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Reply

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Reply

Reply to Comment on "The Jurassic-Cretaceous basaltic magmatism of the Oued El-Abid syncline (High Atlas, Morocco): Physical volcanology, geochemistry and geodynamic implications" by André Michard et al., (2013) Journal of African Earth Sciences, Volume 88, December 2013, Pages 101–105.

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We welcome the comment by Michard et al. (2013) as it gives us the opportunity to better discuss the Jurassic-Cretaceous magmatism of the High Atlas (Morocco). In their comment, Michard et al. (2013) focus on three main points which are: (i) the age of the basalts from Naour, (ii) the structural history of the Central High Atlas and (iii) the geodynamic significance of the related Jurassic-Cretaceous magmatism. We will address these questions in the following sections.

1. Age of Naour basalts : B1 or B2 volcanic pulse?

In our previous study (Bensalah et al., 2013), the age of the Naour basalts was considered as formed during the B1 volcanic event based upon K-Ar dating on plagioclase (Westphal et al., 1979). Indeed, the base and the top of the Naour section gave an age of 173 ± 4 Ma and 166 ± 3 Ma, respectively (Westphal et al., 1979). Moreover, in the 1/100.000 geological map of Imilchil (Fadile, 2003), the Naour basalts are indicated as interstratified within sedimentary rocks of the Guettioua Formation and are considered as Bathonian (~164-167 Ma). However, we pointed out in our original study that the K-Ar age of the Naour basalts is subject to revision due to outdated analytical procedures, as well as alteration state of the plagioclases. Conversely, micropaleontological data (charophytes and ostracods) suggested that the Naour basalts are interstratified within the Jbel Sidal Formation (Barremian) and thus are Cretaceous in age (Haddoumi et al. 2010; Charrière et al. 2011). A Cretaceous age is also supported by pioneer paleomagnetic data of the Naour basalts (Westphal et al., 1979), for which the position of the virtual paleomagnetic poles of the base, middle and top of the sections are closer to the Cretaceous (poles at 140-100 Ma) rather than the Jurassic (180-150 Ma) segment when compared to a global apparent polar wander path (GAPWP) (Torsvik et al., 2012) (Fig. 1A).

We also performed new paleomagnetic investigations in the Naour and Aït Attab South sections, but results were not available before the submission of the revised version of our original manuscript (Bensalah et al., 2013; Font, E., unpublished data). In both sections, we sampled all the lava flows and treated the samples by alternating field demagnetization in order to calculate the directions and polarity of the magnetic remanence recorded in these flows. Our new paleomagnetic data confirm the transition from normal (positive) to reverse (negative) magnetic directions at the base of the Naour section (between the second and third lava flow), as previously observed by Westphal et al. (1979). In addition, we identified the same magnetic polarity transition in the second and third flow of the Aït Attab South section (Fig. 1B). These new magnetostratigraphic data thus suggest that the Naour and Aït Attab South lava flows have the same age. Micropaleontological analysis of the red bed located below and above the Aït Attab basalts revealed a transition of the charophyte biozones, from *Globator mutabilis* of a lower Barremian age to the biozone with *Globator trochilidiscoïdes* of an upper Barremian age (Haddoumi et al. 2002; Mojon et al. 2009; Haddoumi et al. 2010).

Resuming, we agree with Michard et al. (2013) that the eruptions of the Naour basalts should be assigned to the B2 event, and we bring new magnetostratigraphic evidences to confirm a Cretaceous age for both the Naour and Aït Attab South sections. Independently of the age of the Naour basalts, the main implications of the Bensalah et al. (2013) work still remains valid.

2. The geodynamic significance of the Central High Atlas Jurassic-Cretaceous magmatism.

In our paper, we mainly focus on the petrological aspects of the Central High Atlas magmatism and on its geodynamic significance on the basis of new geochemical and mineralogical data. In addition, during the preparation of the paper, it clearly appeared that, despite the number of studies carried out on the Atlas chain, the structure and the Mesozoic evolution of the High Atlas remains unclear and a consistent geodynamical model is still lacking. We thus limited the paper to the petrological aspects and postponed the interpretation of geodynamic aspects to a future paper which will be based on multiple data sources, including the publications referred to by Michard et al. (2013).

2.1. Age of emplacement of the magmatic rocks

We agree with Michard et al. (2013) that the role of halokinesis could have been important for the development of the High Atlas folds, as first suggested by Ettaki et al. (2007), and that dating the formations at the anticline tops (Charrière et al., 2009) removed the inconsistency of the exhumation of the magmatic bodies in such a short interval. This is supported by recent thermochronologic data suggesting that plutonic rocks were still located at depth in the 90-80 Ma time lapse (Barbero et al., 2007), as reported in our paper (Bensalah et al., 2013).

2.2. The West Moroccan Arch

The West Moroccan Arch (WMA) structure was first identified as a topographic structure, based on stratigraphic successions and palaeogeographic maps (Roch, 1950; Choubert and Faure-Muret, 1962; Favre and Stampli, 1992, Stets, 1992, Medina, 1995). The structure was named "Terre des Almohades" by Choubert and Faure-Muret (1962) and later renamed WMA, based on the fission track results by Ghorbal et al. (2008) and Saddiqi et al. (2009). Regrettably, the works of Choubert and Faure-Muret are rarely cited in modern literature.

2.3. Causes of the uplift of the Central High Atlas

Michard et al. (2013) write: "its [the WMA] general uplift, occurred during the Bathonian-?Callovian, shortly before the beginning of emplacement of the Central High Atlas gabbroic magmas. […]. Should a rifting event have occurred at that time, subsidence would have occurred in the Atlas Domain, not uplift and emersion. In fact, neither the hypothesis of a Mid-Jurassic compressional phase (Laville & Piqué, 1992), nor that of a Middle-Late Jurassic rifting event (Bensalah et al., 2013) can explain at the same time the regional emersion, restricted continental sedimentation and coeval magmatism of the Central High Atlas". We suppose that Michard et al. (2013) refer to the uniform thinning model of McKenzie (1978). When we consider the more general models, such as those of Royden and Keen (1980), Sclater and Christie (1980) and Hellinger and Sclater (1983), in which the lithospheric mantle is stretched more than the crust, the three phenomena can be simultaneous. Therefore, a small stretching factor at the base of the lithosphere can lead to surface doming, not subsidence (Figure 3 of Royden and Keen, 1980), to continental sedimentation (depending however on the ratio of sea level variations to uplift velocity), and to partial melting. Moreover, an abnormal hot (potential) temperature at the base of the lithosphere (1400 °C), should also induce uplift rather than subsidence (White and McKenzie, 1989).

Michard et al. (2013) add: "We reiterate our proposal of thermal doming without significant crustal extension (Frizon de Lamotte et al., 2009). The anomalous mantle structure would have maintained over 40 Ma (not 140 Ma as indicated by Bensalah et al., 2013), which is an acceptable duration, before a new geodynamic cycle began (Cretaceous worldwide transgression, Alpine orogeny).". However, the authors do not give any value on the thermal anomaly nor an estimates on the time necessary (their "acceptable duration") to recover the normal thermal regime.

Nevertheless, they go back to the idea that: "A possible origin of asthenosphere doming could be the edge-driven convection (EDC) process (King and Anderson, 1998) involving small-scale convection at the boundary between the West-African craton and the Meseta-Atlas lithosphere, thinned by the Triassic-Liassic rifting. The EDC model would again account for the Cenozoic uplift and magmatism of the Moroccan Hot Line, about 100 Ma later (Missenard and Cadoux, 2012)". Again, Michard et al. (2013) propose a model which paradoxically is the same proposed for the Peri-Atlantic Alkaline Province Pulse (PAAP), without providing physical/numerical quantification as in King and Anderson's (1998) paper.

Michard et al. (2013) disagree with the proposal that this system "was reactivated as normal faults. In fact this time span [Middle to Upper Jurassic–Cretaceous rifting event] basically corresponds to a post-rift period even if the main rifting episode responsible for the formation of the Atlas Basin can continue up to the Middle Jurassic in the Middle Atlas […]. […], some extension did occur in the uplifted crust during the Upper Jurassic-Lower Cretaceous, allowing the gabbroic magma to ascend through some of the pre-existing faults, but this is not sufficient to depict a rifting event. In the Central High Atlas, all the normal faults coeval with the Middle Jurassic-Barremian continental sedimentation are linked to halokinesis of Upper Triassic salt deposits …". Here again, Michard et al. do not make the difference between surface and deep processes. As stated previously, extension and rifting can take place in the lithospheric mantle without major crustal extension.

Concerning the main role of halokinesis and the absence of extensional tectonics in the Western High Atlas, although it is certain that salt motion was important during this period, especially in the offshore domain, a major extensional event was observed by Ruellan (1985) northwards within the Mazagan plateau, where salt tectonics is weak. The plateau is affected by a set of planar (not listric) faults affecting the Late Jurassic platform and overlain by the Early Cretaceous series. This system can also be observed onshore (Witam, 1988).

2.4. Does the High Atlas magmatism belong to the PAAP?

Matton and Jébrak (2009) found that nearly half of the peri-Atlantic Mesozoic alkaline magmatic rocks fall within the 125–80 Ma interval with two major peaks: the first at about 125 Ma, and the second at about 85 Ma. The authors called this intense and widespread alkaline activity of the Atlantic realm ‘‘the Peri-Atlantic Alkaline Province Pulse’’ (PAAP). Whether the rocks studied here may be considered part of this widespread province will be discussed. Based on absolute ages published for the Jurassic-Cretaceous igneous rocks from the High Atlas (Table 1 in the electronic supplementary material accompanying this manuscript), there are two major peaks on the cumulative Gaussian and Histogram plots (Figure 2): the first clustering at about 152 Ma, and the second at about 118 Ma which respectively correspond to B1 and B2 pulses. Accordingly, the B2 pulse is an integral part of the PAAP. The main reason why Matton and Jébrak (2009) did not include the lava flows from the High Atlas is because they have restricted their compilation to alkaline rocks only, while the B2 pulse (lava flows and sills of Aït Attab/Ouzoud) was considered as transitional. However as shown in our paper (Bensalah et al., 2013) B2 magmas originate from a mantle source chemically similar to those of the alkaline B1 magmas. Thus the chemical characteristics of their mantle source do not preclude their integration in the PAAP. This allows concluding that the spatial and temporal delineation of the PAAP remains unclear

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Figure captions

Figure 1. A) Virtual Geomagnetic poles of the Naour section (Westphal et al., 1979) compared to the global apparent wander path (GAPWP) of Torsvik et al. (2012) in Northwestern African coordinates (NAB=Naour base; NAM=Naour middle; NAT=Naour top). B) Stratigraphic log of the Naour and Aït Attab South sections (modified from Haddoumi et al., 2010) showing that both sections share a geomagnetic reversal at the boundary between the second and third flows.

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Figure 2. Cumulative Gaussian and Histogram plots of the K-Ar dating of the Jurassic-Cretaceous magmatic rocks of the High Atlas. Based on the compilation of table 1

Table captions

Table 1. Compilation of K-Ar and Ar-Ar ages of Jurassic-Cretaceous magmatic rocks of the High Atlas.

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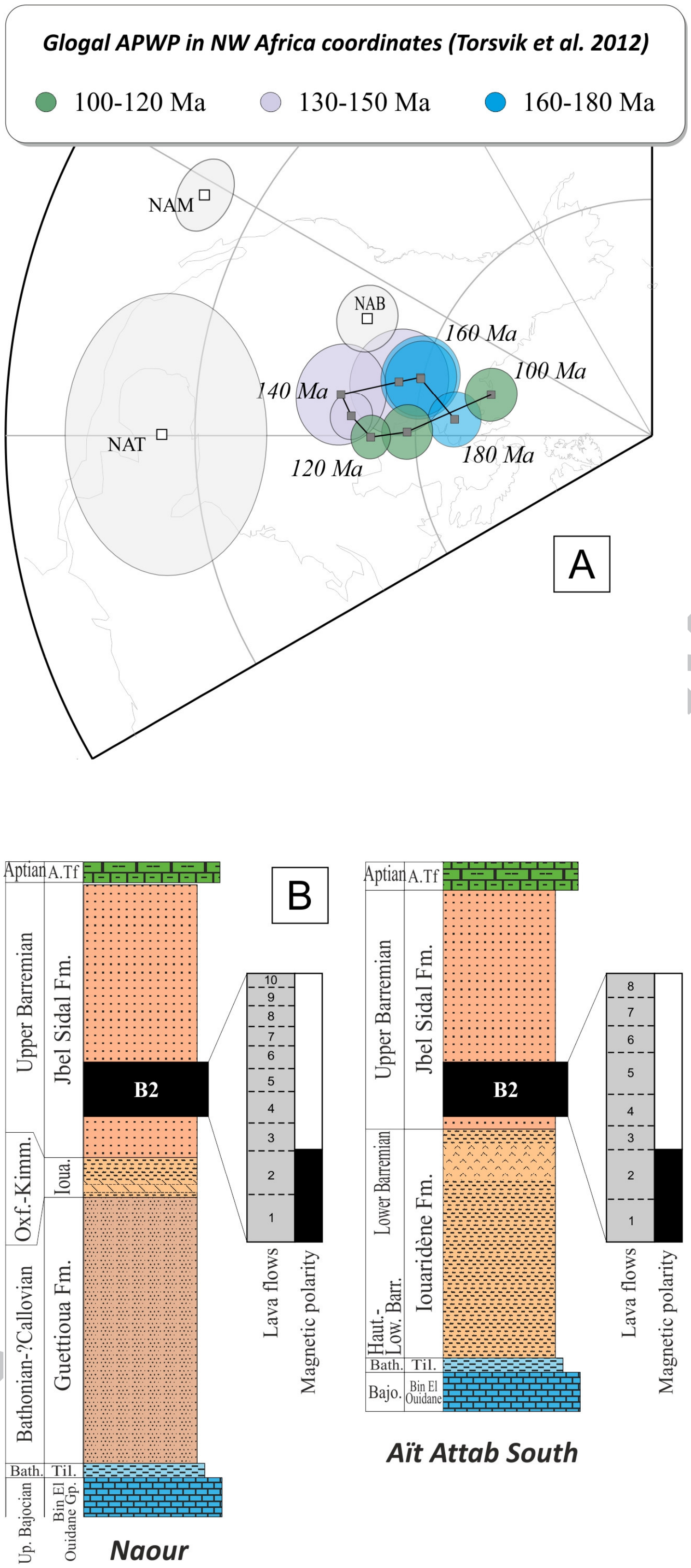
Glogal APWP in NW Africa coordinates (Torsvik et al. 2012)
100-120 Ma
130-150 Ma
160-180 Ma
NAM
NAB
NAT
160 Ma
100 Ma
140 Ma
120 Ma
180 Ma
A
B
Aptian
A.Tf
Upper Barremian
Jbel Sidal Fm.
B2
Oxf.-Kimm.
Ioua.
Bathonian-?Callovian
Guettioua Fm.
Bath.
Til.
Up. Bajocian
Bin El Ouidane Gp.
Lava flows
Magnetic polarity
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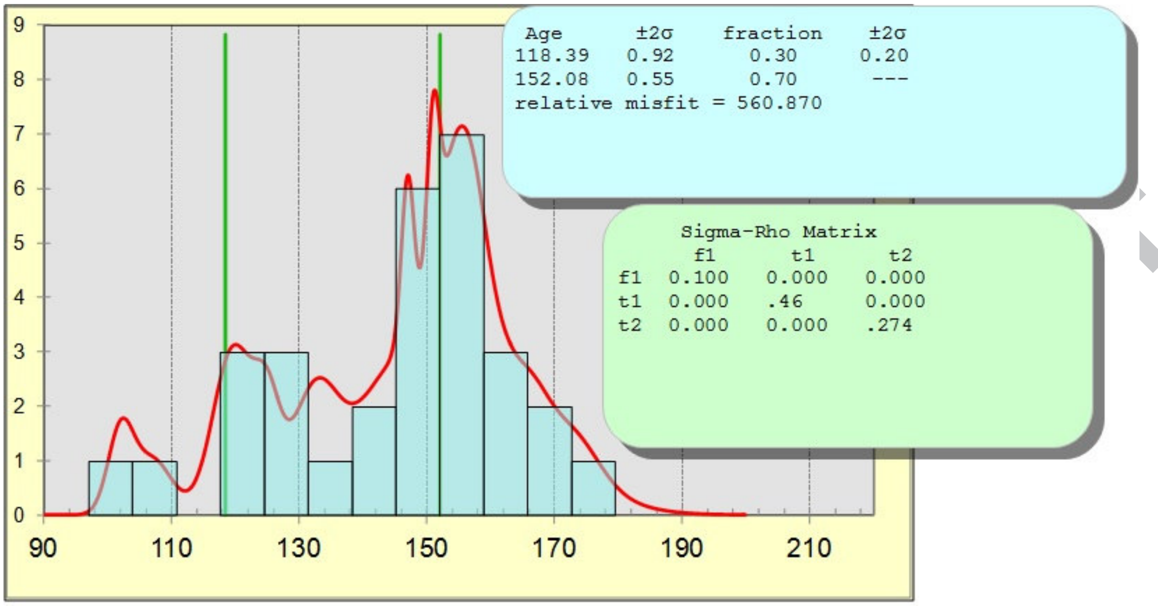
Iouaridène Fm.
Bajo.
Bin El Ouidane
Aït Attab South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118.39 0.92 0.30 0.20
152.08 0.55 0.70 ---
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Sigma-Rho Matrix
f1 t1 t2
f1 0.100 0.000 0.000
t1 0.000 .46 0.000
t2 0.000 0.000 .274
0 1 2 3 4 5 6 7 8 9
90 110 130 150 170 190 210

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