High-pressure relics and structure of the Bou Azzer Neoproterozoic ophiolite (Anti-Atlas, Morocco)

Relictos de alta presión y estructura de la Ofiolita Neoproterozoica de Bou Azzer (Anti-Atlas, Marruecos)

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RESUMEN

La ofiolita de Bou Azzer marca la sutura del orógeno Pan-africano en el Anti-Atlas (Marruecos). En esta ofiolita se ha observado una paragénesis relicta de granate y rutilo, que sugiere un episodio inicial de alta presión. Tras este episodio, la ofiolita sufrió, durante su exhumación, una retrogradación a facies esquistos verdes, al tiempo que se desarrollaba la fábrica plano-linear (S_2, L_2) que domina en estas rocas. La macroestructura asociada a esta fábrica principal consiste en pliegues volcados vergentes al SW y cabalgamientos con movimiento de bloque de techo al W/SW. Estas estructuras emplazaron la ofiolita sobre rocas de la plataforma continental del Cratón Oeste Africano. Una sucesión clástica (Formación Tiddiline) aparece discordante sobre la ofiolita, las rocas de arco y los sedimentos de plataforma, estando a su vez deformada por pliegues erguidos de dirección ESE-WNW y fallas inversas. La convergencia Neoproterozoica concluyó con el desarrollo de fallas de salto en dirección izquierdo.

***Key words**: Ophiolite; Neoproterozoic; high-pressure; Bou Azzer; Anti-Atlas*

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Introduction and general description

The Bou Azzer - El Graara outcrop (henceforth Bou Azzer) is one of a series of Proterozoic outcrops in the Anti-Atlas region of southern Morocco (Figs. 1A, 1B). Widespread research of Choubert in the Anti Atlas (Choubert *et al*., 1974) was followed by studies of Leblanc at Bou Azzer (Leblanc, 1975, 1981). Among the many subsequent works in the area, those by Bodinier *et al*. (1984) and Naidoo (1988) provided with a lot of geochemical data, Saquaque *et al*. (1989) re-interpreted Bou Azzer as a composite terrane and Thomas *et al*. (2002), Inglis *et al*. (2005) and Gasquet *et al*. (2005) provided with radiometric data. In this paper, we document new aspects of the structure, kinematics and metamorphic history of the ophiolite.

The Proterozoic rocks of Bou Azzer crop out in the core of a NW-SE open antiform. The oldest rocks at Bou Azzer are granitoid gneisses and metagabbros, until now attributed to the Eburnean (~2000 Ma) basement. However, D'Lemos *et al*. (2006) have determined ages around 750 Ma for these rocks. Over these meta-igneous rocks, there are clastic/carbonate deposits of a platform sequence (Leblanc, 1975). The ophiolite, which lies on this platform sequence, is made up of ultramafites (serpentinites), cumulates, gabbros, basalts and some volcanoclastites, with minor volumes of clastics and red cherts. Metaluminous diorite-to-granodiorite plutons intruded the ophiolite, displaying foliation and mineral lineation in continuity with their host rocks (Fig. 1B). Their geochemistry is typical of arc magmatism (Beraaouz *et al*., 2004), with ages between 641 and 654 Ma (Inglis *et al*., 2005). The Tiddiline Formation is a younger clastic sedimentary sequence. Finally, a calc-alkaline sequence of andesites, dacites, volcanoclastic rocks and inmature epiclastic sediments (Ouarzazate Formation; Leblanc, 1975, 1981) unconformably blankets all the Proterozoic units previoiusly described. Its age is Ediacaran (Thomas *et al*., 2004; Gasquet *et al*., 2005), with Early Cambrian rocks deposited in continuity.

Structure

Neoproterozoic deformational events

Apart from minor Variscan/Alpine reworking, the formation of the Bou Azzer structure took place in the Proterozoic, as evidenced by the Late Neoproterozoic Ouarzazate Formation blanketing the structure.

In some lithologies of the ophiolite, two distinctive foliations can be observed: S_1 is a relic foliation intensely crenulated by a second one (S_2). However, ophiolitic gabbros and basalts show usually a single composite foliation (S_{1+2}), which generally dips to the NE. Associated with the S_{1+2} foliation, a E/NE-plunging stretching/mineral lineation developed (Fig. 2A). The foliation S_{1+2} is folded by steeply-inclined E-W-trending folds.

In the metasediments and igneous rocks of the continental margin, the first foliation is either a slaty cleavage or a mylonitic foliation, with the same attitude that the S_{1+2} in the ophiolite. A stretching lineation is frequently associated, which plunges to the E or NE. A spaced crenulation/disjunctive cleavage is axial plane of late, E-W trending, steeply-inclined, metric and cartographic folds, affecting the slaty cleavage. We correlate the slaty cleavage in these metasediments with the S_2 in the ophiolite, while the second

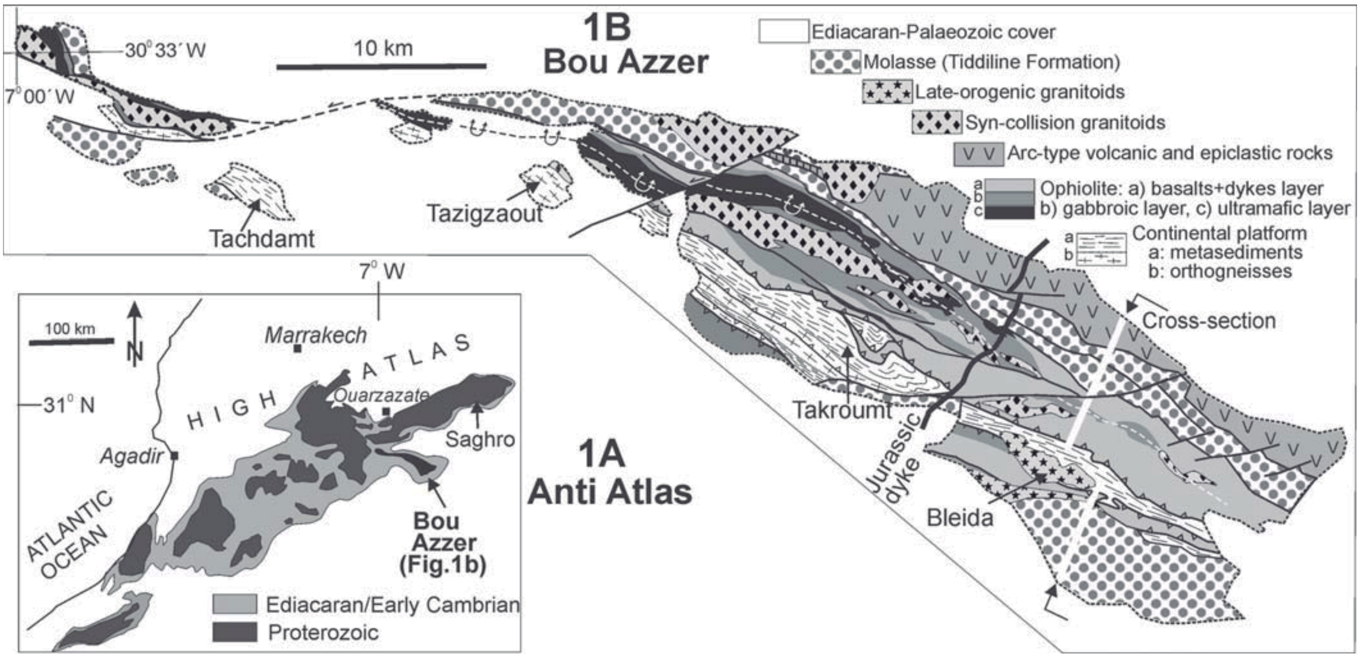

Fig. 1.- 1A: Sketch map of the Anti-Atlas, showing the Proterozoic outcrops and the location of Bou Azzer. 1B: Sketch map of the Bou Azzer Proterozoic outcrop.

Fig. 1.- 1A: Afloramientos del Proterozoico en el Anti-Atlas, con la localización de Bou Azzer. 1B: Mapa esquemático de Bou Azzer.

generation folds correlate with the latest upright folds in the ophiolite.

In the molassic Tiddiline sediments, a rough spaced cleavage is frequently observed. It is axial plane of km-scale upright folds, which correlate with the latest folds in the underlying ophiolite and metasediments of the continental margin.

To sum up, the Bou Azzer rocks record three penetrative deformational events. The first one is observed only in the ophiolite, as a first foliation (S_1) associated with a relic mineral assemblage suggesting high-pressure conditions (see metamorphic evolution below). The second deformational event is recorded in both the ophiolite (S_2, stretching lineation) and the platform sediments (slaty cleavage, stretching lineation). In the ophiolite, the mineral assemblages associated with S_2 indicate retrogressive metamorphic conditions, while this was a prograde low-grade metamorphic stage in the continental margin sediments. The tectonic meaning of this second event is the exhumation and emplacement of the ophiolite onto the continental margin. The third deformational event is recorded in the ophiolite, the platform sediments and the Tiddiline sediments as open-to-close upright folds and reverse faults/thrusts, all these structures accommodating shortening during the late collisional stage. The Neoproterozoic collision ended with ENE-WSW to E-W left-lateral faulting (Fig. 1B).

Kinematics of the ophiolite emplacement

The ophiolite emplacement onto the continental margin is related to the second deformational event defined above. The direction of movement may be equated with the ENE-WSW mean trend of the stretching lineation and striae on thrust planes (Fig. 2A). As regards the sense of movement, the following indicators are observed: asymmetric boudinage (Fig. 2B), s-type mantled porphyroclasts, C’-type shear bands and oblique quartz subgrains (Fig. 2C). These indicators point to a top-to-the W/SW kinematics, i.e. westwards thrusting with minor left-lateral component. In the metasediments of the platform, the southwestern vergence is coupled with upward stratigraphic younging, in agreement with the kinematics of the ophiolite.

Macrostructure of the Bou Azzer outcrop

The structure of Bou Azzer is illustrated here by means of the general cross-section in figure 3.

The northern belt of arc-type rocks (Saquaque *et al*., 1989) apparently lies over the oceanic rocks, but the contact between the two units is covered by molassic sediments (Fig. 1B). Thus, two possibilities emerge: i) an oceanic crust directly overlain by an island arc (Leblanc, 1993) or ii) two widely separate terranes now accreted (Saquaque *et al*., 1989).

We interpret the map pattern of ophiolitic lithologies as due to a SW-vergent anticline, though great complexity is displayed at small scale, with systematic repetitions suggesting pervasive thrusting. In the cross-section in figure 3, we have slightly simplified this complexity. The Tiddiline rocks show upright folding and reverse faulting, being unconformably covered by the sediments and volcanics of the latest Neoproterozoic Ouarzazate Formation.

The schematic map of figure 1B, largely based on Leblanc (1975), includes our new structural data. In our map, there are no outcrops of Eburnean basement: they actually correspond either to igneous rocks of the continental platform (witnessing a 750 Ma rifting event, according to D’Lemos *et al*., 2006, and our preliminary geochronological data) or to the ophiolite itself, which reappears to the southwest due to folding. Another new feature of this map is the interpretation of the rocks at Takroumt as platform deposits equivalent to those of Bleida, passing upwards to an olistostrome derived from the thrusting ophiolite.

Metamorphic evolution: evidence for an early stage of high-pressure

Mineral assemblages of low-grade metamorphism dominate the rocks of the Bou Azzer outcrop. The sediments of the continental platform were affected by a single event of low-grade, plus local contact metamorphism. In contrast, the

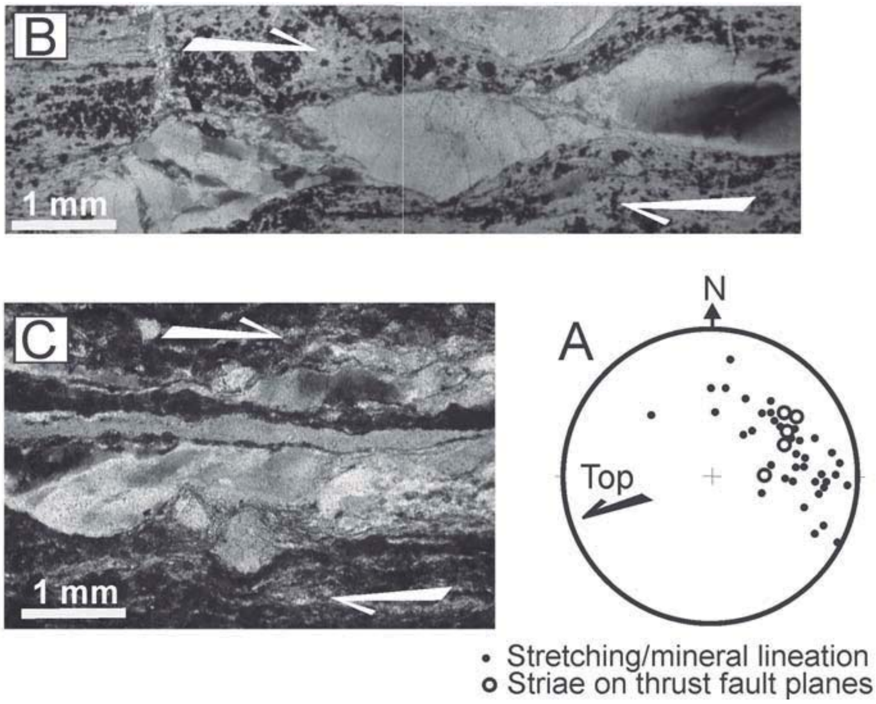

Fig. 2.- Kinematics of the Bou Azzer ophiolite exhumation. 2A: stereogram showing the orientation of stretching lineation and striae on thrust planes. 2B: asymmetric boudinage of a quartz ribbon. 2C: Quartz subgrains oblique to the foliation.

Fig. 2.- Cinemática de la exhumación de la ofiolita de Bou Azzer. 2A: estereograma de la lineación de estiramiento y de estrías en planos de cabalgamiento. 2B: boudinage asimétrico de una cinta de cuarzo. 2C: subgranos de cuarzo oblicuos a la foliación.

ophiolite rocks show pervasive greenschist facies retrogression related to the development of the S_2, with some relics of their previous evolution. One of these evidences is the blue amphibole (crossite and magnesioriebeckite) described by Hefferan *et al*. (2002), from which medium-pressure conditions (» 5 kbar) have been inferred.

In distinctive albite-epidote-chlorite-muscovite schists and epidote-muscovite schists, probably pyroclastic rocks in origin, a S_1 relic foliation has been observed. It is marked by micro-hinges in domains bounded by S_2 crenulation, and internal trails of inclusions in garnet grains surrounded by S_2. Garnet appears transformed into chlorite and oxides, but preserves rutile grains (Fig. 4). Rutile has been unambiguously identified by optical microscopy, Environmental Scanning Electron Microscopy (ESEM) and energy-Dispersive X-ray (EDX).Textural evidence suggests that garnet and rutile were part of an early paragenesis, later on retrogressed to greenschist facies assemblages when S_2 developed. The paragenetic association of garnet and rutile suggests pressures greater than 9 kbar (Yardley, 1989), i.e. significantly higher than previous pressures reported for the ophiolite (Hefferan *et al*., 2002).

Neoproterozoic evolution of Bou Azzer

The tectonic setting of the Bou Azzer ophiolite is still controversial. Geochemistry of basalts is rather heterogeneous, including MORB and arc-related compositions (Leblanc, 1993; Naidoo *et al*., 1993). However, a number of data point to a close proximity of the ophiolite to a volcanic arc, namely: i) the presence of volcanic-derived detritus in the ophiolite sediments, ii) the arc-type plutons intruding the ophiolite, and iii) the present-day location of the ophiolite next to a volcanic arc represented by the northern terrane of Bou Azzer and the volcanics of the Saghro inlier.

The earliest tectonometamorphic event is recorded as a high-pressure mineral assemblage and a first foliation in the oceanic rocks. Consequently, we infer a subduction stage of the oceanic rocks, probably under a volcanic arc, at present represented by the rocks of the northern terrane. The age of this subduction event is not well constrained, though it must be older than 650 Ma, which is the age of the syn-kinematic calc-alkaline plutons intruding the ophiolite.

After subduction, the oceanic rocks underwent a history of exhumation during which the early fabric was strongly obliterated. A new tectonic fabric characterized by foliation and stretching lineation penetrated the ophiolite and the rocks of the platform, causing retrogression in the ophiolite rocks and prograde low-grade metamorphism in the platform-ones. The kinematics of this stage has been established as a top-to-the-W or-SW displacement. The relationships between the oceanic terrane and the northern arc terrane during the exhumation cannot be determined, because the contact between these two is hidden by the Tiddiline rocks. Nevertheless, if the oceanic rocks were deeply subducted under the volcanic arc, a normal fault displacement is needed between the two terranes (Fig. 3). The end of the

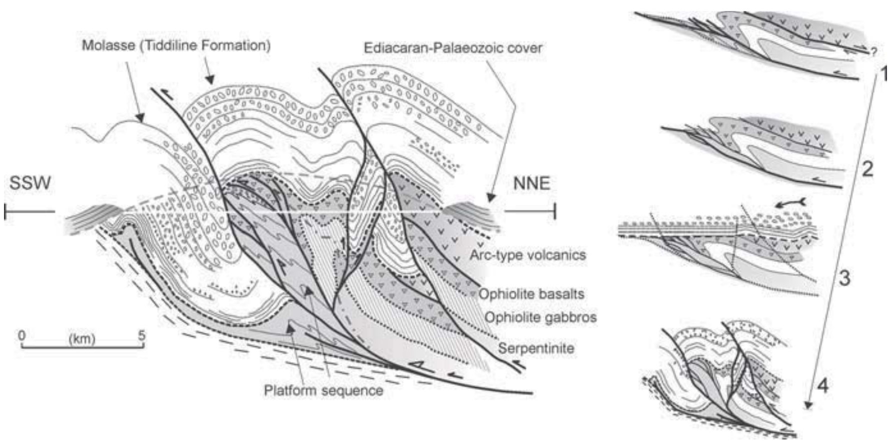

Fig. 3.- Cross-section illustrating the macrostructure of the Bou Azzer outcrop (see location in Figure 1B). To the right, sketches illustrating the evolution of the structure during the emplacement of the ophiolite and arc-related rocks onto the continental margin.

Fig. 3.- Corte geológico que ilustra la estructura del afloramiento de Bou Azzer (localizado en Fig. 1B). A la derecha, esquemas sucesivos de la evolución de la estructura.

exhumation stage was the emplacement of the oceanic and arc terranes onto the continental margin (Fig. 3).

The coarse-grained sediments of the Tiddiline Formation attest intense erosion due to mountain building. These sediments indicate a deformational wave propagating southwestwardly, which accommodated shortening at the end of the continental collision (Fig. 3). The very final stage consisted in left-lateral displacements occurred at discrete left-lateral faults, just before the definitive locking of the collision.

Conclusions

The structure of the Bou Azzer area has been significantly reinterpreted, with the new structure being schematically displayed in the sketch map of figure 1 and the general cross-section of figure 3.

We confirm a recent proposal casting doubt on the existence of Eburnean basement outcrops in Bou Azzer. Rocks previously assumed to be Eburnean are either igneous rocks formed in a »750 Ma rifting stage of the continental margin or fragments of the ophiolite itself. This conclusion is based on geochronological data (D'Lemos *et al*., 2006, and our unpublished preliminary data) as well as in the new structural work summarized in this paper.

The ophiolite emplacement onto the continental margin took place with top-to-the W/SW kinematics, as demonstrated from mesoscopic and microscopic indicators.

There is evidence of an early stage of high-pressure metamorphism affecting the ophiolite. Consequently, we infer a subduction stage of the oceanic rocks, probably under a volcanic arc, at present represented by the rocks of the northern terrane.

After subduction, the oceanic rocks underwent a history of exhumation during which the early fabric was strongly obliterated. A new tectonic fabric characterized by foliation and stretching lineation penetrated the ophiolite and the rocks of the platform, causing retrogression in the ophiolite rocks and prograde low-grade metamorphism in the platform-ones.

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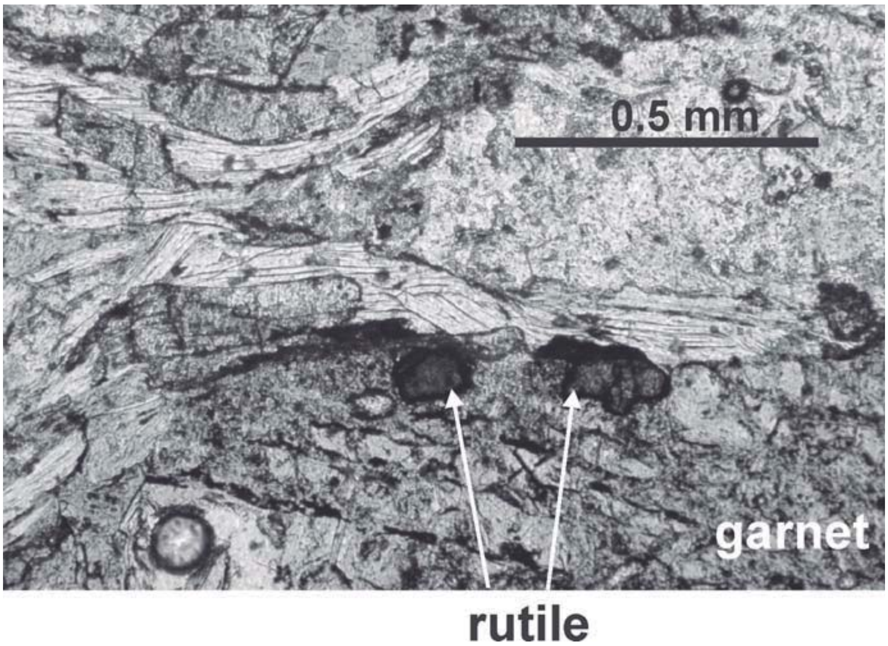

Fig. 4.- Rutile grains at the border of a garnet grain (optical microscopy, polarized light).

Fig. 4.- Granos de rutilo en el borde de un granate (microscopio óptico, luz polarizada).

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