C. R. Geoscience 350 (2018) 279–288

Contents lists available at ScienceDirect

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Tectonics, Tectonophysics

The Anti-Atlas Pan-African Belt (Morocco): Overview and pending questions

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ARTICLE INFO

Article history:
Received 6 June 2018
Accepted after revision 2 July 2018
Available online 2 August 2018

Handled by Isabelle Manighetti

Keywords:
Paleoproterozoic
Neoproterozoic
Collision belt
Eburnian
Pan-African
Anti-Atlas
Post-collisional magmatism

ABSTRACT

Between the High Atlas and the Saharan platform, the Anti-Atlas of Morocco offers large exposures of Precambrian rocks beneath the moderately folded Paleozoic series. These inliers allow reconstructing a segment of the Pan-African Belt and of its foreland at the northern outskirts of the West African Craton (WAC). From ~885 Ma to ~540 Ma, three periods are recognized in the Pan-African cycle. The Tonian–Cryogenian period ends with the obduction of supra-subduction ophiolite and oceanic arc material at ~640 Ma. The Early Ediacaran period is marked by the development and subsequent closure of a wide marginal basin next to a likely Andean-type arc. The Late Ediacaran period is recorded by subaerial molasse deposits associated with post-collisional high-K calc-alkaline to shoshonitic magmatism. Although a wide consensus has been reached based on the number of new robust datings, several questions still remain pending, which we address taking into account relevant African and European correlations.

1. Introduction

The Precambrian inliers of the Anti-Atlas mountain range (Fig. 1) have been studied for long (Choubert, 1952, 1963; Neltner, 1938). They expose wide outcrops of the Neoproterozoic Pan-African belt and of its Paleoproterozoic foreland (Gasquet et al., 2008 and references therein). Recent studies are numerous and provide a remarkable wealth of structural, geochronological, and geochemical data, as reported below. Despite such a rich documentation, controversies remain on important issues: (i) the evolution of the Neoproterozoic oceanic domain from which the ophiolites and arc units exposed in the suture zone come from (e.g., Triantafyllou et al., 2018); (ii) the discrimination between the post-Eburnian platform cover recently dated to the Late Paleoproterozoic (Ikenne et al., 2017) and the Neoproterozoic passive margin sequence (Leblanc and Moussine-Pouchkine, 1994); (iii) the geodynamic interpretation of the post-obduction magmatism and sedimentation that developed during the Early Ediacaran (Abati et al., 2010; Letsch et al., 2018b); (iv) the nature of the continental block that bounded the oceanic domain to the north (present coordinates) and then collided against the WAC during the Ediacaran; (v) the origin and tectonic framework of the Upper Ediacaran volcanic/sedimentary cover series that overlie unconformably the deformed Pan-African units and immediately predate the Cambrian deposits.

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https://doi.org/10.1016/j.crte.2018.07.002

Our goal is to present a short review of the state of the art in the geology of the Anti-Atlas Pan-African belt, making a point on the five key issues cited above. In the following, the cited ages are U–Pb zircon ages, unless otherwise stated. Table 1 (Supplementary Material) lists the most important U–Pb zircon dates available in each of the Anti-Atlas inliers, generally obtained by SHRIMP or LA–ICP–MS methods.

2. Geological setting

The Anti-Atlas mountain range is a hierarchical, nested range. At the largest scale, the range corresponds to an ENE-trending lithospheric fold cored by Paleozoic and Proterozoic rocks, and whose envelope is made of thin Cretaceous–Neogene strata that form the "hamadas" plateaus in the South, and the Souss and Ouarzazate–Ar-Rachidia basins in the North (Fig. 1). This fold echoed the Atlas compressional orogeny (Frizon de Lamotte et al., 2009), but the Anti-Atlas fold crest elevation was increased by about 1000 m due to the development of a hot mantle anomaly underneath, which also caused the high elevation of the Atlas domain farther to the northeast (Fullea et al., 2010; Missenard et al., 2006). Late Miocene to Quaternary alkaline volcanism occurs above this hot anomaly, well-illustrated in the Anti-Atlas by the Siroua strato-volcano erected on top of the Siroua plateau (Admou and Soulaimani, 2011).

The more internal, but still large-sized part of the range corresponds to the Variscan fold belt. This belt formed at the expense of the thick Paleozoic series deposited on the rifted margin of the West African Craton (WAC; Burkhard et al., 2006; Michard et al., 2010). The Anti-Atlas fold belt is the thick-skinned foreland belt common to the Mauritanide in the west and to the Meseta Paleozoic orogen in the north. Inversion of the faults formed in the Cambrian-Ordovician and Late Devonian rifting events occurred during the Late Carboniferous–Permian (Baidder et al., 2016), and resulted in the uplift of the present-day Precambrian inliers.

Two contrasting groups of inliers are recognized, separated from each other by the Anti-Atlas Major Fault (AAMF; Choubert, 1947). Along the AAMF (Bou Azzer and Siroua inliers) and farther to the northeast (Saghro and Ougnat massifs, Ouzellarh massif of the Marrakech High Atlas, Skoura massif north of Ouarzazate), the Precambrian inliers only display Neoproterozoic terrains. In contrast, those to the southwest of the AAMF only expose Paleoproterozoic terrains that include Eburnian basement rocks and their Upper Paleozoic cover series (see below).

3. The Tonian-Cryogenian pre- to syn-Pan-African times

3.1. Evolution of the oceanic domain

The occurrence of ophiolites in the Bou Azzer and Siroua inliers (Figs. 1 and 2) was introduced by Leblanc (1972) and raised immediately a major interest, not only from a geodynamic point of view, but also because of the particular metallogeny of these rocks. A wealth of structural, petrological, and geochronological studies developed during the last three decades helped to reach a consensus about the major stages of the evolution of the Pan-African oceanic domain. This consensus is summarized as follows, mostly after Blein et al. (2014a), Hefferan et al. (2014) and Triantafyllou et al. (2016, 2018):

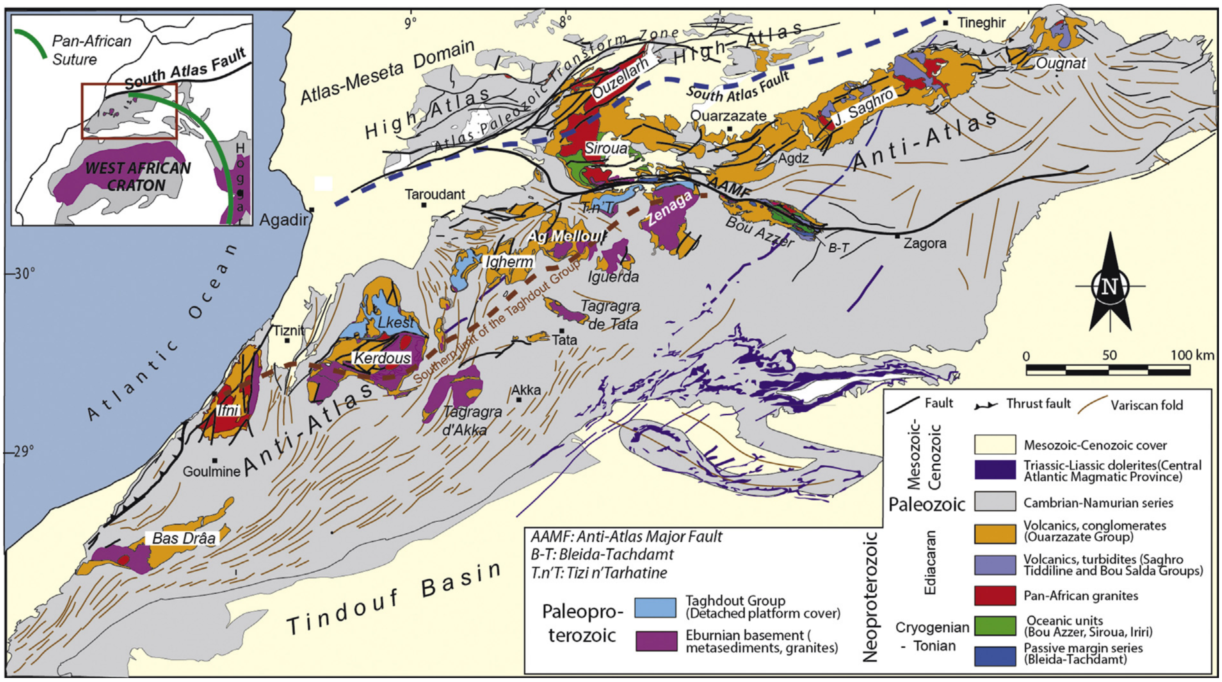

Fig. 1. The Anti-Atlas mountain range, after Gasquet et al. (2008), modified.

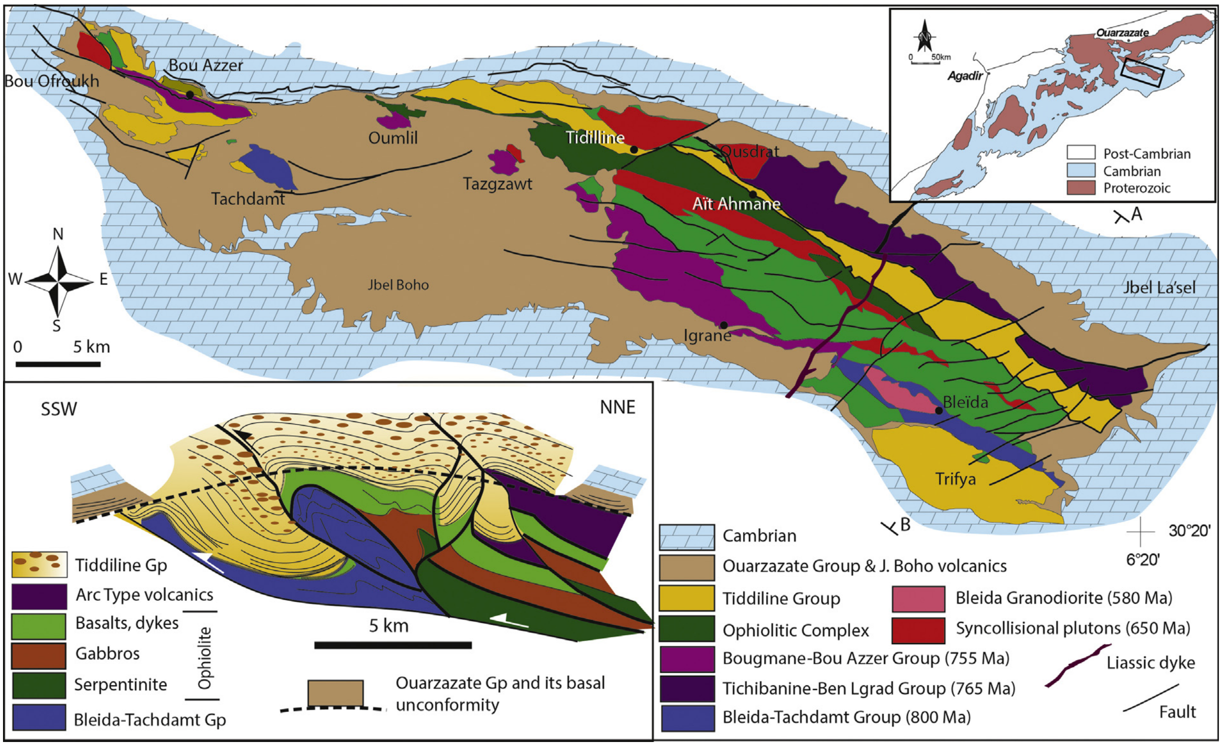

Fig. 2. Structural map and cross-section of the Bou Azzer inlier, modified after Blein et al. (2014a) and El Hadi et al. (2010), respectively.

- the oceanic domain includes ophiolitic sequences and oceanic arc units, partly dismembered along the polyphased, and eventually sinistral AAMF;
- the ophiolitic sequences formed during the Cryogenian, with dates spanning between 760–660 Ma (Table 1, Supplementary Materials);
- their geochemical signature points to an emplacement in a supra-subduction zone setting;
- the rocks typical of intra-oceanic arc setting consist of (i) low-grade metamorphic rocks such as greywackes, basalts, andesites, rhyolites and tuffites in the Tichibanine arc domain, north of the Bou Azzer inlier; (ii) high-grade orthogneiss, intrusive metagabbro, and crosscutting leucogneiss in the Bougmane (aka Bougmmane) arc complex, south of the main ophiolitic axis of the Bou Azzer inlier (Blein et al., 2014b; Triantafyllou et al., 2018), and (iii) a single, Iriri–Tachakoucht–Tourtit complex arc composed of schists, gneiss, and intrusive leucogneiss and hornblendites in the Siroua inlier (Triantafyllou et al., 2016);
- according to most authors, the subduction of the oceanic crust was outboard with respect to the WAC (i.e. north-dipping in present coordinates), at least up to 640–630 Ma (Soulaimani et al., 2006).

However, the consensus abuts on the interpretation of the radiometric ages obtained from these varied arc complexes. The arc volcanism of the Tichibanine complex is dated back to ~760–740 Ma (Soulaimani et al., 2013), whereas the orthogneiss and meta-gabbros of the Bougmane (Admou et al., 2013) and Tachakoucht (Thomas et al., 2002) arcs materials exhibit ages spanning from ~760 to 660 Ma (Table 1, Supplementary Materials). Two alternative interpretations have been proposed (Fig. 3), involving either the activity of two arcs of different ages (Admou et al., 2013; Soulaimani and Hefferan, 2017), or the polyphase evolution of a single arc (El Hadi et al., 2010; Hefferan et al., 2014; Triantafyllou et al., 2018; Walsh et al., 2012). The two-arcs hypothesis is mainly supported by the separate outcrops of the Tichibanine and Bougmane arcs in the Bou Azzer structure (Fig. 2). The alternative, one-arc hypothesis relies on the distinction between deformation events versus magmatic events (Triantafyllou et al., 2018).

3.2. The foreland and its passive margin

The Precambrian massifs southwest of the AAMF (Fig. 1) are cored by low- to high-grade schists and granitoids that yielded a number of U–Pb zircon dates ranging from ~2200 to ~2030 Ma (Aït Malek et al., 1998; Barbey et al., 2004; Blein et al., 2014a; Ennih and Liégeois, 2001; Ennih et al., 2001; Gasquet et al., 2004, 2008; O'Connor et al., 2010; Walsh et al., 2002). Thus, these rocks have recorded the Eburnian (Birimian) orogeny, as those of the northern Reguibat Rise (Peucat et al., 2003; Schofield et al., 2006). They correspond to the exhumation of the WAC upper crust in the Anti-Atlas axis north of the Tindouf syncline.

The Eburnian rocks of the Anti-Atlas are overlain at first glance unconformably by low-grade metasedimentary rocks including abundant quartzites and minor stromatolite-bearing carbonates, and currently labeled Taghdout–Lkest Group (shortly, Taghdout Gp; Thomas et al., 2004).

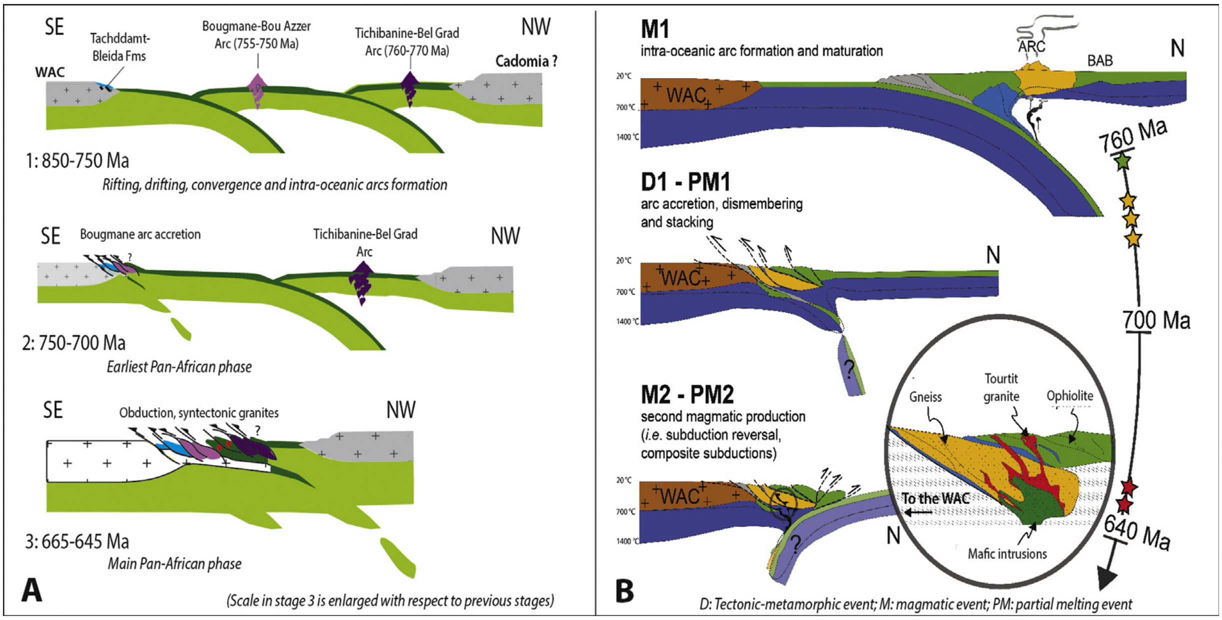

Fig. 3. Alternative interpretations of the Cryogenian evolution of the Anti-Atlas Pan-African belt. A. Two-arc hypothesis (after Admou et al., 2013, modified by Soulaimani and Hefferan, 2017). B. One-polyphase-arc hypothesis (Triantafyllou et al., 2018, simplified).

The Taghdout Gp. was attributed to the Neoproterozoic, more particularly Tonian–Cryogenian, based on the assumption that it should be the inner platform equivalent to the passive margin series described at the southern border of the Bou Azzer inlier by Leblanc and Moussine-Pouchkine (1994) under the name of Bleida–Tachdamt series. The Bleida–Tachdamt series involves a platform sequence of quartzite and stromatolitic limestones overlain by tholeiitic basalts, metapelites and volcano-sedimentary rocks. The minimum age of the Bleida–Tachdamt lower series was given by the Rb/Sr method at 789 ± 10 Ma (Clauer, 1974) for the metamorphic walls of mafic dykes intruding the metasedimentary beds.

Doubt began to rise about the Neoproterozoic age of the Taghdout Gp. when Abati et al. (2010) showed that the Taghdout quartzites (Mimount Fm. overlying the basal, carbonate–quartzite–metapelite formations next to Taghdout village at the northern border of the Zenaga inlier, see Thomas et al., 2002) do not contain detrital zircons younger than ~1809 Ma. Neoproterozoic detrital zircons only appear in the overlying formations referred to the Saghro or Bou Salda groups (see below) in the Siroua inlier (Abati et al., 2010).

The demonstration that the Taghdout Gp. is indeed Late Paleoproterozoic was brought by Ikenne et al. (2017) following a line of investigation suggested by Youbi et al. (2013). A minimum age of ~1710 Ma was obtained (ID-TIMS U–Pb on baddeleyite) on a mafic sill intruding the Taghdout Gp. of the Igherm inlier. Mafic dykes and sills are numerous within the Paleoproterozoic basement, and part of them have been dated back to *ca.* 885, 1416–1380, 1650, 1750, and 2040 Ma (Kouyaté et al., 2013; Youbi et al., 2013). The fact that the Taghdout Gp. is crosscut by a ~1710-Ma-old mafic intrusion allows interpreting the shallow-water carbonate-clastic Taghdout Gp. series as the Upper Paleoproterozoic platform deposits that were overlying the rifted Eburnian orogen about one billion years before the Neoproterozoic rifting of the WAC margins. Therefore, the Neoproterozoic, Bleida–Tachdamt passive margin formations can no longer be classified in the same group as the Paleoproterozoic, Taghdout platform formations. Moreover, the problem of their possible relationships is open. Unfortunately, the Taghdout Gp. and the Bleida–Tachdamt series are separated by the densely faulted AAMF zone, which juxtaposes narrow folded units belonging to these sedimentary series (Bouougri and Saquaque, 2004) in a transpressional, sinistral strike-slip setting. The effects of the Pan-African tectonics are recorded not only along the suture zone, but also in the foreland domain. This has been locally demonstrated in the Kerdous (Hassenforder, 1987) and Zenaga (Ennih et al., 2001) inliers. We suggest that the deformation of the Paleoproterozoic cover in front of the obducted Pan-African units is one of the Anti-Atlas frontiers today.

4. The Early Ediacaran late Pan-African times

4.1. The Early Ediacaran folded units of the Anti-Atlas

Moderately deformed, weakly metamorphic clastic series occur in the suture zone (Siroua and Bou Azzer inliers) and farther to the northeast (Saghro and Ougnat inliers). In the current nomenclature, these series are labeled the Anezi, Bou Salda, Saghro, and Tiddiline Gps. (Gasquet et al., 2008). All are topped by the Ouarzazate Gp, whose lowest dated volcanic flows have ages in the range 575–565 Ma around the Kerdous inlier (O'Connor et al., 2010), at Bou Azzer (Blein et al., 2014a), and in the J. Saghro massif (Walsh et al., 2012).

The Anezi Gp. (in its restricted definition by O'Connor et al., 2010) of the Kerdous inlier follows upward thick felsic volcanics that unconformably overlie the folded platform units (Taghdout Gp.) and the eroded Eburnian basement. An ignimbrite flow from the basal volcanics has been dated back 614 ± 38 Ma (U–Pb zircon; O'Connor et al., 2010). The Bou Salda Gp. is a clastic and volcano-clastic series with both flysch and molasse features that overlies with angular unconformity the Eburnian schists and their platform cover, and also the oceanic units and the Saghro Gp. outcrops of the Siroua and Bou Azzer inliers (Thomas et al., 2002). The youngest zircon population in a quartzite cobble from a conglomerate of the Bou Salda Gp. is 610–620 Ma, whereas most zircon grains of that sample yield Eburnian dates (Abati et al., 2010). Two rhyolitic units from the Bou Salda Gp. yielded 605 ± 9 and 606 ± 6 Ma ages (Thomas et al., 2002).

The Saghro Gp. is a ~ 8-km-thick series that extends over 300 km in length and more than 50 km in width from the Siroua to the J. Saghro and Ougnat massifs in the eastern Anti-Atlas (Fig. 1). Dominant lithologies are turbiditic greywackes with mixed volcanic and terrigenous inputs, interbedded toward the bottom with some pillow basalts, or with andesites and rhyolites in the Siroua inlier. The basalts show calc-alkaline to subalkaline characters and affinities with initial rift tholeiites, continental tholeiites or oceanic island alkali basalts (Fekkak et al., 2002, 2003; Thomas et al., 2002). The turbidites and associated debris-flows and slumps suggest sliding of the sediments along steep slopes. The base of the group is exposed nowhere in the suture zone or further to the north, except at the very northern border of the Zenaga inlier (Letsch et al., 2018b; Thomas et al., 2002). Locally in the Saghro massif, small serpentinite bodies associated with jaspers and carbonates are tectonically included in the turbidites, and the hypothesis of a deep-water basin formed above the thinned crust of the ocean-continent transition is likely (Fekkak et al., 2002). The arkosic upper part of the Saghro Gp. suggests a decrease in water depth related to the continuation of convergence (Thomas et al., 2004). Reworked marine diamictites have been recognized in the Siroua inlier (Thomas et al., 2002). In the Bou Azzer inlier, the Bou Lbarod Gp., consisting of volcanic rocks of andesitic composition, overlies unconformably the Tichibanine arc formations, and could be correlated with the lower part of the Saghro Gp. (Blein et al., 2014a).

The Tiddiline Gp. is exposed in two folded (sub-) basins of the Bou Azzer inlier, i.e. the northern (Tiddiline *s. str.*) and southern (Trifya) sub-basins (Fig. 2; Letsch et al., 2018b; Soulaimani et al., 2013). They both expose a clastic, coarsening upward succession of turbidites and siltstones with diamictites (interpreted as marine tilloids with dropstones), and eventually arkoses and conglomerates with andesitic cobbles. This group unconformably overlies Cryogenian rocks deformed by the main Pan-African obduction phase.

The age of the Saghro and Tiddiline Gps. is younger than 620–610 Ma, based on detrital zircons dating (Abati et al., 2010; Liégeois et al., 2006, in Gasquet et al., 2008). Their age is therefore bracketed between ~ 620 Ma and 570–580 Ma (the age of the base of the overlying Ouarzazate Gp.). In the Sirwa inlier, the Sarhro Gp. is even older than 615 Ma, the age of the oldest granite (Ida Ou-Illoun batholith) that intrudes these rocks (Thomas et al., 2004). In the Bou Azzer inlier, the minor Bou Lbarod Gp. is intruded by dioritic dykes dated back to 625 ± 8 Ma (Blein et al., 2014a). Hence, the lower part of the Saghro Gp. would have been deposited between 620 and 610 Ma, contemporaneously with the activity of an andesitic arc system. In the diamictites of the northern Tiddiline basin, the detrital zircon age distribution displays broad Paleoproterozoic peaks and narrow Ediacaran peaks, centered at ~ 593 Ma, thus revealing a younger age of sedimentation (Letsch et al., 2018b). The latter authors found similar Early Ediacaran peaks in the distribution of the detrital zircons from the diamictites of the Izdar Fm. at the bottom of the Saghro Gp. overlying the Taghdout quartzites of the northern Zenaga inlier. In line with Gasquet et al. (2008), they conclude that the diamictites of the Saghro and Tiddiline Gps. would broadly correspond to the ~ 580 Ma Gaskiers glaciation.

The Saghro Gp. is characterized by its tight folding and the development of sub-vertical, dominantly northeast-trending axial-plane slaty cleavage. Likewise, the Tiddiline Gp. is folded and affected by a sub-vertical, axial-plane slaty cleavage. Based on their similar minimum age, lithology, and structure, the Saghro and Tiddiline Gps. may be regarded as lateral equivalents, with the latter group deposited in a more proximal and shallower basin with respect to the Saghro Gp.

4.2. Geodynamic interpretation

The correlation between the Anti-Atlas Neoproterozoic belt and the western Hoggar "Pharusian" (Trans-Saharan) belt (Fig. 1, insert) has been proposed for long (Caby, 1970–1983; Fabre, 1976), based on their ophiolitic remnants. Michard et al. (2017) pointed to the occurrence of another correlation between the Saghro Gp. and the "Série verte" (Caby, 1970–1983; Caby et al., 2010) or "Pharusian II" (Bertrand and Caby, 1978) of the western Hoggar, via the southern Ougarta belt. Thus, following Michard et al. (2017), we may assume that the Saghro Gp. and the "Série verte" accumulated within a large subsiding basin extending along the northeastern WAC. Subsidence and closure of this basin occurred during the last stages of the Pan-African orogeny, with some along-strike differences both in timing and deformation mode. In the Anti-Atlas, the basin subsided from ~ 620 to 580 Ma and closed before ~ 570 Ma, as reported above. In the western Hoggar, the "Série verte" sedimentation began after 680 Ma (Caby et al., 2010), and the basin closed before 620–610 Ma. Besides this diachronism, folds trend differently in Saghro-Ougnat and the western Hoggar, suggesting a difference in the direction of convergence of the colliding continental blocks: NW–SE in the Anti-Atlas, and ENE–WSW in the western Hoggar.

Two questions arise concerning the Saghro Gp.–"Série verte" basin, i.e. (i) the nature of its crust, and (ii) the location of the andesitic arc responsible for part of its infilling. In the western Hoggar, Caby (2003) and Caby et al. (2010) interpret the "Série verte" as the sedimentary prism formed on the eastward-subducting Pharusian oceanic crust. They locate the volcanic arc on the active margin of the continental block east of the subducting ocean; in contrast, they describe the WAC margin as a typical passive margin. Yet, this cannot be extrapolated to the Anti-Atlas. There, Early Ediacaran andesitic and rhyolitic volcanism is important in some parts of the orogen foreland (e.g., Anezi Fm. and underlying volcanics of the Kerdous inlier), showing that the WAC margin was not a typical passive margin at that time. So, in line with Triantafyllou et al. (2018), we may consider the possibility of an incipient south-dipping subduction beneath the WAC margin at about 640–620 Ma (see Fig. 3B).

4.3. The Cadomian "Northern Block" of the Anti-Atlas Pan-African belt

The Pan-African orogeny of the Anti-Atlas resulted from the collision of a northern continental block against the WAC. Which was this "Northern Block"? The continental units observed today north of the Anti-Atlas Pan-African suture zone correspond to the Atlas–Meseta domain (shortly: Meseta) of the Variscan belt. The boundary between the Meseta and the Anti-Atlas is a system of intracontinental, Paleozoic, and Mesozoic–Cenozoic reverse-dextral faults (Atlas Paleozoic Transform Fault or South Meseta Fault, and South Atlas Fault, respectively; Fig. 1). So, it is currently admitted that the Moroccan Meseta did not move over large distances since the Cambrian-Ordovician, when the earliest rifting events affected the northwestern WAC (Letsch et al., 2018a; Michard et al., 2010; Ouanaimi et al., 2016). This implies that the Neoproterozoic "Northern Block" corresponds to the Precambrian basement of the Meseta.

Knowledge of the Meseta basement has recently made great progress. The occurrence of Late Precambrian rhyolites was known for long in the Coastal Block at El Jadida (Fig. 1). Ediacaran rhyolites are now accurately dated back to 593–584 Ma (Baudin et al., 2003; El Houicha et al., 2018). Some granites at the very base of the Paleozoic series also yielded Ediacaran ages in the western High Atlas (625 Ma, Eddif et al., 2007) and the central Meseta (605–610 Ma, Tahiri et al., 2010; 625–600 and 552 Ma, Ouabid et al., 2017). On the other hand, metarhyolites have been dated to 2050 ± 3 Ma beneath the unconformable Lower Cambrian marbles of southwestern Meseta (Pereira et al., 2015). Neoproterozoic and Paleoproterozoic zircon xenocrysts are frequently found in the late Variscan dykes and plutons (Dostal et al., 2005; Oukemeni et al., 1995; Tahiri et al., 2010). Hence, the Meseta basement displays the geochronological signature of northwestern Gondwana, which is also that of the Cadomian terranes included in the Variscan belt of central and western Europe (Drost et al., 2011; Linnemann et al., 2014). Cadomian terranes (or Cadomia) have a polycyclic evolution. They first formed by rifting of the northwestern Gondwana margin in a Western Pacific tectonic style. A volcanic arc developed on the rifted crust, which then moved back to Gondwana and collided at *ca.* 540 Ma (e.g., Linnemann et al., 2014, their figs. 1, 5). This evolution corresponds to the Cadomian orogeny as defined in northern Armorica (Ballèvre et al., 2009). In that sense, the Cadomian orogeny is coeval with the whole Pan-African orogeny, and not only with its latest phase, as suggested by Hefferan et al. (2014) and Michard et al. (2017). After this early evolution, the (proto-) Cadomian terranes were rifted and drifted off the Gondwana margin during the Cambrian and Ordovician opening of the Paleozoic oceans (Iapetus and Rheic, respectively; Murphy et al., 2006; Nance et al., 2012), and then they come back toward Gondwana during the Pangea amalgamation. This is the same evolution as that of the Moroccan Meseta, except that the Meseta did not drift away from the proximal WAC margin. The (Cadomian) "Northern Block" would not be labeled as an Avalonian block (Hefferan et al., 2000; Liégeois et al., 2006, in Gasquet et al., 2008), since in contrast to Cadomia, Avalonia have a 1.3–1.0 Ga crustal basement (Linnemann et al., 2014; Murphy et al., 2013).

5. The Late Ediacaran post-orogenic times

5.1. The Ouarzazate Group

The Ouarzazate Gp. (Thomas et al., 2002) refers to the generally undeformed, subaerial clastic and volcanic series that overlie unconformably the folded and stacked units of the Anti-Atlas Pan-African orogen, as well as the Paleoproterozoic units of its foreland domain. The Ouarzazate Gp. thus surrounds all the Anti-Atlas inliers (Fig. 1), being followed upward by Cambrian deposits. It is worth noting that the term "Ouarzazate Supergroup" (Thomas et al., 2004) is frequently used improperly instead of "Ouarzazate Group", as it refers to both the latter and the (folded) Bou Salda and Saghro Gps.

The Ouarzazate Gp. is a pile of subaerial, volcano-sedimentary sequences, ~2 km in thickness, next to Ouarzazate city. The sequences mainly consist of coarse volcanic conglomerates, ignimbrites, rhyolites, trachytes, andesites, basaltic trachyandesites and tuffites in varied proportions. Coeval gabbro intrusions are also observed locally (e.g., minor gabbro of Tagmout in central Saghro massif, 556 ± 5 Ma; Walsh et al., 2012). Rare interbedded stromatolitic layers occur, probably developed around alkaline lakes (Álvaro et al., 2010). A number of U–Pb zircon datings have been obtained, mostly from the rhyolite domes or flows, spanning from *ca.* 580 to 540 Ma (Blein et al., 2014b; Gasquet et al., 2005; O'Connor et al., 2010; Walsh et al., 2012). Granitoid plutons or dykes emplaced within the lower Ouarzazate Gp. or underlying units during the same time span. All the Ouarzazate plutonic and volcanic rocks belong to high-K calc-alkaline, to alkaline, and eventually to shoshonitic magmatic series (Gasquet et al., 2005, 2008). Most of the high-K calc-alkaline intrusions yield U–Pb ages close to 580 Ma (Askaoun granodiorite in the Siroua inlier: 575 ± 8 Ma; Bleida granodiorite in the Bou Azzer inlier: 579 ± 1 Ma). Magmatism became more and more alkaline with time. For example, in the Kerdous inlier, the Tarçouate gabbro-diorite and granodiorite laccolith yielded a U–Pb age at 581 ± 11 Ma, whereas the Tafraoute and Tazoult alkaline granites were dated back to 549 ± 6 and 548 ± 11 Ma, respectively (Gasquet et al., 2008, and references therein). In the J. Saghro, the Iknioun granodiorite, which intrudes the Saghro Gp. and is unconformably overlain by an upper member of the Ouarzazate Gp, yielded an age of 563.5 ± 6.3 Ma (Tuduri et al., 2018).

5.2. Tectonic setting and geodynamic interpretation

The tectonic context of the Ouarzazate Gp. accumulation may be approached through the examination of its bounding unconformities and synsedimentary faults. The unconformity at the bottom of the group is everywhere an angular unconformity, which implies significant erosion and change of strain regime from compressional to extensional. For example, the Ouarzazate (Tanalt) Gp. unconformity on top of the J. Lkest quartzites implies that the latter have been exhumed after their folding in chloritoid-bearing greenschist-facies conditions (Hassenforder, 1987) at ~6–8 km depth. The basal unconformity of the Ouarzazate Gp. is most often marked by diamictites, by place exposed above a glacial floor (Vernhet et al., 2012). In the Agadir Melloul inlier, extremely coarse conglomerates with boulders up to 3 m^3 in size occur at the bottom of the Ouarzazate Gp, showing the characters of fluvio-glacial or lahar deposits accumulated next to steep slopes (Soulaimani et al., 2013). In the same inlier, the J. Iguiguil quartzites are bounded to the south by a tilted paleofault associated with monogenic scarp breccias that form the very base of the coarse conglomerates mentioned above (Ouanaimi and Soulaimani, 2011, their fig. 4.12). A few kilometers farther to the east, several growth faults active during the accumulation of the Ouarzazate Gp. are exposed (Soulaimani et al., 2014). In the Bou Azzer inlier, Azizi-Samir et al. (1990) recognized sinistral strike-slip movements along the east–west-trending AAMF system, associated with a NW–SE extension recorded by hectometric-sized grabens with fanned growth strata in the volcaniclastic sequence. Likewise, in the Saghro massif, local observations along the east–west-striking Imiter fault suggest that it evolved from a pure extensional regime to a sinistral transtensional regime (Levresse, 2001; Ouguir et al., 1996). Transpressional conditions occur locally in relation with plutonic emplacement, as illustrated by the 563-Ma-old Iknioum intrusion, 20 km south of Imiter (Errami and Olivier, 2012; Tuduri et al., 2018).

Based on discrimination diagrams applied to the geochemistry of the volcanic rocks, it was proposed that the Ouarzazate Gp. would be linked to an Andean-type arc (Bajja, 1998; El Baghdadi et al., 2003; Walsh et al., 2012), a model involving the subduction of the oceanic crust beneath the WAC margin. Likewise, Hefferan et al. (2014) adopt basically the Walsh et al.'s model and suggest a flip of subduction from outboard to inboard between 640–620 Ma. In contrast, taking into account the extensional-transtensional tectonic setting of the Ouarzazate Gp, most authors defined the Late Ediacaran magmatism as post-collisional or post-orogenic (Gasquet et al., 2005, 2008; Pouclet et al., 2007; Thomas et al., 2002; Toummite et al., 2012), and explained the apparent arc-related signature of part of the volcanic rocks of the group by geochemical inheritance from the oceanic arc rocks previously subducted in the mantle from which the Ouarzazate Gp. magmas were sourced.

In fact, it was recognized that conventional geochemical discrimination diagrams are not highly informative in the case of post-collisional granitoids (Liégeois et al., 1998; Pearce, 1996). This idea has been repeatedly stressed for a number of chronological and geographical settings from Neoproterozoic (Bitencourt and Nardi, 2000; Eyal et al., 2010), Variscan (Couzinié et al., 2016; Moyen et al., 2017; Seltmann et al., 2011), and Alpine belts (Dilek and Altunkaynak, 2007; Lustrino and Wilson, 2007).

On the other hand, the large distribution of the Late Ediacaran high-K calc-alkaline to shoshonitic magmatism is a critical observation to approach its origin (Fig. 4). Gasquet et al. (2008) emphasized that "geodynamic behavior of SW and NE Anti-Atlas are similar: Ediacaran high-K calc-alkaline rhyolites and granites have similar ages and the same Sr–Nd isotopic ratios, indicating the presence at depth of the Eburnian basement even if it is cropping out only to the SW of the AAMF." In fact, those rocks extend not only in the whole Anti-Atlas, but also in the Atlas–Meseta "Northern Block" of the Pan-African belt, as well as in the Ougarta belt (Bouima and Mezghache, 2002). Abundant high-K calc-alkaline to shoshonitic granite intrusions are also scattered in the Trans-Saharan belt from western Hoggar to Niger (in the SE continuity of the area shown in Fig. 4), as well as farther to the east in the central Hoggar (Azzouni-Sekkal et al., 2003; Liégeois et al., 1998). Such a large distribution of the Late Ediacaran magmatism makes the hypothesis of an Andean-type WAC margin at that time unrealistic.

The high-K calc-alkaline, to alkaline to shoshonitic magmatic series of the Ouarzazate Gp. evolved eventually towards alkaline and minor tholeiitic lavas at the beginning of the Cambrian anorogenic extensional period (Gasquet et al., 2008; Pouclet et al., 2007; Toummite et al., 2012). This reinforces the idea, already stressed by Soulaimani et al. (2003), of a continuous, post-collisional geodynamic setting characterized by extensional collapse of the Pan-African belt, combined with transcurrent movements and evolving into passive margin rifting. Ganne et al. (2016) stressed that the amalgamation of supercontinents results in the warming of

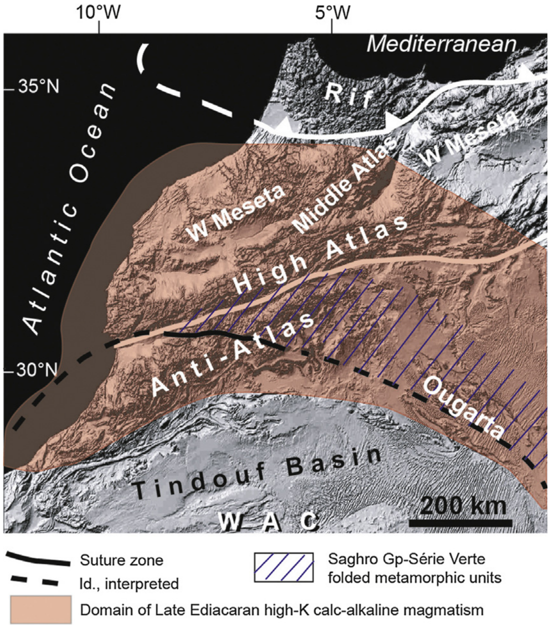

Fig. 4. Regional extension of the Late Ediacaran high-K calc-alkaline magmatism on both sides of the Pan-African suture zone.

the sub-continental asthenospheric mantle and triggers post-collisional magmatism. The Pan-African belts indeed result from the amalgamation of the wandering continents originating from the breakup of Rodinia, and eventually regrouped to form the penultimate supercontinent Gondwana (Meert, 2012).

6. Conclusion

Based on the U–Pb *in situ* datings of magmatic and detrital zircons, three periods are now recognized in the Pan-African cycle that built the Anti-Atlas crust. The Tonian–Cryogenian period ends with the obduction of supra-subduction ophiolite and oceanic arc material at ~640 Ma. The Early Ediacaran period is marked by the development of a wide marginal basin, which then closed at ~580 Ma. The Late Ediacaran period is recorded by subaerial molasse deposits associated with high-K calc-alkaline to shoshonitic magmatism. Despite the consensus on these main lines, several questions remain unsolved. We suggest that the most important one concerns the precise stratigraphy of the Taghdout Gp. platform series, recently dated back to the Late Paleoproterozoic, and its distinction from the Bleida–Tachdamt passive margin series. This distinction depends on a better understanding of the foreland tectonics, a topic that has been so far neglected. Another important question concerns the geodynamic interpretation of the huge Ediacaran magmatism, that evolved from the late orogenic to the post-orogenic times. Addressing this question needs a multi-disciplinary approach combining magmatic geochemistry, sediment provenance study, and structural geology.

Acknowledgements

During the preparation of this paper, we have benefited from discussions with many Moroccan colleagues and with Yvette Kuiper (Colorado School of Mines). We thank sincerely Delphine Bosch (Montpellier University) and Julien Berger (Toulouse University) who provided thorough reviews of an early draft of this paper. We warmly thank Moha Ikenne (Agadir University) and Nasser Ennih (El Jadida University) for their thoughtful reviews, and Isabelle Manighetti (Nice University) for her careful editorial handling and numerous comments.

Appendix A. Supplementary material

Supplementary material associated with this article can be found in the online version available at https://doi.org/10.1016/j.crte.2018.07.002.

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