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Eoalpine (Cretaceous) evolution of the Oman Tethyan continental margin: insights from a structural field study in Jabal Akhdar (Oman Mountains)

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ABSTRACT

A structural study in Jabal Akhdar (an autochthonous window in the Oman Mountains) shows that the thrusts and imbrications, mapped in the Permian-Cretaceous formations of the Arabian Platform, have a vergence top to the north-northeast and are associated with a regional cleavage resulting from a ductile shear deformation of the same vergence. This deformation affects the entire autochthonous unit, from the southwestern edge of Jabal Akhdar to the northeastern edge of Saih Hatat, with an increasing strain intensity towards the northeast. The same domain is also affected by a HP/LT metamorphism with a northeastward increase from chlorite facies to blueschist and eclogite facies, i.e. characteristic of a northeast-dipping subduction. However, the retrograde character of the metamorphic parageneses associated with the ductile shear, as well as its north-northeast vergence, indicate that this deformation is linked to the exhumation of the autochthon during the Campanian.

These observations have been synthesised in a new lithospheric-scale interpretation of the geodynamic development of the North Oman continental margins during the middle to late Cretaceous. The sequential evolution along a transect passing from southwest of Jabal Akhdar to northeast of Muscat can be summarised as follows:

An intra-continental subduction zone affected the autochthon of the Arabian Platform with a basal rupture lying in the proximal part of the continental margin, to the south of the northern edge of the carbonate platform. A North Muscat microplate was created between the intra-continental subduction zone and the intra-oceanic subduction that gave rise to the Samail Ophiolite; this microplate includes the outer part of the Arabian Platform, the continental slope and the entire Hawasina Basin.

From Early Turonian to Late Santonian the obduction and the intra-continental subduction were coeval and parallel. The northeast edge of the North Muscat microplate plunged below the Samail Nappe whilst the emergent southwest part overthrust the innermost parts of the Arabian Platform. The leading edge of the Samail and Hawasina Nappes advanced across the southwestern border of the North Muscat microplate just before obduction and intra-continental subduction ceased at the Santonian–Campanian boundary. Towards the end of the intra-continental subduction, the lower part of the crust of the subducted autochthon delaminated the upper part, marking the first stage of the metamorphic rocks exhumation.

From Early Campanian to Early Maastrichtian, the North Muscat microplate moved to the northeast, its northeastern edge sinking by gravity into the asthenosphere. The subducted autochthon rose up, and came into contact with the base of the obducted units. The resulting uplift of the ophiolite nappes produced its emergence and partial erosion. Local crustal thickening, related to the lithospheric delamination, caused doming at Saih Hatat and subsequent erosion that locally extended to the pre-Permian sedimentary basement during the Early Maastrichtian. The present day domal shape of Jabal Akhdar is however related to Tertiary tectonic events.

INTRODUCTION

Location and Geological Setting

The Sultanate of Oman is situated close to the northeastern margin of the Arabian Plate in a zone of convergence between the Arabian and Eurasian plates (Figure 1). The Arabian Plate is bounded (a) to the northeast by the Bitlis–Zagros collision zone and the Makran subduction zone, (b) to the northwest and southeast by the Levant and Owen strike-slip faults, respectively, and (c) to the southwest and south by the active spreading axes of the Red Sea and Gulf of Aden rifts. Convergence along the North Oman continental margin is accommodated by subduction of the Gulf of Oman oceanic lithosphere below the Makran accretionary prism and Eurasian continental lithosphere.

The northern Oman Mountains extend for 700 km from the Musandam Peninsula in the north to the Batain coast in the southeast (Figure 1). This arcuate mountain chain, whose width varies from 40 and 150 km, comprises three major structural units that, from the base up, are the so-called Autochthon, Allochthon and NeoAutochthon, respectively (Le Métour et al., 1995).

The autochthonous unit consists of:

- the crystalline basement, of Late Proterozoic age (Roger et al., 1991), which crops out mainly in the Jabal Ja'alan area, in the southeastern part of the mountain chain, and which is composed of igneous and metamorphic rocks on top of which is deposited the sedimentary succession;
- the lower sedimentary sequence (Autochthon A), of late-Proterozoic to Devonian age (Figure 2), which crops out mainly in Jabal Akhdar and Saih Hatat (Rabu, 1988; Le Métour, 1988) in the central part of the Oman Mountains (Figure 3), and locally in the southeastern and northern parts of the chain; and

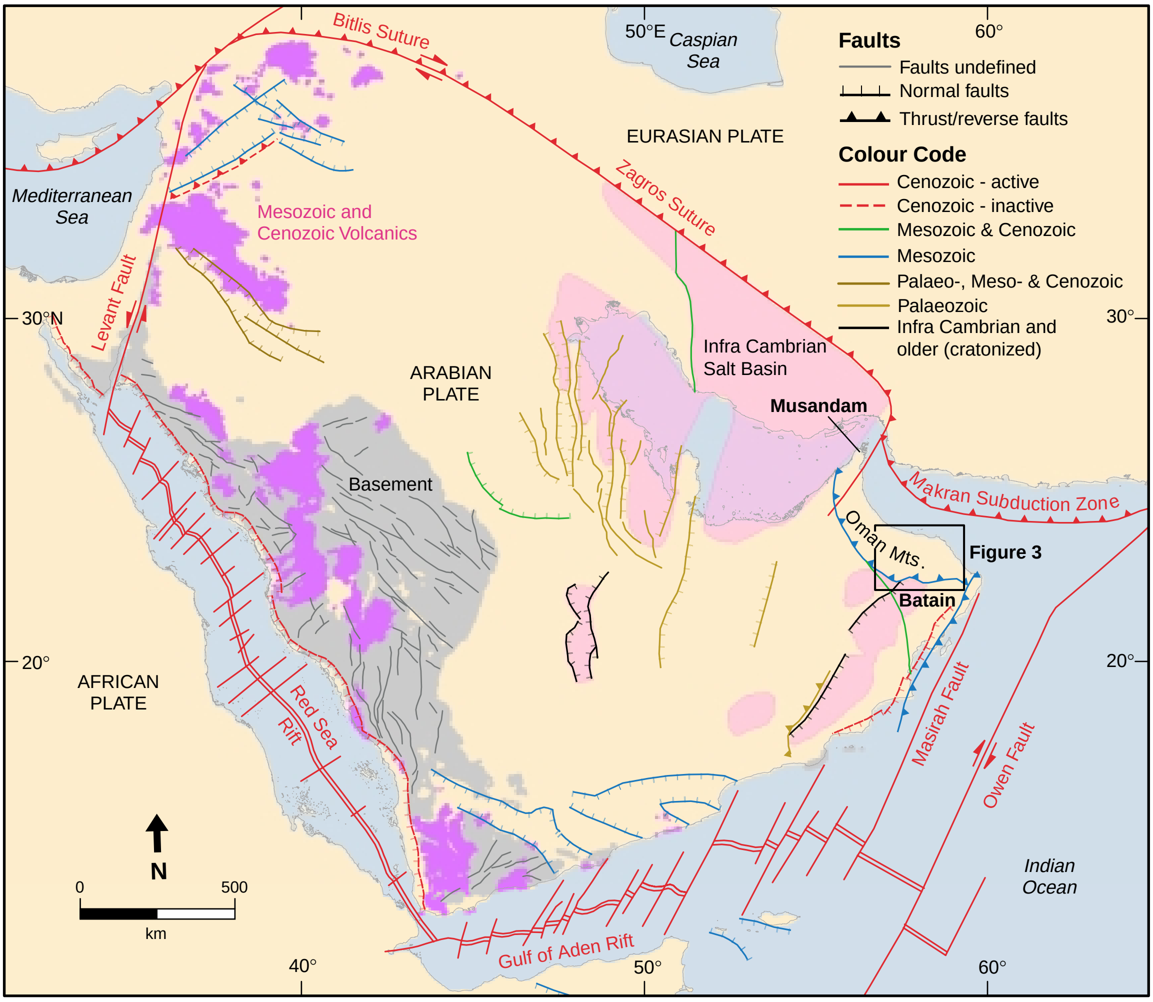


Figure 1: Simplified plate tectonic setting of the Arabian Plate with major techtonic elements. Map courtesy of GeoTech, MEGMaps-2 project.

- the Hajar Unit (Autochthon B), of Middle Permian to mid-Late Cretaceous age (Figure 2), which unconformably overlies the lower sedimentary sequence and mainly comprises shallow marine carbonates of the Arabian Platform. It crops out in the northern Musandam Peninsula (Ricateau and Riche, 1980), Jabal Akhdar and Saih Hatat (Rabu, 1988; Le Métour, 1988), in the central part of the Oman Mountains (Figure 3).

The allochthonous unit comprises several nappes that were obducted and stacked onto the Permian-Cretaceous Arabian Platform during the Late Cretaceous. Two main types of nappe are distinguished:

- the Sumeini and Hawasina nappes (Glennie et al., 1974; Béchennec, 1988), of Middle Permian to Late Cretaceous age, which are essentially made up of typical slope to basin sedimentary rocks with associated volcanic rocks (Figure 2), and which crop out all along the chain; and
- the overlying Samail Nappe, which represents relics of the Cretaceous Neotethyan oceanic lithosphere (Beurrier, 1988; Nicolas and Boudier, 1988).

The neoautochthonous unit unconformably overlies the other units (Figure 3) and represents a post-nappe sedimentary cover of Latest Cretaceous to Late Tertiary age (Glennie et al., 1974; Nolan et al., 1990 and Roger et al., 1991).

Previous Tectonic Work in Jabal Akhdar and Saih Hatat

In the Oman Mountains the hypothesis of allochthonous sequences, overthrust and stacked upon an autochthonous sequence, was first proposed by Lees (1928) and later confirmed by Allerman and Peters (1972) and Glennie et al. (1974).

The formation of the Jabal Akhdar anticline was attributed to Cretaceous-Tertiary uplift and a major orogenic deformation, in the core of the range, considered to be of Late Proterozoic age (Tschopp, 1967).

Glennie et al. (1974) and Glennie (1977) described NE-SW folds and thrust imbrications affecting the pre-Permian rocks of Jabal Akhdar and Saih Hatat with a deformation of increasing intensity towards the northeast . They also considered this deformation to be syn-metamorphic and Hercynian in age. This was further supported by Michard (1982). They also suggested that the present form of Jabal Akhdar and Saih Hatat resulted from Oligocene-Miocene uplift accompanied by gravity tectonism, rather than ophiolite obduction-related deformation.

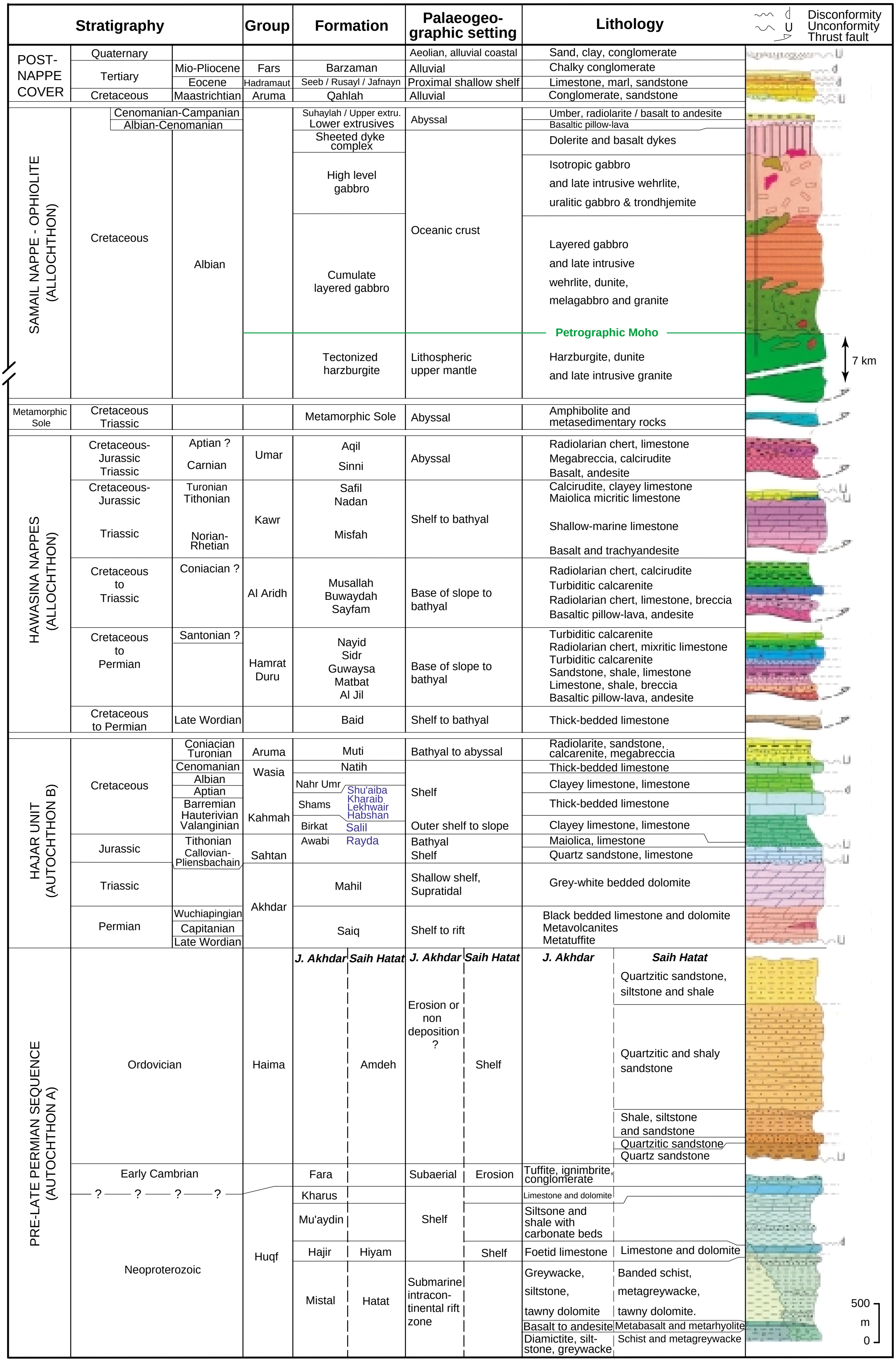
Lovelock et al. (1981), were finally able to confirm the age of the Amdeh Formation as Ordovician, suggesting a probable Hercynian age for the first phase of folding.

Within the Saih Hatat autochthon recumbent folds of multi-kilometre amplitude are associated with a pervasive cleavage and a greenschist to amphibolite facies metamorphism (Bailey, 1981).

Lippard (1983) reported the presence of garnetiferous glaucophanite near As Sifah, marking the imprint of the HP/LT metamorphism and Michard et al. (1983) introduced the concept of ''Muscat metamorphic nappes" with blueschist-facies metamorphism.

In the course of the 1:100,000-scale mapping of the Oman Mountains, carried out by BRGM, Rabu (1988) and Le Métour (1988) gave the first detailed stratigraphic, palaeontological and structural study of the Jabal Akhdar and Saih Hatat autochthonous windows. Their most striking conclusions can be summarised as follows:

- regional foliations and cleavages affect the entire autochthonous series A and B up to the Muti Formation and therefore are post-Coniacian in age;
- pre-Permian units are affected by a deformation prior to the regional cleavage , without associated metamorphism;
- the intensity of metamorphism and deformation decreases from northeast to southwest and disappears at the southern border of Jabal Akhdar. This is interpreted as the result of a northeastward subduction of the autochthon;


Stratigraphy
Group
Formation
Palaeogeo-graphic setting
Lithology
Disconformity
Unconformity
Thrust fault
POST-NAPPE COVER
Quaternary
Aeolian, alluvial coastal
Sand, clay, conglomerate
Tertiary
Mio-Pliocene
Fars
Barzaman
Alluvial
Chalky conglomerate
Eocene
Hadramaut
Seeb / Rusayl / Jafnayn
Proximal shallow shelf
Limestone, marl, sandstone
Cretaceous
Maastrichtian
Aruma
Qahlah
Alluvial
Conglomerate, sandstone
SAMAIL NAPPE - OPHIOLITE (ALLOCHTHON)
Cenomanian-Campanian
Albian-Cenomanian
Suhaylah / Upper extru.
Lower extrusives
Abyssal
Umber, radiolarite / basalt to andesite
Basaltic pillow-lava
Sheeted dyke complex
Dolerite and basalt dykes
Cretaceous
Albian
High level gabbro
Isotropic gabbro
and late intrusive wehrlite,
uralitic gabbro & trondhjemite
Oceanic crust
Cumulate layered gabbro
Layered gabbro
and late intrusive
wehrlite, dunite,
melagabbro and granite
Petrographic Moho
Tectonized harzburgite
Lithospheric upper mantle
Harzburgite, dunite
and late intrusive granite
7 km
Metamorphic Sole
Cretaceous Triassic
Metamorphic Sole
Abyssal
Amphibolite and metasedimentary rocks
HAWASINA NAPPES (ALLOCHTHON)
Cretaceous-Jurassic Triassic
Aptian ?
Carnian
Umar
Aqil
Sinni
Abyssal
Radiolarian chert, limestone
Megabreccia, calcirudite
Basalt, andesite
Cretaceous-Jurassic
Turonian Tithonian
Kawr
Safil
Nadan
Shelf to bathyal
Calcirudite, clayey limestone
Maiolica micritic limestone
Triassic
Norian-Rhetian
Misfah
Shallow-marine limestone
Basalt and trachyandesite
Cretaceous to Triassic
Coniacian ?
Al Aridh
Musallah
Buwaydah
Sayfam
Base of slope to bathyal
Radiolarian chert, calcirudite
Turbiditic calcarenite
Radiolarian chert, limestone, breccia
Basaltic pillow-lava, andesite
Cretaceous to Permian
Santonian ?
Hamrat Duru
Nayid
Sidr
Guwaysa
Matbat
Al Jil
Base of slope to bathyal
Turbiditic calcarenite
Radiolarian chert, mixritic limestone
Turbiditic calcarenite
Sandstone, shale, limestone
Limestone, shale, breccia
Basaltic pillow-lava, andesite
Cretaceous to Permian
Late Wordian
Baid
Shelf to bathyal
Thick-bedded limestone
HAJAR UNIT (AUTOCHTHON B)
Cretaceous
Coniacian Turonian
Aruma
Muti
Bathyal to abyssal
Radiolarite, sandstone, calcarenite, megabreccia
Cenomanian
Wasia
Natih
Thick-bedded limestone
Albian
Aptian
Nahr Umr
Shu'aiba
Shelf
Clayey limestone, limestone
Barremian
Hauterivian
Valanginian
Kahmah
Shams
Kharaib
Lekhwair
Habshan
Thick-bedded limestone
Birkat
Salil
Outer shelf to slope
Clayey limestone, limestone
Jurassic
Tithonian
Callovian-Pliensbachian
Sahtan
Awabi
Rayda
Bathyal
Shelf
Maiolica, limestone
Quartz sandstone, limestone
Triassic
Akhdar
Mahil
Shallow shelf, Supratidal
Grey-white bedded dolomite
Permian
Wuchiapingian
Capitanian
Late Wordian
Saiq
Shelf to rift
Black bedded limestone and dolomite
Metavolcanites
Metatuffite
PRE-LATE PERMIAN SEQUENCE (AUTOCHTHON A)
J. Akhdar
Saih Hatat
J. Akhdar
Saih Hatat
J. Akhdar
Saih Hatat
Ordovician
Haima
Amdeh
Erosion or non deposition ?
Shelf
Quartzitic sandstone, siltstone and shale
Quartzitic and shaly sandstone
Shale, siltstone and sandstone
Quartzitic sandstone
Quartz sandstone
Early Cambrian
Fara
Subaerial
Erosion
Tuffite, ignimbrite, conglomerate
? ? ? ?
Kharus
Limestone and dolomite
Neoproterozoic
Huqf
Mu'aydin
Shelf
Siltsone and shale with carbonate beds
Hajir
Hiyam
Shelf
Foetid limestone
Limestone and dolomite
Mistal
Hatat
Submarine intracon-tinental rift zone
Greywacke,
siltstone,
tawny dolomite
Banded schist,
metagreywacke,
tawny dolomite.
Basalt to andesite
Metabasalt and metarhyolite
Diamictite, silt-stone, greywacke
Schist and metagreywacke
500
m
0

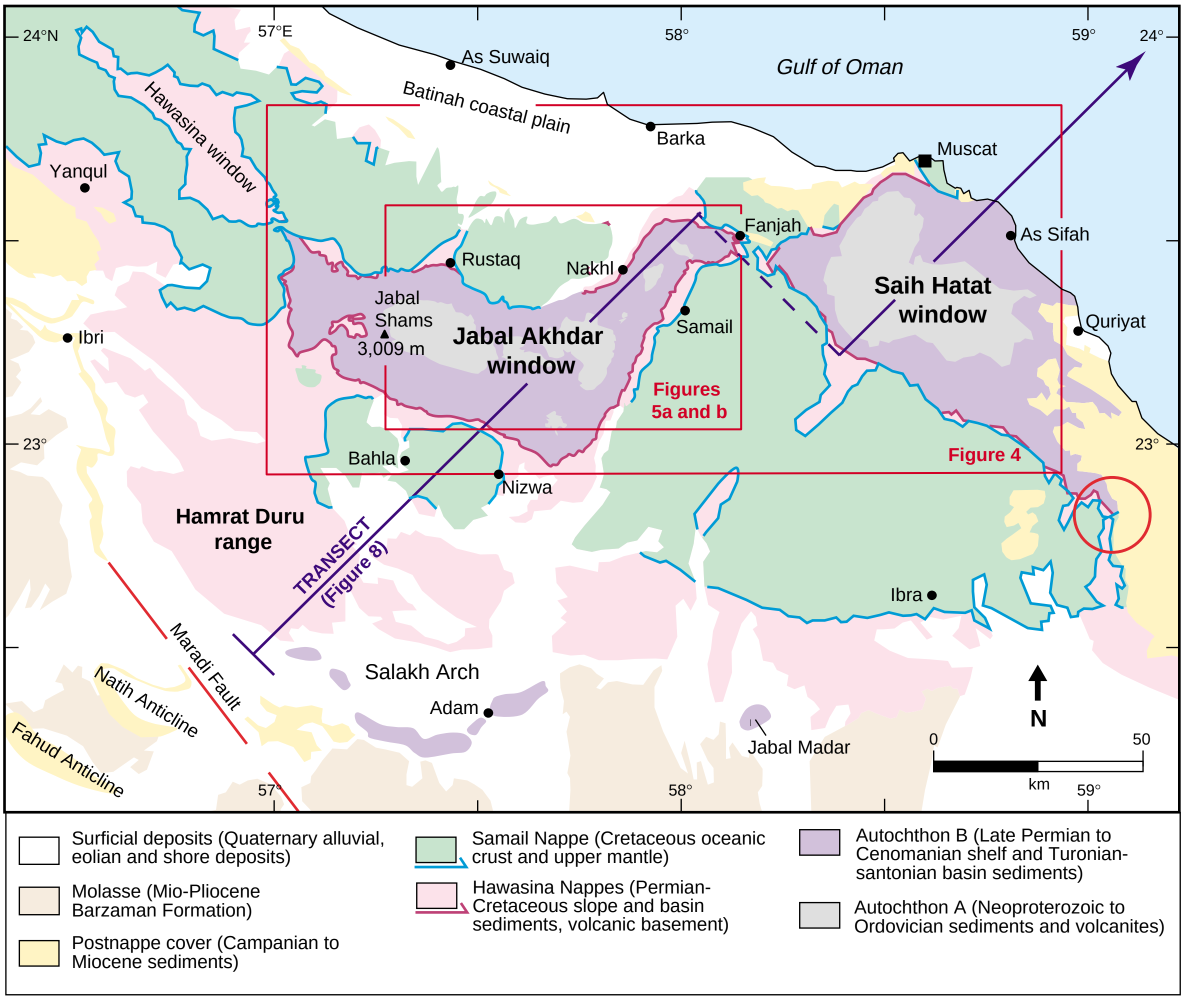


Figure 3: Geological setting of Jabal Akhdar and Saih Hatat (see Figure 1 for location); from the Geological Map of Oman, scale 1:1,000,000 (Le Métour et al. 1993). The red circle, south of Quriyat, shows the unconformable contact between the base of the postnappe cover and the underlying thrusts.

- the cleavage/bedding obliquity is constant throughout Jabal Akhdar and the external zone of Saih Hatat. The shear criteria associated with the cleavage indicate a sense of shear top to the north-northeast for this phase of deformation, as well as for the multiphase deformation in the internal zone of Saih Hatat; and
- the doming of Jabal Akhdar was post-cleavage and multiphase.

Mann and Hanna (1990) attributed the pre-Permian folds and imbrications in Jabal Akhdar to a Late Paleozoic ductile deformation event associated with the cleavage. Hanna (1990) argued that general south-westerly thrusting of the autochthon was responsible for the doming of the range as a flat-topped ramp anticline, synchronous with the emplacement of the Samail-Hawasina nappes above. It must be noted that according to this model, the whole autochthon of the North Oman Mountains would therefore be considered para-autochthonous.

Coffield (1990) interpreted the décollement surfaces and associated cleavage and folds, observed in the autochthon of the northeastern end of Jabal Akhdar and of the western end of Saih Hatat, as a syn-obduction deformation that had been reactivated by gravity collapse on the flanks of a culmination formed during the Campanian.

Figure 2 (left): Lithostratigraphic column of the Jabal Akhdar - Saih Hatat area; from the Geological Map of Seeb, scale 1:250,000 (Béchennec et al., 1992). The subsurface formation names of the Kahmah Group (Hughes-Clarke, 1988) are written in blue.

On the basis of laboratory scale experiments, Chemenda et al. (1996) interpreted the structure of the Saih Hatat dome as a result of: (a) the detachment of the continental subducted crust from its mantle counterpart, and (b) its buoyancy driven uplift into the interplate zone under a compressional regime of low intensity.

Mount et al. (1998) suggested that the doming of Jabal Akhdar and Saih Hatat represented frontal tip folds related to blind reverse basement faults. They argued that these dipped steeply towards the north-northeast along the southern dome flanks, rooting into a deep décollement to the north. Using apatite fission tracks data, they dated compression and the resulting fast uplift as Oligocene.

In the internal zone of Saih Hatat, Miller (1998), Miller et al. (1998, 1999, 2002) presented evidence for a regional ductile thrust zone with a top to the north-northeast sense of shear. This shear zone separates two main units the so-called upper and lower slab. They attributed the syn-schistose deformation, associated to retrograde metamorphism, to the exhumation of the subducted autochthon.

Finally a SSW-NNE seismically-constrained crustal transect by Al-Lazki et al. (2002) crossing the Jabal Akhdar range from Fahud to the coastal plain provided a more precise view of the different crustal units. This demonstrated that there was no major repetition within the autochthon, but did suggest the presence of a crustal root beneath Jabal Akhdar.

STRUCTURAL FEATURES

Structural and Metamorphic Zoning of the Autochthon

The entire sedimentary sequence making up the Jabal Akhdar and Saih Hatat autochthonous windows is affected by a top to the NNE shear deformation characterised by a steep structural and metamorphic gradient (Le Métour, 1988) (Figure 4).

External zone

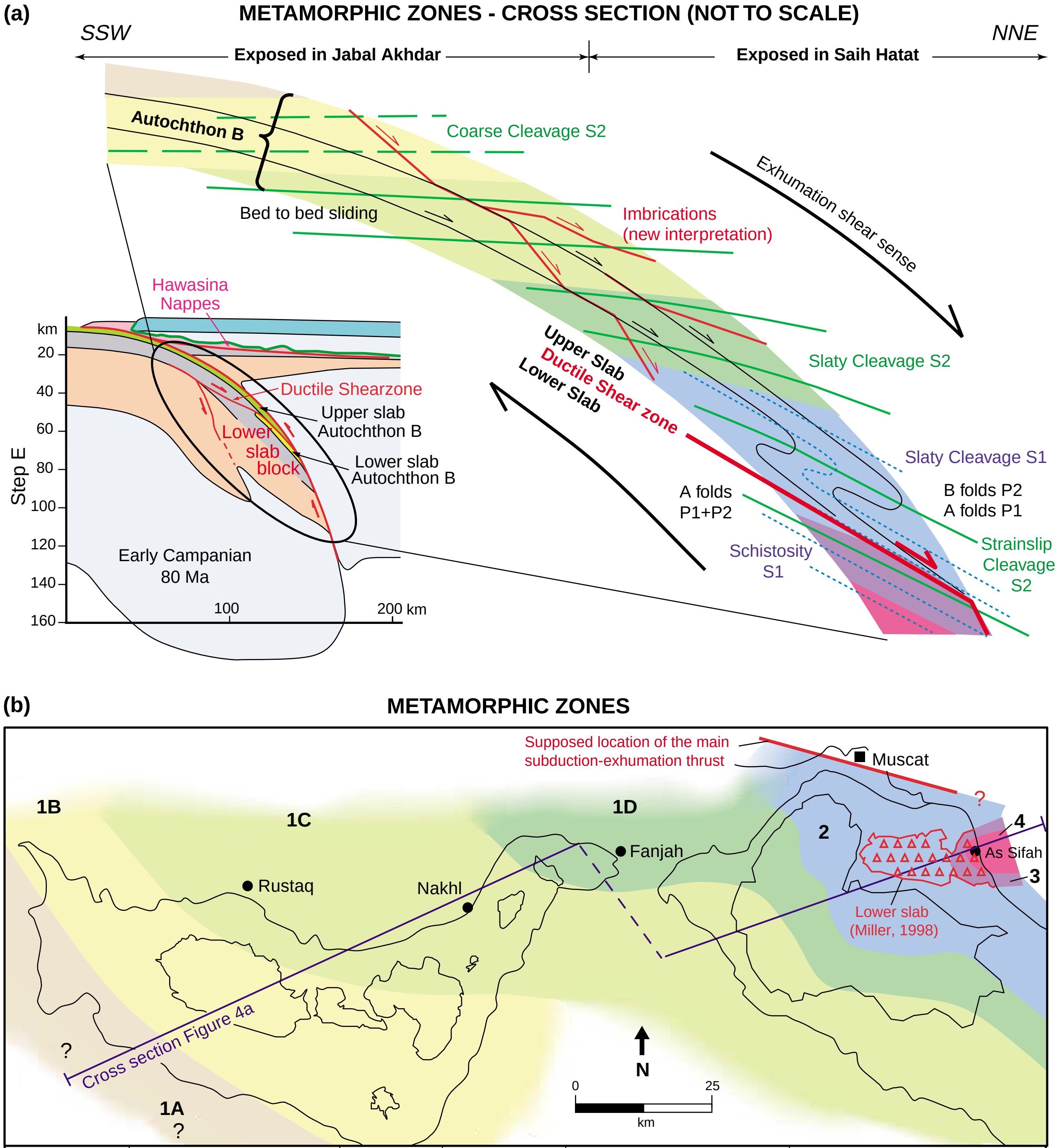
At the southwestern edge of Jabal Akhdar (Zone 1A, Figure 4) the deformation is very weak and marked only by a coarse pressure-solution cleavage restricted to the less competent beds within the Nahr Umr Formation.

To the northeast (Zone 1B, Figure 4), the fracture cleavage becomes more regular within the incompetent lithologies, while interbedded limestone displays incipient boudinage. A NNE-stretching lineation appears, marked by the deformation of fossils and elongation of pressure shadows (Rabu, 1988). Folds and shear bands are rare in this domain (Figures 5a and b).

Over the entire northern flank of Jabal Akhdar (Zone 1C, Figure 4), the cleavage becomes progressively penetrative within the incompetent lithologies and refracts in the limestone interbeds. Stress-related recrystallisation of the rocks becomes important and the stretching lineation is marked by fibres of quartz and calcite and by the alignment of chlorite and newly-formed white mica (Rabu et al., 1993). Bedding parallel shear (C type shear bands) becomes pervasive in the bedded limestone layers (Figure 6) and large scale shear planes (imbrications of Rabu, 1988) develop at the boundaries of more massive units with general flat-ramp-flat type structures, leading to local thickening and superposition rather than local thinning or disappearance of involved layers. Friction along ramps gave birth to duplexes in which the stacking direction of the horses (Figure 7) indicates a general sense of shear top to the north-northeast (Figure 5b). In the Nakhl anticline (northeastern part of Jabal Akhdar) and the southern edge of Saih Hatat, the north-northeast stretching becomes intense and the axes of recumbent folds become parallel to the lineation (Figure 5a).

At the northeastern end of Jabal Akhdar and in the central zone of Saih Hatat (Zone 1D, Figure 4), the metamorphism increases with the appearance of pumpellyite and epidote, locally associated with rare blue amphibole (Le Métour et al., 1990).

In summary, the regional ductile deformation forms a coherent system throughout the external zone that corresponds to a flat lying shear deformation with a top to the north-northeast sense of shear (Figure 4).



Zone		Metamorphic facies	Pressure	Temperature	Cleavage		Structures
EXTERNAL	1A	Upper Anchizone	2 to 4 kb	< 200°C	One cleavage	Coarse pressure-solution	Rare imbrications and B folds (axis ⊥ to stretching lineation)
	1B	Upper Anchizone	2 to 4 kb	< 200°C	One cleavage	Regular pressure-solution	Rare imbrications and B folds (axis ⊥ to stretching lineation)
	1C	Deep Anchizone	2 to 4 kb	< 200°C	One cleavage	Penetrative pressure-solution to slaty	Bedding slip, imbrications, B (axis ⊥ to stretching lineation), to A (axis // to stretching lineation) recumbent folds
	1C, 1D	Pumpellyite/lawsonite - albite - chlorite	4 to 7 kb	200 to 300°C	One cleavage	Composite, slaty to schistosity S1-2	Bedding slip, imbrications, B (axis ⊥ to stretching lineation), to A (axis // to stretching lineation) recumbent folds
INTERNAL	2	Glaucophane blueschist	6 to 10 kb	250 to 435°C	Several cleavages	Strain-slip S2 Schistosity S1	Regional recumbent B folds P2, A folds P1, imbrications
	3	Glaucophane - almandine blueschist	6 to 15 kb	380 to 500°C	Several cleavages	Strain-slip S2 Schistosity S1	Large recumbent A folds P1 and P2 (axis // to stretching lineation)
	4	Glaucophane eclogite	15 to 20 kb	500 to 580°C	Several cleavages	Strain-slip S2 Schistosity S1	Large recumbent A folds P1 and P2 (axis // to stretching lineation)

Figure 4a and b: Metamorphic and tectonic evolution of the Autochthon from SW of Jabal Akhdar to NE of Saih Hatat ; modified from Rabu (1988), Le Métour (1988), El-Shazly and Coleman (1990), Le Métour et al. (1990, 1995), Rabu et al. (1993), Wendt et al. (1993), Miller (1998) and Miller et al. (1998, 1999, 2002). See Figure 3 for location.

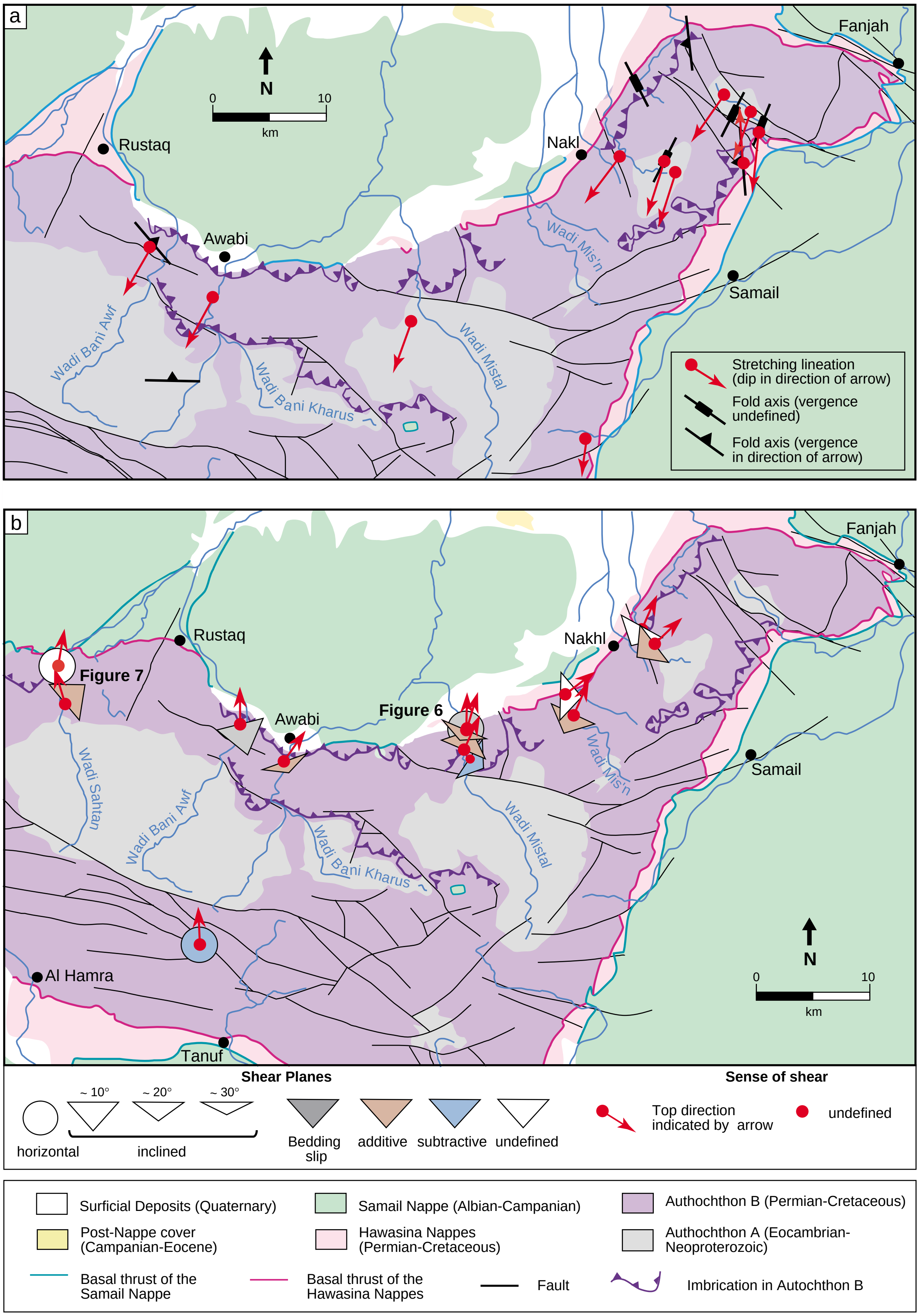


Figure 5: (a) Relationship between the stretching lineations and the fold axes in the NE part of Jabal Akhdar (rotated attitudes by returning the local S0 to horizontal). (b) Sense of shear of the imbrications in Jabal Akhdar (rotated attitudes by returning the local S0 to horizontal). Figures 5a and b from the Geological map of Seeb, scale 1:250,000 (Béchennec et al., 1992). See Figure 3 for location.

Internal zone

The internal zone encompassing the north-eastern part of the Saih Hatat area, is marked by a very significant increase in both metamorphic facies and intensity of tectonic deformation (Le Métour, 1988). Crossite blueschist facies is observed in the outerpart (Zone 2, Figure 4), passing to almandine blueschist facies towards As Sifah on the coast (Zone 3, Figure 4), and finally glaucophane eclogite facies (Zone 4, Figure 4) in the immediate vicinity of As Sifah. The structure of the internal zone results from two major phases of ductile deformation, each with similar sense of shear to the north-northeast and strong associated stretching in the same direction (Le Métour, 1988; Miller, 1998). A regional ductile shear zone with a top vergence to the north-northeast, duplicating the Saiq Formation (Miller et al., 1998) separates an upper slab from a lower slab (Figure 4). The first cleavage S1 (slaty cleavage in the southwestern part of the internal zone becoming a foliation in the northeastern part), is parallel to the axial plane of large scale similar recumbent folds (with axes parallel to the stretching lineation), observed in the lower slab and at the base of the upper slab close to the shear zone. The second cleavage S2, that is of strain-slip type, is parallel to the axial plane of large multi-kilometre scale recumbent cylindrical folds (Figure 4), the axes of which are oblique to perpendicular to the stretching lineation. These folds, observed in the upper slab evolve to similar recumbent folds, with axes parallel to the stretching lineation, in the vicinity of the shear zone and in the lower slab where they refold the P1 folds.

Tectonic Interpretation

Subduction and exhumation of the autochthon

Increasing intensity of metamorphism and orientation of the HP/LT facies zones (Figure 4) appears to reflect the increasing burial of the autochthon towards the northeast in a manner characteristic of a subduction zone (Le Métour et al. 1990). The As Sifah metabasic rocks are interpreted to have been eclogised at depths ranging between 40 and 70 km by various authors (Le Métour, 1988; El-Shazly and Coleman, 1990; Wendt et al., 1993). The ductile deformation, whose sense of shear is consistently top to the north-northeast and parallel to the stretching lineation, decreases in intensity towards the south-west as does the metamorphism. However this regional scale vergence is opposite to the sense of shear that would result from the descending movement of a subducted unit. The observed kinematics are compatible with an exhumation of the autochthon. This finds support in the retrograde metamorphic character of the syn-cleavage paragenesis. The only evidence of the subduction phase itself appears to be south-southwest top verging microfolds, whose axial plane foliation is associated with a prograde paragenesis in the eclogite (Miller, 1998). According to Miller (1998), the foliation fabrics of zones 3 and 4, outside the eclogite, show a paragenesis with a post-eclogite character (garnet ghosts). Within Zone 2, the mineral parageneses defining the S1 foliation, in the axial plane of the folds, with relics of sodic amphibole in the epidote crystals, provides further evidence of retrograde metamorphism (Miller et al., 1999). Moreover, the mineral paragenesis defining the S2 strain slip cleavage, in the axial plane of the regional recumbent folds, characterises a further stage of retrograde metamorphism in the greenschist facies with sodic amphibole relics within the albite crystals (Le Métour, 1988).

The two-phase character of the deformation in the internal zone reflects two stages of exhumation. The first stage, during which syn-S1 foliation developed, reflects the movement of the lower slab (Miller et al., 1998) and only affected the internal zone. It corresponds to the onset of exhumation of the deepest part of the subducted autochthon along the ductile shear zone separating the upper and lower slabs (Figure 8, Step E). The second stage corresponds to the total exhumation of the autochthon, with deformation affecting both internal and external zones (Figure 8, Steps F and G). In this new interpretation (adapted from Miller et al., 2002) incorporating Jabal Akhdar and Saih Hatat, we suggest that the single regional cleavage of the external zone (S1 of Le Métour, 1988 and Rabu, 1988) would correspond to the S2 strain-slip cleavage of the internal zone.

EOALPINE GEODYNAMIC EVOLUTION OF THE OMANI TETHYAN CONTINENTAL MARGIN

Our revised interpretation of the late Cretaceous evolution of the Oman continental margin is illustrated by a sequence of seven sections at lithospheric scale along a same transect (Figure 8) drawn for 5 Ma time intervals from the Late Albian (100 Ma) to the Early Maastrichtian (70 Ma). The transect (Figure 3) is oriented

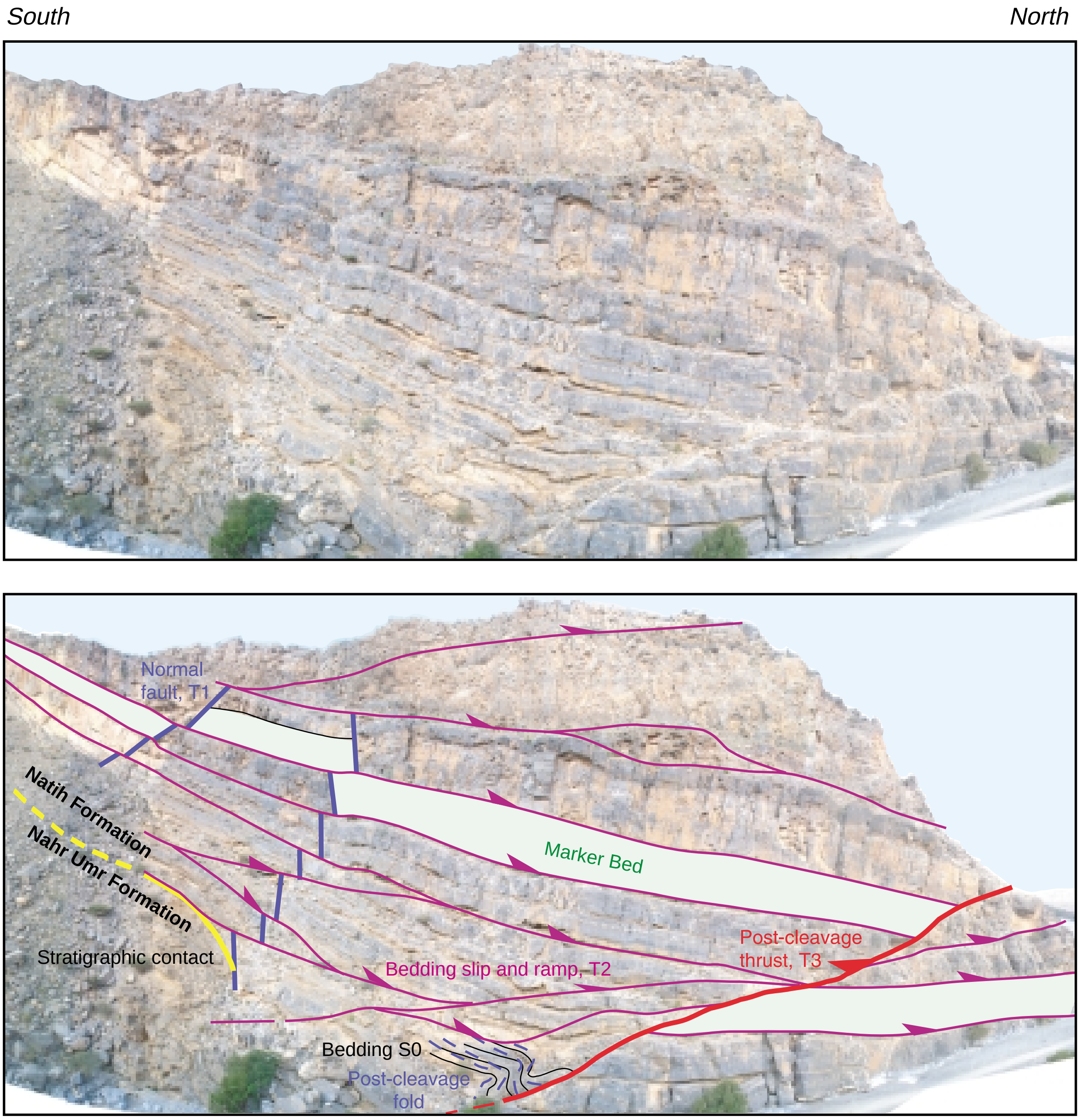


Figure 6: Chronological relationships between normal faults [T1] truncated by bedding parallel slips and associated ramps [T2] truncated by a post-cleavage thrust [T3] (left bank of Wadi Mistal). View due east, the cliff is about 150 m high. See Figure 5 for location.

SW to NE from south of the Hamrat Duru Range, across the eastern part of Jabal Akhdar to Fanjah. There it is offset by 50 km to the SE and continues from the southern edge of Saih Hatat north-eastward into the Gulf of Oman.

Premises and Onset of the Subductions

The passive margin in Albian times (Figure 8, Step A)

The Salakh Arch – Jabal Akhdar domain forms the north-eastern part of the Arabian Platform (African Plate) with, from the top down, 2,500 m of Permian-Cretaceous Autochthon B (Hajar Unit), 8,000 m of Neoproterozoic Autochthon A and 30 km of crystalline basement (Al Lazki et al., 2002). The 300 km continental margin represents a NeoTethyan boundary initiated by intra-Gondwanian rifting in the Middle Permian and evolving into an open seaway separating the Iran - Mega Lhasa block from the Gondwana supercontinent (Ricou, 1994). This margin is marked by progressive crustal thinning towards the north-east with three main zones:

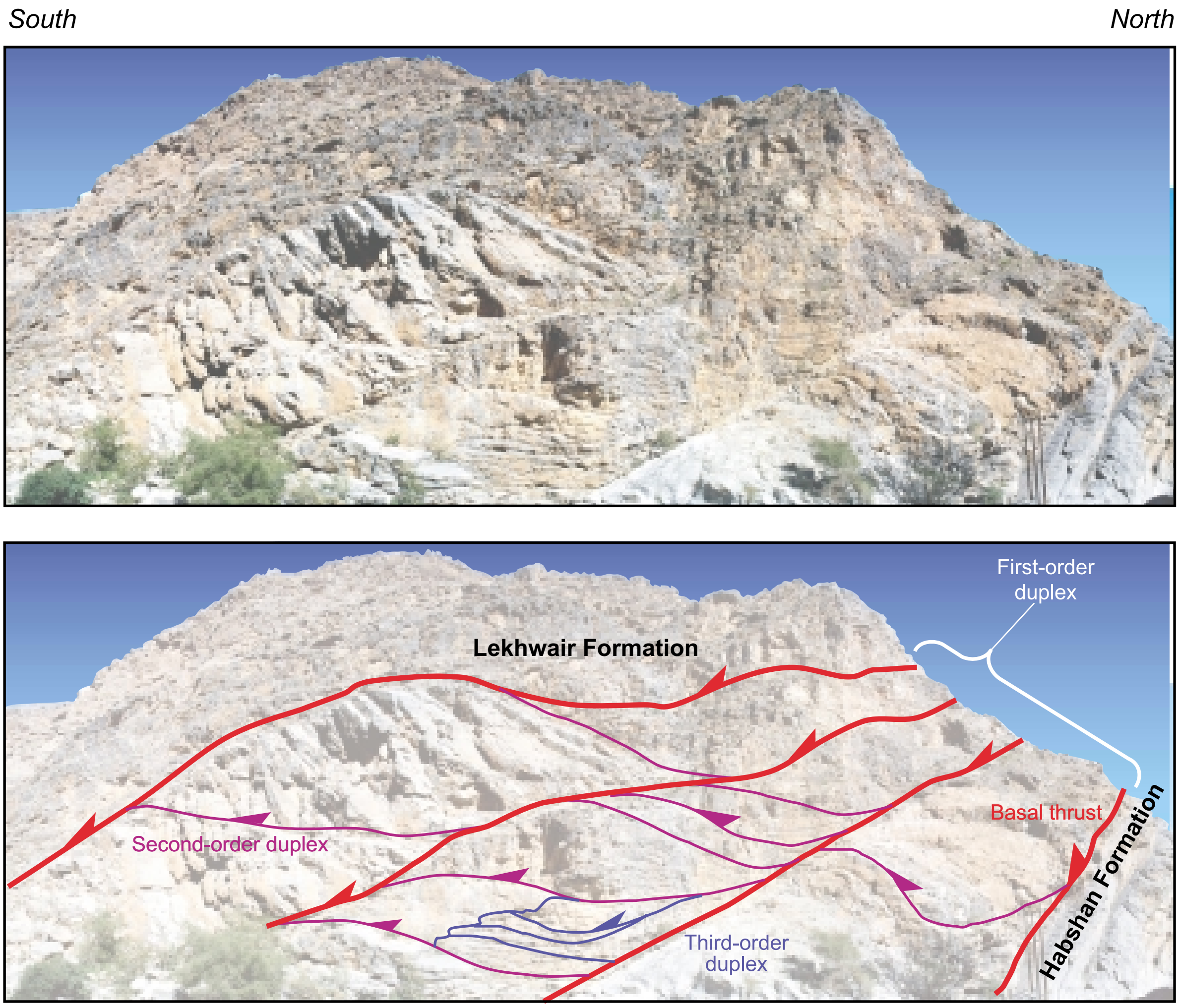


Figure 7: Duplex-type structures at the base of the Lekhwair Formation (right bank of Wadi Sahtan). View due west. The cliff is about 100 m high. See Figure 5 for location.

- The proximal zone (Saih Hatat and north Muscat, 110 km wide) forming the outer part of the Triassic to Cretaceous carbonate platform.
- The continental slope (60 km wide) where slope facies formed from the Late Permian to the Cretaceous (Glennie et al., 1974).
- The Hawasina Basin (at least 400 km wide), which can be divided into three domains: (1) the Hamrat Duru Basin (180 km wide which opened in the Middle Permian (Béchennec, 1987)), (2) the Kawr Platform and (3) the Umar Basin, which opened in the Carnian (Béchennec et al., 1990) through oceanic accretion from a new ridge (Ricou, 1994).

The Samail Basin, which extends north-east from the Umar Basin is floored by Albian oceanic crust (Beurrier, 1988) formed by a new spreading ridge at around 110 Ma, along the southern edge of the Neotethys (Ricou, 1994).

The entire transect zone was below sea level at the end of the Late Albian (100 Ma), with the deposition of marls and limestones (Nahr Umr Formation) on the platform and turbidite to pelagic facies in the adjacent continental slope and outboard Hamrat Duru, Umar and Samail Basins, where an oceanic ridge was still active.

Cenomanian: Intra-oceanic detachment and subduction (Figure 8, Step B)

Anticlockwise rotation of the African plate during the initial opening of the South Atlantic (100 and 95 Ma) gave rise to an inversion of the oceanic accretion ridges bordering Arabia (Ricou, 1994). This was responsible for the development of an intra-oceanic subduction zone with a top vergence to the southwest, within the Samail Basin, outboard of the North Oman continental margin. The initial location of the detachment is under debate (Figure 8, Step A). According to different authors, the detachment is located either along the earlier oceanic ridge where the mechanical strength of the crust might be expected to be relatively weak (Boudier et al., 1985), or at the transition zone between the older (Triassic to Jurassic) crust and the Samail Basin (Beurrier et al., 1989). Partial melting of subducted oceanic lithosphere gave rise to a second phase of intrusive and extrusive igneous activity within the upper plate (Samail Nappe), from Cenomanian to Late Turonian (96 to 88 Ma) as indicated by the age of overlying pelagic sediments (Beurrier, 1988). Thrusting of a hot lithosphere induced a syn-tectonic amphibolite to granulite-facies contact metamorphism (865°C, 2 kb) at its base (Boudier et al., 1985), with an inverse gradient of metamorphism, that affected the volcanites of the old subducted and accreted oceanic crust (Rabu, 1988). The average radiometric age of the metamorphism peak is 97 Ma (Boudier et al., 1985; Montigny et al., 1988). The sediments of the distal part of the Umar Basin were in turn subducted (Figure 8, Step B) and affected by a greenschist-facies metamorphism (400°C, 5 kb). Ortho-amphibolite and accreted metasediments formed the metamorphic sole; its outliers mark the base of the Samail Nappe.

Intra-continental detachment and onset of subduction: earliest to Middle Turonian (Figure 8, Step C)

The major intra-continental detachment that would give rise to subduction of the Jabal Akhdar – Saih Hatat autochthon occurred to the north of Muscat, in the outer part of the carbonate platform (Figure 8, Step B). Its appearance is reflected by a radical change in the platform palaeogeography during the early Turonian. The whole of the platform became exposed and was affected by erosion increasing towards the north-east from the southern border of Jabal Akhdar and cutting down to the lower part of the Sahtan Group near Muscat (Rabu, 1988; Le Métour, 1988). This erosion indicates a very broad doming (Béchennec et al., 1995) which could reflect the response of the thick continental crust (forebulge) to the onset of intra-continental subduction.

Before the middle Turonian, the entire platform that covers the northern part of Oman deepened (Béchennec et al., 1995; Le Métour et al., 1995) to form a basin in which the Muti Formation pelagic sediments were deposited unconformably (Glennie et al., 1974). The progression of the subduction to the north of Saih Hatat (north of Muscat) drove back the large forebulge over 300 km to the southwest, leaving space for the foredeep and the associated Muti Basin (Figure 8, Step C).

Formation of the North Muscat Microplate

Obduction and subduction: Middle Turonian to latest Santonian (Figure 8, Step D)

During the Early Turonian, a North Muscat microplate was formed between the intra-continental subduction zone of Saih Hatat and the intra-oceanic subduction zone of the Samail Nappe (Figure 8, Step C). From south-west to north-east this microplate included: (1) the outer part of the carbonate platform, (2) the continental slope, and (3) the whole of the Hawasina Basin. From the Early Turonian to the end of the Santonian, the two subductions were coeval (Figure 8, Step C, D and E). The intra-oceanic subduction became an obduction (as defined by Coleman, 1971) during the Middle Turonian when the Samail Ophiolite nappe (oceanic lithosphere) overthrust the continental crust of the margin (Hamrat Duru Basin).

The progression of the Samail Ophiolite Nappe is dated by the age of the tectonic truncation of the underlying Hawasina units (Béchennec, 1988): i.e. Middle Turonian for the Kawr platform, Santonian for the Hamrat Duru Basin. The final structure of the Hawasina Nappes results from an underthrusting-accretion process comparable to that observed in present-day subductions (Lallemand, 1999). Part of the Hamrat Duru sediments formed a frontal accretionary prism, represented in the transect by the Hamrat Duru Range.

The evolution of the intra-continental subduction is recorded by the Muti Formation facies. Over the whole of the Jabal Akhdar and Saih Hatat area, the upper part of the Muti Formation contains megabreccias and olistoliths whose components originate from the outer part of the carbonate platform located to the north-east (Muscat - Musandam horst of Le Métour, 1988; Rabu, 1988). This slope-toe debris shows signs of karstification and their ages range from Late Permian to Early Cretaceous. The pelagic matrix of the megabreccia has been dated in a few places only from Middle-Late Turonian in the south of Saih Hatat and north of Jabal Akhdar to Coniacian-Santonian on the south-western edge of Jabal Akhdar (Le Métour, 1988; Rabu, 1988). The overthrusted south-western edge of the North Muscat microplate had thus been exposed and deeply eroded since the Early Turonian (Figure 8, Step D). The debris, which were deposited from Middle Turonian to Santonian in the foredeep at the toe of the thrust front, were progressively underthrusted, from north of Muscat to the southwestern edge of Jabal Akhdar. The Muti Formation can thus be considered as a typical wildflysch.

The autochthon's descent along the intra-continental subduction zone has not been satisfactorily constrained by radiometric dating of the HP/LT facies minerals. For the deepest facies (Zones 3 and 4, Figure 4), the ages range from 130 to 83 Ma (Montigny et al., 1988; El-Shazly and Lanphere 1992; Searle et al., 1994; Miller et al., 1999). Only the ages younger than 90 Ma are compatible with the stratigraphic data (age of the Muti Formation involved in the subduction). These last ages indicate that the As Sifah area (southeast of Muscat, Figures 3 and 4) reached a depth in the region of 40 to 70 km at the end of the Santonian (Figure 4 and Figure 8, Step D).

End of obduction and subduction: Early Campanian (Figure 8, Step E)

The end of the obduction is characterised by the arrival of the Hamrat Duru allochthonous units in the north of the foreland basin (north of Natih, Figure 3) during the Early Campanian (Boote et al., 1990, Warburton et al., 1990). By late Santonian, the Samail Nappe and accreted Hawasina units had crossed the North Muscat microplate and advanced 20-40 km beyond its southern margin, before finally coming to a halt in the foreland basin south-west of Jabal Akhdar (north-eastern border of the African Plate sensu stricto) at the beginning of the Campanian (Figure 8, Step E). The Early Campanian age of the youngest pelagic sediments covering the Samail Nappe (Beurrier, 1988) indicates that it remained submerged up until the end of obduction. Meanwhile, the North Muscat microplate, formed of oceanic crust in the northeast and of highly thinned continental crust in the south-west, gradually sunk isostatically beneath the ophiolitic nappe (Figure 8, Steps B to D and E).

The HP/LT peak is dated from the Ruwi lawsonite schist (Muscat) at 80 Ma (El-Shazly and Lanphere, 1992), whilst the post-eclogite fabrics marking the first syn-S1 deformation of the internal zone are dated at 82 to 79 Ma (Miller et al., 1999). This indicates that the end of the intra-continental subduction was synchronous with the end of the obduction and that the deformation giving the S1cleavage in the internal zone began slightly before the end of subduction. In the internal zone, the formation of the lower slab and the north-northeasterly top vergence of the ductile shear zone separating it from the upper slab (Miller et al., 1998) are interpreted as the impingement of a lower block into the overlying crust (Figure 8, Step D and E). This wedging movement took place along two conjugate shear zone ramps, the lower one in the crystalline basement and the upper one in the sedimentary cover (autochthons A and B). The buoyant uplift, proposed by Chemenda et al. (1996) is interpreted herein to be responsible only for the delamination of the Arabian continental plate by the impingement of this block made of light continental crust. As obduction and intra-continental subduction ended in the Early Campanian, the convergence zone between the Eurasia and African plates jumped to the Makran subduction zone of southeastern Iran (Glennie et al., 1990).

Post-obduction Exhumation and Uplift

Exhumation of the autochthon: Campanian to Early Maastrichtian (Figure 8, Step F)

The earliest post-nappe sediments, resting unconformably on the thrust stack, are represented by the Qahlah Formation (Glennie et al., 1974) exposed near Al Khawd and Fanjah. These thick fluviatile sediments include conglomerates whose pebbles, according to Nolan et al., (1990), comprise Hawasina chert, Hajar Unit limestone and Amdeh Formation quartzite (Figure 2). This continental formation, dated as Late Campanian to Early Maastrichtian (Nolan et al., 1990), indicates that erosion during this period reached the Autochthon A of Saih Hatat, which was exhumed and exposed. The exhumation implies a northeastward displacement of the North Muscat microplate by 100 km (Figure 8, Step E to F), and resulted from the sinking into the asthenosphere of its northeastern part, composed of heavy old oceanic crust. Hence the movement became reversed (normal shear) along the intra-continental subduction plane, and the uplift of the autochthon induced NNE-top-verging shear deformation in the ductile cover. This deformation is responsible for S2 cleavage in the internal zone of Saih Hatat and the regional cleavage in the external zone up to the southwestern edge of Jabal Akhdar. The retrograde metamorphic parageneses associated with the deformation fabrics in the lower and upper slabs of the internal zone are dated at 76 to 70 Ma (El-Shazly and Lanphere, 1992; Miller et al., 1999). However, these ages appear slightly too young to fit the stratigraphic data (age of the Qahlah Formation).

The straightening of the continental crust combined with the northeastward movement of the North Muscat microplate brought the top of the Autochthon B (top of the Muti Formation) in contact with the base of the Allochthon (Figure 8, Step F). At the contact, mylonitisation (Le Métour, 1988; Rabu, 1988) reflects a relative movement whose vergence and amplitude remain to be determined. The regional tectonic contact between Allochthon and Autochthon (Figure 3), classically considered to be the obduction contact, is here interpreted as due to the exhumation of HP metamorphic rocks.

General uplift: Middle Campanian to Maastrichtian (Figure 8, Step G)

This episode was accompanied by a general uplift of the margin, giving rise to the emergence of the Samail Ophiolite and the beginning of its erosion in the Late Campanian. The erosion was accompanied by isostatic uplift until equilibrium was reached in the Middle Maastrichtian. Local crustal thickening resulting from the impingement of the lower block of the autochthon into the delaminated Arabic continental Plate, resulted in the doming of Saih Hatat range and exposure of the autochthon with erosion down to the pre-Permian rocks. During the same time, the Autochthon of Jabal Akhdar remained flat and covered by the Hawasina nappes and a non-eroded part of the ophiolite (Figure 8, Step F). Its doming and uplift are related to the later Tertiary tectonic events.

CONCLUSION – DISCUSSION

Interpretation keypoints

Three remarkable geodynamic characteristics of the North Oman margin in the Upper Cretaceous have been highlighted in this analysis:

1) The development of a northeast verging intra-continental subduction zone along the old NeoTethyan continental margin, which ruptured the overlying Mesozoic carbonate platform and formed a foredeep fed by detritus from the uplifted outboard part of the shelf.
2) The subducted margin reveals no collision-type deformation along the studied transect, to the point that no accretion structure (fold-and-thrust-belt) could be identified (no pre-S1 imbrication with a southwest vergence involving the crystalline basement and duplication of the Saih Hatat and Jabal Akhdar sequence). On the contrary, the only deformation which is coeval with the continental subduction consists of normal faults affecting the Natih Formation from the foreland up to Saih Hatat (Boote et al., 1990; Rabu, 1988; Le Métour, 1988). These NW-SE trending normal faults die out in the Muti Formation or are sealed at its base. They could be linked to the pulling down of the continental lithosphere. Moreover, this extensional event is confirmed by the intercalations of pillow basalts observed in the Muti Formation (Rabu, 1988; Le Métour, 1988).
3) Based upon the ratio between the length of the subducted continental plate and the depth reached by its extremity (about 100 km for the crystalline basement), the subduction zone appears to have been very steeply dipping. This is quite surprisingly considering its thickness (30 km) and the low density of the subducted continental crust (Figure 8, Step D).

Origin of the Intra-continental subduction

From a mechanical point of view, the horizontal movement of the Samail Nappe, which suggests low basal friction, is difficult to reconcile with the steep angle of the intra-continental subduction zone. The driving force of such an intra-continental subduction likely results from an initially complex 3-D geometry of the continental margin and kinematics of surrounding oceanic domains.

The structure of the Saih Hatat half-window indicates that the subduction died out to the west-northwest: on the one hand, the deepest metamorphic facies lie to the east, along the coast line of As Sifah (Figure 4), and on the other hand the periclinal termination of the dome to the west seems to indicate that the crustal thickening dies out rapidly to the west. According to Ricou (personal communication) an intra-oceanic subduction with a top-to-the-south-west vergence could have originated at about 100 Ma, from a transform fault located to the east of the North Oman margin and

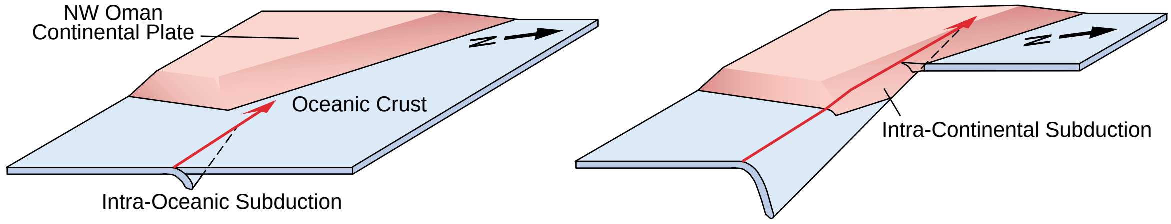


Figure 9: Hypothetical lateral progression of an intra-oceanic subduction zone into the North Oman continental margin (sketch diagram).

close to the Eurasia–Africa–India triple point. This subduction, linked to the Africa–India convergence, would have involved a gravity descent of the cold and heavy Permian-Triassic oceanic lithosphere. It is thus possible that it propagated laterally to the north-east and penetrated the North Oman margin at the Cenomanian–Turonian boundary (Figure 9). The bending of the pre-Cretaceous oceanic lithosphere would have been transmitted laterally to the continental lithosphere where it would have rapidly died out due to lighter weight and higher strength. The straightening of the subducted continental lithosphere, beginning in the Early Campanian, implies that it became disconnected from the eastern oceanic lithosphere, possibly favouring the formation of the Masirah Fault (Figure 1)? Further investigation should benefit from palaeomagnetic measurements which could reveal differential rotations. The interpretation of a deep seismic line to the east of the Oman coast could provide answers as to the origin of the Oman intra-continental subduction.

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REFERENCES

Al-Lazki, A.I., D. Seber, E. Sandvol and M. Barazangi 2002. A crustal transect across the Oman Mountains on the eastern margin of Arabia. GeoArabia, v. 7, no. 1, p. 47-78.

Allermann, F. and T. Peters 1972. The Ophiolite-radiolarite belt of the north-Oman Mountains. Eclogae Geologie Helvetica, v. 65, p. 657-669.

Bailey, E.H. 1981. Geological map of Muscat-Ibra area, Sultanate of Oman. Journal of Geophysical Research, v. 86, no. B4, p. 2495-2782.

Béchennec, F. 1988. 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, C. Bourdillon-Jeudy-de-Gricssac, P. De Wever, M. Beurrier and M. Villey 1990. The Hawasina Nappes: stratigraphy, palaeogeography and structural evolution of a fragmant of the south-Tethyan passive continental margin. In, A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society of London, Special Publication no. 49, p. 213-224.

Béchennec, F., J. Roger, J. Le Métour and R. Wyns 1992. Geological map of Seeb, sheet NF40-03, scale 1:250,000 and explanatory notes. Ministry of Petroleum and Minerals, Directorate General of Minerals, Sultanate of Oman.

Béchennec, F., J. Le Métour, J.-P. Platel and J. Roger 1995. Doming and down-warping of the Arabian platform in Oman in relation to Eoalpine tectonics. In, M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences Conference, GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 167-178.

Beurrier, M. 1988. Géologie de la Nappe Ophiolitique de Samail dans les Parties Orientale et Centrale des Montagnes d'Oman. Doctorate of Science thesis, Pierre et Marie Curie University, Paris. BRGM Document 128, 412 p.

Beurrier, M., M. Ohnenstetter, B. Cabanis, J.L. Lescuyer, M. Tegyey and J. Le Métour 1989. Géochimie des filons doléritiques et des roches volcaniques ophiolitiques de la nappe no. 2, p. 205-219

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 of London, Special Publication no. 49, p. 397-418.

Boudier, F., J.L. Bouchez, A. Nicolas, M. Cannat, G. Ceuleneer, M. Misseri and R. Montigny 1985. Kinematic of oceanic thrusting in the Oman Ophiolite: model for plate convergence. Earth and Planetary Sciences Letters, v. 75, p. 215-222.

Chemenda, A.I., M. Mattauer and A.N. Bokum 1996. Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman. Earth Planetary Science Letters, no. 143, p. 173-182.

Coffield, D.Q. 1990. Structures associated with nappe emplacement and culmination collapse in the 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 of London, Special Publication no. 49, p. 447-458.

Coleman, R.G. 1971. Plate tectonic emplacement of upper mantle peridotites along continental edges. Journal of Geophysical Research, no. 76, p. 1212-1222.

El-Shazly, A.K. and R.G. Coleman 1990. Metamorphism in the Oman Mountains in relation to the Semail Ophiolite emplacement. In, A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society of London, Special Publication no. 49, p. 473-493.

El-Shazly, A.K. and M.A. Lanphere 1992. Two high pressure metamorphism events in NE Oman: evidence from 40Ar/39 dating and petrological data. Journal of Geology, no. 100, p. 731-751.

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

Glennie, K.W., M.G.A. Bœuf, M.W. Hugues-Clarke, M. Moody-Stuart, W. Pilaar and B.M. Reinhardt 1974. Geology of the Oman Mountains. Koninklijk Nederlands Geol. en Mijnbouw. Genootschap,Transactions, no. 31.

Glennie, K.W., M.G.A. Bœuf, M.W. Hugues-Clarke, M. Moody-Stuart, W. Pilaar and B.M. Reinhardt 1990. Interrelationship of the Makran-Oman Mountains belts of convergence. In, A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The Geology and Tectonics of the Oman Region. Geological Society of London, Special Publication no. 49, p. 773-786.

Hanna, S.S. 1990. The Alpine deformation of the 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 of London, Special Publication no. 49, p. 341-359.

Hughes-Clarke, M.W. 1988. Stratigraphy and rock unit nomenclature in the oil-producing area of interior Oman. Journal of Petroleum Geology, v. 11, no. 1, p. 5-60.

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., D. Rabu, M. Tegyey, F. Béchennec, M. Beurrier and M. Villey M. 1990. Subduction and obduction: two stages in the Eo-Alpine tectonometamorphic evolution of 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 of London, Special Publication no. 49, p. 327-339.

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., J.C. Michel, F. Béchennec, J.-P. Platel and J. Roger 1995. Geology and mineral wealth of the Sultanate of Oman. Ministry of Petroleum and Minerals, Directorate General of Minerals, Oman, 285 p.

Lallemand, S. 1999. La subduction océanique. Gordon and Breach Science Publishers, Netherland, p. 1-194.

Lees, G.M. 1928. The geology and tectonics of Oman and parts of south eastern Arabia. Quarterly Journal of the Geologic Society of London, v. 84, p. 585-670.

Lippard, S.J. 1983. Cretaceous high pressure metamorphism in NE Oman and its relation to subduction and ophiolite nappe emplacement. Journal of the Geological Society of London, v. 140, p. 97-104.

Lovelock, P.E.R., T.L. Potter, E.B. Walsworth-Bell and W.M. Wiemer 1981. Ordovician rocks in the Oman Mountains: the Amdeh Formation. Geol. Mijnbouw, p. 487-495.

Mann, A. and S.S. Hanna 1990. The tectonic evolution of pre-Permian rocks, central and southeastern 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 of London, Special Publication no. 49, p. 307-325.

Michard, A. 1982. Contribution à la connaissance de la marge nord du Gondwana, une chaîne plissée Paléozoïque, vraisemblablement hercynienne en Oman. C.R. Acad. Sci. Paris, 22 p.

Michard, A., B. Goffé and M. Ouazzani 1983. Obduction related high pressure-low temperature metamorphism in upper crustal materials, Oman. 2nd European Union Geoscience Meeting, Strasbourg. Terra Cognita, 3, p. 187 (Abstract).

Miller, J.McL. 1998. The structure, metamorphism and 40Ar/39Ar geochronology of northeast Saih Hatat, Oman: implications for the formation and preservation of high pressure rocks. Unpublished PhD thesis, Monash University, Clayton, Melbourne, Australia.

Miller J.McL., D.R. Gray and R.T. Gregory 1998. Exhumation of high-pressure rocks, north-eastern Oman. Geology, no. 26, p. 235-238.

Miller, J.McL., R.T. Gregory, D.R. Gray and D.A. Foster 1999. Geological and geochronological constraints on the exhumation of a high-pressure metamorphic terrane, Oman. In, U. Ring, M.T. Brandon, G.S. Lister and S.D. Xillet (Eds.), Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society of London, Special Publication no. 154, p. 241-260.

Miller, J.McL, D.R. Gray and R.T. Gregory 2002. Geometry and significance of internal windows and regional isoclinal folds in northeast Saih Hatat, Sultanate of Oman. Journal of Structural Geology, no. 24, p. 359-386.

Montigny, R., O. Le Mer and H. Whitechurch 1988. K-Ar and 40Ar/39 study of metamorphic rocks associated with the Oman ophiolite: tectonic implications. Tectonophysics, v. 151, p. 345-362.

Mount, V.S., R.I.S. Crawford and S.C. Bergman 1998. Regional structural style of the central and southern Oman Mountains: Jebel Akhdar, Saih Hatat, and the northern Ghaba basin. GeoArabia, v. 3, no. 4, p. 475-490.

Nicolas, A. and F. Boudier (Eds.) 1988. The Ophiolites of Oman. Tectonophysics, Special issue, v. 151, 401 p.

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 of London, Special Publication no. 49, p. 495-519.

Rabu, D. 1988. Géologie de l'autochtone des montagnes d'Oman la fenêtre du Jabal Adkar. La semelle métamorphique de la Nappe ophiolitique de Semail dans les parties orientale et centrale des Montagnes d'Oman: une revue. Document BRGM Orléans, no. 130, p. 1-582.

Rabu, D., P. Nehlig, J. Roger, F. Béchennec, M. Beurrier, J. Le Métour, C. Bourdillon-de-Grissac, M. Tegyey, J.J. Chauvel, C. Cavelier, H. Al Hazri, T. Juteau, D. Janjou, B. Lemière, M. Villey and R. Wyns (Eds.) 1993. Stratigraphy and structure of the Oman Mountains. Document BRGM Orléans, no. 262.

Ricou, L.E. 1994. Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from central America to south-eastern Asia. Geodynamica Acta (Paris) 1994, 7 (4), p. 169-218.

Ricateau, R. and P.H. Riche 1980. Geology of the Musandam Peninsula (Sultanate of Oman) and its surroundings. Journal of Petroleum Geology, v. 3, p. 139-152.

Roger, J., F. Béchennec, D. Janjou, J. Le Métour, R. Wyns and M. Beurrier 1991. Geological map of the Ja'Alan Quadrangle, Sultanate of Oman. Geoscience map, scale 1:100,000, sheet NF 40-8E and explanatory notes. Ministry of Petroleum and Minerals, Directorate General of Minerals, Sultanate of Oman. 90 p.

Searle, M.P., D.J. Waters, H.N. Martin and D.X. Rex 1994. Structure and metamorphism of blueschisteclogite facies rocks from the NE Oman Mountains. Journal of the Geological Society of London, no. 151, p. 555-576.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.A. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate Sequence Stratigraphy. Geoarabia Special Publication 2, Gulf PetroLink, Bahrain, 371 p.

Tschopp, R.H. 1967. The general geology of Oman. Proceedings of the 7th World Petroleum Congress, Mexico, v. 2, p. 213-242.

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 of London, Special Publication no. 49, p. 419-427.

Wendt, A.S., P. D'Arco, B. Goffé and R. Oberhänsli 1993. Radial cracks around a-quartz inclusions in almandine: constrains on the metamorphic history of the Oman mountains. Earth Planetary Science Letters, no. 114, p. 449-461.

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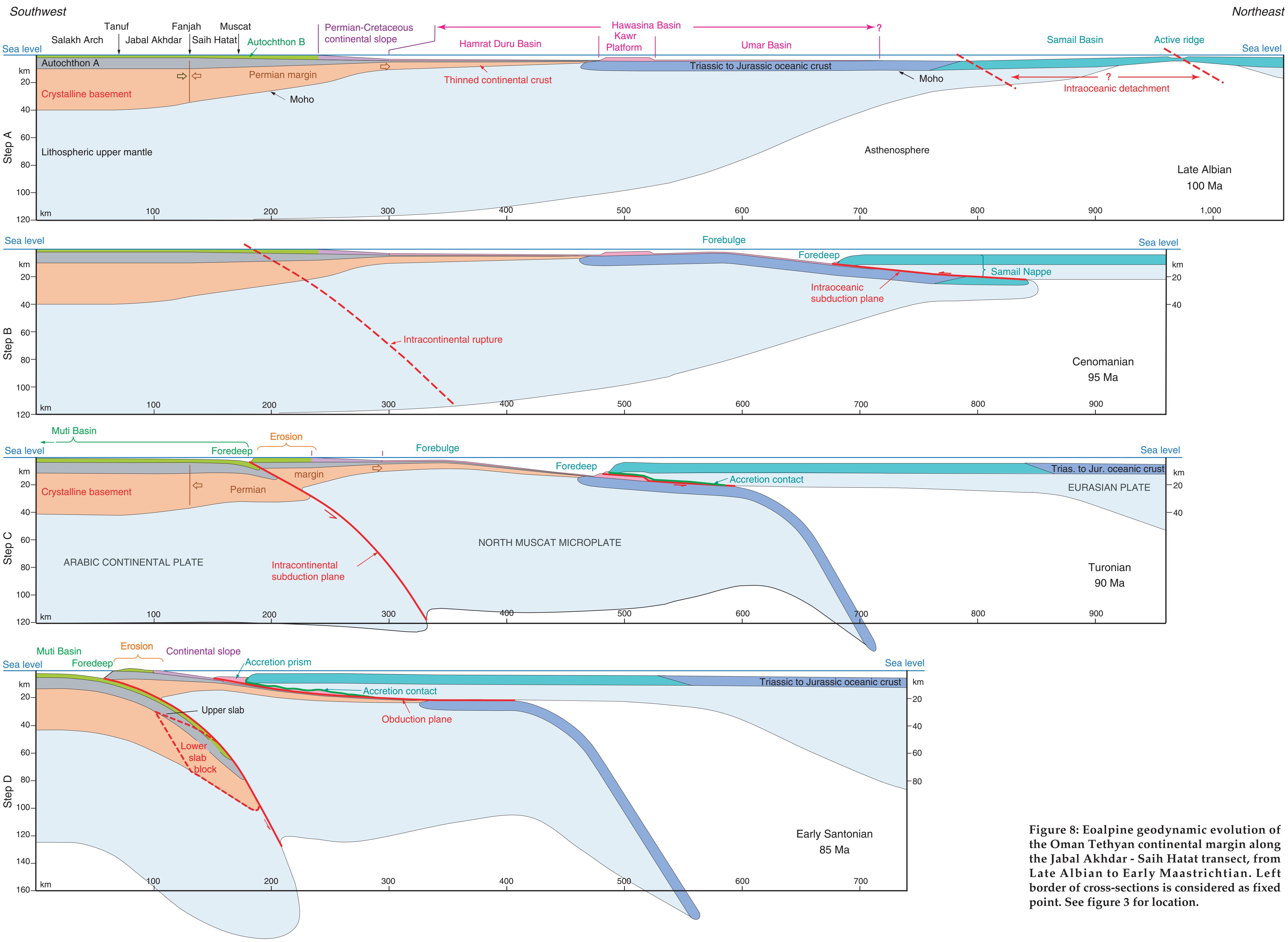
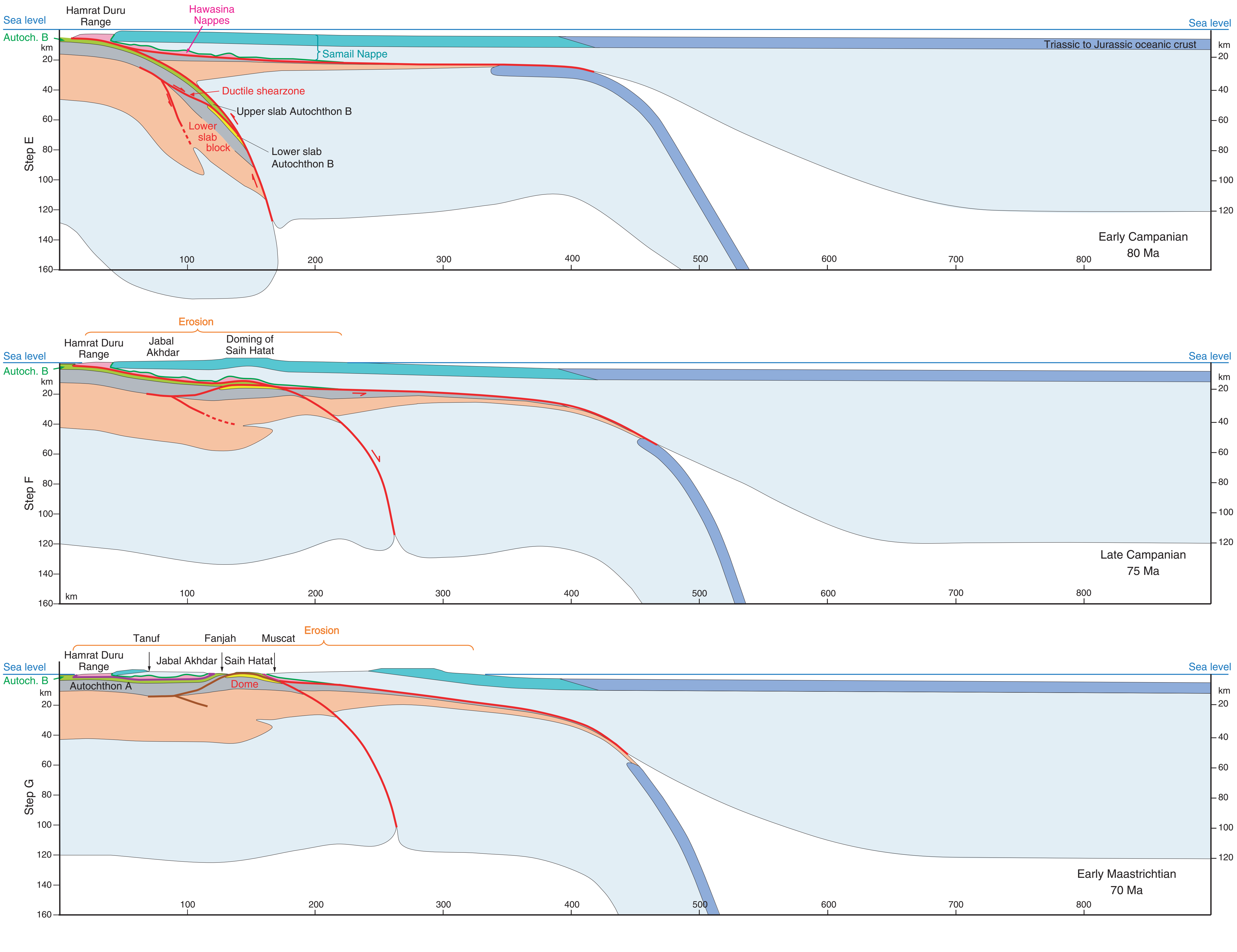


Figure 8: Eoalpine geodynamic evolution of the Oman Tethyan continental margin along the Jabal Akhdar - Saih Hatat transect, from Late Albian to Early Maastrichtian. Left border of cross-sections is considered as fixed point. See figure 3 for location.



Sea level
Hamrat Duru Range
Hawasina Nappes
Sea level
Autoch. B
km
Samail Nappe
Triassic to Jurassic oceanic crust
Ductile shearzone
Upper slab Autochthon B
Lower slab block
Lower slab Autochthon B
Step E
Early Campanian
80 Ma
Erosion
Hamrat Duru Range
Jabal Akhdar
Doming of Saih Hatat
Step F
Late Campanian
75 Ma
Tanuf
Fanjah
Muscat
Erosion
Hamrat Duru Range
Jabal Akhdar
Saih Hatat
Autochthon A
Dome
Step G
Early Maastrichtian
70 Ma