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Discussion

The Moroccan Anti-Atlas: the West African craton passive margin with limited Pan-African activity. Implications for the northern limit of the craton: reply to comments by E.H. Bouougri

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We agree with El Hafid Bouougri (EHB) that Anti-Atlas geology is complex and that only a multidisciplinary approach can bring new constraints. In our paper (Ennih and Liégeois, 2001), we tried to show that this partly results from particular localization of the Anti-Atlas on the shoulder of a craton, namely the West African craton (WAC). During the Pan-African orogeny, the latter acted as a rigid body but was partly destabilized at its margin, allowing a major but late high-K calc-alkaline plutonism and volcanism to be emplaced (610–560 Ma; Thomas et al., 2002). Before that event, an oceanic terrane built at around 750 Ma accreted at 685–665 Ma (Leblanc and Lancelot, 1980; De Wall et al., 2001; Thomas et al., 2002; Admou et al., 2002), generating a major thrust event affecting also the passive margin series. No continental collision affected the Anti-Atlas during the Pan-African orogeny, rendering its geological interpretation useless through usual interpretations and explaining the diversity of geological models proposed for Anti-Atlas, as remarked by EHB.

We thank EHB for his comments, this will allow us to specify some points that were misunderstood and to answer well-taken points. This will also allow us to make reference to studies published after the writing of our paper and to include an updated version of the figure summarizing our model.

1. Evidence for a Palaeoproterozoic basement in Saghro?

The area located between the South Atlas Fault (SAF) and the Anti-Atlas Major Fault (AAMF) is marked by a thick sedimentary sequence (the Saghro Group) intruded by late granitoids. Outcrops of the basement of this series are therefore unlikely to be found. Our main arguments to infer the presence of the WAC below the Saghro group are: (1) the rheological behaviour of this area during the Variscan and Alpine orogenies, which is similar to the WAC; the SAF marks a strong

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rheological contrast, not the AAMF (e.g. Black and Liégeois, 1993); (2) S to SE vergent thrust tectonics affecting the Saghro Group, suggesting a rigid body below; (3) the presence of Eburnian material in Saghro sediments (Fekkak et al., 2000), indicating a close Eburnian continent at the time; (4) the isotopic old crustal signature present in the granitoids cross-cutting the Saghro group (Errami et al., 2002), similar to contemporaneous granitoids to the south of AAMF.

The AAMF worked mainly late during the Pan-African orogeny as a transcurrent fault strongly affecting the ophiolitic remnants such as that in Bou Azzer and in Sirwa. This movements probably preserved this oceanic material which, in turn, gave a high status to AAMF in the geological literature.

2. The Anti-Atlas: the same and unique margin or two opposite margins?

We never wrote (1) that the Kerdous schists belongs to Neoproterozoic, (2) that the volcano-sedimentary series north to AAMF all belong to the lower Neoproterozoic WAC passive margin and (3) that the lower Proterozoic sedimentary series have the same characteristics to the N and to the S of AAMF.

(1) Nachit et al. (1996) denied the existence of Palaeoproterozoic in the Kerdous inlier, but we wrote that U–Pb ages by Aït Malek et al. (1998) in adjacent inliers indicate without ambiguity the existence of Eburnian basement. This was one of our goals to demonstrate the major role played by the Eburnian orogeny in the Anti-Atlas. If the turbidites described by Nachit et al. (1996) belong to the Eburnian basement, we acknowledge the remark, which moreover agrees well with our model (shallow water sediments to the south of AAMF).

(2) Concerning the series north of AAMF, we wrote (p. 293): 'More work is needed to determine the amount of island arc material actually present in the Saghro'. We are convinced that both juvenile and cratonic materials are present in the Saghro Group but data are lacking to constraint their proportion and their relationships. This work is currently in progress.

(3) We suggested that the AAMF corresponded to a boundary fault of the aulacogen described by Fekkak et al. (2000). This implies turbiditic sequences to the north and shallow water sequences to the south as in the case to the north of the Zenaga inlier. We correlated these series only for their potential age. As written above, we agree that these series need more work, which is in progress.

To the north of Zenaga inlier, the passive margin series consists of shallow water sediments and not turbidites. The word 'turbiditic' is obviously a typographical error (in obvious opposition with the description that follows p. 293) that our vigilance let escaped. We thank EHB for this well-taken remark.

We agree that the series north of AAMF ('fold-belt domain' of EHB) are allochthonous (to the south thrusting) but let us note that the shallow water sequence are also thrust towards the south as revealed by recent geological mapping (De Kock et al., 2000). As said above, AAMF is indeed considered as the transition between an aulacogen (or a thick passive margin) and the cratonic platform.

We can only agree with EHB that the Saghro corresponds to the superposition of a rifted continental margin and an arc-related basin (in our model, juvenile thrust sheets onto the passive margin series). On the other hand, we do not believe that palaeocurrent data can localize unequivocally the source of aulacogen or passive margin sediments particularly when they are thrust.

3. Aulacogen versus passive margin and the 100 m.y. quiescence period?

3.1. Aulacogen

Following Bates and Jackson (1980; Glossary of Geology), an aulacogen is 'a tectonic trough on a craton, bounded by convergent normal faults; aulacogens have a radial orientation relative to cratons and are open outward'. This is then less

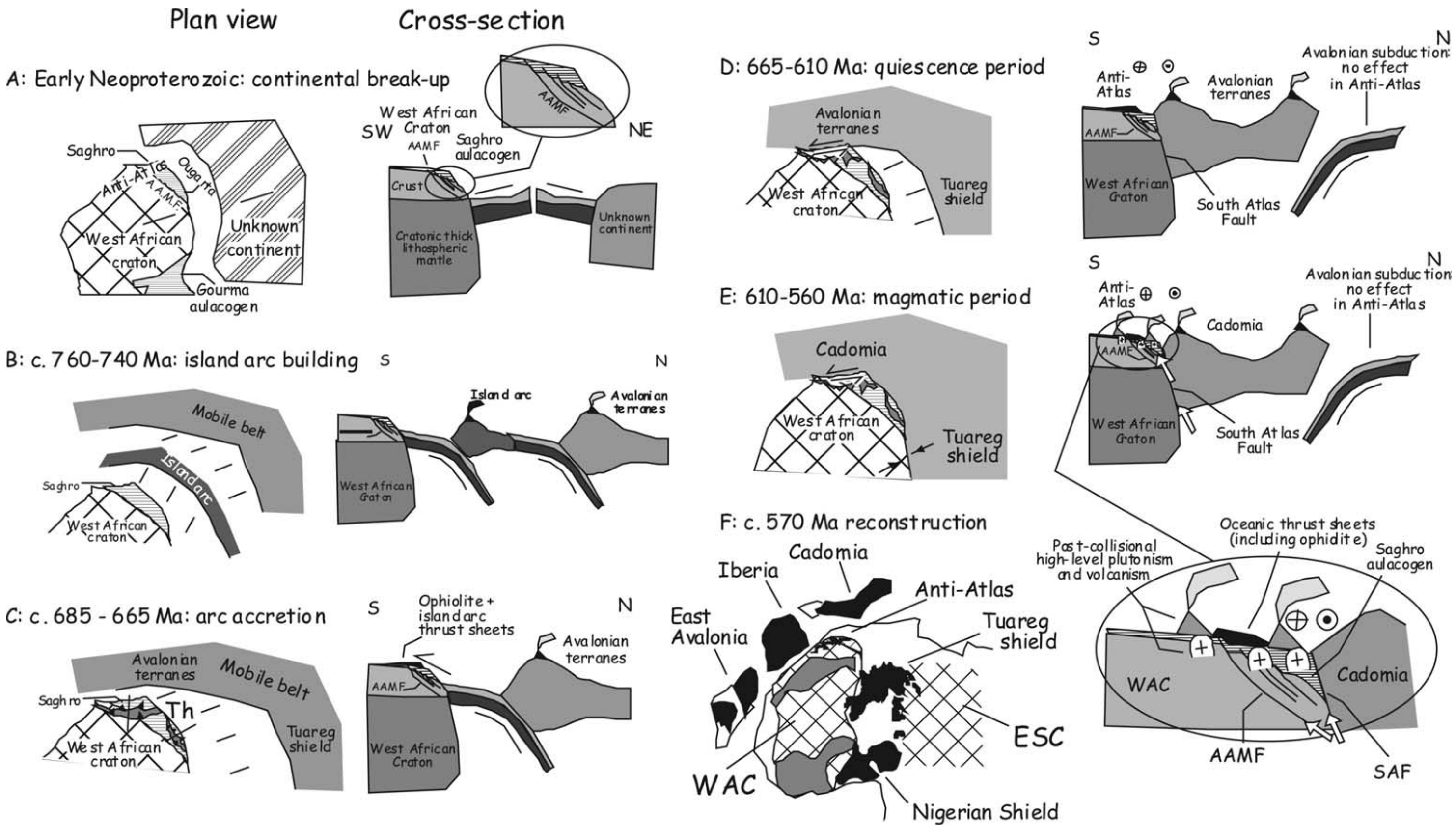

Fig. 1. Simplified model of the Anti-Atlas behaviour during the Neoproterozoic. Modified and updated from Ennih and Liégeois (2001). Ages are from Leblanc and Lancelot (1980), Mrini (1993), Errami (1993), Nachit et al. (1996), Aït Malek et al. (1998), De Beer et al. (2000), De Kock et al. (2000), De Wall et al. (2001), Admou et al. (2002), Thomas et al. (2002). (A) Saghro aulacogen (Fekkak et al., 2000) or passive margin formation marking a continental break-up. AAMF is a main border fault, with differences in passive margin sediment thickness on each side. (B) Island arc building stage. (C) Material from the island arc (including ophiolite) is thrust upon the craton mainly from N to S at c. 685–665 m%; Avalonian terranes are not far in the open sea, accretion beginning there at c. 650 m% (Strachan et al., 1996). (D) Quiescence period (665–610 m%) with no event in the Anti-Atlas region due to relatively free movement of the rigid WAC; Avalonian terranes, by contrast, are subjected to various metamorphic and magmatic events (Murphy et al., 2000); the Avalonian subduction zone represented has no effect on Anti-Atlas; (E) Emplacement of Pan-African high-K calc-alkaline and alkaline granitoids and lavas (pathways indicated in the cross-section by white arrows) at the end of the orogeny (610–560 m%) on both sides of AAMF, during the main squeezing of the terranes in the Tuareg shield that induced additional stress on the northern boundary of the WAC. (F) Position of the Anti-Atlas within the reconstituted Pan-African belt at 630–570 m% (after Nance and Murphy, 1996). WAC, West African craton; AAMF, Anti-Atlas Major Fault; SAF, South Atlas Fault.

restrictive than the definition proposed by EHB. We proposed the existence of an aulacogen to the north of AAMF because (1) the sedimentary sequence thickens rapidly when crossing the AAMF towards the north, (2) this sedimentation is subcontemporaneous with continental break-up that affected the WAC (3) Fekkak et al. (2000) already proposed this possibility after a detailed study of the Kelaat M'Gouna series; (4) the similarity with the Gourma aulacogen in Mali. We agree that this constitutes only a hypothesis that needs to be further tested. However, if this series is actually only a former thick passive margin linked to the continental break-up that affected the WAC during the early Neoproterozoic, this will not change a lot our model (Fig. 1A). (4a, in the model).

3.2. *Quiescence period of 100 m.y.*

We agree that Pan-African granitoids in the Anti-Atlas can be as old as 615 Ma (Thomas et al., 2002). However, this does not alter our model as we correlate this magmatic event with the collision with the Tuareg shield that began at c. 625 Ma (Jahn et al., 2001). Our main concern is to separate an accretion event at c. 685–665 Ma and the intrusion of late granitoids linked to transpression, with a quiescence period in between. The latter is then only shorter. As shown in Fig. 1E 4d in the model, these granitoids are considered as having been contemporaneous with major transpressive tectonic phase that was active along the AAMF, which explains the localization of the older granitoids (so far dated) along this fault.

3.3. *Events at c. 740 Ma*

Several subduction-related rocks have recently been dated at c. 740 Ma (De Beer et al., 2000; De Wall et al., 2001; Thomas et al., 2002; Admou et al., 2002). Although we know that these oceanic rocks were not much older than 685 Ma, their age of accretion, these ages were unfortunately not available to the authors at the time of writing. This is the reason why we omitted the island arc stage in our figure 4 (Ennih and Liégeois, 2001). However, it is obvious that for thrusting an island arc assemblage at c. 685 Ma, a building stage for this arc is needed. We do not see why these lithologies are problematic in our model as written by EHB. We propose here an updated version of our model including the very recent ages available (Fig. 1).

In conclusion, we consider that most of the observations recalled by EHB can be integrated in the model we proposed. In particular we note that EHB describes in Saghro a 'back-arc domain (Saghro massif), which partly overlaps on early northern rifted margin sequences' what is close to what is represented in our model (Fig. 1, although we would privilege rather a fore-arc than a back-arc basin). However, we believe that EHB underestimates the displacements generated by the thrusting event at c. 685–665 Ma, in particular for ophiolites whose allochtony renders them unlikely marking the location of a suture.

We are also convinced that putting the limit of a craton at the last outcrop observed is an error: a cratonic margin is not subvertical but goes down progressively as shown at current oceanic cratonic margins. This buried shoulder part of cratons is probably often ignored in geological studies dealing with continental interiors as they are uneasy to observe and are then often misunderstood.

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