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Early Cretaceous intra-oceanic rifting in the Proto-Indian Ocean recorded in the Masirah Ophiolite, Sultanate of Oman

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Abstract

The Masirah Ophiolite (Sultanate of Oman) was part of an oceanic basin (Proto-Indian Ocean) formed by the break-up of Gondwana in Late Jurassic times similar to the Somali basin. It was obducted onto the Arabian continental margin in the Early Paleocene, 100 Ma after its formation. Hence, it is possible to investigate the different tectonic and magmatic processes that have affected the oceanic lithosphere during these 100 Ma. Tithonian ridge magmatism, tectonism and hydrothermal alteration are responsible for the formation of the oceanic crust of the Masirah Ophiolite. In the Early Cretaceous (Hauterivian–Barremian), after 20 Ma of normal drift and subsidence, the oceanic lithosphere underwent extensional tectonics and renewed magmatism. Geometry, kinematics, intrusion mechanisms and related sedimentation during this intra-oceanic rifting are widely described and illustrated by field observations. Exhumation of deep-seated oceanic lithosphere, alkaline volcanism, intrusion of a hornblende gabbro–dolerite–granite suite and uplift of crustal blocks to sea level with the unconformable deposition of platform carbonates are the processes characterising this intra-oceanic rifting. The Hauterivian–Barremian age of oceanic rifting coincides with an important reorganisation of the motion of the Indian plate relative to Africa, Antarctica and Australia. We interpret the rifting recorded in the Masirah Ophiolite as the local response to the motion of the Indian plate due to the opening of the South Atlantic and the spreading in the Eastern Indian Ocean.

Keywords: oceanic lithosphere; rifting; ophiolite; Early Cretaceous; Masirah Island; Oman

1. Introduction

Since the pioneering work of Steinmann (1924), geophysical and geological studies of the oceanic crust occurring in actual oceans or in ophiolite complexes have revealed the layered geometry and thickness of the oceanic lithosphere (Nicolas, 1989). Unfortunately, ophiolites have often been obducted shortly after their formation and intensely dismembered during the obduction processes. Therefore, they record generally only a limited portion of the history of the particular ocean basin. The Masirah Ophiolite in Oman drifted for 100 Ma prior to obduction onto the Arabian continental margin and consequently offers a unique opportunity to study the long-standing evolution of a piece of oceanic crust.

The aim of this paper is to present new insights in the geometry, deformation, magmatism and sedi-

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mentation related to an oceanic rifting event which affected the 20 Ma old oceanic lithosphere of the proto Western Indian Ocean. This study is based on detailed mapping and careful combined petrological and structural studies of the oceanic lithosphere occurring on Masirah Island, off the southeast coast of the Sultanate of Oman. We discuss here the changes of the bulk geometry of the older oceanic crust under the influence of the new extensional regime, the structures related to the emplacement of magma bodies and the kinematics of their subsequent deformation as well as the changes in the sedimentary record. Finally, we link the intra-oceanic rifting to coeval reorganisation of the plate tectonic framework.

2. Geological setting

The Masirah Ophiolite was originally assumed to be part of the mid-Cretaceous Semail Ophiolite (Morton, 1959; Moseley, 1969; Glennie et al., 1974; Moseley and Abbotts, 1979, 1984; Abbotts, 1978, 1979, 1981). The finding of Late Jurassic radiolaria in the sediments intercalated with pillow lavas by Beurrier (1987) and new radiometric dating by Smewing et al. (1991) provided evidence of a different oceanic history between the Masirah and Semail ophiolites (Le Métour et al., 1992). In the context of the Masirah Project of the University of Bern (1992–1996) the following contributions considerably added to our knowledge of the geology of the Masirah Island.

(1) A new geological map of the whole island was established (Peters et al., 1997).

(2) Immenhauser (1996) has described and dated a complete stratigraphic succession ranging from the Tithonian up to the Early Oligocene. His biostratigraphic ages are in good agreement with radiometric age determinations on the magmatic rocks (Peters and Mercolli, 1997; Peters et al., 1997).

(3) The lithostratigraphical and compositional relationships within the mantle and crustal sequence have been described by Peters and Mercolli (1997) and the peculiar extremely reduced thickness of the oceanic crust are discussed by Peters and Mercolli (1998).

(4) Meyer et al. (1996) have studied the Early Cretaceous alkaline magmatism.

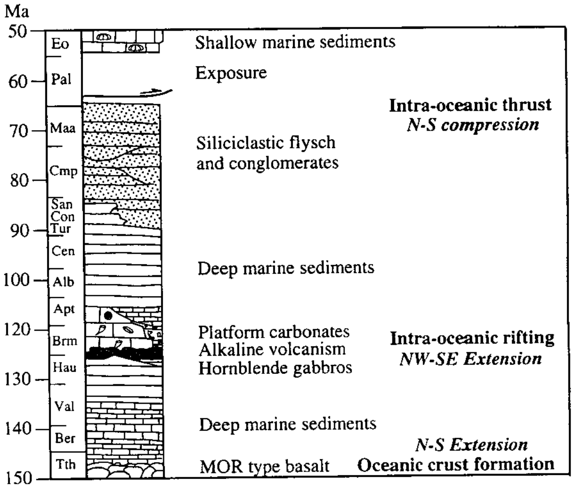

Fig. 1. Summary of the main tectonic events in the Masirah Ophiolite and sketch of the main types of sediment deposits, not scaled (time scale: Harland et al., 1982).

(5) Marquer et al. (1995) have demonstrated the presence of two ophiolite nappes on Masirah as the product of an intra-oceanic thrusting event pre-dating the obduction of the whole ophiolite onto the Arabian continental margin.

(6) A palaeomagnetic study (Gnos and Perrin, 1996) has revealed that the Masirah Ophiolite was formed in the proto Indian Ocean at around 40°S and moved subsequently northwards together with the Indian plate.

The results of these studies have allowed a reinterpretation of the evolution of the Masirah Ophiolite (Peters and Mercolli, 1997), which can be summarized as follows (Fig. 1)

The oceanic crust was formed in Tithonian times (Beurrier, 1987; Immenhauser, 1996) as a consequence of rifting between Africa and Madagascar/India, similar to the Somali basin (Gnos and Perrin, 1996). Peculiar characteristics of this oceanic crust are its extremely reduced thickness (max. 2 km) and the transitional N- to E-MORB affinity of the basaltic rocks (Peters and Mercolli, 1998). After a period of quiet subsidence recorded by pelagic sedimentation during 25–30 Ma (Immenhauser, 1996), a rapid tectonic event modified the previous oceanic lithosphere geometry. This short-lived event between the late Hauterivian and the early Barremian was associated with shallow marine deposits, platform

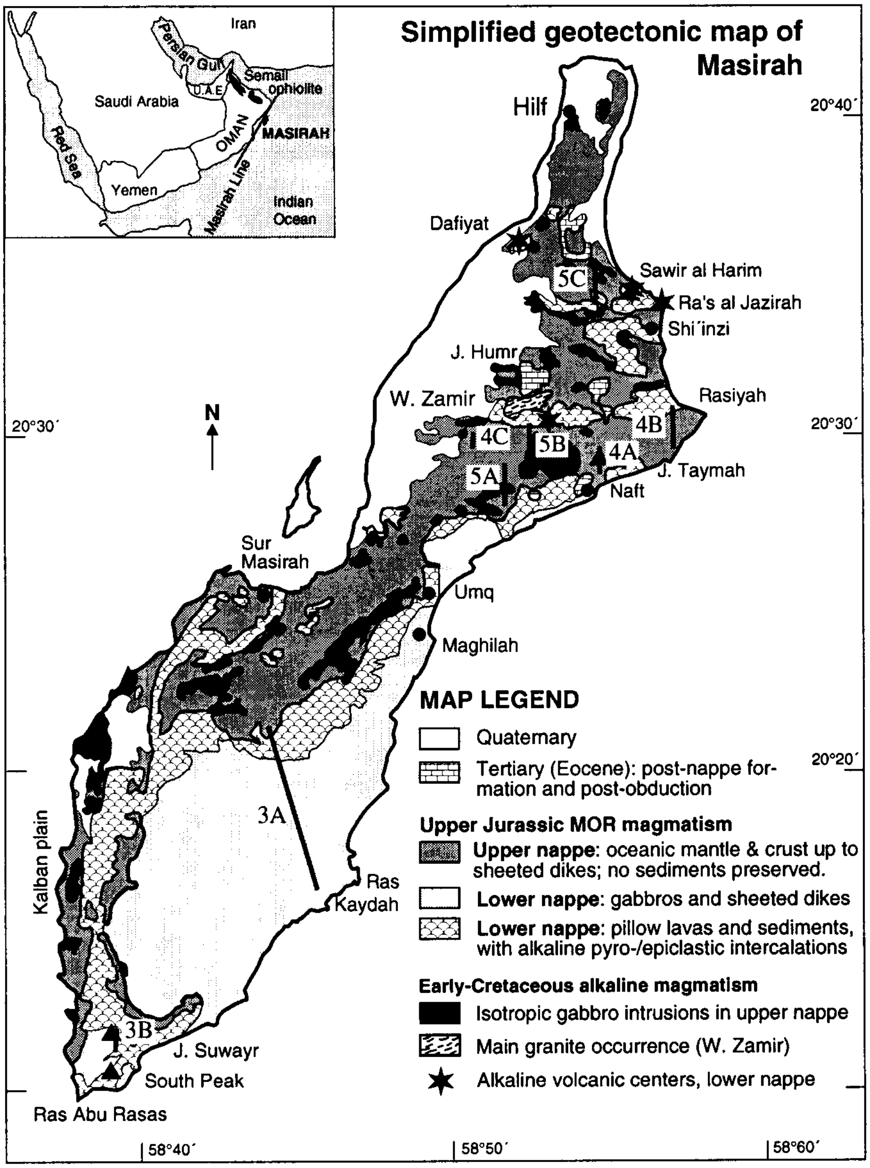

Fig. 2. Simplified geotectonic map of Masirah Island. The cross-sections presented in the following figures are indicated by heavy black lines.

carbonates, turbidites and debris flows (Immenhauser, 1996). Alkaline volcanism of OIB affinity (Meyer et al., 1996) and the intrusion of a hornblende gabbro–granite suite (Peters and Mercolli, 1997) affected the Late Jurassic oceanic lithosphere at this time (130–125 Ma). After this tectono-magmatic event, 40 Ma of quiet pelagic sedimentation and subsidence took place. During the Campanian–Maastrichtian time, a siliciclastic flysch sequence formed (Immenhauser, 1996), which pre-dates the intra-oceanic thrusting event. This Paleocene convergent event led to the superposition of two nappes, the Lower and the Upper Masirah Nappes (Fig. 2) separated by the Main Masirah Thrust (MMT) (Marquer et al., 1995). Shear sense indicators give consistent indications for a top-to-the-south movement of the Upper Masirah Nappe (Marquer et al., 1995). As the Upper Masirah Nappe overlies upper Maastrichtian sediments a minimum age of about 65 Ma for this major tectonic event is inferred (Fig. 1). This intra-oceanic nappe thrusting shortly pre-dates the obduction of the Masirah Ophiolite on the Arabian continental margin. Middle Eocene marine deposits, corresponding to a shallow marine transgression, unconformably overlie the nappe pile. Finally, intense brittle extensional tectonics have affected the whole ophiolitic sequence (Marquer et al., 1995), leading to the present-day complicated shape of Masirah Island (Fig. 2).

3. Geometry of the oceanic crust

Four major tectonic events affected the Masirah Ophiolite leading to its present-day geometry (Fig. 1): (1) the Late Jurassic spreading phase with the formation of new oceanic lithosphere; (2) the Early Cretaceous oceanic rifting related to renewed magmatism and drastic change in sedimentation regime; (3) the Early Paleocene intra-oceanic thrusting of the two Masirah ophiolite nappes and the subsequent obduction; (4) the post-Early Oligocene block faulting.

In order to understand these complex structural relationships, we describe below structural and petrological relationships along a series of cross-sections through the Lower and Upper Masirah Nappes (see cross-section locations in Fig. 2).

3.1. Geological description of the Lower Masirah Nappe

The oceanic lithosphere of Masirah Island is strongly perturbed by Late Tertiary faulting. However, Late Jurassic ridge-related magmatism and subsequent sedimentation is well represented in the Lower Masirah Nappe (Fig. 3). Mapping of the Lower Masirah Nappe showed that mainly Late Jurassic crust occurs in this lower structural unit. Cross-sections reveal a classical layering of the oceanic lithosphere which from bottom to top comprises: harzburgite, petrographical moho, layered olivine gabbros with intrusions of melanotroctolite, wehrlite and plagioclase dunite, foliated gabbros intruded progressively by the sheeted dike complex, volcanics and deep marine sediments. The peculiar characteristic of this primary oceanic crust is its extremely reduced thickness (Peters and Mercolli,

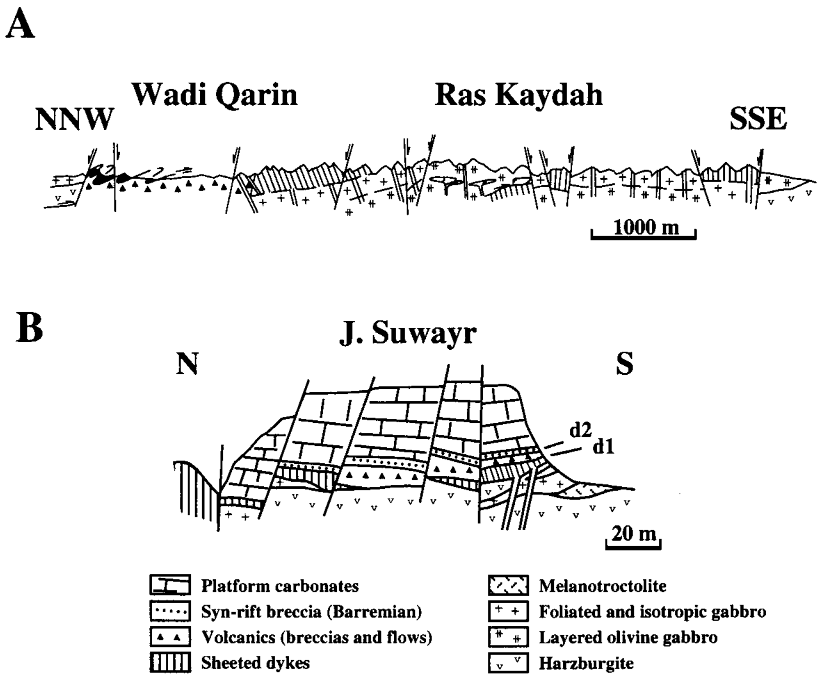

Fig. 3. Cross-sections of the Late Jurassic thin oceanic crust in the Lower Masirah Nappe. See location in Fig. 2.

1998). A cross-section between Wadi Qarin and Ras Kaydah shows that the entire thickness of the oceanic crust hardly exceeds 1.5–2.0 km (Fig. 3A). The presence of intense faulting and some local block tilting interrupting the vertical and lateral continuity of the profiles, makes it difficult to measure accurately the thickness of each layer. Nevertheless, in combining many different profiles, the excellent three-dimensional exposure over the entire island allows a realistic estimation of the thickness of each layer. The unusually thin crust is almost entirely due to the abnormally reduced gabbro layer (layer 3). In fact, the thickness of the gabbroic sequence between the mantle harzburgite and the sheeted dike complex, never exceeds 500 m and shows important variations within the different profiles. In contrast to the thin lower crust, the upper crust shows a more normal thickness of around 1.0–1.5 km. The sheeted dike complex is estimated to be at most 1 km thick, whereas pillow lavas and sediments rarely exceed 250–500 m in thickness.

The complex internal structure of the gabbroic lower crust is related to the internal dynamics of the magma chamber, i.e. intrusion and subsequent viscous deformation of the suite of plagioclase dunites, plagioclase wehrlites and melanotroctolites in the layered gabbro. In spite of this internal complexity, no evidence of important post-emplacement discontinuities and/or strongly deformed zones was found in the lower crust. Internal layering of the gabbros and the attitude of the peridotitic intrusions are normally subparallel to the Moho (Fig. 3A and also Fig. 4A for

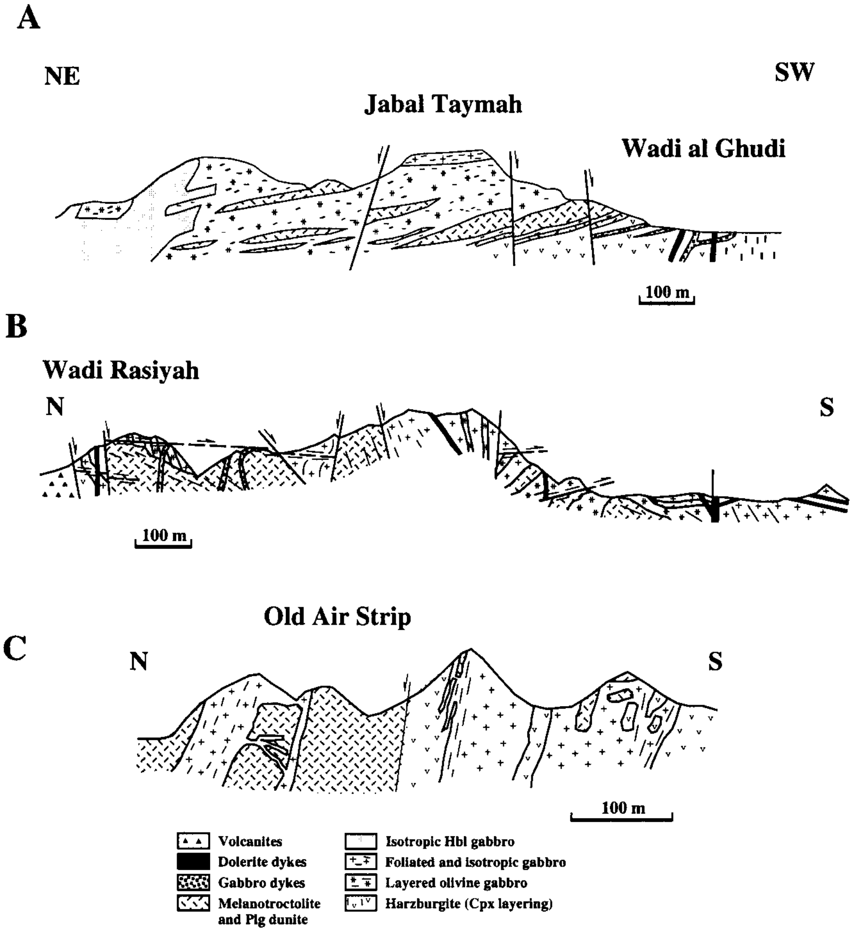

Fig. 4. Cross-sections of the Late Jurassic oceanic crust in the Upper Masirah Nappe. See location in Fig. 1.

the Upper Masirah Nappe). The transition of gabbro to sheeted dike is gradual, marked by the continuous upwards increase of the dike frequency. All these observations point to the same conclusion: the lower and the upper limits of the gabbro layer have been preserved in the original attitude, unaffected by important post-emplacement tectonics. Consequently, the estimated thickness of maximum 500 m should correspond to the original thickness of the gabbro layer of the Late Jurassic oceanic crust.

The dikes of the sheeted dike complex in the Lower Masirah Nappe strike mainly E–W with dips varying between 70° and 90° (Fig. 9A).

The crustal rocks underwent an intense brittle faulting which was related to the ridge tectonics and which is particularly well visible in the sheeted dike complex. The faults form an orthogonal network with the dominant direction oriented parallel to the dike walls (i.e. E–W). The frequency of these faults is extremely high, with 2–4 small faults per metre and each fault showing a vertical displacement of several centimetres. These fault types are always filled with prehnite and are crosscut by late dikes indicating that they were produced just after the emplacement of the dikes during ridge-related hydrothermal activity (Peters et al., 1997).

In summary, the lithostratigraphic sequence of the Late Jurassic crustal rocks in the Lower Masirah Nappe contains all members of a model oceanic crust (Anonymous, 1972) in the correct vertical relationships, but with an anomalous reduced thickness of the gabbroic lower crust.

The sediments on top of the volcanic pile (Figs. 1 and 3A) range from radiolarian micrite of Tithonian to Valanginian age at the base, up to Hauterivian ribbon bedded radiolarian cherts at the top (Maghilah Unit, Immenhauser, 1996). At the end of the Hauterivian, the sedimentary record changes drastically (Immenhauser, 1996). Sedimentary breccias in half-graben structures occur at Suwayr, in the south of the island (Figs. 3B and 8A). There, Barremian conglomerates (Fig. 3B, d2) followed by reefal platform carbonates lie directly and unconformably on an eroded basement of harzburgite, foliated gabbros and sheeted dike complex. These conglomerates overlie locally alkaline volcanic breccias and flows, which themselves lie unconformably on the eroded rocks of the oceanic crust located below (Fig. 3B, d1). There, alkaline volcanics are widespread and occur on top of the Lower Masirah Nappe, representing a new magmatic event after Late Jurassic ridge magmatism. They coincide with the change in the sediments from deep to shallow marine deposits (Meyer et al., 1996).

Barremian and Aptian times are characterised by local build up of reefal platform carbonates, limestone breccias and renewed subsidence with the sedimentation of radiolarian micrite (lower Kalban Unit, Immenhauser, 1996). From the Albian to Coniacian/Santonian, the whole Lower Masirah Nappe was subsided and ribbon bedded radiolarian cherts were deposited (upper Kalban Unit, Immenhauser, 1996). The top of the Lower Masirah Nappe is formed by flyschoid sediments with continental detritus of Coniacian/Santonian to late Maastrichtian age (Fayah Unit, Immenhauser, 1996).

3.2. Geological description of the Upper Masirah Nappe

The Upper Masirah Nappe shows a more complex geometry and lithological composition than the Lower Masirah Nappe. It consists partly of Late Jurassic oceanic crust similar to the Lower Masirah Nappe. This crust was affected by strong Early Cretaceous faulting and the related intrusion of a suite of isotropic/pegmatitic hornblende gabbros, dolerites and granites. In contrast to the Lower Masirah Nappe, the Upper Masirah Nappe ends with a few outcrops of pillow lava and no sedimentary cover has been preserved on the top.

The section at the Jabal Taymah (Fig. 4A) shows mantle and lower crustal sequences with a geometry and composition identical to the Lower Masirah Nappe. The Moho is flat or gently dipping towards the northeast. Above the Moho, numerous melanotroctolite bodies intrude the layered olivine gabbro parallel to its internal structure. At the top of the Jabal Taymah, a gradual transition between olivine gabbro and foliated gabbro is exposed.

The sections south of Wadi Rasiyah (Fig. 4B) and near the Old Air Strip (Fig. 4C) show the same petrographic sequences at the transition of mantle to lower crust, albeit with a different geometry. At Wadi Rasiyah (Fig. 4B) the layering in the gabbros and the contacts of the melanotroctolite intrusions

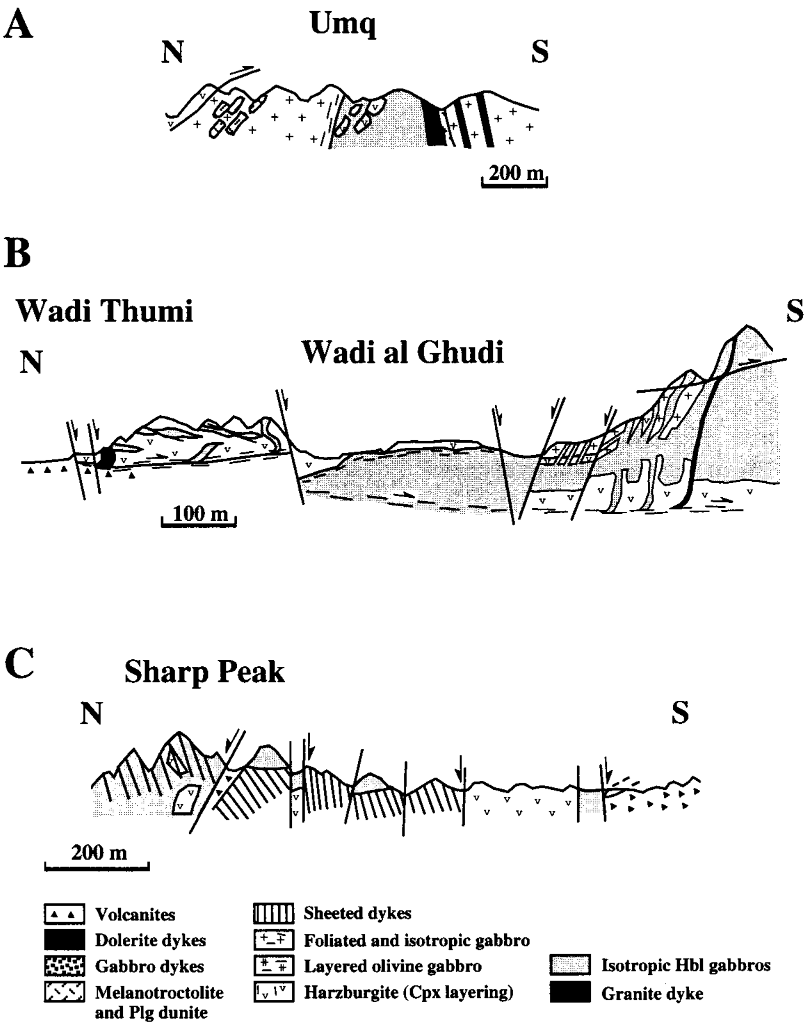

Fig. 5. Cross-sections showing the intrusive relationships between the Early Cretaceous hornblende gabbro–dolerite–granite suite in the Late Jurassic oceanic crust of the Upper Masirah Nappe. See location in Fig. 2.

dip clearly steeper (40°–60°) as at the Jabal Taymah (20°), and at the Old Air Strip the same lower crustal structures become subvertical. In this last section (Fig. 4C), the episodic growing of the Late Jurassic crust through multiple intrusion processes is demonstrated by the widespread occurrence of huge blocks of harzburgite, layered olivine gabbro and melanotroctolite within the foliated gabbro (stopping structures).

In the northern part of the island, near Hilf, a dike complex develops directly from the mantle harzburgite without the presence of lower crustal gabbroic rocks. Dike complexes with harzburgite screens crop out also in the region between Dafiyat and Shi'inzi (Fig. 2), particularly at Sharp Peak (Fig. 5C). Since in this region the same dikes intrude also the Early Cretaceous isotropic/pegmatitic hornblende gabbro (Fig. 5C), it is assumed that a conspicuous portion of sheeted dike outcropping in the northern part of the Upper Masirah Nappe is not related to the Late Jurassic ridge magmatism but is part of the Early Cretaceous extension event (see section on structures and kinematics). The absence of contact metamorphism between harzburgite (now nearly completely serpentinized) and the dikes demonstrates that the harzburgite was not serpentinized at the time of the intrusion.

A peculiar characteristic of the Upper Masirah Nappe is the intrusion of a suite of isotropic/pegmatitic hornblende gabbro associated with dolerite dikes and granites in the lower part of the Late Jurassic crust. The three rock types are always clearly associated with each other. The hornblende gabbros form large (several km^2) bodies, but also decimetre- to metre-thick dikes, intruding, at the Moho level, mantle harzburgite and lower crustal gabbros. The intrusive character is well demonstrated by the widespread occurrence of harzburgite, layered olivine gabbro and melanotroctolite blocks (roof pendants) at the borders of the hornblende gabbro bodies (Fig. 5). Dolerite dikes crosscut the hornblende gabbro and with increasing dike frequency a new sheeted dike complex develops (Fig. 5C). Locally, doleritic material forms mingling structures (enclaves, schlieren) within the hornblende gabbro. Granite dikes and small bodies are often associated with the hornblende gabbro. The granite intruded the gabbro along brittle fractures and angular gabbro blocks are dispersed in the granite. Furthermore, the dolerites consistently show mingling structures with the granite demonstrating a close genetic and temporal relationship between the two rock types.

Several hornblende gabbro bodies are roughly elongated and aligned NE–SW (Fig. 2). This direction is the same as the strike direction of the dolerite and granite dikes (Fig. 9B) and of the Early Cretaceous alkaline dikes in the Lower Masirah Nappe.

The age of the suite is best constrained by Ar/Ar ages on biotite and hornblende ranging from 125 to 130 Ma (Peters and Mercolli, 1997). A detailed mineralogical and geochemical description of the hornblende gabbro, dolerite and granite suite is presented by Peters and Mercolli (1997), whereas the isotopic characteristic of the granites is discussed by Nägler and Frei (1997).

3.3. The Early Cretaceous event

Before the Early Tertiary thrusting phase, the Upper Masirah Nappe was located at least 100 km further north with respect to the Lower Masirah Nappe (Marquer et al., 1995). Two synthetic cross-sections of the Upper and Lower nappes summarize the main results concerning the bulk geometry of the Masirah ophiolite (Fig. 6).

Both nappes contain an essentially complete Late Jurassic oceanic sequence. In the Lower Masirah Nappe, the Hauterivian/Barremian half graben structures (Fig. 8A) and the platform carbonates deposited unconformably on harzburgite, gabbro and sheeted dikes (Fig. 3B) are evidence for strong extension tectonics with denudation of the Late Jurassic oceanic lithosphere until the oceanic mantle was exhumed to the surface. This extension is coeval with the eruption of alkaline volcanites (Meyer et al., 1996) and is sealed by the Barremian sedimentation. At the same time in the Upper Masirah Nappe, the hornblende gabbro–dolerite–granite suite intrudes the cold Late Jurassic oceanic lithosphere (130–125 Ma, Peters and Mercolli, 1997). The variation in dip of the primary, ridge-related structures (Fig. 4) together with the emplacement of sheeted dikes directly in the mantle harzburgite is interpreted as block tilting during the Early Cretaceous extension tectonics. In the following section, we will focus on the deformation and kinematics coeval with Early Cretaceous magmatism.

4. Structures and kinematics of the Early Cretaceous event

Evidence of extension and thinning of the Late Jurassic oceanic lithosphere is observed in different members of the Masirah Ophiolite. Here, we describe first a syn- to post-tectonic ductile extension in the Early Cretaceous hornblende gabbro–dolerite–granite suite and secondly normal faulting and brittle extension of the Late Jurassic oceanic crust.

4.1. Syn-to post-emplacement extension in the hornblende gabbro–dolerite–granite suite

High-temperature (upper greenschist–lower amphibolite facies) ductile shear zones are present in the hornblende gabbros and granite bodies (Fig. 8D). As these ductile structures have only been observed in the Early Cretaceous intrusions and not in the Late Jurassic rocks, this deformation is claimed to be closely related to the emplacement and cooling of these bodies. The Early Cretaceous age of this deformation is confirmed by Ar/Ar dating on green actinolitic hornblende from the mylonitic shear zones yielding ages between 120 and 130 Ma (Frei et al., in prep.). Most of these strongly deformed

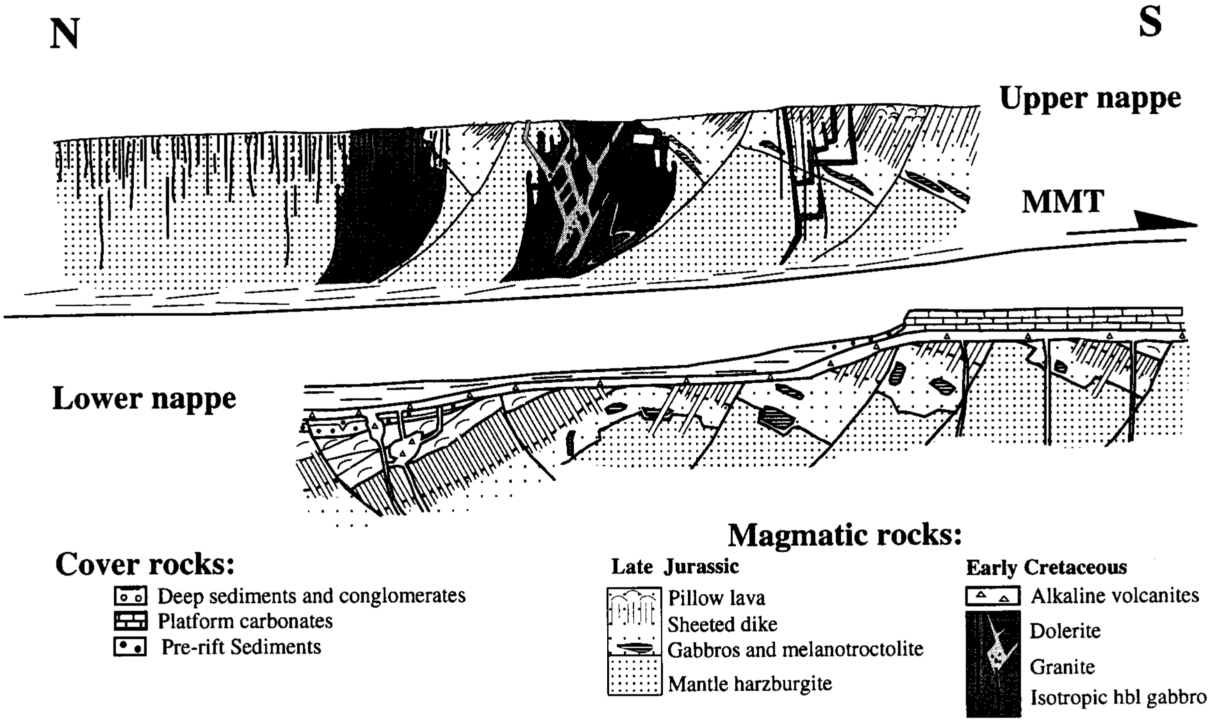

Fig. 6. Sketch of the geometry and magmatic relationships in the Upper and Lower Masirah Nappes based on the cross-sections previously presented.

zones are flat or show shallow dips towards the northwest and the southeast (Fig. 7A, circles). The associated stretching lineation, shown by preferred hornblende and aggregate orientations, strikes in a NW–SE direction, mainly down-dip on the shear zone planes (Fig. 7A, white squares). The shear criteria, well-expressed by C/S structures, asymmetric porphyroclasts or asymmetric deviation of old planar

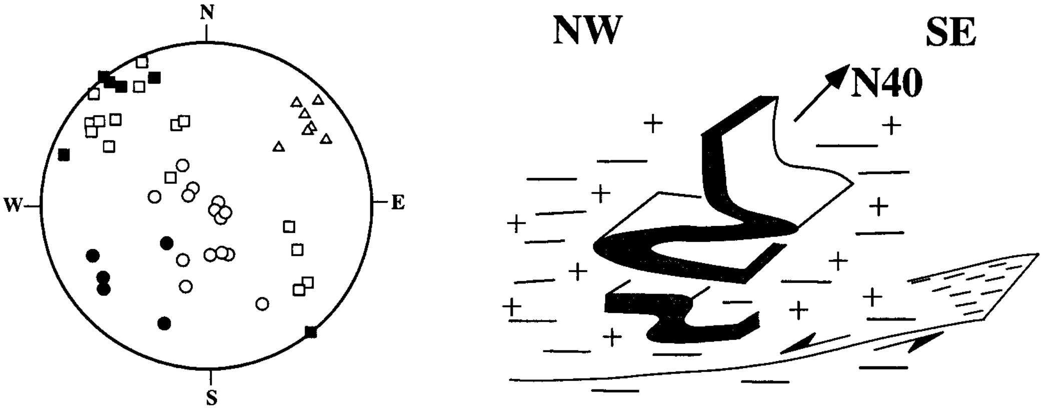

Fig. 7. High-temperature shear zone geometry and fold axes of granitic dikes. (A) Wulff stereogram (lower hemisphere); circles and white squares represent respectively poles of extensive shear zones and associated stretching lineations; dots and black squares represent respectively poles of sinistral shear zones and associated stretching lineations; triangles are fold axes of dikes. (B) Sketch of the relationships between extensional shear zones and dike folding in gabbroic rocks.

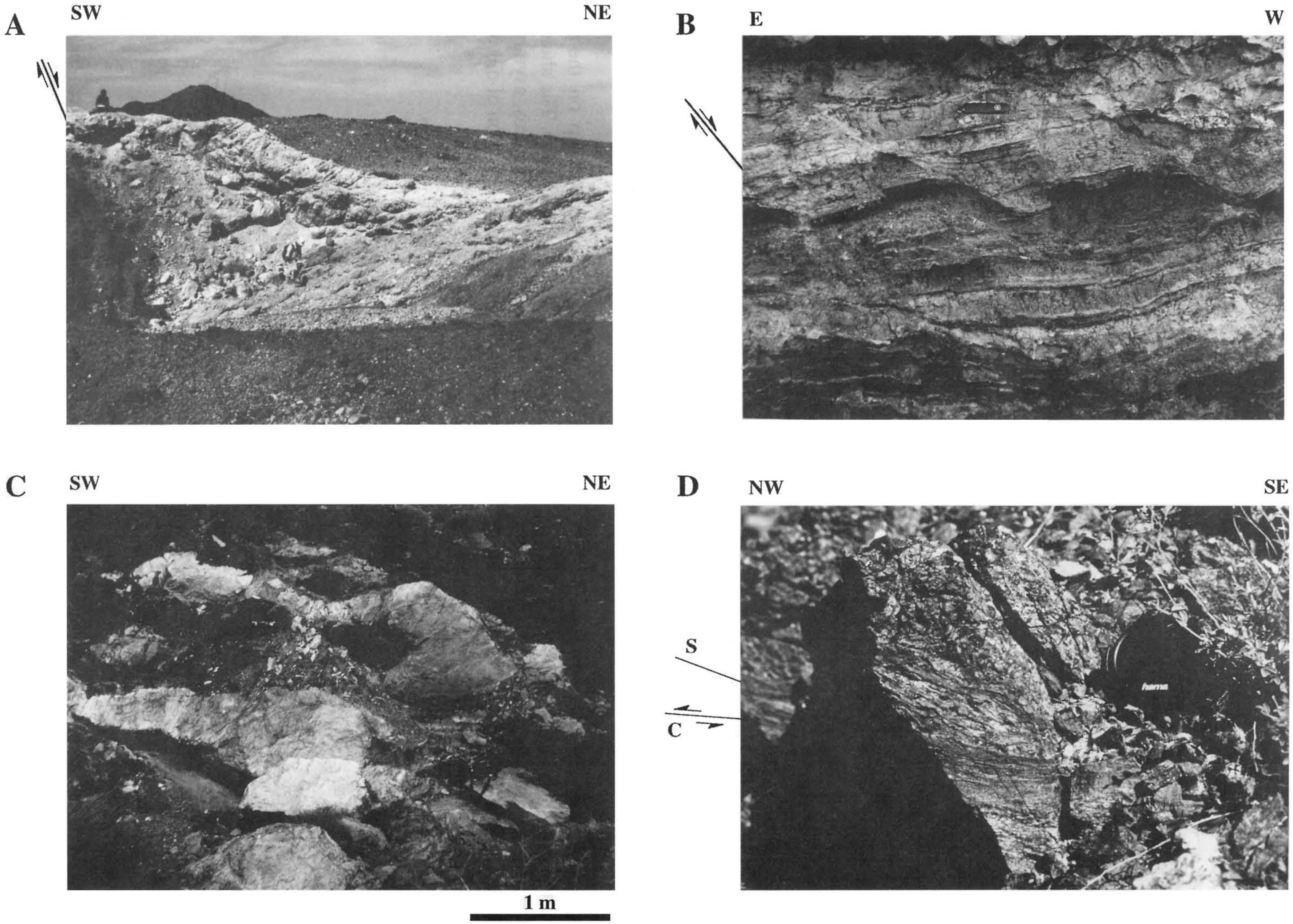

Fig. 8. Tectonic structures coeval with the rifting of the oceanic lithosphere. (A) Half graben, lying in harzburgite with infilling of volcanics and breccias and covered discordantly by Barremian platform carbonates, Wadi Suwayr. (B) Syn-sedimentary normal faults, Wadi Shi'inzi. (C) Folded granite dike, Wadi Gudi. (D) Amphibolite shear zone in hornblende gabbro, Wadi Shi'inzi.

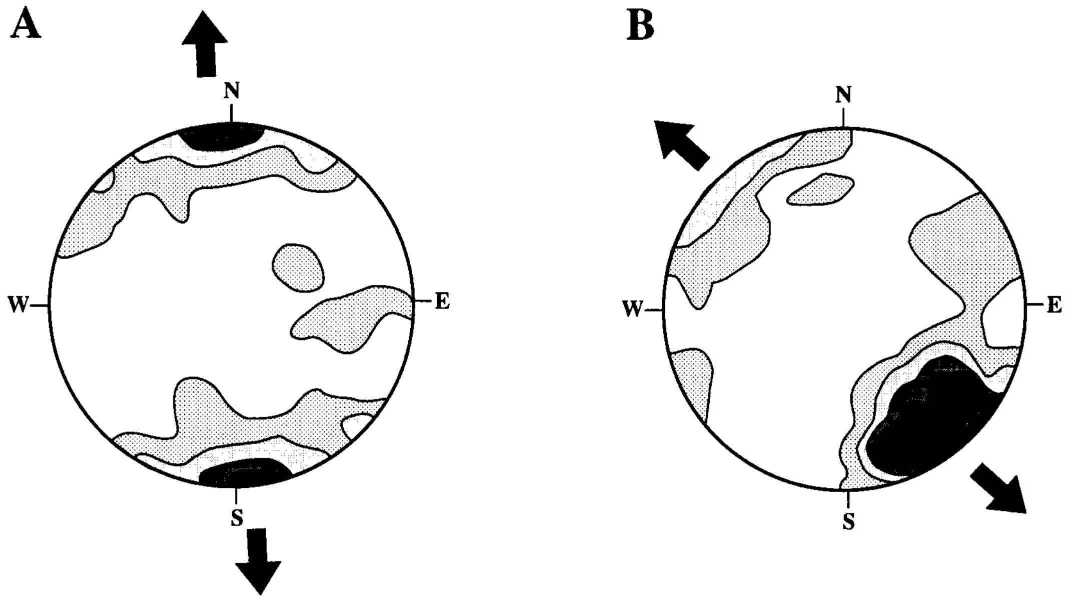

Fig. 9. Schmid equal area stereogram (contours every 25%). (A) Poles of the dolerite dikes from the Late Jurassic sheeted dike complex (438 data). (B) Early Cretaceous alkaline dolerites, granite dikes and associated dolerites (104 data).

structures (Berthé et al., 1979; Simpson and Schmid, 1983), are coherent with a bulk NW–SE extension because all these flat shear zones act as two conjugate sets of ductile normal faults. A third set of shear zones occurs and corresponds to NW–SE-oriented ductile sinistral zones (Fig. 7A, dots) with a shallow plunge of the stretching lineations (Fig. 7A, black squares). These sinistral shear zones are coeval with the ductile normal shear zones and compatible with the NW–SE extension. They have the orientation of ductile transform faults accommodating the horizontal NW–SE bulk displacement.

This evidence for ductile extension is associated with the observation of strong ductile vertical shortening (Figs. 7 and 8C). Folding is observed in various dike types intrusive into harzburgite or hornblende gabbro. A consistent fold geometry is recognized independent of the dike-type. The fold axes are gently northeast dipping in a N40–60 direction (Fig. 7, triangles) and the axial plane presents shallow dips of about 10–25° towards the northeast. These flat axial planes are consistent with a vertical ductile shortening of the oceanic crust, while the fold directions, corresponding to the direction of the Early Cretaceous dikes, give an indication for the extension direction during this tectono-magmatic event.

4.2. Brittle extension and thinning of the primary oceanic crust

The sheeted dike complex is the major brittle tectono-magmatic structure in the oceanic crust, reflecting the direction of the expansion of the oceanic lithosphere. Taking into account the geometry of the Late Jurassic oceanic crust, the direction of the dolerite dikes in the sheeted dike complex indicates a bulk north–south oceanic spreading direction (Fig. 9A). On the other hand, a new sheeted dike system formed in Early Cretaceous times, intruding the hornblende gabbro and the mantle harzburgite (Fig. 5C and Fig. 6). These dikes strike in a NE–SW direction and indicate a NW–SE direction of spreading during the Early Cretaceous tectono-magmatic event (Fig. 9B).

The consistent direction of the new extensive structures localized at different levels in the crust in the Upper Masirah Nappe (extensional shear zones, horizontal fold axial plane and direction of dikes), corresponds to a major normal faulting event recorded in the Hauterivian/Barremian sediments at the top of the Late Jurassic crust of the Lower Nappe. There, asymmetric half-grabens (Fig. 8A), syn-sedimentary faulting (Fig. 8B) and

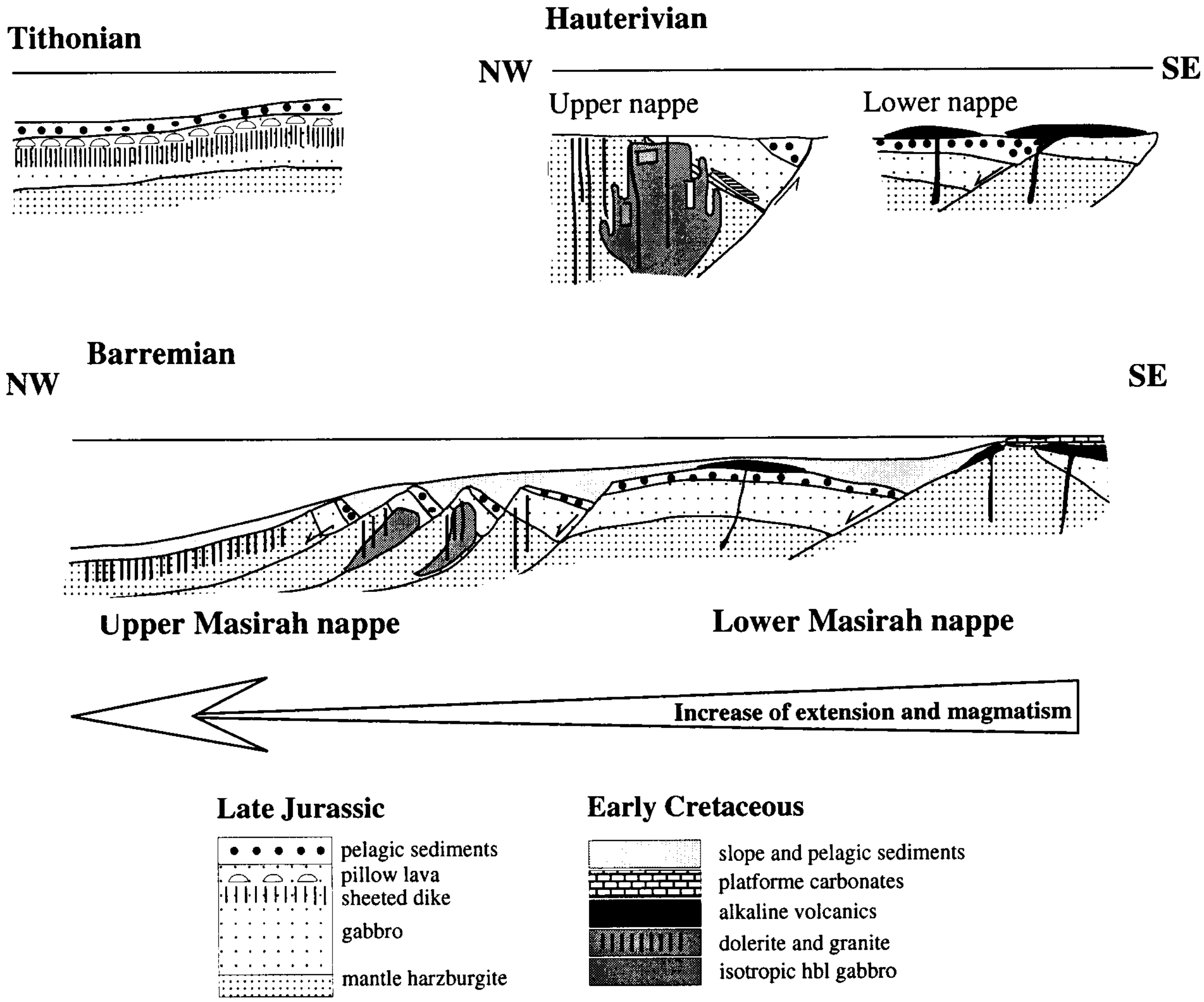

Fig. 10. Sketch of the bulk geometry of the Early Cretaceous rifting affecting the oceanic crust of the Masirah Ophiolite. Lower Masirah Nappe and Upper Masirah Nappe have been restored to their suggested original position prior to the Lower Tertiary thrusting.

occurrences of breccias with gabbro and harzburgite pebbles develop directly on the mantle harzburgite (Immenhauser, 1996). The occurrence of Barremian platform carbonates in the southern part of the island, lying directly on gabbros or harzburgite (Fig. 3C) are also indicative of a rapid extension and the occurrence of large detachment faults during Hauterivian/Barremian times. The mechanism governing the local uplift of crustal blocks allowing the deposition of the Barremian platform carbonate, however, remains unclear.

Finally, the regular NE–SW-striking alkali–basaltic and trachytic dikes of the Hauterivian/Barremian alkaline magmatism of the Lower Masirah Nappe (Meyer et al., 1996) outline once more the NW–SE Early Cretaceous extension (Fig. 9B).

This tectonic event is summarised in Fig. 10, where the Upper Masirah Nappe is restored in a northward direction in order to locate this part of the oceanic crust to its pre-intra-oceanic thrusting position. On this reconstruction, an increase of extension and magmatism is revealed towards the northwest. This tectonic event leads to mantle denudation with direct deposition of conglomerates and breccias on the top of harzburgite and the lower oceanic crustal rocks in the vicinity of the main normal faults.

Early Cretaceous magmatism seems to increase towards the northwest. In the Lower Masirah Nappe (SE) it is represented by the extrusion of small volumes of alkali–basaltic pillow lavas and breccias and the formation of kilometre size, isolated, seamount structures (Meyer et al., 1996). In the Upper Masirah Nappe (NE) large volumes of hornblende gabbro (kilometric sizes) intruded the lower crustal sequence and further northeast the exhumed mantle harzburgite is intruded by a large quantity of dikes. The lack of Early Cretaceous sediments, the scarcity of pillow lavas and the presence of large outcrops of mantle harzburgite and lower crustal gabbros in the Upper Masirah Nappe are interpreted to result from block tilting and strong erosion during the Early Cretaceous extensional phase.

5. From ocean floor formation to oceanic rifting

The tectono-magmatic and sedimentary events recorded in the Masirah Ophiolite emphasise that this portion of oceanic crust underwent a major rifting phase in Hauterivian/Barremian times, 20 Ma after its formation in Tithonian times. This observation integrated within a larger plate tectonic context permits a scheme for the early evolution of the Western Indian Ocean to be proposed (Figs. 1 and 11).

The Masirah Ophiolite formed in Late Jurassic times by the opening of the proto Western Indian Ocean between the African and Madagascar/Indian cratons (Coffin and Rabinowitz, 1992). It was located around 40°S (Gnos and Perrin, 1996), northeast of the coeval Somali Basin (Rabinowitz et al., 1983). The extremely variable and overall reduced thickness of the oceanic crust, particularly the fact that the gabbro layer never exceeds 500 m, is the major characteristic of this crustal building event. The lack of evidence for tectonic thinning during this first stage has led Peters and Mercolli (1998) to interpret the anomalous thin crust as the result of low magma supply with respect to the spreading rate at the end of a ridge segment close to the inside corner of a ridge-transform intersect. Due to the fit of the palaeomagnetic poles recorded in the Masirah Ophiolite with the Polar Wander Path of the Indian plate, Gnos and Perrin (1996) have suggested that the Masirah oceanic crust belonged to the Indian plate. As spreading in the proto Western Indian Ocean only just started in Late Jurassic times (Somali Basin: M22, Rabinowitz et al. (1983) or M25, Ségoufin and Patriat (1980)), the Masirah oceanic crust was not far away from the Indian continental margin, even if evidence for continentally derived detritic sediments is missing. After about 20 Ma of southwards motion and normal subsidence, a second tectono-magmatic event took place. A NW–SE extensional regime favoured the emplacement of alkaline seamounts on top of the pelagic Lower Cretaceous sediments (Fig. 10, Hauterivian). More or less coeval with alkaline volcanism, a suite of isotropic hornblende gabbro, dolerite and granite intruded the Late Jurassic harzburgite and layered olivine gabbro. Kinematics of lower-amphibolite to upper-greenschist facies extensional mylonite in the hornblende gabbro, strikes of the dolerite and granite dikes, and subhorizontal fold axial planes of granite dikes, all point to a NW–SE-directed extensional regime that developed in the pristine oceanic lithosphere.

The geochemical characteristics of the two Early Cretaceous magmatic events are quite different. The alkaline magmatism has a marked affinity to OIB magmatism and Meyer et al. (1996) have suggested a possible influence of a hot spot through the contribution of melts. It is interesting to note that the Masirah crust could have reached 50°S around 130 Ma. This means approximately the actual position of the Marion hot spot, which can be traced back until around 100 Ma along the east coast of Madagascar (Storey et al., 1995). On the other hand, the coeval hornblende gabbro–dolerite–granite suite maintains a MORB character, but with a clear tendency to an enrichment of the light REE (Peters and Mercolli, 1997). Its isotopic composition (Nägler and Frei, 1997) deviates only slightly from the signature of the Late Jurassic MORB's, whereas the composition of the alkaline rocks (T.F. Nägler, pers. commun.) points to a more enriched mantle source for these melts. It is therefore difficult to link the two Early Cretaceous magmatic events to a unique mantle source and to explain the differences in composition only by changing degrees of partial melting of the same source. One can tentatively argue that the primitive melts of the alkaline volcanics of the Lower Masirah Nappe were produced at considerable depth by low degrees of partial melting of an

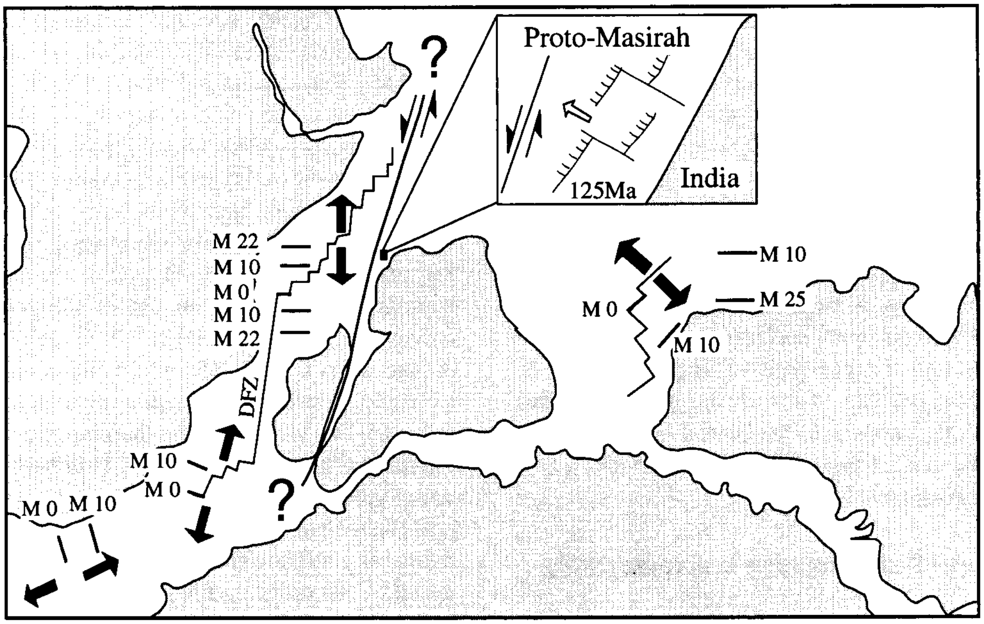

Fig. 11. Sketch of the suggested development of a dextral transform fault (or fault system) between India and Madagascar in Hauterivian–Barremian times, as a mechanism able to produce lithospheric extension in the Masirah basin. Plate reconstruction after Royer et al. (1992) at M0 (119 Ma), 5 to 10 Ma after the Early Cretaceous rifting event. As reference for the beginning of the rifting, the approximate position of the chron M22 (150 Ma) and M10 (130 Ma) are indicated. *DFZ* = Davie fault zone.

enriched mantle (Proto-Marion plume?), while the primitive melts of the hornblende gabbro–dolerite–granite suite of the Upper Masirah Nappe were produced by a higher degree of partial melting of a more depleted mantle source. This interpretation would fit the observation of the increase in volume of magmatic rocks from the Lower Masirah Nappe to the more NW located Upper Masirah Nappe (Fig. 10).

The sedimentary record on top of the Lower Masirah Nappe (Figs. 6 and 10) provides strong evidence for a lithospheric extension classically described in the passive margin during continental rifting processes (Lemoine et al., 1987; Boillot et al., 1995). The interaction between old ridge geometry and the new tectonic regime is believed to have caused the local uplift of blocks up to sea level with the subsequent deposition of Barremian platform carbonates on deeply eroded oceanic lithosphere (Fig. 3). This Early Cretaceous extension of the oceanic lithosphere in the Masirah basin, appears to be the local response to the global rearrangement of plate motion starting at this time. At M11 (ca. 130 Ma) the Southern Atlantic Ocean started to open between Africa, South America and Antarctica, while coeval oceanic crust developed between India and Australia. On the other side, east and west of the Davie Fault Zone the Somali and the Mozambique basins continued to spread in a north–south direction until M0 (119 Ma) (Fig. 11). We suggest that the Hauterivian/Barremian NW–SE extensional tectonics is related to the beginning of the relative motion between the Madagascar and the Indian plates. During this new northern motion of the Indian plate, probably along a sinistral strike slip fault, relaxation of buoyancy forces in the western Indian continental margin and adjacent oceanic crust (Masirah basin) could have led to the creation of normal faults with directions parallel to the continental margin (Fig. 11). This horizontal extension associated with vertical uplift and strong tilting of rigid blocks (Fig. 10) could be related to a local isostatic rebound as described in analogue experiments (Brun et al., 1994). The vicinity of the Indian continental crust and the occurrence of magmatic activity, leading to deep-seated low-viscosity heterogeneities, could be responsible for this isostatic rebound. Furthermore, as the upwelling of an asthenospheric mantle plume (proto Marion hot spot, Meyer et al., 1996) is assumed to be the cause of the renewed magmatic activity (alkaline magmatism and the gabbro–dolerite–granite suite), we suggest that this mantle anomaly could also have initiated the localisation in the Masirah basin and the decoupling between the N–S spreading in the Somali basin and the new NE-directed motion of the Indian plate.

6. Conclusions

Unlike other ophiolite complexes, the Masirah Ophiolite remained for nearly 100 Ma after formation part of an ocean basin before obduction in Early Tertiary times onto the Arabian continental margin. This peculiar history allows different tectonic, magmatic and sedimentary cycles affecting this portion of oceanic lithosphere to be described. To our knowledge, this is the first description of the timing, geometry, magmatism and sediment deposits associated with an intra-oceanic rifting in an ophiolite sequence. This Early Cretaceous oceanic rifting occurred at about 20 Ma after the Late Jurassic formation of the Masirah oceanic crust. The oceanic lithosphere of the Masirah basin was stretched in a NW–SE direction along NE–SW-trending normal faults. Half grabens filled with clastic sediments laying on tilted and deeply eroded oceanic lithosphere which have been sealed by Barremian shallow water platform carbonates, limestone breccias or deeper radiolarian micrites, are sedimentary indicators of this extensional tectonic phase. Alkaline volcanics and small seamount structures were emplaced at the same time along NE–SW-striking fractures in the Lower Masirah Nappe. In the Upper Masirah Nappe, a suite of intimately associated hornblende gabbros, dolerites and granites intruded the Late Jurassic crust at Moho levels following similarly NE–SW-oriented structures. These rocks show a syn- to post-emplacement extensional shearing and folding. Both magmatic events and related deformation emphasise the major contribution of the intra-oceanic rifting to the growth and tectonic development of the Late Jurassic lithosphere formed at a mid-ocean ridge by the opening of the Proto Indian Ocean. The Hauterivian/Barremian age of oceanic rifting coincides with an important reorganisation of the motion of the Indian plate relative to Africa, Antarctica and Australia. We interpret the rifting recorded in the Masirah Ophiolite as the local response to the NE-directed escape of the Indian plate due to the opening of the South Atlantic and spreading in the Eastern Indian Ocean.

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