Detrital zircon ages of Neoproterozoic sequences of the Moroccan Anti-Atlas belt

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ABSTRACT

Detrital zircon dating from Neoproterozoic successions in the Sirwa inlier of the Anti-Atlas belt in Morocco confirms that the maximum depositional age of the main stratigraphic groups is significantly younger than has been previously proposed in lithostratigraphic correlations. This can probably be extended to the whole Anti-Atlas according to other recent data from the Saghro inlier. Although the relative stratigraphic position of the different units remains valid as published previously, a crucial implication of the new ages is that the sequences believed to be contemporaneous with oceanic crust and island arc formation during the rifting and break-up of the northern margin of the West African Craton (WAC), and believed to be involved in the first phases of the Pan-African orogeny, are actually late to post-orogenic. The age of the main deformation associated with the collision of the oceanic- and arc-derived terranes to the WAC, allegedly affecting the sediments of the Saghro Group, has been estimated at around 663–640 Ma. However, the youngest zircon populations of sediments of the Saghro and Bou Salda Groups, obtained in this study, cluster around 620–610 Ma, constraining the maximum age of deposition. This age of sedimentation is indistinguishable from the age of intrusive high-K calc-alkaline plutons of the Assarag Suite, suggesting a very rapid cycle of magmatism, relief formation, erosion and sedimentation in an active geodynamic scenario. Moreover, the proportion of the 610 Ma detrital zircons becomes less with respect to the Paleoproterozoic zircons at higher stratigraphic levels, suggesting that the source of young zircons was progressively eroded and more extensive cratonic areas, that probably underlie the Neoproterozoic rocks, were exposed. We interpret these data in terms of the development of a ca. 610 Ma magmatic arc, built upon WAC basement, and its progressive dismantling. This arc can be correlated with the voluminous late Neoproterozoic (ca. 640–570 Ma) arc magmatism characteristic of the north Gondwana margin and the peri-Gondwanan terranes. The diamicite beds that appear in the Imghi Formation of the Saghro Group have been correlated with the Sturtian glacial period ca. 700 Ma. However, zircons from one sample of these diamicites indicate that this correlation cannot be longer maintained, and instead they should be correlated with the Marinoan glacial period ca. 630–610 Ma, with a widespread distribution of glaciogenic deposits in West Africa. In addition, around 375 U-Pb concordant analyses obtained from Paleoproterozoic zircons from six samples represent a statistically significant population of this area of the WAC basement, which can be a useful database for comparison with the detrital zircon populations of the peri-Gondwanan terranes of Europe and North America, as the WAC margins were one of the major sediment suppliers for these terranes.

Keywords:
Anti-Atlas belt
Morocco
Detrital zircon
U–Pb

1. Introduction

Determining the age of statistically meaningful populations of detrital zircons within clastic sedimentary rocks has proven to be a powerful method to obtain relevant information on the nature of the crustal elements in the source region. This information has helped to resolve paleogeographic positions and geodynamic realms of terranes and paleocontinents by comparing the ages of the sediment provenance areas with the zircon signature of the stable cratonic areas of old continents or with the age of characteristic tectono-metamorphic events. Recently, detrital zircon spectra have been widely used in the paleogeographic reconstruction of the Neoproterozoic margin of north Gondwana and the complex ensemble of terranes which originated around this margin (Fig. 1): the peri-Gondwanan terranes (e.g. Fernández-Suárez et al., 2002, 2003; Avigad et al., 2003; Murphy et al., 2004; Linnemann et al.,
Fig. 1. Simplified paleogeography of Gondwana and related major peri-Gondwanan terranes at ca. 570 Ma (modified from Linnemann et al., 2007 and Díez Fernández et al., in press). Numbers in the cratonic areas summarize their main zircon age spectra for provenance constraints.

2. Geological setting

The West African Craton (WAC) is composed of three Archean and Paleoproterozoic metamorphic and magmatic shields separated by two cratonic sedimentary basins: the Reguibat Shield and the Anti-Atlas belt to the north and the Man shield to the south (Fig. 2; Ennih and Liégeois, 2008). The basement of the WAC was built through several major orogenic cycles: the Paleoarchean-Leonian cycle (different episodes between 3.5 and 3.0 Ga) related to continental accretion and volcano-sedimentary activity whose chronology remains uncertain (e.g. Rocci et al., 1991; Potrel et al., 1996; Krakrner et al., 2001; Thiéblemont et al., 2004), the Liberian cycle (2.95–2.75 Ga; Hurley et al., 1971; Auvray et al., 1992; Potrel et al., 1998; Key et al., 2008), the Eburnian-Birimian cycle (2.2–1.75 Ga; Abouchami et al., 1990; Liégeois et al., 1991; Boher et al., 1992; Hirdes et al., 1992; Ait Malek et al., 1998; Schofield et al., 2006) and the Pan-African orogenic event (760–660 Ma; Leblanc and Lancelot, 1980; Saquaque et al., 1989; Hefferan et al., 2000; Thomas et al., 2002; Samson et al., 2004). One of the main char-
The Anti-Atlas belt of southern Morocco is located at the northern edge of the West African Craton (WAC) (Fig. 2). It is separated to the north from the High-Atlas and the Meseta domain by the South Atlas Fault (Fig. 2b) and is subdivided into three geographic domains: the western Anti-Atlas composed by Kerdous, Bas Ora, Ifni and Ighrem inliers; the central Anti-Atlas including the Sirwa, Zenaga and Bou-Azzer Inliers; and the eastern Anti-Atlas made up of Saghro and Ougnat inliers (Ennih and Liegeois, 2008; Fig. 2b). The Anti-Atlas consists essentially of: (1) basement rocks of Paleoproterozoic age (ca. 2 Ga) (Fig. 2b); (2) Neoproterozoic sequences with lowermost units involved in the Pan-African orogeny and (3) unconformably overlying Paleozoic rocks (Tata and Taroudant Groups; Thomas et al., 2002).

2.1. Paleoproterozoic basement

The Paleoproterozoic basement (2030–2200 Ma) (Ait Malek et al., 1998; Thomas et al., 2002; Walsh et al., 2002) forms the northern margin of the WAC (Fig. 2a). It outcrops in several inliers (Zenaga, Ighrem, Kerdous, Ifni, Taghra d’Akka, etc.; Fig. 2a) and mostly consisting of phyllites, schistes, gneisses and migmatites which are intruded by calc-alkaline plutonic rocks. These basement rocks record low- to medium-grade metamorphic event attributed to the Eburnian–Birimian orogeny. The latest magmatic Paleoproterozoic event identified in the Anti-Atlas has been dated at ca. 1760 Ma (Gasquet et al., 2005).

2.2. Neoproterozoic sequences

These sequences are composed of units involved in the Pan-African orogeny and the uncomfortably overlying post-collisional volcano-sedimentary rocks (Ouarzazate Group of Thomas et al., 2002; Fig. 2b). The Paleoproterozoic rocks underlying the Ouarzazate Group are subdivided into lower units (Taghdout, Bou-Azzer and Ifni Groups; Fig. 3), affected by the main Pan-African orogenic events, and the upper sequences (Saghro and Bou Salda Groups) only affected by the latest stage of Pan-African orogeny. The lower Paleoproterozoic units are presumed to have been deposited over a long period of time involving a sequence of geodynamic settings starting with a rifting phase and the creation of ocean basins, and subsequent subduction-arc complex formation, and finally to accretionary collision (Thomas et al., 2002).

2.2.1. Pre- to syn-Pan-African evolution

The nomenclature and descriptions used in this section are taken mainly from Thomas et al. (2002, 2004). The break-up and rifting of the northern margin of the WAC led to the formation of a passive margin sequence (Taghdout and Lkest Groups) which consists essentially of stromatolite-bearing carbonates at the bot-
Fig. 3. Simplified geological map of the Sirwa inlier (modified after Thomas et al., 2002) with the location of the samples. More detailed maps are shown in Figs. 5 and 6.

2.1. Early to mid-Pan-African evolution

The Pan-African collision was followed by the deposition of the Saghro Group. This group is defined in the Sirwa window by Thomas et al. (2002) as a thick pile of flysch sediments, volcanic rocks with calc-alkaline composition, volcanoclastic and clastic rocks, deformed and metamorphosed under greenschist-facies conditions (Thomas et al., 2002). The Saghro Group is interpreted as a sequence of tectonic and magmatic events related to the Pan-African collision.

The cores and overgrowths of zircon grains from the Iriri migmatite yielded two U-Pb SHRIMP ages at 743 ± 14 and 663 ± 13 Ma respectively (Thomas et al., 2002). The older age obtained from the cores is interpreted as the age of crystallization and emplacement of the protolith to the migmatite in an island-arc complex, whereas the younger age is thought to represent the ophiolite obduction and arc accretion onto the northern edge of the WAC (Thomas et al., 2002). In the Bou Azzer inlier, U-Pb zircon dating of the gneissic and metagabbroic rocks of the Tazigzaout complex yielded similar protolith ages of 753 ± 2 and 743 ± 14 Ma respectively (D'Lemos et al., 2006). Leucogranites post-dating the gneissic and mylonitic fabrics of these rocks yielded an age of 700 Ma (D'Lemos et al., 2006). This second magmatic phase is interpreted as a continuous arc-building event by Gasquet et al. (2008).

In the Bou-Azzer inlier, the age of the main phase of Pan-African collision is constrained by syn-tectonic calc-alkaline intrusions which yielded U-Pb zircon ages of 654 and 640 Ma (Inglis et al., 2004).

2.2. Late- to post-collisional Neoproterozoic evolution

The Pan-African collision was followed by the deposition of the Saghro Group. This group is defined in the Sirwa window by Thomas et al. (2002) as a thick pile of flysch sediments, volcanic rocks with calc-alkaline composition, volcanoclastic and clastic rocks, deformed and metamorphosed under greenschist-facies conditions (Fig. 3). These authors have defined six lithostratigraphic formations showing a lower flysch succession with the occurrence of glacial diamictites in one of the lower formations (Imghi Formation) and an upper succession with clastic deposits. Numerous geodynamic scenarios have been proposed for the Saghro Group. Most of them considered the group to be the pre-Pan-African dis-
3.1. Taghdout Group

The zircon age spectra (Figs. 6 and 7) show a major Paleoproterozoic event around 1809 ± 15 Ma (98% concordance) and the youngest population age is 1818 Ma, giving a maximum age of sedimentation. The oldest zircon is 2936 ± 15 (99% concordance). To facilitate the comparison between samples, we have included the 207/206 ages in age intervals representing the major orogenic events of the West African Craton, with the percentages of each group represented in circular diagrams (Fig. 7).

3.2. Saghro Group

The succession of this group mainly consists of sedimentary rocks with subordinate volcanics. In the Sirwa inlier, the Saghro Group was subdivided by Thomas et al. (2002) into six formations which are from bottom to top: the Tittalt, Agchtim, Tizoula, Imghi, Azarwas and Tafiat Formations. The two upper formations correspond to coarse-grained clastic rocks, while the lowermost succession is a volcanic turbidite and flysch-like sequence (Thomas et al., 2002, 2004). The following lithological descriptions of the Imghi and Azarwas Formations, where the samples AA3, AA5 and AA6 were collected, are in part after De Kock et al. (2000) and Thomas et al. (2002, 2004).

3.2.1. Imghi Formation (diamictite: AA3 and arkose: AA5)

This formation (Fig. 5b) is composed by thick beds of greywacke and turbidite displaying WSW-ENE paleocurrent directions (Thomas et al., 2002). It is characterized by the occurrence of several folded and faulted diamictite beds of 1-30 m in thickness. The top of the sequence comprise subarkosic sandstone and quartz-pebble conglomerate with interbedded cherts. The diamictites are overlain towards the south by a succession of graded conglomerate with interbedded shale. Stratigraphic way-up structures suggest that this succession is younging to the north (Gresse et al., 2000). Bedding is well developed and dips steeply to the north. The shales are affected by an incipient cleavage which is generally parallel to bedding. The massive diamictites consist of pebbles of granite, schists, gneisses and Mimount quartzite in medium- to coarse-grained quartz-feldspathic matrix. The clasts and the matrix are generally poorly sorted and well rounded, corresponding to second- or third-cycle deposits and show parallel slip fractures (striations). They have been interpreted as reworked glacial-derived clasts which were transported into the basin by turbidity currents (Gresse et al., 2000).

Sample AA5 (30°44′49.8″N/7°27′54.3″W): it is a light-grey, fine to medium-grained immature feldspathic sandstone (arkose). It consists predominantly of quartz, plagioclase, and microcline, with minor amounts of muscovite and biotite. A mesoscopic lamination defined by lamination-parallel microliths probably represents primary stratification. From 124 zircon grains analyzed, only 64 are <5% discordant. They gave a mixture of Paleoproterozoic and Neoproterozoic dates, with a significant proportion of young zircons (80-20%; Figs. 7 and 8a, b). The youngest zircon found gave a date of 588 ± 10 Ma (105% concordant) and the youngest population age is 620 Ma. The oldest zircon is 2610 ± 14 (96% concordant).

Sample AA3 (30°44′58.0″N/7°27′50.9″W): sampled in a higher stratigraphical level of the Imghi Formation than AA5, it is an unsorted, matrix-supported and poorly stratified conglomerate level (diamictite) with a fine-grained quartz-feldspathic matrix and numerous clastic fragments. The clasts show a gradation in
size from fine rock fragments to coarse cobbles (up to 20 cm). The most typical clasts are rounded quartzite pebbles, and less frequent are fragments of igneous and metamorphic rocks, with occasional angular faces. 126 concordant zircon analyses show essentially a sub-equal mixture of Paleoproterozoic and Neoproterozoic ages (Figs. 7, 8c, d), and only two Archean grains. The only remarkable difference with the previous sample (both from the Imghi Formation) is a significantly lower proportion of young zircons: 50–50% compared to 80–20% in the AA5 arkose. The probability plots of Fig. 7 show that the Archean and Paleoproterozoic zircon populations of this sample are similar to the AA1 quartzite (and also similar to the other samples), except for the absence of Liberian (2.95–2.75 Ga) zircons. The distribution of Paleoproterozoic zircons is 43% for the Eburnian interval (2.2–1.78 Ga) and 5% for the 2.75–2.25 Ga. The youngest Paleoproterozoic zircon has an age of 1789 ± 22 Ma (97% concordance) and the youngest population age is 1798 Ma. The oldest zircon was dated at 2722 ± 14 (100% concordance).

The Neoproterozoic populations have been represented in more detail in the concordia and probability plots of Fig. 8c, d. In the probability plots the 206/238 ratios have been used, because at this age range they are much more precise than the 207/206 ratios. The younger Neoproterozoic zircons show a marked peak at 610 Ma. The age of the youngest zircon is 591 ± 12 Ma (101% concordance), and the oldest Neoproterozoic zircon was dated at 714 ± 12 Ma (101% concordance). The probability plot shows another minor peak at 635 Ma which extends until 644 Ma, and after that a significant gap is observed between 644 and 714 Ma (one zircon) with only two ages at 661 and 662 ± 12 Ma. The age distribution is 50% of zircons of 0.55–0.65 Ga, and 2% of 0.66–0.77 Ga.

3.2.2. Azarwas Formation (whitish arkosic sandstone: AA6)

This formation comprises three members, from bottom to top: Wissadene, Amajjar and Tougmast Members (Thomas et al., 2002). The Wissadene Member consists of sandstone, arkose and conglomerate. The Amajjar Member contains arkosic sandstone, shale and siltite. The Tougmast Member is the most extensive; the main body consists of arkosic greywacke, cross-bedded arkosic sandstone, whitish arkose and interbedded siltstone with subordinate shale and conglomerate and some basic and acid volcanic rocks.

Sample AA6 (30°39'34.0"N/7°22'17.0"W): whitish arkosic sandstone collected west of Adrar Tougmast (Fig. 6a). The zircon age population in the collected sample is quite different with respect the other samples of the Saghro Group (arkose AA5 and diamictite AA3), because is restricted to two age groups and the proportions of each group are very different. The presence of Ediacaran zircons (0.65–0.55 Ga) is much lower, only seven grains from 107 (6.5%), with 206/238 ages of 600 ± 12 (two grains), 607 ± 11 and 621 ± 13 Ma (Fig. 8e, f). The remaining 93% zircons are in the Eburnian–Birimian interval (2.2–1.78 Ga).

3.3. Bou Salda Group (AA4: conglomerate)

Although this formation is considered as a volcano-sedimentary sequence occupying a transitional stratigraphic position between the underlying Saghro Group and the overlying Ouarzazate Group, it presents some similarities with the Azarwas Formation. Their occurrence is limited to narrow fault-bounded troughs. It is considered by Thomas et al. (2002) as a syn-collisional molasse consisting of arc-derived volcanoclastic rocks deposited in a fore-arc basin. The Bou Salda Group is mainly composed by two members which
are from bottom to top: Ighil and Imakzhene Members (Thomas et al., 2002). The latter member essentially presents conglomerates, arkosic gritstones and sandstones with interbedded greywackes, shales, tuffs, basalts and cherts. The Ighil Member comprises basaltic rocks, andesite and rhyolite. In the N'Kob area (Fig. 3) the Bou Salda Group exhibits two other members overlying the clastic member described above: the basal member comprises rhyolitic ignimbrites, basalts and dolomites overlying the Lmakhzane sequence, and an uppermost member consisting of shales and quartzites (Thomas et al., 2002).

**Sample AA4 (30°45′17.4″N/7°27′63.5″W):** Quartz cobbles of a conglomerate from the Lmakhzane Member collected north of Tizwad (Fig. 5b). Here, the Bou Salda Formation is bounded by subvertical strike-slip faults separating it from the Imghi and the Tachakout formation. It consists of basaltic rocks of the Ighil Member and the overlying conglomerate of the Lmakhzane unit. The latter is composed of massive rounded quartzic cobbles and boulders up to 1.5 m in diameter. Similarly to the previous sample (AA6), the proportion of Neoproterozoic/Paleoproterozoic zircons is low, with only six “young” zircons from a total concordant population of 81 (7.5%; see circular diagram of Fig. 7). The 206/238 ages are 600±12, 603±13, and 625±12 Ma (Fig. 9a). The youngest ages provide a maximum age for the quartzite clasts in the conglomerate, and hence also for the Bou Salda Formation. The presence of Pan-African zircons precludes the possibility that the quartzite boulder came from the Taghdout quartzites. The similarity with the samples of the Saghro Group

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*Fig. 5.* (a) Geological map of the southern part of the Sirwa window at Taghdout locality. (b) Geological map of the central part of the Sirwa window at the North of the Izwad Village. Modified from the 1:50,000 geological maps of the Taghdout and Tamallakout sheets (Geological Survey of Morocco, 2000).
Boutazarte Granite (Ammassine suite)
Arg Gabbro (Assarag suite)
Younger cover rocks
Sandstones, Tuff
Conglomerates
Dacites
Andesites
Rhyolite and trachytes
Epiclastic rocks

Saghro Group
Arkoshic sandstone, sandstone, conglomerate

Thrust
Fault

Fig. 6. (a) Geological map of southern part of the Sirwa inlier, modified from the 1:50,000 geological map of Taghdout sheet (Geological Survey of Morocco, 2000). (b) Geological sketch map of the Zenaga inlier.
Fig. 7. Probability plots of detrital-zircon U–Pb age populations from the Neoproterozoic formations of the Anti-Atlas belt samples analyzed in this study. Plots are arranged with the oldest stratigraphic unit sampled at the bottom and the youngest unit at the top.
Fig. 8. U–Pb Concordia diagrams and detailed relative probability plots depicting the Neoproterozoic zircon populations for samples AA5 (a, b), AA3 (c, d) and AA6 (e, f). They are arranged from bottom to top according to their stratigraphic position.
suggests that it could be reworked sedimentary rocks from this Group.

3.4. Ouarzazate Group

Sample AA7 (30°32'50.5"N/7°07'17.4"W): epiclastic conglomerate of the Ouarzazate Group just above the discordant contact with the materials of the Saghro Group (Fig. 6b). 97% of the zircon population is the 550-650 Ma interval, and the remaining 3% (two grains) have 207/206 ages around 2100 Ma. The maximum of the young zircon population is 571 Ma which, given the volcanlastic nature of the conglomerate, is probably very close to the deposition age. The youngest zircon found was dated at 537 ± 12 Ma (96% concordance) and the youngest population age is 557 Ma. The oldest zircon gave an age of 2121 ± 17 (101% concordance).

4. Discussion

4.1. Passive margin sequence

The age of the platform margin sequence covering the Paleoproterozoic basement (Taghdout and Ikest Groups) is not well constrained. The dikes crosscutting the basal part of the series are dated by an old Rb-Sr whole rock at 787 ± 10 Ma (Cahen et al., 1984a,b). The other constrains are indirect: they are below the Bou Azzer ophiolitic complex with an obduction age of 660 Ma, and a minimum age of 788 ± 9 is indicated by a Rb-Sr age on clay fractions from Taghdout metasediments (Clauer, 1976). The new zircon data obtained in this study from the Taghdout quartzite (AA1) do not narrow very much the previous time constraints; the youngest zircon is 1809 Ma, thus not precluding the possibility that the sequence could be Paleoproterozoic.

The quartzite only contains Archean and Paleoproterozoic zircons, whose main characteristics are discussed below. The lack of zircons with more than 3.0 Ga (Leonian orogeny) indicate that the provenance area of the sediments was relatively far away of the principal potential source of Meso- and Paleoarchean zircons, located in the Man and Nigerian shields in the south part of the WAC (Fig. 2; Rocci et al., 1991; Kröner et al., 2001; Thiblemont et al., 2004). The only known source of zircons of that age in the northern part of the WAC is restricted to small parts of the Amsaga area in the Reguibat shield (Auvray et al., 1992; Potrel et al., 1996; Key et al., 2008). Therefore, the source area of the quartzites is inferred to be the proximal, autochthonous basement of the Anti-Atlas belt,
formed essentially by Paleoproterozoic components (Fig. 10). As a more general conclusion, an interesting feature of the zircon signature of sediments whose source area is the northern part of the WAC should be the absence of more than 3.0 Ga zircons. The oldest groups of Archean zircons is very scarce and only have been found in the Taghdout quartzite (AA1), where they only represent 2% of the total zircon population. Their ages vary from 2936 to 2746 Ma, and can be ascribed to the Libyan orogeny. The following younger group of zircons, between 2.75 and 2.25 Ga, represent a significant group with a proportion 17% (see circular diagrams in Fig. 7). It is the most intriguing population, because the Archean and Paleoproterozoic evolution of the WAC does not register any tectonothermal event in that range of ages (typical zircon age ranges of the WAC are shown in Fig. 1). The youngest granitoids related with the Neoarchean development of the Regubat shield are 2726 ± 7 Ma (Potrel et al., 1998; Key et al., 2008), and the following registered events are the early Eburnian ca. 2250 Ma. Thus, a gap on zircon ages between ca. 2700 and 2050 Ma is assumed to be characteristic of rocks coming from the WAC (Nance et al., 2008). The presence of these concordant zircon ages in the platform sequence located directly over the WAC suggest that some important magmatic or orogenic event within this age interval should be registered in some part of the northern WAC basement that have not been discovered yet. It is interesting to note that small populations of zircons between 2.75 and 2.25 Ga are present in the sediments of some peri-Gondwanan terranes of NW Iberia whose source area is assumed to be the WAC (e.g. Ñiez Fernández et al., in press). Within the zircons of this group, the main age peaks are located at 2450 and 2514 Ma. One possible location for these basement rocks could be the Eglab Massif an the north of the Regubat shield in Algeria, where some Sr and Nd model ages suggest the presence of rocks about 2.4–2.5 Ga (Peucat et al., 2005), although the ages have not been confirmed by U–Pb in zircon. The third group of zircons is the main population of zircons (83%, Fig. 7) coming from the “old” basement (2.2–1.78 Ga). This group is related with the important Eburnian–Birmanian tectono-magmatic activity registered elsewhere in the WAC, especially in the northern part of the Regubat shield and in the basement of the Anti-Atlas belt.

4.2. Saghro, Bou Salda and Ouarzazate Groups

Neoarchean and Paleoproterozoic zircons. The first age group found is between 2.75 and 2.25 Ga. It is lacking in samples AA6 and AA7, represents a small proportion in samples AA3 and AA5 (1% and 5%), and only reaches a significant proportion, 17% and 16%, in samples AA1 and AA4 respectively (Fig. 7). A possible source area for these zircons could be the northern terrane that should have been accreted to the WAC margin immediately after the obduction of the ophiolites (Gasquet et al., 2008; Fig. 10). This terrane would be further to the north of the Saghro arc, and at present is hidden by the south Atlas major fault (Fig. 2), but it would presumably be equivalent to the basement of the present peri-Gondwanan Meseta terranes to the north of the Atlas chain (Ennih and Liegeois, 2008). The last group corresponds to the Eburnian cycle (2.2–1.78 Ga), and their proportion with respect to the total population varies between 93% (sample AA6, sandstone from Azarwas) and 3% in the younger sample (AA7, Ouarzazate Group conglomerate).

Neooproterozoic zircons. The proportion of Neoproterozoic/Paleoproterozoic zircons varies considerably from the bottom to the top of the sedimentary sequence, showing the fluctuations in the source area, depending on the nature of the exhumed rocks that were being uplifted and eroded: the cratonic basement or the rocks related with the Pan-African orogeny. The oldest passive margin Taghdout quartzite (AA1), located below the suture, does not have any Neoproterozoic zircons, and going to the top of the sequences above the suture, the proportion of Neoproterozoic zircons in each sample is 80% (AA5), 52% (AA3), 7% (AA6), 5% (AA4) and 97% (AA7) (Figs. 4 and 7). The youngest zircon population in Saghro and Bou Salda Groups is 610–620 Ma, whereas in the discordantly overlying Ouarzazate Group is 557 Ma. In the case of the zircons from the Imghia Formation (arkose AA5 and diamictite AA3), the differences in the zircon population could be related with a proximal supply of sediments for the arkose and a more distal source for the diamictite, due to longer transport in ice blocks favouring a higher proportion of zircons from the Eburnian basement.

In tectono-stratigraphic reconstructions of the Anti-Atlas belt, the deformation affecting the Saghro Group was classically attributed to the Pan-African collision, and according to this view, the age of this group should be older than 660–700 Ma (Thomas et al., 2004). However, recent U–Pb zircon dating of the turbidites from the Saghro inlier place this group in the 630–610 Ma age range (Gasquet et al., 2008). Our new data presented here from the Sirwa inlier are in the same age range. Thus, one important conclusion of this study is the confirmation that the deposition of the Saghro Group actually post-dates the accretion of the ca. 750 Ma ophiolites and arc derived terranes (Irirí arc) to the WAC margin, which probably occurred during the second phase of the Pan-African deformation (ca. 660 Ma; D2 of D’Lemos et al., 2006). The deposition age younger than 610 Ma demands a reassessment of the origin and stratigraphic position of the Saghro Group. The deformation described on the sediments of the Saghro Group can no longer be related with the main phase of Pan-African deformation, instead it should be ascribed to a post-610 Ma deformational
The subsequent decreasing of this group of zircons going to higher ages (Fig. 1), characterized by abundant calc-alkaline volcanic rocks and cogenetic plutons, sedimentation and deformation associated with the opening and closing of arc-related basins that gave rise to the peri-Gondwana terranes and finally to the opening of the Rheic Ocean (e.g., Murphy and Nance, 1989; Keppie et al., 1996; Murphy et al., 2004; Nance et al., 2008). The different proportions of sediments coming from the arc with respect to the basement can be interpreted in terms of the birth, development and erosive dismantling of the arc. The strong signal of ca. 650–550 Ma (50% of the zircons) appearing in sample AA3, reaching a maximum of 70% in sample AA5 (Fig. 7) would be related with the formation of the arc. The subsequent decreasing of this group of zircons going to higher stratigraphical levels (7% and 4% in samples AA6 and AA4) would be associated with the progressive dismantling of the arc.

According to the former interpretation of the age of the Saghro Group, the diamictite beds that appear in the Imghi Formation have been correlated with the Sturtian glacial period ca. 700 Ma (Thomas et al., 2002, 2004). However, the zircons from one sample of these diamictites (sample AA3) indicate that the correlation cannot be maintained longer, and instead they should be correlated with the Marinoan glacial period ca. 630–610 Ma (Kennedy et al., 1998), with a widespread distribution of glaciogenic deposits in West Africa (Deynoux et al., 2006).

5. Conclusions

1. The lack of zircons older than 3.0 Ga indicates that the source of the Neooproterozoic sedimentary sequences of the Anti-Atlas belt was the northern part of the WAC autochthonous basement (Reguibat shield).

2. The group of Neoarchean–Paleoproterozoic zircons (2.75–2.25) suggests the existence of a tectonothermal event(s) in the northern part of the WAC with a peak at ca. 2.5–2.4 Ga, which have not been described yet.

3. The major zircon source of the sediments was the igneous and metamorphic Eburnian rocks located in the Reguibat shield (except for the Ouarzazate Group).

4. The depositional age of the Saghro Group is younger than 620–610 Ma and hence the deformation that affects the sediments should be late- to post-collisional.

5. The sedimentary sequences of the Saghro Group probably reflect the development and subsequent erosive dismantling of a magmatic arc located to the north of the Pan-African suture and built upon north WAC basement.

6. This arc can be correlated with the long-lived arc-system surrounding the northern Gondwana margin during the Neooproterozoic–Lower Cambrian.

7. The diamictite beds appearing in the Saghro Group are related to the Marinoan glacial period.

Acknowledgments

We would like to express our thanks to Bob Thomas, an anonymous reviewer and the editor P. Cawood for helpful and constructive reviews. Field work was funded by project A-7287-06 from the Agencia Española de Cooperación Internacional (AECI), and analytical work was funded by project CM-UCM-910129 from the Comunidad de Madrid.

Appendix A. Supplementary data

Supplementary Frei and Gerdes, 2009; Gerdes and Zeh, 2009; Jackson et al., 2004; Janousek et al., 2006; data associated with this article can be found, in the online version, at doi:10.1016/j.jprecamres.2010.05.018.

References


