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## Comment on “Evidence of extensional metamorphism associated to Cretaceous rifting of the North-Maghrebian passive margin: The Tanger-Ketama Unit (external Rif, northern Morocco)” by Vázquez *et al.*, Geologica Acta 11 (2013), 277-293

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In northern Morocco, the Rif Belt displays two peculiarities with respect to the adjoining West Mediterranean Alpine belts (Fig. 1); i) the scarcity of ophiolite remnants; and ii) the occurrence of two suture zones (Benzaggagh *et al.*, 2013; Michard *et al.*, 2014) where oceanic sediments and pillow lavas, gabbros or ultramafics are observed. The classical suture zone is that of the Maghrebian flysch extending between the widely displaced Internal Zones or Alboran Domain (common with the Betic Cordilleras) and the External Zones originated from the African paleomargin (Intrarif, Mesorif, Prerif, from north to south). Surprisingly, this main suture zone, that extends from the Tyrrhenian Arc to the Gibraltar Arc (Durand-Delga, 1980), does not contain ophiolite west of the Lesser Kabylia transect. In particular, in the Rif Belt (Fig. 1B), only three tiny units of E-MORB pillow lavas have been recognized within the stacked flysch nappes (Durand-Delga *et al.*, 2000). In contrast, the Mesorif Suture Zone (MSZ) has been defined by the occurrence of serpentinites and metabasites in the eastern Rif (Beni Malek Massif) (Michard *et al.*, 1992, 2007). Recently, ophiolite remnants have been described in the Central Rif (Benzaggagh *et al.*, 2013; Michard *et al.*, 2014), which increases significantly the importance of the MSZ.

Metamorphic recrystallizations can be observed on both sides of the MSZ. They are particularly important in the eastern Rif, south of the suture zone, which is well marked by the Beni Malek serpentinised peridotite massif (Michard *et al.*, 1992). In the uppermost Tamsamani massif (Ras Afraou unit), beneath the peridotite massif, recrystallizations characterize the chloritoid-phengite medium-pressure, low-temperature greenschist facies (Negro *et al.*, 2007). Similar metamorphic units are known further east in the Oran Mountains (Guardia, 1975), suggesting that the MSZ continues eastward over at least 200km (Michard *et al.*, 2007). On the other hand, low-grade metamorphism has been recognized since years (Mattauer, 1963; Andrieux, 1971) in the Intrarif Ketama Unit and repeatedly studied in the last decades (Monié *et al.*, 1984; Frizon de Lamotte and Leikine, 1985; Leikine *et al.*, 1991; Azdimousa *et al.*, 1998, 2003). We are indebted to Vázquez *et al.* (2013) for bringing new data about the varied grades and possible age of metamorphism in this important unit of central-eastern Rif. However, we have major divergences about the structural data presented by the authors, the meaning of the already published K-Ar and <sup>40</sup>Ar-<sup>39</sup>Ar ages, and the proposed scenario of a Late Cretaceous extensional metamorphism.

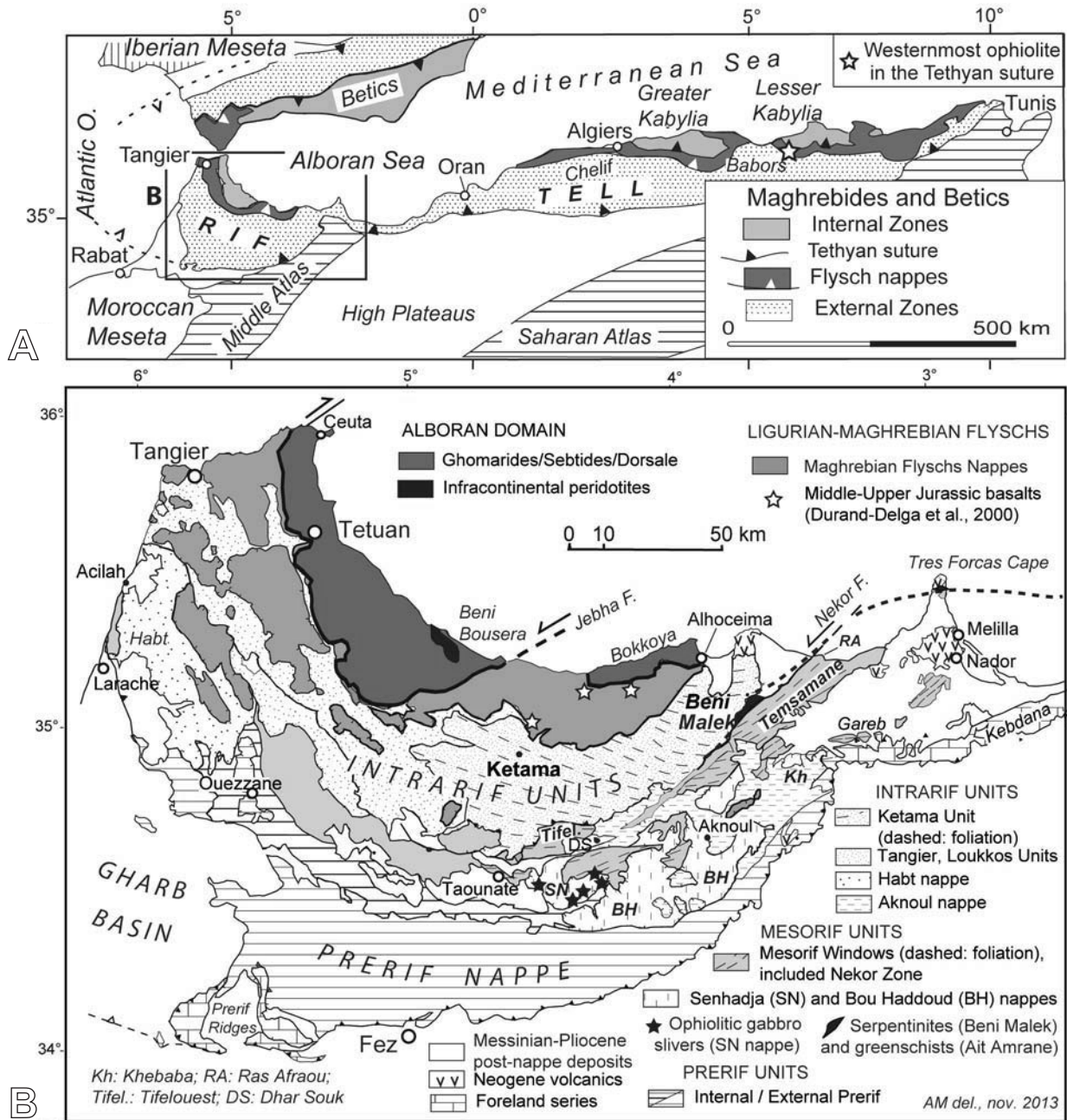


FIGURE 1. A) Sketch map of the Maghrebides, after Durand-Delga, 1980, modified. B) Structural map of the Rif Belt, after Chalouan *et al.*, 2001, modified.

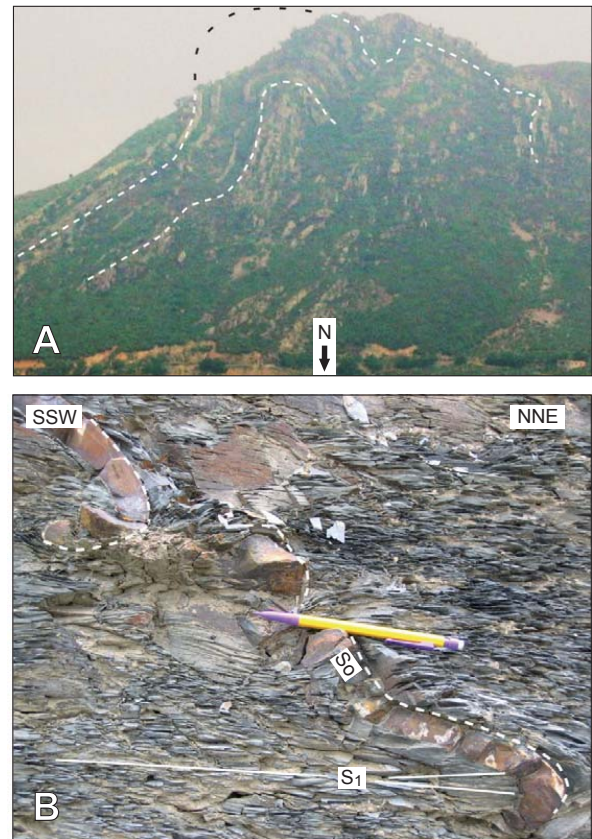
**COMPRESSIONAL VERSUS EXTENSIONAL METAMORPHISM**

Vázquez *et al.* (2013) classify the metamorphic grade of the Ketama Unit as diagenetic to anchizonal, based on illite cristallinity and clay mineral assemblages. However, previous studies (Frizon de Lamotte, 1985, p.244-246; Frizon de Lamotte and Leikine, 1985; Leikine *et al.*, 1991) recognized anchizonal to epizonal conditions (illite, paragonite, Si-rich chlorite, rutile), suggesting

metamorphism at 200°C < T < 300°C. The change in grade classification seems to result merely from a change in the laboratory protocol for measuring the cristallinity index), which is a classical problem (*e.g.* Blenkinsop, 1988; Mählmann, 2001; Árkai *et al.*, 2003). Indeed, the peak T conditions proposed by Frizon de Lamotte (1985) and Leikine *et al.* (1991) are accepted by Vázquez *et al.* (2013), as shown by their Figure 8A. However, contrary to all previous assumptions (see Frizon de Lamotte, 1985, p.235), Vázquez *et al.* (2013) claim that the peak metamorphic

conditions were reached in synsedimentary, extensional conditions prior to folding, so the main foliation  $S_1$  would be systematically parallel to bedding  $S_0$ . According to the authors, folding of the Ketama Unit would only correspond to kink-folds with horizontal axial planes, postdating the peak of very low to low-grade metamorphism, and would be associated to sub-horizontal crenulation cleavage, labelled  $S_2$  in their Figure 3A and  $S_3$  in their Figure 3F. This contradicts the previous descriptions by Andrieux (1971), Frizon de Lamotte (1985) and Favre (1992), as well as our personal observations. Conspicuous upright or weakly reclined folds with axial plane cleavage can be observed in the northern part of the unit (Figs. 2A, 3A), whereas more reclined folds occur in the south, being associated with synmetamorphic minor folds in the appropriate lithologies (Figs. 2B, 3B). Superimposed folds with crenulation cleavage develop in place (Fig. 3C), but the general pattern is that of compressional stack of folded sub-units (Fig. 3D; Frizon de Lamotte, 1985). We cannot accept the Vázquez *et al.* (2013) proposal of an extensional setting during the metamorphic recrystallization of the Ketama Unit (their figure 8A) as, i) this setting does not offer any explanation for the association of the synmetamorphic foliation with compressional folds, and ii) the suggested temperature of 200–300°C reached in the Lower Cretaceous sediments would imply, even with a high geothermal gradient of 40°C/km, a burial beneath 5–7.5km of the Cretaceous deposits (admitting the 80Ma age for the metamorphism proposed by the authors), whereas the stratigraphic thickness of the Ketama-Tanger Cretaceous series ranges between 1.5km (Andrieux, 1971) and 2.5km (Lespinasse, 1975; Frizon de Lamotte, 1985; Chalouan *et al.*, 2008). In contrast, we maintain that recrystallization of the Ketama unit occurred during the Miocene thrust nappe tectonics when the Intrarif domain (and particularly the Ketama Unit) was thickened by its own folding, and buried contemporaneously beneath the internally folded flysch Nappes (Andrieux, 1971; Frizon de Lamotte, 1985; Frizon de Lamotte *et al.*, 1991; Frizon de Lamotte *et al.*, 2004; Chalouan *et al.*, 2006; Crespo-Blanc and Frizon de Lamotte, 2006). This occurred in the frame of an accretionary prism at the front of the Alboran Domain, so the deepest part of the Ketama Unit was at about 10km-depth (Chalouan *et al.*, 2001, 2008).

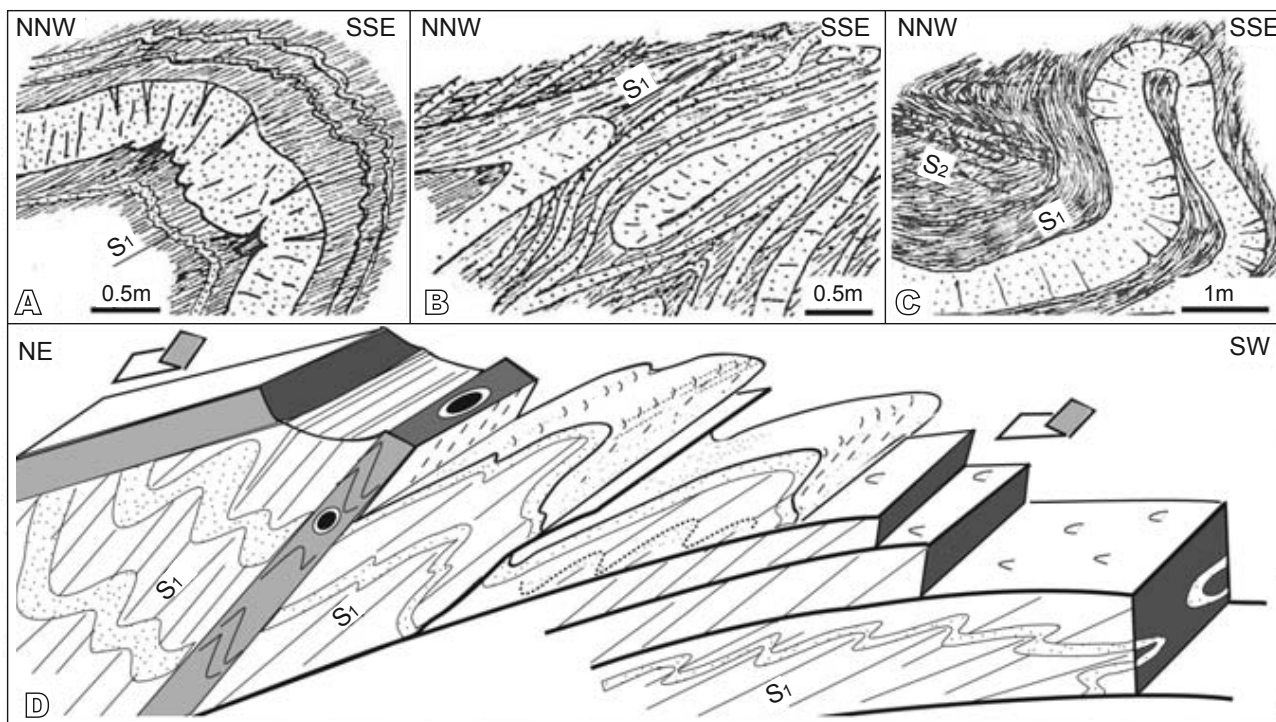
The concept of extensional metamorphism proposed by Vázquez *et al.* (2013) concerns not only the Ketama Unit, but also the Beni Malek serpentinite massif and adjoining Ait Amrâne metabasites and marbles units. The authors refer to Michard *et al.* (1992) and Chalouan *et al.* (2008) with some bias when they argue (p.283) that the Beni Malek massif was on the seafloor during the Lower Cretaceous since mafic and ultramafic clasts occur within sediments of this age south of the Beni Malek serpentinites. In fact, i) the marbles with serpentinite clasts that drape the serpentinite massif are the only sediments clearly emplaced



**FIGURE 2.** Synmetamorphic folds in the Ketama Unit. A) Major E-trending fold in the northern part of the unit. B) Minor fold and associated foliation in the southern part of the unit. After Chalouan *et al.*, 2011.

on top of these ultramafics and they are regarded as likely Late Jurassic by Michard *et al.* (1992) and Vázquez *et al.* (2013, p.281, 290); ii) the Ait Amrâne marbles with similar serpentinite and metabasites clasts are also regarded as Late Jurassic (Michard *et al.*, 1992; Vázquez *et al.*, 2013, p.290). Contrary to the latter authors, Michard *et al.* (1992) consider that the sandy-pelitic Lower Cretaceous sediments of the Ketama Unit are separated from the underlying Beni Malek and Ait Amrâne units by a thrust fault (see also Michard *et al.*, 2007, Fig. 8A). This fault accounts for the difference in peak metamorphic conditions between the Ketama Unit (200°C–300°C) and the Ait Amrâne unit (where the biotite-bearing upper greenschist facies suggests peak temperatures around 350°C–450°C according to most metamorphic grids (Bousquet *et al.*, 2012; Brown, 2014). The superposition of less metamorphic rocks upon more metamorphic rocks could be related to the late extensional exhumation of the latter, probably coeval with the opening of the Alboran Basin.

Moreover, the Beni Malek massif and adjoining units would no longer be regarded as the stratigraphic base of the Ketama Units when their correlation with the oceanic



**FIGURE 3.** Structure of the Ketama Unit. A-C) Minor folds and associated cleavages observed in the Aptian-Albian sandy-pelitic series of the central Ketama unit, after Andrieux (1971), D) Broad structure of the eastern Ketama Unit, after Frizon de Lamotte (1985).

floor remnants (ophiolite units; Benzaggagh *et al.*, 2013; Michard *et al.*, 2014) at the bottom of the Mesorif Senhadja Nappe (black stars in Fig. 1B) would be accepted. The 166Ma-old, “alkaline intrusive diorite” quoted by Vázquez *et al.* (2013) is in fact the westernmost ophiolite units.

### GEOCHRONOLOGICAL DATA

The geochronological data reported by Vázquez *et al.* (2013) from the Ketama Unit have been previously published by Azdimoussa *et al.* (1998), and Azdimoussa *et al.* (2003) with additional data from the overlying flysch Nappes, not considered here. They include K-Ar, zircon fission-track (ZFT) and apatite fission-track (AFT) data. The AFT apparent ages (ranging between  $13.9 \pm 1.8$  and  $20.0 \pm 2.4$ Ma) documenting the Miocene exhumation of the Ketama Unit; are not discussed here. Regarding the ZFT results, spanning from 76Ma to 525Ma, Azdimoussa *et al.* (1998) pointed out that, i) none of the four zircon samples passed the  $khi_2$  test, and ii) in each sample, some zircon grains give ages older than their stratigraphic age, due to metamorphic temperatures below that of total track annealing ( $330\text{--}350^\circ\text{C}$ ). Therefore we consider the ZFT measurements as unreliable for dating the metamorphism of the Ketama Unit.

Concerning the K-Ar results, we reiterate our disapproval (Chalouan *et al.*, 2008, p.258): although

measurements were operated on mica fractions  $<2\mu$ , this method is not reliable due to the low to very low metamorphic grade of the studied rocks, in contrast to the  $^{40}\text{Ar}\text{--}^{39}\text{Ar}$  method when documented with petrographic data (Negro *et al.*, 2008). In fact, the two ages of the Lower Cretaceous metapelites of the Ketama Unit ( $78.0 \pm 1.2$  and  $81.6 \pm 4.0$ Ma) may well correspond to mixed ages from partially resetted crushed detrital micas likely from Paleozoic sources) and metamorphic illite grains. This is also true for the very distinct ages ( $131.9 \pm 3.2$  and  $126.6 \pm 2.1$ Ma) of the Upper Jurassic sandy pelites (“ferrysch”) south the Ketama Unit in the Tifelouest-Dhar Souk area. Partial resetting of the K-Ar system has also been evidenced in the Ghomaride nappes of the Internal Rif, which record similar low grade metamorphic conditions (Negro *et al.*, 2006).

The “dichotomy” in the K-Ar ages between the Tifelouest Jurassic pelites and the Ketama Cretaceous metapelites can be simply related to the occurrence of a thrust fault in between (Favre, 1992; Asebriy, 1994), which would also explain the paradoxical difference in the peak metamorphic temperatures in these units, mentioned by Azdimoussa *et al.* (1998), *i.e.* lower than  $200^\circ\text{C}$  in the Jurassic pelites, and  $300^\circ\text{C}$  in the superimposed Ketama Unit. According to Favre (1992) and Vidal (1983), the low-grade, foliated Jurassic units of the Jebel Tifelouest (WNW of Dhar Souk) beneath the Ketama Unit, are unconformably

overlain by poorly dated Upper Oligocene–Miocene blocky marls and olistostromes with foliated Mesozoic–Eocene elements. Therefore, the very-low grade metamorphism of the Tifelouest units would have occurred before the Upper Oligocene (?)–Lower Miocene.

Vázquez *et al.* (2013) also mention  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  date at 80Ma from the Ait Amrâne marbles (southwest Beni Malek unit) after Jabaloy *et al.* (2012). This age has not been documented yet by petrographic data supporting its interpretation. We noticed above that the Ait Amrâne metabasites/metasediments unit is significantly more metamorphic than the Ketama Unit. Therefore, the date from the Ait Amrâne unit cannot inform on the age of the Ketama low-grade recrystallization. We must be particularly cautious with the interpretation of this 80Ma date as it concerns one of the allochthonous oceanic units of the Mesorif Suture Zone, which were affected by oceanic metamorphism at some time between the Late Jurassic and Late Eocene, before the collisional evolution of the Maghrebides (Benzaggagh *et al.*, 2013; Michard *et al.*, 2014). After the pioneering study by Monié *et al.* (1984), Negro *et al.* (2008) performed a detailed  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  dating in the Tamsamane massif, in the Mesorif immediately east of the Beni Malek–Ait Amrâne units. Vázquez *et al.* (2013) mention briefly Negro *et al.*'s study in their Geological setting section without turning back on these data in the Discussion section. However, this data have been carefully correlated by Negro *et al.* (2008) with the recrystallization events observed in the northern, most internal units of the Tamsamane massif (Ras Afraou unit and equivalents). Results of *ca.* 23–20Ma characterize the minimum age of high-Si phengite grains preserved in the intrafolial quartz segregates from both units, being referred to the peak pressure metamorphism. A second group of results at ~15–10Ma characterize the phengite lamellae from the foliation, and are referred to the ductile deformation associated with the south-westward exhumation of the metamorphic units. The low-temperature dates at ~10–6Ma are obtained from the illite–kaolinite-bearing retrogressed samples, thus reflecting the late brittle–ductile deformation of the tectonic pile. The peak P–T conditions in the northernmost units (Ras Afraou, Tres Forcas) are estimated at 7–8kbar,  $350\pm 30^\circ\text{C}$ , corresponding to medium pressure, low temperature (MP–LT) metamorphism, and suggesting subduction down to *ca.* 20km depth at an age  $t > 23\text{Ma}$ . There is no indication of any Cretaceous metamorphic event there. The 15–10Ma  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  ages in the Tamsamane are in good agreement with the AFT ages in the Ketama unit, suggesting a common exhumation history (Negro *et al.*, 2008).

## CORRELATIONS AND CONCLUSION

Vázquez *et al.* (2013) mainly propose Iberian, Alpine and Pyrenean comparisons in support of their idea of an

extensional Cretaceous metamorphic event in the External Rif. The comparison of the Beni Malek exhumation with that of the peridotite ridge exhumed at the foot of the Galician margin during the Early Cretaceous is in line with Michard *et al.* (1992). Likewise, Michard *et al.* (2007) emphasized the similarities of the Beni Malek setting with that of the Middle–Late Jurassic Austroalpine margin as described by Manatschal and Bernoulli (1999). However, neither along the Galician margin nor along the Austroalpine any metamorphic event, coeval with the continental crust breakup and serpentinised peridotite exhumation, was described in these Ocean–Continent Transition zones (see Manatschal and Müntener, 2009, and references therein).

The authors, then, evoke (p.289) the North Pyrenean metamorphic zone as a natural model for the allegedly associated Ketama metamorphism and Beni Malek serpentinite exhumation. They report mainly after Fabriés *et al.* (1998), Lagabrielle and Bodinier (2008) and Lagabrielle *et al.* (2010) the occurrence of an early Late Cretaceous extensional metamorphism linked to mantle rocks exhumation in an extensional setting. This interpretation has been discussed (Debroas *et al.*, 2010, 2013), and reaffirmed in several publications (Clerc *et al.*, 2012, 2013, 2014). However, the age of mantle exhumation is younger in the Pyrenees (Albian–Cenomanian) than in the Eastern Rif (Late Jurassic?). Moreover, in the central-eastern North Pyrenean Fault Zone, the exhumed mantle rocks are lherzolites instead of serpentinites and the Cenomanian–Turonian metamorphism is characterized by high temperature–low pressure assemblages (scapolite, biotite, andalusite) and accompanied by Na–Ca and Na metasomatism and alkaline magmatism (Fallourd *et al.*, 2014, and references therein). This is not the case in the External Rif. So, we consider that the Pyrenean comparison is not appropriate. Not only the age, also the kinematics and velocity of rifting and extension/mantle exhumation are probably different in the Rif and Pyreneas study cases.

In contrast, the Tellian correlations are much more pertinent as they concern the Maghrebide Belt itself in the eastern continuity of the Rif (Fig. 1). In contrast to Azdimoussa *et al.* (1998) who cited the works of Lepvrier (1978) and Obert (1984), the useful correlations of this authors are not considered by Vázquez *et al.* (2013). They only cite one Tellian paper (Kuhnt and Obert, 1991) as a reference for the paleogeography of the North African margin. However, a pertinent comparison could have involved the Infra-Tellian units at the bottom of the Tellian External domain. In the western, central and eastern transects (Fig. 1A; Oran Mountains: Centène *et al.*, 1978; Chélif = Zaccar and Bou Maad: Lepvrier, 1971, 1978; Babors: Obert, 1974, 1984), various structural and paleontological observations have been reported in support

of a Late Cretaceous age for the low-grade metamorphism and the E–W trending penetrative deformation that affect these Infra-Tellian massifs. Unfortunately, these conclusions have been contradicted decisively as follows.

In particular, in the western Tellian Zones, the chaotic breccias, on top of the metamorphic units, dated at Upper Cretaceous by Centène *et al.* (1978) contain Lower Miocene planktonic foraminifera (Jenny *et al.*, 1986). In line with Guardia (1975) and Fenet (1975), Jenny *et al.* (1986) concluded that the folded, low-grade metamorphic units overlain by the Miocene breccia are equivalent to the Tamsamani and/or Ketama Units, whose metamorphism was dated as Miocene (Monié *et al.*, 1984) –now as the latest Oligocene (Negro *et al.*, 2008). In relation to the Zaccar massif, Monié *et al.* (1984) evokes “a preliminary  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  determination on chlorite at  $85\pm 8\text{Ma}$ ” in Maluski *et al.* (1979), but also notice “this mineral has been shown to be poorly adequate to  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  dating because of his high  $\text{H}_2\text{O}$  content”. In the Blida Mountains, Blès (1971) demonstrates the post-Early Eocene age of the low-grade greenschist facies recrystallizations and associated synfolial folding that affect the continuous Jurassic–Early Eocene stratigraphic succession. In the Babors, Obert (1984) recognizes that the lack of significant burial is a problem for understanding the birth of the allegedly Vraconian metamorphism. Then, he proposes “d’aménager le schéma classique”, *i.e.* to modify the classical P-T conditions for metamorphic recrystallizations to occur, which is not receivable. Moreover, in the Chéelif transect (Lepvrier, 1978), the synmetamorphic structures are major recumbent folds with south polarity, which clearly does not support an extensional tectonic setting during metamorphism.

To conclude, we may understand why Vázquez *et al.* (2013) did not refer to any Tellian comparisons: they are at odds with their own proposal of a Late Cretaceous extensional metamorphism in the External Rif. Several robust datings of Cretaceous (128–80Ma) extensional metamorphism in the Algerian Maghrebides have been actually published. However, these concern high temperature (*ca.* 450°C) ductile shear zones in the lower unit of the Alger Massif or Greater Kabylia core complexes (see review in Michard *et al.*, 2006). According to Saadallah and Caby (1996), the  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  plateau ages around 80Ma relate to extensional tectonics during Mesozoic thinning of the south European margin. This concerns the Algerian equivalent of the allochthonous Alboran Domain, not the North African paleomargin.

## ACKNOWLEDGMENTS

We are sincerely grateful to Ana Crespo-Blanc and an anonymous Reviewer for their invigorating criticism and detailed

comments of the early draft of this paper. Thanks are also due to Dominique Frizon de Lamotte for his pertinent advices.

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**Manuscript received December 2013;**  
**revision accepted April 2014;**  
**published Online February 2015.**