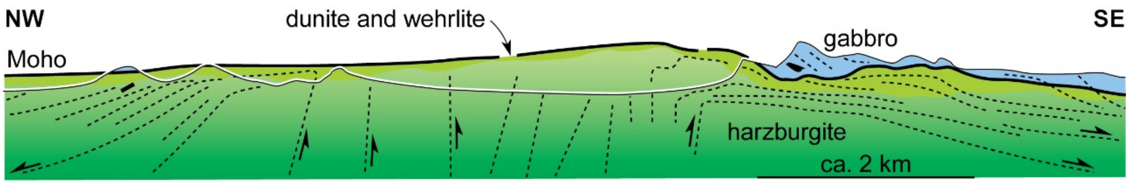
The upper part of the gabbroic sequence (< 1 km thick) mostly consists of massive quartz gabbro, gabbro and troctolite with minor diorite, quartz diorite, trondhjemite, plagiogranite, and granophyre. The gabbroic sequence is characterized by the upward steepening of the fabric, which may be primary. Foliation at the top is parallel to the strike of the sheeted dike complex. The bottom, lower crustal gabbroic sequence (1-4 km thick) is characterized by rhythmic compositional layering on the scale of 0.5 cm to 2 m, parallel to the flat, bottom contact with ultrabasic mantle rocks. Most layers are homogeneous between the sharp top and bottom boundaries. Few graded layers demonstrate the normal position of the sequence. Layering is attributed to cyclic plating on the inverted walls of a tent-shaped magma chamber. Various wehrlites with MORB-like and calc-alkaline affinity have intruded the layered gabbros.

The crust/mantle transition zone (Moho) is a few meters to a few hundred meters thick. Gabbro lenses are imbedded in dunite, plagioclase and clinopyroxene-impregnated dunite, and depleted harzburgite. The gabbro content increases upwards at the expenses of other rock types.

Note:
Since the crust/mantle interface is preserved, the Moho is not a plane of subduction and décollement.

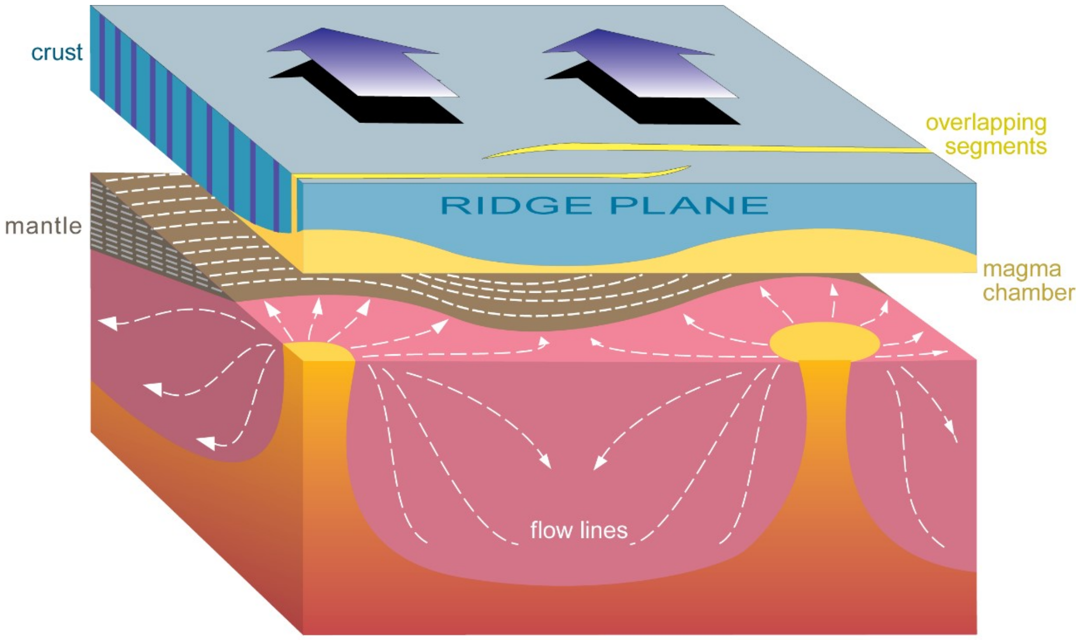
Mantle rocks

Most of the mantle sequence is composed of coarse-grained harzburgite with dunite and pyroxenite "layers". Early high-temperature (> 1000°C) orthopyroxene fabrics are interpreted as mantle flow patterns. Residual orthopyroxene shows that most dunite results from the dissolution of harzburgite pyroxene by melts circulating towards the crust at the time of ophiolite formation.



Cross section with flow lines and flow directions through the Maqsad mantle diapir
after Ceulener *et al.* (1988) *Tectonophysics* **151(1-4)**, 1-26 and Jousselin *et al.* (1998) *J.Geophys. Res.* **103B8**, 18153-18170

The dominant mantle flow is orthogonal to the spreading axis in a plane sub-parallel to the lower boundary of the layered gabbros, i.e. the petrological Moho, which suggests steady-state oceanic accretion. This regular flow geometry is disturbed by diapirs, 10-15 km across, around which the uppermost mantle flow diverges. These diapirs were the conduits through which melt was channeled on its ascent beneath the ridge. Along-strike variations in both the geometry of the asthenospheric flow and the sheeted dike complex show that the ridge was **segmented** on a scale of 50-100 km.



possible relationships between mantle diapirs and ridge segmentation
after Nicolas 1990 Les montagnes sous la mer, Editions du BRGM, 187 p.

The mantle peridotites witness two successive ductile deformation events:
-1) the earlier produced a pervasive coarse porphyroclastic foliation. It corresponds to high-temperature, low-stress asthenospheric flow (lithospheric accretion).
-2) the second one produced a fine-grained mylonitic foliation in the lower 150-2000 m of the peridotite. It reflects the lower temperature, higher stress imprint of intra-oceanic thrusting setting the initial stages for the obduction. Related shear zones strike parallel to the paleo-ridge, as defined by the orientation of the dikes, and are in structural continuity with the underlying metamorphic sole.

Metamorphic sole

The base of the Sumail Ophiolite is a high-temperature metamorphic shear zone with a condensed, inverted metamorphic gradient. This up to a few hundred meters thick **metamorphic sole** includes HT (800 to 1000°C) peridotite-mylonites underlain by discontinuous lenses of amphibolite grade metabasalts, marbles, schists, and metacherts, which were likely scraped off the subducted plate. The amphibolites, overprinted by greenschist-facies assemblages, are geochemically different from the overlying ophiolites. Instead, they may represent an oceanic crust older (Triassic or Jurassic) than the Sumail Ophiolite.
A major thrust separates the metamorphic sole from footwall lower-grade sedimentary and volcanic rocks. The sole fabrics are consistent with transport in a NE-SW direction.

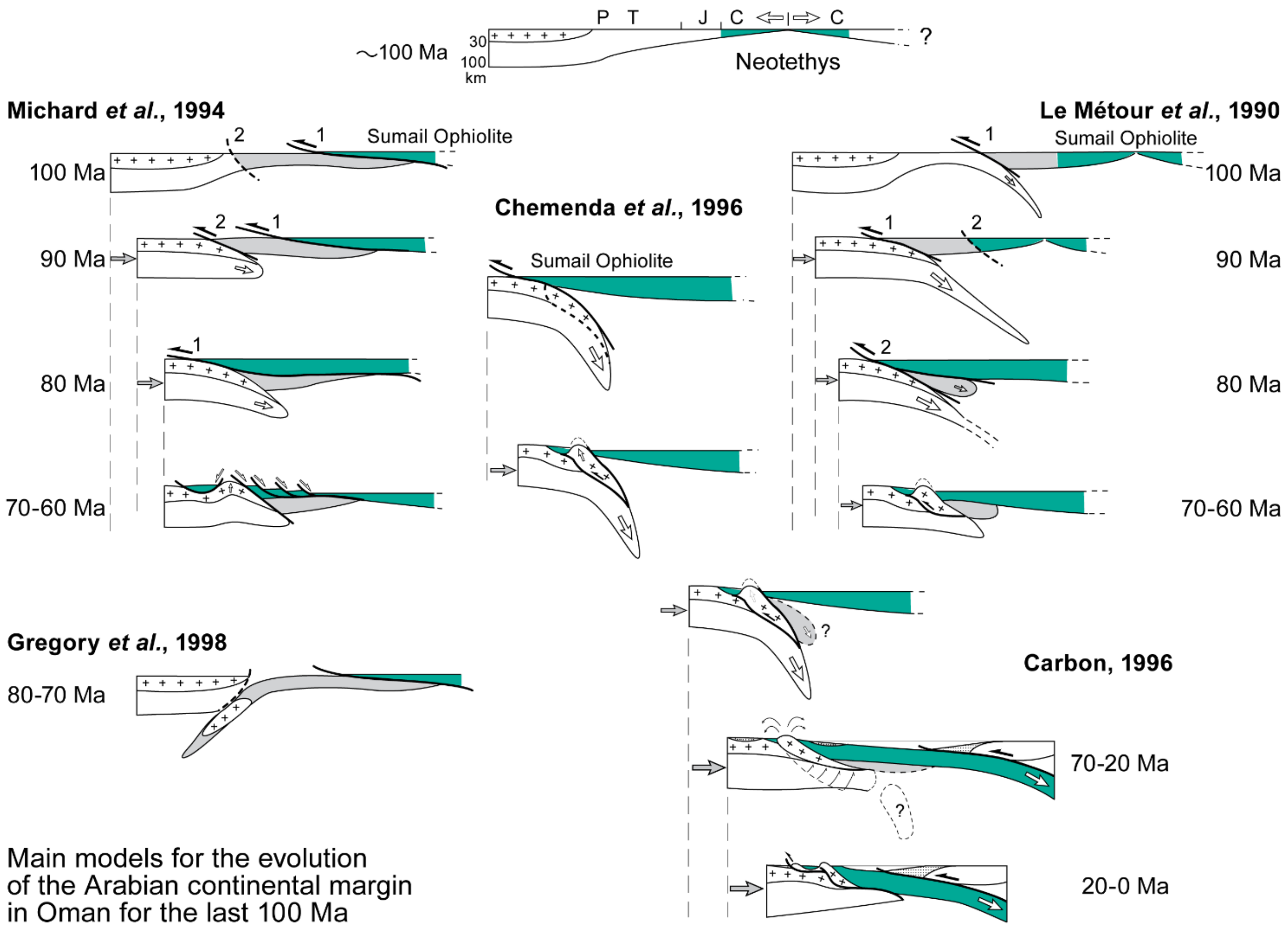
Obduction

Convergence began in the Aptian–Albian (110-120 Ma). It is related to a change in the displacement of Africa with respect to Eurasia (and the coeval opening of the South Atlantic Ocean), which in turn may have been triggered by a superplume event.
The geological record permits to decipher two main stages:
1) Thrusting of the oceanic lithosphere soon after its creation onto the adjacent oceanic crust without emergence. The Mesozoic Tethys oceanic lithosphere and its sedimentary cover were first consumed in a NE-dipping, intraoceanic subduction zone.
2) Thrusting of the oceanic lithosphere onto the continental margin with emergence. As the continental margin of the Arabian plate arrived in the trench, the slab pulled it down into subduction.

Intraoceanic subduction

There are three independent arguments for early, intraoceanic subduction initiated close to a spreading ridge:

- Transitional to calc-alkaline volcanism found on the ophiolites indicates fusion of a hydrated, thin mantle wedge with partial melting at high temperature (hence, subduction bringing hydrated material beneath this wedge).
- Negative εNd and U-Pb dates from hydrated mantle dikes further suggest that intraoceanic thrusting was established within 0.25–0.5 Ma after the formation of the ophiolitic crust.
- Ar-Ar ages of hornblende minerals separated from the sole amphibolites range from 96 to 91 Ma, which, owing to fast cooling, slightly post-dates the inception of intraoceanic thrusting. The brief time between the crystallization of the oceanic crust and cooling of the metamorphic sole supports the interpretation of cold material subducted beneath an active spreading center, i.e. near-ridge subduction.



Main models for the evolution of the Arabian continental margin in Oman for the last 100 Ma

Therefore, the Sumail ophiolites were thrust while young and hot. This conclusion raises the question of how old was and can be the youngest subducted oceanic lithosphere.

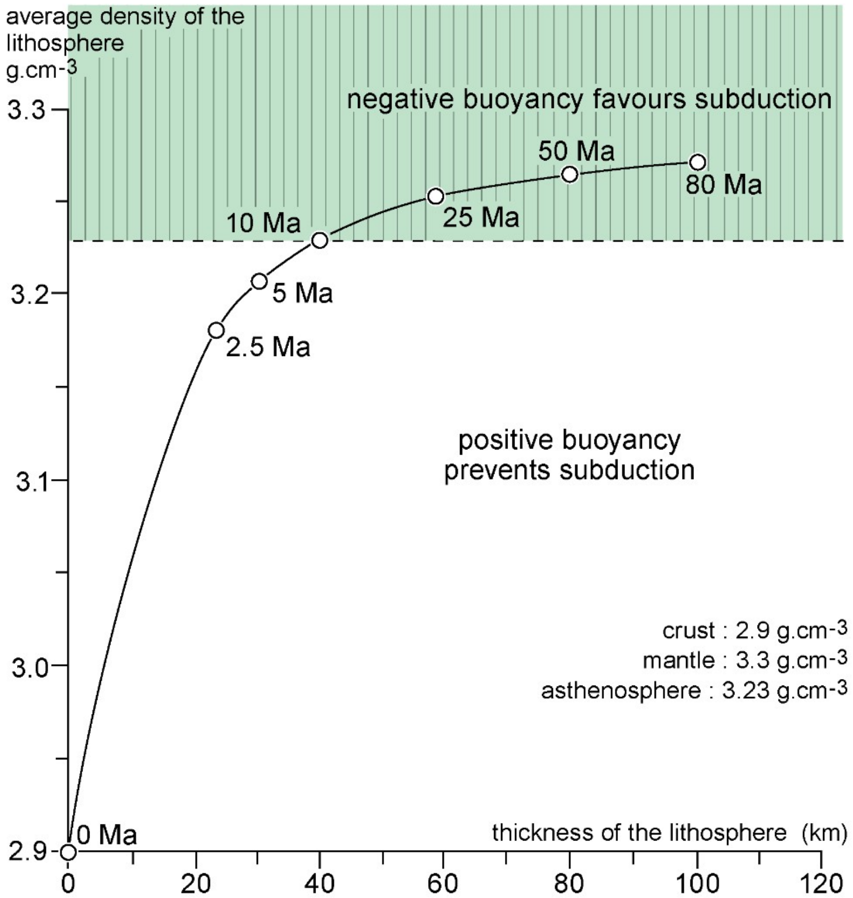
Isostatic conditions

Lithospheric buoyancy is the factor that determines the ability of a plate to be subducted. The density of oceanic lithospheres increases with cooling, after formation at spreading ridges, which is reflected in the deep bathymetry of the ocean floor away from the spreading ridge axis. Rewording the question from density considerations is: where does thermal maturation produce a lithosphere cold – dense enough to be more likely subducted than obducted?

Approximations assuming local isostasy indicate that average oceanic lithospheres become negatively buoyant when they are 5-10 Ma old, 15-20km thick. This age is still difficult to reconcile with the interpretation of a near-ridge event, if the ridge was fast (the 10 Ma old crust is 500 km away from the ridge for a 5 cm/yr half-spreading rate). Since a gravitational instability was not sufficient no initiate subduction in Oman, a tectonic event (a change in plate motions) should be responsible for choking the ridge and causing shortening.

<u>*Exercise*</u>

Calculate the average density of the oceanic lithosphere in function of its age. Assume a constant thickness of 5km and a density of 2.9 g/cm³ for the oceanic crust, a density of 3.3 g/cm³ for the mantle lithosphere and 3.25g/cm³ for the asthenosphere. Generate the resulting curve and comment on isostasy property of the oceanic lithosphere



Relationship between the age of the oceanic lithosphere and its buoyancy
after Cloos (1993) *Geol. Soc. Am. Bull.* **105(6)**, 715-737

These considerations lead to the following general conclusions concerning obduction:

(1) Ophiolites are only 0–10 Ma old oceanic lithospheres at the time of obduction.
(2) Mechanical considerations require maximum temperature about the decoupling zone to be no greater than 1000°C.

Thrusting of the oceanic lithosphere

Progressive thrusting and eventual emplacement of the ophiolites on to the continental rocks led to the development of a peripheral bulge and foreland basin. Thin-skinned tectonics dominates the entire northern Oman continental margin with a main basal detachment in the Pre-Permian basement.
High Pressure-Low Temperature (HP-LT) metamorphism in the basement and shelf deposits of the continental margin (Saih Hatat window) indicates subduction of the leading edge of the continental margin. This event is responsible for Fe/Mg-carpholite ± lawsonite-bearing rocks (0.6–1 GPa),

blueschists (1.2–1.5 GPa) and eclogites (ca. 2 GPa). Ar-Ar geochronology on white micas yields cooling ages (130-82 Ma) older than nappe emplacement (75-70 Ma).

Sedimentary record

The tectonic/sedimentary records of early obduction are:

* Accumulation of siliceous sediments and redeposited lithoclastic carbonates in a foredeep basin in the Turonian.

* Formation of a mélange in the NE (Batain). This is a tectonic formation, with indefinite, non-stratigraphic contacts and scanty matrix. It has been more or less gravity-driven sliding. Blocks of Permian and Triassic limestones are often associated with basalts.

These features are used in the following interpretation:

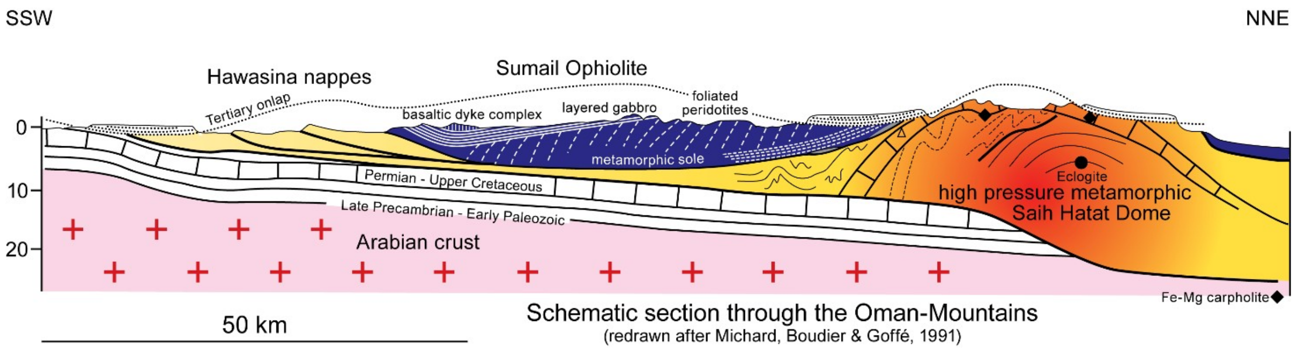
(1) Initial imbrication of deep-water successions far from the continental margin. That was foreland-directed, piggy-back thrusting with thrusts propagating into the footwall. The overall structure is simple and all the stratigraphic section preserved; therefore, restoration is possible.

(2) Mid-Late Cretaceous emplacement (Campanian)

Metamorphic record

The two-stage obduction history produced two distinct types of Cretaceous metamorphism:

1) High temperature at the base of the Sumail ophiolites;
2) High pressure (blueschist - eclogite facies) metamorphism in rocks of the Arabian continental margin that outcrop in the Saih Hatat tectonic window.

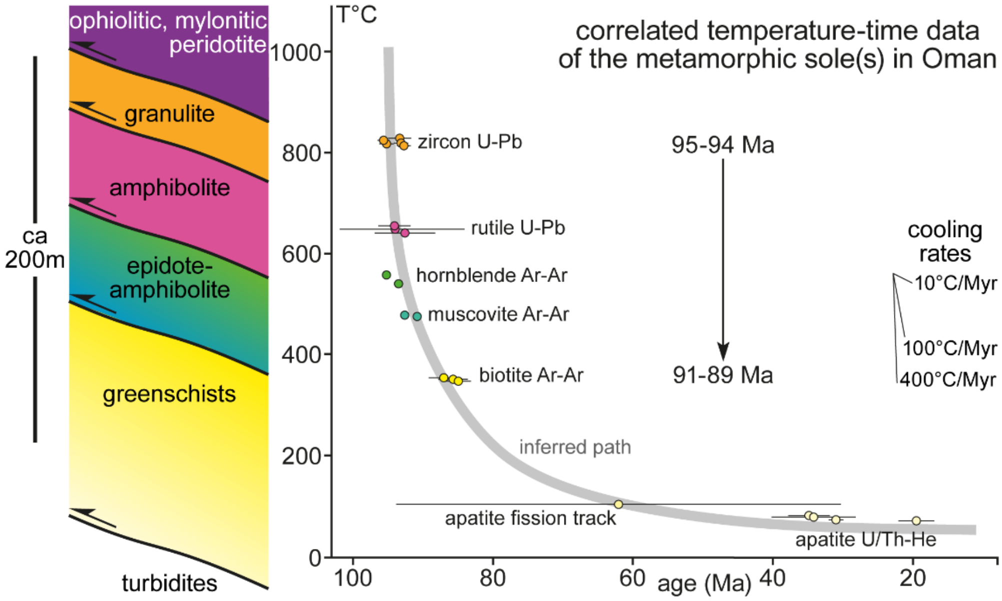


Schematic section through the Oman-Mountains
(redrawn after Michard, Boudier & Goffé, 1991)

High-Temperature metamorphic sole

Downward heat transfer from hot young oceanic lithosphere thrust over colder lithosphere produces high-temperature metamorphic soles. This interpretation explains inverted metamorphic field gradients, which in Oman are sharply decreasing downward from ca 1000°C mylonitic peridotite through superposed slices of granulite-, amphibolite- (T = 750-900°C and P = 0.5-1.4 GPa, i.e. 15 to 50 km depth) and greenschist-facies (T ~500°C) basic rocks onto very low grade (<100°C) material. The high-temperature metamorphic conditions of the partially molten granulite to upper amphibolite facies sole (< 500m thick) are consistent with ridge inversion and rapid thrusting of peridotites with sublithospheric temperatures. The steep thermal gradient may result from multiple thrust slices imbricating granulite and amphibolite facies rocks and accreting greenschist facies meta-sediments and lavas to the base of the amphibolites. The final, low-temperature emplacement involved at least 250 km of thrusting.

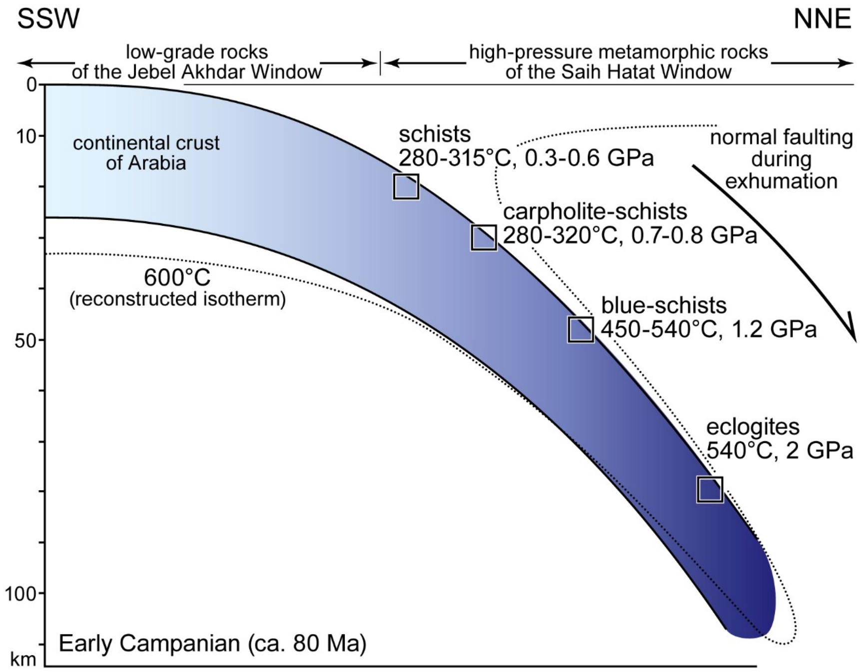
modified after Cowan *et al.* 2014 *Geol.Soc.London Spec.Pub.* **392** 155-175
and Roberts *et al.* 2016 *Geoscience Frontiers* **7(4)** 609-619



Ar-Ar age of hornblende and concordant zircons in leucosomes date cooling of the metamorphic sole at ca. 95 Ma. The same ages for the high-temperature metamorphism in the sole and ophiolitic trondhjemites further suggest intra-oceanic thrusting of very young oceanic lithosphere, i.e. near the ridge.

High-Pressure sequences

Both strain and metamorphic grade increase towards the northeast, with the successive appearance of pumpellyite, epidote and blue amphiboles in the autochthonous and par-autochthonous units. This bulk zonation is consistent with northeast-dipping subduction but exhibits two separate structural levels:



Reconstruction of the subducted arabian continental margin in Oman
(metamorphic data from Searle *et al.* 2004 *J. Struct. Geol.* **26(3)**, 451-473

1) The deepest structural levels, in a window within the Saih Hatat window, are represented by eclogitic mafic boudins that have recorded minimum pressures of 2 GPa. They indicate that the

northern margin of the Arabian continental crust was subducted to depths of more than 60 km. Glaucophane indicates that eclogites recrystallized at 1-1.2 GPa 500-580°C. U–Pb dating of zircons extracted from eclogites and Sm-Nd garnet-garnet leachate -- whole-rock isochrons constrain the age of peak metamorphism between 110 ± 11 and 79.1 ± 0.3 Ma. Ages older than the 95-Ma-old ophiolite indicate subduction-related metamorphism. Cooling ages (Ar-Ar and K-Ar methods) related to this metamorphism range between 90 and 70 Ma.

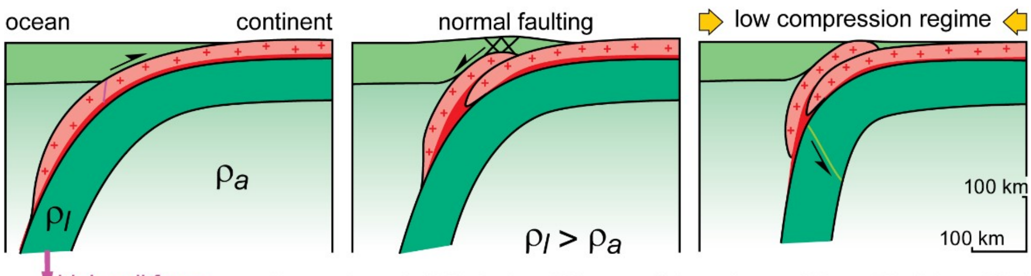
2) Higher structural levels, in the southern part of the Saih Hatat window and the northeastern Jebel Akhdar window, are high-pressure greenschist facies schists containing carpholite, lawsonite, and sodic amphibole. Carpholite-kaolinite assemblages were recrystallised at 180-250°C, 0.8-1 GPa and carpholite-pyrophyllite assemblages at 250-350°C, 0.6-0.8 GPa. The petrology is insufficient to reconstruct accurately the P-T path. Ar-Ar ages on micas from low-pressure fabric elements are about 80 Ma.

High-pressure rocks remained virtually undisturbed after reaching the surface as early as late Maastrichtian (before 65 Ma). The exhumation rate of blueschists and eclogites is estimated at 3 to 5 mm/yr.

Exhumation problem?

Structural studies demonstrated that partial exhumation of the high-pressure rocks occurred during northeastward shearing, while high-pressure metamorphism was still taking place. To explain this vergence, opposite to the regional stack of thrust units, the exhumation of the high-pressure rocks has been attributed to:

- Extension;
- Extensional collapse;
- Buoyancy during regional convergence.



Chemenda *et al.* 1996 *Earth and Planetary Science Letters* **143(1-4)** 173-182, modified

Kinematics and structures

As the Sumail Ophiolite was converging with Arabia, the continental margin approached the subduction zone and thin-skinned thrusts flaked the basin sediments onto the margin. The strain increases from the southwestern edge of Jebel Akhdar to the Saih Hatat window characterized by intense transposition foliation. Associated stretching directions are NNE-SSW and sense of shear criteria indicate south-southwestward thrusting. This deformation phase corresponds to the subduction of the Arabian continental margin.

Overprinting surge zones, extensional duplexes, and isoclinal folds are related to northeastward shearing. This opposite sense of shear is attributed to the exhumation of the subducted material.

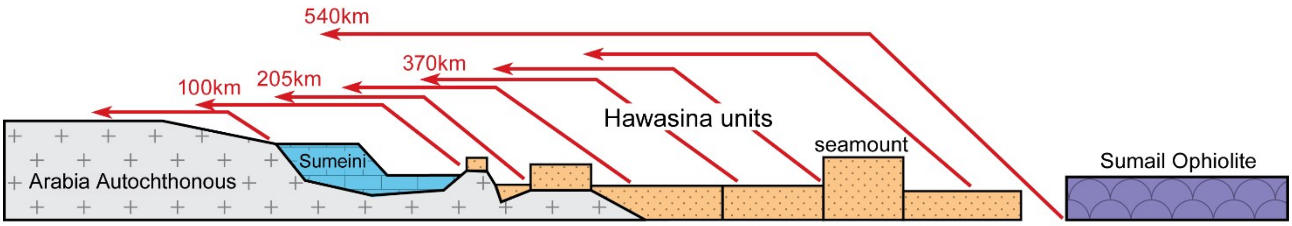
Thin-skinned tectonics

The Sumail Ophiolite formed an orogenic lid that acted, like the East-Alpine nappes in the Alps, as a "*traîneau écraseur*". Thrusting of the ophiolite involved piggyback emplacement of successively outboard thrust sheets including Permian–Mesozoic ocean floor and continental rise sediments (Hawasina sequence), which in turn overlie time equivalent Permian–Mesozoic slope and shelf facies carbonates (Sumeini and Haybi Groups).

The Hawasina, Sumeini and Haybi sequences represent sedimentary nappes separated from their original basement. The major sole thrust lies in pre-Permian rocks (as pre-Permian occurs within the culminations) and emerges to the S.

Hawasina nappes

A part of the Hawasina sequence was intensely deformed and metamorphosed below the ophiolite nappe. This part crops out in the Hawasina window and is analog to the sedimentary nappes in the Valais and Grisons regions of the Alps. The other part has been pushed towards the foreland by the Sumail Ophiolites and forms a typical fold-and-thrust belt in the Hamrat Duru Ranges, comparable to the pre-Alpine fold nappes in the Alps. Thrusting has first transported the youngest, Jurassic and Cretaceous sediments of the Hawasina Basin, which are tectonically overlain by the older, Triassic sequences. Typically, the sequences are repeated several times by thrusting and folding, a standard imbricate stack that usually comprises more distal units overlying ones that are more proximal.



Schematic representation of the thrust sheets in the Oman Mountains and their palinspatic position
km-numbers are horizontal amounts of transport from the original setting
adapted from Bechennec *et al.* 1990 *Geol. Soc. Spec. Pub.* **49**, 213-223

The major translation of Hawasina accretionary wedge took place in the Coniacian-Campanian (90-72 Ma). The structural growth of culminations marked this thrusting event. WSW propagating sole thrusts are emergent to the S and the stack displays a characteristic arcuate shape sub-parallel to the Oman Mountains. The full travel of the Hawasina sediments is estimated at around 400 km.

The first appearance of igneous detritus on the Arabian craton in the mid to Late Campanian (78-72 Ma) signals the end of the emplacement process. Restoration of the thrust sheets suggests that the ophiolite traveled 250-350 km over the basin, slope and shelf deposits and another 150 km over the continent after the ~95 Ma intraoceanic thrusting along the metamorphic sole and before the arrival of the ophiolite on the continent by ~75 Ma.

This equates with underthrusting-accretion beneath the Sumail Ophiolite with stacking of distal to proximal units.

Exercise

Since the obduction history spans ca. 27 Ma, calculate the average convergence rate of the Sumail ophiolite relative to the passive continental margin. Does it fit the plate tectonic data? ca 17 mm/year.

Northeast-directed shearing

The northern boundary of the Saih Hatat window exposes a major detachment surface that separates high-pressure blueschist facies rocks and eclogites from less metamorphosed rocks. Both sides of the detachment are derived from Permian sediments. A drastic metamorphic contrast (up to 0.6 GPa) occurs along this north-dipping and shallow-dipping normal shear zone. This metamorphic discontinuity implies a large displacement of the hanging wall whose intense fabric denotes noncoaxial, top-to-the-northeast shearing. The related exhumation rate of high-pressure rocks in the footwall of these shear zones is estimated at 3-5 mm/yr. between 80 and 70 Ma). Northeast-directed shearing is responsible for regional foliation and duplex-like imbrications in the Permian-Cretaceous platform sediments of the Jebel Akhdar region.

Gravity folds occur on both flanks of the domes, with relative movements towards both the south and the north. Extensional structures are attributed to gravity sliding on the flanks of the syn-obduction culminations. This culmination collapse varies in age.

Dome structures

Cenozoic deformation of the Oman Mountains has produced large antiforms eroded to form a series of box-shaped tectonic windows (from east to west: Saih Hatat, Jebel Akhdar, and Hawasina) that fold the ophiolitic nappe and the underlying basement. The domal culminations would be ramp-related anticlines that fold an earlier, pre-Permian foliation. Ramp anticlines would be contemporaneous with the emplacement of the ophiolite nappes. Alternatively, they may represent post-obduction frontal tip folds of Cenozoic age, possibly above blind thrusts affecting the basement.

Saih Hatat Window

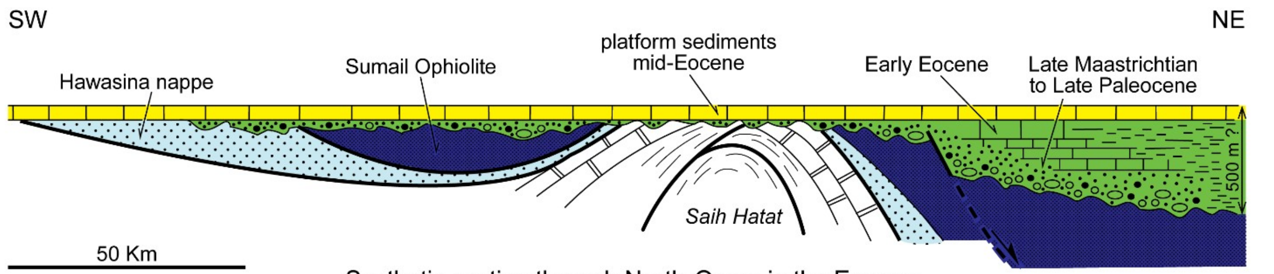
The Saih Hatat window represents the deepest exposed levels of the Oman Mountains. It contains a major, refolded, NE facing, recumbent, anticlinal fold-nappe within Pre-Ordovician sedimentary cover (autochthon) and Mesozoic platform carbonates. Deformation intensity and metamorphic grade increase towards the NE where eclogites occur as mafic boudins in the As Sifah sub-window, in the northeast part of the Saih Hatat Window. Rocks exhibit a consistent NE-SW trending stretching lineation.

Jebel Akhdar window

The Jebel Akhdar window exposes a very low- to low-grade, external zone of the Arabian shield with respect to the Saih Hatat window. The two major phases of ductile deformation accompanied by synmetamorphic, NE-SW trending stretching lineations found in pre-Permian rocks of this window may have formed during the same ductile events as in the Saih Hatat window.

Cenozoic tectonics

Maastrichtian shallow marine carbonate sedimentation resumed over the subsiding obduction structures. Carbonate sedimentation was nearly continuous until into the Oligocene, local angular unconformities suggesting minor block faulting attributed to differential uplift along the eroded mountain belt and sea-level fluctuations on a rather stable continental margin.



Synthetic section through North-Oman in the Eocene,
illustrating the relationships between the unconformable, shallow marine sediments and the obduction-related structures
after Carbon 1996 PhD Thesis, Montpellier

The uplift and present-day morphology of Oman Mountains is due to Oligocene foreland-directed thrusting and folding. Renewed compression reactivated Late Cretaceous thrusts, producing fault propagation folds parallel to the arcuate Oman Mountains. Related shortening seems to increase northward around the mountain arc with thin-skin tectonics caused by increasing proximity to the Cenozoic continent-continent (Arabia-Eurasia) collision zone in the Zagros Mountains.

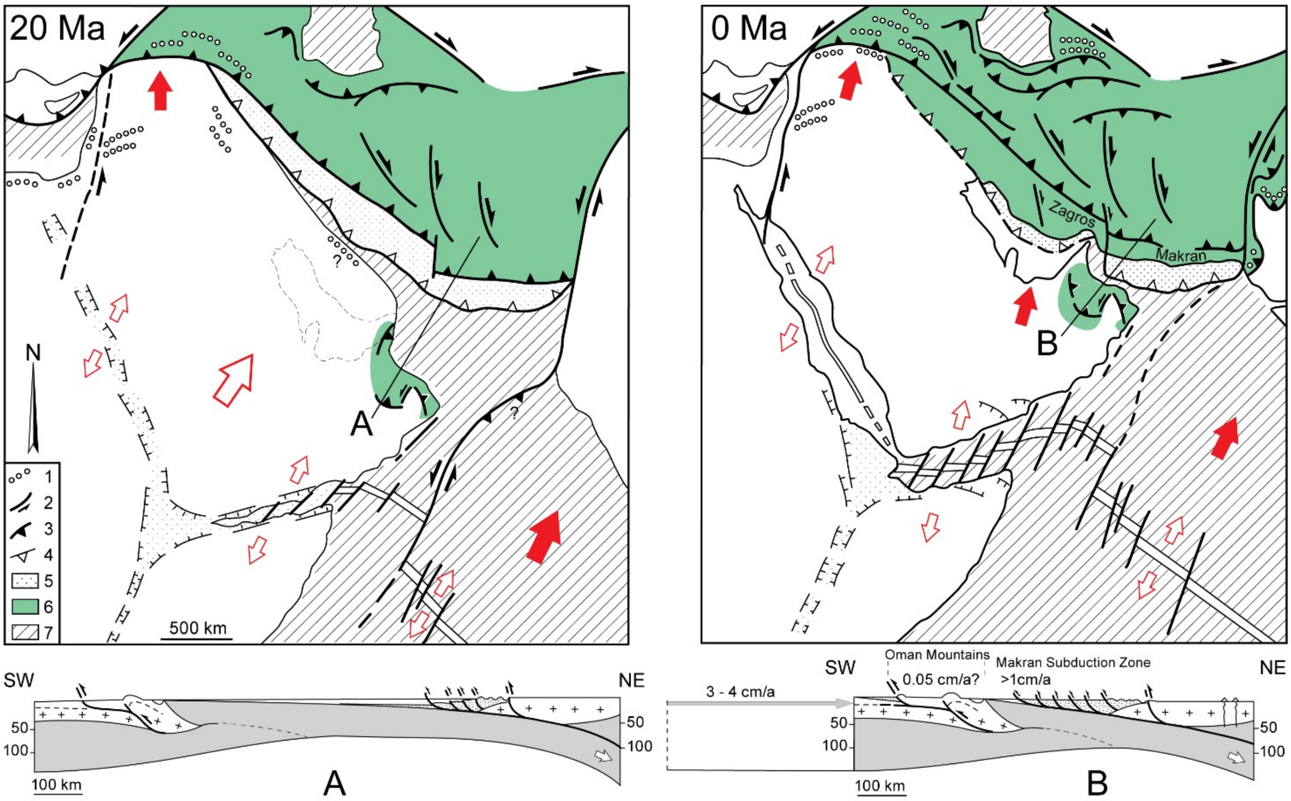
Fission track data suggest a post-obduction, two-stage cooling history: rapid at ca. 45–35Ma followed by slow cooling from 25 Ma to the present. The first stage may represent a distant, early phase of the Zagros collision, to the northwest in Iran; coeval erosional exhumation led to the deposition of a thick sedimentary succession in the foreland basin. The post 20 Ma event and contemporaneous fan conglomerates are tentatively linked to the main folding phase and subsequent erosion of the Zagros orogeny.

Mid-late Miocene is dominated by gravity tectonics.
Several levels of terraces and raised strandlines along the coast demonstrate recent uplift.

Platform deposition after thrust emplacement

A major unconformity with late Maastrichtian (68–65 Ma) rudist-bearing beach deposits overlies all allochthonous units, and in particular the obducted Sumail Ophiolites. This unconformity indicates that the Oman Mountains were emergent in the early Maastrichtian with evidence for erosion transgression, onlapping, fluviatile to shallow marine Maastrichtian.

Geodynamic context of the Arabian Plate in the Early Miocene (20 Ma) and Present (0 Ma).

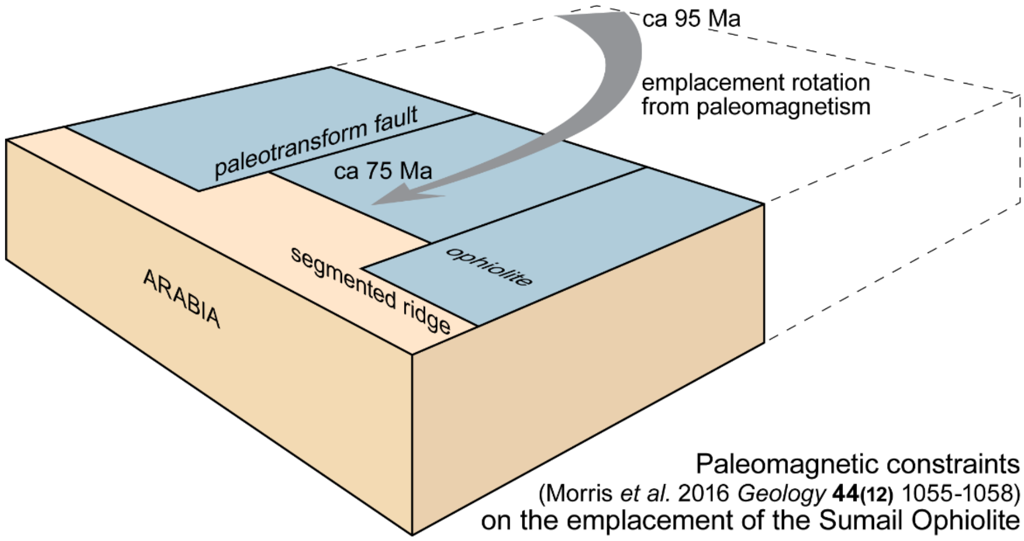


1- Folds, 2- Strike-slip faults, 3- Thrusts, 4- Front of the accretion wedge, 5- Sediments in accretionary and extensional areas, 6- high topography due to convergence, 7- oceanic domain

Shallow marine, fossiliferous carbonate sedimentation resumed along the northern flank of the mountains during the late Palaeocene to Middle–late Eocene (58–42Ma) while the northern Oman Mountains remained structurally high.
Stable, shallow marine carbonate sedimentation lasted 20–25 million years from middle Palaeocene to late Eocene, before regression. Oligocene marine carbonates deposited on both the northern and southern flanks of the mountains. This cover, shelf sequence has been folded in the Miocene, a deformation phase associated with the major uplift of the Oman Mountain. Gentle upright folds indicate minor amounts of shortening. Both N–S and E–W axes of Tertiary folds indicate a dome-and-basin-type interference pattern due to biaxial folding.
Tertiary (35-45 Ma) alkaline volcanic rocks occur along reactivated fault zones and indicate an intermediate extension period, possibly predating the Red Sea Rift.

Paleomagnetic data

Paleomagnetic data suggest a large clockwise rotation of the ophiolites during intraoceanic thrusting and obduction. Albian-Cenomanian metalliferous sediments interbedded with the ophiolitic volcanites define a well-dated paleo-horizontal. Low inclinations confirm that the Sumail Ophiolites formed and were thrust at equatorial latitudes.



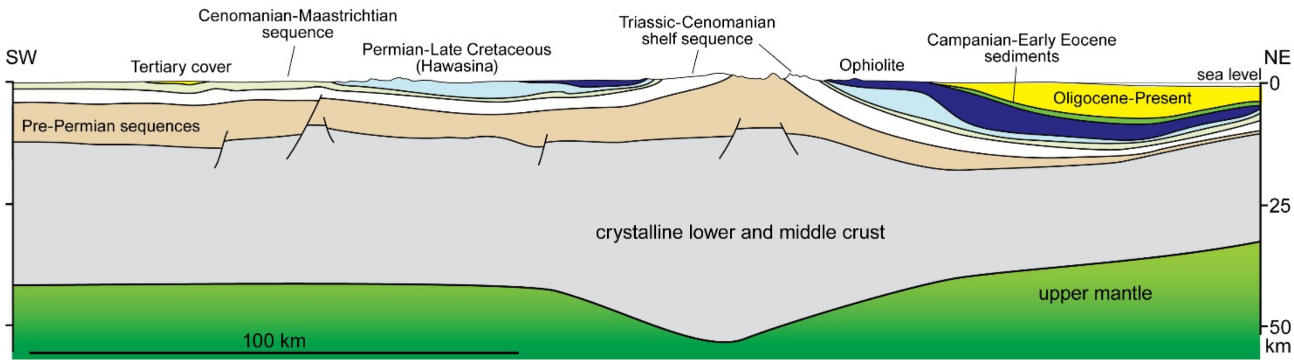
Paleomagnetic declinations vary from ENE-WSW to NW-SE directions. However, individual rotations of separated klippen are unlikely because dikes are nearly parallel and both declination directions may exist in the same klippe. Serpentinization and other hydrothermal processes have played an important role in these multiple phases of magnetization. Systematic sampling of continuous ophiolite sections indicates that ENE magnetizations at the top of the lower crust change downwards to NNW in foliated and layered gabbros. This reveals remagnetization from the base upwards, replacing early remanences in lower crustal gabbros but preserving original ENE magnetizations at higher levels.

Seismic information

Crustal-scale structure

Oil exploration seismic profiles and wells along with gravimetric data constrain well the structure of the upper 5 km of the crust. The depth and shape of the Moho are less constrained. Although limited, the information indicates a 60 km deep crustal root beneath the dome-shaped windows.

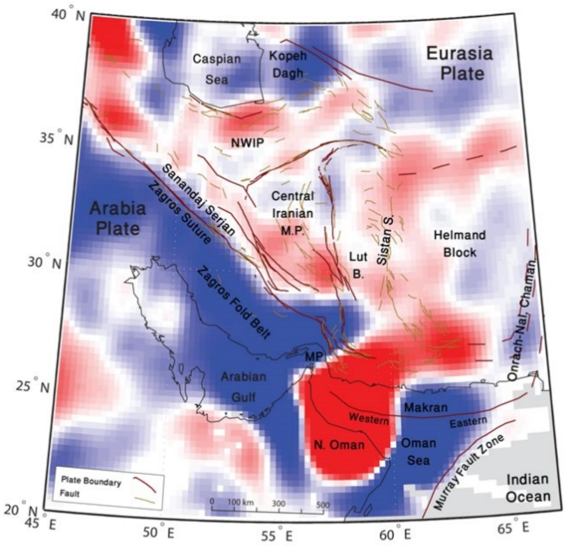
Crustal-scale profile after gravimetric and seismic data across the Oman Mountains
redrawn after Al-Lazki *et al.* 2002 *GeoArabia* **7(1)** 47-78



The foreland Arabian crust is 40-45 km thick, consistent with an old craton. Conversely, the depth to Moho decreases northward to less than 40 km beneath the coastal plain, which is consistent with the area representing the former passive margin. Further north, the Moho is 25-30 km deep below the Oman seafloor. The allochthonous interpretation of ophiolites is confirmed, with the main klippen being ca 1km thick to the south of the main tectonic windows whereas ophiolites are ca 5 km thick to the north.

Mantle

Tomography shows that Arabia has a cold lithospheric mantle, as expected beneath an old craton. On a larger scale, a hot lithospheric mantle underlies Eurasia, with the Arabia–Eurasia lithospheric suture approximately following the surface suture mapped in Zagros along the northeastern side of the Zagros Mountains. The lithospheric suture is offset at the Zagros-Makran boundary from where the Arabia lithosphere is inferred to extend northward beneath the Lut Block of Central Iran.



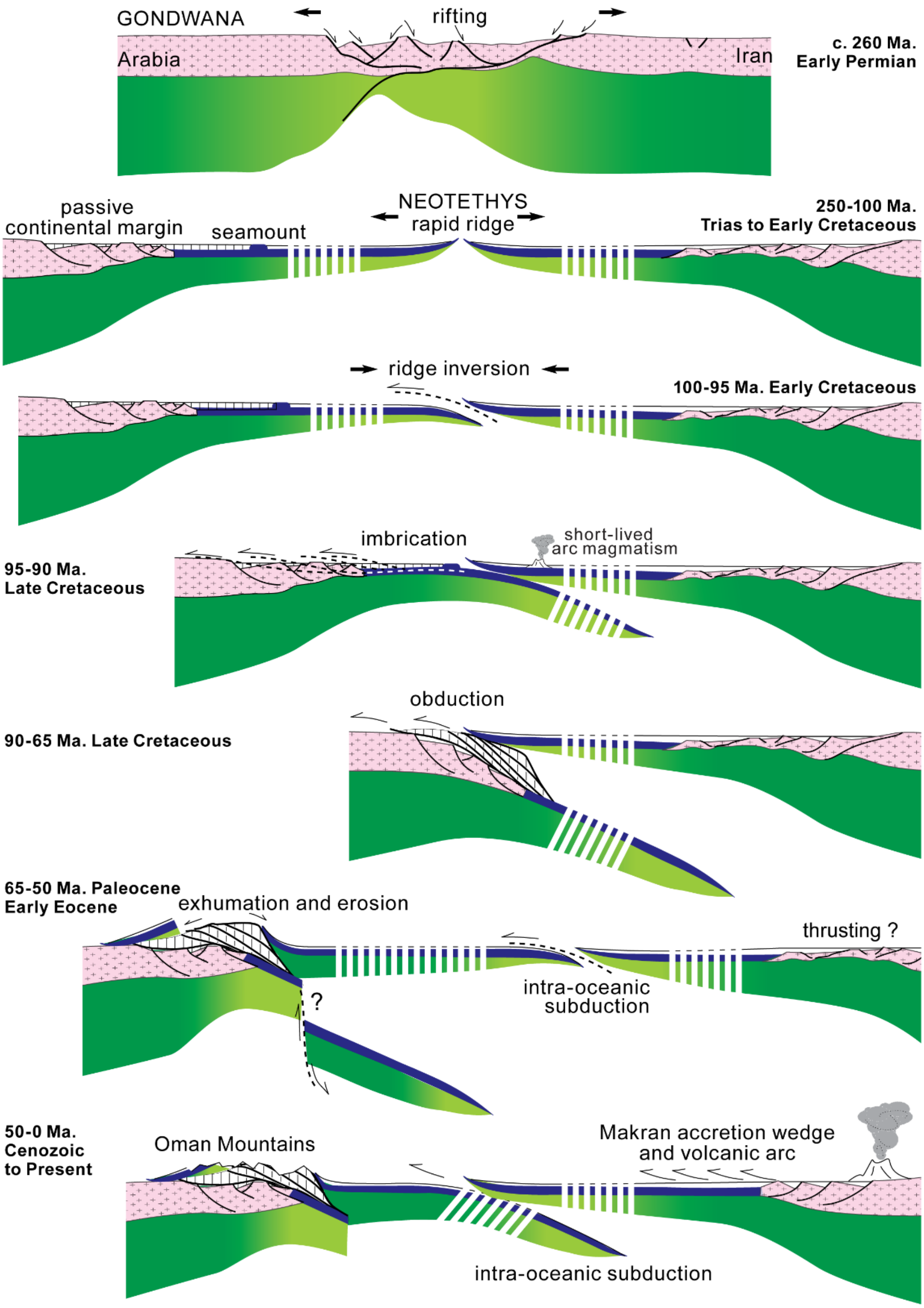
From Al-Lazki et al. 2014 *Geological Society, London, Special Publications*, **392**, 45–60

The high-velocity Arabian lithosphere has a sharp contact with a low-velocity region beneath western Makran, which in turn displays a sharp boundary with velocities beneath eastern Makran. This lithospheric-scale information suggests segmentation of the Oman subduction zone, but the seismic network is insufficiently dense to provide high-resolution pictures of the active system.

Conclusions – Tectonic evolution of the Oman Mountains

- Oman and Central Iran were together parts of Gondwana in Precambrian to Paleozoic times.
- An Uplift event in the Late Carboniferous is associated with abundant volcanism, which may be the earliest signs of rifting and separation of these two continental blocks.
- Mid- to Late Permian extension produced a large intracontinental basin on the northeast margin of the Arabian platform. Further rifting of the basin and crustal separation along the northern margin of Arabia led to the initiation of the Tethys Ocean in Middle to Late Triassic time. From Late Permian to mid-Cretaceous times Oman formed part of a large carbonate platform on the passive, southern continental margin of the Tethys Ocean in which sediments typified by the Hawasina deep-sea sequences were deposited.
- In Jurassic to Early Cretaceous, slow pelagic sedimentation was dominant.
- Intraoceanic subduction initiated at ca. 95 Ma near a dead oceanic ridge. This subduction starting age is remarkably consistent along the collision zone from Turkey to Oman. The late Cretaceous, north dipping and intra-oceanic subduction zone located to the north of the Arabian continent consumed the Tethys oceanic lithosphere. The sedimentary cover of Tethys built up an accretion wedge (Hawasina and mélange with exotic blocks) until the Late Campanian.
- As the Arabian plate moved progressively northwards, it entered into the subduction zone below a slice of the Tethys oceanic lithosphere. Obduction (i.e. subduction of the Arabian continental margin under the overriding oceanic plate) began at near 90 Ma; 200 to 600 km of the transient and continental lithosphere was subducted in this zone. The entire obduction and emplacement of the Sumail Ophiolites lasted about 27 million years from 95 to 68 Ma, during the Late-Cretaceous, while the average rate of ophiolite displacement was ca. 2cm/yr. During this time interval, the allochthonous

nappes were assembled from the intense imbrication of oceanic and slope sediments originally developed on the Oman continental margin with Tethys ocean floor.



- High-Pressure rocks were brought to the surface just after obduction (80-70 Ma).
- Continuing convergence created another subduction trench (proto Makran). The resulting crustal relaxation on the earlier subduction site permitted uplift of the half-buried Oman continental margin. The gravity-driven extension around basement structural culminations subsequently disrupted the ophiolitic thrust sheet further onto the Arabian shelf. The mechanisms of rapid exhumation during

plate convergence are a subject of discussion. The question is how normal faulting and associated rapid exhumation of high-pressure rocks combine with coeval thrusting and plate convergence.
By Maastrichtian time (70-65 Ma) all nappes had been partially eroded and transgressed by shallow-water carbonate rocks.
The Makran accretion wedge of Maastrichtian to Eocene age underlies an ophiolite hanging-wall due to post-Early Eocene and still active convergence between Eurasia and Arabia.
Late folds began their main development in the Pliocene (like in Zagros).
Continent/continent collision has not occurred between Oman/Makran.

QUESTIONS

Why did Obduction stopped and shifted northward in the Makran system?

How were deep rocks (blue-schist sequences) exhumed in a convergent system?

Recommended literature

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