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A newly discovered orogenic event in Morocco: Neoproterozic ages for supposed Eburnean basement of the Bou Azzer inlier, Anti-Atlas Mountains

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Abstract

The Bou Azzer inlier within the Anti-Atlas orogenic belt of Morocco exposes a dismembered ophiolite, long considered to mark a Late Neoproterozoic suture between the West African Craton (WAC) in the south, and Neoproterozoic arcs to the north. Southern parts of the Bou Azzer inlier include meta-igneous units, paragneiss, schist and muscovite-bearing granite that have until now been regarded as the *c*. 2 Ga Eburnean WAC basement onto which the ophiolite was obducted. An example of supposed Paleoproterozoic basement occurs at Tazigzaout. The main units within this complex are metagabbro, augen granite gneiss, finely banded granite gneiss and variably sheared syn-tectonic leucogranite, all of which are intercalated within a complex sub-vertical, upper greenschist facies, ductile dextral shear zone. The meta-igneous rocks are crosscut by a sheeted muscovite-biotite granite pluton. Three concordant U–Pb analyses of zircon from an augen granite gneiss provide a date of 753 +1/−2 Ma. Zircon from a nearby metagabbro provide an indistinguishable date of 752.2 ± 2.4 Ma. Both dates are considered best estimates of the crystallization ages of their igneous protoliths. Analyses of zircon from two crosscutting leucogranite bodies provide younger dates of 705 +2/−3 Ma and 701 +2/−1 Ma. The initial ε_{Nd} values of all lithological units in the complex range from +4.9 to +6.0, with depleted mantle model (T_{DM}) ages of 890–790 Ma.

The high, positive ε_{Nd} values for all of these igneous units is indicative of an isotopically juvenile source, such as depleted-mantle derived material, and precludes substantial interaction with old, evolved crustal sources. These data demonstrate that the "basement" rocks of the Tazigzaout complex are Neoproterozoic intrusions, not *c*. 2 Ga Eburnean units, as found in more southerly Anti-Atlas inliers. The structural relationships and U–Pb ages are interpreted as recording dextrally transpressive deformation of *c*.755 Ma juvenile crust after *c*. 750 and before 700 Ma. This Neoproterozoic deformation occurred as much as 100 Ma prior to the top-to-the-north thrusting of the meta-igneous units over units of the ophiolite and arc, and provides strong evidence for two discrete 'Pan African' events in Morocco.

Keywords: Anti-Atlas; Morocco; U–Pb geochronology; Palaeoproterozoic; Neoproterozoic; Orogeny

1. Introduction

During the Neoproterozoic Pan-African orogeny, the margin of the West African Craton (WAC) underwent repeated tectonic cycles associated with the formation, collision, accretion and dismemberment of oceanic crust and island arcs. The Anti Atlas region of Morocco

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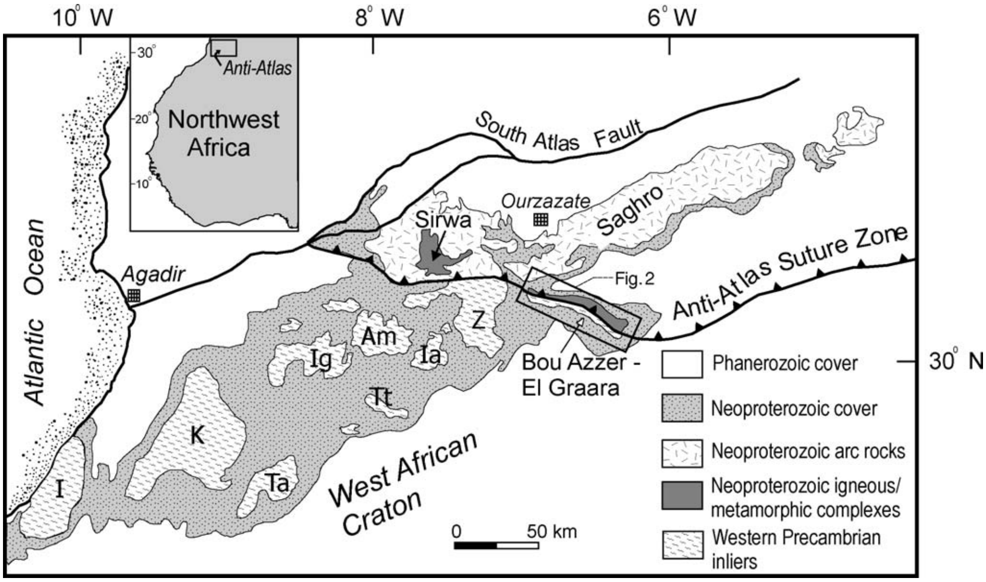

Fig. 1. Map of the Anti-Atlas region of Morocco showing generalized geologic features. Inliers indicated by abbreviations are as follows: Am: Agadir Melloul; I: Ifni; Ia: Iguerda; Ig: Igherm; K: Kerdous; Tt: Tagragra de Tata; Z: Zenaga. Inset: location of Anti-Atlas Orogen within northwest Africa.

(Fig. 1) is important to understanding the Pan-African evolution of the WAC margin as it exposes windows through the Palaeozoic cover where deformation related to the accretion of arcs to the WAC in the late Neoproterozoic is preserved (Hefferan et al., 2000; Ennih and Liégeois, 2001; Thomas et al., 2002). These inliers expose igneous units emplaced at various stages prior to, during and following obduction events and thus offer

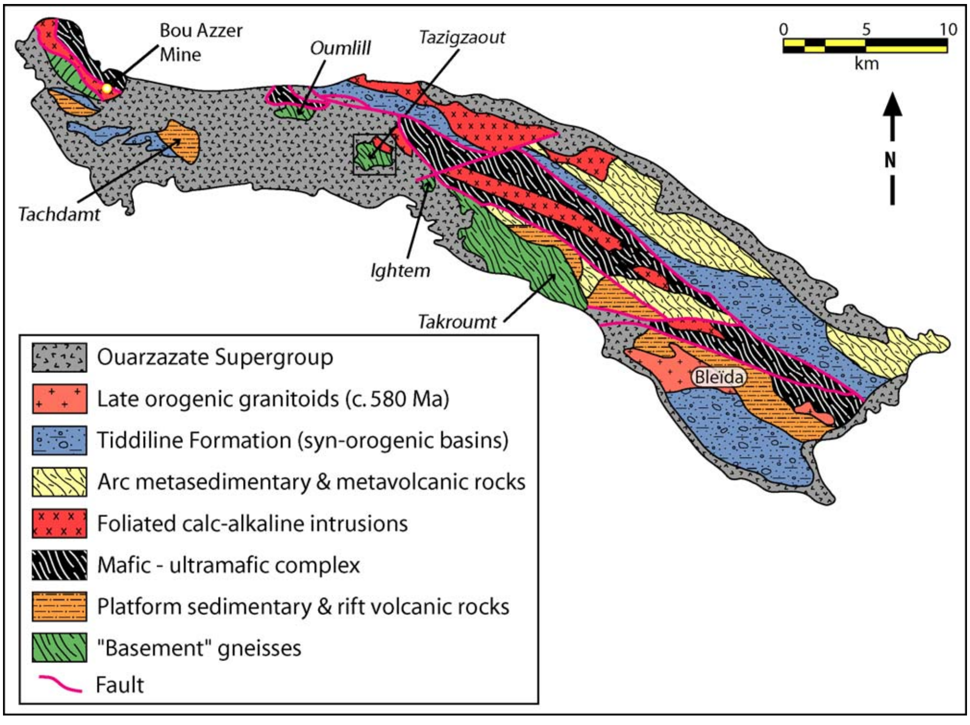

Fig. 2. Generalized geological map of the Bou Azzer inlier, Anti-Atlas Morocco, showing location of the Tazigzaout inlier. Rectangle illustrates location of Fig. 3. Modified from LeBlanc (1981b).

a unique opportunity to determine the timing of these major events. A precise chronology of such events is fundamental to a full understanding of supercontinent formation and evolution.

One of the best-preserved and best-exposed examples of a Neoproterozoic suture zone occurs in the Bou Azzer-El Graara inlier where the seminal work of Leblanc (1975, 1981a) described basement and a passive margin cover sequence (craton margin), an ultrabasic suite (ophiolite), and volcano-sedimentary sequences and intrusions (accreted arc). While many workers have developed Leblanc's model in the last two decades (e.g. Saquaque et al., 1989; Villeneuve and Cornée, 1994; Hefferan et al., 2000; Ennih and Liégeois, 2001), resolution of a detailed evolution of the Anti-Atlas has been hampered by a lack of geochronologically-supported lithostratigraphic, structural and geochemical studies. This has necessitated a generalized lithological approach to the regional correlation of units. One particular difficulty regards the correct identification

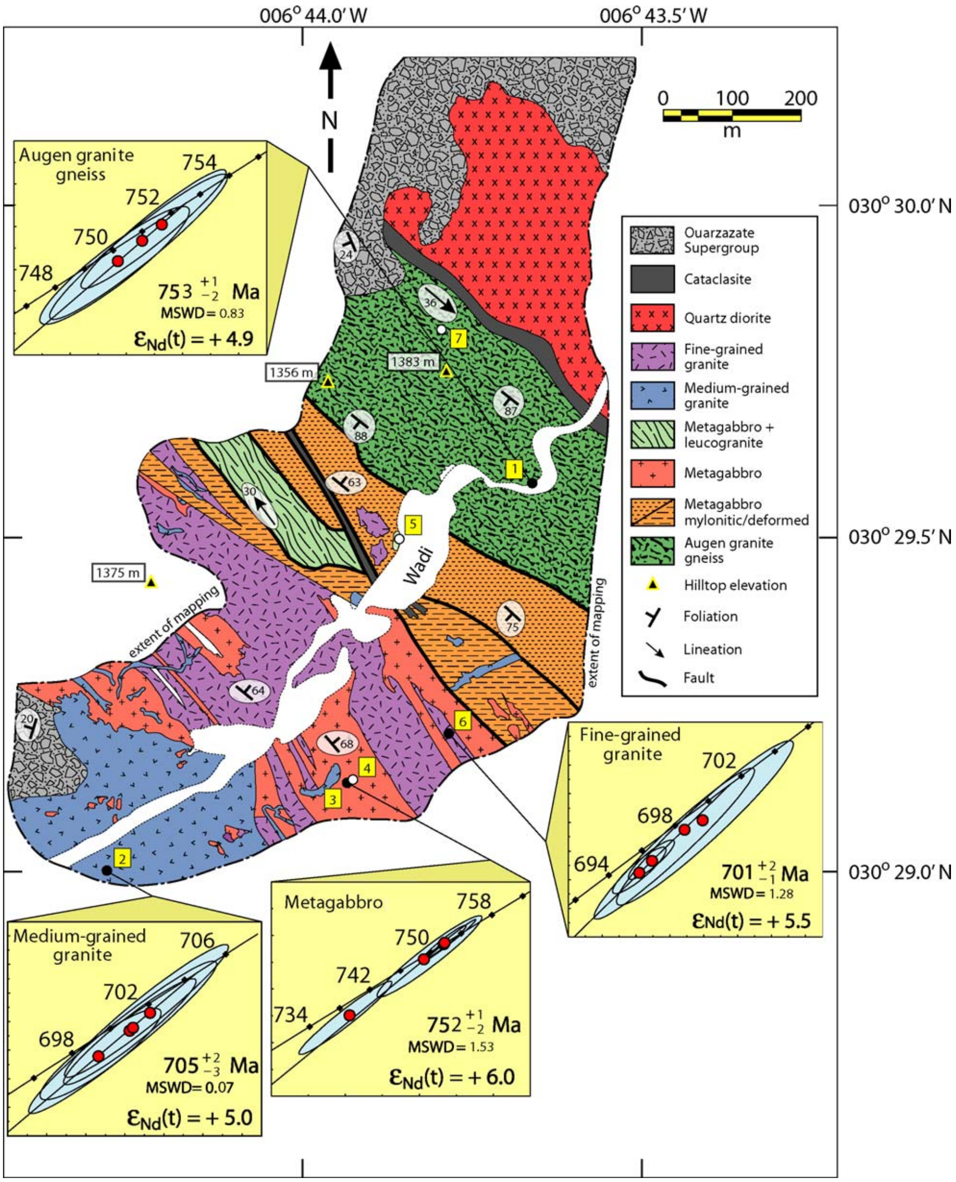

Fig. 3. Geological map of the Tazigzaout inlier. Open circles identify the location of samples analyzed for Nd isotopic composition, filled circles are the locations of samples analyzed for both Nd isotopes and U–Pb geochronology. Concordia diagrams for the four units dated are shown with two sigma error ellipses.

and discrimination between Pan-African and pre-Pan-African intrusions and structures. For example, all of the gneisses, meta-igneous units, and majority of igneous units to the south of the proposed suture of the Bou Azzer inlier, have collectively been considered to be *c*. 2 Ga Eburnean, or older, basement which formed the palaeomargin of the WAC. The structural and metamorphic history of this basement has been considered to largely or entirely pre-date Pan-African events. The assignment of these gneissic and meta-igneous units as *c*. 2 Ga basement is based either on the more intense deformation and/or higher grades of metamorphism when compared to the majority of rocks within the inlier, and/or because they share broad lithological similarities with rocks ascribed to Eburnean basement elsewhere on the WAC (e.g. Choubert, 1963; Leblanc, 1981a). In general, granitic rocks which carry foliations, or muscovite-bearing granitic lithologies (often pegmatite and aplite sheets) have all been considered Eburnean basement. However, none of these supposed Eburnean basement units within the Bou Azzer inlier have been previously dated by robust geochronological methods.

In an attempt to better understand the early evolution of the Anti-Atlas belt, we have undertaken mapping and U–Pb dating of selected localities within the Bou Azzer inlier where basement has previously been inferred (e.g. Leblanc, 1981a). The intention of this work was to test correlations between basement rocks within the Bou Azzer inlier with those elsewhere (e.g. Zenaga inlier) and to enable structural comparisons to be made with basement units away from the suture zone to assess the degree of Neoproterozoic reworking of the basement. In this paper we present lithological and structural features and high precision U–Pb zircon dates from a small (<5 km^2) complex exposed beneath late Neoproterozoic Ouarzazate Supergroup (terminology after Thomas et al., 2004) deposits at Tazigzaout (Figs. 2 and 3). This complex, which is part of the larger Bou Azzer-El Graara inlier, was selected for study because (1) it exposes a range of foliated acid to basic meta-igneous rocks, in particular augen granite gneisses and muscovite leuco-granite); (2) structures within the complex are similar to those present within other "basement" parts of the Bou Azzer-El Graara inlier; and (3) because the meta-igneous rocks are in exposed contact with (Pan African aged) quartz diorite, typical of a suite of well-documented intermediate intrusions that occur throughout the Bou Azzer inlier. Additionally, the units and structures are demonstrably overlain unconformably by a latest Neoproterozoic volcanic sequence (Ouarzazate Supergroup, 580–560 Ma; Thomas et al., 2002) so that it is certain that none of the ductile structures present relate to post Pan-African faulting.

Augen granite gneiss, mylonitic metagabbro and leucogranite all give upper intercept U–Pb ages in the range 755–700 Ma. We interpret these new data as demonstrating that the meta-igneous rocks are Neoproterozoic intrusions and were thus previously incorrectly correlated with *c*. 2 Ga Eburnean basement. Combined structural and isotopic data bracket an age of *c*. 755–700 Ma for deformation of these juvenile basement units. This tectonothermal event, approximately 50–100 Ma older than the age of the main stage of Pan-African orogenesis described elsewhere within the Anti-Atlas region (e.g. Inglis et al., 2005), has not previously been recognised in Morocco. Given that these rocks share many lithological and structural similarities with other "basement" exposures in the Bou Azzer inlier, the case for 2 Ga basement being present anywhere within the Bou Azzer inlier is considerably weakened.

2. Geological background

Archean to Palaeoproterozoic rocks that make up the West African Craton are exposed in two main regions, the Man Shield in the south and the Reguibat rise in the north. It is generally accepted that the WAC consists of a collage of Archean and Palaeoproterozoic terranes or microcratons. Recent geochronological studies have shown the WAC formed upon early Archean (*c*. 3500 Ma) basement (e.g. Potrel et al., 1996, Mauritania; Thiéblemont et al., 2001, Guinea; Kröner et al., 2001, northern Nigeria). In the west of the craton two younger Archean events have been identified, the Leonian (*c*. 3050–2950 Ma) and the Liberian (2850–2700 Ma). The craton was affected by widespread metamorphism and intense magmatism at *c*. 2–1.8 Ga during a period of extensive crustal growth termed the Eburnean (Birimian) orogeny (Abouchami et al., 1990; Liégeois et al., 1991; Boher et al., 1992; Thiéblemont et al., 2001). Zhao et al. (2002) have examined the links between the Eburnean orogeny and other *c*.2.1–1.8 Ga orogens and suggest that the WAC may have been part of a pre-Rodinian supercontinent (i.e. Columbia; Rogers and Santosh, 2002) during the Palaeoproterozoic. Palaeoproterozoic aged rocks exposed in the southern Anti-Atlas are believed to represent the northern margin of the Craton which is thought to have formed as the result of extensive Eburnean magmatism and metamorphism at *c*. 2.1–2.0 Ga. Eburnean (*c*. 2 Ga) basement has been recognised in a series of inliers in southern Morocco, including the Kerdous, Igherm, Iguerda and Zenaga inliers (Fig. 1). Recently, U–Pb zircon dating has confirmed the Eburnean age of some granitoids within the Bas Draa inlier (Ait Malek et al., 1998), Tagragra d'Akka inlier (Charlot-Prat et al., 2001), Tagragra de Tata inlier (Walsh et al., 2002), and Kerdous inlier (Barbey et al., 2004). The Zenaga inlier (Fig. 1), neighbouring the Bou Azzer inlier, contains a variety of rock types including orthogneiss, paragneiss, migmatite, augen granite gneiss, and variably sheared to only weakly deformed granite, intruded by sheets of muscovite pegmatite and leucogranite. The oldest rocks of the Zenaga region comprise a high grade paragneissic succession including schist, gneiss and migmatite, thought to record the peak of Eburnean metamorphism in the north of the WAC (Ennih et al., 2001; Thomas et al., 2002). Thomas et al. (2002) reported U–Pb SHRIMP dates of 2037 ± 9 Ma, 2037 ± 7 Ma and 2032 ± 5 Ma from three granitic units which intrude the paragneissic host rocks of the Zenaga inlier. The dates were interpreted as best estimates of the timing of emplacement of the granites and of deformation and high-grade metamorphism during the Eburnean Orogeny. North of the Zenaga inlier, in the Sirwa inlier (Fig. 1), two dismembered ophiolite sequences occur. The larger Tasriwine, and the much smaller N'Qob, ophiolites, include ultramafic cumulates, gabbro cumulates and a sub-vertical sheeted dyke complex (Admou, 2000). Samson et al. (2004) dated two plagiogranite intrusions within the Tasriwine ophiolite, 761 +1.9/−1.6 Ma and 762 +1.0/−2.0 Ma, which were interpreted to date formation of oceanic crust. In the central part of the Sirwa inlier medium to high grade metamorphic rocks comprising tonalitic and amphibolitic gneisses with minor interlayered migmatites are thought to represent the roots of an arc complex estimated to be 743 ± 14 Ma in age, based on a SHRIMP U–Pb zircon date from the Iriri migmatite (Thomas et al., 2002). The best current estimate for the timing of collision in the Sirwa region is 663 ± 14 Ma, provided by a SHRIMP date from rims on the zircon of the Iriri migmatite interpreted as having grown metamorphically during the collisional event (Thomas et al., 2002).

The Bou Azzer-El Graara inlier (Fig. 2) is of particular importance to the understanding of Pan-African events, as it is believed to expose the dismembered relics of a Neoproterozoic suture zone (Leblanc, 1981a; Saquaque et al., 1989; Hefferan et al., 2000) marking the boundary between the Paleoproterozoic Eburnean basement of the WAC, and Neoproterozoic accreted arcs to the north. In the southern sectors of the Bou Azzer inlier a variety of deformed igneous, meta-igneous and metasedimentary rocks (Leblanc, 1981a) occur, including augen granite gneiss, muscovite pegmatite and leucogranite. On the basis of their deformational state and lithological similarities with rocks of the nearby Zenaga massif these units have been considered to be 2 Ga Eburnean basement by all previous workers (e.g. Leblanc, 1981a; Saquaque et al., 1989; Saquaque, 1991). Such "basement" occurs at a number of localities (Fig. 2). These igneous and metamorphic units have also been considered to be the local basement to widespread quartzite and stromatolite-bearing carbonate units believed to be the Neoproterozoic passive margin cover sequence overlying the Eburnean basement on this portion of the WAC (Saquaque et al., 1989; Leblanc and Moussine-Pouchkine, 1994; Hefferan et al., 2002; Bouougri and Saquaque, 2004). However, although passive margin units occur in close proximity to their supposed basement, we have been unable to verify a basement-cover unconformity at any locality within the Bou Azzer inlier, all contacts being either tectonic or unexposed. Northern parts of the Bou Azzer inlier expose volcano-sedimentary sequences (e.g. Tichibinine Formation) considered to be parts of an arc/fore-arc related sequence that is Neoproterozoic in age. Mafic rocks, ultramafic rocks and rare blueschists occur in a discontinuous central zone between the northern and southern parts of the Bou Azzer inlier and have been interpreted to be a dismembered ophiolite fragment (Saquaque et al., 1989; Admou, 2000; Hefferan et al., 2002). Many units within the central and northern parts of the Bou Azzer inlier are intruded by a suite of broadly quartz dioritic bodies which are believed to have been emplaced syn-tectonically during the main period of Pan-African orogenesis (Saquaque, 1991) and have been dated at *c.* 650–640 Ma (Inglis et al., 2005). A folded, but only weakly metamorphosed late-orogenic sedimentary sequence, locally referred to as the Tiddeline Formation, occurs in fault bounded basins (Hefferan et al., 1992). The majority of the above units are unconformably overlain by a thick succession of sub-horizontal ignimbrite and conglomerate termed the Ouarzazate Supergroup. A suite of undeformed intrusions occurs in the south, near the village of Bleida (Leblanc, 1981a; Inglis et al., 2004). This suite includes the Bleida granodiorite, which has recently been re-dated at 579.4 ± 1.2 Ma (Inglis et al., 2004), superceding the previous date of 615 ± 12 Ma (Ducrot, 1979). Inglis et al. (2004) argue that the 580 Ma age of emplacement of the Bleida granodiorite constrains the timing of the end of Pan-African deformation in the eastern Anti-Atlas. The Ouarzazate Supergroup is overlain by the largely shallow marine carbonate Adoudounian Formation, which is latest Neoproterozoic to Cambrian in age (Latham and Riding, 1990). Variscan deformation during the Carboniferous to Permian produced the Precambrian-cored domes and

Paleozoic-filled basins that characterise the Anti-Atlas (Donzeau, 1974; Jeannette and Piqué, 1981). Alpine deformation in the middle Tertiary uplifted the region and led to the exhumation of the Bou Azzer inlier (Choubert, 1963; Cahen et al., 1984).

3. The Tazigzaout complex

The Tazigzaout complex within the Bou Azzer inlier (Fig. 3) comprises a variety of strongly deformed meta-igneous gneisses and schists and igneous rocks which underlie the sub-horizontal *c*. 580 Ma (Thomas et al., 2002) Ouarzazate Supergroup. The main units within the complex are intermediate to basic mylonitic schist (whose metagabbroic protolith is recognisable in low strain zones), augen granite gneiss, finely banded granitic gneiss and variably deformed leucogranite sheets, all of which are intercalated within a complex WNW-ESE trending sub-vertical shear zone. The range of lithologies and intercalated and banded nature indicates that the precursor was a composite igneous mass. Homogeneous medium grained alkali-feldspar augen granite gneiss constitutes the major part of the northern section of the shear zone. The augen granite gneiss carries strongly developed foliations picked out by biotite and muscovite foliae, quartz ribbons and feldspar augen. In localised regions the augen granite gneiss is more strongly mylonitised to form finely banded granitic gneiss and muscovite schist. The finely banded gneiss consists of discontinuous quartz, muscovite and feldspar layers alternating on a 2–5 mm scale. The mylonitised units are in tectonic contact with a minimally deformed quartz diorite pluton. The quartz diorite is mineralogically, texturally, and isotopically similar to, and thus correlated with, a series of bodies which occur elsewhere within the Bou Azzer inlier. These include the Bou Afrou, Bou Azzer, Ait Ahmaine and Ousdrat diorites, which have emplacement ages between 652–640 Ma (Inglis et al., 2005).

Mineral parageneses and structures present provide information concerning metamorphism and kinematics. The metagabbro located within the central and southern part of the shear zone is extensively retrogressed to a lower greenschist facies assemblage of chlorite, albite, zoisite and quartz, although relic hornblendes indicate that higher grades of upper greenschist to possible amphibolite facies metamorphism were attained. The metagabbro is believed to form the protolith to heterogeneously developed finely banded mylonitic schists. Dark bands consist of fibrous chlorite, actinolite and ilmenite overprinting relic hornblende while pale bands are sercitised plagioclase, chlorite and quartz. Across the shear zone there is considerable variation in the size and distribution of the melanocratic and leucocratic layers within the basic mylonitic schists reflecting strong strain localisation. Although reactivation of earlier structures cannot be ruled out, we suggest this variation in strain localisation reflects micro- and meso-scale rheological contrasts provided by the differing aggregate compositions of interlayered metagabbro and more felsic protoliths.

The dominant structure (Figs. 3 and 4) within the shear zone consists of a generally WNW-ESE striking and NE dipping ductile fabric (S_1) observable in the basic mylonitic schists, augen granite gneiss and finely banded granitic gneiss. An extension lineation (L_1) that plunges at shallow angles (10–30°) to the NW is commonly associated with S_1. Within granite gneiss the S_1 fabrics are defined by the compositional segregation of quartz and feldspar. Ribbons and interconnecting bands of plastically deformed quartz surround less deformed aggregates and individual crystals of plagioclase and alkali-feldspar. Both alkali and plagioclase feldspar form augen with core and mantle structures, indicative of ductile deformation above 500 °C (e.g. Passchier and Trouw, 1996). Mica is also deformed and kinked in a ductile manner forming mica fish that display dextral kinematic indicators. Intra and intercrystalline fractures healed with quartz crosscut the ductile structures within the feldspar augen and imply continued fabric development at lower temperatures (<500 °C). Within the basic mylonitic schists the S_1 fabric is composite, consisting of successive generations of co-planar fabrics. Early S_1 foliations are folded, forming rootless co-planar folds with hinges at a high angle to L_1, surrounded by the later generation of the S_1 fabric. Kinematic analyses of sections parallel to the lineation indicate that ductile deformation within the shear zone was dominated by dextral shear. Several generations of leucogranite sheets crosscut the S_1 foliation. In regions of high shear, these sheets are intruded sub-parallel to S_1 and carry a moderate solid-state metamorphic fabric. Other sheets with similar compositions possess only a weak solid-state overprint and preserve magmatic mineral alignment. In places, the leucogranite sheets are themselves folded forming folds with hinges at a high angle to L_1. Although it is possible that the differently deformed leucogranites are unrelated, the range in intensity of deformation linked with the coincidence in orientation of deformation structures and down-temperature fabric development indicates that the leucogranites were emplaced at different stages during the same ductile shearing event. We thus view them as late syn-tectonic with respect to S_1 fabric development in the shear zone. The gneisses and variably sheared leucogranites are crosscut by a sheeted pluton of

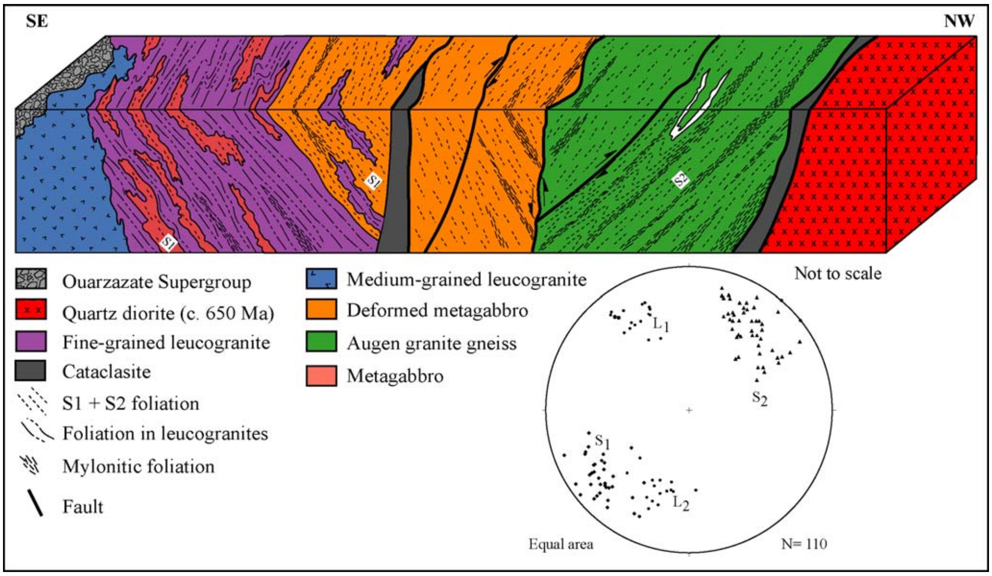

Fig. 4. Schematic cross-section through the Tazigzaout inlier illustrating the structural relationships between the inlier's igneous and metamorphic units and the S_1 and S_2 fabrics. Inset diagram; Lower Hemisphere equal area stereonet projection of (i) poles to planes of the S_1 and S_2 foliation and; (ii) L_1 and L_2 lineation.

muscovite-biotite granite, which is largely undeformed. However, a weak magmatic biotite fabric occurs which broadly parallels S_1. Sheets of the same granite and of pegmatite occur sporadically within the complex.

Within 200 m of the contact with the quartz diorite body (Fig. 4) a lower greenschist facies (S_2) fabric, most notable within localised regions of shear, overprints the higher grade fabrics within the augen granite gneiss. Although variable, the foliation generally dips to the SW. A down-dip stretching lineation (L_2) is formed on the S_2 foliation surfaces, which in combination with kinematic indicators (c–s fabrics, ∂-augen) records top-to-the-north transport. The intensity of S_2 fabric development increases in proximity to the contact forming a *c*. 50 m wide zone in which augen granite gneiss is intensely mylonitised and recrystallised to mica schist. The augen granite gneiss S_2 is characterised by seams of disaggregated feldspar, quartz and phyllosillicates indicative of reaction softening at lower greenschist facies temperatures. Within localised zones of reactivation S_2 is overprinted by lower to sub-greenschist facies semi-brittle shearing and cataclasis. This low temperature deformation is also observed in quartz-diorite in the footwall. Within 10 m from the contact the quartz diorite is largely undeformed although a weak magmatic fabric is occasionally seen (and is also picked out by weakly oblate mafic enclaves). Overall, the tectonic contact between the "basement" components and the quartz diorite displays early top-to-the north shearing, indicating that the gneisses were thrust northwards over the quartz diorite. This is consistent with the comparative degree of intensity of deformation in the gneisses (hanging wall) and quartz diorite (footwall). The last stages of brittle reactivation were associated with extension were marked by top to-the-south kinematics and NW-SE orientated sub-vertical transcurrent sinistral shear. In conclusion, the complex displays foliations which, although broadly parallel (trending WNW-ESE), were formed at different times and under a range of tectonic regimes (D_1 transcurrent shearing, D_2 thrusting and subsequent extension) and metamorphic conditions (upper greenschist facies and lower greenschist facies).

4. Analytical techniques

4.1. U–Pb geochronology

In an attempt to constrain the protolith age of the basement units of the Tazigzaout inlier samples of augen granite gneiss, metagabbro, sheared leucogranite and muscovite-biotite granite were collected for high precision U–Pb zircon dating. Rock samples were reduced and dense minerals were concentrated using methods outlined by Samson and D'Lemos (1999). Zircon crystals were examined using a binocular microscope. Crystals chosen for abrasion were selected by choosing the clearest, crack-free grains containing no, or a minimum number of, inclusions. The majority of zircon crystals were doubly terminated, simple prisms, less than 150 μm in length, with length to width ratios between 3 and 4.

Table 1
U–Pb isotopic data for the basement rocks of the Tazigzaout inlier, Bou Azzer, Anti-Atlas, Morocco

Analysis[a]	Total U (ng)	Total Pb (pg)	Total common Pb (pg)	Atomic ratios								Ages (Ma)			
				^{206}Pb[a]/^{204}Pb	^{206}Pb[b]/^{208}Pb	^{206}Pb[c]/^{238}U	% Error	^{207}Pb[c]/^{235}U	% Error	^{207}Pb[c]/^{206}Pb	% Error	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	ρ[d]
Augen granite gneiss															
A (2)	0.36	47.0	1.1	2395	6.54	0.1236	0.38	1.0959	0.39	0.06432	0.12	751.1	751.4	752.2	0.95
B (1)	0.29	38.1	1.1	1993	6.02	0.1234	0.45	1.0949	0.47	0.06434	0.14	750.2	750.9	752.9	0.95
C (4)	0.53	72.2	4.9	765.2	5.242	0.1232	0.37	1.0932	0.40	0.06433	0.15	749.2	750.0	752.7	0.92
Medium grained granite															
D (1)	0.24	29.6	1.9	926.2	7.44	0.1147	0.53	0.9945	0.56	0.06291	0.17	699.8	701.0	705.1	0.95
E (2)	0.15	18.4	0.9	1178	8.22	0.1143	0.46	0.9915	0.51	0.06289	0.22	697.9	699.5	704.6	0.90
F (4)	0.19	23.5	1.6	869.1	6.74	0.1149	0.66	0.9962	0.69	0.06286	0.19	701.4	701.8	703.4	0.96
G (1)	0.15	17.3	1.5	792.3	10.3	0.1146	0.76	0.9938	0.79	0.06290	0.21	699.3	700.7	705.0	0.96
Metagabbro															
H (1)	0.12	16.3	1.5	633.1	4.323	0.1209	0.92	1.0700	0.96	0.06418	0.25	735.9	738.8	747.5	0.97
I (4)	0.41	55.8	1.6	1760	4.85	0.1237	0.42	1.0967	0.44	0.06428	0.12	752.0	751.8	751.0	0.96
J (1)	0.11	14.6	1.6	538.4	4.52	0.1232	1.01	1.0927	1.06	0.06432	0.31	749.1	749.8	752.2	0.96
K (2)	0.24	33.2	0.9	1834	4.61	0.1238	0.52	1.0982	0.53	0.06433	0.11	752.5	752.5	752.5	0.97
Fine grained granite															
L(1)	0.15	18.2	1.6	712.4	8.31	0.1144	0.82	0.9921	0.86	0.06290	0.25	698.2	699.8	704.9	0.96
M (4)	0.77	87.3	3.6	1480	11.0	0.1137	0.23	0.9844	0.26	0.06277	0.11	694.4	695.9	700.6	0.89
N (1)	0.17	19.7	1.4	832.4	7.96	0.1141	0.76	0.9885	0.78	0.06283	0.20	696.5	698.0	702.6	0.96
O (5)	0.87	102	2.2	2722	7.95	0.1139	0.20	0.9858	0.23	0.06278	0.11	695.2	696.6	700.9	0.88

Note: All zircons were extensively abraded prior to analysis.

[a] Number of zircon crystals analyzed given in parentheses.

[b] Measured ratio (uncorrected for fractionation).

[c] Corrected for fractionation plus Daly bias ($0.18 \pm 0.09\%$ amu^{-1}), spike, blank, and initial Pb. Errors are 2σ. Total laboratory Pb blank ranged from 0.5–2.5 pg (±50%) during the course of the study; U blank is $\leq$0.5 pg (±50%). Initial common Pb composition is estimated using the crustal growth model of Stacey and Kramers (1975).

[d] ^{207}Pb/^{235}U–^{206}Pb/^{238}U error-correlation coefficient (following Ludwig, 1989).

Table 2
Sm–Nd isotopic data for intrusive rocks in the Tazigzaout inlier

Sample	Age (Ma)	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd^{a}/^{144}Nd$	$\varepsilon_{Nd}(0)^{b}$	$\varepsilon_{Nd}(t)^{b}$	$T_{DM}{}^{c}$
1. Augen granite gneiss	753	8.74	1.94	0.1340	0.512582 ± 5	−1.1	+4.9	890
2. Medium grained granite	705	4.42	0.94	0.1279	0.512574 ± 7	−1.2	+5.0	840
repeat		4.46	0.94	0.1281	0.512576 ± 8	−1.2	+5.0	840
3. Gabbro	752	8.18	1.71	0.1265	0.512602 ± 7	−0.7	+6.0	780
4. Gabbro	752	9.69	1.92	0.1199	0.512564 ± 7	−1.4	+5.9	790
5. Metagranite	750	12.8	3.02	0.1427	0.512667 ± 8	+0.6	+5.8	820
6. Fine grained granite	701	8.88	1.90	0.1293	0.512608 ± 7	−0.6	+5.5	795
7. Granitic dike	700	16.6	2.91	0.1060	0.512490 ± 5	−2.9	+5.3	790

[a] Measured ratio, corrected for spike and normalized to $^{146}Nd/^{144}Nd = 0.7219$. Uncertainties ($\pm 2\sigma_m$) refer to least significant digit.
[b] $\varepsilon_{Nd}(0) = (\{[^{143}Nd/^{144}Nd]^{sample} - [^{143}Nd/^{144}Nd]^{bulk\ earth}\}/[^{143}Nd/^{144}Nd]^{bulk\ earth}) \times 10^4$; Bulk Earth values: $^{143}Nd/^{144}Nd = 0.512638$; $^{147}Sm/^{144}Nd = 0.1966$.
[c] Depleted mantle model age following model of DePaolo (1981).

All crystals were extensively abraded (1–3 psi for 1–3 days), using pyrite as the abrading medium, in an attempt to remove the portions most likely to have suffered Pb loss (e.g. Krogh, 1982). Procedures for further treating, selecting, and dissolving zircon follow those described by Samson and D'Lemos (1999). Details of U and Pb separation and mass spectrometric techniques are given in Samson and D'Lemos (1999). Data reduction protocols follow those of Ludwig (1990). Further details of analytical techniques are given in Table 1.

4.2. Sm–Nd isotope geochemistry

Seven samples, taken as representative of the main lithologies exposed in the inlier, were analyzed for Nd isotopic composition. The details of the procedures followed for whole-rock dissolution, chemical separation, and mass spectrometry are given in Samson et al. (1995). Typical reproducibility of $^{147}Sm/^{144}Nd$ ratios is typically better than 0.2% and initial ε_{Nd} values can usually be reproduced to within ±0.5 epsilon units. Initial ε_{Nd} values for the dated intrusions were calculated based on the new U–Pb zircon dates. The undated granites were calculated at 700 Ma, based on the 705 and 701 Ma ages of the two dated granitic intrusions. Additional details are given in Table 2.

5. Analytical results

5.1. U–Pb geochronology

Of three analyses of the augen granite gneiss, including a single grain and two analyses of ≤4 four crystals, one proved concordant while the two other are slightly discordant (Fig. 3). Together the three analyses provide an upper intercept date of 753 +1/−2 Ma (MSWD = 0.83) which is considered the best estimate for the timing of crystallization of the protolith to the augen granite gneiss. Of four analyses from a sample of the metagabbro, two are concordant while the remaining two are slightly discordant (2–3%). The two concordant analyses yield a weighted average $^{206}Pb^{*}/^{238}U$ date of 752.2 ± 2.4 Ma. Combining the two slightly discordant analyses with the concordant points produces an upper intercept date of 752 +1/−2 Ma. We consider this date as reflecting the timing of crystallization of the protolith to the metagabbro. A sample of the medium-grained muscovite granite was taken from the central portion of the intrusion. Of four analyses, including a single grain and three analyses of group ≤5 crystals, one is concordant and the three others slightly discordant (0.5–1%). Taken together, the four analyses provide an upper intercept date of 705 +2/−3 Ma. This upper intercept date is considered the best estimate for the timing of crystallization of the intrusion. A final sample was taken from a deformed sheet of the fine-grained leucogranite. Of four analyses of small groups of crystals, two are nearly concordant while the other two are more discordant (3–5%). The relatively large error ellipses on two of the analyses reflects the very small amount of radiogenic Pb (<20 pg) that was analysed. Together, the four analyses yield an upper intercept date of 701 +2/−1 Ma which is considered the best estimate for the timing of crystallization of the intrusion.

5.2. Sm–Nd isotope geochemistry

The initial ε_{Nd} values of all of the lithological units in the Tazigzaout inlier are very uniform, ranging from +4.9 to +6.0. The total range in depleted mantle model (T_{DM}) ages is 890–780 Ma, although five of the units have T_{DM} ages ≤820 Ma.

5.3. Interpretation

The high, positive ε_{Nd} values for all of the igneous units within the complex is indicative of an isotopically very juvenile source, or sources, of the intrusions, such as depleted-mantle derived material. This does not imply direct partial melting of the mantle as the source of the magmas, which in fact is inconsistent with the very siliceous nature of most of the intrusions. However, partial melting of juvenile crust that had already been extracted from depleted mantle is consistent with the data. Significant interaction with crustal materials that had very negative ε_{Nd} values at 750 Ma (either ancient crust or younger, but very evolved crust) is ruled out as it would require the mantle-derived component to have impossibly high ε_{Nd} values. The Nd isotopic data thus effectively rule out the possibility that the Neoproterozoic U–Pb zircon dates reflect the time of significant resetting or metamorphism rather than providing the timing of crystallization of the granite gneiss protoliths. If the granite gneisses were 2 Ga, but were significantly deformed between 752–700 Ma, they would have T_{DM} ages ≥2 Ga. Since the T_{DM} ages are no more than 150 m.y. older than the zircon ages (i.e. not 1300 m.y. older), the intrusions cannot be reworked Eburnean basement.

6. Discussion

6.1. Age of basement in the Bou Azzer inlier

The meta-igneous units and widespread muscovite pegmatite and leucogranite present within the Tazigzaout complex and numerous other sub-Ouarzazate Supergroup inliers within the Bou Azzer inlier have previously been considered to be *c*. 2 Ga Eburnean basement (Choubert, 1963; Leblanc, 1981a; Saquaque et al., 1992). This interpretation was made on the basis of lithological and deformational similarities to WAC basement units to the south and west of the Bou Azzer-El Graara inlier (e.g. Zenaga inlier). We interpret our U–Pb zircon data as demonstrating that the protoliths to the gneissic and igneous basement rocks within the Tazigzaout complex (part of the Bou Azzer-El Graara inlier) were emplaced at *c*. 755 and *c*. 700 Ma and hence the widely accepted view that all gneisses within this inlier are *c*. 2 Ga Eburnean basement is incorrect. Moreover, the ages for these units are significantly older than, and lithologically distinct from, the *c*. 650 Ma and younger "Pan-African" units of the Bou Azzer inlier. They thus relate to a previously unrecognized Neoproterozoic tectonothermal episode in the region. The rocks of the Tazigzaout complex do share many lithological and structural features with other, also supposedly Eburnean, basement exposures elsewhere within the Bou Azzer inlier. Our dating demonstrates the untrustworthiness of using broad lithological similarities to assign ages to units within the Bou Azzer inlier by correlation to those outside of the inlier elsewhere on the WAC. This raises the question about the existence of 2 Ga Eburnean basement *anywhere* within the Bou Azzer inlier. Since the only basement units within the Bou Azzer inlier to have been dated using modern techniques have now been shown to be Neoproterozoic, we urge caution in interpreting any meta-igneous units within the Bou Azzer inlier rocks as being 2 Ga basement without careful re-assessment or dating. While 2 Ga Eburnean gneisses may be present, there is currently no compelling structural, lithological or isotopic argument to demand its existence. Indeed, based on the new data, we suggest that exposures of Eburnean basement may be completely absent from the Bou Azzer inlier.

6.2. Ages of deformation events in the Bou Azzer inlier

Mineralogies and microstuctures from the augen granite gneiss and metagabbroic units of the Tazigzaout complex demonstrate that the first recorded deformational event (D_1) involved upper greenschist to amphibolite facies metamorphism and dextrally transpressive deformation. The upper age limit of this tectonothermal event is constrained by the protolith crystallisation age of the augen granite gneiss and metagabbro, but as the mineralogies and microstructures in the gneisses are wholly metamorphic (i.e. there is no evidence for syntectonic emplacement), deformation could have been significantly after *c*. 750 Ma. We believe that the intrusion of the variably deformed syn-tectonic leucogranite sheets took place during the later stages of the same, single ductile deformation event recorded in the gneisses. The weakly deformed sheets and undeformed leucogranite pluton which we have dated were emplaced late-syntectonically at 705–701 Ma close to, or following, cessation of ductile deformation within the shear zone, placing a lower limit on the D_1 tectonothermal event. Hence the age of deformation was certainly between 753 and 701 Ma, but, if our field interpretation is correct, and unless this was a prolonged event, it is most likely that deformation occurred towards the younger extent of this age range (i.e. *c*. 700 Ma).

A change in kinematics and metamorphic grade indicate that top-to-the-north thrusting and lower greenschist facies fabric development in the narrow shear zone which juxtaposes the gneisses and quartz diorite took place during a second, discrete, tectonothermal event (local D_2). This must clearly post-date emplacement of the quartz diorite, and we consider that this was at a late stage during the lower greenschist facies events observable across other parts of the Bou Azzer inlier. Deformation across much of the Bou Azzer inlier is recorded by folding in various volcano-sedimentary sequences, shearing of ophiolite units and emplacement and deformation of numerous syn-tectonic quartz diorites (Saquaque et al., 1992; Inglis et al., 2005). The intrusion of quartz diorite bodies occurred throughout the interval of 652 ± 2 Ma to 640 ± 2 Ma (Inglis et al., 2005). The age of the localised reworking and extension is not well constrained, but was accomplished prior to the eruption of the overlying lavas of the late Neoproterozoic Ouarzazate Supergroup (*c.* 580 Ma) which are apparently unaffected.

6.3. Relevance of c. 750 and 700 Ma magmatism in the Bou Azzer inlier

Because of the deformed nature of the units, the tectonic contacts, and limited exposure it has proven impossible to determine what the host rocks to the Tazigzaout complex were. Based on structural data and field relationships it is not clear whether the complex was intruded into basement of the WAC, or whether the units represent an entirely allochthonous terrane accreted to the WAC. However, the Nd isotopic data for all samples from Tazigzaout indicate a very juvenile source. Magmas generated by melting of 2 Ga or older WAC crust would have ε_{Nd} (750 Ma) values of approximately -14 to -12, assuming typical upper continental crustal $^{147}Sm/^{144}Nd$ ratios (i.e. 0.12) and that the 2 Ga crust itself was juvenile. Even incorporating just 20% of such material in depleted-mantle derived melts would produce ε_{Nd} (750 Ma) values closer to 0 rather than +5 or +6. Thus we suggest that the igneous units within the Tazigzaout complex were not intruded into Paleoproterozoic crust of the WAC and thus either the WAC does not exist beneath the Bou Azzer region, or the 750–700 Ma magmatism occurred elsewhere, and the complex is part of an allochthonous terrane.

Although a 750–700 Ma juvenile magmatic belt in Morocco had not previously been identified, there are other similar crustal belts of this age in proximity to the WAC. In Mali, between the westernmost Tuareg Shield and the eastern margin of the WAC, there is an elongate belt of gneisses and metavolcanic and metavolcaniclastic rocks of the Tilemsi Group (Caby et al., 1989). Emplaced into the Tilemsi Group are gabbroic, quartz dioritic, and trondhjemitic bodies. U–Pb zircon dates for these intrusions include 726 +7/−3 Ma for a quartz diorite sheet, and 710 +6/−3 Ma for a trondhjemite (Caby et al., 1989). This region is also envisioned to have formed on oceanic crust, i.e. it too must be considered an allocthonous terrane, as the $\varepsilon_{Nd}(t)$ values of the rocks range from +4.3 to +9.5 (Liégeois et al., 1987; Caby et al., 1989). A further similarity between the Tilemsi Group rocks of Mali and the Tazigzaout rocks in Morocco is that both contain $\geq$700 Ma rocks in close proximity to intrusions nearly 100 m.y. younger. Although such similarities do not demand any links between the two regions, the available data are consistent with a single origin of the two regions, followed by separation and a distinct transport history. At the very least, documenting that there are two areas of significant 750–700 Ma deformed crustal belts bordering the WAC indicates that this interval of Neoproterozoic time was very important for the production and subsequent orogenesis of juvenile continental crust.

There are other, non-African, regions of ~700 Ma juvenile crust that are thought to have at least a peri-Gondwanan, if not West African, origin that might also have links to the newly discovered Neoproterozoic Tazigzaout belt. A recently identified unique portion of the Cadomian Orogen in France contains isotopically juvenile gneisses ($\varepsilon_{Nd}(t) \approx +5$) with protolith ages of 750–740 Ma (Samson et al., 2003). This region, called the Port Morvan terrane, contrasts strongly with typical Cadomian crust which is isotopically very evolved ($\varepsilon_{Nd}(t) = -10$ to -5) and approximately 150–135 m.y. younger. Similarly, the Burin Group, an intriguing group of oceanic-like rocks in southeastern Newfoundland considered part of the Avalon terrane, have been dated at 763 ± 3 Ma (Krogh et al., 1988). This age is much older than typical Avalonian rocks and it may prove to part of a distinct terrane, just like the Port Morvan terrane within Cadomia. Thus, although speculative, there is at least the possibility that such regions may be related to the Tazigzaout complex and that each was once part of a much larger belt that was subsequently fragmented into disparate pieces. Clearly much more work is required to fully characterize each of the regions before this speculation can be considered further.

6.4. Broader implications

Our geochronological and structural studies have demonstrated an early, previously unrecognized period of Neoproterozoic deformation in the Bou Azzer inlier, bracketed between 752 and 701 Ma. This tectonothermal event took place *c.* 50–100 Ma before what has previously been attributed to the main period of Pan-African deformation in Morocco at *c*. 650 Ma. Although the various-age fabrics exhibit a similarly oriented regional structural grain, the significant time gap makes it unlikely that the two events are directly related. We therefore consider there to be evidence for two discrete Neoprototerozoic (Pan-African) events in the Anti-Atlas of Morocco. This situation is similar to that described from outside of Morocco (e.g. the Tuareg shield, Liégeois et al., 1994; Liégeois et al., 2003).

It is the mineralogies and structures resulting from the early (our D_1) Pan-African event that have been previously misidentified as being Eburnean. This is understandable as they do indeed pre-date what has long been thought of as the main phase of Pan-African deformation (our D_2). However, this means that there is a high likelihood that many deformational features identified as predating a Pan-African event in the Anti-Atlas of Morocco may also be mistakenly identified as Eburnean features. Indeed, given the intensity of the deformation of the relatively young rocks in the Tazigzaout complex, the possibility that a significant component of the deformation observed within *bona-fide* Eburnean units on the nearby margin of the WAC could actually be early - late Neoproterozoic rather than Paleoproterozoic must be raised. Hence, the new data presented here demands a careful reassessment of the deformational history of the basement units within the entire margin of the WAC in Morocco with regards to which features are Palaeoproterozoic and which are much younger.

We have shown that at least one example of supposed Eburnean basement within the Bou Azzer inlier, is in actuality a fragment of a Neoproterozoic meta-igneous complex. Our ongoing field investigations indicate that the remaining "basement" exposures of the Bou Azzer inlier share many characteristics with the Tazigzaout complex, and we see no compelling reason to now regard any of these units as being Eburnean in age. Moreover, given the deformational state of these Neoproterozoic rocks, we consider it most likely that together these units represent fragments of an allochthonous terrane that has been tectonically emplaced onto the WAC, possibly along with the ophiolitic and arc volcanic units that comprise much of the remainder of the Bou Azzer inlier. As such, it may have been transported (thrust) a significant distance. The absence of WAC basement, and the allochothonous nature of the opholitic/arc units, would mean that the placing of the WAC plate boundary through the Bou Azzer region as depicted on many geological maps could be incorrect, as has also been suggested by Ennih and Liégeois (2001) on the basis of other arguments.

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