Geochemistry
Geophysics
Geosystems
G^3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 3, Number 7
31 July 2002
10.1029/2001GC000228
ISSN: 1525-2027

Kinematics of mantle flow beneath a fossil Overlapping Spreading Center: The Wuqbah massif case, Oman ophiolite

Jacques Girardeau, Christophe Monnier, Patrick Launeau, and Frédéric Quatrevaux
UMR-CNRS 6112, Laboratoire de Planétologie et Géodynamique, Faculté des Sciences et Techniques, Université de Nantes, BP-92208, 44322, Nantes cedex 3 (Jacques.Girardeau@chimie.univ-nantes.fr)

[1] The Wuqbah massif (central Oman Ophiolite) comprises a well preserved <2 km thick crustal unit over a 6–8 km thick mantle sequence. The mantle comprises harzburgites and few dunites cut by various types of dykes. With the exception of basal and late fault zones, peridotites display granoblastic and porphyroclastic textures, acquired by high-temperature plastic deformation. They locally suffered important recrystallization as shown by neoblastic shapes and arrangements. Macroscopically, the peridotites have well-defined foliations and lineations, whose features allow the massif to divide into three structural domains. It comprises a N110° trending central zone that suffered an anticlockwise rotation, with an upwelling zone in its southwestern part, bound between two NS areas sheared in right-lateral conditions. This peculiar geometry is thought to reflect an overlapping spreading center (OSC) where the east and west bordering zones would define the trace, in the mantle, of two ridge segment terminations and the oblique N110° central zone the axial part of the overlap area. It is proposed that the northward migration of the southwest branch and its concomitant EW spreading caused the deformation and rotation of the overlap zone. In our OSC model, flow in the mantle would be continuous from one spreading center branch to the other, being curved in the overlap area to accommodate the offset. The mantle flow would therefore be more and more decoupled with the brittle crust when approaching the overlap zone, where extensional tectonics can occur. We consider that some mantle upwelling is possible due to its specific location, in between two ridge segments and over the main mantle flow. The distance between the two ridge axes is ~15 km, which means that this paleo-OSC can be ranked in the class of intermediate OSCs, illustrating a third-order ridge segmentation. At the scale of the ophiolite, the Wuqbah OSC is located northwest of a major domain marked by the presence of a NW-SE trending propagating ridge responsible for the formation of a new oceanic crust. It is suggested that the Wuqbah OSC formed earlier and underlines the trace of a ridge that had later migrated to the East.

Components: 8405 words, 12 figures,

Keywords: Structural data; Oman ophiolite; mantle dynamics; overlapping spreading center; propagating ridge.

Index Terms: 0930 Exploration Geophysics: Oceanic structures; 3035 Marine Geology and Geophysics: Midocean ridge processes; 8030 Structural Geology: Microstructures; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general.

Received 14 September 2001; **Revised** 8 February 2002; **Accepted** 15 March 2002; **Published** 31 July 2002.

Girardeau, J., C. Monnier, P. Launeau, and F. Quatrevaux, Kinematics of mantle flow beneath a fossil Overlapping Spreading Center: The Wuqbah massif case, Oman ophiolite, *Geochem. Geophys. Geosyst.*, *3*(7), 10.1029/2001GC000228, 2002.

1. Introduction

[2] Many scientists currently working on ophiolites agree that the Oman ophiolite represents several segments of an ancient oceanic lithosphere that was formed at a rather fast-spreading ridge, at spreading rates between 5 and 10 cm yr^{-1} [*Harcker et al.*, 1996; *Nicolas et al.*, 2000], either in small back arc basins [*Rothery*, 1983, *Lippard et al.*, 1986] or, more likely, in larger true oceanic domains [*Boudier and Coleman*, 1981; *Ceuleneer et al.*, 1988; *Juteau et al.*, 1988a, 1988b; *Nicolas et al.*, 1988a, 1988b]. On the basis of petrostructural studies carried out on this ophiolite, many across-strike models of spreading center dynamics have been proposed using data concerning either the crustal part of the ophiolite, mainly gabbros and sheeted dyke [*Smewing*, 1981; *Pallister and Hopson*, 1981; *Dahl*, 1984; *Ernewein et al.*, 1988; *Juteau et al.*, 1988a, 1988b; *Nicolas et al.*, 1988a, 1988b; *Boudier et al.*, 1996; *Kelemen et al.*, 1997] or the peridotites structures attitudes [*Ceuleneer et al.*, 1988; *Nicolas et al.*, 1988a, 1988b; *Ceuleneer*, 1991; *Reuber et al.*, 1991; *Ildefonse et al.*, 1995; *Jousselin et al.*, 1998].

[3] Most recent work on the Oman ophiolite has been concerned with along ridge variations evidenced by (1) changes in the nature and attitude of the sheeted dyke [*Reuber*, 1988; *MacLeod and Rothery*, 1992; *Nicolas et al.*, 2000], (2) thickness variations of the crustal unit [*Juteau et al.*, 1988a, 1988b] and of the mafic-ultramafic transitions zones [*Nicolas et al.*, 1988a, 1988b], or (3) the presence of mantle diapirs in relation or not with propagating rifts [*Ceuleneer et al.*, 1988; *Nicolas et al.*, 1988a, 1988b; *Ceuleneer*, 1991; *Reuber et al.*, 1991; *MacLeod and Reuber*, 1990; *Jousselin et al.*, 1998; *Nicolas et al.*, 2000]. Recognition of these later structures, marked by steep foliations and lineations, is of great interest because they describe mantle upwelling zones that relate the paleoridge dynamics. For instance, most of the diapirs present in the southern and central parts of the ophiolite (Samad-Maqsad-Bahlah-Nakhl-Rustaq-Haylayn), which are all aligned in the NW-SE direction, would reflect the northward propagation of a NW-SE trending new ridge segment into an older lithosphere formed along a NE-SW trending paleoridge [*Nicolas et al.*, 1988a, 1988b; *Nicolas et al.*, 2000]. However, such an origin has not been invoked for the Mansah diapir, located in the NE part of the Sumail massif, that has been interpreted as the deep root of an off-axis oceanic seamount [*Jousselin and Nicolas*, 2000b].

[4] The nature and origin of the diapiric structure identified in the Wuqbah massif [*Nicolas et al.*, 1988b], just west of the main propagator zone defined by the Samad-Haylayn alignment (Figure 1), is more enigmatic and questioned in a more recent paper [*Nicolas et al.*, 2000]. This is because it occurs at the end of a ridge segment and because it is potentially linked with the existence of an overlapping spreading center (OSC), as proposed by *MacLeod and Rothery* [1992] using data on the sheeted dyke complex. However, such settings are not expected to host mantle diapirs because the ends of ridge segments and OSCs are supposed to be low magma production zones and hence relatively cold areas devoid of upwelling centers [*MacDonald and Fox*, 1983; *MacDonald et al.*, 1986; *Martínez et al.*, 1997]. A first hypothesis was therefore that the Wuqbah diapir was not a mantle upwelling zone in the sense of the Maqsad diapir but another type of structure of unknown origin. A test of this hypothesis was the aim of our study of the Wuqbah massif, for which we have done a detailed sampling and structural mapping of its ultramafic part. On the basis of the mantle deformation field and on its kinematics, we propose that the Wuqbah massif and its associated upwelling zone reflect the geometry of the deep flow beneath a fossil OSC and discuss its formation and geodynamic significance.

2. Geology of the Wuqbah Massif

[5] The Wuqbah massif contains a large NW-SE trending syncline-like structure (~60 km long by 30 km large). In the center, the crustal rocks have been largely eroded. Mantle rocks are exposed at around (Figure 1) and are in thrust contacts with the nappe series (Sumeini and/or Hawasina). In the peridotites, contacts are always marked by the presence of low-temperature peridotites, generally transformed in schistose serpentinites, and in the nappe series, by

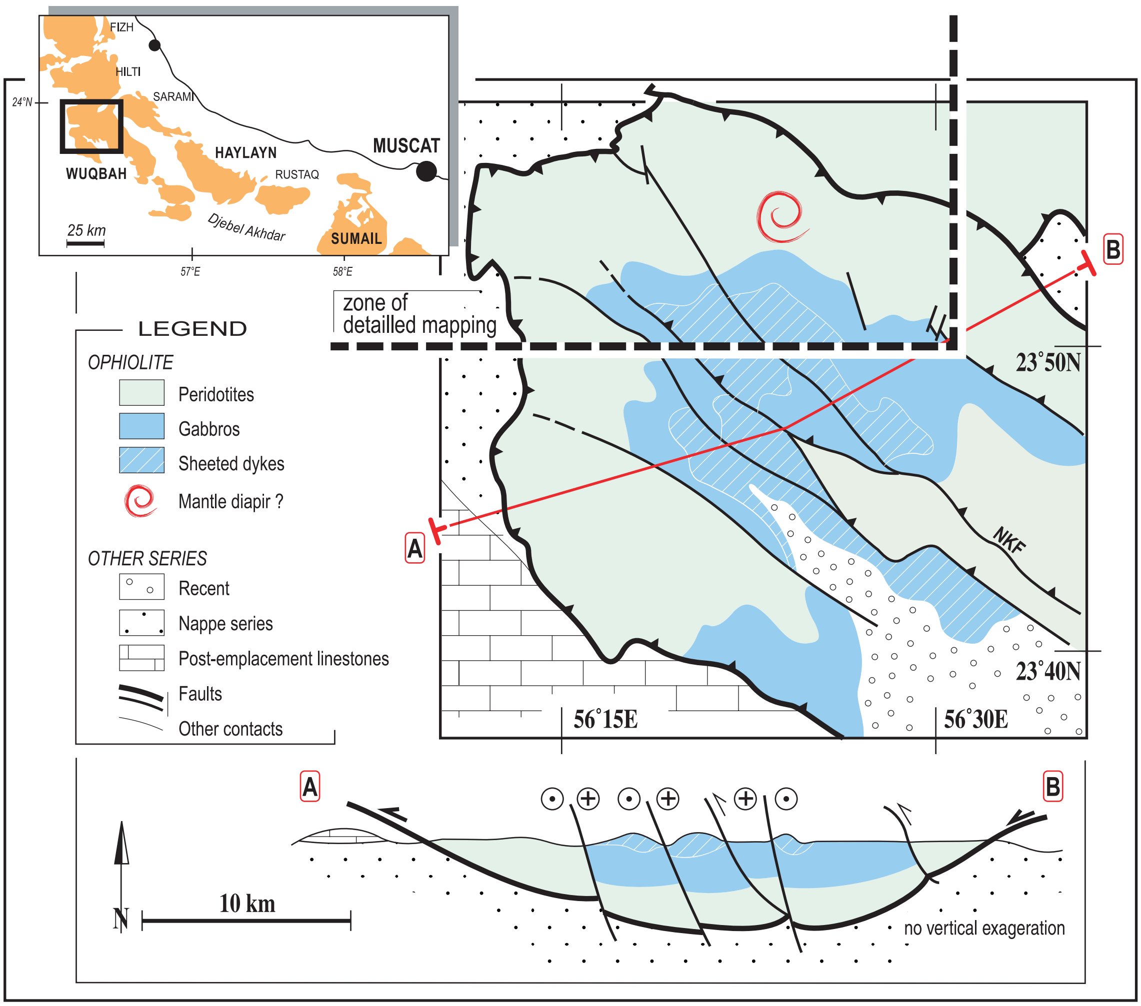


Figure 1. Location of the Wuqbah block in central Oman ophiolite (NKF, Najh al Kabstein Fault; modified after *Le Métour et al.* [1989], *Nicolas and Boudier* [1995], and *Rothery* [1982]).

a tectonic melange and/or brecciated rocks [*Glennie et al.*, 1974; *Le Métour et al.*, 1989; *Nicolas and Boudier*, 1991]. From the analyses of maps published by the latter authors, it was suggested that the Wuqbah block was imbricated by two NE dipping thrust sheets and later cut by vertical faults that cross through the whole ophiolite sequence. On the basis of the attitudes of the sheeted dykes that trend at about N160° to the north of the Najh al Kabstein fault (NKF) and at N175° southwest of it, *Rothery* [1982] divided the Wuqbah block into two parts separated by this fault and proposed that the northern block underwent a rotation of 15° relative to the southern block. This interpretation is no longer confirmed by our data, which indicate that dykes with the N160° trending attitudes are also present in the southwestern part of the NKF but that they are cut by the N175° dykes that constitute the main sheeted dyke complex. With the exception of this block rotation, *Rothery* [1982] considered that the stratigraphy of the ophiolite and the attitudes of the crustal main structures had not been significantly modified by the deformation related to ophiolite emplacement.

[6] *Rothery* [1982] described a complete ophiolitic sequence in the Wuqbah massif, including a thin, less than 2 km thick crustal unit comprising lavas, sheeted dykes, and gabbros, both isotropic and layered, over a 6–8 km thick harzburgitic mantle sequence. Whereas the lavas have been largely eroded and rare and only present in the SW part

of the massif where their structural thickness does not exceed 100 m, the sheeted dyke complex displays a considerable spatial distribution, typically forming vertical swarms of meter-thick grey to green dykes with common chilled margins over a thickness of nearly 0.5 km. Because of the MORB-type chemistry of the lavas and of the dykes, this ophiolite was considered as formed at an oceanic spreading center [*Rothery*, 1982].

[7] Underneath the sheeted dyke complex, dykes either cut already cooled gabbros or root into coarse isotropic gabbros. This is well seen in the eastern part of the massif where isotropic gabbros are rich in secondary amphiboles formed by replacement of clinopyroxene due to hydrothermal circulation. These gabbros grade locally into foliated rocks that display a vertical magmatic lamination parallel to the edges of crosscutting dykes. This indicates that the dykes were emplaced in a still hot and not consolided crust, likely above the magma chamber [*Rothery*, 1982]. The isotropic gabbros progressively pass downward into layered gabbros that contain olivine, plagioclase, and clinopyroxene compositional variations at the centimeter to meter scale. In the western part of the massif, dykes cut these already cooled layered gabbros. For *MacLeod and Rothery* [1992], these dykes underline along ridge intrusions of magma fed laterally from a magma chamber. For these authors, dykes from the western (laterally propagating) and eastern (rooted) parts of the massif originated in two distinct segments of ridge, a feature which is thought to occur at ridge segment terminations and/or in OSCs settings.

[8] These <1 km thick gabbros rest over mantle peridotites. The contact zone between the crustal rocks and the mantle unit is locally marked by a 200 m thick transition zone (MTZ) comprising dunites, wehrlites, and various types of gabbros. It is generally steeply dipping at more than 70°, a feature which is not related to late emplacement tectonics because of the lack of cold deformations along the contacts, but may have been acquired earlier, in the Wuqbah ridge environment, as already proposed for the Haylayn [*Juteau et al.*, 1988b; *Reuber et al.*, 1991; *Nicolas and Boudier*, 1995] and Fizh massifs [*Nicolas et al.*, 2000]. The presence of a steep Moho is significant because it is thought to occur at the tip of propagating ridges [*MacLeod et al.*, 1996; *Nicolas et al.*, 2000]. Both the rocks of the MTZ and the overlying gabbros are also locally cut by diabase dykes that continue upward into the sheeted dyke complex that largely outcrops in the southern part of the massif.

[9] The Wuqbah mantle unit mainly comprises serpentinized clinopyroxene-poor harzburgites and very few dunitic and chromitite pods. The peridotites were considered to be mantle tectonites, deformed at high temperature, at the mantle ridge axis [*Rothery*, 1982]. In these peridotites, whose general tectonic features were outlined, the presence of a mantle diapir (Figure 1) was suspected [*Nicolas and Boudier*, 1995].

3. Peridotites

[10] The Wuqbah peridotites are well exposed in the northern part of the Wuqbah block, where they constitute rather high, rugged, and poorly accessible mountains (elevation between 700 and 1300 m) cut by narrow wadies. We mapped in an area ∼20 km long (EW direction) by 6 km wide, located at the northwestern tip of the Wuqbah massif, in a zone thought to have been least affected by late deformation (Figure 1). Two hundred and fourteen samples were collected [*Quatrevaux*, 1995]. Their lithological and structural features are given here.

[11] The peridotites are mostly harzburgites (180 samples, 90%), locally rich in orthopyroxene, which either forms centimeter size layers parallel to the main foliation in the rocks or metric diffuse patches. It also comprises dunites (34 samples, 10%) that form patches and layers, and which toward the Moho are locally enriched in clinopyroxene along feeder zones, leading in places to the formation of wehrlites quite similar to those previously described in other Oman peridotites [*Jousselin and Nicolas*, 2000a, 2000b; *Nicolas*, 1986a, 1986b; *Reuber et al.*, 1991]. All the ultramafic rocks are cut by dykes, generally less than 10 cm thick, which grade from websterite in the basal part of the mantle sequence to gabbros and diabases in the upper levels. While most peridotites at the base of the sequence are mostly totally serpentinized,

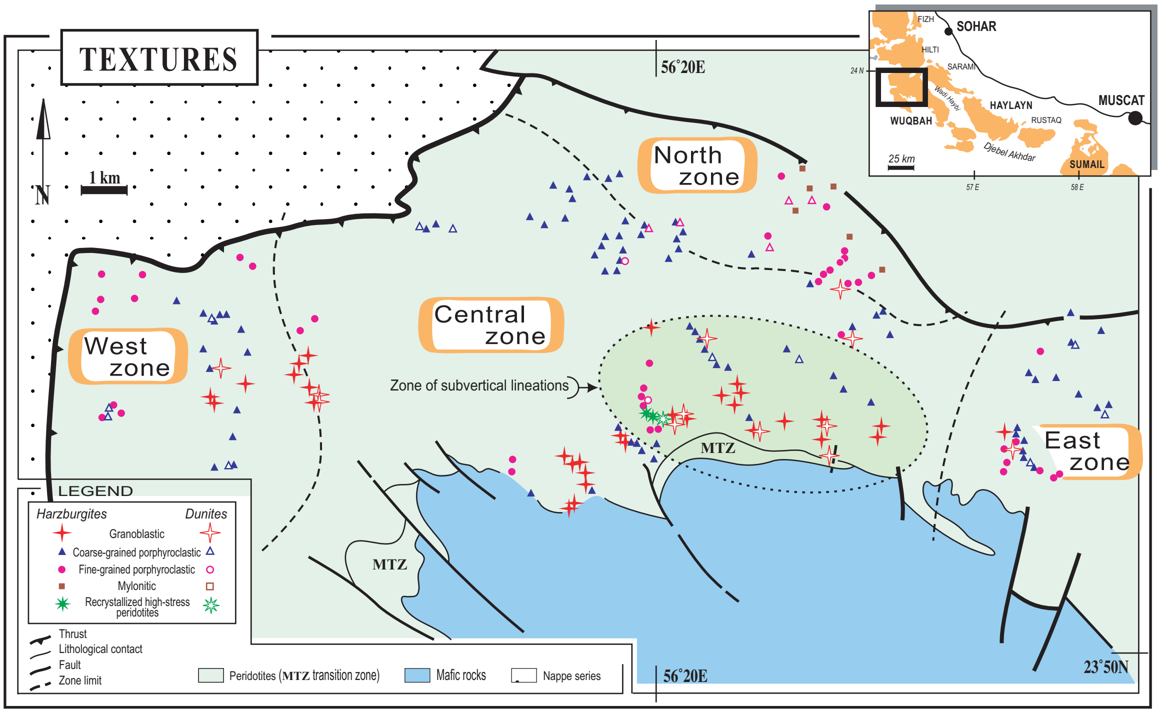


Figure 2. Map repartition of the different textures in the Wuqbah peridotites.

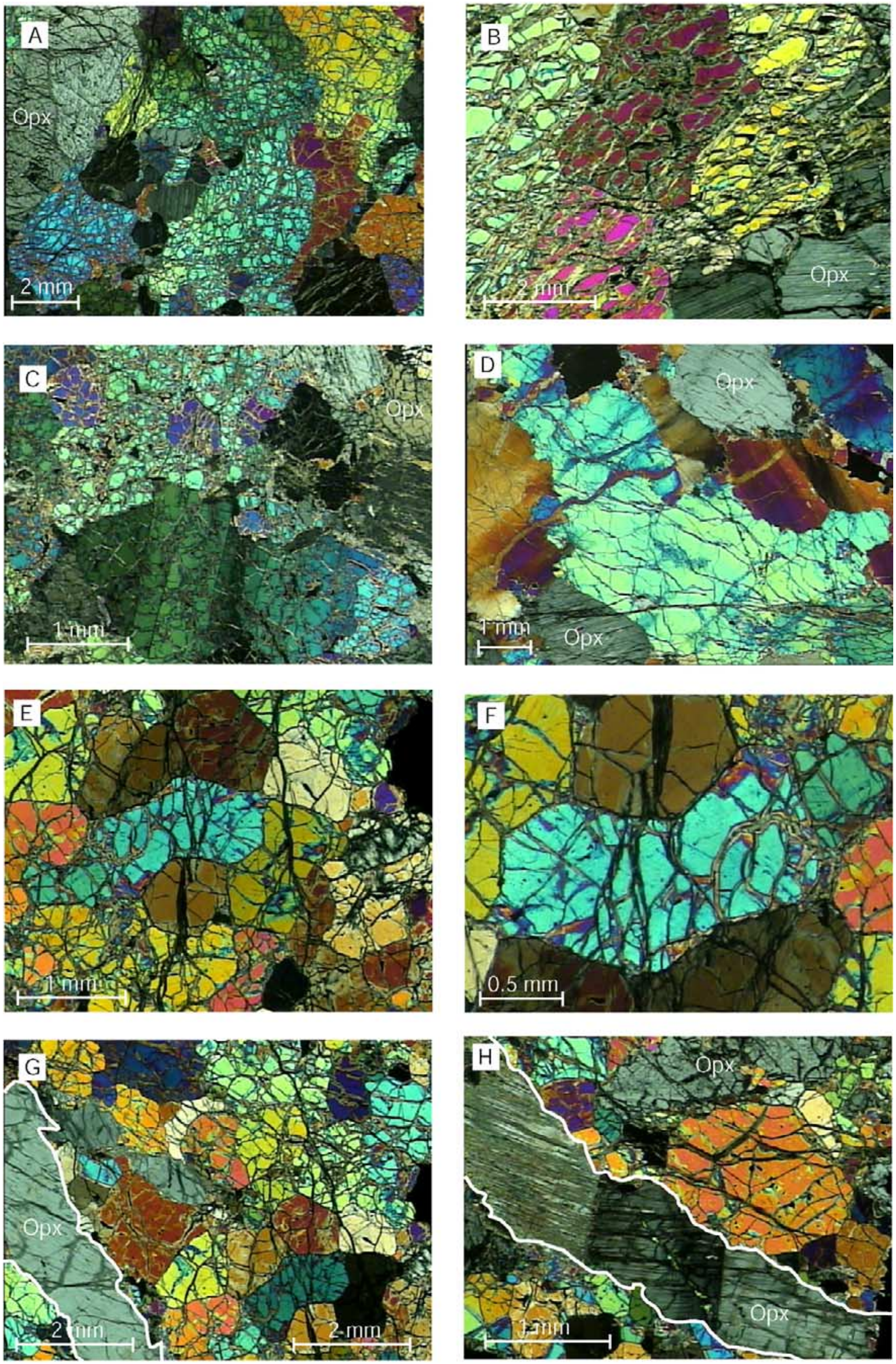
schistosed, and commonly strongly brecciated due to the ophiolite emplacement ("Basal Serpentinites" of *Rothery* [1982]), those from the central and uppermost parts of the sequence are rather fresh, with less than 30% of serpentine. Their total thickness is estimated at 6–8 km.

3.1. Textural Data

[12] Macroscopically, two dominant metamorphic structures were recognized within the peridotites, coarse textures associated with a weak shape preferred orientation of crystals and porphyroclastic structures marked by well–defined foliations and lineations. Under microscope, they correspond to the granoblastic and porphyroclastic textures that are commonly observed in mantle peridotites from massifs and xenoliths [*Harte*, 1977; *Mercier*, 1984; *Mercier and Nicolas*, 1975; *Nicolas*, 1986a, 1986b]. They have been found in both harzburgites and dunites. A few mylonitic structures were also found in peridotites from the basal parts of the massif and along some NW-SE faults that cut the peridotite massif, mainly in the western and central parts of the massif.

[13] Granoblastic textures are common in the Wuqbah peridotites (Figures 2, 3a, and 3b). This is significant because such textures are thought to represent the hottest and earliest texture recorded in the mantle unit. They are characterized by the presence of large (4–9 mm) and weakly strained olivine crystals, with rather irregular and curved grain boundaries. These have locally recrystallized into large (up to 1 mm) and totally unstrained neoblasts that display straight boundaries and common triple points. The associated orthopyroxenes form aggregates (4 mm) or occur as isolated crystals (same size) that locally show traces of resorption. Spinel crystals are always less than 1 mm in size and have irregular to dentritic shapes when associated with the orthopyroxene. However, when present at olivine grain boundaries, they form small and rounded crystals.

[14] The coarse-grained porphyroclastic textures (Figures 2, 3c and 3d) are characterized by large olivine porphyroclasts (6 × 2 mm), significantly strained, as indicated by widely spaced subgrain boundaries, and by the presence of small size (0.5–1 mm) neoblasts with rather regular outlines, sug-


A
Opx
2 mm
B
Opx
2 mm
C
Opx
1 mm
D
Opx
Opx
1 mm
E
1 mm
F
0.5 mm
G
Opx
2 mm
2 mm
H
Opx
Opx
1 mm

gesting an origin by subgrain rotation recrystallization. In these rocks, the orthopyroxene forms locally elongate aggregates (3–4 mm in size), or occurs as isolated rounded crystals (same size). Spinel (millimeter in size) generally occurs at the periphery of the orthopyroxene crystals or as scattered crystals associated with olivine. In the later case, it mostly displays irregular holly leaf type shapes, underlying the foliation that is also emphasized by olivine and orthopyroxene crystals or clusters.

[15] In granoblastic and coarse-grained porphyroclastic rocks, olivine displays good preferred orientations with the [010] axes oriented at high angle to the foliation and the [100] axes close to the lineation (Figures 4a and 4b). This indicates that deformation occurred in rotational conditions by translation glide of the (010) [100] system, which is activated at high temperature [*Ave Lallemant and Carter*, 1970; *Carter and Ave Lallemant*, 1970; *Karato et al.*, 1986; *Zhang and Karato*, 1995; *Bystricky et al.*, 2000; *Zhang et al.*, 2000]. However, in the coarse-granular rock (Figure 4a), the fabric is lesser defined with combined [100] slip directions, which are largely dominant, and [001] axes in the (010) plane, a feature which has been already described in annealed porphyroclastic peridotites from kimberlites [*Mercier*, 1984].

[16] Both the granoblastic and coarse-grained porphyroclastic rocks are characterized by the presence of unstrained large-sized olivine neoblasts that have straight or gently curved grain boundaries, defining common triple points (Figures 3e and 3f). This indicates grain growth, a process that can have achieved at slow strain rate deformations or in lithostatic conditions as for annealing [*Karato et al.*, 1980; *Mercier*, 1984; *Karato et al.*, 1986; *Karato*, 1989]. It is interesting to notice that in the Central zone, the grain growth clearly postdates a main plastic deformation responsible for the formation of high-strain textures. This is demonstrated by the existence, in a few rocks, of strained and elongated orthopyroxene crystals (5 × 1 mm) that are surrounded by large (1–2 mm size) and totally unstrained olivine neoblasts (Figures 3g and 3h) with curved to straight joins, locally forming triple points.

[17] Peridotites having granoblastic and coarse-grained porphyroclastic textures are spatially associated and overlap at the massif scale (Figure 2). They are found everywhere, except along the borders of the massif, which display finer-grained structures. The granoblastic rocks, however, are more abundant closer to the Moho. They are also found in the southern part of the area of vertical lineations of the central zone and at the boundary between the west and central zones.

[18] A few peridotites also display fine-grained porphyroclastic structures with strongly strained olivine and pyroxene porphyroclasts in the millimeter range. Olivine is largely recrystallized into neoblasts (0.3–0.5 mm), reaching locally up to 30% modal content in some rocks. The associated orthopyroxene is also finer grained and highly strained and the spinel has holly leaf shapes. These textures, locally grade into mylonitic type fabrics, marked the development of abundant small size (0.1–0.2 mm) olivine and pyroxene neoblasts along shear bands and by the presence of elongated pyroxenes (>5 × 1 mm).

[19] In the fine-grained porphyroclastic and mylonitic peridotites, the olivine porphyroclasts also display good preferred orientations (Figures 4c and 4d), with the [010] axes oriented at high angle to the foliation and the [100] axes close to the lineation. However, in the mylonitic rock (Figure 4d), the [100] and [010] directions display weaker maxima, probably because the data set include neoblasts (30%). These fabrics are indicative of plastic deformation of the rocks at high temperature under rotational conditions. Such high-temperature fabrics are

Figure 3. (opposite) Photomicrographs of the principal textures of the Wugbah peridotites. Background of each photo is made by olivine and serpentine in cracks. Opx, orthopyroxene; Cpx, clinopyroxene; Sp, spinel. (a, b) Granoblastic harzburgites (sample 93b-F and 191F, respectively). (c, d) Coarse-grained porphyroclastic harzburgites (Figure 3c is poorly strained type, sample 175F; Figure 3d is strongly strained rock, sample 33F); (e, f) Strongly recrystallized porphyroclastic rocks (sample 99F), (g, h) Evidence of recrystallization post-dating stretching of the orthopyroxenes (porphyroclastic peridotite, sample 99bF).

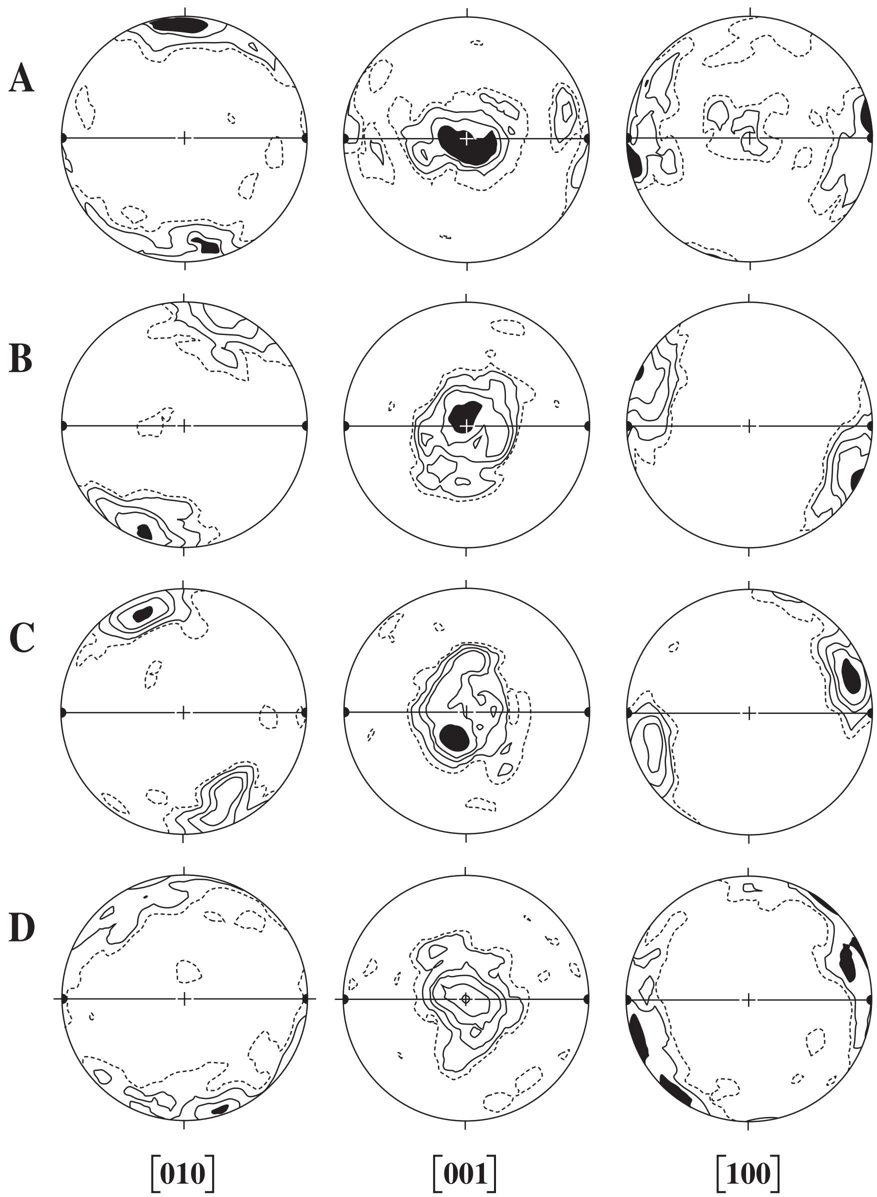


Figure 4. Olivine preferred-orientation for the principal microstructural types of peridotites in the Wuqbah massif (normalized projection: solid line indicates foliation; solid dot indicates lineation). (a) Granoblastic texture (sample 177, 102 measurements; contours 1, 2, 4, 6, 10%). (b) Coarse-grained porphyroclastic texture (sample 33, 101 data, contours 1, 2, 4, 6, 10, 15%). (c) Fine-grained porphyroclastic texture (sample 58, 102 data, contours 1, 2, 4, 6, 10, 15%). (d) Mylonitic texture (sample 185, 100 data, contours 1, 2, 4, 6, 10, 15%).

not rare in natural mylonitic peridotites, as described in peridotites from the oceanic domains (Mark area, Atlantic Ocean [*Ceuleneer and Cannat.*, 1997]), Alpine-type massifs (Ronda [*Tubia*, 1994] and Lanzo [*Boudier*, 1978]), and also ophiolites (Oman for instance [*Boudier and Coleman*, 1981]). According to the neoblast size [*Mercier*, 1984], it is likely that this high-temperature deformation occurred at increasingly more elevated deviatoric stress and/or strain rate conditions from the fine-grained porphyroclastic structures to the mylonitic ones.

[20] The fine-grained porphyroclastic and mylonitic rocks are dominantly found at the periphery of the massif, mostly in the northern part. However, a few samples in which we suspect a former high

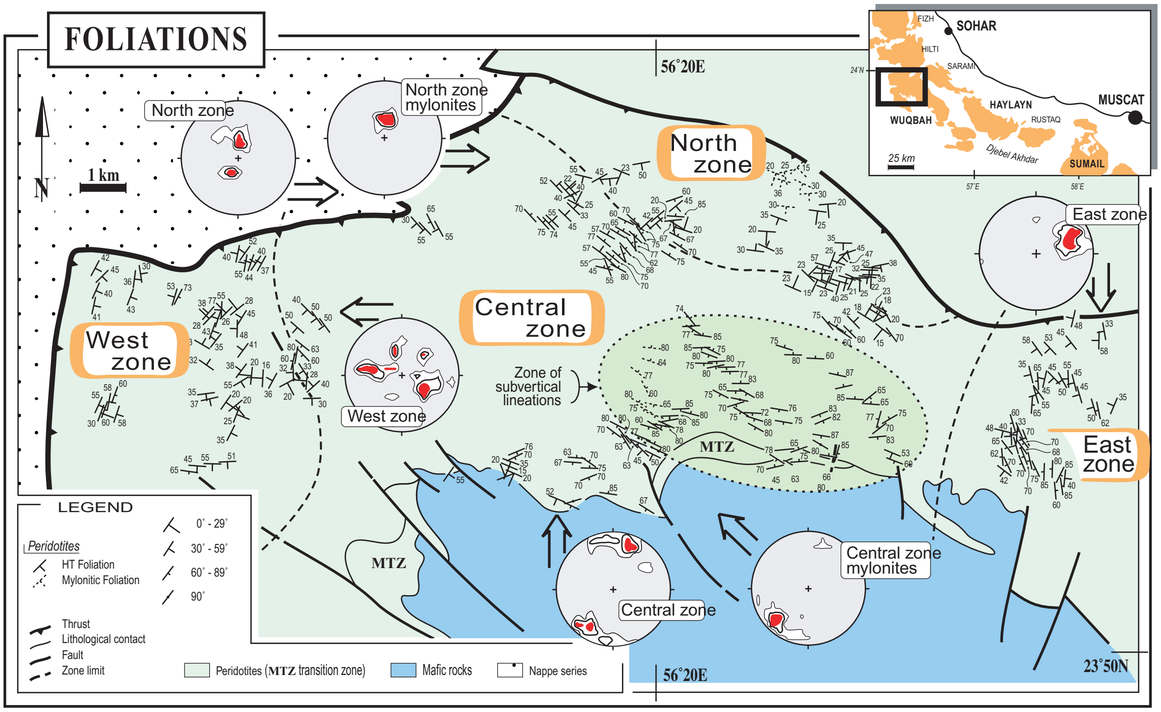


Figure 5. Map and stereographic projections of foliations in the Wuqbah peridotite. Stereograms: equal area, lower hemisphere. West zone (66 data, contours 3, 6, 9, 12%), central zone (103 data, contours 2, 4, 6, 8%), north zone (53 data, contours 4, 8, 12, 16%), north zone mylonites (18 data, contours 8, 16%, 24%), east zone (46 data, contours 3, 6, 9, 12%).

stress deformation prior to their recrystallization are also present in the western part of the area of vertical lineations of the central zone (Figure 2).

3.2. Structural Data

[21] Macroscopically, all the Wuqbah peridotites have tectonite structures, including the granoblastic peridotites, which have weaker fabrics. Hence they all display foliations and lineations that were determined using spinel shape fabrics, crystal alignments, and, in the case of the mylonites, elongate orthopyroxene crystals. These structures have been measured in the field where several measurements were systematically collected at each station of observation. These data were confirmed in the laboratory on bleached samples (more than 250), which makes significant the measurements plotted on the structural maps. Thin sections were cut systematically in the *XZ* plane for strain analysis and shear sense determination. The latter was estimated from the obliquity between the foliation and the shear plane, determined using petrofabric diagrams (on 14 samples), the sugbgrain boundary attitudes and also the reading of the transmitted light intensity which depends on the lattice orientation, a method described by *Nicolas and Poirier* [1976] and tested over years in controlled natural situations [*Michibayashi et al.*, 2000, and references therein] and eventually confirmed experimentally [*Zhang and Karato*, 1995; *Zhang et al.*, 2000]. In the mylonites, we also use the orthopyroxene crystals which, when elongated, allow a direct determination of the shear plane by using their exsolution lamellae (see method by *Nicolas and Poirier* [1976]).

[22] Maps including stereogram projections of foliation and lineation data (Figures 5 and 6) show variations in the attitudes of the main structures at the massif scale and allow to deliminate four zones in which the structures are relatively homogeneous. These zones match those defined by the textures (Figure 2), the east, central, and west zone having dominantly granoblastic and coarse-grained porphyroclastic peridotites and the north zone mostly

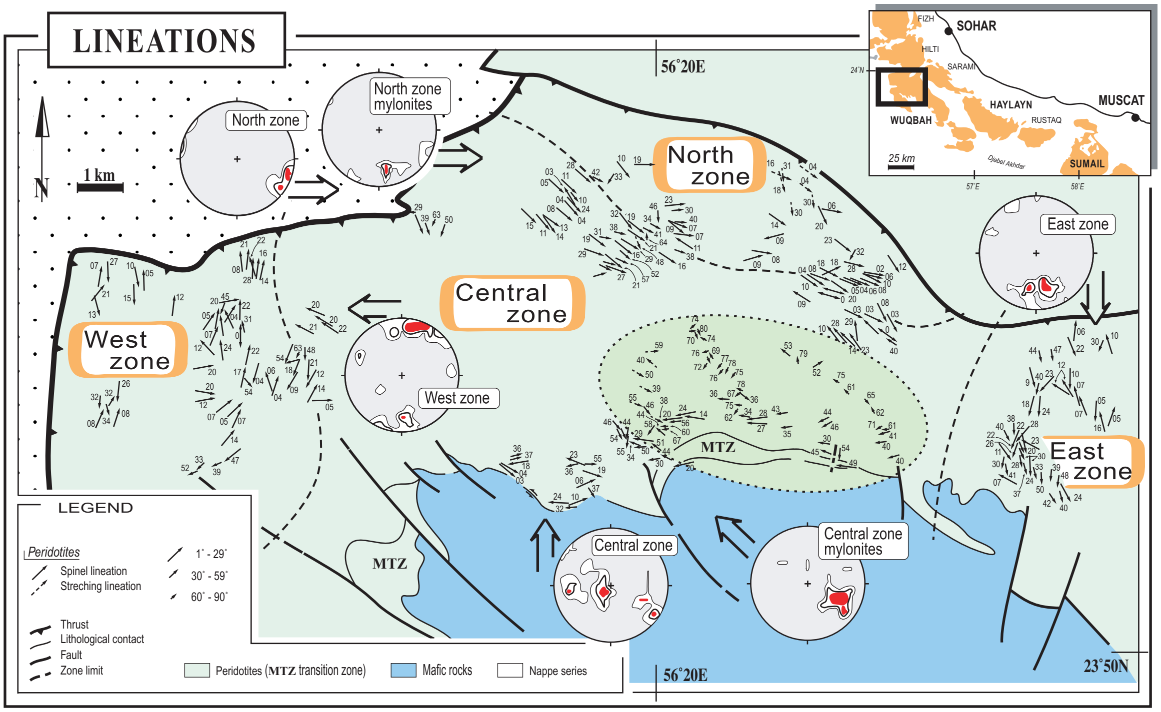


Figure 6. Map and stereographic projections of lineations in the Wuqbah peridotite. Stereograms: equal area, lower hemisphere. West zone (62 data, contours 2, 4, 6, 8%), central zone (99 data, contours 2, 4, 6, 8%), north zone (53 data, contours 4, 8, 12, 16%), north zone mylonites (14 data, contours 8, 16%, 24%), east zone (45 data, contours 3, 6, 9%).

fine-grained porphyroclastic and mylonitic ones. The zone boundaries are not marked by faults and seem to be gradual at the massif scale.

[23] In the east zone, the foliations and lineations display homogeneous attitudes with the foliation oriented N160°, 55°W (Figure 5) and the lineation plunging 30°S in the foliation plane (Figure 6). Shear measurements indicate a dextral displacement of the rocks, with a normal component, which implies a northward movement of the hanging wall (overlying western block) relative to the footwall (underlying eastern block) (12 measurements normal, 1 inverse, Figure 7).

[24] In the central zone, the trend of foliation plane is constant at about N110°. Its dip is always greater than 75°, toward the north in the northern part of the zone and in the opposite sense in the south (Figure 5). The lineation is dominantly subhorizontal, becoming subvertical toward the southeastern part of the zone, in a 6 × 2 km area trending N°110 (Figure 6). In areas with low lineation plunges, the shear sense has a marked left-lateral component and indicates a west-northwest movement of the hanging wall relative to the footwall (12 measurements normal, 1 inverse, Figure 7). In the area of subvertical lineations, the shear sense delimites poorly defined dip normal displacements.

[25] In the west zone, structures are more heterogeneous (Figures 5 and 6), partly due to local tilting of the foliation by late faults. The foliation attitude ranges from N05°, 50°E to 45°W, and seems to have been folded about N05° subhorizontal axes. The associated porphyroclastic lineations are, however, consistently oriented and have average orientations close to the fold axis, which suggest that folding of the foliation is a primary feature as it is associated with fabrics developed under mantle conditions. In these rocks, the shear sense indicates a southward movement of the hanging wall relative to the footwall (11 measurements normal, 4 inverse, Figure 7).

[26] In the north zone where fine-grained porphyroclastic peridotites dominate together with some mylonites present at the contact zone with the

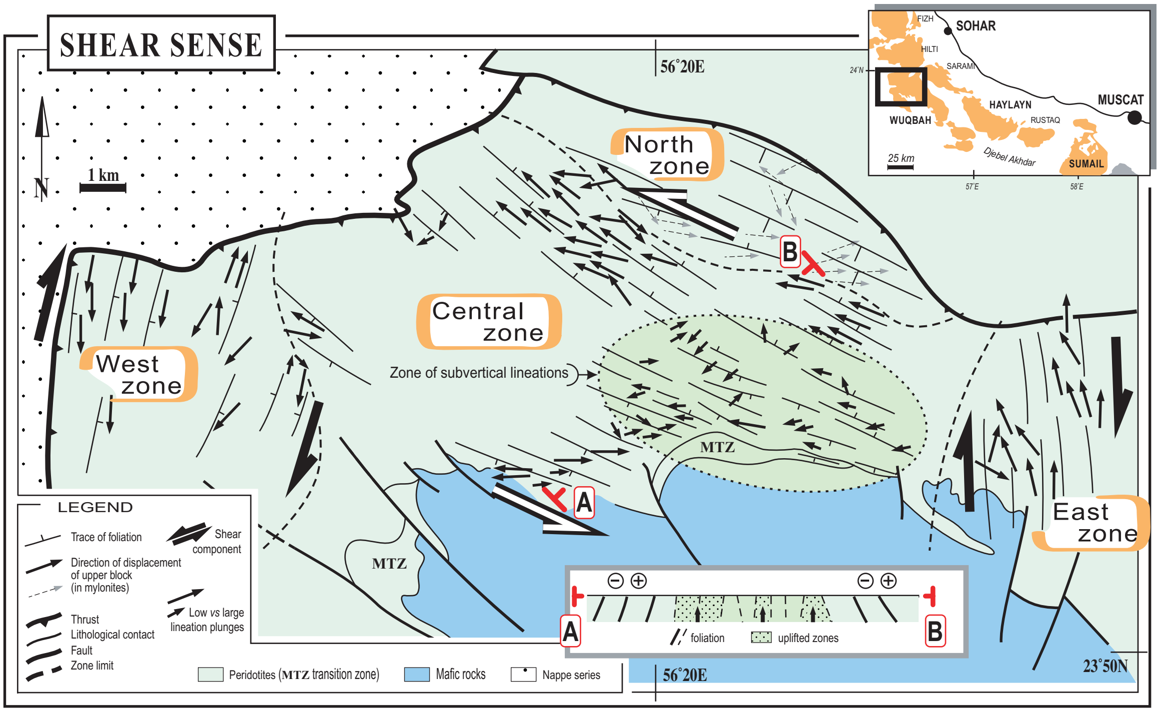


Figure 7. Strain trajectories and shear senses in the Wuqbah peridotites.

underlying nappe series, the foliations display relatively homogeneous attitudes at about N115°, 25°S to 25°N (Figure 5). Lineations are consistently oriented at N115°, 10°E (Figure 6), except in the mylonites where they trend N135° as previously shown by *Nicolas and Boudier* [1995]. In these two rock types, the shear sense indicates an east to east-southeast movement of the overlying block relative to the underlying one (13 measurements normal, 1 inverse, Figure 7). Because of the location of the mylonites at the basal part of the mantle unit, it is considered that these textures were acquired during the first stages of the ophiolite emplacement and, hence, will not be used for to reconstruct the dynamics of the paleoridge.

[27] This work shows that there are significant variations in the attitude of the peridotite primary high-temperature structures in the Wuqbah massif. This is evident in Figure 7 which illustrates the existence of a N110° trending zone, sheared under left-lateral conditions, with dip-slip motion in the southeastern part of the zone. This N110° trending zone lies in-between two domains deformed under right-lateral conditions, oriented N160° (east zone) and N05° (west zone). It evidences an anticlockwise rotation, which is out of keeping with the shear sense determined in its bordering zones, a problem which is tentatively explained in the discussion section.

4. Dykes

[28] Dykes intrusive within the Wuqbah ophiolitic series consist of pyroxenites, gabbros, and diabases (Figure 8). Those found in the deepest levels of the peridotites are thin (<10 cm thick) pyroxenite dykes or layers which are commonly folded and boudinage (Figure 9a). Most of these dykes were clearly emplaced before or during the latest stages of the plastic deformation of the surrounding peridotite. Crosscutting relationships indicate that they predate the gabbros (Figure 9a). They are oriented at various angles to the foliation in the peridotites, often at up to 60° in the west and east zones but at less than 20° in the main central zone (Figure 8). Because of their early origin and relative scattered attitudes, these pyroxenite dykes and layers will not be used for kinematic reconstructions.

[29] However, the peridotites have also been intruded by gabbro dykes, which are domi-

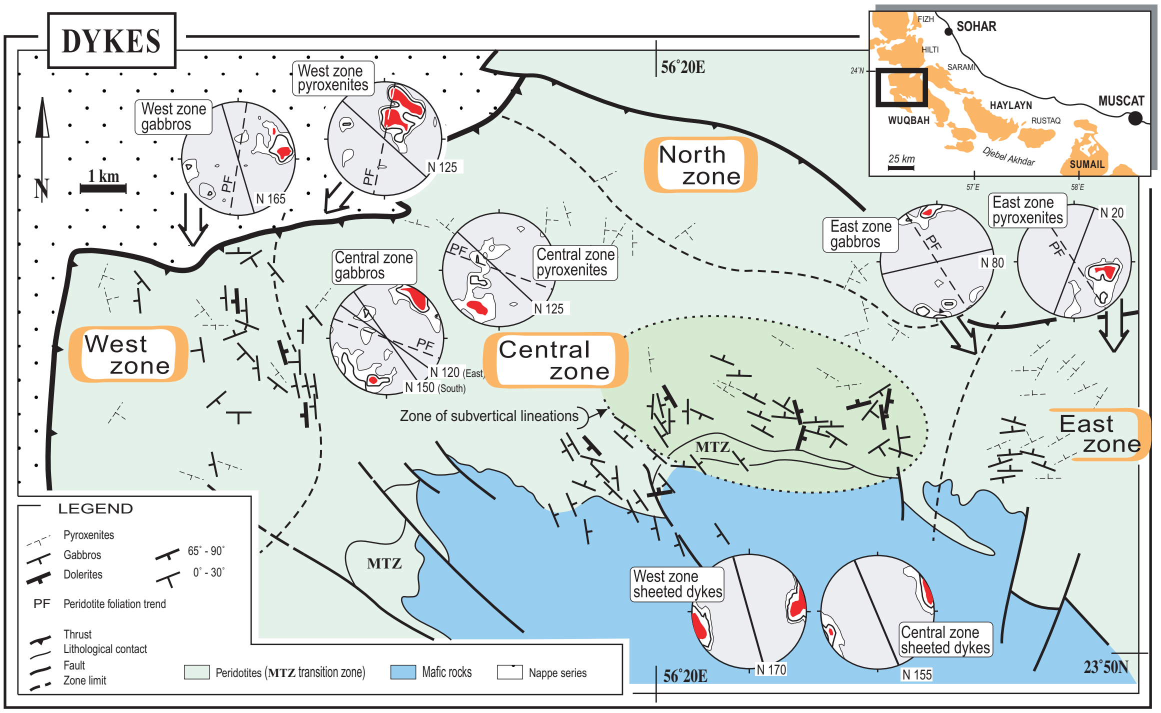


Figure 8. Map and stereographic projections of dykes (pyroxenite, gabbros, and diabases) attitudes in the Wuqbah massif. Stereograms: equal area, lower hemisphere. West zone gabbros (90 data, contours 2, 4, 6, 8%), west zone pyroxenites (61 data, contours 2, 4, 6, 8%), central zone gabbros (99 data, contours 2, 4, 6, 8, 10%), central zone pyroxenites (74 data, contours 2, 4, 6, 8, 10%), east zone gabbros (36 data, contours 2, 4, 6, 8%), east zone pyroxenites (107 data, contours 2, 4, 6, 8%), west zone sheeted dykes (395 data, contours 4, 8, 12, 16%), central zone sheeted dykes (151 data, contours 2, 4, 6, 8%).

nantly present in the upper levels of the mantle unit, particularly when approaching the Moho (Figure 8). These dykes are a few centimeters to 1 m thick and generally weakly or not deformed (Figure 9b). They are oriented N165° in the west zone, N150° in the southwest part of the central zone, N120° in the eastern part of the central zone, and N80° in the east zone. In the southcentral part of the central zone, the gabbro dykes locally cut the MTZ and the overlying layered gabbros of the base of the crustal unit. As they grade upward into the diabases that form the sheeted dyke complex [*Rothery*, 1983], they likely represent segregations from the magmas that fed the sheeted dykes, which suggests that they can be used to determined the fossil trend of the paleoridge.

[30] A few diabase dykes are also present within the main mantle unit (Figure 9c), in the eastern central part of the west zone (Figure 8), where they trend on average at N165°. They also cut the Moho zone, with a mean attitude at N150°, in the south-central part of the central zone (Figures 8 and 9d). Their attitude is very close to that of the dykes present within the gabbros (N155°, Figure 9e) and that grade into the main sheeted dyke complex (Figure 8). The latter is oriented at N170° in the west zone, very close to the orientation of the gabbro intrusives, and at N150° in the central zone, at ~30° from the average gabbro dyke trend (Figure 8). Our field observations show that the N°150 dykes are also present in the west zone, where they are cut by the N170° family dykes which is dominant (Figure 9f). This indicates that the west zone did not suffer any significant rotation during the obduction process as proposed by *Rothery* [1982]. The fact that in the central zone, a few diabase and gabbro dykes cut across the Moho while maintaining similar attitudes in the crust and in its underlying mantle also indicates that the geometry of the studied zone has not been significantly modified by ophiolite emplacement tecton-

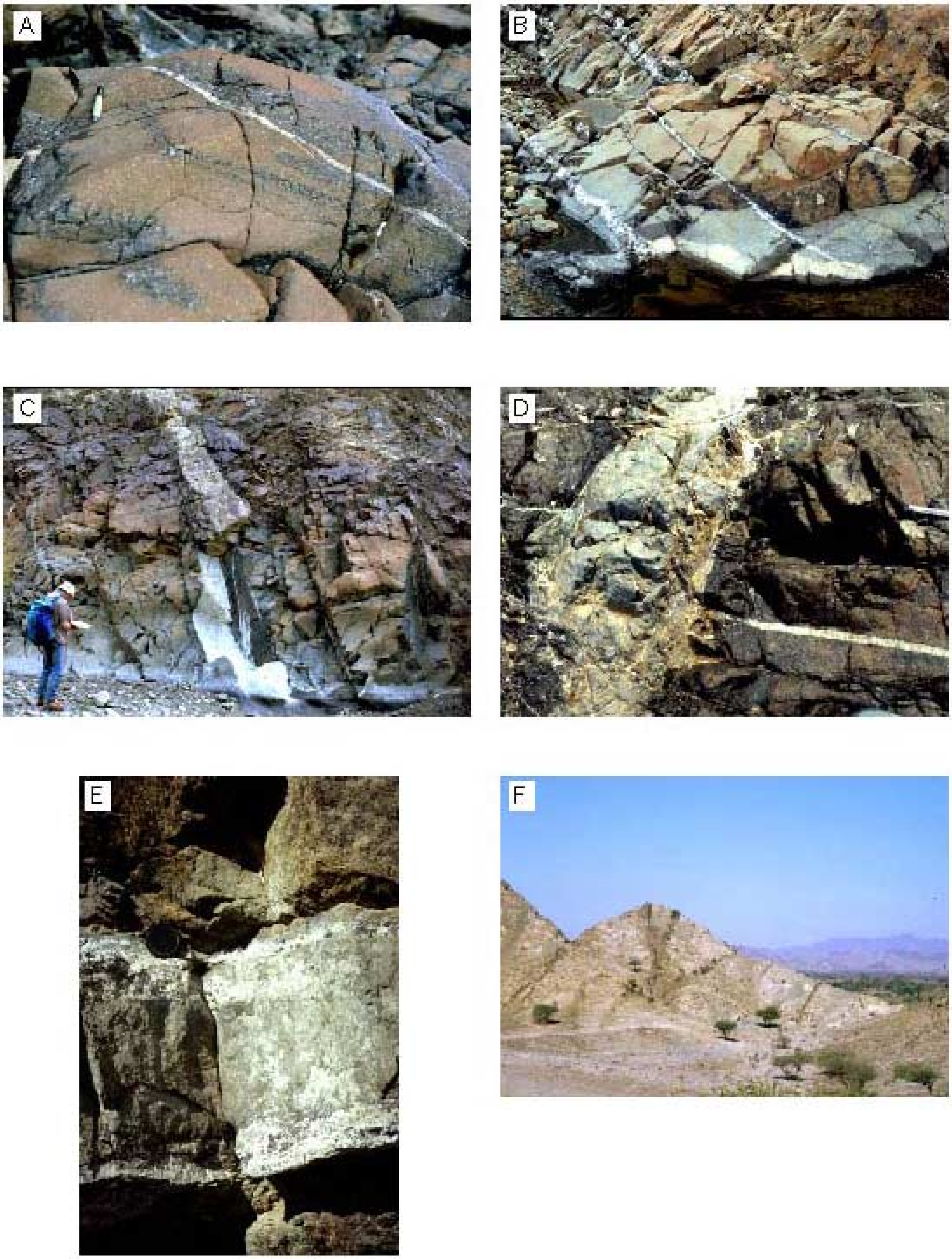


Figure 9. Photographs displaying the various types of dykes present in the Wuqbah massif. (a) Pyroxenite dyke folded and boudinaged within the peridotite and later cut by a thin undeformed gabbro dyke. (b) The 5 to 55 cm thick undeformed gabbro dykes intruded into depleted peridotites. (c) Meter-thick altered diabase dyke intruded into the peridotites in the West zone. (d) Diabase dyke cutting through a gabbro dyke in intrusion witin the mantle peridotites. (e) Pegmatitic gabbro dyke intruded into the gabbros. (f) Occurrence of N180° dykes cutting through the preexisting N150° dykes in the West zone of the Wuqbah massif.

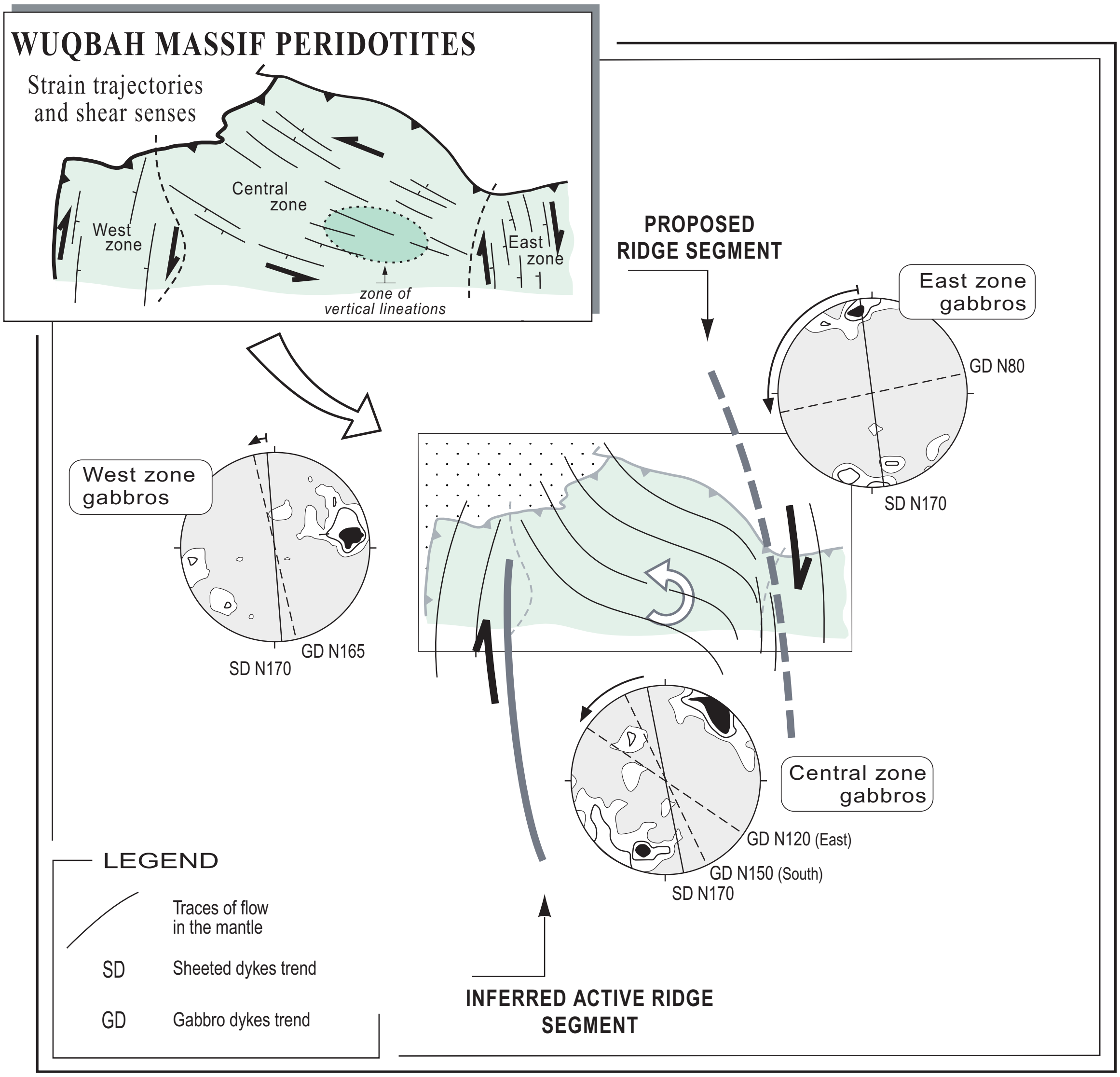


Figure 10. Sketch diagram displaying the paleoridge axis orientations and the rotation of the central zone as described by the peridotite deformation (upper box to the left) and by the gabbro dykes (main figure).

ics, in agreement with the absence of serpentinite breccias along the crust-mantle contact. This means that the strain pattern revealed by our data is related to ridge dynamics.

[31] In the west zone, the strong similarity between the attitude the dykes that form the sheeted dyke complex (trending at N170°) and those that cut already cooled peridotites and layered gabbros (trending at N165°) suggests that all formed during a single magmatism episode. Such dykes would underline along-strike penetration zones of magmas fed laterally from a magma chamber [*MacLeod and Rothery*, 1992] and therefore the trace of a paleo-segment of ridge (Figure 10). Note that the main foliation in the peridotites from that zone is oriented close to this inferred paleosegment of ridge trend.

[32] In the east zone, diabase dykes were not seen within the peridotites. They are rooted within the upper gabbros, a feature suggesting that the feeder zone was located beneath the dykes that grade upward into the N150° trending sheeted dyke complex [*MacLeod and Rothery*, 1992]. As they are cut in the west zone by the N165°–170° family

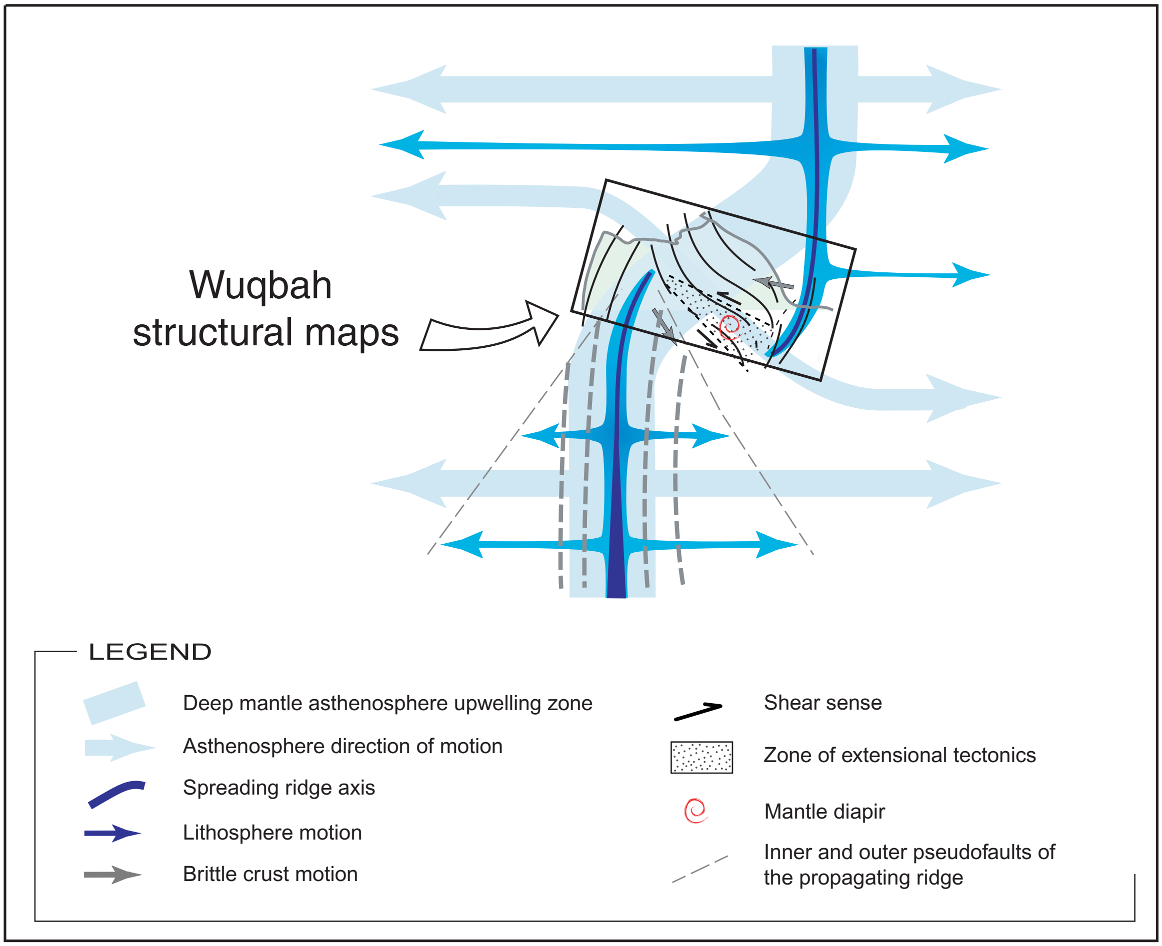


Figure 11. Model for the development of the Wuqbah overlapping spreading center. The ridge is represented by a thick line and the asthenosphere by the larger dashed line. Arrows give the flow trajectories in both units.

of dykes, they emplaced earlier and likely underline an "older" segment of ridge.

[33] If we compare the trend of the gabbro dykes present within the peridotites in the three zones of the Wuqbah massif with respect to that of the sheeted dyke complex in the west zone (Figure 10), we see that the gabbros and diabase dykes in the west zone are almost parallel (5° difference). This is not the case for the dykes present in the central zone, which present an angle of 20° (western part) to 50° (eastern part). Such angle increase from the west to the east describes the rotation we have defined from the peridotites foliation attitudes and shear sense (Figure 7). In the east zone, the gabbro dykes are oriented at a high angle (70°) to the sheeted dyke trend which may indicate a larger rotation or record a specific magmatic event related with the formation of the zone of vertical lineations.

5. Discussion and Conclusions

5.1. OSC Model

[34] The mantle deformation field of the Wuqbah massif documented here roughly recalls that drawn by seafloor lineaments at intermediate to large OSCs associated with a propagating rift, i.e., in a nontransform ridge offset [*Hey et al.*, 1980; *MacDonald and Fox*, 1983; *Sempéré et al.*, 1984; *MacDonald et al.*, 1986; *Hey et al.*, 1988, 1995; *Livermore et al.*, 1997; *Martínez et al.*, 1997]. By

analogy, and using the structural pattern and kinematics of deformation within the Wuqbah peridotites, we attempt to reconstruct the mantle geometry of such a system.

[35] In the model (Figure 11), the west and east zones define the traces, in the mantle, of two ridge segment terminations, and the oblique N110° trending eentral zone represents the axial part of the overlap. We propose that the southwestern segment of the ridge was propagating northward. It is suggested by the presence in the Wuqbah massif of a steep Moho, a feature that is supposed to occur at the tip of propagating ridges [*MacLeod et al.*, 1996; *Nicolas et al.*, 2000]. It is also supported by the presence, in the southwestern part of the massif, of the N170° trending dykes that underline along strike injections of magmas, in an "older" crust marked by the N150° dykes [*MacLeod and Rothery*, 1992]. Conversely, we propose that formation of this "older" crust occurred along a regressive segment of ridge, arbitrarily located in the east zone of the Wuqbah massif.

[36] A major question was to explain the anticlockwise rotation displayed by the central part of the Wuqbah massif. In our opinion, this rotation is not consistent with the right-lateral shear sense determined along the east and west borders. It can be easily explained if we link it to the northward migration and concomitant E-W spreading of a propagating ridge that would have been located in the southern part of the Wuqbah west zone, as proposed above (Figure 11). Such a propagator would have produced a left-lateral shear couple at the northern and southern edges of the overlap area, responsible for the anticlockwise rotation of the overlap area as already given by *Wetzel et al.'*s [1993] models.

5.2. Consequence for the Crust and Mantle Dynamics

[37] The peridotite train trajectories suggest that the flow in the upper mantle was continuous from one branch to the other of the system and curved in the overlap area to accommodate the offset. It indicates subhorizontal movements, except in the southeastern part of the overlap area where it is vertical. This zone can be seen at depth as a zone of intense shearing in which the deformation conditions have likely varied from moderate stress conditions at the beginning of the OSC formation, just after the ridge breakup, to lower stress conditions latter. The coarse-grained high-temperature textures displayed by the central zone peridotites (Figures 2, 3a, and 3b) and the presence of a few rocks that contain relics of high-stress orthopyroxene surrounded by coarse unstrained neoblasts (Figures 3g and 3h) are in agreement with this hypothesis.

[38] The overlap zone was likely an area of major decoupling between the brittle crust and the ductile upper mantle. It is a zone of oblique stretching where extensional tectonics likely occurred due to the separation of the two ridges, as indicated by the existence of deeps in OSCs [*MacDonald and Fox*, 1983; *Sempéré et al.*, 1984; *MacDonald et al.*, 1986; *Livermore et al.*, 1997; *Martínez et al.*, 1997]. In our model, because of the angle existing between the directions of movement on each side of the overlap zone, extension was likely maximum in the southeastern part of the overlap area. It may have produced partial denudation of the upper crust, which might explain why the crust, which is intruded by the diabases at Wuqbah, was so thin.

[39] Although steep lineations associated with outward dipping foliation may, in some cases, reflect a tanspressive regime [*Robin and Cruden*, 1994], our data and model better points to a transtensive context. In such an extensional regime, some mantle diapirism can have occurred at depth. This can explain the zone of vertical motion mapped within the mantle in the southeastern part of the central zone. However, although this mantle structure is marked by steep foliations and lineations, it does not exhibit the same divergent flow as other diapiric zones in the southern part of the Oman ophiolite [*Nicolas and Boudier*, 1995]. Nevertheless, its presence indicates that a deep mantle instability has developed in the overlap area. This is consistent with the presence of the coarse recrystallized textures present in that area, which are indicative of stress relaxation at high temperature, conditions that can be achieved at the core of an upwelling zone. Such a structure can have formed because of the specific location of the overlap in

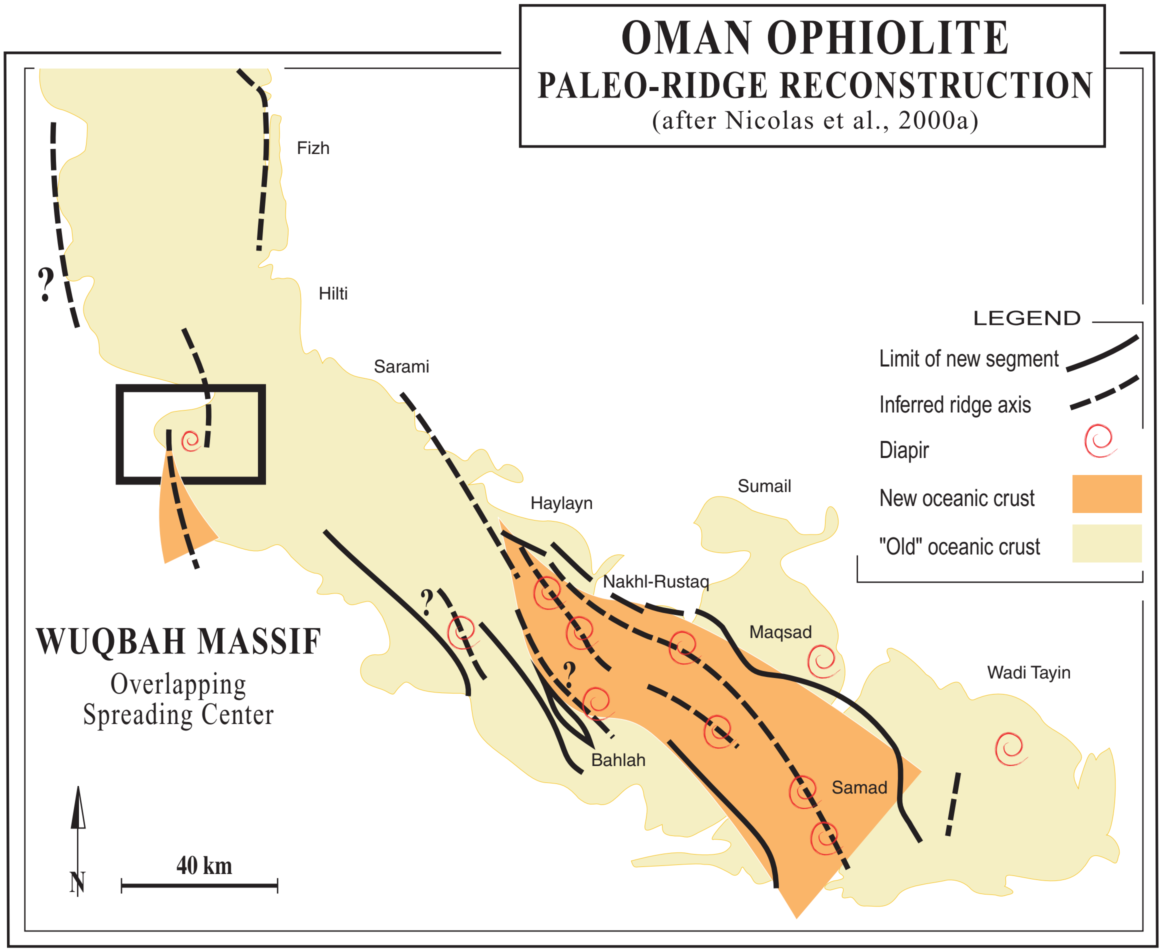


Figure 12. Paleoreconstruction of the Oman showing integrating the Wuqbah OSC (after *Boudier et al.* [1997] and *Nicolas et al.* [2000]).

between two ridge segments and above the main ridge deep asthenospheric upwelling.

5.3. Implications for the Oman Ophiolite Reconstruction

[40] Since the distance between the two ridge axes inferred for the Wuqbah fossil OSC is less than 15 km (Figures 10 and 11), it can be ranked as a small to intermediate OSC [*Gente*, 1987; *Lonsdale*, 1983; *MacDonald and Fox*, 1983; *MacDonald et al.*, 1984; *Sempéré et al.*, 1984]. However, one of its segments is a propagator, as in the OSCs described along the East Scotia ridge (6–7 cm Ma^{-1}) at 57°S [*Livermore et al.*, 1997] and at 29°S on the East Pacific rise [*Martínez et al.*, 1997], both of which having larger sizes.

[41] At the Oman ophiolite scale, the Wuqbah OSC likely represents a third-order ridge segmentation. It is located northwest of a major domain (Figure 12), marked by the presence of a NW-SE propagating ridge (Samad-Maqsad-Bahlah-Nakhl-Rustaq-Haylayn diapirs alignment), that is at the origin of the formation of a new oceanic crust within an ancient one [*Nicolas et al.*, 2000]. Although the orientation of the Wuqbah fossil OSC is compatible with that of the large propagator, it is very unlikely that the two structures formed at the same time, mainly because the Samad-Haylayn propagator probably continues to the northwest in the Haylayn block [*Nicolas et al.*, 2000]. As there is no major fault between the Wuqbah and the Haylayn massifs, it is suggested that the Wuqbah OSC formed earlier and defines the

trace of a ridge that migrated to the east and was abandoned, as is commonly observed in modern oceanic domains [*Schouten et al.*, 1977].

Acknowledgments

[42] Financial support was provided by the Centre National de la Recherche Scientifique (CNRS) in the frame of the IT program. We are indebted to Hilal Al Azri, Director of the Oman Geological Survey, and to J.-P. Breton, Director of the BRGM Station in Oman, for their support. We thank anonymous reviewers for improving our manuscript, Adolphe Nicolas and Sandy Cruden for their constructive comments, and Laurent Le Mée, who is in charge of the petrological study of the diabase dykes, for its help and the constructive discussions we had in our laboratory. We also thank A. Cossard who has drawn many of the figures and Eric Boeuf and Hervé Loyen who have done the thin sections.

References

Ave Lallemant, H. G., and N. L. Carter, Syntectonic recrystallization of olivine and modes of flow in the upper mantle, *Geol. Soc. Am. Bull.*, *81*, 2203–2220, 1970.

Boudier, F., Structure and petrology of the Lanzo peridotite massif (Piemont Alaps), *Geol. Soc. Am. Bull.*, *89*, 1574–1591, 1978.

Boudier, F., and R. G. Coleman, Cross-section through the peridotite in the Samail ophiolite, Southeastem Oman Mountains, *J. Geophys. Res.*, *86*, 2573–2592, 1981.

Boudier, F., A. Nicolas, and B. Ildefonse, Magma chambers in the Oman ophiolite: Fed from the top or from the bottom?, *Earth Planet. Sci. Lett.*, *144*, 239–250, 1996.

Boudier, F., A. Nicolas, B. Ildefonse, and D. Jousselin, EPR microplates, a model for Oman ophiolite, *Terra Nova*, *9*, 79–82, 1997.

Bystricky, M., K. Kunze, L. Burlini, and J.-P. Burg, High shear strain of olivine aggregates: Rheological and seismic consequences, *Science*, *290*, 1564–1567, 2000.

Carter, N. L., and H. G. Ave Lallemant, High temperature flow of dunite and peridotite, *Geol. Soc. Am. Bull.*, *81*, 2181–2202, 1970.

Ceuleneer, G., Evidence for a paleo-spreading center in the Oman Ophiolite: Mantle structures in the Maqsad area, in *Ophiolite Genesis and Evoltition of the Oceanic Lithosphere*, edited by T. Peters et al., pp. 147–173, Kluwer Acad., Norwell, Mass., 1991.

Ceuleneer, G., and M. Cannat, High temperature ductile deformation of Site 920 peridotites, *Proc. Ocean Drill. Program Sci. Results*, *153*, 23–34, 1997.

Ceuleneer, G., A. Nicolas, and F. Boudier, Mantle flow patterns at an oceanic spreading centre: The Oman peridotites record, *Tectonophysics*, *151*, 1–26, 1988.

Dahl, R., Etude géométrique, pétrologique et géochimique de la séquence crustale de l'ophiolite d'Oman, massif de Rustak (Bloc d'Haylayn): Un modèle tridimentionnel de zone d'accrétion, Thèse de Doctorat d'Université, Nantes, 1984.

Ernewein, M., C. Pflumio, and H. Whitechurch, The death of an accretion zone as evidenced by the magmatic history of the Sumail ophiolite (Oman), *Tectonophysics*, *151*, 247–274, 1988.

Gente, P., Etude morphostructurale comparative de dorsales océaniques à taux d'expansion variés, Thèse de doctorat d'Université, UBO - Brest, 1987.

Glennie, K. W., M. G. A. Boeuf, M. W. Hugues Clarke, M. Moody Stuart, W. F. H. Pilaar, and B. M. Reinhardt, Geology of Oman Mountains, Kon. Ned. Geol. Mijboukundig Genoot. Verh., 423 p., 1974.

Harcker, B. R., J. L. Mosenfelder, and E. Gnos, Rapid emplacement of the Oman ophiolite: Thermal and geochronologic constraints, *Tectonics*, *15*, 1230–1247, 1996.

Harte, B., Rock nomenclature with particuliar relation to deformation and recrystallization textures in olivine-bearing xenoliths, *J. Geol.*, *85*, 279–288, 1977.

Hey, D., F. K. Duennebier, and W. J. Morgan, Propagating rifts on mid-oceanic ridges, *J. Geophys. Res.*, *85*, 3647–3658, 1980.

Hey, D., H. W. Menard, T. M. Atwater, and D. W. Caress, Changes in direction of seafloor spreading revisited, *J. Geophys. Res.*, *93*, 2803–2811, 1988.

Hey, D., P. D. Johnson, F. Martinez, J. Korenaga, M. L. Somers, Q. J. Huggett, T. P. LeBas, R. I. Rusby, and F. Naar, Plate boundary reorganization at a large-offset, raptdly propagating rift, *Nature*, *378*, 167–170, 1995.

Ildefonse, B., S. Billiau, and A. Nicolas, A detail study of mantle flow away from diapirs in the Oman ophiolite, in *Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites*, edited by R. L. M. Vissers, and A. Nicolas, pp. 163–177, Kluwer Acad., Norwell, Mass., 1995.

Jousselin, D., and A. Nicolas, The Moho transition zone in the Oman ophiolite-related with wehrlites in the crust and dunites in the mantle, *Mar. Geophys. Res.*, *21*, 229–241, 2000a.

Jousselin, D., and A. Nicolas, Oceanic ridge off-axis deep structure in the Mansah region (Sumail massif, Oman ophiolite), *Mar. Geophys. Res.*, *21*, 243–257, 2000b.

Jousselin, D., A. Nicolas, and F. Boudier, Detailed mapping of a paleospreading center in the Oman ophiolite, *J. Geophys. Res.*, *103*, 18,153–18,170, 1998.

Juteau, T., M. Beurrier, R. Dahl, and P. Nehlig, Segmentation at a fossil spreading axis: The plutonic sequence of the Wadi Haymiliyah area (Haylayn Block, Sumail Nappe, Oman), *Tectonophysics*, *151*, 167–197, 1988a.

Juteau, T., M. Ernewein, I. Reuber, H. Whitechurch, and R. Dahl, Duality of magmatism in the plutonic sequence of the Sumail nappe, Oman, *Tectonophysics*, *151*, 107–135, 1988b.

Karato, S., Grain growth kinematics in olivine aggregates, *Tectonophysics*, *168*, 255–273, 1989.

Karato, S., M. S. Paterson, and J. D. FritzGerakd, Rheology of synthetic aggregates: Influence of grain size and water, *J. Geophys. Res.*, *91*, 8151–8176, 1986.

Karato, S., M. Toriumi, and T. Fujii, Dynamic recrystallization of olivine single crystals during high-temperature creep, *Geophys. Res. Lett.*, *7*, 649–652, 1980.

Kelemen, P., K. Koga, and N. Shimizu, Geochemistry of gabbro sills in the crust-mantle transition zone of the Oman ophiolite: implications for the origin of the oceanic lower crust, *Earth Planet. Sci. Lett.*, *146*, 475–488, 1997.

Le Métour, J., F. Béchennec, M. Beirrier, D. Janjou, J. Roger, and R. Wyns, Dank, Oman, 1:100 000, Min. of Petrol. and Mineral., Sultanate of Oman, 1989.

Lippard, S. J., A. W. Shelton, and I. G. Gass, *The Ophiolite of Northern Oman*, Geol. Soc. of London, London, 1986.

Livermore, R., A. Cunningham, L. Vanneste, and R. Larter, Subduction influence on magma supply at the East Scotia Ridge, *Earth Planet. Sci. Lett.*, *150*, 261–275, 1997.

Lonsdale, P., Overlapping rift zones at the 5.5°S offset of the East Pacific Rise, *J. Geophys. Res.*, *88*, 9393–9406, 1983.

MacDonald, K. C., and P. J. Fox, Overlapping Spreading Centers: A new kind of accretion geometry on the East Pacific Rise, *J. Geophys. Res.*, *88*, 9393–9406, 1983.

MacDonald, K. C., J. C. Sempéré, and P. J. Fox, The East Pacific Rise from the Sequeiros to the Orozco fracture zones: Along strike continuite of the axial neovolcanic zone and the structure and evolution of Overlapping Spreading Centers, *J. Geophys. Res.*, *89*, 6049–6069, 1984.

MacDonald, K. C., J. C. Sempere, and P. J. Fox, Reply: The debate concerning Overlapping Spreading Centers and mid-ocean ridge processes, *J. Geophys. Res.*, *91*, 10,501–10,511, 1986.

MacLeod, C. J., and I. Reuber, Complex rift geometry in the northern Oman ophiolite: A possible overlapping spreading center, in *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*, edited by T. J. Peter, A. Nicolas, and R. G. Coleman, pp. 200–229, Kluwer Acad., Norwell, Mass., 1990.

MacLeod, C. J., and D. A. Rothery, Ridge axial segmentation in the Oman ophiolite: evidence from along-strike variations in the sheeted dyke complexe, in *Ophiolites and their modern oceanic analogues*, edited by L. M. Parson, B. J. Murton, and P. Browning, pp. 39–63, 60, Geological Society Special Publication, London, 1992.

MacLeod, C. J., B. Célérié, G. L. Frür-Green, and C. E. Manning, Tectonics of Hess Deep: A synthesis of drilling results from Leg 147, *Proc. Ocean Drill. Program Sci. Res.*, *147*, 461–475, 1996.

Martínez, F., N. H. Richard, and P. D. Johnson, The East ridge system 28.5–32°S East Pacific rise: Implications for overlapping spreading center development, *Earth Planet. Sci. Lett.*, *151*, 13–31, 1997.

Mercier, J. C., Olivine and pyroxenes, in *Preferred Orientation in Minerals and Rocks: An Introduction to Modern Texture Analysis*, edited by H. R. Wenk, pp. 407–430, Kluwer Acad., Norwell, Mass., 1984.

Mercier, J. C. C., and A. Nicolas, Textures and fabrics of upper mantle peridotites as illustrated by xenoliths from basalts, *J. Petrol.*, *16*, 454–487, 1975.

Michibayashi, K., L. Gerbert-Gaillard, and A. Nicolas, Shear sense inversion in the Hilti mantle section (Oman ophiolite) and active mantle uprise, *Mar. Geophys. Res.*, *21*, 259–268, 2000.

Nicolas, A., A melt extraction model based on structural studies in mantle peridotites, *J. Petrol.*, *27*, 999–1022, 1986a.

Nicolas, A., Structure and petrology of peridotites: clues to their geodynamic environment, *Rev. Geophys.*, *24*, 875–895, 1986b.

Nicolas, A., and F. Boudier, Rooting of the sheeted dyke complex in the Oman ophiolite, in *Ophiolite Genesis and Evoltition of the Oceanic Lithosphere*, edited by T. Peters et al., pp. 39–54, Kluwer Acad., Norwell, Mass., 1991.

Nicolas, A., and F. Boudier, Mapping oceanic ridge segments in Oman ophiolite, *J. Geophys. Res.*, *100*, 6179–6197, 1995.

Nicolas, A., F. Boudier, B. Ildefonse, and E. Ball, Accretion of Oman and United Arab Emirates Ophiolites - Discussion of a new structural map, *Mar. Geophys. Res.*, *21*, 174–179, 2000.

Nicolas, A., G. Ceuleneer, F. Boudier, and M. Misseri, Structural mapping in the Oman ophiolites: Mantle Diapirism along an oceanic ridge, *Tectonophysics*, *151*, 27–56, 1988a.

Nicolas, A., and J. P. Poirier, Crystalline plasticity and solid state flow in metamorphic rocks, 444 pp., J. Wiley, New York, 1976.

Nicolas, A., I. Reuber, and K. Benn, A new magma chamber model based on structural studies in the Oman ophiolite, *Tectonophysics*, *151*, 87–105, 1988b.

Pallister, J. S., and C. A. Hopson, Samail ophiolite plutonic suite: field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber, *J. Geophys. Res.*, *86*, 2593–2644, 1981.

Quatrevaux, F., Etude pétrologique des péridotites des massifs de Maqsad et Wuqbah, ophiolite d'Oman, Thèse de Doctorat d'Université, Paris VII, 1995.

Reuber, I., Complexity of the crustal sequence in the northern Oman ophiolite (Fiz and southern Aswad blocks): The effect of early slicing?, *Tectonophysics*, *151*, 137–165, 1988.

Reuber, I., P. Neihlig, and T. Juteau, Axial segmentation at a fossil oceanic spreading center in the Haylayn block (Semail nappe, Oman): Off-axis mantle diapir and advancing ridge tip, *J. Geod.*, *13*, 253–278, 1991.

Robin, P.-Y. F., and A. R. Cruden, Strain and vorticity patterns in ideally ductile transpression zones, *J. Struct. Geol.*, *16*, 447–466, 1994.

Rothery, D. A., The evolution of the Wuqbah block and the applications of remote sensing in the oman ophiolite, Ph D., Open Univ., Oman, 1982.

Rothery, D. A., The base of a sheeted dyke complexe Oman ophiolite: Implications for magma chambers at oceanic spreading axes, *J. Geol. Soc. London*, *140*, 284–296, 1983.

Schouten, H., H. J. B. Dick, and K. D. Klitgord, Migration of oceanic ridge volcanic segments, *Nature*, *326*, 453–464, 1977.

Sempéré, J. C., K. C. MacDonald, and S. P. Miller, Overlapping spreading centers: A three-dimensional inversion of the magmetic field at 9°03′N on the East Pacific Rise, *Geophys. J. R. Astron. Soc.*, *79*, 799–811, 1984.

Smewing, J. D., Mixing characteristics and compositional différences in mantle-derived melts beneathspreading axes: Evidence from cyclically layered rocks in the ophiolite of North Oman, *J. Geophys. Res.*, *86*, 2645–2659, 1981.

Tubia, M. J., The Ronda peridotite (Los Reales nappe): An example of the relationship between lithospheric thickening by oblique tectonics and late extensional deformation with the Betic Cordillera (Spain), *Tectonophysics*, *238*, 381–398, 1994.

Wetzel, L. R., D. A. Wiens, and M. C. Kleinrock, Evidence from earthquakes for bookshelf faulting at large non-transform ridge offsets, *Nature*, *362*, 235–237, 1993.

Zhang, S., and S. Karato, Lattice prefferred orientation of olivine deformed in simple shear, *Nature*, *375*, 774–777, 1995.

Zhang, S., S. Karato, J. Fritz Gerald, U. H. Faul, and Y. Zhou, Simple shear deformation of olivine aggregates, *Tectonophysics*, *316*, 133–152, 2000.