Comment on “The Mesozoic Margin of the Maghrebian Tethys in the Rif Belt (Morocco): Evidence for Polyphase Rifting and Related Magmatic Activity” by Gimeno-Vives et al.

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COMMENT
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Key Points:
- The main Mesorif gabbros emplaced in a Liassic oceanic domain and do not belong to the Central Atlantic Magmatic Province (CAMP)
- CAMP dolerites may occur separately next to the oceanic gabbros in the structurally complex Mesorif zone
- The prerift/synrift cover of the distal margin could have emplaced by gravity sliding onto the Mesorif oceanic crust

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Comment on "The Mesozoic Margin of the Maghrebian Tethys in the Rif Belt (Morocco): Evidence for Polyphase Rifting and Related Magmatic Activity" by Gimeno-Vives et al.

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1. Introduction

In the southern branch of the Gibraltar Arc, that is, the Rif Belt, the External Zones expose nappes of sedimentary or low-grade metasedimentary material deriving from the North-African, Mesozoic-Cenozoic passive margin and stacked broadly to the SW during the Oligocene-Neogene (Figure 1). The geological setting of the area is well illustrated in Gimeno-Vives et al. (2019, hereafter referred to as Gimeno-Vives et al.). Some mafic/ultramafic rocks also occur in the axial units of the External Zones, in the so-called Mesorif zone. They include the Beni Malek serpentinized lherzolites in the Eastern Mesorif (Michard et al., 1992, 2007) and several gabbro massifs in the Central Mesorif, which allowed Michard et al. (2007), then Benzaggagh et al. (2014) and Michard et al. (2014) to elaborate the concept of "Mesorif Suture Zone" (MSZ). According to Michard et al. (2018), the rocks that delineate the MSZ lineament have been sampled from an oceanic crust located northeasterly with respect to their present (post thrusting) position. The latter authors obtained a U-Pb laser ablation-inductively coupled plasma-mass spectrometry zircon age of 190 ± 2 Ma from a trondhjemite pocket in the Bou Adel gabbro (western MSZ; Figure 1) and then suggested that this oceanic domain connected at that time with the Central Atlantic realm, bounding the continental crust of the western Rif. They also defined another narrow zone, a bit more external than the MSZ as it extends at the Mesorif-Prerif boundary, by the association of tholeiitic pillow basalts and polygenic breccias of basalts and platform carbonates dated to the Kimmeridgian-Berriasian (Benzaggagh et al., 2014). This Mesorif Basalts-Breccias lineament would be a transported segment of the east trending, North-African Transform that bounded the margin during the Alpine Tethys opening (Lemoine et al., 1987; Rosenbaum et al., 2002).

In their paper, Gimeno-Vives et al. discard the notion of MSZ. They accept to recognize an oceanic crust or ocean-continent transitional crust sliver in the Beni Malek serpentinites, but they assume that the Mesorif gabbros and dolerites all belong to the Central Atlantic Magmatic Province (CAMP) and intruded the thinned continental crust of the North-African margin. They propose an attractive description of the Triassic-Early Cretaceous units of the so-called Senhadja nappe that overlies the gabbro massifs, and they consider these units as the stratigraphic cover of the gabbros in the distal part of the hyperextended margin.

During the Late Triassic, the External Rif crust was certainly thinned (Michard et al., 2014, Figure 12a) and intruded by CAMP dolerites. This is suggested by the diapirs of the Prerif zone showing Upper Triassic clays and evaporites associated with spilitized dolerites (Chalouan et al., 2008, Figure 5.32) and by the huge Nekor Triassic breccia (Leblanc, 1980). However, the idea of ascribing all the Mesorif gabbros and dolerites to the CAMP, an attractive idea in its simplicity, is not consistent with the available data (Benzaggagh et al., 2014; Michard et al., 2014, 2018). In the following comment, we argue that at least the most typical Mesorif gabbros, that is, the Bou Adel and Kef el Ghar (Kef el Rhar) massifs cannot be interpreted as intracontinental

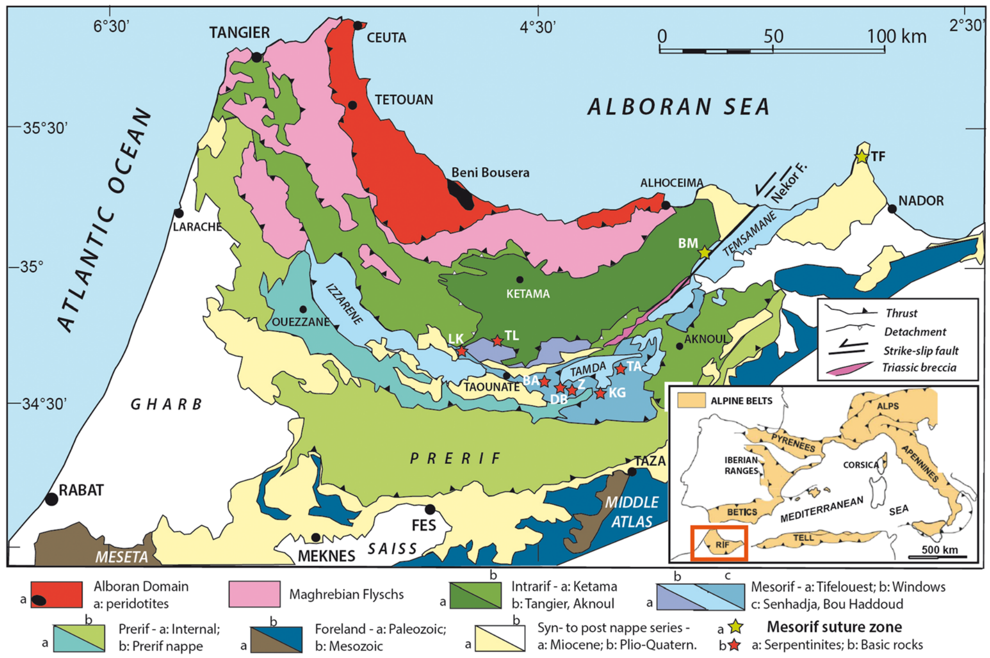

Figure 1. Structural map of the Rif belt with emphasis on the external zones, after Suter (1980) and Chalouan et al. (2008). BA: Bou Adel; BM: Beni Malek; DB: Dar bou Aza; KG: Kef el Ghar; LK: Laklaaia (Klaia); TA: Taineste; TF: Tres-Forcas; TL: Taounat Lechkar; Z: Zitouna.

CAMP intrusions, and we suggest an alternative interpretation, which can explain the coexistence of continental and oceanic basic rocks.

2. Are the Mesorif Gabbros CAMP Intrusions Into the Continental Crust?

2.1. Field Evidence

Gimeno-Vives et al. give a detail description of the Senhadja terrains of Sof Teirara that overlie the Kef el Ghar gabbro (Figure 1). They interpret convincingly the relationships of the Lower Liassic limestones with the juxtaposed Middle and Upper Jurassic strata as recording a second rifting event superimposed to the first, Triassic rifting event. They correctly observed the occurrence of tectonic contact between the Sof Teirara and the gabbros, marked by vacuolar breccias ("cargneules"), brecciated evaporites lenses, and cutoff of the overlying limestones beds. They recognize similar contacts above the Bou Adel and Taineste gabbros.

We certainly agree with the occurrence of a major, brittle tectonic contact at the bottom of the Senhadja units, but not with the interpretation proposed by Gimeno-Vives et al. They assume that this tectonic contact derives from a primary, stratigraphic relationship of the gabbros with the Triassic evaporites and the Lower Liassic limestones that would have been divided into tilted blocks during the Middle Jurassic rifting event and detached from the gabbros by the combined effects of a low-angle extensional fault (see Figure 13b in Gimeno-Vives et al.) and of salt tectonics. Contrastingly, we argue that the basal tectonic contact of the Senhadja units does not occur, except locally, on top of the gabbros themselves but rather on top of an oceanic-type cover sequence stratigraphically attached to the gabbros.

This oceanic-type sequence, a few tens of meters thick, includes from bottom to top (Benzaggagh et al., 2014; Michard et al., 2014) (i) ophicalcites, basalts and basalt breccias (up to 30 m thick), micritic limestones with basalt clasts, and coarse-grained limestones (~10 m) with 5- to 10-cm-thick interbedded ophiolitic sands (at Bou Adel and partly at Dar Bou Aza and Taineste) and (ii) fault scarp gabbro breccias (~2 m), radiolarites (~10 m), and some pelite-calcschist alternations (at Kef el Ghar). The gabbro-gabbro breccias-radiolarite sequence (Figure 2) is classical in the Bathonian-Oxfordian ophiolites of the Western

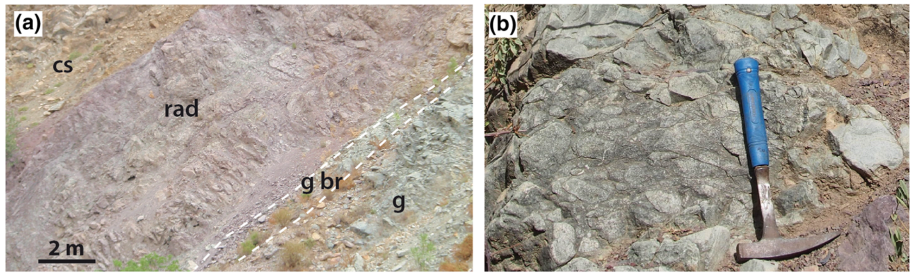

Figure 2. (a) Oceanic sequence on top of the Kef el Ghar gabbro (g); g br: gabbro breccia; rad: radiolarites; cs: calcschists. (b) Close view of the gabbro breccia. Global Positioning System coordinates: 34°31′27″N, 4°16′14″W.

Alps-Liguria-Corsica-Apennine domain (Balestro et al., 2019; Lagabrielle & Lemoine, 1997). In contrast, it is unknown in the CAMP outcrops. Gimeno-Vives et al. did not take into account the Kef el Ghar radiolarites (see Benzaggagh et al., 2014, Figures 9c and 9d) and did not discussed them in spite of the explicit mention of radiolarian fossils (unfortunately undeterminable) in these rocks (Michard et al., 2018). A Late Jurassic age of the oceanic-type cover of the Bou Adel gabbro is supported by its similarity with that of the Beni Malek serpentinites and by the likely correlation with the Taounat Lekchour volcanogenic level interbedded within the Upper Jurassic-Lower Cretaceous layers of the Ketama unit (Zaghloul et al., 2003).

2.2. Petrographic and Geochemical Evidence

From a petrographic point of view, one could argue that CAMP magmatism includes also layered mafic complexes such as those of Freetown in the basement of Sierra Leone (Callegaro et al., 2017) and the Kakoulima complex of Guinea (Deckart et al., 2005; Diallo et al., 1992; Konaté & Pan, 2013). These continental complexes comprise thick layers of gabbroic compositions such as troctolite and anorthosites (and ultramafic cumulates at Kakoulima), but they are not associated with trondjhemites to the contrary of the Bou Adel gabbroic complex. Moreover, all these CAMP intrusions differ from the typical Mesorif gabbros (Bou Adel and Kef el Ghar) by their geochemical affinities.

Concerning the geochemical data, Gimeno-Vives et al. propose as supporting information (their Figure S1) four discrimination diagrams from the same samples used for zircon isotopic analysis. Based on these diagrams, they assign the Mesorif gabbros and dolerites to the CAMP. Unfortunately, the authors do not publish entirely their new geochemical data and they do not report on their diagrams any CAMP reference analyses to test their hypothesis. An examination of the diagrams of Gimeno-Vives et al. combined with the geochemical data from Bou Adel and Kef el Ghar gabbros (Benzaggagh et al., 2014) is sufficient to discard the hypothesis of ascribing these gabbros to the CAMP. Two points are emphasized hereafter:

1. In the primitive mantle-normalized multielement patterns (Figure S1c of Gimeno-Vives et al.), the Mesorif gabbros from Kef el Ghar and Bou Adel do not display a negative Nb-Ta anomaly (the fractionation between Nb and Ta in one of the Bou Adel samples is suspected to be analytical). This anomaly, which is a characteristic feature of the CAMP rocks, is found also in many continental flood basalts. In our Figure 3a, a negative Nb anomaly is seen in the trace element patterns of the CAMP mafic rocks from the Anti-Atlas, Morocco (Bas Draa sills and Foum Zguid dyke; Marzoli et al., 2019); the CAMP intrusive rocks of southwestern Algeria (Ksiksou and Fersiga dykes, Tindouf, Reggane, and Hank sills; Chabou et al., 2010); and the two CAMP layered intrusions (Kakoulima and Freetown complex; Callegaro et al., 2017; Deckart et al., 2005). In contrast, the gabbros from Bou Adel (and from Kef el Ghar in the Figure S1c of Gimeno-Vives et al.) do not show any Nb anomaly. Instead, the patterns of the Laklaaia and Zitouna dolerites show a Nb(-Ta) negative anomaly (Figure S1c of Gimeno-Vives et al.) and suggest their CAMP affinity.
2. In the Th/Yb versus Nb/Yb diagram (Pearce, 2008, 2014; Figure 3b), the Bou Adel gabbros fall within the MORB-OIB array, which is characteristic of mid-ocean ridge ophiolites in particular (Pearce, 2014) and oceanic basalts in general (Pearce, 2008). In contrast, the CAMP mafic rocks from North-West Africa plot above the MORB-OIB array with higher Th/Yb.

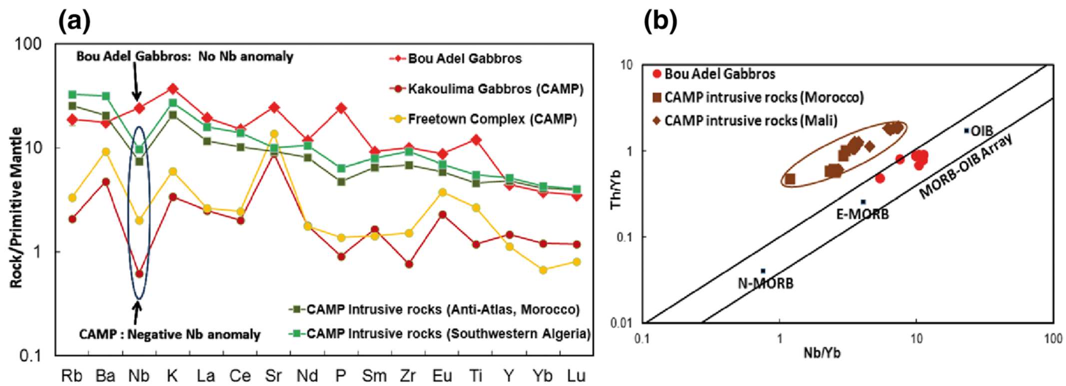

Figure 3. (a) Primitive mantle-normalized multielement diagrams of Central Atlantic Magmatic Province (CAMP) intrusive rocks of North-West and West Africa compared with that of Bou Adel gabbros. The data (average of data) for the Anti-Atlas (Morocco) and southwestern Algeria are respectively from Marzoli et al. (2019) and Chabou et al. (2010), for the Kakoulima laccolith from Deckart et al. (2005), for Freetown layered complex from Callegaro et al. (2017), and for Bou Adel gabbros from Benzaggagh et al. (2014). Normalizing values are from Sun and McDonough (1989). (b) Th/Yb vs. Nb/Yb diagram (Pearce, 2008) for the Bou Adel gabbros (Benzaggagh et al., 2014) and the CAMP intrusive rocks of Morocco (Marzoli et al., 2019) and Mali (Verati et al., 2005).

2.3. Geochronological Data Set

Gimeno-Vives et al. do not use statistical analysis of U-Pb zircon results for a given population of grains. Instead, they select the oldest ages of each sample and in this way produce four dates from two dolerites (Laklaaia, 200 ± 4 Ma, and Kef el Ghar, 195 ± 4 Ma) and two gabbros samples (Bou Adel, 196 ± 4 Ma, and Kef el Ghar, 192 ± 4 Ma). Finally, they retain “a 195 to 200 Ma age range, which fits with the peak age of the CAMP.” We observe that only the Laklaaia dolerite yields an age compatible with the CAMP peak at ~201 Ma (Davies et al., 2017; Marzoli et al., 2018, 2019). The other dates, as well as the date for the Bou Adel trondjhemite (190 ± 2 Ma; Michard et al., 2018), are significantly younger (mean value 193.2 ± 4.5 Ma) than the CAMP peak. In contrast, they match the 190- to 170-Ma age of the early opening of the Central Atlantic (Labails et al., 2010).

During their study, Gimeno-Vives et al. found one zircon grain dated at 450–460 Ma in the Kef el Ghar gabbro. They argue that this “confirms the emplacement of the magmas in a continental setting.” Even adding the case of the Paleoproterozoic zircon (~2 Ga) reported by Michard et al. (2018), this argument is not robust, as inherited zircons can be stirred in the upper mantle through varied processes (Pilot et al., 1998; Varas-Reus et al., 2018).

In conclusion, field and geochemical evidence as well as the geochronological data preclude any belonging of the typical Mesorif gabbros from Bou Adel and Kef el Ghar to the CAMP. In contrast, the assignment of the dolerites from Laklaaia to the CAMP is consistent with its structural location (Suter, 1964), the (few) geochemical data, and the U/Pb zircon age presented by Gimeno et al. We do not comment here on the case of the Zitouna dolerites whose structural position is unclear.

3. An Alternative Scenario

How reconcile the latter conclusion with the convincing description of the Senhadja units as distal blocks of the hyper-extended African margin proposed by Gimeno-Vives et al.? We think that it is useful to refer here to another example of conjugate, hyperextended paleomargin repeatedly studied in the last couple of years, that is, the North Iberian Mesozoic paleomargin now inverted in the western Pyrenean Belt (Asti et al., 2019; Jammes et al., 2009). The Aptian-Albian rifting resulted in mantle exhumation followed by the gravity sliding of the prerift sedimentary sequences of the continental margin toward the oceanic domain. We propose that a similar process operated onto the slope of the North African paleomargin during the Early Cretaceous (Figure 4).

As extension/transtension went on from the Triassic to the Middle-Late Jurassic, the Liassic gabbro pockets formed in the oceanic domain (stage 1 of the Alpine Tethys evolution in Balestro et al., 2019) may have

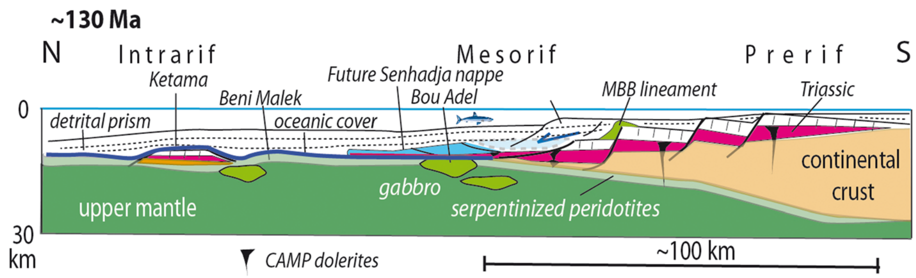

Figure 4. A new scenario for the origin of the Senhadja nappe: the gravity sliding of the passive margin series (not to scale). The Middle-Upper Jurassic extension has resulted in the exhumation of the Liassic gabbros and the accumulation of basalts, breccias, micrites, and radiolarites (oceanic cover) on the gabbros. During the Early Cretaceous, and likely in relation with the detrital overload, the passive margin prerift and synrift units and some CAMP dolerites detached on the Triassic evaporites and slid down onto the oceanic crust.

been exhumed up to the seafloor by lithosphere-scale detachments and oceanic core complexes (stages 2 and 3) and then overlaid by a thin, uneven accumulation of basalts, breccias, radiolarites, and limestones (stage 4). The sedimentary cover of the nearby distal margin slid down on the Triassic evaporites and emplaced onto the oceanic domain. This gravity-driven emplacement would have occurred at the onset of the huge postrift detrital infilling (Late Jurassic and Early Cretaceous turbidites) of the Mesorif, Intrarif, and Maghrebian Flyschs domains (Chalouan et al., 2008). Sedimentary overload is recognized as a triggering factor for the sliding of the passive margins prisms (Peel, 2014). The CAMP dolerites occurring next to the Mesorif oceanic gabbros can either have slid down with the overlying units or belong to the parautochthonous Mesorif domain. During the Cenozoic shortening of the former Ocean-Continent-Transition domain, this displaced sedimentary material would have formed the Senhadja nappe carrying at its sole some slivers of the former oceanic domain, such as the Bou Adel and Kef el Ghar gabbro massifs (Figure 4).

4. Conclusion

Gimeno-Vives et al. do not present convincing data in support of their claim that the Senhadja Mesozoic units are the stratigraphic cover of the Mesorif gabbros. They forsake the occurrence of typical oceanic formations on top of part of these mafic rocks. They ascribe all the Mesorif gabbroic rocks to the CAMP, which is contradicted by the age of the main gabbro massifs (mean U-Pb zircon age ~193 Ma instead of ~201 Ma) and by their petrographic and geochemical signature (presence of trondhjemite pockets and lack of Nb negative anomaly, among others). Therefore, we propose that the main Mesorif gabbros at least define an oceanic suture (MSZ) connected to the Central Atlantic eastern margin.

However, Gimeno-Vives et al. present a convincing description of the Senhadja units in terms of tilted blocks of prerift and synrift sedimentary units from the distal North-African margin. We propose that these units detached on the Triassic evaporites and slid down onto the adjacent oceanic crust by the end of the Jurassic extensional/transtensional tectonics. Such a gravity-driven process could reconcile Gimeno-Vives et al.'s observations with ours.

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