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Proterozoic blueschist-bearing mélange in the Anti-Atlas Mountains, Morocco

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Abstract

Blueschists from the Bou Azzer inlier provide compelling evidence for Late Proterozoic subduction in the Anti-Atlas Mountains of Morocco. High-pressure/low-temperature metabasites containing blue amphibole minerals crossite and magnesioriebeckite record pressures in excess of 5 kbar. Together with regional relationships, the geologic setting of the blueschists constrains the polarity of Pan African subduction in this region, which occurred from $\sim$750 to 600 Ma. Blueschist facies rocks crop out in a heterogeneous assemblage of variably deformed and metamorphosed tectonic slices of ophiolitic fragments enclosed in a schistose serpentinite matrix. The mélange belt containing the blueschist facies rocks is intruded by a number of diorite plutons, one of which has yielded a U/Pb radiometric age of 650 Ma. Together with Transaharan Belt to the southeast, the Anti-Atlas suture zone exposed within the Bou Azzer inlier contains among the oldest known blueschist-bearing, ophiolitic mélanges in the world.

Keywords: Pan African orogeny; Neoproterozoic; Blueschist; Ophiolites; Anti-Atlas Mountains

1. Introduction

One of the most diagnostic characteristics of Phanerozoic subduction is the formation of high-pressure/low-temperature metamorphic suites (Miyashiro, 1973; Maruyama et al., 1998). Blues-

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chists mark the leading edge of a subduction plate boundary and indicate subduction polarity by pressure increases (Dewey and Bird, 1970; Sengör, 1984). While Precambrian orogenic belts have been convincingly interpreted in terms of terrane elements known from modern plate boundaries (Gass, 1981; Kröner, 1983; Karson, 2001), Precambrian blueschist-bearing subduction mélanges are exceedingly rare (Liou et al., 1990), reflecting the well known observation that blueschist facies lithologies appear to become less common with age. Explanations for the paucity of ancient high-pressure metamorphic rocks include: their precarious positions at the leading edges of subduction zones that make them vulnerable to subduction and crustal recycling (Möller et al., 1995); uplift and erosion during continental collisions; retrogression to greenschist facies assemblages during later tectonic events (Zwart, 1967; Ernst, 1988); elevated Precambrian geotherms (DeRoever, 1956; Burke et al., 1977); more limited upper mantle convection and thinner lithosphere in the Precambrian (Liou et al., 1990).

Few well-documented examples of Precambrian blueschist terranes in collisional orogens exist. Most of the known Precambrian blueschists occur in coherent terranes, not as tectonic blocks encased in ophiolite-bearing mélanges (Liou et al., 1990). Blue amphiboles, eclogites, and other high-pressure metamorphic rocks have been reported from the Pharusian and Dahomeyide orogens of the Transaharan Belt (Caby et al., 1981; Affaton et al., 1991; Caby, 1994; Jahn et al., 2001). The Transaharan Belt occurs 2000 km southeast of the Anti-Atlas region, and probably represents a continuation of the same Pan African orogenic belt (Leblanc, 1975; Caby et al., 1981; Hefferan et al., 2000). Together, the Transaharan and Anti-Atlas belts contain among the oldest known high-pressure/low-temperature ophiolite-bearing mélanges in the world. In this paper, we will discuss the occurrence of blueschists within the Bou Azzer inlier and address regional implications.

1.1. The Anti-Atlas Pan-African suture

The southern Anti-Atlas belt of central Morocco (Fig. 1) is marked by a Late Proterozoic suture ('accident majeur' of Choubert, 1947) between the northern rifted margin of the West African craton with a Neoproterozoic magmatic arc (Saghro) to the north (Saquaque et al., 1989a,b). The northern margin of the West African craton consists of 2.0–2.1 Ga Eburnian gneisses and granites (Charlot, 1978; Boher et al., 1992; Walsh et al., 2002; Thomas et al., 2002). These Eburnian gneisses are overlain by relics of a late Proterozoic sequence of quartzite and carbonate rocks and alkaline basaltic lavas. The overlying sedimentary rocks and alkaline basaltic lavas are interpreted as the remnants of a Neoproterozoic rifted margin of the West African craton (Leblanc and Moussine-Pouchkine, 1994; Bouougri and Saquaque, 2000).

The Anti-Atlas is nonconformably overlain by a thick blanket of mildly deformed and metamorphosed pyroclastic and epiclastic rocks (Ouarzazate Formation) and carbonate and clastic rocks (Adoudounian Formation) that span the Cambrian/Precambrian boundary (Precambrian III of Choubert, 1947). These nonconformably overlying rocks mask the underlying Pan African exposures. However, erosional inliers provide windows to the underlying Pan African structures. The Bou Azzer and Siroua inliers occur north of the West African craton, exposing critical segments of the Anti-Atlas suture zone (Fig. 1). These inliers reveal outcrops of complexly deformed medium- to low-grade metasedimentary, metavolcanic and metaplutonic rocks overprinted by a regional schistosity and cut by sinistral shear zones.

The Siroua inlier, located 50 km WNW of Bou Azzer, consists of highly sheared ophiolitic and metasedimentary rocks intruded by mafic to intermediate plutonic bodies (Choubert, 1947; Leblanc, 1975; Admou and Juteau, 1998; Admou, 2000; Thomas et al., 2002) and reportedly containing boninitic lavas (Chabane, 1991). Recent precision U–Pb dating provides temporal constraints on Pan African intrusions. Admou et al. (2002) report precise U–Pb date of 760 Ma for syn-orogenic diorites at Assif n'Tinzla and Assif n'Tourtit (Khzama, Siroua). Thomas et al. (2002) present new U–Pb SHRIMP dates which include: 2.035 Ga granitic orthogneisses of the Eburnian shield intruded by $\sim$780 Ma tholeiite dikes; 743+

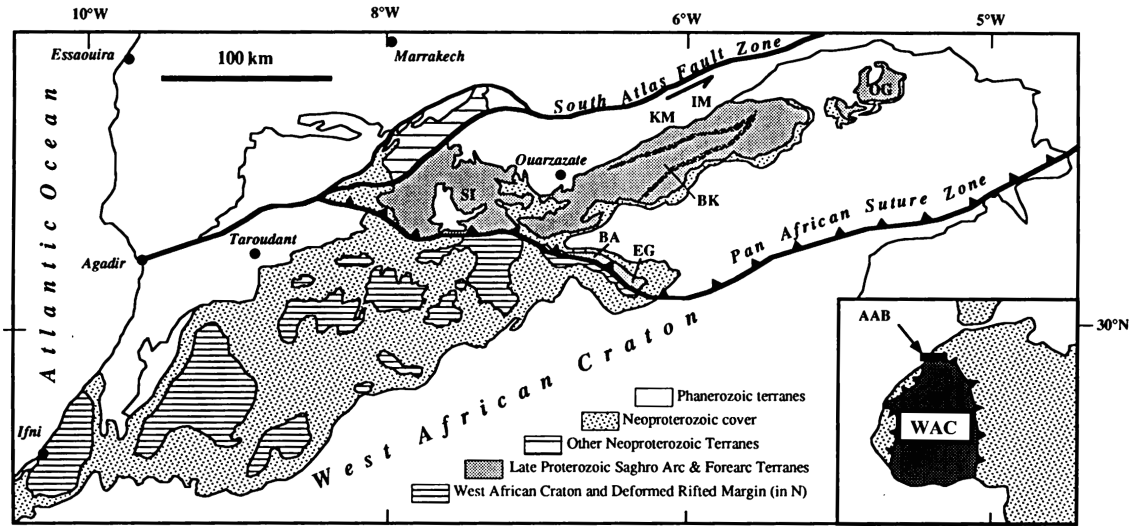

Fig. 1. Tectonic sketch map of the Anti-Atlas Belt (AAB in insert) of central Morocco. The Pan African suture zone in this region separates the Neoproterozoic Saghro Arc terrane to the north from the deformed rifted margin of the West African Craton to the south. Neoproterozoic arc and forearc terranes (truncated by the South Atlas Fault to the north) are exposed in inliers in Neoproterozoic to Lower Cambrian cover sequences. Arc Inliers: OG, Ougnat; IM, Imiter; KM, Kelaa des Mgouna; BK, Bouskour. Forearc Inliers: SI, Siroua; BA, Bou Azzer; EG, El Graara.

14 for syn-orogenic tonalitic orthogneiss; and late- to post-orogenic I-type granites ranging from $\sim$ 614 to 580 Ma. Thomas et al. (2002) attribute these dates to $\sim$780 Ma continental rifting of Eburnian crust, followed by subduction, island arc formation and collision from $\sim$750 to 580 Ma, with ophiolite emplacement occurring $\sim$660 Ma.

Approximately 75 km to the north, the Saghro inlier contains mafic to intermediate plutonic rocks that intrude metasedimentary and metavolcanic rocks. The age of major ENE-WSW trending shear zones are bracketed by pre- to syn-orogenic plutons that reportedly range in (U/Pb, zircon whole rock) age from 778 ± 44 to 580 ± 5 Ma (Mrini, 1993). The Saghro region is interpreted as a Neoproterozoic arc complex with intra-arc or back-arc basins built on oceanic crust (Saquaque et al., 1989a, 1992).

Several interpretations have been proposed for the tectonic development of Pan African structures in the Anti-Atlas region. Some authors have considered these inliers to represent a rifted margin and adjacent back-arc basin associated with a south-dipping subduction zone (Leblanc, 1975, 1981; Leblanc and Lancelot, 1980; Leblanc and Moussine-Pouchkine, 1994).

Ennih and Liégeois (2001) suggest that the Anti-Atlas Major Fault is an intracratonic aulacogen, unrelated to subduction. Ennih and Liégeois (2001) propose that much of the Anti-Atlas region is underlain by Eburnian basement. In the interpretation of Ennih and Liégeois (2001), the South Atlas Fault—not the Anti-Atlas Major Fault—represents the Neoproterozoic subduction boundary marking the northern edge of the West African craton.

Saquaque et al. (1989b) interpreted these areas as remnants of a forearc assemblage including an accretionary mélange and a forearc basin that evolved above a north-dipping subduction zone (Fig. 2). These authors interpret the Anti-Atlas 'Major Fault' (Anti-Atlas suture zone) as the locus of suturing between the Saghro Arc to the north and the West African craton to the south (Figs. 1 and 2). The tectonic contact exposed in the Bou Azzer inlier is interpreted as an exposure of the much more extensive Pan-African suture zone, which occurs along the northern edge of the West

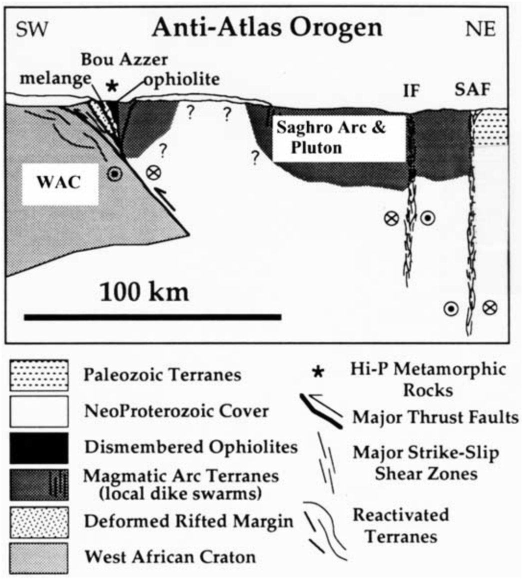

Fig. 2. Schematic cross section of the Anti-Atlas belt showing the tectonic setting of blueschists in the Pan African suture zone exposed in the Bou Azzer inlier.

African craton. The suture occurs in a complexly deformed belt of rifted margin and forearc rocks that have been tectonically shuffled, probably during the late stages of collision. In this interpretation, the Anti-Atlas Major Fault represents the Neoproterozoic suture zone and marks the northern edge of the West African craton.

As discussed in this paper, blueschist exposures in the Bou Azzer inlier strongly favor a history of north-dipping subduction prior to oblique collision along the Anti-Atlas Major Fault.

2. Bou Azzer inlier

In the Bou Azzer inlier (Fig. 3), three separate tectonic units interpreted as Neoproterozoic forearc/accretionary mélange assemblages are sutured against the deformed rifted margin of the West African craton. The forearc assemblages are defined on the basis of their composition, metamorphism, deformation, and igneous history (Saquaque et al., 1989b). They occur in belts only a few kilometers wide that roughly parallel the suture zone and are separated by oblique-slip fault zones. The internal structures and interpretations of these assemblages are outlined below, from south to north.

2.1. Accretionary mélange

A complexly deformed assemblage, adjacent to the West African craton has been interpreted as an accretionary mélange (Saquaque et al., 1989b) and as a rifted platform margin by (Leblanc, 1975; Leblanc and Moussine-Pouchkine, 1994). The accretionary mélange consists of tectonic slices derived from oceanic or arc terranes that have been juxtaposed along faults and shear zones (Fig. 3). The matrix of the mélange varies from schistose serpentinite to complexly deformed metasediment and metabasite (Fig. 4a). The matrix consists of chrysotile, talc, chlorite, epidote, quartz, green and brown hornblende, actinolite, albite, antigorite, lizardite, sphene, clinozoisite and calcite. Multiple cross-cutting schistosities and crenulations occur. Many parts of the mélange are nearly devoid of matrix material. Meter- to kilometer-scale blocks of contrasting lithologies are separated by narrow shear zones or faults.

The tectonic slices include: ophiolitic fragments, metagraywackes, argillites, metabasalts, meta-andesites, metatuffs, amphibolites, quartzites and metabasaltic breccias. A pervasive regional schistosity appears to affect the slices to varying degrees (Fig. 4b). This heterogeneous schistosity is associated with regional greenschist facies metamorphism. On a fine-scale, the retrograde schistosity is manifest as spaced (few centimeters) cleavage cutting sedimentary, volcanic, plutonic and metamorphic protoliths, notably amphibolites and blueschists. Trace element geochemistry of metabasalts from the accretionary mélange assemblage indicates a diverse assemblage of calc-alkaline, enriched tholeiites and alkaline compositions (Naidoo et al., 1991). Naidoo et al. (1991) interpreted these metabasalts as representing island arc, seamount and/or continental rift volcanic sequences.

During terrane assembly, diorite-quartz diorite plutons and diabase dikes intruded these sequences. All units were subsequently deformed and metamorphosed. Radiometric dates on various parts of this assemblage have yielded a broad

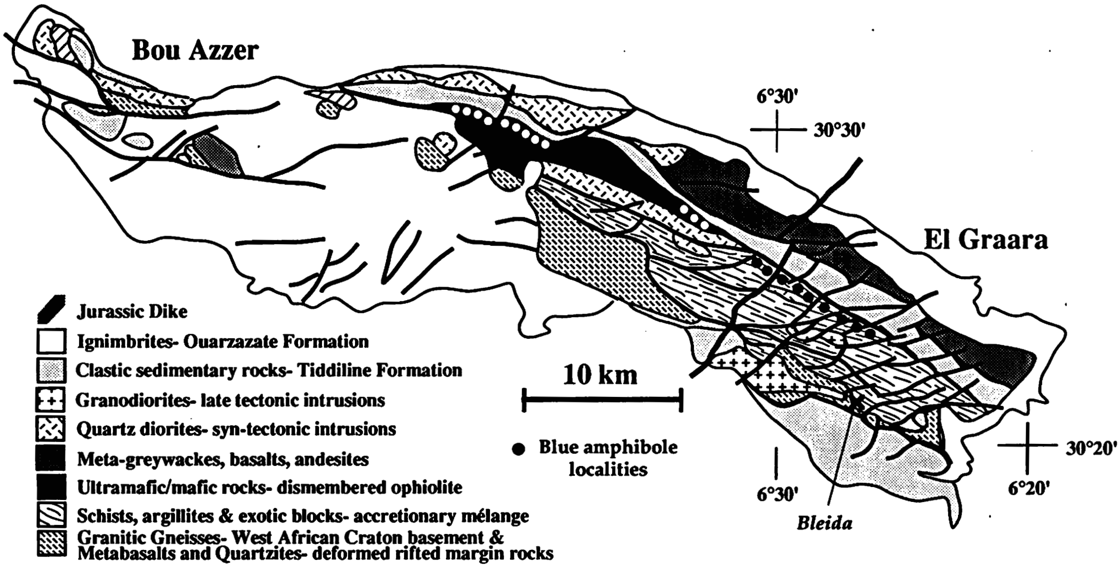

Fig. 3. Highly generalized map of the Bou Azzer Inlier of the southern Anti-Atlas. Blueschist assemblages (black/white dots) occur along the northern edge of the accretionary mélange and the northern edge of large ophiolite slices in the mélange.

range of ages from ~650 to 575 Ma, with a notable pulse of calc alkaline magmatism at ~650 Ma.

The accretionary mélange appears to be a complex ensemble of diverse igneous, metamorphic, and sedimentary rock units that have been juxtaposed and deformed in a sparse, schistose matrix. Although, as noted by Leblanc and Moussine-Pouchkine (1994), coherent stratigraphic relationships can be traced along strike, in some cases for kilometers; however, these are confined to individual rock units separated from other units by tectonic contacts. These types of kilometer-scale coherent sequences occur in other accretionary mélanges (e.g. Raymond, 1974; Kapp et al., 2000) and do not constitute compelling evidence for a continuous stratigraphic succession.

2.2. Ophiolitic rocks

The ophiolitic rocks in the Bou Azzer inlier crop out in exposures about 15 km long and 4 km wide (Fig. 3, the 'central terrane' of Saquaque et al., 1989b). The ophiolitic rocks comprise dismembered tectonic slices of mafic and ultramafic rocks between the accretionary mélange to the south and a forearc basin assemblage to the north. The ophiolitic slices consist of individual and composite masses of ultramafic and mafic plutonic rocks cut by diabase dikes (Admou, 1989). Although it is not clear that all of the slices necessarily come from a single dismembered terrane, the following relations can be inferred from the assemblage viewed as a whole.

The ophiolitic mélange consists of large tectonic slices, some of which are kilometers in length, in a serpentine-rich matrix. The serpentine matrix consists of chrysotile with minor antigorite and lizardite. Tectonic slices include serpentinized harzburgite, dunite, wehrlite/clinopyroxenite masses with minor interlayered gabbros up to 1 km across. These serpentinized ultramafic rocks are cut by at least two generations of minor wehrlite and gabbro bodies and numerous diabase dikes. Slices composed of sheeted dike complex and basaltic volcanic rocks occur locally in fault contact with the other ophiolitic units (Hilal, 1991).

Multiple generations of diabase dikes in the ophiolitic mélange provide evidence of a complex, multistage magmatic history. In regions of schistose serpentinites, the dikes are folded and sheared. Elsewhere, the dikes are little deformed in the massive serpentinite or gabbro slices. Dis-

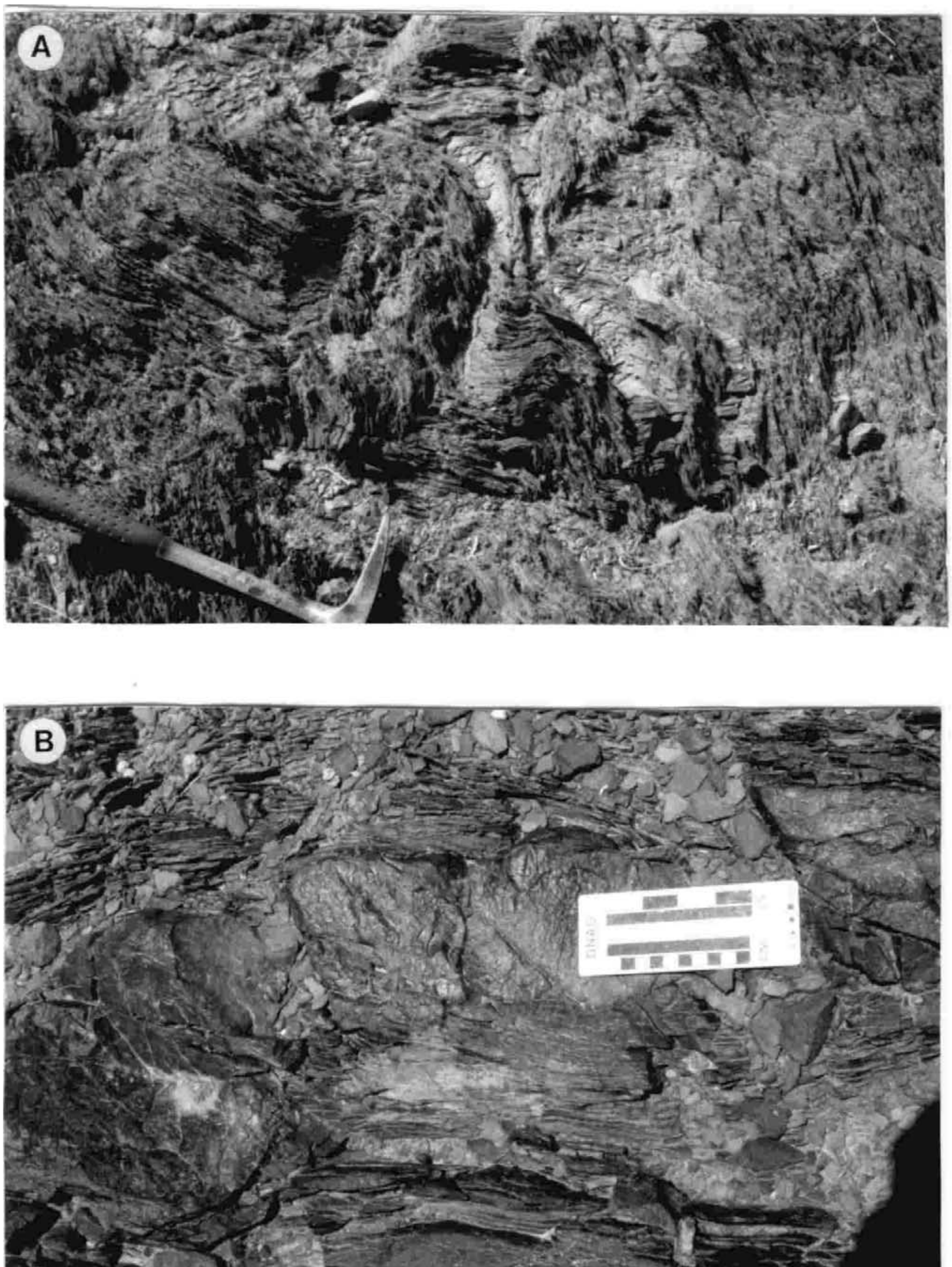

Fig. 4. Typical exposures of accretionary mélange from the southern terrane of the Anti Atlas belt. (a) Complexly deformed mélange matrix with multiple generations of folds and a strong schistosity. (b) Folded metabasite slice in the mélange typical of blueschist-bearing rocks. Cleavage developed along block margins grades into that of the schistose matrix.

crete, spaced (few centimeters) shear zones and fracture surfaces with concentrations of greenschist facies minerals cut all of the ophiolitic lithologies. Kinematic indicators in tectonic slices and matrix (S–C structures) are consistent with sinistral shearing (Admou, 1989; Cisse, 1989; Benyoucef, 1990). Late faults and obliquely trending dextral shear zones with calcite tension gashes cut across some parts of the area.

Geochemistry of the metabasalts indicates a calc-alkaline to arc-tholeiite provenance (Bodinier et al., 1984; Naidoo et al., 1991). A geochemical study conducted by Naidoo et al. (1991) indicated that the volcanic rocks associated with the dismembered ophiolite complex are predominantly low-Ti metabasalts displaying island arc tholeiite affinities.

Moderately deformed diorite to quartz diorite plutons cut the dismembered ophiolite and accretionary mélange assemblages. A diorite intrusion at Ait Ahmane, dated at 650 ± 2 Ma (precision U/Pb on zircon, S.D. Samson, unpublished data) is cut by spaced greenschist facies shear zones correlated with the main schistosity of the mélange belt. At Bleida, a late-orogenic granodiorite pluton cuts the mélange (Leblanc, 1975; Admou, 1989; Cisse, 1989) and has been dated at 575 Ma (precision U/Pb on zircon, S.D. Samson, unpublished data) and 615 ± 12 Ma (U/Pb; Ducrot, 1979).

2.3. Deformed forearc basin

The northern part of the Bou Azzer inlier ('northern terrane of Saquaque et al., 1989b) consists of a complex assemblage of layered metagraywackes, basalts, andesites and relatively undeformed intrusive bodies (Fig. 3, Tekiout et al., 1991). Compared with adjacent assemblages to the south, rock units are less deformed and more continuous in this region. Metagraywackes are interbedded with siltstones and tuffaceous units. The metasedimentary units display fining-upwards sequences, convolute beds and slump deposits suggesting rapid deposition and syn-sedimentary instability, possibly associated with deposition by turbidity currents.

Forearc basin rocks exhibit two folding events. NNE-trending F_1 fold axes are map-scale, lack an axial-plane foliation, and are cut by large interfingering masses of spillite and keratophyre (Leblanc, 1981). WNW-trending F_2 fold axes occur in regions of locally intense deformation, wherein interlayered spilite and keratophyre are isoclinally folded in an axial-plane foliation. The F_2 foliation cuts the axial-planes of the F_1 folds at right angles. F_2 folds are associated with a regional WNW-striking schistosity, steeply dipping to the northeast, and parallel to the inliers tectonic boundaries.

Naidoo et al. (1991) conducted geochemical studies on volcanic rocks ranging in composition from basaltic andesite to rhyolite. Trace element results indicate that the volcanic rocks bear calc-alkaline and island arc tholeiite characteristics, indicating a subduction related origin. Mildly deformed quartz diorite plutons, similar to those in the accretionary mélange, intrude this assemblage.

The forearc basin assemblage is in tectonic contact with the accretionary mélange to the south. The lack of ophiolitic material and other exotic tectonic blocks and the more consistent and coherent stratigraphic relations, suggest that this area may represent a mildly deformed volcanic-sedimentary basin. We interpret this as the remnants of a forearc basin and note that it is very similar to rock units in the Saghro Arc to the north, suggesting that this assemblage may be continuous beneath later cover sequences (Fig. 2).

2.4. Terrane assembly

The intrusion of dikes and plutons and deposition of clastic rock units provide important constraints on terrane assembly described above. Several quartz diorite bodies cut schistosities and contacts between local rock units thereby documenting the piecemeal assembly of many distinct tectonic slices. The mildly deformed Bleida granodiorite (575 Ma precision U/Pb on zircon, S.D. Samson, unpublished data; 615 ± 12 Ma, U/Pb; Ducrot, 1979) intrudes the accretionary mélange, marking the final collision of the Saghro Arc with the rifted margin of the West African craton.

During this collision, a series of elongate basins filled with upward-coarsening sedimentary sequences formed along the major tectonic contacts (Fig. 3). Clastic sedimentary rocks of the Tiddiline Formation are interpreted to have formed in collisional basins during the initial stages of oblique suturing of the forearc assemblages to the West African craton (Hefferan, 1992; Hefferan et al., 1992). Minor felsic porphyry dikes intrude the faulted contacts of the basins (Saquaque, 1992).

Swarms of basaltic dikes cutting both the forearc assemblages and the Tiddiline basins mark the end of strike-slip deformation in the region (Saquaque, 1992). Subsequently, extensive silicic pyroclastic and epiclastic sediments of the late Neoproterozoic Ouarzazate Formation (565 ± 20 Ma, U/Pb, Juery, 1976) were deposited. These, in turn, are overlain by carbonate rocks and continental deposits of the Adoudounian Formation. The Adoudounian Formation is cross-cut by a syenite pluton dated at 534 ± 10 Ma (U/Pb, Ducrot and Lancelot, 1977). Mild extensional deformation during or after the deposition of the Ouarzazate Formation resulted in normal faulting and local angular unconformities between these two units (Choubert, 1947; Leblanc, 1975; Azizi Samir et al., 1990).

2.5. Bou Azzer blueschists

Blueschists containing magnesioriebeckite and crossite occur discontinuously along the northern contact of the accretionary mélange belt and along the northern edge of the ophiolites for a total length of at least 20 km along strike. The blueschists, first reported by Hilal (1991), occur in a series of tectonic slices several kilometers long and a few hundred meters in width. The slices are composed of interlayered metagraywacke, metatuffs, and argillites with minimal matrix (Fig. 4b). Subordinate metabasite layers are 1–2 m thick and calcite-filled amygdules are preserved in some exposures. All lithologies in the slices are highly deformed by a nearly pervasive anastomosing schistosity.

Kinematic indicators (S–C fabrics) in the schists show evidence of two discrete events. An S_1 schistosity observed in blue amphibole samples is consistent with dominantly southward-vergent thrust movements, as previously noted by Leblanc (1975), Saquaque (1992). This appears to have been the dominant sense of motion during Neoproterozoic shortening. The S_1 fabric is overprinted by late retrograde sinistral shear zones concentrated along discrete surfaces with greenschist facies mineral assemblages (Leblanc, 1975; Saquaque, 1992). The retrograde deformation and metamorphism is nearly pervasive in the mélange matrix but is limited to spaced shear zones in the metabasite slices. This regional S_2 schistosity occurs throughout the accretionary mélange and ophiolitic assemblages. Late ENE-WSW sinistral and NNW-SSE dextral shear zones with calcite veining cut the regional S_2 schistosity. Greenschist facies mineralogy dominates most of the metabasite slices; blueschists facies minerals are preserved only locally with currently known exposures being separated by tens of meters. Amphibolite to greenschist facies metamorphic aureoles occur along contacts of diorite-quartz diorite plutons. The plutons cut blueschist-bearing rock units and, therefore, it is possible that local contact metamorphic effects may have obscured or altered nearby blueschists.

2.6. Petrographic characteristics

Petrographic examination of blue amphibole samples indicates a complex history of deformation and metamorphism. Blue amphibole, commonly in dense aggregates, occurs along with the mineral assemblage grossular garnet + epidote + albite + quartz ± oxides (Hilal, 1991). In the best preserved samples, elongated domains (usually less than 1 cm wide) of blue amphibole aggregates and individual crystals parallel compositional banding defined by quartz-rich and amphibole-rich layers. Although strains are clearly very high as evidenced by isoclinal folds and transposed layering, there is little sign of internal strain of the amphibole crystals (Fig. 5a) suggesting an interval of static crystal growth. Multiple generations of amphibole growth are obvious from petrographic relations. For example, strain-free amphibole grains are oriented parallel to the axial-planes of isoclinally

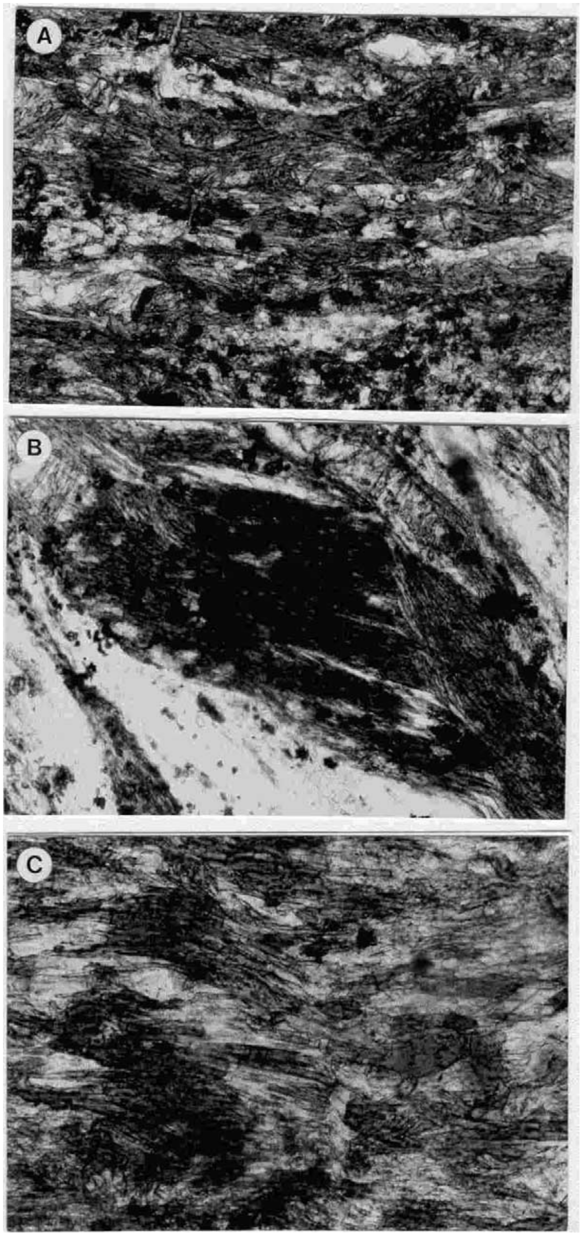

Fig. 5. Photomicrographs of blueschists from the Anti-Atlas subduction mélange. (a) Strong schistosity defined by blue amphibole. (b) Large porphyroblast of blue amphibole overgrown on one edge (right) by later, undeformed blue amphibole. (c) Oblique shear zone (NW/SE in photo) cuts strong schistosity defined by blue amphibole. Shear zone is marked by fibrous yellow–green actinolite amphibole. Field of view is 4 mm in long dimension.

folded layers of magnesioriebeckite, crossite and albite + quartz and transect the older folded schistosity. Thin sections display discrete domains (1–2 mm wide) of greenschist facies mineralogy (albite + epidote + chlorite + actinolite ± quartz ± calcite) or finely recrystallized quartzite that separate microlithons of blueschist mineralogy. Some amphibole porphyroblasts have extensional microfractures and veins that appear to have opened during rotation. Locally, rotated equant porphyroblasts of amphibole have sigmoidal pressure-shadows of later blue amphibole fibers (Fig. 5b and c) reflecting fluctuating temperature/pressure conditions over time.

2.7. Mineral chemistry

Chemical analyses of Bou Azzer blue amphibole samples are presented in Table 1 (after Droop, 1987) and shown graphically in Figs. 6 and 7. Microprobe analyses were conducted on 18 blue amphiboles from metabasites within the mélange. As depicted in Fig. 6, the blue amphibole samples cluster tightly along the border separating the fields of crossite and magnesioriebeckite. Blue amphiboles from the fine-grained metabasites have been plotted on a Na versus Al^{IV} diagram (after Brown, 1977). As illustrated in Fig. 7, the blue amphibole samples from the metabasites are highly sodic and likely formed at pressures in excess of 6–7 kbar. The Al_2O_3 content (2.67–3.83 wt.%) of the blue amphibole samples suggest pressures in excess of 4.5–5 kbar (Maruyama et al., 1986). In the lower blueschist facies, magnesioriebeckite and epidote are stable at pressures as low as 5 kbar, and crossite is stable in the temperature range 350–400 °C at pressures ~ 6.5 kbar (Evans, 1990). The Bou Azzer metabasite compositions are typical of sodic amphiboles of the lower blueschist facies conditions (e.g. Brown, 1977). The mineral assemblages and mineral chemistry of the Na-amphiboles indicates that the blue amphibole-bearing components of the accretionary mélange formed under high-pressure/low-temperature conditions typical of subduction zones.

Table 1
Table presents the microprobe results of 18 blue amphiboles samples

Sample Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	54.96	56.16	55.99	56.05	55.28	55.84	54.63	55.74	55.87	55.55	55.61	54.83	55.29	53.71	54.79	55.68	56.04	55.50
Al_2O_3	2.92	3.53	3.75	3.61	2.96	3.53	2.67	3.83	3.73	3.35	3.28	2.95	3.00	2.81	3.59	3.80	3.77	3.73
TiO_2	0.04	0.01	0.04	0.05	0.07	0.04	0.02	0.06	0.02	0.03	0.08	0.08	0.11	1.15	0.08	0.24	0.04	0.13
FeO	19.52	19.24	19.68	19.80	19.10	20.01	18.98	21.53	21.55	21.94	22.45	23.41	23.30	22.96	21.86	21.16	21.96	21.41
MnO	0.21	0.28	0.33	0.23	0.32	0.18	0.32	0.31	0.27	0.18	0.37	0.30	0.33	0.29	0.24	0.20	0.28	0.34
MgO	9.79	9.67	9.84	9.69	10.10	9.23	10.37	8.24	8.28	8.29	7.66	7.26	7.63	7.33	8.04	8.03	8.16	8.26
CaO	1.88	1.60	1.61	1.83	2.28	1.22	3.27	1.09	1.15	0.67	0.97	1.19	1.16	2.10	1.53	0.69	0.77	1.25
Na_2O	6.28	6.34	6.69	6.42	6.04	6.67	5.31	6.43	6.34	6.29	6.32	6.28	6.14	6.27	5.80	6.68	6.81	6.10
K_2O	0.04	0.00	0.00	0.02	0.00	0.03	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.05	0.00	0.00	0.03
Total	95.64	96.83	97.93	97.70	96.15	96.75	95.60	97.24	97.22	96.30	96.74	96.31	96.96	96.63	95.97	96.48	97.83	96.74
Si	8.47	8.55	8.41	8.46	8.48	8.51	8.47	8.53	8.56	8.60	8.61	8.56	8.57	8.37	8.55	8.58	8.51	8.56
Al(IV)	0.02	0.00	0.08	0.04	0.03	0.00	0.06	0.03	0.01	0.01	0.00	0.00	0.02	0.09	0.05	0.00	0.02	0.03
Al(VI)	0.51	0.63	0.58	0.60	0.51	0.63	0.43	0.66	0.67	0.60	0.60	0.54	0.53	0.42	0.61	0.69	0.65	0.65
Fe^{3+}	1.24	1.20	1.26	1.21	1.21	1.22	1.20	1.36	1.36	1.60	1.39	1.40	1.53	1.04	1.44	1.25	1.37	1.40
Ti	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.14	0.01	0.03	0.00	0.02
Mg	2.25	2.19	2.20	2.18	2.31	2.10	2.40	1.88	1.89	1.91	1.77	1.69	1.76	1.70	1.87	1.84	1.85	1.90
Fe^{2+}	1.28	1.25	1.21	1.29	1.24	1.33	1.26	1.40	1.40	1.24	1.51	1.66	1.49	1.95	1.41	1.48	1.42	1.36
Mn	0.03	0.04	0.04	0.03	0.04	0.02	0.04	0.04	0.04	0.02	0.05	0.04	0.04	0.04	0.03	0.03	0.04	0.04
Ca	0.31	0.26	0.26	0.30	0.37	0.20	0.54	0.18	0.19	0.11	0.16	0.20	0.19	0.35	0.26	0.11	0.13	0.21
Na	1.81	1.87	1.86	1.83	1.75	1.93	1.59	1.91	1.88	1.89	1.90	1.90	1.85	1.77	1.76	1.99	2.00	1.83
Na (A)	0.06	0.00	0.09	0.05	0.04	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00
K	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00

These samples were obtained from metabasites exposed in the Bou Azzer accretionary mélange. Note that trivalent iron was not analyzed directly but calculated in order to optimize the amphibole formula to 13 cations and 23 oxygens (after Droop, 1987).

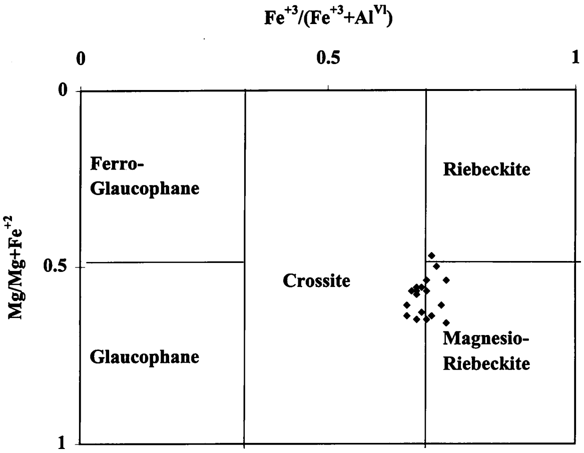

Fig. 6. Compositions of eighteen blue amphibole samples from fine-grained metabasites in the accretionary mélange of the Bou Azzer inlier. Crossite to magnesioriebeckite compositions are typical of blueschists from Phanerozoic accretionary mélanges. Plot for Na-amphibole compositions after Leake (1978).

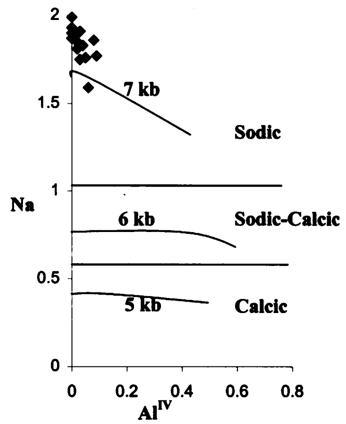

Fig. 7. Plot of Na vs. Al^{IV} (after Brown, 1977) for eighteen blue amphibole samples from fine-grained metabasites in the accretionary mélange of the Bou Azzer inlier. Mineral chemistry indicates relatively high-Pressure metamorphic conditions.

3. Discussion

The blueschist facies includes a range of temperature/pressure conditions such that workers have sub-divided the blueschist facies (e.g. Liou and Maruyama, 1987). As noted by Liou and Maruyama (1987), Ca- and Na-pyroxenes and glaucophane do not occur with metabasites of the intermediate facies series such as the Sanbagawa belt. Rather, Na-amphiboles such as crossite and magnesioriebeckite are associated with the Sanbagawa Facies Series. The epidote-blueschist paragenesis, defined by the stable mineral assemblage of epidote+crossite+quartz, occurs in higher temperature conditions exceeding the stability field of lawsonite (Evans, 1990). The epidote-blueschist paragenesis is an important lower blueschist assemblage that develops in metabasites.

Many other convergent margin assemblages record lower blueschist facies metamorphism in Phanerozoic subduction environments. In examining the Puerto Nuevo mélange complex of Baja, Mexico, Moore (1986) noted that Sanbagawa metabasites contain actinolite, epidote, and crossite rather than glaucophane, as well as calcite rather than aragonite. Milovanovic et al. (1995) document crossite-bearing schists from a suture zone assemblage within the Fruska Gora Mountains, Yugoslavia. Crossite, albite, epidote and phengite, corresponding to the epidote-blueschist paragenesis, indicate $P = 7–9$ kbar and $T = \sim 400$ °C. Helper (1986) estimated $P = >4–5$ kbar and $T = <360$ °C in epidote-blueschist paragenesis assemblages from the Condrey Mountain Window, Klamath Mountains of Oregon and California. Trouw et al. (1998), using crossite as a geobarometer (Brown, 1977), document $P = 4.6–6$ kbar in a subduction complex of the South Shetland Islands, Antarctica. In the Oman ophiolite, schists containing crossite, epidote and magnesioriebeckite indicate $T = 400–460$ °C and $P = 6.5–8.5$ kbar. This assemblage formed in an eastward-dipping subduction zone, based upon observed increases in metamorphic grade eastward (El-Shazly et al., 2001). Modern crossite-bearing schists have been reported by Fryer et al. (1999) in the Marianas forearc. Surface exposures of subduction zone mud containing serpentine, crossite and serpentinized mantle peridotite attest to the rapid rise of high-pressure fluids from depths as great as 25 km (Fryer et al., 1999).

The blueschist assemblage exposed in the Bou Azzer inlier has mineral assemblages similar to the well documented subduction mélanges described above, notably marked by the occurrence of crossite+epidote+magnesioriebeckite, and the absence of higher pressure minerals such as lawsonite, glaucophane, aragonite and jadeite. Available evidence suggests that the Bou Azzer blueschist rock samples formed at pressures in excess of 5 kbar pressure, and at temperatures ~350–400 °C, within the Sanbagawa Facies Series.

In the Bou Azzer inlier, meter- to kilometer-scale crustal blocks of dismembered ophiolites and metabasites bear the mark of blueschist metamorphism. Blueschist metamorphic assemblages may have once been much more extensive in the Bou Azzer region, but have been overprinted by greenschist facies metamorphism or altered in metamorphic aureoles of plutons. The sparse matrix of the mélange and shear zones that separate the discrete slices are structurally complex, even though the internal structure of the larger slices is commonly preserved. Deformation, metamorphism, and intrusion that attended initial suturing and later oblique convergence have probably modified this region to some extent.

The occurrence of blueschist facies metamorphic rocks in the accretionary melange, and the presence of greenschist facies metamorphism and calc-alkaline intrusions to the north, supports the northward dipping subduction model of Saquaque et al. (1989b). Saquaque et al. (1989b) propose that the Saghro magmatic arc and associated forearc assemblages in the Bou Azzer and Siroua inliers developed above a north-dipping subduction zone. Models which would place the Bou Azzer inlier and their blueschists in a back-arc setting (Church, 1980; Leblanc and Lancelot, 1980; Leblanc, 1981; Bodinier et al., 1984) would necessarily involve a subduction zone polarity flip from northward to southward subduction. No evidence exists for Neoproterozoic, pre-collision, subduction-related magmatism south of the Bou Azzer region. While southward dipping subduction north of the Saghro region is theoretically possible, no evidence for such a subduction zone or suture has been documented.

Ennih and Liégeois (2001) suggested that the Anti-Atlas Major Fault represents an aulacogen, asserting that the South Atlas Fault may represent the Neoproterozoic West African craton subduction zone. While an interesting proposal, the aulacogen model does not account for the occurrence of blueschists, the widespread calc-alkaline magmatic activity recorded from ~650 to 575 Ma and the pressure increase recorded from north to south within the Bou Azzer inlier

Despite the similarities with Phanerozoic blueschist-bearing accretionary mélanges, the provenance of the blueschist-bearing slices in the Bou Azzer inlier is not entirely clear. They may represent fragments of subducted forearc basement or a portion of the rifted margin of the West African craton that was subducted beneath the forearc. Exposure of previously subducted oceanic material could be accomplished by extreme extension perpendicular to the arc (Lister et al., 1984; Platt, 1986; Shermer, 1990) or by extension associated with oblique subduction (Avé Lallemant and Guth, 1990). Kinematic analysis of the deformation of the Anti-Atlas forearc is most compatible with the latter (Admou, 1989; Saquaque et al., 1989b; Saquaque, 1992).

4. Conclusions

Neoproterozoic blueschists within the Bou Azzer inlier mark the former location of a Pan African subduction zone. Evidence presented in this study suggests that rock samples containing crossite, magnesioriebeckite and epidote formed in depths exceeding 5 kbar and temperatures greater than 350 °C.

While Precambrian blueschists are uncommon, Precambrian blueschist-bearing mélanges in ophiolite belts are exceedingly rare (Liou et al., 1990; Maruyama and Liou, 1998). Other known Precambrian blueschist melanges of comparable age are those of the South Delhi Fold Belt of India (Sinha-Roy and Mohanty, 1988), the Aksu and Banxi Belts of China (Liou et al., 1990), the Avalon of New Brunswick (White et al., 2001) and in the Transaharan belt of West Africa (Caby, 1994; Jahn et al., 2001). Caby et al. (1981) note the occurrence of blue amphibole and aegerine in metabasites from a chaotic serpentinite mélange along the Pan African suture in northern Mali. Unlike the blueschists of the South Delhi Fold Belt and the Banxi Belt, the Anti-Atlas blueschists formed in ophiolite bearing accretionary mélanges produced along the leading edge of subduction zones.

The blueschist facies assemblage contained in Bou Azzer is similar to that reported for the Aksu blueschist belt in northwestern China, which may reportedly be ~700 Ma. Aksu contains Na amphiboles which include crossite and minor magnesioriebeckite (Liou et al., 1990; Maruyama et al., 1998). Liou et al. (1990) suggest that Precambrian blueschists may typically contain crossite, epidote, chlorite, albite, quartz ± actinolite, rather than higher pressure minerals such as glaucophane.

The Bou Azzer blueschist-bearing accretionary mélange was assembled during a protracted period (~750–600 Ma) of Pan African subduction and plutonism, followed by arc-continent collision. This inferred age of subduction is generally in accord with the timing of arc magmatism in the Saghro Arc to the northeast and with the Transaharan belt to the east, as indicated by Mali's 620 Ma UHP belt (Jahn et al., 2001). The initial collision with the rifted margin of the West African craton occurred ~615 Ma. Final suturing and strike-slip movements continued until about 565–575 Ma when pyroclastic, volcanic and carbonate rocks blanketed the entire region (Hefferan et al., 2000). Together with exposures in the Transaharan belt to the southeast, these Pan African blueschists may constitute among the oldest known blueschist-bearing, ophiolitic mélanges in the world. The Neoproterozoic blueschists exposed within the Bou Azzer inlier provide compelling evidence for north-dipping subduction during the Pan African orogeny. This polarity is consistent with the east-dipping subduction evidenced from southwest Algeria to the Gulf of Benin (Jahn et al., 2001). Alternative hypotheses suggesting that the southern Anti-Atlas represents an aulacogen or back arc basin environment are inconsistent with the occurrence of blueschist-bearing mélange in the Bou Azzer inlier.

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