Chapter 2
The Pan-African Belt

D. Gasquet, N. Ennih, J.-P. Liégeois, A. Soulaimani and A. Michard

In memory of Georges Choubert, the pioneer of modern Anti-Atlas studies, and Anne Faure-Muret, who joined him for establishing international correlations in the Precambrian of Morocco

2.1 General

References: Since the milestone works of Choubert (1963), and Choubert & Faure-Muret (1970), a number of papers have proposed synthetic, and often contrasting views on the structure and evolution of the Precambrian inliers of the Anti-Atlas, e.g. Benziane & Yazidi (1992), Hefferan et al. (2000), Ennih & Liégeois (2001, 2003, 2008), Thomas et al. (2002, 2004), Inglis et al. (2004), Helg et al. (2004), Gasquet et al. (2005), Deynoux et al. (2006), Liégeois et al. (2006), Bousquet et al. (2008), with references therein. References more specific to the varied tectonic complexes of the area are given in the further sections. The Adrar

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A. Michard et al., *Continental Evolution: The Geology of Morocco*. Lecture Notes in Earth Sciences 116,

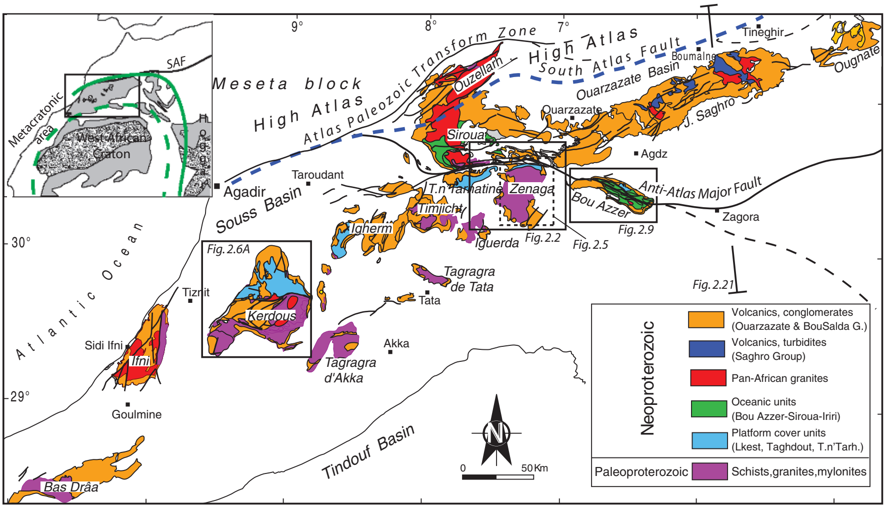


Fig. 2.1 Schematic map of the Anti-Atlas Precambrian inliers (≪boutonnières≫), and location of the maps, satellite views and lithospheric profile presented hereafter

Souttouf Precambrian units are described by Rjimati & Zemmouri (2002) and Villeneuve et al. (2006).

The Pan-African belt exposures in Morocco mainly correspond to large inliers (Fig. 2.1) within the NE-SW oriented Anti-Atlas Paleozoic fold belt (cf. Chap. 1, Fig. 1.4). Each inlier corresponds to a structural culmination of the Variscan fold belt (Chap. 3), but crops out frequently at elevations lower than the overlying, less easily eroded Cambrian sediments, which explains their traditional name "boutonnières" (Fig. 2.2). The exhumation of the Precambrian antiformal boutonnières in the Anti-Atlas axis occurred through erosion of their Paleozoic cover during the Late Carboniferous-Permian, just after the Variscan orogeny, then during the Triassic-Jurassic, when the Anti-Atlas formed the shoulder of the Atlantic and Atlas rifts, and eventually during the Late Eocene-Pleistocene, contemporaneously with the uplift of the Atlas belt itself. Pan-African rocks are also exposed in the eastern block of the High Atlas Paleozoic massif, i.e. the Ouzellarh "promontory", which connects with Anti-Atlas through the Siroua (Sirwa) massif. Additionally, Pan-African rocks make up the allochthonous nappe material of the Mauritanide Variscan belt in the Dhlou and Adrar Souttouf areas (Chap. 1, Fig. 1.11).

The Pan-African belt formed during the Neoproterozoic around the Paleoproterozoic West African Craton (WAC), as reported in Chap. 1. During the last decade, deciphering the successive orogenic events in the Anti-Atlas Precambrian inliers greatly benefited from the Moroccan National Geological Mapping Project, including numerous high sensitivity or conventional U-Pb zircon dates and other geochemical studies. As a result, some of the ideas widely accepted a few years ago concerning, for example, the northern limit of the Paleoproterozoic basement or the

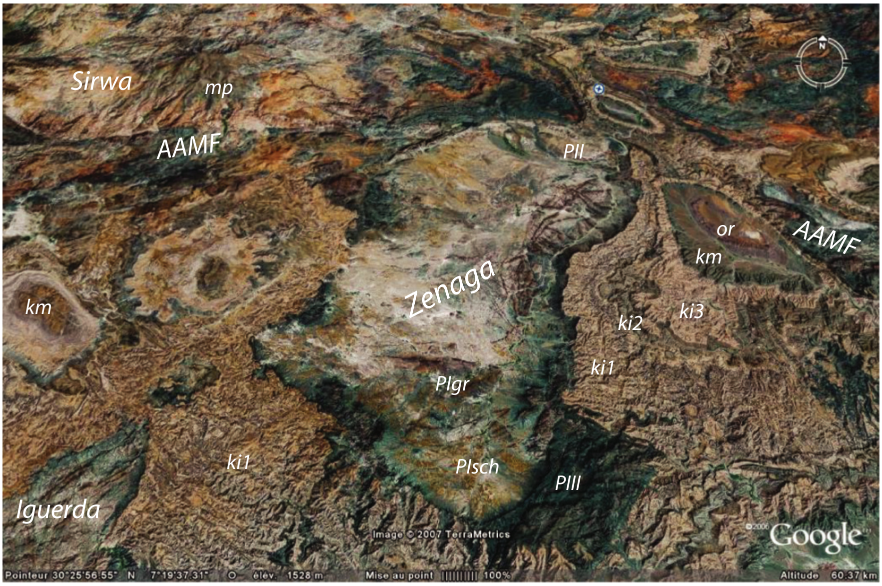


Fig. 2.2 Central Anti-Atlas from space: Google Earth oblique view of the Zenaga-Sirwa area (see Fig. 2.1 for location). The scene is about 70 km wide. Note the shallow elevation of the Zenaga and Iguerda "boutonnières" with respect to their Early Cambrian carbonate blanket (ki1: Adoudounian; ki2: Lie-de-vin Fm; ki3: Calcaires supérieurs). The Zenaga inlier (see map Fig. 2.5) exposes poorly resistant Paleoproterozoic schists and granites (PIsch, PIgr), early Neoproterozoic quartzites and limestones (PII), unconformably overlain by late Neoproterozoic volcanics (PIII). The Sirwa (Siroua) inlier is higher, with the Sirwa Miocene-Pliocene volcano (mp) culminating at 3300 m above sea level. The Anti-Atlas Major Fault (AAMF) marks the southern boundary of the thrust ophiolite and arc units. On the right margin of the scene, note the 5 km left-lateral throw along the AAMF shown by the two white spots that are the two shifted half of the Bou Azzer quartz diorite pluton intrusive in the ophiolite (see Fig. 2.9 for comparison). Variscan deformation is shown by open Middle Cambrian (km)-Ordovician (or) synclines between the Precambrian antiforms

age of the Neoproterozoic Saghro Group, have been challenged. This move is likely to continue for some time, so the present synthesis must be regarded as provisional.

Two groups of Precambrian inliers can be recognized, respectively south and north of the E-trending "Accident Majeur de l'Anti-Atlas" (AAMF, Anti-Atlas Major Fault; Figs. 2.1, 2.2), each group being characterized by partly contrasting lithostratigraphic columns (Fig. 2.3). In the southwestern group (Bas Draa, Ifni, Kerdous, Igherm, Tagragras of Akka and Tata, Iguerda and Zenaga), a Paleoproterozoic crystalline and metasedimentary basement (formerly labelled "PI") occurs beneath Neoproterozoic shallow water metasediments ("PII") affected by the Pan-African orogeny. The basement units are dated at ~ 2 Ga and correlate with the Eburnian basement of the Reguibat Arch (Reguibat Shield or Rise). The Neoproterozoic orogeny generated abundant granites and rhyolites from 630 to 560 Ma (from "PII" to "PIII"). This southwestern part of the Anti-Atlas basement corresponds to the deformed, autochthonous northern rim of the West African Craton (WAC).

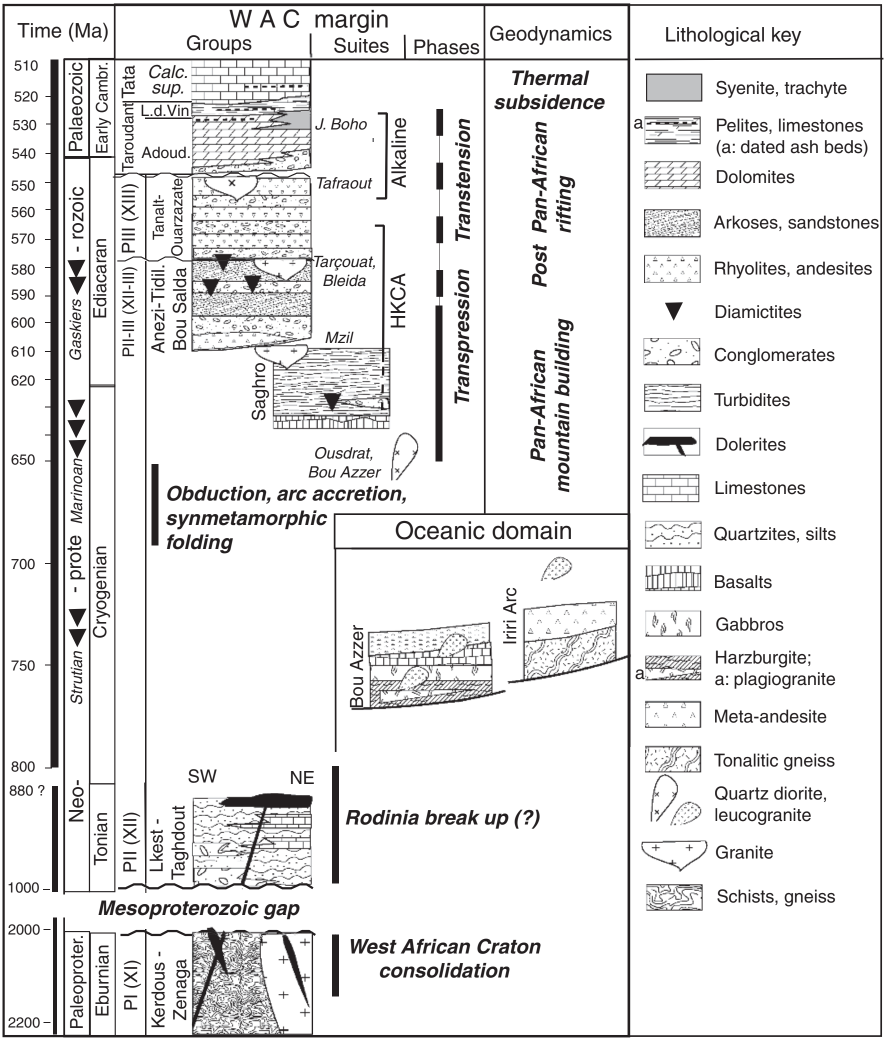


Fig. 2.3 Generalized lithostratigraphic column for the Anti-Atlas Pan-African orogen. "PI" = "XI", etc. are the classical stratigraphic symbols used on Anti-Atlas geological maps. HKCA: High-K calc-alkaline (granitoids). After Thomas et al. (2004), modified after Gasquet et al. (2005) and Liégeois et al. (2006), and redrawn

In contrast, Eburnian exposures are lacking in the northeastern group of Precambrian inliers, north of the AAMF (J. Siroua, Ouzellarh, J. Saghro, Ougnat). These "boutonnières" no longer display Neoproterozoic platform metasediments, but comprise only oceanic or island arc lithologies below the Pan-African late orogenic formations. This has been considered, and is still considered by some, as the evidence of an ophiolitic suture zone between the WAC and a northern Neoproterozoic continent or island arc, mainly 760–700 Ma in age, represented in the north by the Saghro volcano-sedimentary Group (formerly labelled "PII") and by the granitoids intrusive into this group. The suture was classically localized in the Bou Azzer-El Graara boutonnière that straddles the AAMF and exposes both ophiolite/arc remnants and supposedly Eburnian orthogneiss units to the north and south of the AAMF, respectively. However, new data have undermined this model: (1) the Saghro granitoids are now precisely dated between 615 and 560 Ma and they are not related to an island arc; their Sr-Nd isotope signatures require an Eburnian basement at depth; likewise, Eburnian xenolithic zircons do occur in the Ougnat rhyolites at Bou Maadine; (2) the detrital zircons within the Saghro Group are coming from the WAC, from the Bou Azzer oceanic complex and from young magmatic bodies between 630 and 612 Ma; (3) the Pan-African magmatic activity on both sides of the AAMF is very similar; (4) the Bou Azzer oceanic complex, precisely dated between 760 and 700 Ma has been overthrust on the WAC at about c. 665 Ma; (5) part if not all of the allegedly Eburnian orthogneisses of the Bou Azzer inlier are Neoproterozoic plutons formed at the expense of a juvenile crust at about 750–700 Ma, and thus are allochthonous as the ophiolite itself (D'Lemos et al., 2006); (6) during the Phanerozoic, the main rheological contrast lies along the SAF and not along the AAMF.

This indicates that the 760–700 Ma rocks are restricted to the allochthonous Bou Azzer/Siroua strip, which underlines the AAMF. The AAMF is bounding to the north the last Eburnian outcrops of the WAC in the Zenaga inlier, but the Eburnian crust continues at depth up to the SAF. Actually, the Pan-African evolution of the Anti-Atlas corresponds to the partial although major destabilization of the northern boundary of the WAC (the "rajeunissement monstrueux" of Choubert & Faure-Muret, 1983), i.e. its metacratonic evolution. The more classical Pan-African belt occurs mostly in the Peri-Gondwanan (or Avalonian) terranes that drifted away during the Phanerozoic.

Similarly, the Pan-African rocks of the Adrar Souttouf include high-grade metabasites and serpentinites (meta-ophiolites) as well as schists and granites in continental units, thrust together upon the Reguibat shield and its Ordovician-Devonian cover (see Chap. 3). An eclogite outcrop south of the Morocco-Mauritania border yielded a U-Pb age of 595 Ma on individual zircon grains, interpreted as the protolith age, whereas garnets from the same rock yielded a Sm-Nd age at 330 Ma (Variscan metamorphism). K-Ar dates from central Adrar Souttouf units are scattered between 1800 and 262 Ma, consistent with a polyphase Paleoproterozoic-Paleozoic evolution. In the following sections, only the Anti-Atlas Precambrian inliers are considered.

2.2 The Paleoproterozoic Basement

References: Structural, geochemical and geochronological data on the Anti-Atlas Paleoproterozoic rocks can be found in Hassenforder (1985, 1987), Aït Malek et al. (1998), Mortaji et al. (2000), Ennih et al. (2001), Ennih & Liégeois (2001, 2008), Benziane et al. (2002), Walsh et al. (2002), Gasquet et al. (2004), Soulaimani & Piqué (2004), Barbey et al. (2004), Benziane (2007). A review of the Eburnian-Transamazonian belt was published by Bertrand & Jardim de Sá (1990). Other references concerning this belt in the Reguibat Shield are given in Chap. 1.

The basement units of the Anti-Atlas Precambrian massifs south of the AAMF include both metamorphic and magmatic rocks, referred to as "PI" or "XI" on geological maps. The metamorphic rocks range from low-grade phyllites and greenschists ("Bas Draa" and "Had n'Tahala Groups") to amphibolite facies schists and migmatites ("Zenaga Group"). The dominant trend of the Eburnian foliation is ESE, before further deformation, which is consistent with the SE structural trends in the eastern Reguibat Arch (Yetti, Eglab). In the Tagragra of Tata, the schist series contain felsic metatuffs that yielded a zircon age of 2072 ± 8 Ma. However, the Zenaga Group is possibly as old as c. 2170 Ma, based on U-Pb SHRIMP dates from relic zircon cores from intruding granites. The occurrence of Archaean relics (former "P0") is not yet established by reliable dating.

The metamorphic rocks are intruded by syn-tectonic to post-tectonic dolerites and granitoids. Several granitoids exposed in the Bas Draa, Kerdous (Tahala granite), Tagragras of Tata and Akka (Fig. 2.4), and Igherm inliers yielded dates of c. 2000–2050 Ma (U-Pb zircon), strongly contrasting with the age of the late Pan-African plutons of the same inliers, i.e. 580–560 Ma. A similar, Paleoproterozoic age (c. 2030 Ma, U-Pb zircon) was obtained for the Azguemerzi peraluminous granodiorite and Tazenakht porphyritic monzogranite, which intrude the Zenaga micaschists and migmatized paragneisses (Fig. 2.5).

More precisely, two plutonic events have been recognized in the Paleoproterozoic basement of the western Anti-Atlas: the first consists of a calc-alkaline suite of diorites, monzogabbros-diorites, granodiorites and granites reflecting a lower crustal or mantle origin with variable contamination by crustal material; the second corresponds to peraluminous granodiorites, granites and leucogranites originating from a crustal source. The siliciclastic nature of the host schist protoliths implies the

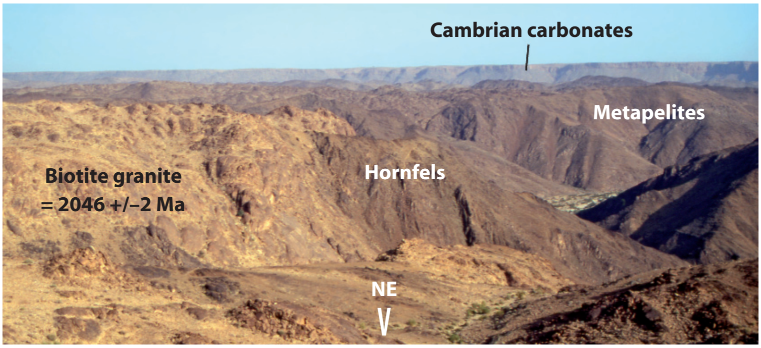


Fig. 2.4 Paleoproterozoic basement of the Tagragra of Akka (southeastern part) surrounded by the Adoudounian (Latest Ediacaran-Early Cambrian) cliffs in the background (NE). Note the importance of recent uplift and correlative deep incision of the Mesozoic peneplain, now elevated at c. 1400 m a.s.l. in the area. Photograph by D.G.

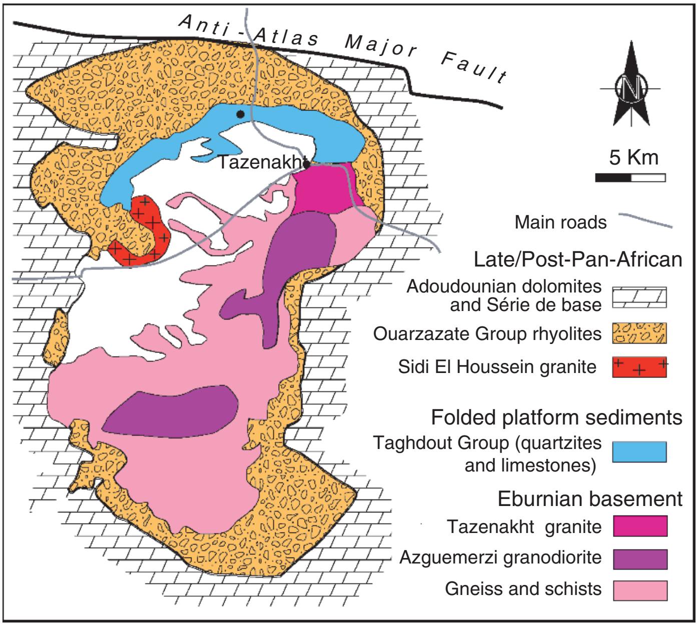


Fig. 2.5 Schematic geological map of the Zenaga boutonnière (compare with Fig. 2.2). The Azguemerzi pluton is a peraluminous granodiorite-monzogranite; the Tazenakht pluton is a porphyritic monzo-syenogranite; both are dated at c. 2030 Ma. The country-rocks are amphibolite facies schists and gneisses. The Pan-African greenschist facies deformation developed under N–S directed stress, which formed tight folds in the Neoproterozoic Quartzites and Limestones (Taghdout Group), and caused mylonitization of the northern part of the Tazenakht pluton with sinistral strike-slip. The Sidi el Hussein ring-dyke granite ("PIII") is dated at 579 ± 7 Ma. After Ennih & Liégeois (2001), redrawn

existence of a neighbouring older domain of probable Archaean age. A few detrital Archaean zircons have been found in the Saghro Group, corroborating this model. Contribution of both juvenile (granites) and recycled (metasediments) Archaean material suggests that, during the Paleoproterozoic, the Anti-Atlas was a zone of accretion close to an Archaean nucleus comparable to that known in the southwestern Reguibat Arch. The geodynamic setting of the Anti-Atlas (WAC) Eburnian belt is reminiscent of the Archean-type granite-greenstone belt associations. By contrast, 2 Ga high-grade gneisses, nappes and syntectonic granites are mostly known as reworked terranes within the Pan-African (-Braziliano) mobile belt, suggesting that the location of the latter belt was controlled by the major structures inherited from the Early Proterozoic (Bertrand & de Sá, 1990).

Numerous mafic (gabbros, dolerites) and felsic (microgranites) dykes crosscut the Paleoproterozoic basement of the western Anti-Atlas. Most can be assigned to the Neoproterozoic rifting of the Paleoproterozoic craton (see next section), but a dolerite dyke from the Tagragra of Tata yielded a SHRIMP age at 2041 ± 6 Ma (Walsh et al., 2002; Benziane et al., 2002). A microgranite from the Kerdous inlier (Fig. 2.6), and pegmatites from the Kerdous and Tagragra of Akka inliers have been

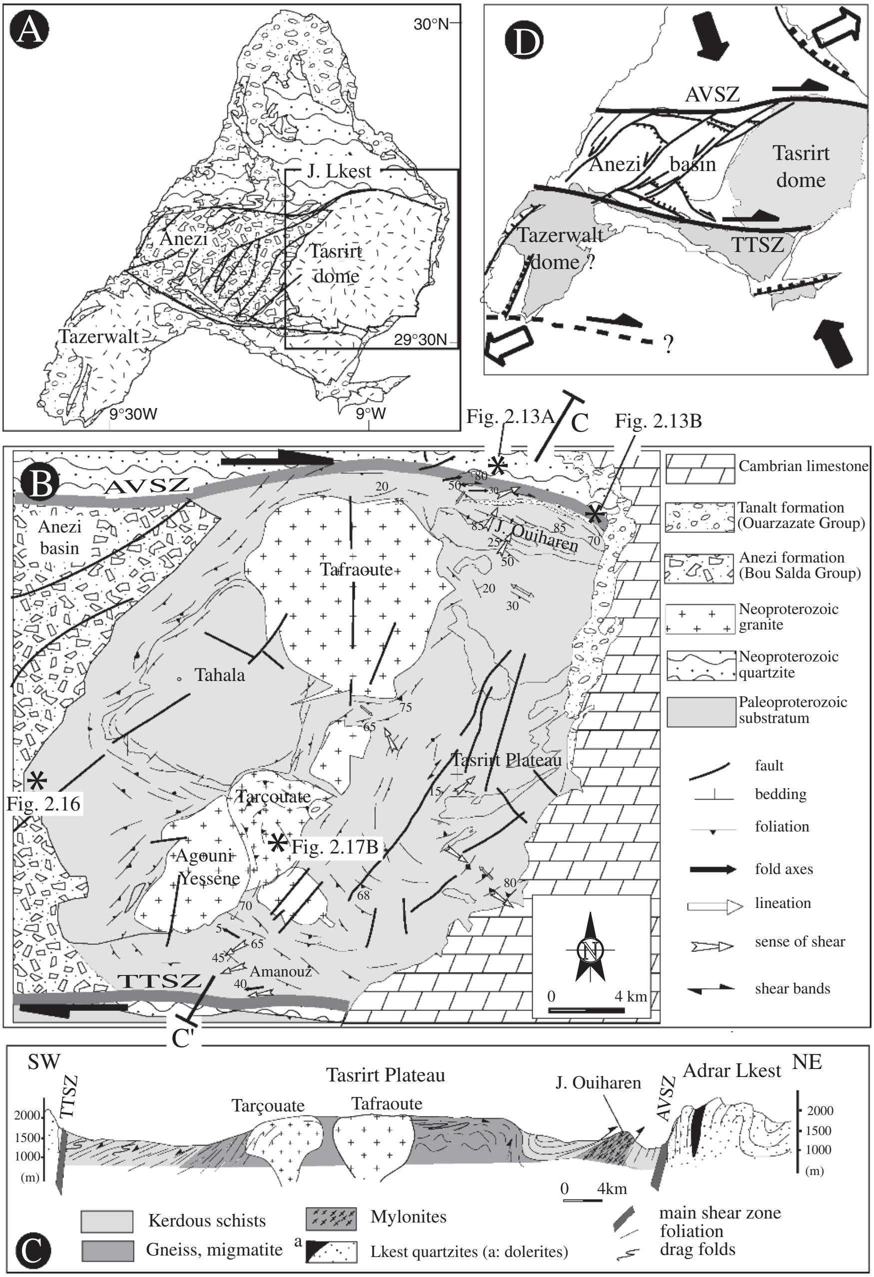


Fig. 2.6 Pan-African structure of eastern Kerdous inlier. (**A**): Schematic map of the inlier (see Fig. 2.1 for location). – (**B**): Structural map of the southeast J. Lkest-Tasrirt Plateau area. – (**C**): Cross-section (trace CC′ in map (**B**)). – (**D**): Interpretation of the regional stress orientation by the end of the synmetamorphic greenschist facies compression. AVSZ, TTSZ: Ameln Valley and Tighmi-Tifermit Shear Zones. Age of granite intrusions as follows: Tahala, 2044 ± 2 Ma (Barbey et al., 2004); Tarçouate, 581 ± 11 Ma Aït Malek et al. (1998); Tafraoute and Agouni Yessen, 549 ± 6 Ma (Pons et al., 2006)

dated at c. 1760 Ma (zircon, monazite and muscovite ages; Gasquet et al., 2005). The latter dykes are linked to a late Paleoproterozoic (Statherian) magmatic event otherwise unidentified in the Anti-Atlas.

Pan-African greenschist-facies retrogression and mylonitization obviously affect the Paleoproterozoic granites and their country-rocks together with their overlying Neoproterozoic cover, although with no significant lithospheric thickening. The Neoproterozoic Taghdout passive margin sediments are still well preserved including sedimentary features such as ripple marks or mud cracks (Fig. 2.7A, B). This Pan-African event has no resolvable imprint on the isotopic system of the zircons but has been able to affect the Sm-Nd isotopic ratios of a part of the Eburnian rocks: this is related to the abundant fluid movements that occurred during the emplacement of the huge Ouarzazate volcanic Supergroup. The exhumation of the Paleoproterozoic units during the Pan-African orogeny can be ascribed either to the dominantly left-lateral transpressive tectonics that occurred between 630 and 580 Ma or to the subsequent transtensional tectonics (580–550 Ma), or else to both these superimposed phenomena. A good example of a Paleoproterozoic dome uplifted at the same level as the folded Taghdout metasediments is found in the Kerdous massif (Tasrirt dome, Fig. 2.6). The dome is bounded north and south by two major dextral shear zones, which operated under greenschist followed by cataclastic conditions. Both shear zones are sealed by the Ouarzazate conglomerates (Tanalt Fm). The Tasrirt dome has been interpreted by one of us (A.S.) as a Late Neoproterozoic diapiric gneiss dome emplaced in a NE-SW pull-apart system.

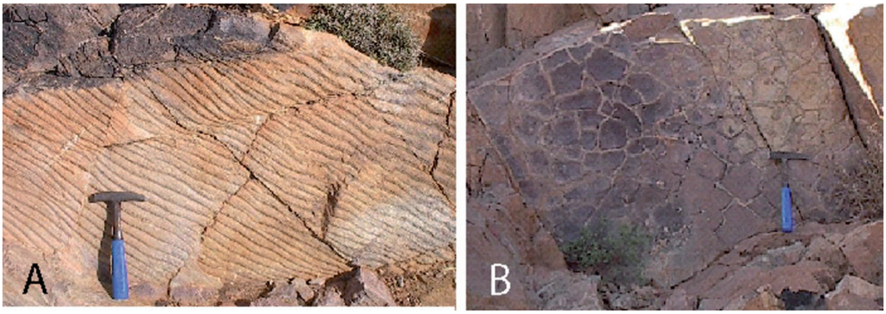


Fig. 2.7 Sedimentological features from the Taghdout Group, Zenaga boutonnière. – **A**: Ripple marks on top of a quartzite layer. – **B**: Mud cracks in argillite interleaved in a sequence of stromatolitic-thrombolitic limestones. Photographs by N.E.

2.3 The Early Neoproterozoic Platform Margin

References: The early Neoproterozoic cover of the WAC margin and the associated basic sills and dykes are described in Choubert (1963), Clauer (1976), Moussine-Pouchkine & Bertrand-Sarfati (1978), Benziane & Yazidi (1982), Hassenforder

(1987), Ikenne et al. (1997), De Beer et al. (2000), El Aouli et al. (2001), Ennih et al. (2001), Benziane et al. (2002), Thomas et al. (2002), Bouougri & Saquaque (2004), Deynoux et al. (2006), with references therein. About the concept of supercontinent Rodinia, see Dalziel (1997), Weil et al. (1998), Cordani et al. (2003). The Proterozoic glaciations have been reviewed by Ramstein et al. (2004).

Considering the recent data that place the Saghro Group in the 630–610 age range (see Sect. 1.3.2), only a single (meta) sedimentary group can be considered now as pre-Pan-African, which is labelled the “Taghdout Group” in the Zenaga inlier and “Lkest Group” in the Kerdous massif (see also “Tizi n’Tarhatine Group”). Both these equivalent groups include thick, layered quartzites with conspicuous sedimentary structures (ripple marks, mud cracks, bioturbations, etc.), stromatolitic carbonates and sandy-pelitic beds (Fig. 2.7A, B). A progressive change of the sedimentary facies is observed from SW to NE: conglomerates and sandstones dominate in the Bas Draa and Ifni inliers, quartzites and pelites in the Kerdous and Igherm inliers, and quartzites, limestones and pelites in the Tata, Zenaga and Bou Azzer inliers, closer to the AAMF. These shallow water formations represent a cover sequence with respect to the Paleoproterozoic basement, although their common contact is generally faulted. The major unconformity on top of the Eburnian schists is locally well-preserved (Taghdout, Tizi n’Tarhatine; Fig. 2.8). The detrital zircons from the quartzites above the Tagragra of Tata schists yielded consistent U-Pb SHRIMP dates between 1990–2080 Ma (Benziane, 2007).

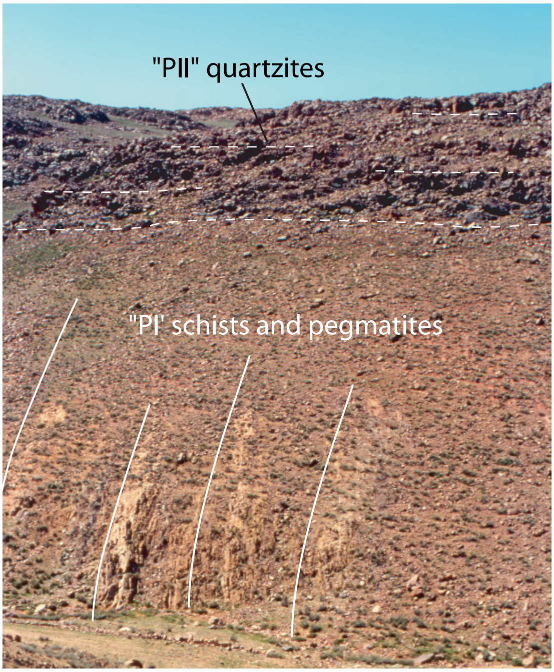


Fig. 2.8 The Tizi n’Tarhatine unconformity between Eburnian schists (“PI”) intruded by c. 2 Ga old pegmatites and Neoproterozoic conglomeratic quartzites (“PII”, Taghdout-Lkest Group). The first published photograph from the area was by L. Neltner in 1938, as evidence of the “Algonkian” unconformity over allegedly “Archean” terranes. However, G. Choubert observed that the unconformity also corresponds to a décollement level related to tight, dysharmonic Pan-African folds (cited in Michard, 1976, pp. 47 and 56). Photo by D.G.

The Taghdout Group sediments are intruded by abundant dykes and sills of dolerites and gabbros (e.g. J. Lkest, Fig. 2.6C), also found as dyke swarms in the Paleoproterozoic basement (e.g. Igherm, Tagragra of Akka, Kerdous, Zenaga). These rocks (Ifzwane Suite; Thomas et al., 2004) are broadly akin to continental tholeites, although with strong chemical heterogeneity, and could be associated with the increasing rifting of the WAC margin. They are not directly dated.

The depositional age of the Taghdout Group itself is not well constrained. The presence of stromatolites (Choubert, 1963) points to a Neoproterozoic age, i.e. younger than 1000 Ma. Location of the Taghdout Group below the Bou Azzer oceanic complex indicates an age older than 660 Ma, which is the age of obduction. An age of 788 ± 9 Ma (Clauer, 1976) obtained by Rb-Sr on clay fractions from Taghdout metasediments gives a minimum age for the deposition of the Group. However, detrital 880 Ma old zircons from the Saghro Group (Liégeois et al., 2006) suggest a still older minimum age as these zircons can be attributed to the magmatic event associated to the Ifzwane Suite intrusive in the Taghdout Quartzites and Limestones. If correct, the Taghdout shallow water sediments would have accumulated from about 1000 Ma to > 880 Ma, in a proximal passive margin environment upon the northern border of the WAC.

The correlations at the craton scale favourably support the latter proposal. The Taghdout sediments compare with the Char and Atar Groups, which can be traced all along the south border of the Reguibat Arch/north border of the Taoudenni Basin (Atar, Richat, and Hank areas; see Fig. 1.11 for location). These groups form a c. 1000 m thick succession beginning with siliciclastic deposits that range from fluvial to wave- or tide-dominated sediments (Char Group), and passing upward to sandy, stromatolite–bearing carbonate shale sequences (Atar Group; see Deynoux et al., 2006). A clay fraction from the Char Group yielded a Rb-Sr age at 998 ± 32 Ma, whereas Rb-Sr and K-Ar dating of clay fractions from the Atar Group yielded ages between 890 ± 35 and 775 ± 52 (Clauer, 1976). Likewise, correlations can be extended up to the Gourma aulacogen (Moussine-Pouchkine & Bertrand-Sarfati, 1978), on the eastern side of the WAC/southeast side of Taoudenni Basin. Everywhere on the WAC, the dominantly Early Neoproterozoic (Tonian, 1000–850 Ma) platform sedimentation can be related to the break-up of the hypothetical supercontinent Rodinia, as proposed for the Gourma aulacogen. Remarkably, this sedimentation occurred after nearly 1 Ga of quiescence in the West African craton (no event is recorded between 1.7 Ga and the sedimentary onlap).

2.4 The Ophiolite/Arc Complex and its Accretion (Pan-African I Phase)

References: The Pan-African oceanic/transitional units from the Bou Azzer, Siroua and Saghro inliers are described by Leblanc (1981), Saquaque et al. (1989), Admou & Juteau (1998), De Beer et al. (2000), Wafik et al. (2001), Thomas et al. (2002), Hefferan et al. (2002), Samson et al. (2004), Fekkak et al. (2003), Beraaouz et al. (2004), D'Lemos et al. (2006), Soulaimani et al. (2006), Bousquet et al. (2008).

2.4.1 The Oceanic Complex (760–700 Ma)

Well-preserved meta-ophiolites ("Bou Azzer Group") are shown in the Bou Azzer (Ait Ahmane; Fig. 2.9) and Siroua (Khzama, Nqob) inliers. They comprise mantle harzburgites, and a crustal sequence typical for fast oceanic ridges, including layered gabbros and sheeted dykes beneath the pillow basalts section (Fig. 2.10). Only rare metasediments associated with volcanic layers are found on top of the oceanic complex (e.g. Ambed Co-bearing calcareous jaspers at Bou Azzer; ketatophyric tuffites and flows upon the Khzama pillow lavas).

The second component of the lost oceanic domain is best defined as the "Iriri island arc" in the Siroua inlier by a metamagmatic association comprising

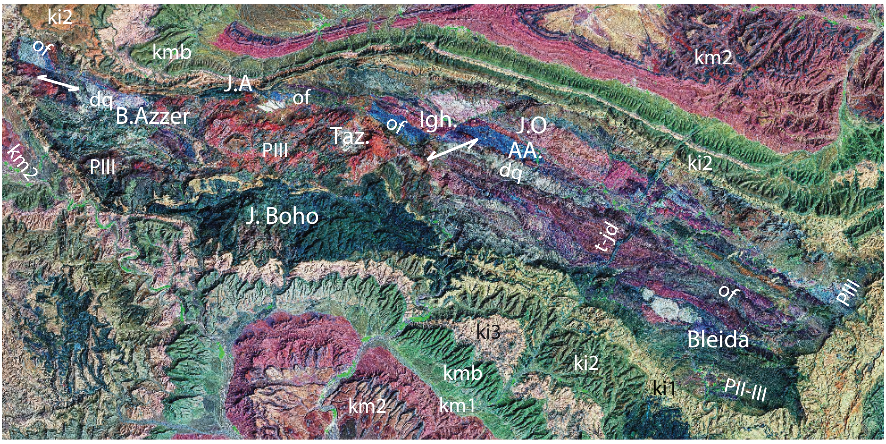


Fig. 2.9 Landsat image of the Bou Azzer-El Graara inlier (see Fig. 2.1 for location). The scene is about 60 × 45 km large. The WNW-ESE stripes of ophiolitic remnants (of), ∼ 750 Ma old, and quartz diorite plutons (dq), c. 650 Ma, mark the trend of the Anti-Atlas Major Fault (AAMF) along the axis of the Precambrian boutonnière. Note the sinistral throw of the quartz diorite pluton on the AAMF axial branch west of the Bou Azzer mining centre. The AAMF and associated (Riedel) faults such as between Igherm (Igh.) and Aït Ahmane (AA) are sealed by the Ouarzazate Group (PIII) volcanics (c. 570–560 Ma) and overlying Lower Cambrian carbonates (ki1). J. Ousdrat (J.O.) is a syn-accretion quartz diorite similar to the Bou Azzer one. In contrast, the 580 Ma old Bleida granodiorite cross-cuts the regional fabric; it would even postdates the Tiddiline series (PII–III) deformation (arcuate north-dipping layers south of Bleida). In the Cambrian blanket, the J. Boho alkaline volcanics are clearly intercalated in the Adoudounian carbonates (ki1). The J. Aghbar (J.A.) is a coeval (530 Ma) syenite sill. Note the mild Variscan deformation of the Paleozoic sequence (ki2: Lie-de-vin series; ki3: Calcaires supérieurs; kmb: Grès terminaux, earliest Middle Cambrian; km1: Schistes à Paradoxides; km2: Grès du Tabanit, late Middle Cambrian). The 200 Ma old Foum Zguid dolerite mega-dyke (t-jd) cross-cuts the Variscan belt and the Precambrian basement with few post-emplacement faulting

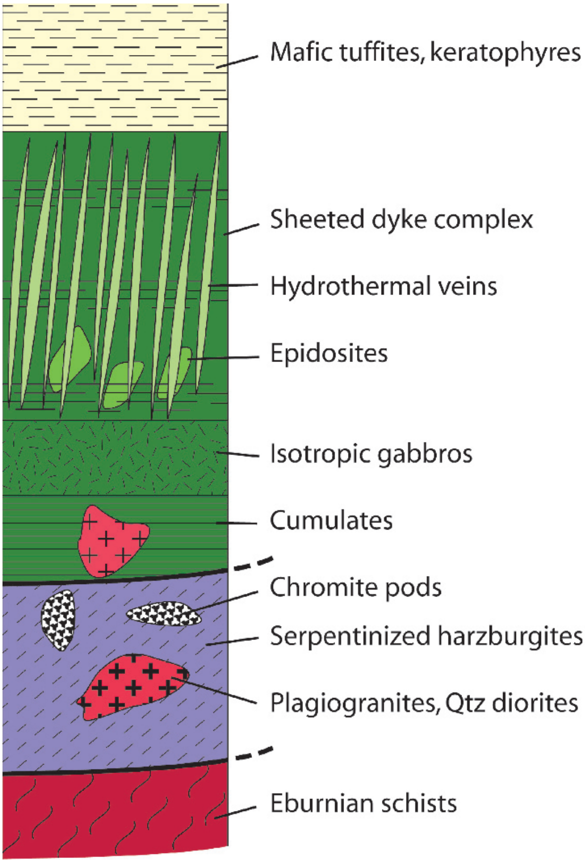


Fig. 2.10 Restored stratigraphic column of the Khzama ophiolite, Siroua massif, after Wafik et al. (2001), redrawn. At regional scale (including Bou Azzer), gabbroic rocks are c. 760–750 Ma old, whereas the juvenile leucogranites and quartz diorites (schematically shown) emplaced at 750–700 Ma and 650–640 Ma, respectively (Thomas et al., 2002, 2004)

medium-grade biotite-rich (andesitic) schists and layered tonalitic orthogneisses (Fig. 2.11). The arc units also include the Ourika complex from the Ouzellarh block.

A main island arc episode occurred in the 760–740 Ma period: an ophiolitic basalt from the Siroua massif was dated by Sm-Nd at c. 740 Ma, two tholeiitic plagiogranites from the ophiolitic sequence of the same massif yielded U-Pb dates of 761 ± 2 Ma and 762 ± 2 Ma; in Bou Azzer the Tazigzaout augen gneiss (previously regarded as Eburnian) yielded an age of 753 ± 2 Ma, and a metagabbro an age of 752 ± 2 Ma; the protolith of the Iriri migmatites has been dated as 743 ± 14 Ma. A second phase occurred at c. 700 Ma with the intrusion of juvenile leucogranites post-dating the deformation of the earlier plutons. A continuous event (arc building) between 760 and 700 Ma is possible.

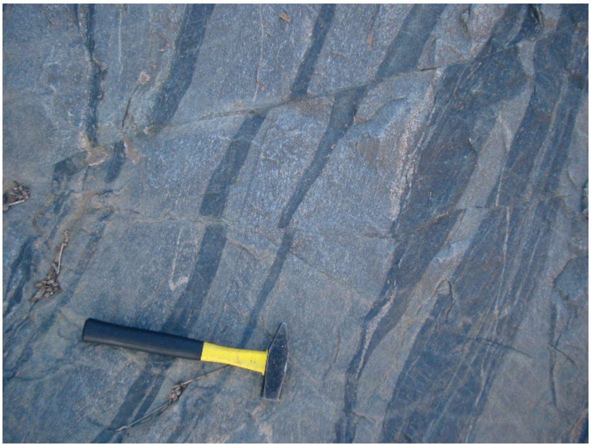


Fig. 2.11 Tonalitic migmatite including foliated metabasic intrusions. Iriri arc, Siroua inlier (*vertical* view). Photo JP.L. The protolith of the Iriri migmatites is dated at 743 ± 14 Ma (Thomas et al., 2004)

The Bou Azzer – Siroua oceanic complex is known only as a discontinuous strip along the AAMF and represents nearly all the Neoproterozoic juvenile magmatic rocks known in the Anti-Atlas. The younger magmatism always comprises an important contribution from the old WAC lithosphere, except in the first basaltic events from the Saghro Group. Nowhere has been found typical high-pressure mineral associations and the alleged blueschist facies mineral associations correspond only to crossite/Mg-riebeckite-bearing HP-greenschist conditions (5–6 kbar, 500–550 °C; Bousquet et al., 2008). The ophiolites and arc units emplaced as south-vergent thrusts (obduction) above a basal mélange onto the WAC passive margin, which means that the root of the oceanic suture has to be located somewhere north of the SAF, not along the AAMF itself. This is supported by the magnetic modelling of the Bou Azzer ophiolitic suture (Fig. 2.12), which suggests the occurrence of a shallow, north-dipping subduction zone up to the High Atlas region.

2.4.2 The Pan-African I Syn-Metamorphic Phase (660–640 Ma)

The accretion of the oceanic complex towards the WAC probably occurred at 663 ± 13 Ma, the age of the zircon rims in the Iriri migmatites. Greenschist facies metamorphism and coeval folding affected the platform beneath the obducted terranes and in front of them. Subsequently, juvenile quartz diorites intruded at 652 ± 2 Ma and 640 ± 2 Ma in the Bou Azzer inlier (e.g. Ousdrat pluton), the significance of which is not well understood (slab breakoff? See last section). These intrusions give an accurate upper limit for the age of the accretion phase.

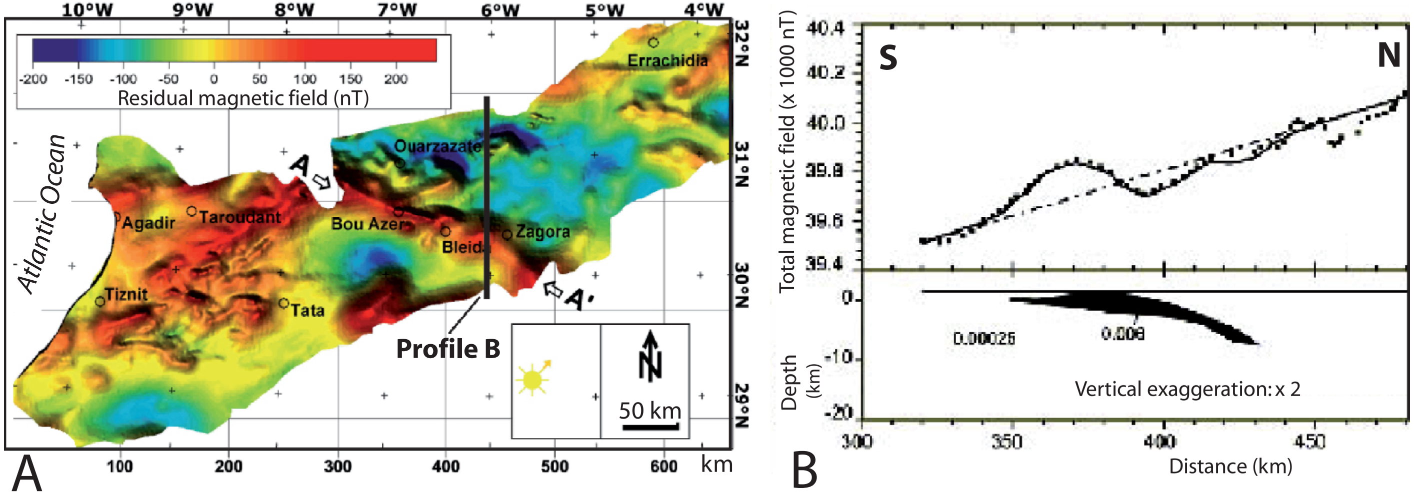


Fig. 2.12 Magnetic modelling of the Bou Azzer-El Graara ophiolite. (**A**): Map of the residual magnetic field of the Anti-Atlas. (1): shading direction; A–A′ arrows: location of the Central Anti-Atlas negative anomaly. – (**B**): Magnetic modelling along profile 40 east of Bleida (for location, see map (**A**)). The major negative anomaly A–A′ coincide with the ophiolite outcrops along the AAMF (compare with Fig. 2.1). Taking into account the latitude and the lack of remnant magnetization, this indicates a north-dipping ophiolitic body, as quantitatively modelled in (**B**). After Soulaimani et al. (2006)

The deformation of the Taghdout Group sediments south of the AAMF is likely coeval with this "Pan-African I phase". Shortening was associated with widespread décollement from the underlying Eburnian basement. Greenschist facies mineral assemblages, locally with chloritoid and andalusite occurrencies (J. Lkest) are typical for this event. Folding developed in relation with compression or transpression under N–S to NW–SE oriented maximum stress. In the Kerdous massif (Fig. 2.6), north of the Ameln Valley Shear Zone, the J. Lkest range shows WNW-trending fold axes that roughly parallel the mylonitic corridor (Fig. 2.13A). The Tasrirt-Ouiharen basement south of the shear zone tends to overthrust the Lkest cover unit, and displays superimposed Eburnian and Pan-African microstructures. The horizontal shear component is right-lateral in that case, whereas it is mainly left-lateral along the AAMF at Bou Azzer (Fig. 2.9), although dextral ductile shear was also described in part of the latter inlier (Tazigzaout). The Anezi ("PII-III") and Tanalt-Ouarzazate conglomerates ("PIII") unconformably overlie the folded platform units after deep erosion (Fig. 2.13B).

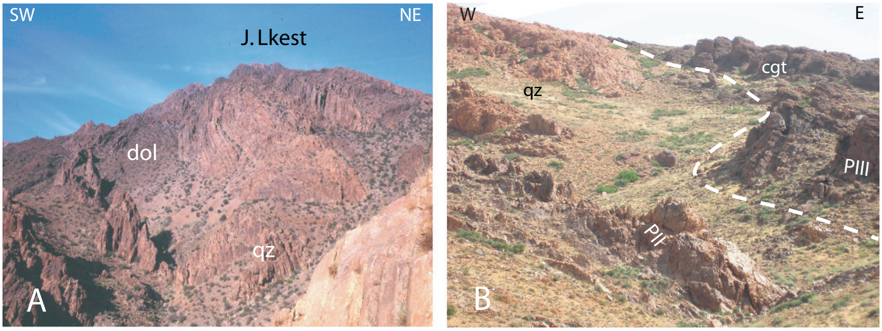


Fig. 2.13 The J. Lkest Pan-African fold range (**A**) and its unconformable late Neoproterozoic cover (**B**), north and east of the Ameln Valley Shear Zone (see Fig. 2.6 for location). (**A**): The elevated Lkest range consists of Neoproterozoic quartzites (qz) and intrusive dolerites (dol) tightly folded together. – (**B**): The slightly tilted Late Ediacaran conglomerates of the Tanalt Group (PIII, cgt) unconformably overlie the nearly vertical Lkest quartzites at the northeast border of the massif

2.5 The Pan-African II Metacratonic "Phase" and Coeval Formations (630–550 Ma)

References: The earliest sedimentary formations (Saghro Group) from this period have been described, and considered as distal equivalent of the platform formations in the following papers: Fekkak et al. (1999, 2001, 2003), De Beer et al. (2000), Thomas et al. (2002, 2004). The relatively young age of these formations and their geodynamic setting are established by Errami et al. (2006), Liégeois et al. (2006).

The more recent, late orogenic to post-orogenic formations, i.e. Bou Salda and equivalents (Anezi, Tiddiline?) and Ouarzazate Groups, and the associated magmatic suites and geodynamics are described in Hassenforder (1987), Lécolle et al. (1991), Benziane & Yazidi (1992), Mokhtari et al. (1995), Aït Malek et al. (1998), De Beer et al. (2000), Errami (2001), Thomas et al. (2002, 2004), Lécolle et al. (2003), Inglis et al. (2004), Levresse et al. (2004), Gasquet et al. (2005), Benziane (2007), with references therein. The importance of extension during the last period (Neoproterozoic-Cambrian boundary) is emphasized by Soulaimani et al. (2003, 2004), Soulaimani & Piqué (2004) and Gasquet et al. (2005).

Late Proterozoic glaciations in the Saharan and Oman areas are discussed in Deynoux et al. (2006) and Le Guerroué et al. (2005), respectively. See also the general review by Ramstein et al. (2004).

Most Anti-Atlas ore deposits are related to the late Neoproterozoic magmatic events and coeval extensional tectonics. Recent metallogenic data can be found in Ouguir et al. (1994), Mouttaqi (1997), Cheilletz et al. (2002), Barakat et al. (2002), Abia et al. (2003), Levresse et al. (2004), Benchekroun & Jettane (2004), Gasquet et al. (2005), Marcoux & Wadjinny (2005).

Three volcano-sedimentary groups occurred during that long lasting period: the Saghro Group (630–610 Ma), the Bou Salda Group (610–580 Ma) and the Ouarzazate Group (580–545 Ma). The earliest group (Saghro Group) still suffered low grade greenschist facies deformation; the Bou Salda Group show significant brittle deformations, whereas the youngest group (Ouarzazate Group) is clearly transitional with the post-orogenic formations.

2.5.1 The Saghro Group and the Greenschist Facies Transpressive Event

The sedimentary-volcanoclastic sequence of the Saghro Group (Sidi Flah, Kelaat Mgouna, Boumalne, Imiter subgroups) corresponds to a great thickness (up to 6000 m) of siliciclastic turbidites, grading upward from shales, siltstones and sandstones at the bottom to coarser deposits on top, with rare limestone layers (Fig. 2.14A). It is worth noting that one of the lowermost turbidite formations contains several diamictite horizons. These deposits alternated with basaltic flows (locally with pillow structures; Fig. 2.14B) having the chemical signatures of rift tholeites and alkaline intraplate basalts, and with volcanoclastic keratophyres and tuffites layers. Small (20–50 m) ultramafic lenses occasionally occur, associated with hydrothermal jaspers and ophicalcites.

Classically, this group was supposed to be a distal equivalent of the “PII” Taghdout Group. However, a comprehensive U-Pb dating (laser ICP-MS) of detrital zircon from the Saghro Group has recently been realized (Liégeois et al., 2006): four samples were dated from the bottom to the top of the Kelaat Mgouna subgroup (Fig. 2.15). The number of Neoproterozoic zircons increases from the bottom (10%) to the top (67%), the rest being Eburnian zircons from the WAC; moreover the

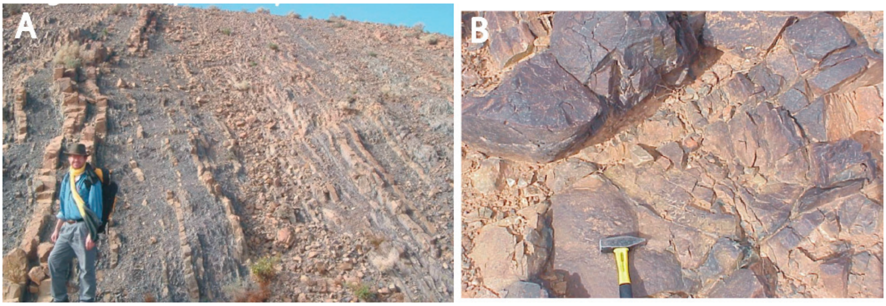


Fig. 2.14 Typical outcrops from the Saghro Group. (**A**): Steeply dipping turbiditic layers, folded under lower greenschist facies condition about 600 My ago. – (**B**): Pillow lavas near the bottom of the turbiditic sequence, recording the early rifting of the metacratonic margin (TDM Nd model ages between 640 and 580 Ma). Photos JP.L.

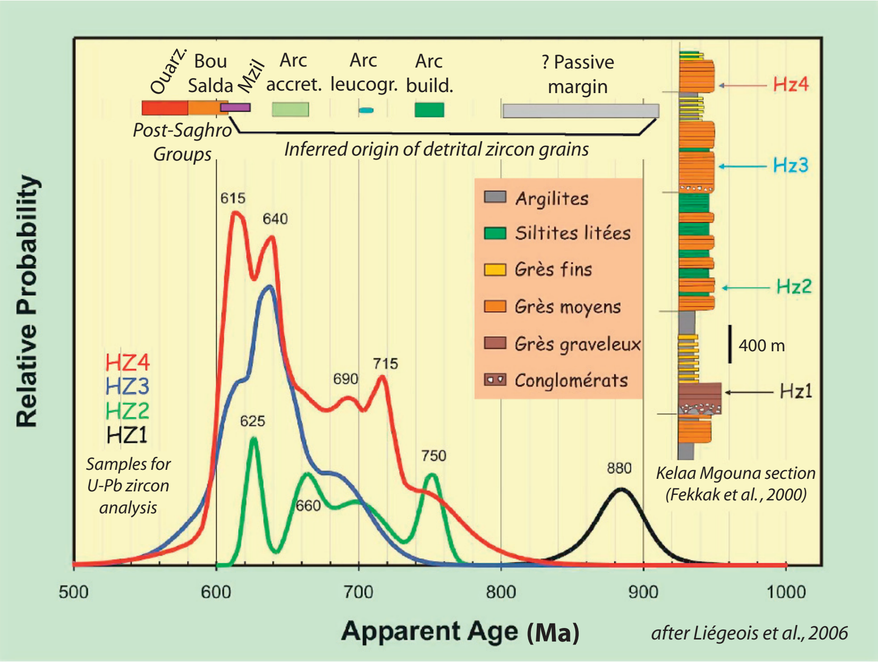


Fig. 2.15 Dating the Saghro turbidites through their detrital zircons (Liégeois et al., 2006). Four samples (HZ1–4) were acquired from bottom to top of the Kelaa Mgouna section (*right*). The dates show that there is a mixing of Paleoproterozoic (2000–2050 Ma) and Neoproterozoic zircons, with a progressive increase of the proportion of Neoproterozoic zircons from the base (10%) to the top (67%). The Neoproterozoic zircon ages correspond to different events known in the Anti-Atlas: (1) the Ifzwane doleritic suite (c. 880 Ma) from the WAC passive margin; (2) the ophiolitic sequence (750, 700 and 660 Ma) and (3) younger intrusions in the ophiolite/arc units and the Saghro Group itself with ages between 630 and 612 Ma (e.g. Mzil granite, c. 614 Ma). The increasing abundance and the younging of the Neoproterozoic zircons indicate that the deposition of the Saghro group occurred during the onset and growing of an Ediacaran volcanism (626–612 Ma) that evolved toward the volcanism of the Bou Salda Group (which overlie the Saghro Group), finally resulting in the huge volume of volcanic rocks and granitoids belonging to the Ouarzazate Group (580–550 Ma)

youngest zircon become younger towards the top of the series (from 626 Ma to 612 Ma). This shows that the Saghro Group was deposited between 630 and 610 Ma during the uplift of the WAC and the beginning of the Pan-African magmatism that culminated during the next Ouarzazate period. The Mzil granite (614 ± 10 Ma) could be a syn-Saghro intrusion, although the age bracket allows this granite also to be contemporaneous with the Bou Salda Group. The pillow basalts present in the Saghro Group have a mean Nd depleted mantle model age (TDM) of 650 ± 30 Ma, indicating a mantle origin without old crust contribution. The diamictite levels from the lower flysch-like formations of the Saghro Group should thus be correlated with the Marinoan ice age (650–630 Ma, late Cryogenian-earliest Ediacaran) widely observed in West Africa and Oman.

The tectonic deformation in the Saghro Group is dominantly shown by SSW- to SE-vergent folds; the metamorphism is low (greenschist facies). Detail tectonic studies are lacking, but in the present state of knowledge, a transpressive system along the northern margin of the WAC can be proposed as it has been demonstrated for the subsequent Bou Salda Group: this can account for the uplift of the WAC, the turbiditic nature of the Saghro group made at the base mainly of detritus from the WAC, and the progressive appearance of the magmatism without any crustal thickening allowing, for instance, the preservation of the Taghdout Group.

2.5.2 The Bou Salda Group and Equivalents

The Bou Salda Group of the Siroua massif rapidly follows the Saghro group: the youngest detrital zircon in Saghro is c. 612 Ma (206Pb*/238U, laser ICP-MS, discordance 0–5%) and two rhyolite sills attributed to Bou Salda have been dated by SHRIMP ages at 606 ± 5 Ma and 606 ± 9 Ma (206Pb*/238U ages on slightly discordant zircons). We must note however that these two rhyolites are intrusive in the uppermost part of the Saghro Group. They could thus date the end of the Saghro Group deposition. Anyhow, Bou Salda deposition occurred after the folding of the Saghro Group. This group, for many aspects, is intermediate between the Saghro and Ouarzazate Groups. Its contacts with other lithologies are either tectonic or intrusive; it is preserved in narrow fault-bounded troughs. Its thickness is highly variable from a few tens of metres to more than 3000 m in the AAMF region. Its lower part comprises amygdaloidal basalt with subordinate andesite and rhyolite and its upper part is mainly sedimentary with poorly sorted conglomerates (boulders up to 2 m in diameter), arkoses and sandstones with interbedded greywackes, shales, tuffs, basalts and cherts. The Bou Salda Group was deposited during a dextral transpressive period. It is especially deformed along the AAMF (spaced cleavage in the shales, folding in the sandstones).

This Group exists throughout the Anti-Atlas (former "PII-III"). A typical example is that of the "Série d'Anezi", a 2000 m thick volcanic and alluvial fill preserved in a pull-apart basin within the Kerdous inlier (Fig. 2.16). The "Série d'Anezi"

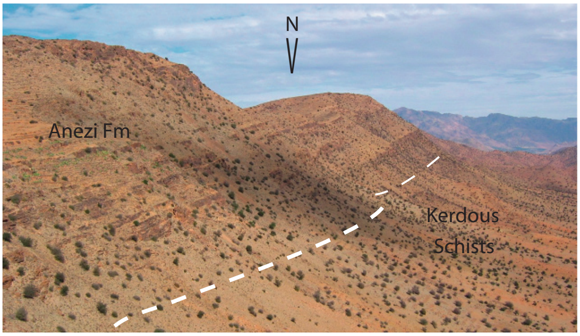


Fig. 2.16 View on the eastern edge of the Anezi basin, central Kerdous massif (see Fig. 2.6 for location). Conglomerates and sandstones of the lowest Anezi member (c. 600 Ma) dip about 30° WNW. They overlie the less resistant, retromorphic Kerdous schists (c. 2 Ga). Acidic tuffites are located at the very base of the Anezi Fm in the foreground (not seen), and rapidly vanish northward

can be subdivided into the basal “Tafraoute Group”, dominated by dacitic-rhyolitic ignimbrites, and the “Anezi Group”, dominated by sandstones and conglomerates. So far, the age of the Anezi sequence is not precisely known. The periglacial features recorded in the Anezi deposits should correlate with the youngest Gondwana glacial events (“Gaskiers”, 590–580 Ma). Most of the basin remained undeformed, except at its margins. Other western Anti-Atlas inliers (Igherm, Aït Abdallah) display proximal diamictite facies with coarse quartzitic breccias and huge quartzite lenses which could originate either from former inselbergs or chaotic collapses.

The Tiddiline series from the Bou Azzer inlier (Fig. 2.9) consists of coarsening upward siltstone-sandstone-conglomerate sequences which contain diamictites interpreted as marine tilloids with dropstones. They could be compared with the Anezi series, but this is controversial because no reliable age is currently available on these series. The fact that the Tiddiline series is more strongly tilted, faulted and folded than Anezi, with local development of axial-plane cleavage can be attributed to its localization along the AAMF, or to an older age, intermediate between that of the Saghro and Bou Salda Groups. The 580 Ma-old (U-Pb zircon) Bleida granodiorite which cross-cuts the regional fabric provides a firm constraint on the latest stage of transpressive brittle movements in the Bou Azzer inlier (Inglis et al., 2004).

The earliest high-K calc-alkaline intrusion is the Mzil granite in the Siroua massif dated at 614 ± 10 Ma. Similar ages have been measured at Ifni from both granite intrusion and trachytic flow. However, most of the high-K calc-alkaline intrusions yield U-Pb ages close to 580 Ma (ex: Amlouggi tonalite, 586 ± 8 Ma; Askaoun granodiorite, 575 ± 8 Ma; Bleida granodiorite, 579 ± 1 Ma), but can be also younger: Imourkhsane granite, 562 ± 5 Ma, Tazoult quartz porphyry, 559 ± 6 Ma, and appear to be coeval with the accumulation of the Ouarzazate Group.

2.5.3 The Ouarzazate Group

The unconformable "Ouarzazate Group" (formely "PIII") represents a volcano-sedimentary sequence highly variable in thickness (from 0 to 2 km near the Ouarzazate town) consisting of coarse volcanic conglomerates (Fig. 2.17A), ignimbritic rhyolites, trachytes, andesites, basaltic trachyandesites, tuffites, and rare interbedded stromatolitic layers and fault scarp breccias.

Various types of intrusions, such as granitoid massifs, necks, dykes or ring dykes emplaced within the early Ouarzazate Group or underlying units. In the Zenaga inlier, the Sidi El Houssein alkaline granite (579 ± 7 Ma) is a typical example of ring-complex intrusion within the Eburnian basement (Fig. 2.5). All the Ouarzazate plutonic and volcanic rocks belong to a high-K calc-alkaline to alkaline magmatic series (Fig. 2.18). Rhyolites from the Ouarzazate Group have been dated at 577 ± 6 and 571 ± 8 Ma. In the Kerdous massif (Fig. 2.6), the Tarçouate granodiorite laccolith (2.17B) yielded an U-Pb age of 581 ± 11 Ma, whereas the Tafraoute alkaline granite and the equivalent Tazoult pluton yielded U-Pb ages at 549 ± 6 and 548 ± 11 Ma, respectively. The Bou Maadine rhyolitic dome (Ougnat inlier) and the Tachkakacht rhyolitic dyke (Saghro-Imiter) also rank among the youngest, alkaline magmatic events of the Ouarzazate Group, being dated (U-Pb zircon) at 552 ± 5 Ma at 543 ± 9 Ma, respectively. The Ouarzazate Group has not recorded the Pan-African deformation, but was deposited on a highly variable basement topography, which, coupled with the big and rapid variations in thickness of the Ouarzazate Group itself, strongly suggests that this group was deposited during active tectonics, most probably transtensional movements.

This huge late Neoproterozoic (Ediacaran) magmatic event coupled with a strong extensional-transtensional tectonics is linked to an intense hydrothermal activity as exemplified by the main deposits of Imiter and Zgounder (Ag-Hg), Bou Azzer (Co-Ni-As-Ag-Au), Iourirn (Au), Bou Madine (Cu-Pb-Zn-Au-Ag) (Fig. 2.19).

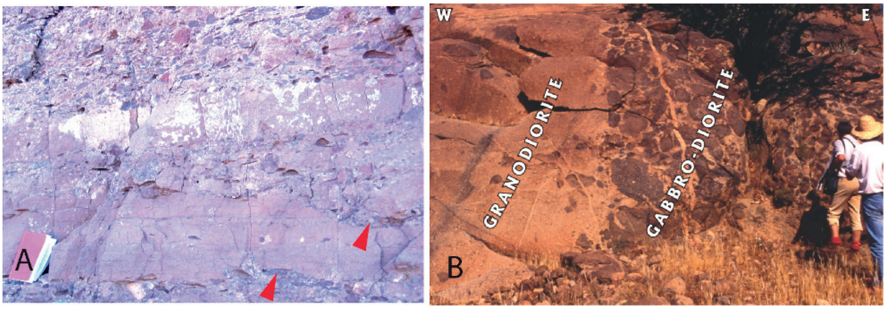


Fig. 2.17 Late Neoproterozoic rocks. (**A**): Ouarzazate volcanoclastic deposits in eastern Siroua inlier; note the uneven surfaces of stratification of the agglomerate layers, whose sub-angular elements are andesites and rhyolites. The notebook is 15 × 20 cm – (**B**): Core of the Tarçouate laccolith (c. 580 Ma) from the central Kerdous inlier (see Fig. 2.6 for location). The steep dip of the modally layered hornblende granodiorite with high amount of monzodioritic enclaves results from tilting above solidus conditions, as suggested by sub-vertical aplite dykes cutting across the igneous layering (Pons et al., 2006). Photo D.G.

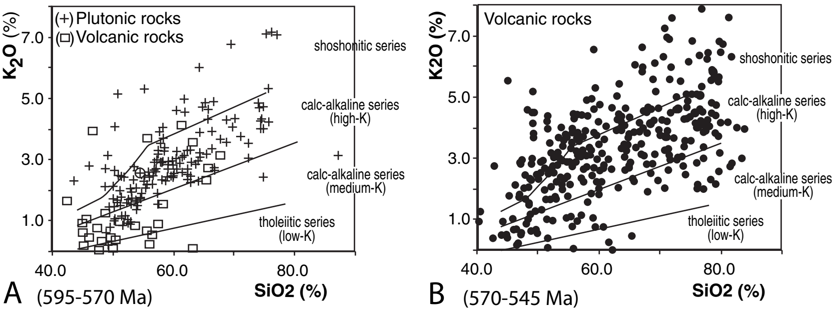
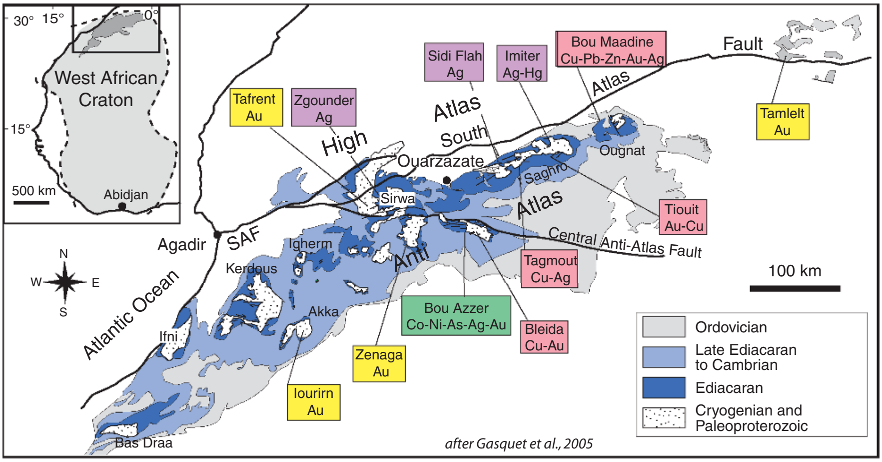


Fig. 2.18 K_2O–SiO_2 plots of Ediacaran calc-alkaline to alkaline plutonic (**A**) and volcanic (**A**, **B**) rocks of the Anti-Atlas belt. The 595–570 Ma magmatism (**A**) mostly show meta-aluminous magmatic rocks ($50\% < SiO_2 < 75\%$), with high-K calc-alkaline affinities. The 570–545 Ma volcanism (**B**) is dominantly effusive (mainly andesitic at the *bottom* of the sequence, rhyolitic-ignimbritic on *top*), and belongs to high-K calc-alkaline to shoshonitic series. After Gasquet et al. (2005)

2.5.4 Post-Orogenic Formations

References: For the location of the Precambrian/Cambrian boundary in the Anti-Atlas sedimentary record, see Latham & Riding (1990) and Maloof et al. (2005). Geochronological data for the Early Cambrian volcanites are given by Ducrot & Lancelot (1977), Gasquet et al. (2005), Maloof et al. (2005), and Álvaro et al.



after Gasquet et al., 2005

Fig. 2.19 Location of the main ore deposits in the Anti-Atlas belt. The calc-alkaline magmatism of the Ediacaran, late Pan-African metacratonic period was associated with large-scale base metal and gold mineralization. Metallogenic activity was greatest during the final extensional stage, at the Precambrian-Cambrian boundary. It is characterized by world-class precious metal deposits, base-metal porphyry and SEDEX-type occurrences (Gasquet et al., 2005)

(2006). The permanent role of extensional tectonics during that period is emphasized by Soulaimani et al. (2003), Soulaimani & Piqué (2004), Gasquet et al. (2005).

With the quasi-cessation of volcanism and the onset of thermal subsidence, the rifted and eroded Pan-African belt was flooded. This occurred before the end of Neoproterozoic times: top levels of the conglomeratic Adoudounian "Série de base" include carbonate deposits with some Ediacaran-type soft-bodied fauna. Then the main, carbonate part of the Adoudounian Fm straddles the Ediacaran-Cambrian boundary (542 Ma), as Tommotian-type calcified Cyanobacteria occur within the limestone layers of the overlying "Lie-de-vin" Fm. Detailed study of the δ13C record and its comparison with palaeontologically calibrated Siberian sections suggests that the Ediacaran-Cambrian boundary is located close to the base of the Adoudounian carbonates where the δ13C excursion to −6% is observed (Maloof et al., 2005). In the upper Adoudounian carbonates, a +7% high corresponds to the Nemakit-Daldyn/Tommotian boundary (ca. 525 Ma).

The Adoudounian basal conglomerates are virtually concordant on the clastic-ignimbritic Ouarzazate Group although in places a weak disconformity can be observed (cf. see Chap. 3). Weak extension tectonics is recorded in the Adoudounian carbonates by synsedimentary faults and slump structures, and by alkaline flows and sills around the Bou Azzer inlier. The J. Boho volcano at the southern border of the inlier is stratigraphically dated as Early Cambrian as its lowest flows and tuffs are interleaved in the uppermost Adoudounian levels (Fig. 2.9), consistent with an U-Pb age at 529 ± 3 Ma. The Aghbar trachytic sill at the northern border of the same inlier is dated at 531 ± 5 Ma. Ash beds from the upper Adoudou and upper Lie-de-vin Fms have been dated at 525 ± 0.5 and 522 ± 2, respectively.

2.6 Plate Tectonic Interpretation

References: The geodynamical interpretation of the Anti-Atlas Pan-African belt is discussed in Saquaque et al. (1989), Ouguir et al. (1996), Hefferan et al. (2000), Ouazzani et al. (2001), Ennih & Liégeois (2001, 2003, 2008), Thomas et al. (2002, 2004), Inglis et al. (2004), Gasquet et al. (2005), Ennih et al. (2006), Liégeois et al. (2006), Bousquet et al. (2008). The West African framework is described in Fabre (2005), Liégeois et al. (2003, 2005), Deynoux et al. (2006).

Varied plate tectonic interpretations of the Pan-African orogeny in Morocco have been proposed for decades and none was able to reach a consensus. In particular, the origin of the oceanic basin(s) and island arc(s), and the dip of the subduction(s) responsible for the ocean closure have varied considerably. However, the various data obtained in the last few years bring important new constraints limiting the possibilities. Note that the tectonic scenario elaborated for the Anti-Atlas Pan-African belt should correlate with those for the neighbouring segments of the belt, and especially with the most important Hoggar-Iforas belt.

2.6.1 The Three Main Neoproterozoic Epochs

In the Anti-Atlas, the Pan-African orogeny is the result of the convergence of the WAC with other terranes, which is also the case in the Tuareg shield, to the east of the WAC. Some correlations will then be proposed with that area for the convergent period.

First, the new geochronological data indicate three main Neoproterozoic epochs

(1) the deposition of the WAC passive margin sediments, probably beginning at ~ 1000 Ma and followed by the intrusion of doleritic dykes and sills at probably ca. 880 Ma. The Anti-Atlas Taghdout-Lkest Group correlates with the Char and Atar-Hank Groups of NW Taoudeni Basin. Shale horizons from the Atar-Hank Groups yielded Rb-Sr and K-Ar ages between 998 and 775 Ma. This passive margin evolution is a pre-Pan-African event to be linked with continental break-up; there is no information concerning the rest of the continent from which the WAC separated.

(2) the Bou Azzer – Siroua island arc building (760–700 Ma; Cryogenian) with its accretion towards the WAC at c. 665 Ma. This island arc complex is limited in surface, forming a strip along the AAMF. It must be noted that there are no other rock types in the Anti-Atlas within that age range. This event could be called early Pan-African accretion stage. It is accompanied and followed by the earliest greenschist deformation of the foreland between 660 and 640 Ma. This evolution can be correlated with the formation of volcanic arcs around 730–720 Ma in the Hoggar transect, with subsequent deposition of the Green Series, and collision with the WAC from 630 to 580 Ma. The Pan-African I phase is dated at 665–655 Ma in the Bassaride belt (Senegal, Guinea) on the opposite side of the WAC.

(3) the metacratonic Pan-African stage (630–550 Ma; Ediacaran) which began with the Saghro Group (630–610 Ma (up to 600 Ma?), consisting mainly of turbiditic sediments but recording an increasing amount of magmatism, tholeiitic at the start, high-K calc-alkaline at the end. After a minor tectonic phase, the Bou Salda Group (610 or 600–580 Ma) is characterized by badly sorted sediments and abundant high-K calc-alkaline volcanism and plutonism; the final phase is the Ouarzazate Group (580–550 Ma) composed mainly of high-K calc-alkaline rhyolites and granites. These three groups have in common: high variability in thickness, from 0 to several thousands of metres; deposition upon unstable basement with alternation of poorly sorted sediments, high energy sediments and volcanic rocks; finally, there is an increase of the volcanic rock proportion with time. The contemporaneous tectonics regimes were transcurrent, transpressive during the Saghro and Bou Salda Groups, and transtensive during the Ouarzazate Group. Periglacial deposits occur at least in the Saghro, Tiddiline and Anezi (Bou Salda) Groups. The Ouarzazate Group could correlate with the very base of the post-orogenic Série Pourprée of the Iforas-Hoggar transect, which is mostly dated between 560 and 530 Ma.

2.6.2 The WAC Northern Extent and Metacratonic Evolution

The geodynamic behaviours 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 outcropping only to the SW of the AAMF. The AAMF is an important feature, having allowed the Cryogenian oceanic complex to be preserved, but it does not mark the northern boundary of the WAC.

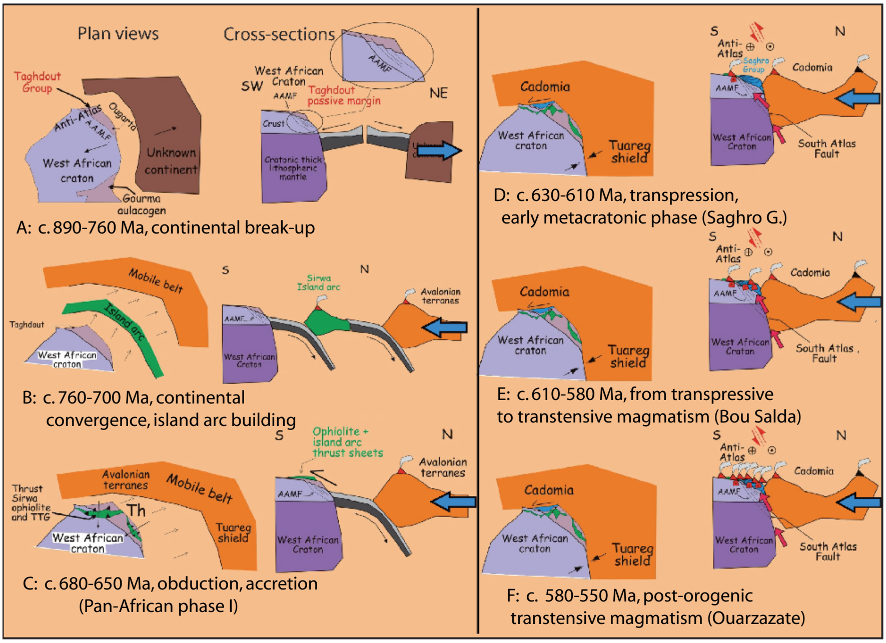
The Anti-Atlas Eburnian basement has not been significantly thickened by the Pan-African tectonics, but only underplated and variably uplifted: the Pan-African effects are limited to greenschist facies metamorphism and mylonitisation accompanied by major amount of fluids, probably especially during the Ouarzazate Group emplacement. The northern WAC border was never transformed to an active margin. In other words, no subduction plane with Franciscan-type metamorphism can be placed below the Anti-Atlas. The northern boundary of the WAC has been dissected by major faults and shear zones which allowed the generation and emplacement of the voluminous Ediacaran magmatism, but has preserved most of its cratonic rigidity: it acted as a rigid or semi-rigid indenter for the peri-Gondawanan terranes during the Pan-African and the Variscan orogenies and currently during the Alpine orogeny. Such a behaviour can be called a "metacratonic evolution", i.e. an evolution after the cratonic stage marked by a partial destabilization of the cratonic area (here the northern margin of the WAC) but preserving a large part of the cratonic rigidity and behaviour. This metacratonic rigidity explains why the early pre-Ediacaran Pan-African structures have been preserved, not only the Eburnian basement but also the c. 900–800 Ma passive margin sediments displaying easily destroyed sedimentary features such as ripple marks or mud cracks, and the thrust Cryogenian oceanic complex.

2.6.3 Location of the Pan-African Mobile Belt

If the Anti-Atlas represents the northern boundary of the WAC metacratonized during the Pan-African orogeny, the true Pan-African mobile belt existed just to the north and west, consisting mostly of peri-Gondwanan terranes which drifted away later, during the Phanerozoic. Complementary information such as the cause of the deformation of the Saghro Group at 610–600 Ma should be searched for within these peri-Gondwanan terranes. Other correlations can be made on the eastern side of the WAC, in the Tuareg shield where the Pan-African terranes that collided with the craton are preserved. It is interesting to note that in the Tuareg shield: (1) several island arc dated at c. 700–750 Ma are known, (2) the collision with the WAC began at c. 630 Ma, which is also the onset of the Saghro Group deposition, (3) the large transcurrent transpressive movements along the mega-shear zones ended mostly at about 580 Ma, passing to transtensional movements accompanied by high-level plutons until c. 560 Ma, corresponding to the Ouarzazate period and (4) that the latest magmatism before the Phanerozoic sedimentation is dated at 535–520 Ma (Taourirt province) contemporaneous to the late alkaline magmatism in the Anti-Atlas. This means that the stress at the origin of the Pan-African orogeny in West Africa can be ascribed to the WAC, as the current stress in Asia can be ascribed to the Indian craton. The collision between the WAC and the Tuareg shield was slightly oblique; in the Anti-Atlas, the Ediacaran Pan-African phase corresponded mainly to a sliding movement, passing progressively from transpression to transtension, metacratonizing the northern boundary of the WAC. This metacratonic reactivation appears to strongly favour magma and fluid generation and movements, mainly during the Pan-African orogeny and subsequently during the early Phanerozoic, including the current uplift and volcanism, eventually leading to the well-known Anti-Atlas mineralizations.

2.6.4 Tectonic Scenario

A relatively simple scenario has been proposed by several authors (including one of us, D.G.) with some variations: it hypothesizes a south-dipping subduction zone operating from ~ 750 Ma to ~ 600 Ma. The protracted subduction would have been



A: c. 890-760 Ma, continental break-up

B: c. 760-700 Ma, continental convergence, island arc building

C: c. 680-650 Ma, obduction, accretion (Pan-African phase I)

D: c. 630-610 Ma, transpression, early metacratonic phase (Saghro G.)

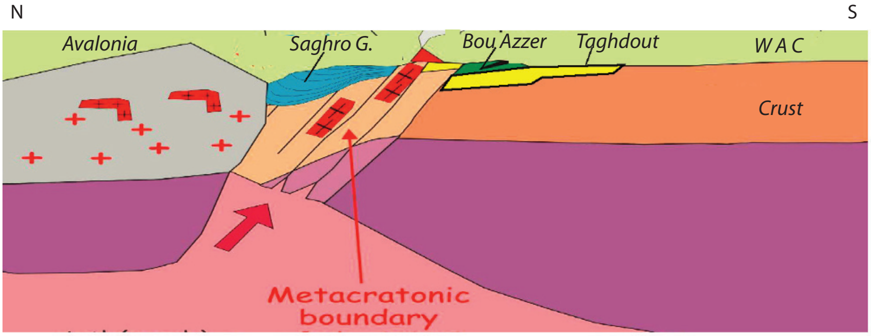
E: c. 610-580 Ma, from transpressive to transtensive magmatism (Bou Salda)

F: c. 580-550 Ma, post-orogenic transtensive magmatism (Ouarzazate)

Fig. 2.20 Geodynamic evolution of the Anti-Atlas domain during Neoproterozoic times: a new scenario for the Pan-African mountain building around the West African Craton, after Liégeois et al. (2006)

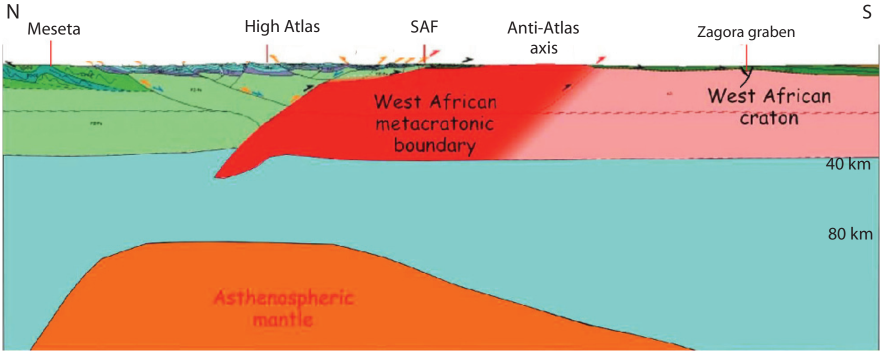
responsible for the building of an island arc at some distance of the WAC margin, the Bou Azzer ophiolites being formed in a back-arc basin. Thus, this setting would compare with that of the western Pacific margins. Following the obduction and arc collision, the Ediacaran episode of high-K calc-alkaline to alkaline magmatism is interpreted as the result of supra-subduction partial melting, slab break off and post-orogenic extension. However, this model is not supported by the new data reported above (age of the Saghro Group, northern extent of the metacratonic basement, lack of HP-LT metamorphism).

In contrast, our tectonic scenario (Fig. 2.20) assumes a north-dipping subduction from ~ 760 to 660 Ma. The future ophiolite corresponds either to the oceanic part of the WAC plate or to a fore-arc basin, its obduction and the arc accretion (Pan-African phase I) results from the oceanic lithosphere consumption due to Avalonia/Cadomia convergence towards the WAC (a model similar to the Tethyan setting in Oman). Between 660 and 630 Ma, the earliest quartz-diorite magmatism could result from slab break-off. The metacratonic evolution begins with proximal



(after Liégeois et al., 2006)

A : Restoration of the Pan-African transpressive setting, 630-610 Ma ago



(after Frizon de Lamotte et al., 2004)

B : Transmed I profile, *pars*

Fig. 2.21 Hypothetic structure of the Anti-Atlas lithosphere by the time of the Saghro Group sedimentation and coeval magmatism (**A**), compared with its present-day structure (**B**). In both case, mantle lithosphere is thinned along the transpressive margin of the metacratonic fringe of the WAC, after Liégeois et al. (2006). See Fig. 2.1 for location volcanoclastic turbidites (the newly dated Saghro Group) coeval with high-K calc-alkaline magmatism associated with transpressive deformation of the WAC margin. The asthenospheric uplift beneath the transcurrent margin can be compared with that presently observed beneath the San Andreas transform fault, and more simply, in the present-day asthenospheric uplift which follows the Central Atlantic-Atlas transcurrent rift system (Fig. 2.21). The tectonic regime progressively changes from transpressive to transtensive between 610 and 580 Ma, and thus the magmatism becomes more alkaline. This tendency culminates during the Adoudounian-Early Cambrian.

Acknowledgments This chapter benefited of many international scientific works concerned with the Anti-Atlas domain during the two last past decades. These new discoveries were made during extensive exploration programs carried out as part of the ambitious National Geological Mapping Project funded by the Moroccan Ministry of Energy and Mines. Studies were also supported by scientific grants awarded by ONHYM and ONA-Managem groups to Moroccan and international academic teams. The UNESCO/IUGS international program permitted fruitful exchanges during the IGCP485 meetings. The authors thank Alain Cheilletz (Ecole Nat. Sup. de Géologie, Nancy) and Bernard Hassenforder (Univ. Louis-Pasteur, Strasbourg) for fruitful discussions and Michel Faure (Univ. Orléans), Scott Samson (Syracuse Univ., USA) and Tim Pharaoh (British Geol. Survey, Nottingham) for their careful review and comments of early versions of the text. AM and AS acknowledge logistic support by MAPG and ONHYM during a recent field trip in the western Anti-Atlas accompanied by A. El Ouattaoui.

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