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Saghro Group in the Ougnat Massif (Morocco), an evidence for a continuous Cadomian basin along the northern West African Craton

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ABSTRACT

The Saghro Group (SG) is a folded, low-grade volcano-sedimentary series up to 8 km thick that crops out within and to the north of the Pan-African suture zone in the central and eastern Anti-Atlas. Here we describe the SG of the Ougnat inliers that are exposed in the easternmost Anti-Atlas beneath the unconformable, Late Ediacaran Ouarzazate Group (OZG) volcanic rocks. The Ougnat SG mostly consists of volcaniclastic greywackes accumulated in a peritidal-to-shallow basin. The basin infilling was deformed by NNE-trending, mostly upright folds with axial-planar slaty cleavage and low-grade metamorphism. The deformed SG rocks were intruded by the ~550 Ma Mellab hypovolcanic granodiorite. The latter also crosscuts the lowest OZG rocks that are dated to 574–571 Ma in the western Saghro region. The SG rocks that form the Siroua and Saghro inliers have an oldest age of 620–610 Ma and were folded at ~610–580 Ma at the onset of the Cadomian orogenic events. We show that the SG rocks are similar to the "Série verte" (SV) rocks that are exposed in the Ougarta and western Hoggar east of the Pan-African suture. We infer that the SG and SV rocks accumulated in a same, continuous basin that was bounding the West African Craton to the north and the east. This strongly subsiding basin formed close to a volcanic arc and was folded during the last Pan-African synmetamorphic events. Fold orientation and age of folding differ however along the edge of the West African Craton. The orogenic greywackes that form the remnants of the SG-SV basin thus constitute a precious record of the diachronic Cadomian event *s.l.* along the West African Craton northern margin.

1. Introduction

The Neoproterozoic Pan-African Belt surrounds the Paleoproterozoic West African Craton (WAC) along its northern and eastern borders, i.e., in the Anti-Atlas and the

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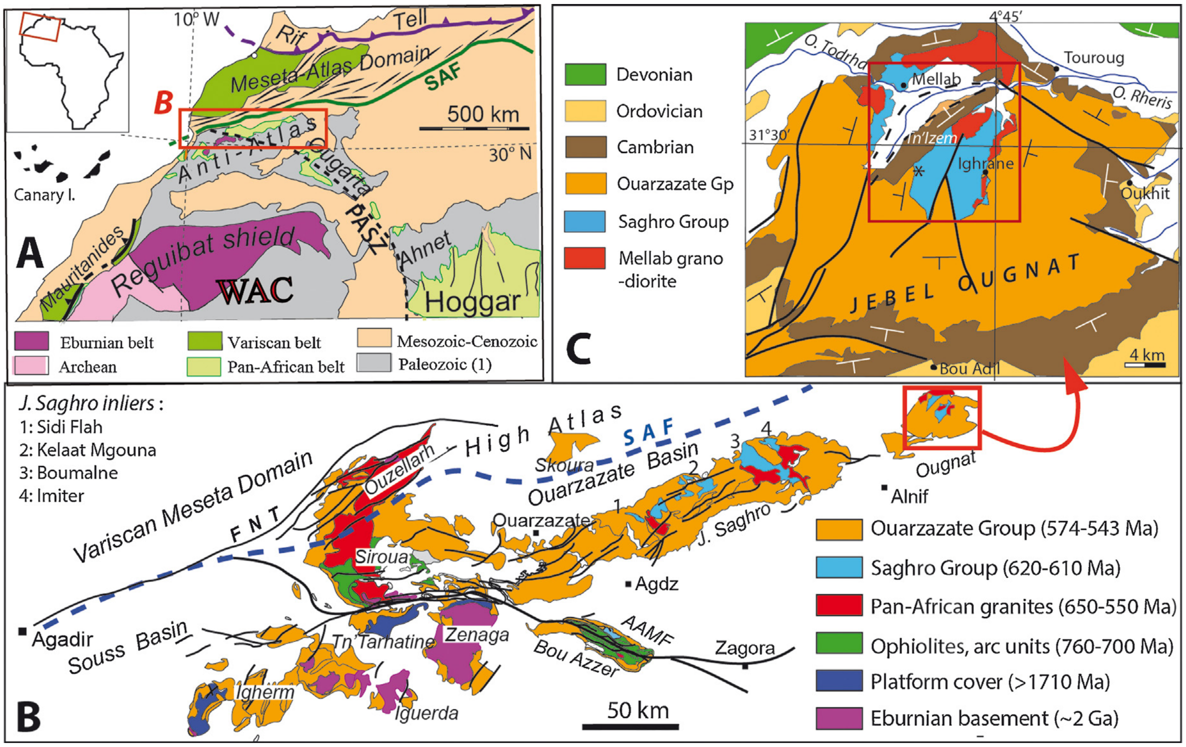

Fig. 1. A. Structural context of the northern WAC. PASZ: Pan-African suture zone; SAF: South Atlas fault. (1): the lowest levels of the southern Reguibat Shield cover are Meso- to Early Neoproterozoic in age (Rooney et al., 2010). B. Map of the central and eastern Anti-Atlas Proterozoic inliers (after Gasquet et al., 2008, modified). C. Sketch geological map of the Ougnat massif (after Destombes and Hollard, 1988). The asterisk marks the dual unconformity on top of the SG.

western Hoggar, respectively (Fig. 1A; Caby, 2003; Ganade de Araujo et al., 2014; Gasquet et al., 2008). The geology of the Anti-Atlas segment of the Neoproterozoic Belt reveals that north-dipping subduction zones were active in the region between ca. 750 Ma and 570 Ma and evolved into dominant strike-slip motion by the end of their activity (Blein et al., 2014a; El Hadi et al., 2010; Thomas et al., 2004). In the western Hoggar region, the Pan-African Belt is characterized by several subduction zones dipping either west or east, and active between ca. 900 Ma and 580 Ma (Bosch et al., 2016; Caby, 2003). In the intervening Ougarta Belt, the Neoproterozoic folded basement crops out intermittently beneath the Late Ediacaran (580–540 Ma) cover series (Bouima and Mezghache, 2002; Caby et al., 2010; Dostal et al., 2002; Fabre, 1976, 1978, 2005), suggesting continuity between the Anti-Atlas and western Hoggar segments of the belt. The eroded Pan-African belt and its Late Ediacaran–Paleozoic cover were subsequently affected by Variscan and Atlasic deformations, which allowed the Pan-African basement to crop out as uplifted inliers ("boutonnières") in the Anti-Atlas (Fig. 1B), Ougarta and western Hoggar (Smith et al., 2006).

In the last decade, the knowledge of the Anti-Atlas Pan-African Belt has been greatly improved through detailed mapping and dating (mainly U–Pb zircon SHRIMP). The age of the ophiolite and oceanic arc units that are exposed in the Siroua–Bou Azzer suture zone (Fig. 1B) has been found to be close to 760–700 Ma, and their emplacement dated at ca. 660–640 Ma (Blein et al., 2014b; El Hadi et al., 2010; Inglis et al., 2005; Soulaimani et al., 2013; Triantafyllou et al., 2016; Walsh et al., 2012). Likewise, the low-grade platform units in the foreland of the Pan-African south of the suture zone (quartzites and carbonates of the Taghdout Group), which were previously ascribed to the Tonian, have been eventually shown to be Late Paleoproterozoic (based on a cross-cutting mafic sill dated c. 1710 Ma [U–Pb baddeleyite; Ikenne et al., 2016] and 1639 ± 34 Ma [U–Pb SHRIMP; Ait Lahna et al., 2016]). In contrast, the youngest folded series of the Pan-African inliers, namely the Saghro, Bou Salda and Tiddiline groups (Thomas et al., 2004) have been poorly studied. Their age has been estimated at ca. 620–610 Ma (Abati et al., 2010; Hefferan et al., 2012; Liégeois et al., 2006, in Gasquet et al., 2008), yet on few data. However, the Saghro Group (SG) is a ca. 8-km-thick series that extends over 300 km of length from the Siroua to the Saghro and Ougnat massifs in the eastern Anti-Atlas, and the available ages are too few to properly characterize its age.

The present paper focuses on the SG inliers of the Ougnat Massif, which we analyze through detailed mapping, and field observations and measurements. We describe the lithostratigraphy and the structure of the Ougnat inliers, then compare them with the classical SG inliers in the Saghro Massif. We then compare the entire set of SG rocks to the "Série verte" (SV) formations that crop out from southeastern Ougarta to Western Hoggar. The ca. 6000-m-thick, volcaniclastic SV series was defined by Caby (1970-1983), mentioned by Fabre (1976, p. 24), and labeled "Pharusian II" by Bertrand and

Caby (1978). Recent descriptions can be found in Bouima and Mezghache (2002), Dostal et al. (2002) and Caby et al. (2010). Our comparison of the SG and SV series suggests that both were deformed during two diachronic, structurally distinct late Pan-African (Cadomian *s.l.*) events along the northern and eastern margins of the WAC.

2. Geological setting

The Saghro and Ougnat massifs constitute isolated exposures of a 30-km-large, ENE-trending Proterozoic basement antiform whose axis is partially buried under folded Paleozoic deposits between Tineghir and Alnif (Fig. 1B). Folding of the Paleozoic series results from the Variscan compression associated with the "Meseta Orogeny" (e.g., Baidder et al., 2016; Michard et al., 2010; Soulaimani et al., 2014), whereas the antiformal structure derives from the subsequent Atlas Orogeny (Frizon de Lamotte et al., 2008, with references therein). The Saghro and Ougnat massifs extend north of the Pan-African suture zone, which is marked by the Siroua and Bou Azzer ophiolites and oceanic arc units (Blein et al., 2014b; Hefferan et al., 2000; Leblanc, 1981; Saquaque et al., 1989; Soulaimani et al., 2006). The "Anti-Atlas Major Fault" (AAMF; Choubert, 1947, 1963; Leblanc, 1975) follows approximately the front of the obducted units. The Anti-Atlas inliers south of the AAMF belong to the deformed margin of the WAC (Ennih et al., 2001; Gasquet et al., 2008), whereas the Saghro-Ougnat units belong to the Pan-African orogenic system, likely thrust over the north-dipping margin of the WAC (Ennih and Liégeois, 2001, 2003, 2008; Gasquet et al., 2008). The Saghro-Ougnat terrains are composed of small SG inliers unconformably overlain by sub-horizontal volcanic (dominantly felsic) and clastic formations that belong to the ca. 570–540 Ma, Late Ediacaran Ouarzazate Group (OZG; Gasquet et al., 2005, 2008; Thomas et al., 2004; Walsh et al., 2012). Numerous granodiorite hypovolcanic plutons and felsic or mafic dykes intrude the SG terrains and the lower part of the OZG (Baidada et al., 2016; Cheilletz et al., 2002; Errami et al., 2009; Youbi et al., 2013).

The Ougnat Massif includes two SG inliers, "Mellab" to the north and "Ighrane" to the south, separated by the "Tizi n'Izem strip" of Cambrian and Ordovician strata (Fig. 1C). These inliers expose outcrops of the SG formations and of the Mellab hypovolcanic granodiorite dated to 547 ± 26 (Rb–Sr; Mrini et al., 1992), which intrudes the SG series. Both inliers are unconformably overlain by Late Ediacaran OZG rocks or by Lower–Middle Cambrian sandstones, themselves followed upward by Ordovician to Devonian formations (Destombes and Hollard, 1988). The OZG begins with coarse breccias, then includes two series of volcanic rocks separated by a discontinuous conglomeratic formation (Abia et al., 2003; Paile, 1983; Raddi, 2014; Raddi et al., 2006, 2012). The major unconformity at the bottom of the OZG reveals that the metamorphic and folded SG terrains were exhumed at that time (ca. 570 Ma) up to the surface. This exhumation likely occurred in a context of extensional faulting associated with post-orogenic collapse and/or incipient continental rifting (Gasquet et al., 2008; Soulaimani et al., 2014). The more moderate unconformity that exists at the bottom of the shallow water Cambrian deposits likely reveals further stages in the rifting evolution further to the west, which resulted in the opening of the Iapetus, and then of the Rheic oceans (Nance et al., 2012).

3. Methods

This work is based on detailed geological mapping of the Bouadil and southern Goulmima areas at a scale of 1:50,000 (Raddi et al., 2006, 2012), combined with structural analysis in the field. We additionally performed remote satellite image analysis to further investigate the geology of the rocks and the relations between the various tectonic structures that cut the surface. The thermal conditions that prevailed during the deformation of the SG rocks are defined through the recognition of specific structural features at the outcrop scale (fold geometry, axial-plane cleavage) and at the optical microscope scale (microstructures and mineral associations in thin sections).

4. Results

4.1. Lithostratigraphy

We built a stratigraphic column across the Ighrane inlier between Tizi n'Izem and Ighrane (Fig. 2). The Mellab inlier exposes mainly the upper part of this column. From the base of the stratigraphy upwards, the SG series contains rhythmically alternating centimeter- to decimeter-thick fine-grained sandstones, arkoses, greywackes, and quartzwackes that are interbedded with black shales. The psammitic units dominate the lower section, and finer grained pelitic rocks become more common in the upper section. Pelitic rocks are interbedded with arkose and quartzwacke beds up to 30–40 cm in thickness (Fig. 3A). The arkose and quartzwacke beds display hummocky cross-stratification (HCS) structures (Fig. 3B), whereas the fine-grained sandstones contain planar cross-bedding. In places, intraformational slump folds are observed (Fig. 3C) locally associated with sandy dykes in silty beds (Fig. 3D). Altogether, these attest to a rapid deposition of wet turbiditic sediments. Near Ighrane, a meter-thick amphibolite bed likely derived from some mafic volcanic or pyroclastic bed is intercalated within the quartz-biotite hornfels derived from the SG sediments next to the Mellab granodiorite contact.

4.2. Petrography

Under the microscope, the coarse lithologies display lithoclasts of quartz, quartz + plagioclase, and quartz + K-feldspar from granitic and/or volcanic, felsic to andesitic sources. In the fine-grained lithologies, a slaty cleavage S1 (tectonic foliation) can be observed; it is oblique to the bedding and cut by tension gashes that are filled with quartz and calcite. This suggests that pressure solution occurred during folding (Fig. SM1) under temperatures in the range of 250–280 °C, which is the boundary between anchizone and lowermost greenschist-facies metamorphism (Verdel et al., 2011; Wood, 1974). However, fresh

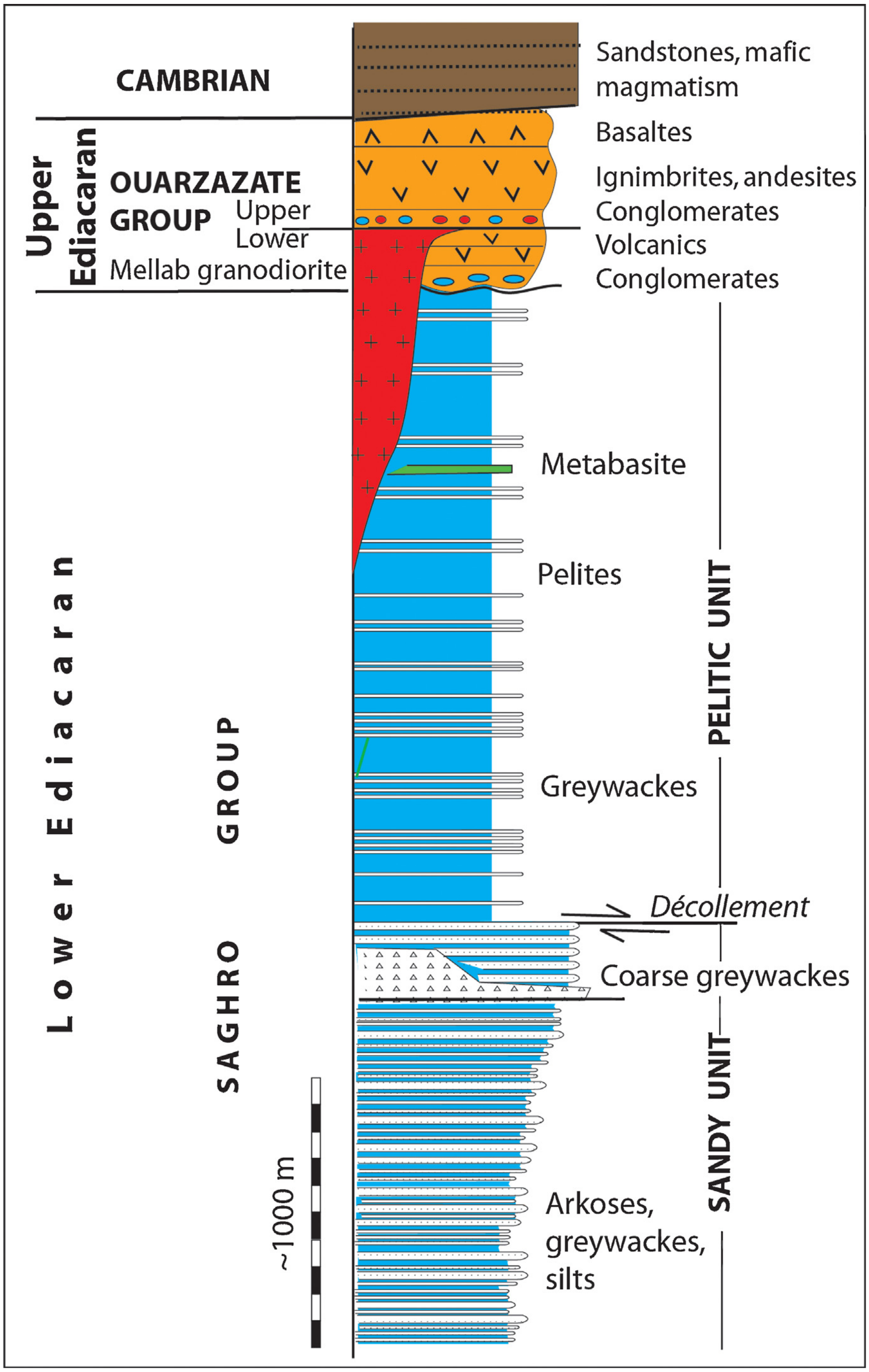

Fig. 2. Stratigraphic column of the Ougnat Massif. Double arrows: potential "décollement" level.

and poorly oriented biotite lamellae are also present in the outcrops adjacent to the Mellab village (Fig. SM1C). Since exposures of the Mellab granodiorite exist 2 km west and 2.5 km northeast of the Mellab village, these biotites might attest to the thermal imprint of the Mellab intrusion. In the proximal aureole of the granodiorite intrusive body, the SG lithologies are transformed into biotite-rich schists, whose foliation is affected by high-temperature folds with polygonal arcs of undeformed micas (Fig. SM1D).

4.3. Structure

The structures observed at the outcrop scale are of three types, which suggest that they have recorded three

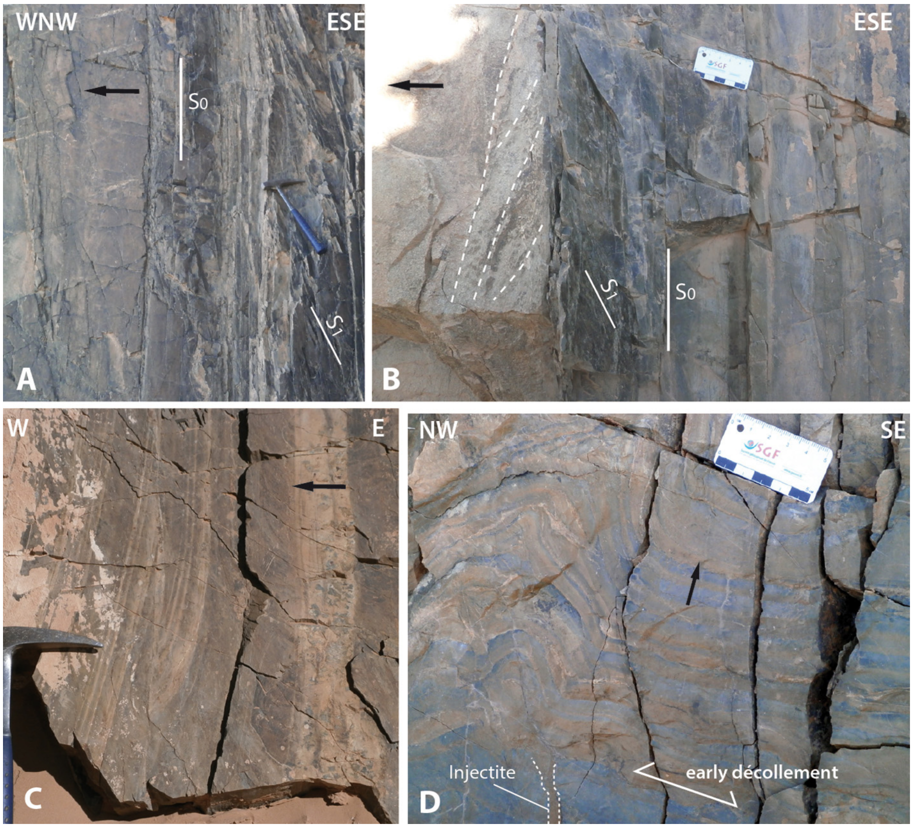

Fig. 3. Typical SG outcrops next to Mellab (A–C) and Tizi n'Izem (D). Bold arrows: sedimentation polarity; S_0: bedding; S_1: slaty cleavage. A. Alternating fine-grained graded greywackes, silts and black shales. B. Thick arkosic bed showing HCS structure interleaved in a sequence of fine-grained beds. C. Isoclinal synsedimentary slump fold in the verticalized sequence (A–C). D. Disharmonic synsedimentary folding associated with bedding-parallel "décollement" and opening of fracture filled with sand (injectite), suggesting incipient detachment of unconsolidated sediments along the basin slope.

superimposed deformational events. The first event is recorded by the synsedimentary intraformational folds and disharmonic folding described above (Fig. 3C, D). This event was most likely a gravity sliding of incompletely consolidated sediments along a basin slope. We labeled this early event "D_0".

The second deformation event is evidenced by the widespread axial-planar foliation "S_1" (Figs. 3A and 4; Figs. SM2, SM3). We labeled it "D1". The tectonic foliation is a slaty cleavage oblique to the bedding, developed in the pelites and siltites and associated with the low-grade greenschist-facies recrystallizations described above. The D_1 folds are either observed or inferred from the S_0/S_1 relationships. They are typically upright or verging to the NW (Fig. SM2A) or SE (Fig. SM2B). Their axial planes trend dominantly NNE–SSW next to Mellab but they rotate progressively to NE–SW in the southeastern part of the Ighrane inlier. Fold axes plunge by less than 30° to the northeast or to the southwest.

In the Ighrane inlier about 2 km south of Tizi n'Izem, a NE-striking, more than 15-km-long fault that splays in the south separates two units of folded SG formations (Fig. SM4). This "F_{0-1}" fault (Fig. 4) is confined in the SG formations and might have a twofold origin linked to the D_0 and D_1 events.

Finally, in the contact aureole of the Mellab granodiorite north of Ighrane (Fig. SM5), a late synmetamorphic compressional event "D2" is recognized. This event caused the tilting of the earlier folds and the refolding of the early metamorphic foliation under hornfels facies conditions.

The original geometry of the SG fold belt has been only slightly modified by the Variscan and the post-Variscan events, as recorded by the deformation of the Late Ediacaran–Paleozoic series (i.e. formation of a NE-trending antiform, then activation of the Akerouz normal faults system; Fig. 4). We restored the pre-Late Ediacaran–Cambrian geometry of the present-day cross-section by tilting the Cambrian strata down to the horizontal. The resulting figure (Fig. SM3C) suggests that the belt was formed by basically upright folds locally affected by longitudinal shear zones (e.g., F_{0-1}).

5. Discussion

5.1. The Ougnat SG basin, part of the Anti-Atlas SG basin

The SG sedimentary sequence in the Ougnat Massif is equivalent to parts of the SG sequences described further to the west in the Saghro and the Siroua (Sirwa) massifs (SMTable 1, left side). Particularly significant are the

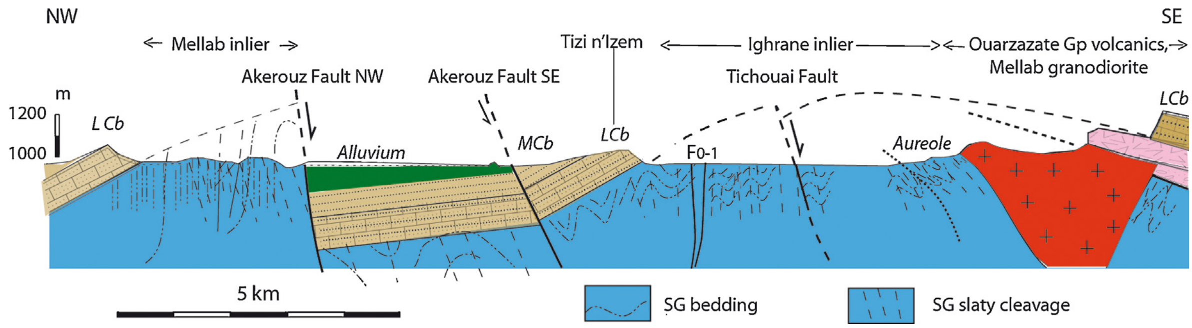

Fig. 4. Schematic cross-section of the Ougnat Massif. F_{0-1}: Precambrian fault (D_0 and/or D1 deformation episodes). See Supplementary Material for location and interpretation.

dominant greywacke facies that reveal mixed volcanic and terrigenous inputs; the frequency of turbidities, debris-flows and slumps, which altogether suggest sediment sliding along steep slopes toward deep-water troughs; the occurrence of interbedded volcanic flows (mostly basalts, but also andesites and rhyolites in Siroua) towards the bottom of some of the SG inliers with calc-alkaline to subalcaline characters and affinities with initial rift tholeiites, continental tholeiites or oceanic island alkali basalts (Fekkak et al., 2000, 2003; Thomas et al., 2002). The upper, arkosic part of the Siroua SG rocks suggests a decrease in water depth, likely related to the onset of convergence (Thomas et al., 2004). In the Ougnat Massif, the graded beds are scarce, no flute casts have been observed, and HCS structures are observed, altogether suggesting shallow to peritidal conditions of sedimentation during the last stages of the basin evolution.

The SG base could be observed nowhere. However, in the Sidi Flah inlier, small serpentinite bodies associated with jaspers and carbonates are tectonically included in the SG (Fekkak et al., 2003), which suggests the proximity of an ophiolite-bearing basement. Ultramafic xenoliths have been described in the granite intrusions of Bouskour and Boumalne that crosscut the Sidi Flah and Boumalne inliers, respectively (Fig. 1B; Fekkak et al., 2003, with reference therein). In the western Saghro, ultramafic boulders are included locally in the basal breccia of the OZG (Walsh et al., 2012). Altogether, this favors the hypothesis of a partly deep-water basin formed above a thinned crust likely at the ocean-continent transition (OCT) (Fekkak et al., 2003).

Liégeois et al. (2006) have estimated the age of the SG sedimentation through U–Pb dating of detrital zircons in the Kelaat Mgouna inlier of the Saghro massif. They found a mixing of Paleoproterozoic and Neoproterozoic ages, with ages of the youngest grains clustering around 620–610 Ma. These younger ages constrain the age of the latest stages of deposition. This is consistent with the T_{DM} model age in the 640–580 Ma time-span for pillow basalt flows interleaved in the Saghro SG (Errami et al., 2009). The source areas of the greywackes deposits would be located in the Paleoproterozoic basement of the northern WAC or/and in the then newly formed Pan-African belt where supra-subduction, pre-collisional granodiorites would have formed from 750 Ma to 614 Ma (Hefferan et al., 2000, 2002; Thomas et al., 2002). Similar results were obtained on detrital zircons from the SG rocks of the Siroua massif: the youngest zircon populations cluster around 620–610 Ma, whereas the proportion of Eburnian (~2 Ga) zircons increases upward (Abati et al., 2010). Based on these results, we suggest that the most probable age of the SG series in the Ougnat massif is 620–610 Ma (Early Ediacaran).

5.2. *Attributing the SG tectono-metamorphic evolution to the late Pan-African, Cadomian event*

In the Ougnat massif, the SG synmetamorphic folding cannot be accurately dated due to the lack of robust U–Pb zircon ages for the Mellab granodiorite and the lowermost overlying OZG volcanics. However, the geochemistry and hypovolcanic characters of the Mellab pluton (Raddi, 2014; Raddi et al., 2006, 2012) suggest that it belongs to the calc-alkaline to high-K granodioritic suite associated with the OZG volcanics, and widely exposed in the Saghro massif (Errami et al., 2009; Gasquet et al., 2005, 2008; Schiavo et al., 2007; Walsh et al., 2012). The Mellab granodiorite actually crosscuts at some places the lower volcanics of the Ougnat OZG (Tamerzaga and Bou Naga formations), and it is unconformably overlain by the Aouja n'Aissa–Iferda ignimbrites of the upper OZG (Raddi, 2014; Raddi et al., 2006, 2012). The ignimbritic series have been dated (U–Pb SIMS zircon ages) at 552 ± 5 Ma in the Ougnat massif (Gasquet et al., 2005), and at 550–543 Ma in the Imiter inlier of eastern Saghro (Fig. 1B; Gasquet et al., 2005; Levresse et al., 2004). In the western Saghro, the equivalent ignimbrites have yielded similar 558–556 Ma ages, whereas other volcanics of the lower part of the OZG formations yielded 574–571 Ma ages (Walsh et al., 2012).

The latter ages would constitute the upper limit for the age of SG folding in the Saghro-Ougnat area. However, this estimate must be corrected taking into account the time needed to exhume the SG low-grade metamorphic units up to the surface. Based on their formation at the anchizone–epizone transition close to ~250–280 °C (sect. 4.2), and supposing a standard geotherm (30 °C/km), we infer that the SG folds have been exhumed from a depth of 8–9 km. This exhumation began in an orogenic, collisional context and went on during the Late Ediacaran magmatic activity and the coeval extension in the Anti-Atlas domain (Blein et al., 2014a; Gasquet et al., 2008). Supposing a very fast exhumation rate of ~1 mm/yr (as currently observed in some orogenic or active rift contexts; e.g., Bauer et al., 2010; Glotzbach et al., 2008), we infer that the SG exhumation might have lasted about 8–9 Myr. Considering a more common, although fast exhumation rate of ∼0.3 mm/yr would suggest an exhumation duration of more than 25 Myr. Therefore a conservative estimate of the age of the folding of the SG formations may be 610–580 Ma.

5.3. From the Anti-Atlas SG to the Ougarta–Western Hoggar SV: a new proposal and implications

The 610–580 Ma SG fold belt records the latest compressional and/or transpressional, synmetamorphic event of the Pan-African orogenic cycle in the Anti-Atlas. This event postdates the major Pan-African events

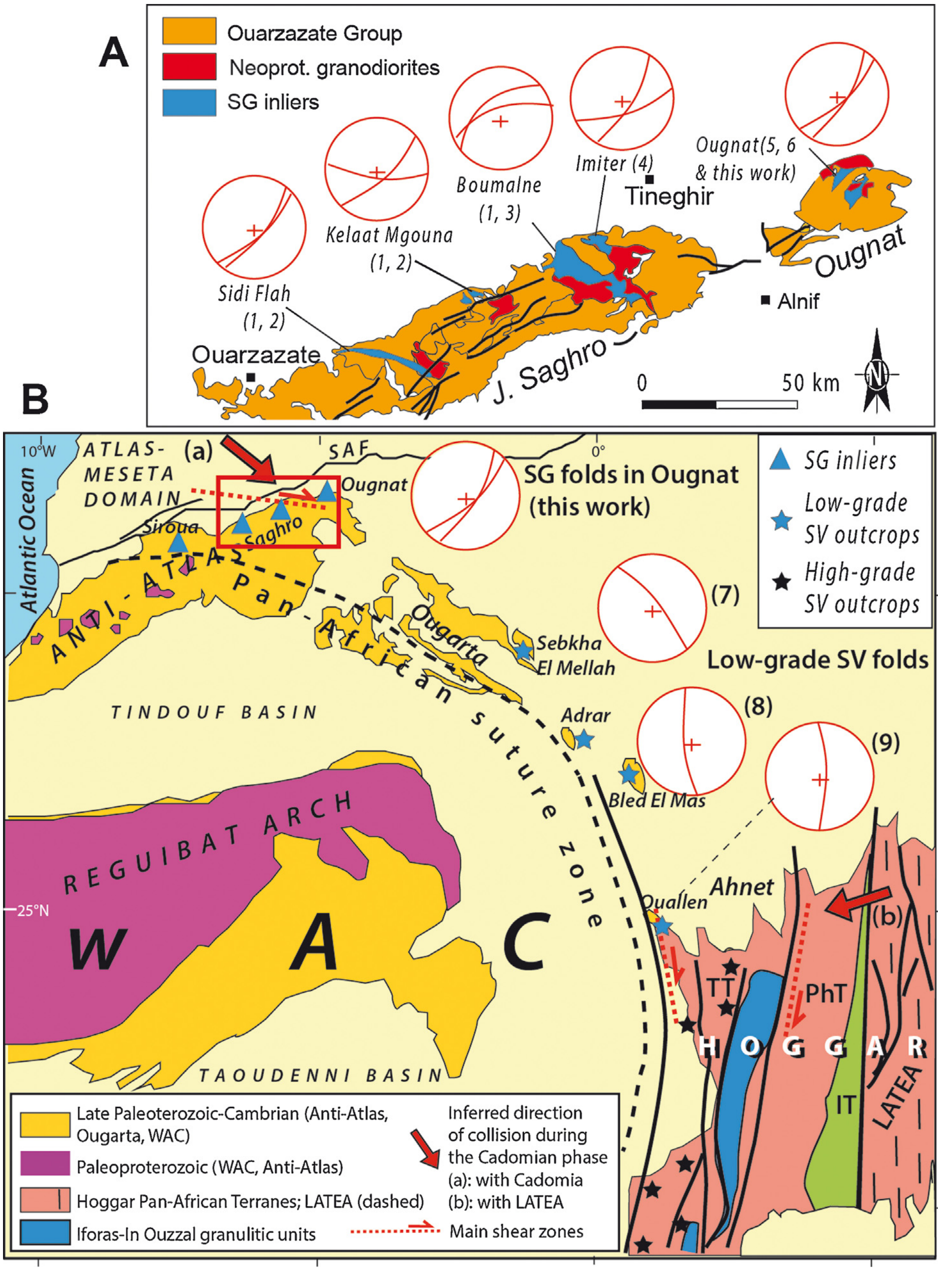

Fig. 5. A. Fold trends in the SG formations of the Saghro and Ougnat massifs shown by schematic stereograms (lower hemisphere) of the dominant strike and dip of the axial-planar slaty cleavage. 1: Fekkak et al., 2001. 2: Fekkak et al., 2003. 3: Fekkak et al., 2002. 4: Ouguir et al., 1996. 5: Raddi et al., 2012. 6: Raddi, 2014. B. Correlations with the southern Ougarta inlier (Sebkha el Mellah), Adrar and Bled El Mas massifs and Ouallen (Ahnet) northwestern Hoggar area. 7: Bouima and Mezghache, 2002; Dostal et al., 2002; Caby et al., 2010. 8: Haddoum, 2009; Caby et al., 2010. 9: Caby, 1970-1983, 2003; Haddoum, 2009. Geological background after the Geological map of Africa, scale 1: 10 million, Commission for the Geological Map of the World (2016), and Bosch et al. (2016) for the Hoggar massif. IT/PhT/TT: Iskel/Pharusian/Tassendjanet Terrane. SV outcrops from Ougarta to western Hoggar after Caby (personal comm., 2016). Paleo- to Mesoproterozoic age of the earliest post-Eburnian sediments in the WAC domain after Rooney et al. (2010), Ikenne et al. (2016) and Ait Lahna et al. (2016).

(760–700 Ma "Iriri–Tichibabine orogeny" and 670–640 Ma "Bou Azzer orogeny" in the sense of Hefferan et al., 2014), and is supposed to mark the onset of the Cadomian Orogeny, which lasted from *ca.* 580 to 550 Ma (Hefferan et al., 2014, with references therein; Linnemann et al., 2014). The post-SG, pre-OZG open folds that affect the Bou Salda and Tiddiline formations are included by Hefferan et al. (2014) in the end of the Cadomian cycle.

In the Anti-Atlas, the trend of the SG folds is dominantly SW–NE (Fig. 5A). The folds appear oriented *en échelon* with respect to the east–west-trending Pan-African suture zone defined in the central Anti-Atlas (Figs. 1B, 5B). This architecture suggests that the collision of Avalonia–Cadomia against the WAC (Ennih and Liégeois, 2003; Gasquet et al., 2008; Hefferan et al., 2000) has been oblique with respect to the margin of the WAC in the Anti-Atlas, with a southeastward direction of convergence (Fig. 5B, upper part). This transpressional regime has actually been evidenced in the Iknioun granodiorite that intrudes the SG series of the Boumalne inlier (Fig. 1B; Errami and Olivier, 2012).

The orientation of the Pan-African suture zone rotates from about east-west in the Anti-Atlas to about north-south in the Ahnet-western Hoggar (Fig. 5B; Bosch et al., 2016; Caby, 2003; Leblanc, 1981). We examine here for the first time the southeastward continuation of the SG formations into the formations termed "Série verte" (SV; SMTable 1), which extend up to the western Hoggar. In the Ougarta Belt, the cores of the Variscan faulted anticlines generally expose molassic-volcanic series termed "Série pourprée" equivalent to the OZG (Bouima and Mezghache, 2002; Caby, 1970-1983; Caby et al., 2010; Donzeau, 1972; Fabre, 2005). However, in the southern part of the belt (Sebkha El Mellah anticline), and further to the southeast in the Adrar and Bled El Mass outcrops, low-grade folded terrains similar to the northwestern Hoggar SV have been recognized beneath the Cambrian conglomerates and sandstones (Bouima and Mezghache, 2002; Caby et al., 2010; Dostal et al., 2002). The SV (Caby, 1970-1983) or "Pharusian II" (Bertrand and Caby, 1978) of northwestern Hoggar (Ouallen in western Ahnet; Fig. 5B) is a thick (> 6000 m) flysch-like succession of mainly volcaniclastic greywackes and conglomerates with abundant andesitic clasts, deposited next to an island arc or an active margin (Bosch et al., 2016; Caby, 2003). Volcanic flows (basalts, andesites, rhyolites) are interbedded with the greywackes. The similarity of the Ougarta–Ahnet SV with the Anti-Atlas SG also holds on their style of folding (upright folds with incipient axial-plane cleavage) and on their associated low-grade greenschist metamorphism. Further to the SSE in the Tassendjanet Terrane, the SV is involved in west-verging nappes, and its metamorphic grade increases up to the amphibolite-facies and anatexis (Bosch et al., 2016; Caby, 2003). In this region, the age of the thermal pic of regional metamorphism is constrained by a monazite *in situ* $^{207}Pb/^{208}Pb$ age at 603 ± 11 Ma (Bosch et al., 2002). However, the peak in pressure conditions is a bit older, 623 ± 3 Ma or 610–615 Ma (Ar/Ar on phengite; Berger et al., 2014; Caby and Monié, 2003; Jahn et al., 2001). The zircon age of ultrahigh-pressure metamorphism in the suture further to the south is 608–611 Ma (Ganade de Araujo et al., 2014).

Thus, we may hypothesize that the SG basin of the Anti-Atlas and the SV basin of the Ougarta–Western Hoggar formed originally a unique, up to 6000–8000 m subsiding basin that was surrounding the WAC by the end of the Neoproterozoic. The basin was deep in most parts, but including also a few shallow water domains. This "SG–SV Basin" was extending next to a volcanic arc that sourced a huge quantity of orogenic greywackes into the basin. Discussing the nature and the location of the arc is beyond the scope of this work. Subsidence and closure of the SG–SV Basin occurred during the last stages of the Pan-African orogenic cycle, but with some along-strike differences both in the timing and the deformation mode. In the Anti-Atlas area, the basin subsided from 610–620 Ma to ~580 Ma and closed during the Cadomian Orogeny (*sensu* Hefferan et al., 2014). In the Saharan regions, the onset of the SV sedimentation has not been dated yet, but postdates 680 Ma (Caby et al., 2010), whereas the basin closed before 620–610 Ma. The basin evolution thus showed some diachronism along strike. The fold belts that subsequently deformed the SG–SV series also show differences along the basin strike: the folds trend northeast to ENE in the Anti-Atlas, and NNW to north-south in the Saharan regions (Fig. 5). This suggests a NW–SE convergence of the Avalonia–Cadomia terranes with respect to the WAC in the Anti-Atlas, contrasting with an ENE–WSW convergence of the eastern Hoggar terranes (LATEA terranes; Liégeois et al., 2003) toward the eastern boundary of the WAC.

6. Conclusion

At the eastern tip of the Anti-Atlas, the Ougnat Massif shows large outcrops of the folded, low-grade volcaniclastic Saghro Group (SG), beneath the unconformable, Late Ediacaran Ouarzazate Group (OZG) volcanic formations and the Lower Cambrian sandstones. The Ougnat SG correlates with the central part of the 8-km-thick SG volcaniclastic deposits recognized further west in the Saghro and the Siroua massifs, where the SG orogenic greywackes have been dated at ~620–610 Ma (Early Ediacaran). These rocks are associated with the dismembered ophiolite remnants of the Pan-African suture zone (Siroua) or are located north of the ophiolitic outcrops (Saghro, Ougnat).

The 3- to 4-km-thick SG greywacke series of the Ougnat inliers has been deformed by NNE–trending, mostly upright folds with axial-planar slaty cleavage attesting to low-grade metamorphic conditions. The fold belt was exhumed up to the surface before the emplacement of the Late Ediacaran volcanics that are dated 574–571 Ma in the western Saghro. Hence folding of the SG deposits occurred at ~610–580 Ma at the onset of the Cadomian events. The Ougnat SG rocks are intruded by the ~550 Ma Mellab hypovolcanic granodiorite that also crosscuts the lowest OZG volcanics.

The base of the SG is nowhere exposed, but the occurrence of ultramafics has been documented locally in western Saghro, suggesting a possible ocean–continent transition domain, next to an oceanic or active margin arc during the last stages of the Pan-African suture evolution. The geodynamic significance of the SG fold belt is better understood through the correlations we propose with the

"Série verte" (SV) rocks that crop out to the southeast of the Ougnat Massif in the Ougarta and western Hoggar regions. Both the SG and SV rocks accumulated next to a volcanic arc in a strongly subsiding basin and were folded during the last Pan-African synmetamorphic events. Fold orientation and age of folding are differ along the basin strike. The orogenic greywackes of the SG-SV Basin constitute a relevant record of the diachronic Cadomian events *s.l.* along the WAC northwestern margin and should be the aim of new geological research.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crte.2017.01.001.

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