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Reply to the comment by Michard *et al.* 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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Michard *et al.* (this issue) commented on certain aspects of the Alpine metamorphism and structural evolution of the Rif belt (Morocco) that were briefly noted in Vázquez *et al.* (2013). In particular, they criticize our interpretation of an extensional setting during the main metamorphic recrystallization of the Tanger-Ketama Unit that we considered related to slaty cleavage (S_1) parallel to the lithological layering generated during the Cretaceous. Michard *et al.* (this issue) interpret the S_1 syn-metamorphic foliation as being related to compressional folds, and the peak metamorphism temperatures, in the Lower Cretaceous sediments, as ranging between 200–300°C. Therefore, they conclude that recrystallization of the Ketama Unit occurred during Miocene thrust nappe tectonics. We explain our view in the following sections.

COMPRESSIONAL VERSUS EXTENSIONAL METAMORPHISM

The S_1 slaty cleavage defined by illite and chlorite growth described by Vázquez *et al.* (2013, see their fig. 3) is systematically parallel to the S_0 bedding. We do not discuss the existence of a sub-horizontal cleavage related to reclined folds and associated with minor folds in the appropriate lithologies that can be interpreted as compressional (Michard *et al.*, this issue), we note only that this is a later crenulation cleavage (S_2) superimposed on the previous S_1 foliation.

Criticism by Michard *et al.* (this issue) on the compressional versus extensional character of the metamorphism is also based on their interpretation of the metamorphic conditions reached by the metapelitic sequence. They dismissed the change in grade classification proposed by Vázquez *et al.* (2013) as it "seems to result merely from a change in the laboratory protocol for measuring the cristallinity index (CI)". However, illite crystallinity values need a standard calibration (Kisch, 1991; Warr and Rice, 1994) that had not been carried out in the previous studies cited by Michard *et al.* (this issue). The calibrated illite crystallinity values (KI) indicate diagenetic to anchizonal conditions for the metamorphism of the Ketama Unit (Vázquez *et al.*, 2013). In any case, such a change of scale (due to the necessity of proper KI calibration), is not critical at all for the conclusions reached by Vazquez *et al.* (2013) because they are not based on the absolute KI value, but on its geological distribution (see fig. 1 from the replay and fig. 5 in Vazquez *et al.*, 2013).

According to the estimates of Merriman and Frey (1999) the transition from late diagenesis to low anchizone occurs at ~200ºC in a normal gradient (25–30ºC/km), whereas the same transition occurs at 230 ± 10ºC in low geothermal gradients (Potel *et al.*, 2006). As pointed out by Michard *et al.* (this issue), zircon fission track (ZFT) results in these rocks indicate that the Tanger-Ketama Unit never surpassed temperatures of the total fission-track annealing (Azdimousa *et al.*, 1998, 2003). Field-based studies yielded effective closure temperatures in zircons ranging between 210–240°C depending on the cooling rate (Zaun and Wagner, 1985; Hurford, 1986; Brandon *et al.*, 1998). Higher effective closure temperatures in zircons, as indicated in the comment, are estimated only in laboratory studies (330–350°C, see Yamada *et al.*, 1995).

Overall, illite crystallinity (IC) and ZFT indicate that the Tanger-Ketama Unit rocks did not surpass 240ºC. However, as mentioned above, the critical point is the distribution of the KI values, which cannot be explained in the model by Michard *et al.* (this issue). Michard *et al.* (this issue) propose that the metamorphic recrystallization of the Ketama Unit occurred within an accretionary wedge (formed by the thickened Intrarif domain) that was buried beneath the internally folded flysch nappes during the Miocene thrust nappe tectonics (Michard *et al.*, this issue, and references therein), when the deepest part of the Ketama Unit reached about 10km in depth (Chalouan *et al.*, 2001, 2008). In the model by Michard *et al.* (this issue), the highest metamorphic conditions must have been attained at the base of the orogenic wedge that reached the greatest depths and decrease towards its upper parts. However, the IC values from Vázquez *et al.* (2013, their fig. 2) indicate that, at the base of the Tanger-Ketama Unit, both the Jurassic rocks and the Early Cretaceous rocks near the basal thrust underwent diagenetic conditions and that the temperature increased towards the central part of the outcrops (Fig. 1).

Another criticism by Michard *et al.* (this issue) is that peak temperatures of around 240ºC in the Lower Cretaceous sediments could not have been reached due to the stratigraphic thickness of the Cretaceous series of the Tanger-Ketama Unit, which ranges from 1.5km (Andrieux, 1971) to 2.5km (Lespinasse, 1975; Frizon de Lamotte, 1985; Chalouan *et al.*, 2008), implying very high geothermal gradients. Chalouan *et al.* (2008) present the lithological column of the Tanger-Ketama Unit with just 1.5km minimum thickness only for the Lower Cretaceous sediments, which are overlain by around 1km of Upper Cretaceous sediments. The Tanger-Ketama sequence ends up with the basal tectonic contact of the "Aknoul nappe, detached from the Ketama Unit on top of the Cenomanian under compacted clays" (Chalouan *et al.,* 2008), thus increasing the minimum thickness of the Cretaceous series of the Tanger-Ketama Unit to a value of 3.5km or higher. Furthermore, Cretaceous extension most probably thinned the Jurassic sedimentary sequence based on data from Benzaggagh *et al.* (2013, their fig. 7) and Benzaggagh (in press) that indicate foliated metamorphic clasts of the Middle–Upper Jurassic formations within Berriasian–Barremian breccias of the Subrif zone, thus proving the exhumation of ductile metamorphic clasts from the base of the sedimentary sequence during the Cretaceous.

Estimates of the geothermal gradients prevalent during the Cretaceous of rocks from the High Atlas to the Rif from Ghorbal *et al.* (2008) and Saddiqi *et al.* (2009) indicate a heating episode that expanded during most of the Late Cretaceous and lasted until the Eocene. This heating episode is usually modelled assuming subsidence of the area and a thermal gradient of 30°Ckm^{-1} but, as mentioned by these authors, the modelled subsidence is somewhat greater than the thickness of Upper Cretaceous to Eocene sediments in the area (see Ghorbal *et al.*, 2008; Saddiqi *et al.*, 2009), indicating higher thermal gradients for this event. It is important to note that, under these conditions, the rocks reached temperatures of 60–80ºC below 1km of sediments, which is compatible with temperatures of over 200ºC below the 2.5–3.5km thick Cretaceous sediments of the Tanger-Ketama Unit.

What is more significant regarding the criticism by Michard *et al.* (this issue) about the distinction between extensional and compressional metamorphism is that they completely ignore the results obtained for the b parameter of micas. According

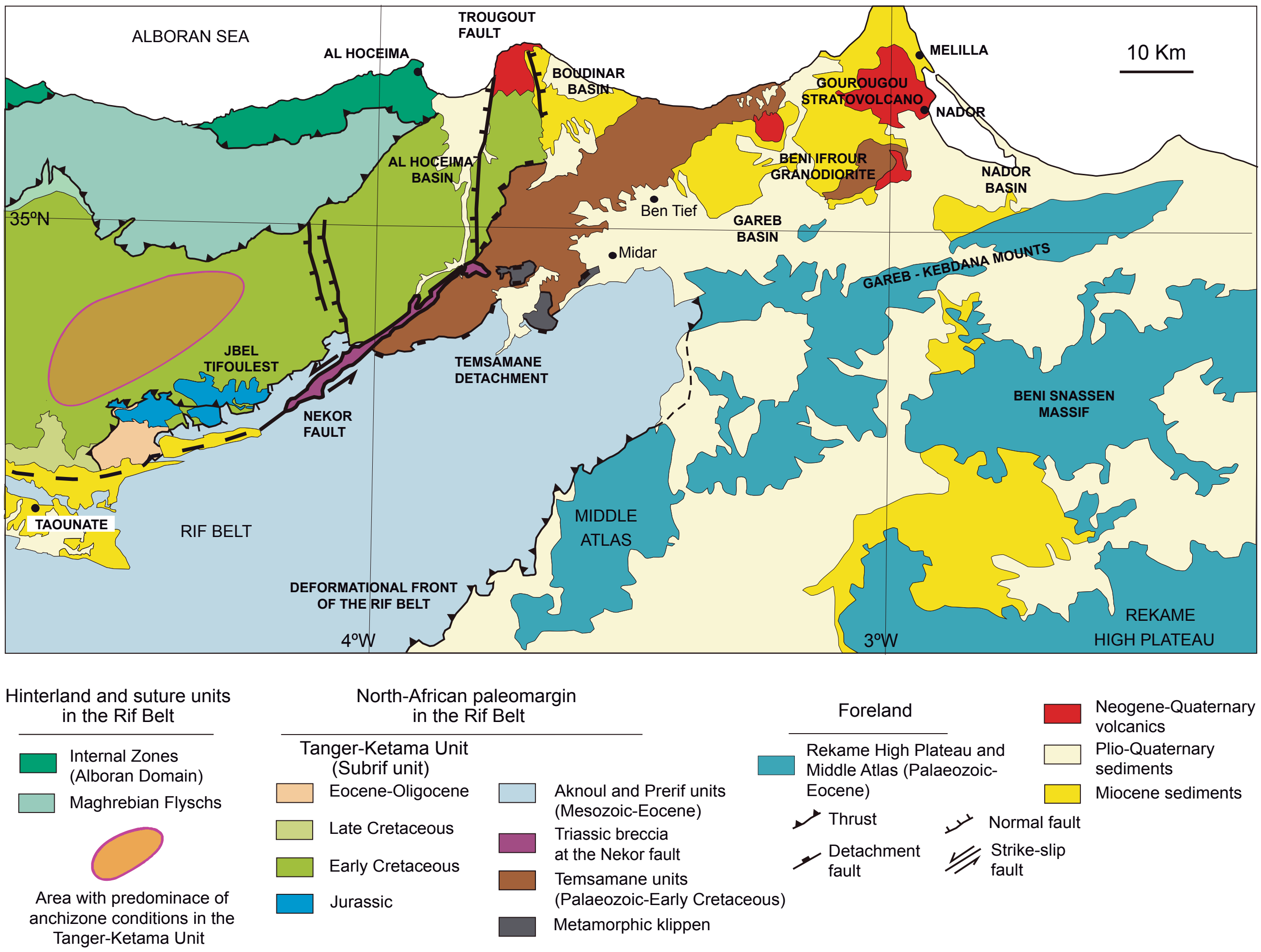

FIGURE 1. Geological map of the eastern Rif including the area with predominant anchizone conditions in the Tanger-Ketama Unit.

to all the basic literature that established the distinction criteria for the two kinds of geotectonic settings in very low-grade metamorphic rocks (Robinson and Bevins, 1989; Merriman and Frey, 1999; Merriman, 2005), the b parameter of mica is the clearest criterion for their distinction. This parameter is related to the phengitic content of micas (Guidotti *et al.*, 1992) and is a classic measurement of the pressure at which micas formed (Massone and Schereyer, 1987). All the b parameters determined by Vazquez *et al.* (2013) are lower than 9.000Å (see Table 1 in Vazquez *et al.*, 2013), that is, clear low-pressure (or high thermal gradient) conditions. All the literature about geotectonic settings in very low-grade metamorphic rocks specifies these b parameter values as one of the defining characteristics of extensional settings.

GEOCHRONOLOGICAL DATA

Another main criticism in the Michard *et al.* (this issue) manuscript is their disapproval of the K-Ar radiometric ages measured on mica fractions of <2µ; for these authors, "this method is not reliable due to the low to very low metamorphic grade of the studied rocks, in contrast to the ^{40}Ar-^{39}Ar method when documented with petrographic data (Negro *et al.*, 2008)". These authors are criticizing the standard methodology and they also forget to mention that no one plateau has ever been found in any of the samples dated by the ^{40}Ar-^{39}Ar method in the External Rif (see Monié *et al.*, 1984 and Negro *et al.*, 2008) except for one biotite concentrate from a granodiorite with a 7.3±1.5Ma cooling age related to the Neogene volcanism in the Gourougou stratovolcano (Fig. 1) (Beni Ifrour granodiorite, Hernandez and Bellon, 1985). Furthermore, an ^{40}Ar-^{39}Ar age spectrum from an amphibole concentrate in greenschists from the Temsamane units includes most of the steps forming a high-temperature component at an average of 132.4±13.3Ma, which is fitted by an isochron at 94.8±9.7Ma (Monié *et al.*, 1984). The latter isochron is in agreement with the data from Azdimousa *et al.* (1998, 2003), and Monié *et al.* (1984) propose that it could correspond to an older metamorphic event.

CORRELATIONS

Michard *et al.* (this issue) claim that there was no metamorphic event coeval with the continental crust breakup and serpentinized peridotite during the Early Cretaceous exhumation described at the foot of the Galician margin. However, in fact, the whole Iberian Peninsula was affected by three large-scale thermal episodes during the Mesozoic: in the Late Triassic, Late Jurassic/Early Cretaceous, and Late Cretaceous (Tritlla and Solé, 1999; Juez-Larré and Ter Voorde, 2009). The second thermal episode ended around 130–120Ma and was recorded by different thermochronometers: apatite fission track, ZFT, ^{40}Ar-^{39}Ar, and K-Ar methods with closure temperatures of 120–325ºC (see Juez-Larré and TerVoorde, 2009, and references therein). This event has been determined in the Cantabrian Mountains (Schärer *et al.*, 1995; Martín-González *et al.*, 2006; Grobe *et al.*, 2010, among others), Pyrenees (Fungenschuh *et al.*, 2003), Catalan Coastal Ranges (Juez-Larré and Andriessen, 2006), Spanish Central System (De Bruijne, 2001), Toledo Mountains (Barbero *et al.*, 2005), West Iberia and Sierra Morena (Pereira *et al.*, 1998; Stapel, 1999), and Betics (Barbero and López-Garrido, 2006). This Late Jurassic/ Early Cretaceous thermal episode corresponded with the northward progression of the Atlantic rifting producing the separation of Newfoundland from Iberia, the emplacement of serpentinized mantle in the west Galician margin and, finally, seafloor spreading in the North Atlantic region (*e.g.* Schärer *et al.*, 1995; Tucholke *et al.*, 2007). This thermal episode can also be directly related to the rifting of the North-African palaeomargin and the onset of oceanic crust development during the Late Jurassic, generating the ophiolitic sequences of the Mesorif described by Benzaggagh *et al.* (2013) and Benzaggagh (in press).

The Late Cretaceous thermal episode was also recorded in the western Iberian Peninsula by the aforementioned thermochronometers: the Cantabrian Mountains (Grobe *et al.*, 2010), Spanish Central System (De Bruijne, 2001), West Iberia and Sierra Morena (Stapel, 1999), and Iberian Range (Del Río *et al.*, 2009). This event was coeval with the intrusion of Late Cretaceous alkaline igneous rocks in central and southern Portugal between 88.3±0.5Ma and 68.8±1.0Ma (Grange *et al.*, 2010) among other magmatic centres in the eastern Central Atlantic (Tore-Madeira Rise), along the western Iberian margin, and the NW of the African plate related to a deep-rooted mantle plume responsible for the thermal input that can explain the high thermal gradients (Grange *et al.*, 2010).

The examples that Michard *et al.* (this issue) cited from the Tell indicate that the Late Cretaceous thermal episode extended through the NW of the African plate and, in fact, the Late Cretaceous thermal episode was also recorded in the AFT T-t histories from the western Moroccan Meseta as a thermal heating of the samples (see Barbero *et al.*, 2011, their fig. 10). Furthermore, it is also recorded in several samples from the High Atlas (Missenard *et al.*, 2008; Balestrieri *et al.*, 2009). In the southern part of the western Moroccan Meseta, a Late Jurassic to Early Cretaceous episode was represented by vertical uplift of the rocks associated to exhumation (Ghorbal *et al.,* 2008; Saddiqi *et al.*, 2009) and was followed by the aforementioned heating episode of the rocks that followed during most of the Late Cretaceous and lasted until the Eocene (Ghorbal *et al.*, 2008; Saddiqi *et al.*, 2009).

In summary, the Late Cretaceous to Tertiary subsidence of the area between the Rif and the Atlas with geothermal gradients higher than 30ºCkm^{-1} are known from the works of Ghorbal *et al.* (2008) and Saddiqi *et al.* (2009) and are coherent with the alkaline magmatism in the eastern Central Atlantic, the western Iberian margin, and the NW of the African plate (Grange *et al.*, 2010). The work of Vázquez *et al.* (2013) proposed that the same subsidence and thermal heating affected the north Maghrebian passive margin where the Tanger-Ketama Unit was deposited, and that it can explain the distribution of the metamorphic temperatures within the unit without invoking ad hoc thrusts.

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