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A new structural interpretation for the emplacement of the Masirah ophiolites (Oman): a main Paleocene intra-oceanic thrust

Une nouvelle interprétation tectonique de l'ophiolite de Masirah (Oman) : un chevauchement intra-océanique paléocène

D. MARQUER, Tj. PETERS* and E. GNOS**

ABSTRACT. – As shown by geological and structural mapping, the oceanic crust of Masirah Island is composed of two nappes. South vergent folds with E-W trending axis, N-S stretching lineations and shear sense indicators are consistent with a shearing to the South of the Upper Masirah Nappe. Thrusting is bounded by late-Maastrichtian sediments below and middle Eocene shallow marine deposits which unconformably overlie the nappe pile. The nappe pile and the Tertiary sediments were strongly affected by extensional tectonics resulting in NNE-SSW trending horst and graben systems, resulting from N-S to NE-SW normal faults. These large scale structures are cross-cut by late E-W normal faults. The so-called "mélange zone" results from of the interference between late normal faults and the flat lying plane of the Main Masirah Thrust (MMT) and does not represent a major transform fault as previously assumed.

Key-words: Oceanic lithosphere, ophiolite, tectonic, intra-oceanic thrust, paleocene, normal fault, Oman.

RÉSUMÉ. – Les nouvelles données géologiques et structurales montrent que la croûte océanique de l'île de Masirah est constituée de deux nappes distinctes. Les plis à vergence sud et d'axes de direction Est-Ouest, les linéations d'étirement Nord-Sud et les critères cinématiques attestent d'un chevauchement majeur de l'unité supérieure vers le Sud. Le chevauchement est postérieur au dépôt des sédiments maestrichtiens et antérieurs à la discordance des sédiments marins peu profonds de l'Eocène. La pile de nappes et les sédiments tertiaires sont intensément affectés par une tectonique extensive tardive qui génère des systèmes de horst et graben de direction générale NNE-SSO. A l'échelle de l'île, ces structures sont recoupées par des failles normales tardives de direction Est-Ouest. La « zone de mélange » antérieurement décrite est en fait le résultat de l'interférence entre les failles normales, tardives, et le plan du chevauchement principal (MMT) : cette zone tectonique complexe ne représente pas une faille transformante majeure.

Mots-clés : Lithosphère océanique, ophiolite, tectonique, chevauchement intra-océanique, paléocène, faille normale, Oman.

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INTRODUCTION

The Masirah Island lies off the SE coast of the Sultanate of Oman, about 250 km south of the Semail Ophiolite (fig. 1). Ever since the sixties, it has been hypothesized that the Masirah ophiolite was part of the Semail overthrust, subsequently transported by a dextral displacement along a NNE trending fault (Morton, 1959; Moseley, 1969; Glennie *et al.*, 1974). After the first comprehensive study of Masirah Island by Moseley and Abbotts (1979), however, much emphasis was laid on the NNE trending zone of the western part of the island, where serpentinite, gabbros, sediments and volcanic rocks occur side by side, apparently in no systematic order. This zone was considered to be an ophiolite mélange. This interpretation was taken up in subsequent papers by Abbotts (1979), Abbotts (1981), Moseley and Abbotts (1984), Smewing *et al.* (1991). Taking into account the ophiolite occurrences of Ras Madrakah and Ras Jibsch, these authors considered this zone as a large transform fault, the Masirah line, along which the continental plate, adjacent to Arabia before the late Jurassic breakup of Gondwana, moved northwards (Shackleton

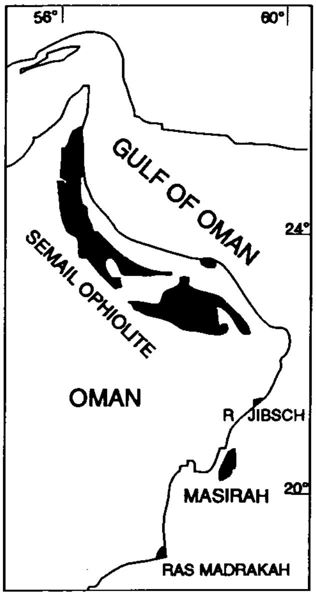

Fig. 1 – **Geological map of East Oman and location of Masirah Island.** Occurrences of ophiolites in black.

Fig. 1 – ***Carte géologique de l'Est du Sultanat d'Oman et position de l'île de Masirah.*** *Les ophiolites sont indiquées en noir.*

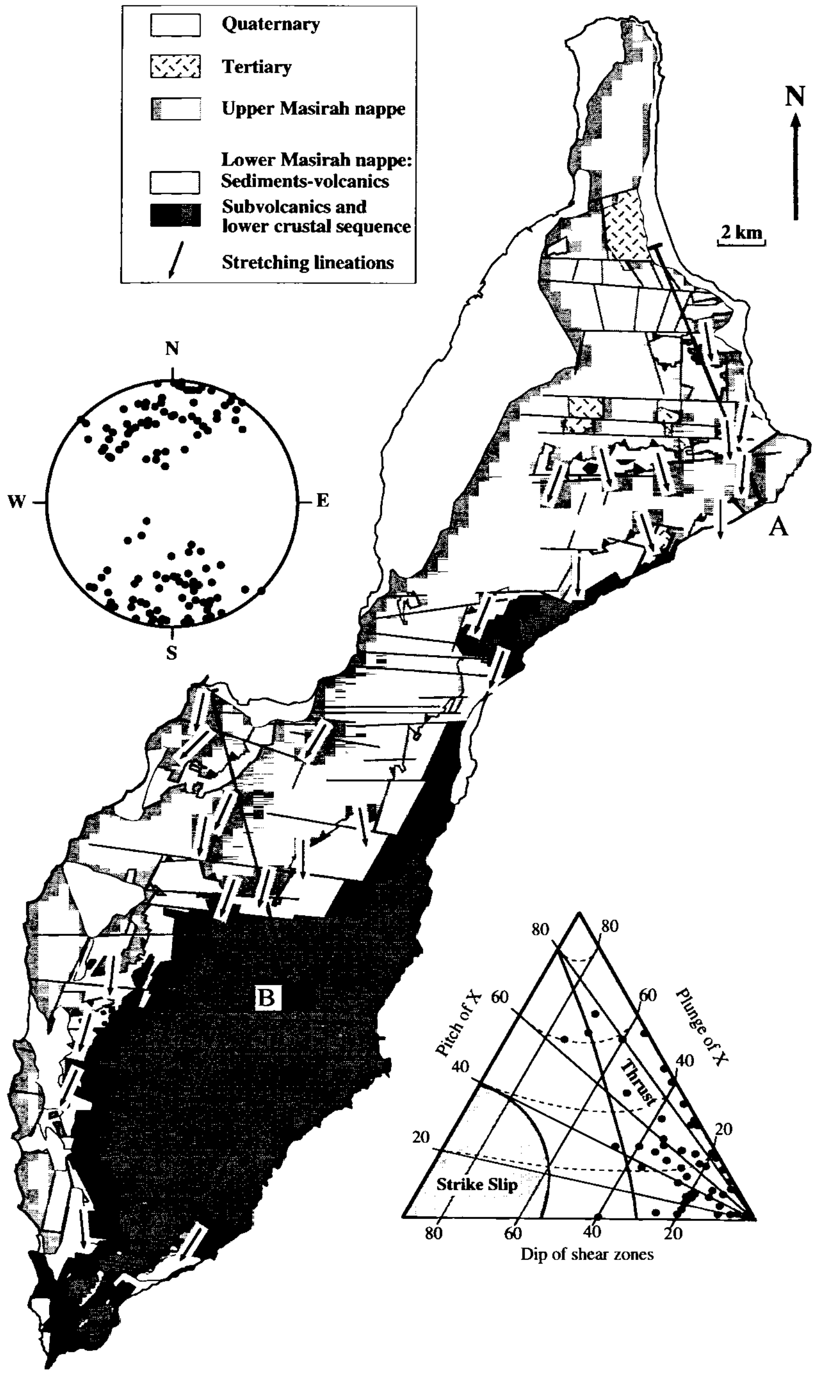

Fig. 2 – **Structural map of Masirah Island.** Lines A and B correspond to the cross-sections on figure 3. The stretching lineations are plotted on the map and on a Wulff stereogram (lower hemisphere, 124 data). Combination of the dips of shear planes and the pitch (or plunge) of the associated stretching lineations are shown on a tri-plot diagram. Straight lines: isopitch of the lineations; Curved dashed lines: isoplunge of the lineations. The grey areas correspond to strike-slip domains or thrust (and normal fault) domains as quoted.

Fig. 2 – ***Carte structurale de l'île de Masirah.*** *Les lignes A et B correspondent aux coupes de la figure 3. Les linéations d'étirement minérales au niveau du chevauchement (MMT) sont indiquées sur la carte et représentées sur un diagramme stéréographique de Wulff (hémisphère inférieur, 124 mesures). Sur un diagramme triangulaire sont indiqués les combinaisons des couples plan-linéation d'étirement. Lignes droites : iso-pitch des linéations sur le plan de cisaillement. Lignes tiretées courbes : iso-plongement des linéations sur le plan de cisaillement. Les domaines des décrochements et des chevauchements (et/ou failles normales) sont également indiqués sur ce diagramme.*

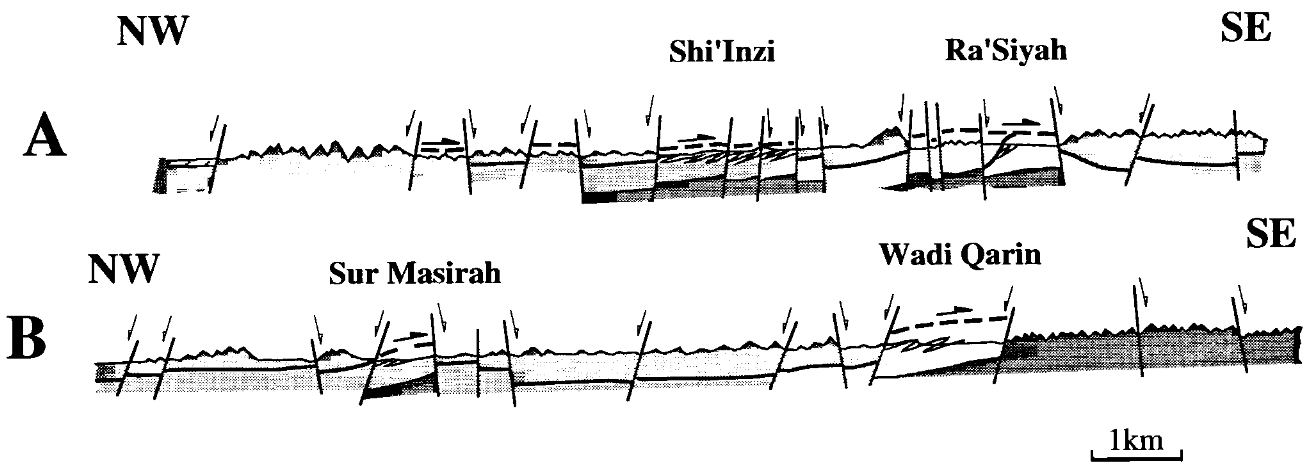

Fig. 3 – **Cross-sections in the NE and SW parts of the island** (see location and legend on figure 2).
Fig. 3 – ***Coupes structurales dans les parties NE et SW de l'île*** *(localisation et légende indiquées sur la figure 2).*

and Ries, 1990). This paper presents results of recent field work which shows that on Masirah Island two ophiolite nappes can be distinguished, and that there is more order in the so-called mélange than previously postulated (Moseley and Abbotts, 1979). New structural and kinematic evidences, supported by stratigraphic and radiometric investigations in progress, allow to propose a new interpretation of the tectonics and emplacement of the Masirah Ophiolites.

GEOLOGICAL UNITS

From structural and geological mapping, two distinct nappes can be recognized at the scale of the island, the Upper and the Lower Masirah Nappe, respectively (fig. 2). Both units are composed of well exposed ophiolite sequences. The mantle sequence consists of harzburgites with variable amounts of gabbro and dolerite dikes. Two types of lower crustal sequence were recognized: 1) a "normal" crustal sequence composed of interlayered olivine gabbros and peridotites, followed by foliated gabbros and 2) an "abnormal" crustal sequence composed of isotropic and pegmatitic gabbros with associated K-feldspar granites in the Upper Masirah Nappe. In some parts, where the sheeted dikes root directly in the harzburgites, no gabbroic lower crustal sequence is developed. The lower crustal sequence continuously grades into the upper crustal sequence, here composed of subvolcanic sheeted dikes. In the Lower Masirah Nappe, an extrusive unit with pillow lavas and sheet flow lavas is exposed, overlain by an autochthonous oceanic sedimentary cover (fig. 2). A characteristic feature of the ophiolite sequences of both Masirah Nappes is the occurrence of a thin and complex lower crustal sequence (maximum of 500 m), which is the subject of another study focusing on the magmatic activity and the prestructuration of this part of the oceanic lithosphere during Valanginian times (paper in prep.).

The autochthonous sedimentary sequence of the Lower Masirah Nappe, starts with radiolarian micrites of Tithonian age, grading upwards into brown cherts of Valanginian and Hauterivian age. This sedimentary sequence is contemporaneous with the Southeastward drift of India/Australia in regard of Africa/Arabia (Coffin and Rabinowitz, 1992; Dercourt *et al.*, 1993). Parts of the oceanic crust were uplifted and eroded, forming horsts and graben (or half-graben with asymetric tilted-blocs) with bimodal alkaline volcanism resulting in alkaline pillow basalts and subvolcanic trachites of Valanginian age (U-Pb zircon ages, 123 ± 2 M.a., Nägler and Frei, 1994). On some of the horsts, Barremian platform carbonates with rudists and corals formed directly on top of the lower crustal sequence and in some places on the top of the harzburgite. On the slopes, breccias with ophiolite pebbles and carbonate components were deposited. In the deeper part of the basin, pelagic radiolarian limestones alternate with ophiolitic turbidites. From the Aptian onwards, a deepening is indicated by the sedimentation of white and red radiolarian micrites, grading into ribbon cherts of Coniacian to Santonian age. These sedimentary deposits could be linked to a thermal subsidence of the oceanic lithosphere. No comparable sedimentary sequence is known neither from the Hawasina nappes

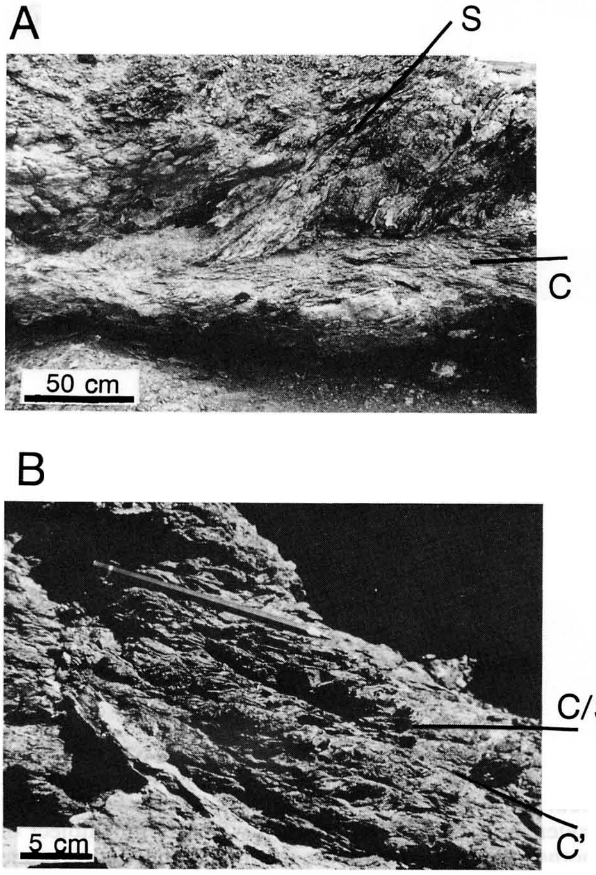

Fig. 4 – **Shear-sense criteria indicating a top-to-south shearing.** A: C/S relationships in serpentinized harzburgite near Wadi Faruk. B: C' structures in serpentinized harzburgite, north of Wadi Thumi. C/S and C' structures, as defined by Berthé et al., (1979). South: top right corner.

Fig. 4 – ***Exemples de critères de cisaillement indiquant un chevauchement vers le sud.*** *A : Structures C/S dans la harzburgite serpentinisée à proximité de Wadi Faruk. B : Structures de type C' dans la harzburgite serpentinisée au nord de Wadi Thumi. Pour les structures C/S et C', voir Berthé et al., (1979). Sud : coin haut droit.*

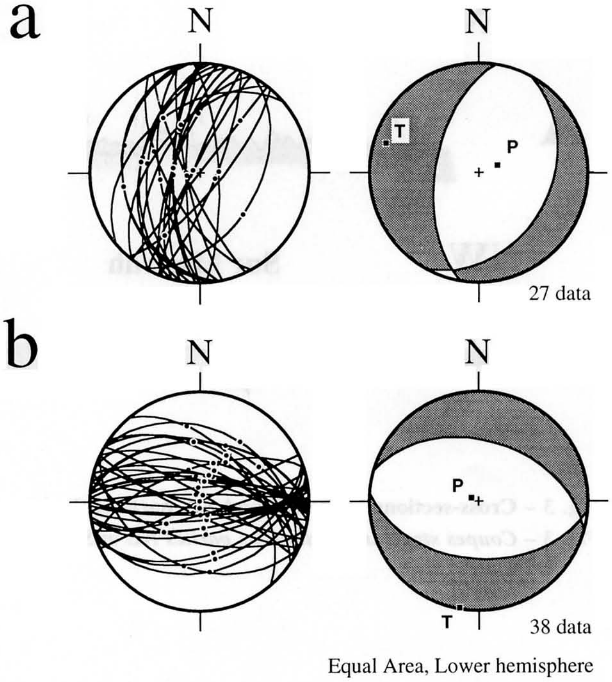

Fig. 5 – **Kinematic analysis of fault/slickenside pairs, according to Angelier and Mechler (1977) and Allmendiger et al. (1989).** a and b correspond to the first and second extensive event respectively. Thin continuous lines: fault planes; Black dots: slickenside lineations; Calculated directions of tension T and compression P.

Fig. 5 – ***Analyse cinématique des couples faille/strie, d'après Angelier et Mechler (1997) et Allmendiger et al. (1989).*** *a et b correspondent respectivement au premier et deuxième événement tardif extensif. Lignes continues : plans de failles; Points noirs : linéations des stries; Les directions calculées de tension T et de compression P sont représentées.*

nor from the autochthonous series of the Arabian platform (Béchennec *et al.*, 1990; Robertson and Searle, 1990). From the Coniacian to the Upper Maastrichtian, however, a sequence of fine- and coarse-grained sandstones interlayered with marls and silts, containing large boulders of granites, gneisses and rhyolites, similar to the Fayah formation in the area of Bani Bin Houssan on the mainland (Schakleton and Ries, 1990), is present in the Lower Masirah Nappe (work in progress, Immenhauser A., von Salis K.) (see flysch, fig. 7).

The ophiolite sequences and the pre-Upper Maastrichtian sediments are unconformably overlain by Tertiary (from Ypresian-Lutetian to lower Oligocene, in Stucky and Briner, 1994) and Quaternary autochthonous deposits (Glennie *et al.*, 1974; Le Métour *et al.;* 1992) (fig. 2).

EMPLACEMENT-RELATED STRUCTURES AND LATE DEFORMATIONS

The two structural units are spatially separated on the island. The Upper Masirah Nappe occurs mainly in the Western and Northern part whereas the Lower Masirah Nappe is much more exposed in the South and South-East area (fig. 2). The sediments and volcanic units of the Lower Masirah Nappe constitute a continuous level separating the two nappes (fig. 2 and 3). The base of the Lower Nappe is never exposed but since this Lower

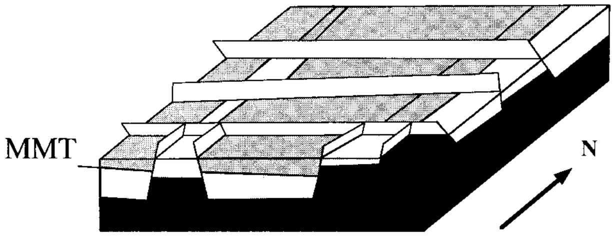

Fig. 6 – **Schematic 3D diagram showing the effect of late normal faulting.** MMT represents the Main Masirah Thrust (same legend as in figure 2).

Fig. 6 – ***Bloc diagramme schématique illustrant les effets des failles normales tardives sur les zones proches du chevauchement principal.*** *MMT : chevauchement principal (même légende que sur la figure 2).*

Ma		MASIRAH OPHIOLITE	SEMAIL OPHIOLITE
	EOCENE	Shallow marine sediments	
53	PALAEOCENE	Intra-oceanic thrust	
65	Maastrichtian		
	Campanian	*Flysch*	Continental subduction Ophiolite obduction
	Santonian		
	Coniacian		
	Turonian		
	Cenomanian	Deep marine sediments	
96			Oceanic crust formation
	Albian		
	Aptian		
	Barremien	*Platform carbonates*	
	Hauterivian		
	Valanginian	*Bimodal alkaline volcanism*	
	Berriasian		
135	MALM	Oceanic crust formation	
154			

Fig. 7 – **Comparison of the ages of the different sedimentation types and the main tectonic events between the Masirah ophiolite and the Semail ophiolite** [Time scale from Odin (1994)].

Fig. 7 – ***Tableau comparatif des âges des différents types de sédimentation et des principaux événements tectoniques entre l'ophiolite de Masirah et l'ophiolite du Semail*** *[échelle des temps d'après Odin (1994)].*

Nappe consists of ophiolite on the Arabian continental margin, a thrust in-between is supported by several authors. Only the ductile deformation which corresponds to the emplacement of the Upper Masirah Nappe can be observed. The thrusting is concentrated in the lower part of the Upper Masirah Nappe and in the sediments that are pinched in-between the nappes. The units below the sediments are weakly deformed and only a few thrusts occur locally in the sheeted dikes and the volcanic units of the lower nappe. In the sediments, the deformation is penetrative and results in south-vergent folds with axes trending East-West and the axial plane evolving from horizontal to 70° North dipping in some places. Some local thrusts also occur and cross-cut these folded sediments. In contrast, the deformation in the rocks of the lower part of the Upper Masirah Nappe is strongly heterogeneous and occurs under greenschist facies conditions (serpentinized harzburgite with chrysotile fibres, metagabbros with actinolite-epidote-plagioclase paragenesis). At various scales, lenses of weakly deformed rocks, as gabbros and serpentinized harzburgites, are surrounded by anastomosed ductile and brittle ductile shear zones, with a geometrical pattern similar to that described in granitic rocks (Bell, 1981; Ramsay and Huber, 1987).

For each measurement locality along the low-temperature contact between the two nappes, a compilation of the directions of the stretching lineations (X: principal axis of finite strain; Ramsay, 1967) observed within the shear zones is indicated (fig. 2, map). At a large scale, these lineations show little scattering with a maximum trend in a North-South direction (fig. 2, stereo). The scattering of the direction of lineations is partly due to late-Tertiary brittle faulting (see below). The frequently exposed basal thrust of the Upper Nappe is generally sub-horizontal and the associated stretching lineations are also gently inclined: along this contact between the upper and the lower nappe, the ductile and brittle-ductile shear zones are in the field of the thrust zones (fig. 2, triangle). These observations point to the occurrence of a major thrust throughout the whole island, named herein the Main Masirah Thrust, rather than to a strike-slip fault, as expected in the hypothesis of a large transform fault (Moseley and Abbots, 1984). On SE-NW cross-sections in the North-Eastern or the Western part of the island, the overall geometry emphasizes the superposition of these two nappes (fig. 3). Along the Main Masirah Thrust, many shear criteria are used to deduce the sense of emplacement of the Upper nappe. Asymmetry of shear zone patterns (Gapais *et al.*, 1987) and C/S relationships or C' structures (Berthé *et al.*, 1979) give consistent indications for a top to the South shear direction (fig. 4). This direction of thrusting is supported by the asymmetry of the folds and the small scale thrusts in the sedimentary cover. As mentioned above, the youngest sediments deformed by the emplacement of the Upper Nappe are upper Maastrichtian in age. This intra-oceanic thrust may have been active during the Late Cretaceous – Palaeocene, since the Tertiary unconformity, starting with Ypresian shallow marine deposits, post-dates the ophiolite emplacement.

On the whole island, the nappe pile and the Tertiary rocks, the youngest have been dated as lower Oligocene, are strongly affected by late extensional tectonics (Le Métour *et al.*, 1992). At the map scale, most lithological contacts result from these late extensional tectonics (fig. 3). The cartographical boundaries of the Tertiary areas correspond to fault systems with different orientations (fig. 2). Using relative chronology around the Tertiary areas, this late extensional tectonic event is divided into two main episodes (fig. 5): 1) The first brittle deformations created horst and graben structures with a general NNE-SSW orientation. These rigid blocks are displaced along normal faults running in N-S to NE-SW directions (fig. 2). The analysis of fault kinematics corresponds to a bulk E-W extension for this first set of faults (fig. 5a). 2) The latest normal faults trend E-W and the analysis of the fault kinematics reveals a N-S extension regime (fig. 5b). This last tectonic event is responsible of a stronger uplift of the southern part than of the northern part of the island. In the sediments, open folding and drag structures are locally associated with late normal faulting events. For example, the spoon-shaped (periclinal-synform structure) of the Tertiary sediments of Naft, in the northeastern part of the island, is an expression of successive N-S, NE-SW and E-W normal fault systems that delimit the shape of this area.

DISCUSSION

The present structural analysis shows that the Masirah Island displays the features of an ophiolitic nappe strongly affected by post Early-Oligocene brittle faulting (fig. 6). No evidence of major strike-slip faults has been observed.

The classical interpretation of the western part of the island as a tectonic mélange (Abbotts, 1979; Moseley and Abbotts, 1979) must be abandoned. The complex geology of the area actually corresponds to an interference between late normal faults and the flat lying plane of the Main Masirah Thrust (fig. 6).

The relatively low vertical displacements along these late structures lead to small disruptions of the major thrust.

As a result, the serpentinized harzburgites, the sediments or the volcanic units are close together at the outcrop scale, but the structural trajectories (fold axes in sediments or stretching lineations) are slightly misoriented with respect to the strike of the regional structures, which generally run in a N-S direction at the scale of the island (fig. 2).

Some of the important geological implications of this new structural interpretation of Masirah Island should be pointed out.

The careful structural and geological mapping of the western and southern part of the island highlights the following structures of the oceanic crust before thrusting. In some places, the Barremian sediments directly overlie harzburgites, gabbros or sheeted-dikes.

This structural relationship, together with occurrences of syn-sedimentary faulting and alkaline volcanism, implies a strong extensional tectonic event during the formation of this part of the oceanic lithosphere at Hauterivian age (fig. 7). The general thinness of the lower part of the upper nappe is possibly related to this complex history of the oceanic crust formation (work in progress). Some intrusive and volcanic rocks were emplaced at this time and cannot be related to the ophiolite obduction as previously proposed by Smewing *et al.*, 1991. This hypothesis is strongly supported by geochemical and geochronological investigations (Nägler and Frei, 1994).

CONCLUSIONS

The structural mapping of Masirah Island associated with detailed investigations of brittle-ductile deformation and structural relationships between the sedimentary cover and the oceanic lithosphere lead us to propose a new tectonic history for the emplacement of the ophiolites: the Main Masirah Thrust corresponds to a major thrust with southward shearing that was active between Maastrichtian and Lower Eocene. This brittle-ductile event is followed, after the deposition of early Oligocene sediments, by two successive episodes of normal faulting striking N-S to NE-SW and E-W respectively. In some parts of the island previously interpreted as tectonic mélanges, late brittle tectonics are responsible for the patchwork appearance when late normal faults cross-cut the Main Masirah Thrust. The term "tectonic mélange" is not relevant to the Masirah structures and should be abandoned. Indeed, the tectonic significance of the Masirah line may be different than previously thought. This structural line can be interpreted as the western limit of the overthrust of the oceanic crust on the Arabian platform.

These new structural data also influence large scale tectonic models. Even if the thrusting directions of the MMT are close to those of the Semail obduction, the geological evolution and the sedimentary cover of the Masirah Island are different from the Semail ophiolite and the Hawasina sediments (Glennie *et al.*, 1974; Béchennec *et al.*, 1990; Robertson and Searle, 1990). Moreover, the ages of thrusting are around 90-80 Ma for the Semail ophiolites (El-Shazly and Coleman, 1990; Gnos and Peters, 1993) and between 65 and 55 Ma for the MMT (fig. 7). This different timing for the obduction of the Semail and the thrusting of the Masirah Island could be related to the northward tectonic motion of Arabia and India respectively (Dercourt *et al.*, 1993).

From Tithonian to Aptian, the complex extensive history occurring during the formation of this part of the oceanic lithosphere may be partly responsible for the thinness and "abnormal" type of the lower crustal sequence in the upper and the lower nappe. The thickness and the geometry of the oceanic sequences mapped on Masirah Island are important to better understand the geological setting and the formation of this kind of thin oceanic lithosphere.

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