A review of Archaean and Paleoproterozoic evolution of the
In Ouzzal granulitic terrane (Western Hoggar, Algeria)

Khadija Ouzegane a, Jean-Robert Kienast b,*, Abderrahmane Bendaoud a, 
Amar Drareni a

b Laboratoire de Géosciences Marines, C.N.R.S.—IPGP, UMR 7097, Université Paris 7, 4 place Jussieu, Tour 26, 3ème étage, Paris Cedex 05 75252, France

Received 20 September 2002; accepted 30 May 2003

Abstract

The In Ouzzal terrane (Western Hoggar) is an example of Archaean crust remobilized during a very-high-temperature metamorphism related to the Paleoproterozoic orogeny (2 Ga). Pan-African events (≈0.6 Ga) are localized and generally of low intensity. The In Ouzzal terrane is composed of two Archaean units, a lower crustal unit made up essentially of enderbites and charnockites, and a supracrustal unit of quartzites, banded iron formations, marbles, Al–Mg and Al–Fe granulites commonly associated with mafic (metanorites and garnet pyroxenites) and ultramafic (pyroxenites, lherzolites and harzburgites) lenses. Cordierite-bearing monzogranitic gneisses and anorthosites occur also in this unit. The continental crust represented by the granulitic unit of In Ouzzal was formed during various orogenic reworking events spread between 3200 and 2000 Ma. The formation of a continental crust made up of tonalites and trondjhemites took place between 3.2 and 2.7 Ga. Towards 2.65 Ga, extension-related alkali-granites were emplaced. The deposition of the metasedimentary protoliths between 2.7 and 2.65 Ga, was coeval with rifting. The metasedimentary rocks such as quartzites and Al–Mg pelites anomalously rich in Cr and Ni, are interpreted as a mixture between an immature component resulting from the erosion and hydrothermal alteration of mafic to ultramafic materials, and a granitic mature component. The youngest Archaean igneous event at 2.5 Ga includes calc-alkaline granites resulting from partial melting of a predominantly tonalitic continental crust. These granites were subsequently converted into charnockitic orthogneisses. This indicates crustal thickening or heating, and probably late Archaean high-grade metamorphism coeval with the development of domes and basins. The Paleoproterozoic deformation consists essentially of a re-activation of the pre-existing Archaean structures. The structural features observed at the base of the crust argue in favour of deformation under granulite-facies. These features are compatible with homogeneous horizontal shortening of overall NW–SE trend that accentuated the vertical stretching and flattening of old structures in the form of basins and domes. The Paleoproterozoic deformation consists essentially of a re-activation of the pre-existing Archaean structures. The structural features observed at the base of the crust argue in favour of deformation under granulite-facies. These features are compatible with homogeneous horizontal shortening of overall NW–SE trend that accentuated the vertical stretching and flattening of old structures in the form of basins and domes. This shortening was accommodated by horizontal displacements along transpressive shear corridors. Reactional textures and the development of parageneses during the Paleoproterozoic suggest a clockwise P–T path characterized by prograde evolution at high pressures (800–1050 °C at 10–11 kbar), leading to the appearance of exceptional parageneses with corundum–quartz, sapphire–quartz and sapphire–spinel–quartz. This was followed by an isothermal decompression (9–5 kbar). Despite the high temperatures attained, the dehydrated continental crust did not undergo any significant partial melting. The P–T path followed by the granulites is compatible with a continental collision, followed by delamination of the lithosphere and uprise of the asthenosphere. During exhumation of this chain, the shear zones controlled the emplacement of carbonatites associated with fenites.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Archaean; Paleoproterozoic; Hoggar massif; Tuareg shield; In Ouzzal; Very-high-temperature granulites

1. Introduction

During the Archaean, various cycles of geodynamic evolution took place in several cratons whereby an episode of island-arc accretion was followed by the formation of tonalites, trondjhemites and granodiorites.
This led to a period of reworking of the crust accompanied by dome-and-basin tectonics, the emplacement of calc-alkaline granites and the development of high-grade metamorphism followed by a long period of quiescence lasting up to 500 million years (Choukroune et al., 1997; Condie, 1997). One of the aims of this review is to highlight the timing as well as the mechanisms of creation, deformation and differentiation of a segment of crust from the Archaean to the Paleoproterozoic. Despite a Paleoproterozoic tectono-metamorphic event (2000 Ma), these granulites preserve the general characteristics of the precursors to the Archaean granite/greenstone belt-like terrains. The topics of geological research on this kind of terrain, are to characterize the nature of the protoliths, the relationships between the meta-igneous and metasedimentary units, the emplacement age of the protoliths and that of metamorphic events. Finally, the structural and metamorphic characterization of granulites is required to establish the pressure–temperature paths followed by these rocks during their evolution.

The Hoggar is composed of well preserved and largely reworked Archean (3200–2500 Ma) and Paleoproterozoic terranes (2000 Ma) and juvenile Pan-African terranes (750–550 Ma). The main tectonic feature of this area is the system of lithospheric north–south shear zones with large movements related to terranes collage and continental collision (Black et al., 1994; Fig. 1A). The In Ouzzal terrane forms an elongated N–S trending block, more than 400 km long and 80 km wide in the north around the In Hihau massif, thinning out until it disappears in the south near the Malian border, where it is then offset towards the Iforas granulitic unit (Fig. 1B). The main relief rising several hundreds of metres above the In Ouzzal granulitic reg (= desert pediment with small pebbles) is made up of ignimbrite massifs dated at 530 Ma (Picciotto et al., 1965), and the Pan-African granites of In Hihau and In Eher in the West, Nahael and Tihimatine in the centre and Ihouhaouene in the East (Fig. 2). The boundaries of the In Ouzzal granulitic terrane with the branches of the Pan-African belt are represented by vertical wrench faults. The East-In Ouzzal mylonitic margin has been studied in detail in the areas of Tirek (Attoum, 1983) and Amesmessa (Djemai, 1996), where it consists of a major vertical fault with a dextral strike-slip component. The West-Ouzzalian wrench fault, on the other hand, has a sinistral displacement (Caby, 1970), the last movements along the fault coincided with the emplacement of the Tin Zebbane alkaline-peralkaline dyke swarm (~592 Ma;
Hadj-Kaddour et al., 1998). Moussine-Pouchkine et al. (1988) pointed out that the extreme northern part of In Ouzzal is overthrust onto the volcanogenic series of Adrar Ahnet. In fact, arc-type formations and glauco-
phane-bearing metamorphic rocks indicate the existence of a Pan-African subduction zone in this area (Caby and Moniez/C19ee, 2003, this issue; Mokri, personal communica-
tion). The recognition of the tectonic contacts and the metamorphic contrast between the In Ouzzal granulitic unit and the Pan-African belt (amphibolite and greens-
chist facies, respectively), along with the Archaean age of the granulite protoliths, suggest that In Ouzzal is an exotic Pan-African terrane made of Archean and Paleoproterozoic rocks (Kienast and Ouzegane, 1987; Black et al., 1994; Caby, 1996).

Lelubre (1952) conducted the first petrological study of In Ouzzal; he stressed the original nature of the series exhibiting "In Ouzzal facies". He compared them with the charnockites of India and proposed that these granulites were much older than the terrains that surround them. In the area around In Hihaou and Tekhamalt, a granulitic complex was described briefly by Giraud (1961) and Le Fur (1966). This complex is com-
posed of charnockites, nodular marbles, garnet–graphite gneisses, quartzites with magnetite and quartzites with garnet–orthopyroxene–sillimanite (Giraud, 1961). Litho-
logically the In Ouzzal formations are very diversified (Kienast et al., 1996) and are composed mainly of two units: (i) a lower crustal unit made up essentially of enderbitic orthogneisses, and (ii) a supracrustal unit composed of quartzites, banded iron formations, mar-
bles, Al–Mg granulites and Al–Fe granulites commonly associated with meta-igneous material such as mafic (metanorites and garnet pyroxenites) and ultramafic (lherzolites, harzburgites and pyroxenites) lenses, as well as anorthosites and cordierite-bearing monzogranitic gneisses. Regarding the supracrustal unit, the most ori-
ginal feature is the abundance and the variety of Al–Mg granulites. These rocks contain parageneses which indi-
cate a very-high-temperature metamorphism at about 1000 °C for a pressure of 10–11 kbar. The marbles with wollastonite–scapolite–calcite–quartz, anorthite–grossu-
larite (Benyahia, 1996; Bourreghda, 2000; Ouzegane et al., 2002) and the spinel–quartz quartzites with or without corundum (Ait Djafer, 1996; Guiraud et al.,
1996; Badani-Djebloun, 1998) also confirm the extreme temperature conditions of this metamorphism.

2. Principal lithological types

2.1. Enderbitic and charnockitic orthogneisses

The charnockitic and enderbitic unit is very exten-
sively exposed, covering most of the area between Oued Tina Tin Tchik Tchik and Tekhamalt (Fig. 2, Ouzegane, 1987; Ouzegane and Kienast, 1996) and form the major part of the outcrops in the areas of Tidrek and Ames-
messa (Fig. 1B). These rocks are also found in the areas of Rocan, Ihouhaouene and Tikechiteine (Fig. 2) associated with marbles and aluminio-magnesian granulites. The foliation trajectories delineate dome structures occupied by the charnockites or enderbites, whereas the metasedimentary formations occur in basins (Fig. 3; Haddoum et al., 1994). Foliation is generally sub-vertical and parallel to the lithological layering, reflecting the effects of tectonic transposition. The stretching linea-
tions show highly variable but generally steep plunges (70–90°). Based on the structural, geochemical and geochronological (U/Pb on zircon) studies, three major
groups of orthogneisses have been distinguished (Haddoum et al., 1994; Peucat et al., 1996):

- the first group corresponds to orthogneisses of the trondhjemite, tonalite and granodiorite type (TTG) that are dated at between 3200 and 2700 Ma;
- the second group corresponds to alkali-granitic orthogneisses dated at 2650 Ma;
- the third group corresponds to a calc-alkaline suite made up of granodiorites and monzogranites emplaced close to 2500 Ma.

The first group comprises folied enderbitic orthogneisses exposed in the areas of Tin Tchik Tchik, Roccan and Tickechitine. The structure of these rocks is generally banded with a foliation defined by dark layers containing pyroxenes. Orthogneisses of trondhjemitic to tonalitic composition exhibit varied mineral associations. The trondhjemitic gneisses are composed of hypersthene, quartz, oligoclase and accessory minerals such as magnetite, ilmenite, apatite and zircon. In certain cases, perthites and biotite also occur around hypersthene. In addition to hypersthene, tonalitic orthogneisses are composed of clinopyroxene, plagioclase (An$_{35-40}$), perthite, quartz, rare biotite, magnetite, ilmenite, apatite and zircon.

The second group includes charnockitic orthogneisses generally forming small ranges that rise more than 60 m above the reg, including Tekhamalt Tan Affela and Tekhamalt Tan Ataram (Fig. 2). These rocks occur also in the reg of Roccan and Oued Ihouhaouène (Fig. 2). The distinctive feature of these rocks is the presence of the association perthite-quartz-ferro-augite, to which can be added oligoclase and green hornblende. The accessory minerals are apatite, zircon, magnetite, ilmenite, pyrochlore and chevkinite (Acef et al., 2001).

The third group consists of calc-alkali orthogneisses forming a granodioritic to monzogranitic suite intruded into the preceding groups, but which are also associated with the supracrustal formations. The mineralogical composition of granodioritic orthogneisses includes plagioclase (An$_{35}$), quartz, perthites and hypersthene, with rare biotite and, sometimes, green hornblende (Lassel, 1990). Monzogranitic orthogneisses contain more biotite than the granodioritic orthogneisses, while hornblende is not observed (Peucat et al., 1996).

Orthogneisses of the first group define a trondhjemitic differentiation trend, with K$_2$O/Na$_2$O ratios <0.5 (Barker, 1979). The spiderdiagram plots normalized to the primitive mantle show patterns for most of the elements that agree with Archaean TTG suites, e.g. negative anomalies in Ta, Nb, P and Ti, but a positive anomaly in Pb (Fig. 4). The low contents of Ta (<0.5 ppm), Nb (9–12 ppm), Y (<20 ppm) and Yb (<1.6 ppm) are comparable with values from igneous rocks of present-day island arcs. As with the Archaean granitoids, the In Ouzzal gneisses with TTG composition show low contents of Yb and a strong fractionation of the REE, suggesting that the source could have been garnet amphibolites. Their contents of Y (7–18 ppm) and Sr/Y ratios (18–62) may be explained by variable quantities of garnet in the residue and varied pressure conditions of formation (Peucat et al., 1996). The U–Pb zircon dating suggest at least two emplacement episodes at 3.2 and 2.7 Ga and a probable reworking of an older crust in the case of the TTG dated at 2.7 Ga, with some of these rocks having $T_{DM}$ model ages of 3.3 Ga (Peucat et al., 1996). Most of these orthogneisses yield $T_{DM}$ model ages around 3.2 Ga, in good agreement with the U–Pb zircon ages, thus supporting the relative immobility of Sm and Nd, and all the rare earth elements (REE). The calculated $\varepsilon_{Nd}$ at 3.2 Ga ranges from +0.4 to +5.3, with a concentration of values around +4 (Peucat et al., 1996) that corresponds to the
depleted mantle at 3.2 Ga. Conversely, the \( I_{\text{Sr}} \) values at 3.2 Ga are much too high since they vary from 0.7021 to 0.7065. This illustrates that these rocks have undergone a Rb loss.

The second orthogneiss type shows alkali-type compositions ranging from granodiorite–monzogranite to granite (\( \text{SiO}_2 = 69–75 \text{ wt.\%} \)). With the exception of the most felsic members, which display a slightly peraluminous trend, the remaining samples are metaluminous. They are rich in \( K_2O > 6 \text{ wt.\%} \), low in \( Na_2O < 2.9 \text{ wt.\%} \), and have very low \( X_{\text{Mg}} \) ratios (0.07–0.11). Their composition suggests a rift-type magmatism (Peucat et al., 1996). The enrichment in incompatible elements such as Ta, Nb, Y, and especially Ba (>1000 ppm), Hf and Zr (500–600 ppm), as well as their high Ga/Al ratios (Peucat et al., 1996) also shows an affinity with intra-plate granites and particularly the type-A2 granites of Eby (1992). Apart from the most mobile elements and Hf and Zr, the trace element contents of the alkali-orthogneisses (Fig. 4) are very close to those of the Archaean ALK3-type granites of Sylvester (1994). For example, the REE are enriched and show relatively weak fractionation ((La/Yb)_N = 6–10), in particular the HREE ((Gd/Yb)_N <1.7). On the other hand, Hf and Zr contents are typical of present-day alkali-granites. Several authors (Anderson, 1983; Creaser et al., 1991) attribute the origin of this type of granite to partial melting of tonalites. However, the binary diagrams trace elements rule out any genetic link with the sampled TTGs. The Rb/Sr pair makes it possible to calculate an isochron at 2.61 ± 0.07 Ga with an initial \( I_{\text{Sr}} \) ratio of 0.709 ± 0.002 (MSWD = 10). This is consistent with the result obtained by the U–Pb method on zircons, which yields an age of 2.65 Ga (Peucat et al., 1996). The \( \epsilon_{\text{Nd}} \) values corresponding to 2.65 Ga are low and relatively homogeneous, being located around –6.5, whereas \( T_{\text{DM}} \) model ages vary between 3.7 and 3.3 Ga. Thus, the isotopic compositions of Sr and Nd suggest the reworking of an older source. However, these alkali granites also exhibit low \( \delta^{18}O \) values (5.95–7.7‰; Peucat et al., 1996), suggesting a re-equilibration at high temperature with their surrounding metasedimentary rocks, which have a low \( \delta^{18}O \). This implies that the alkali-granites have a juvenile origin (or at least are derived by remelting of a juvenile material, for example of mafic-mafic granites). For the type-A granites, the juvenile source could correspond mainly to the lower part of the continental lithosphere enriched in HFSE and the upper part of the asthenosphere, as suggested by Liégeois et al. (1998). The isotopic compositions would thus result from a previously enriched lithosphere or a crustal contamination process (Liégeois et al., 1998; Bonin et al., 1998).

Orthogneisses belonging to the third group have compositions typical of calc-alkaline suites (Peucat et al., 1996). They are divided into two units. The first unit consists of granodioritic to monzogranitic gneisses of very slightly peraluminous composition (A/CNK = 1.01–1.08) having \( X_{\text{Mg}} \) (0.22–0.36) typical of Archaean calc-alkali granites as defined by Sylvester (1994). Elemental abundances normalized to the primitive mantle show patterns similar to those observed in orogenic magmatic suites, with negative anomalies in Ba, Ta, Nb, Sr, P and Ti (Fig. 4). However, just like the Archaean TTGs, these rocks yield highly fractionated REE ((La/Yb)_N ≈50) with a concave-upward pattern for the HREE. In addition to the low contents of \( TiO_2 \) and V, this suggests a residue containing garnet (Sylvester, 1994). Except for the most mobile elements (Cs, U, Rb and Cu), the trace element composition of these ancient granites is comparable to the Archaean CA2-type calc-alkaline granites of Sylvester (1994). This
author attributes their origin to the fusion of a tonalitic Archaean lower crust. Such an origin implies a thickening of the crust or heat event and the prior existence of TTG. The second unit shows a calc-alkaline trend and is made up of orthogneisses with monzogranitic composition. Their major element composition is typical of post-orogenic highly fractionated calc-alkaline granites (Peucat et al., 1996). Their trace element contents resemble those of the Archaean calc-alkaline granites of type CA1. According to Sylvester (1994), such granites would be derived from the melting of tonalites interstratified with metasedimentary rocks, at shallower depths than for the CA2, without leaving garnet in the residue. The U/Pb zircon data indicate an emplacement age of 2.5 Ga for both types of calc-alkali-granites, with a minimum protolith age of 2.94 Ga (Peucat et al., 1996). The Sm/Nd isotopic data for the first unit, with CA2-type composition, provide model ages of around 3.1 Ga. The second unit has more scattered \( T_{DM} \) between 3.05 and 3.5 Ga. Peucat et al. (1996) attribute these values to the presence of an older tonalitic protolith.

### 2.2. Supracrustal mafic and ultramafic meta-igneous granulites

The mafic granulites (metanorites and garnet pyroxenites) are mostly located around In Hihaou, but they also occur in the areas of Tekhamalt, Ihouhaouène and Amesmessa (Figs. 1 and 2). They occur in boudinaged lenses parallel to the foliation in Al-Mg granulites, banded iron formations, marbles, peridotites, enderbitic and charnockitic orthogneisses. Two types of metamorphosed mafic rocks—with or without garnet—are distinguished in the field. The metanorites are composed of salitic clinopyroxene (\( Ca_{48}Mg_{50}Fe_{12} \)), orthopyroxene (\( X_{Mg} = 0.65 \)), plagioclase (\( An_{80} \)), pargasite, magnetite and sometimes biotite. The garnet pyroxenites are composed of two quite distinct parageneses. The primary assemblage is characterized by the presence of garnet, clinopyroxene, pargasite, plagioclase (labradorite), magnetite, rutile and quartz. This assemblage is involved in reactions leading to the development of orthopyroxene–plagioclase symplectites following decomposition (Kienast and Ouzegane, 1987; Djemai, 1996).

The peridotites appear especially in lenticular masses several hundreds of metres thick in the northern part of In Ouzzal (In Hihaou and Tekhamalt), frequently associated with pyroxenites, anorthosites and with metasedimentary formations with which they are folded. These banded rocks generally show a very advanced degree of serpentinization. These peridotites can be classified into two groups (Bendaoud et al., 2001): (1) lherzolites containing olivine (\( FO_{85} \)), diopside, orthopyroxene (\( X_{Mg} = 0.87 \)), spinel (24–42% \( \text{Cr}_2\text{O}_3 \)) and (2) harzburgites containing olivine, orthopyroxene and magnetite. The pyroxenites are characterized in the field by a light green colour, and are composed essentially of orthopyroxene (\( X_{Mg} = 0.75–85 \)) and pargasite (\( X_{Mg} = 0.82–0.90 \)) showing equilibrium textures with triple points. The chromium-rich (6–33% weight oxide) brown spinel forms interstitial fine crystals or inclusions in pargasite or enstatite. Plagioclase (\( An_{80}–90 \)) is ubiquitous, appearing in patches, whereas phlogopite (\( X_{Mg} = 0.87–0.92 \)) and diopside clinopyroxene (\( Ca_{48}Mg_{45}Fe_{6} \)) are rarer.

All the mafic and ultramafic rocks clearly show a mobility in certain elements such as Rb, U and Th, as indicated by Rb/Sr (0.01–3.44), La/Th (<6) and Th/U (<8) ratios that are abnormal for igneous rocks (Peucat et al., 1996). The same probably applies to Na and K. The samples with the highest MgO contents (>20%) are cumulates, as shown by their contents of Ca, K, P and Ti and certain trace elements such as Sm and Yb that are depleted relative to the primitive mantle. These rocks display chondritic values for \( \text{Al}_2\text{O}_3/\text{TiO}_2 \), \( \text{CaO}/\text{Al}_2\text{O}_3 \) and (\( \text{Gd}/\text{Yb} \))\(_N\), with average ratios of 22.3, 0.85 and 1.05, respectively (Bendaoud et al., 2002). The metanorites have MgO between 7.5 and 13.5 wt.%, and are highly magnesian tholeiites. Their REE contents and abundance patterns are comparable with those of Archaean tholeiites (Fig. 5). Some metanorites, like those of Roccan and Tin Tchik Tchik, plot in the fields of calc-alkaline rocks. Even if some of these rocks are clearly depleted in the most mobile elements (Cs, Rb, Th and U), they yield REE patterns and spiderdiagram similar to those of present-day highly magnesian andesites (Fig. 5). Not all of these rocks could be dated. They yield \( f_{Is} \) ratios that remain high even at 3.2 Ga (0.7046–0.7072) and \( T_{DM} \) model ages which vary from 3136 to 4193 Ma (Peucat et al., 1996). These values indicate that the element pairs Rb/Sr and Sm/Nd were strongly disturbed by metamorphic alteration and/or events subsequent to their emplacement. This is often the case for the mafic and ultramafic rocks from Archaean greenstone belts and particularly those having undergone high-grade metamorphism (Gruau et al., 1992; Arndt, 1998).

### 2.3. Supracrustal metasedimentary formations

#### 2.3.1. Al–Mg granulites

Alumo-magnesian granulites are exceptionally well developed near Adrar In Hihaou and in the Tekhamalt area, but also occur more rarely in the areas of Ihouhaouène and Amesmessa (Figs. 1 and 2). These granulites are generally interstratified with rocks of sedimentary origin such as banded iron formations and marbles. They are also in direct contact with metaigneous rocks such as enderbites, charnockites, metanorites or peridotites. A first distinction can be made between two types of alumo-magnesian granulite displaying a clear contrast in the field (Kienast and
One type of granulite is rich in quartz, while the other is quartz-free. However, the majority of these granulites are rich in quartz and form layers with a brown patina of variable thickness (from one to several metres). They are dense massive rocks with a sometimes well-marked foliation. Garnet and orthopyroxene porphyroblasts show a ductile behaviour expressed by an elongation of the grains materialising the sub-vertical stretching lineations as well as the torsion of orthopyroxene cleavage planes. This provides evidence of high-temperature deformation by diffusion-creep at the grain boundaries. Within these quartzitic layers, occur quartz-free lenses of varied sizes (a few cubic centimetres to several cubic metres), easily recognizable in the field because of their blue colour due to the abundance of sapphireine. All these rocks are remarkable in exhibiting the association orthopyroxene–sillimanite along with an extremely diverse mineralogy made up of cordierite, biotite, spinel, plagioclase, potassic feldspar, ilmenite and rutile. Like sapphireine, garnet can be an abundant mineral in certain layers. Based on the presence of certain index minerals and their silica content, aluminio-magnesian granulites can be classified into five groups (Bernard-Griffiths et al., 1996; Ouzegane and Kienast, 1996; Fig. 6): spinel-bearing Al–Mg granulites (SiO$_2$: 37–40%), corundum-bearing Al–Mg granulites (SiO$_2$: 40–45%), quartz-free Al–Mg granulites (SiO$_2$: 43–45%), quartz-bearing Al–Mg granulites (SiO$_2$: 46–63%) and quartzitic Al–Mg granulites (SiO$_2$: 65–85%).

2.3.2. Al–Fe granulites and quartzites

Al–Fe granulites containing garnet and sillimanite are well represented in the area of Ihouhaouene (Fig. 2) near the carbonatite occurrences (Ait Djafer and Ouzegane, 1998). They crop out in an extremely variable way in stratified massive bands that form hills rising 10 m above the reg between carbonatite centres 1 and 2 (Ouzegane, 1987), sometimes in discontinuous disrupted bands forming lenses from 10 to 20 cm in size. Quartzofeldspathic veinlets are distributed in the fold hinges, giving these rocks a migmatitic appearance (Ait Djafer, 1996; Ait Djafer and Ouzegane, 1998). In thin section, these veinlets are composed of quartz in plates with sutured outlines associated with plagioclase (An$_{33}$) and potassic feldspar. Primary garnet ($X_{\text{Mg}} = 0.2–0.4$) is systematically surrounded by cordierite, whereas the spinel occurs as veined grains ($X_{\text{Mg}} = 0.15–0.39$), that grow out from sillimanite to form symplectites with cordierite ($X_{\text{Mg}} = 0.64$ to 0.87). The synchronous development of cordierite and spinel is explained by the breakdown of garnet in contact with sillimanite during decompression. Some large primary spinel crystals are isolated from quartz by a corona of cordierite (Ait Djafer and Ouzegane, 1998).

Gedrite–garnet–sillimanite granulites appear in cm-scale lenses associated with Al–Mg granulites containing sapphireine–orthopyroxene–sillimanite, and with garnet pyroxenites in the area of Amesmessa (Djemai, 1996; Ouzegane et al., 1996). The gedrite–sillimanite association is rare, existing only in few documented localities worldwide (Robinson and Jaffe, 1969; Spear, 1982; Goscombe, 1992; Spear, 1993). The primary paragenesis is made up of garnet (pyrope: 22–50%, almandine: 45–75%), gedrite ($X_{\text{Mg}} = 0.64–0.70$), sillimanite, quartz, plagioclase (An$_{35–42}$), rutile, ilmenite and biotite ($X_{\text{Mg}} = 77–78$). The minerals belonging to the primary
paragenesis are not observed in direct contact with each other. Instead, they are always separated by coronas or symplectites related to the secondary paragenesis made up of cordierite-orthopyroxene (with or without spinel) formed following decompression. The newly formed orthopyroxene displays an enstatite composition near 47–51 mol% when it develops from the reaction: garnet + quartz → orthopyroxene + cordierite, but is more magnesian (enstatite 62–68%) when gedrite participates in the reaction in the presence of quartz. The cordierite–orthopyroxene–spinel symplectites develop at the contacts between gedrite and garnet in the microdomains without quartz. Garnet is surrounded by a corona of cordierite and sillimanite is surrounded by cordierite–spinel symplectites in the microdomains lacking quartz and gedrite, suggesting a decomposition reaction: garnet + sillimanite → cordierite + spinel. Cordierite alone, forming a corona, separates garnet from sillimanite and quartz in the absence of gedrite (Ouzegane et al., 1996).

Al–Fe quartzites containing hercynite–quartz are less rare than the preceding rock-types; they form discontinuous layers generally related to the shear zones at Alouki, Ihouhaouene and Tin Tchik Tchik, where they are associated with rocks of sedimentary origin (Fig. 2). The development of garnet and sillimanite in coronas or symplectites suggests that these minerals are not formed by a process of partial melting but rather by a process of metamorphism involving the hydrothermal alteration of mafic to ultramafic materials in the marine environment (Rahmani, 1992; Bernard-Griffiths et al., 1996). These metasedimentary rocks have δO18 values between 5 and 9.5‰, corresponding to a mixture, in variable proportions, between a mature detrital component (composed essentially of

Fig. 6. Classification of Al–Mg and Al–Fe granulites according to the Mg/Mg + Fe (in mole proportions) versus SiO2 (wt.%) plot showing fields for quartz-free granulites (SiO2 < 45%) and quartz-bearing granulites (SiO2 > 45%). This diagram also distinguishes garnet-free Al–Mg granulite (Mg/Mg + Fe > 0.80) from garnet-bearing Al–Mg and Al–Fe granulites (Mg/Mg + Fe > 0.80); orthopyroxene-free granulites (X_Mg < 0.50) are also shown as a separate field from orthopyroxene-bearing granulites. Data reported in Bernard-Griffiths et al. (1996), Badani-Djebloun (1998) and Ouzegane et al. (2003).
quartz) derived from the erosion of a granitic protolith and an extremely immature component, resulting from hydrothermal alteration of mafic to ultramafic protoliths. This latter component is of chloritic type, rich in Al, Mg, Cr, Co and Ni, with possible additions of chromium-rich spinel and small proportions of illite and/or muscovite to account for the K contents of these granulites (0.3–2%, Bernard-Griffiths et al., 1996). The very high contents of chromium (3960 ppm) and nickel (up to 1100 ppm) in the Al–Mg granulites of In Ouzzal is a typical feature of early Archaean immature sediments (Bernard-Griffiths et al., 1996). Al–Fe granulites also exhibit Cr, Ni and Co contents that are comparable with Archaean and end-Archaean shales, since they result—like the Al–Mg granulites—from the mixing of chloritic and detrital quartzites (Badani-Djebloun, 1998). The Al–Mg quartzites and Al–Fe quartzites show SiO₂ contents varying from 62 to 85 wt.% and chromium contents of up to 100–200 ppm, and are characterized by the presence of detrital chromite in the sedimentary protoliths. These rocks resemble the fuchsite-bearing quartzites of the Archean cratons (Eriksson et al., 1997).

Detrital zircons from the Al–Fe quartzites of Ihouhaouene show growth structures with ancient cores and coronas formed during the granulite-facies event at 2 Ga. Inherited zircon cores indicate ages that are scattered between 3100 and 2700 My (Lancelot et al., 1976; Helal, 1987; Peucat et al., 1996). These geochronological data indicate that the deposition of the supracrustal series probably took place after 2700 Ma (Peucat et al., 1996). Inherited zircons present in the Al–Mg granulites show a spectrum of ages ranging between 2700 and 3200 Ma, which corresponds to the emplacement of the various generations of TTG (Peucat et al., 1996). This implies that part of silica present in these rocks had a detrital origin, possibly derived from the erosion of pre-existing Archaean granites at In Ouzzal.

2.3.3. Magnetite-bearing quartzites (banded iron formation)

The main outcrops of banded iron formation occur in the Alouki massif, where they are involved in map-scale folds that can be followed over more than 20 km. These rocks occur also in the areas of Ihouhaouene, Tin Tchik Tchik, Tekhamalt and Amesmessa in more or less continuous beds from 1 to 50 m thick repeated by isoclinal folds (Fig. 2). While they display a practically constant association with marbles and metanorites, they are also encountered in the area of Ihouhaouene in direct contact with fenites (carbonatite centres 1 and 2; Ouzegane, 1987; Guiraud et al., 1996). Throughout these areas, the iron-bearing formations and their associated rocks make up supracrustal sequences forming basins (Fig. 3) that are separated from domes of enderbites. The mineralogy of the banded iron formation is generally simple, being composed of quartz and magnetite. Magnetite is either disseminated in the rock, or clustered together in beds varying in thickness from 1 cm to 1 m. These rocks are sometimes highly deformed with thin levels of pseudotachylite. There are also some banded iron formations with more varied mineralogy, notably containing associations with corundum–quartz (Ihouhaouene; Guiraud et al., 1996) and garnet–orthoferrlosilite–almandine–spinel (Tekhamalt; Ouzegane and Kienast, 1996; Badani-Djebloun, 1998).

2.3.4. Marbles

The marble layers are generally limited to isolated lenticular bands (a few metres to 100 m thick), but some very extensive outcrops are observed in the areas of Illasa, Ihouhaouene, Roccan, Tekhamalt (Fig. 2), Tirek and Amesmessa (Fig. 1A). They generally form folded layers with vertical axes, like the associated banded iron formations. The In Ouzzal marbles exhibit a wide mineralogical diversity. Two main groups can be distinguished, dolomitic marbles characterized by a paragenesis with dolomite–olivine–spinel–phlogopite–amphibole–clinopyroxene, and dolomite-free marbles with calcite–quartz–gроссularite–andradite–wollastonite (Benyahia, 1996; Boureghda, 2000). Scapolite-bearing marbles are associated with these two categories, but are found in lesser proportions.

The identification of the protoliths of the dolomitic marbles was established by Fourcade et al. (1996), based on the chemical composition and isotopic characteristics of these marbles. The high Al and Mg contents of the dolomitic marbles could be due to the addition of a chloritic component derived from the hydrothermal alteration of a mafic/ultramafic source during carbonate sedimentation. The carbonate sediment protolith would be composed of varied proportions of calcite, dolomite and chlorite. During granulite-facies metamorphism, this impure dolomite produced forsterite–spinel marbles with or without diopside. The isotopic signatures of oxygen (δ¹⁸O = 7.9–18.9‰) and carbon (δ¹³C = −0.8‰ to −4.2‰) are very heterogeneous, indicating that the marbles of In Ouzzal have preserved their pre-metamorphic characteristics. The preservation of such an isotopic heterogeneity implies the absence of homogenizing fluids or percolation of CO₂ of mantle origin during the granulite-facies event (Fourcade et al., 1996).

2.3.5. Al–Mg–Ca granulites (paleoskarns)

Al–Mg–Ca granulites crop out especially in the area of Tekhamalt (Fig. 2), in direct contact with charnokitic orthogneisses of alkali-granitic type, and are systematically associated with the olivine–spinel marbles as in the areas of Alouki, In Hihauou, Tirek and Tekhamalt. They are banded rocks remarkable by the presence of the association spinel–pargasite–anorthite and fassaitetype clinopyroxene, with occasional pyrochlore and
relicts of calcite. In the area of Alouki, there are rare associations containing musgravite–sphene–spinel–phlogopite–corundum–pyrochlore–scheelite–monazite intercalated with layers of pargasite–clinopyroxene–musgravite–spinel–anorthite–pyrochlore and calcite (Benyahia, 1996). Musgravite, a beryl-rich mineral (5–6% Be; Boumaza-Benyahia et al., 2001), is very rare, since there are only five known occurrences worldwide. In the area of Tekhamalt, the dolomitic marbles in contact with charnockites (alkali-granitic orthogneisses) develop Al–Mg–Ca granulites with diopside–anorthite–spinel. Fourcade et al. (1996) interpret these rocks as resulting from decarbonatization, i.e. paleokarns, based on their high W and Ag contents (300 ppm and 325 ppb, respectively). The process of decarbonatization took place before the Paleo- to Mesoproterozoic granulate-facies metamorphism, and is probably contemporary with the emplacement of alkali-granitic orthogneisses at around 2.65 Ga (Fourcade et al., 1996). In the area of Alouki, Al–Mg–Ca granulites containing musgravite also result from a metasomatic process related to these charnockitic granites (rich in Nb, Ta and Be) in contact with dolomitic limestones (Benyahia-Boumaza et al., in preparation).

2.4. Paleoproterozoic magmatic activity

The magmatic events that accompanied the Paleoproterozoic granulate-facies metamorphism have resulted in the emplacement of anorthosites, small masses of cordierite-bearing monzogranitic gneisses (Peucat et al., 1996) and carbonatites. In the area of Tierek, syenites intruded along the shear zones over a distance of more than 50 km (Haddoum, 1992) yield U/Pb zircon dates of 1 991 ± 20 Ma (Semiani, 1995).

2.4.1. Anorthosites

Anorthosites crop out either in the form of metre-scale disrupted lenses associated with the supracrustal series or in more massive layers attaining 1 km thick. The massive anorthosites exposed in the area of Tikechite show stratified structures evocative of cumulate textures. Pyroxenes are variably distributed, sometimes concentrated in more or less well defined beds of a few decimetres to a few centimetres thick. In outcrop, we can observe a sharp or gradual transition from anorthosites to leuconorites, with field relations similar to those seen in layered complexes (Ashwal, 1993). Pyroxene also occurs in metre-scale veins in the metanorites and garnet pyroxenites, where these veins are folded along with the country rocks. Plagioclase (labradorite–bytownite) forms the essential mineral of the rock, and coexists with orthopyroxene or clinopyroxene, accessory minerals such as titanite, apatite, spinel and ilmenite and, less constant, quartz, antiperthite and hornblende. Garnet can be present surrounded by reaction rims with hornblende-plagioclase. Very rare zircon is also observed.

The only dated anorthosite was sampled in the Alouki area, where this rock-type occurs as veins (50 cm) associated with metanorites. This rock shows a composition similar to the plagioclase-amphibole cumulates observed in certain layered mafic intrusions, yielding an age of 2002 ± 7 Ma (U/Pb on zircon; Peucat et al., 1996). However, Sr–Nd isotopic analyses on ten samples from a more massive anorthositic unit in the Tikechite area yield older dates (Archaean, with an age around 3 Ga, Aït-Djafer et al., in preparation).

2.4.2. Cordierite-bearing monzogranitic gneisses

Cordierite-bearing monzogranitic gneisses occur throughout the In Ouzzal terrane, from North to South. They form massive leucocratic layers, sometimes exceeding 100 m in thickness and showing the same deformation characteristics as the supracrustal series. These rocks occur also in cm-thick veinlets associated with Al–Mg granulites or cutting the metanorites. From the chemical point of view, they represent metamorphosed S-type granites (Peucat et al., 1996). Quartz occurs in equant patches or polycrystalline plates. Plagioclase is oligoclase; antiperthite coexists with fine perthites that are sometimes transformed into microcline. The rocks contain also biotite, garnet, cordierite, ilmenite and zircon. These rocks show a peraluminous composition (A/CNK = 1.05–1.08) and are very rich in SiO2 (≥78 wt.%), K, Ba and Rb, and poor in Ti, Al, Fe, Mn, Mg, P, Ta, Nb, Ga, Y, Zn and REE. SHRIMP U–Pb dating of overgrowths and euhedral clear zircon yielded 207Pb/206Pb age of 1983 ± 15 Ma (Peucat et al., 1996).

2.4.3. Carbonatites and fenites

In the area of Ihouhaouene, numerous carbonatite masses (Fig. 2) occur that are systematically associated with fenites at their contact with the granulites (Ouzegane, 1987; Ouzegane et al., 1988; Bernard-Griffiths et al., 1988; Carpena et al., 1988; Fourcade et al., 1996). These rocks display some very particular features, differing from usual carbonatites by the lack of feldspaths and the abundance of wollastonite which coexists with calcite and quartz. These rocks show an extreme mineralogical diversity, containing carbonates (calcite, bastnaesite), phosphates (apatite, monazite and britholite) and silicates (clinopyroxene, amphibole, biotite, and potassic feldspar). Accessory minerals include titanite, allanite, fluorite, magnetite and grossularite-andradite garnet. In the field, a relative chronology comprising several stages can be established for the emplacement of the carbonatite complex (Ouzegane et al., 1988; Fourcade et al., 1996). Two carbonatite generations are distinguished. The fenites are cut by sovite veins with mylonitized margins. These carbonatite
veins (1–500 m thick and up to 2 km long) can be anastomosed, forming a true network. The fragments in the carbonatite breccias are made up of fenites rich in clinopyroxene clusters surrounded by grossularite-andradite, and potassic feldspar xenoliths. In the matrix cementing the fragments, calcite predominate (50–70%). These rocks are characterized by pink apatites (0.5–1.5% REE, Ouzegane et al., 1988). The second generation of intrusions is represented by pegmatitic carbonatite veins of restricted size (maximum 5 m thick) cuts the brecciated carbonatites. Very large crystals of apatite (up to 1 m; Fourcade et al., 1996) make up to 50% of the modal composition. They contain many microinclusions such as monazite, quartz, bastanaesite and britholite. The britholite in exsolution in apatite can occupy more than the composition. They contain many microinclusions such as monazite, quartz, bastanaesite and britholite. The britholite in exsolution in apatite can occupy more than 40% of the volume of the apatite. Substitutions of the britholite in exsolution in apatite can occupy more than 40% of the volume of the apatite. Substitutions of the type $P + Ca \rightarrow REE + Si$ can account for the exceptionally high rare earth contents of these apatites (1–7% REE) and of the britholites (30–62% REE, Ouzegane et al., 1988). The brecciated carbonatites systematically cut across two types of fenite—red or white—located at the margins of the complexes in direct contact with the granulites, from which they are derived by metasomatic transformation (Fourcade et al., 1996). The wollastonite-bearing white fenites show a clear foliation concordant with the foliation of the granulites, with vertical to subvertical dips. The red fenites are rocks with banding formed of dark clinopyroxene and pale-red layers rich in potassic feldspar. Garnet, titanite, calcite, apatite and quartz are in small amounts. Wollastonite can be well developed in the white fenites, associated with potassic feldspar, garnet and apatites rich in britholite (Fourcade et al., 1996).

The compositions of carbonatites and fenites from the Ihouhaouene massifs are characterized by high contents in light REE (LREE), Th, U, F, Ba and Sr, but are relatively depleted in Nb, Ta, Hf, Zr and Ti (Ouzegane et al., 1988; Bernard-Griffiths et al., 1988; Fourcade et al., 1996). The emplacement of carbonatites in the Ihouhaouene area has been dated at 1 994 ± 15 Ma by U/Pb zircon (Bernard-Griffiths et al., 1988), which confirms the earlier result of Allègre and Caby (1972) who obtained an age of 2 090 ± 20 Ma on a fluoroapatite rich in thorium. Carbonatite emplacement is coeval with the functioning of ductile shear zones under granulite-facies conditions (Ouzegane et al., 1988; Bernard-Griffiths et al., 1988; Fourcade et al., 1996). The isotopic signatures in the fenites and the carbonatites represents one of the most particular features of the Ihouhaouene massifs. In terms of $\varepsilon_{Nd}$ (−6.3 to +1.0) and $\varepsilon_{Sr}$ (0.7093–0.7104) at 1994 Ma, the radiogenic isotope composition of the carbonatites and $\delta^{18}O$ values of metasomatic clinopyroxenes ($=6.9–8.8\%$), indicate that the fluids from which they derive underwent an intense interaction with the crust during their ascent. The isotopic composition of carbon ($\delta^{13}C = -3.5\%$ to $+9.7\%$) suggests that these fluids probably originate from the mantle by degassing of mantle-derived magmas at great depth (Fourcade et al., 1996). The migration of fluids through the crust via major shear zones could have redistributed the elements dissolved in these fluids (starting from orthogneisses with TTG composition), particularly the LREE, K, Sr and Th (Fourcade et al., 1996).

3. Dome and basins structure reworked by Paleoproterozoic tectonics

Geologically, the In Ouzzal terrane is characterized by NE–SW to ENE–WSW closed structures trending that correspond to domes of enderbitic orthogneiss (Fig. 2). The supracrusted formations are made up of metamorphosed sedimentary rocks and mafic/ultramafic igneous rocks that occupy the basins (Fig. 3) between these domes (Haddoum, 1992; Haddoum et al., 1994). In certain parts of In Ouzzal, the supracrustal synforms and orthogneiss domes exhibit linear corridors near their contacts corresponding to shear zones. The shear zones are preferentially formed in quartzites and marbles that are often ultramylonites (Alouki, Ihouhaouene and Tirek). In these shear zones, the deformation related to vertical kinematics interferes with ductile strike-slip deformation, in which the horizontal stretching directions are superimposed on NE–SW sinistral shearing in Alouki and ENE–WSW dextral shearing in Tin Tchik Tchik (Fettous, 2001). Locally, these shear zones host granulitic pseudotachylites with orthopyroxene recrystallisation occupying tiny pull-apart structures and cm-scale gashes indicating a NE–SW stretching during NW–SE shortening (Fettous, 2001). The formation of these very-high-temperature pseudotachylites is probably due to the rheology of these completely dehydrated rocks (Clarke and Norman, 1993). In the linear corridors, the folds are well expressed and have a sheath geometry consistent with ductile deformation during the transcurrent shearing (Haddoum, 1992). The folding affects all lithologies. In the Ihouhaouene area, the fenites have planar structures that are concordant with the foliation of the surrounding granulites with horizontal mineral lineations. The strike of the foliations is oblique to the shear zones, thus making it possible to recognize conjugate movements that are sinistral (NE–SW) as well as dextral (ENE–WSW). These observations are compatible with the NW–SE shortening recorded in the surrounding granulites. The emplacement of the first generation of carbonatites occurred during this transcurrent shearing. The foliation of the fenites in the most highly deformed domains is involved in sheath folds that accommodate the horizontal displacements. These folds are well studied in the mylonitic zones, being attributed to intense deformation with a strong shearing component. Various studies on the structures forming these
4. Paleoproterozoic paragenetic evolution and metamorphic conditions

The ages of 2100–1950 Ma on minerals by Rb/Sr method (Allègre and Caby, 1972), U/Th/Pb on zircon (Lancelot et al., 1976; Peucat et al., 1996) and Sm/Nd on garnet (Ben Othman et al., 1984; Peucat et al., 1996) imply that the In Ouzzal terrane acquired its metamorphic imprint during the Eburnean orogeny. The granulites of In Ouzzal are particularly well suited for the reconstruction of the metamorphic history based on the chemical compositions of minerals and rocks. This approach makes it possible to determine the variations of pressure, temperature and $X_{H_2O}$. The estimation of the conditions of pressure and temperature has been carried out using Al–Mg granulites (Ouzegane, 1987; Kienast and Ouzegane, 1987; Bertrand et al., 1992; Ait Djaffer, 1996; Boumaza, 1996; Mouri et al., 1996; Ouzegane and Boumaza, 1996; Adjerid, 2002), Al–Fe granulites (Ait Djaffer, 1996; Djemai, 1996; Ouzegane et al., 1996), corundum–magnetite quartzites (Guiraud et al., 1996), calc-silicate granulites (Benyahia, 1996) and garnet pyroxenites (Ouzegane, 1987; Kienast and Ouzegane, 1987; Djemai, 1996). The most complete sequence of reactions could be identified in the aluminomagnesian granulites, where a prograde metamorphism is recorded under granulite-facies conditions at extreme temperatures (Ouzegane, 1987; Kienast and Ouzegane, 1987; Bertrand et al., 1992; Ouzegane and Boumaza, 1996; Ouzegane et al., 2003). Although there is a continuum in the succession of parageneses, the metamorphic history can be subdivided into two major stages (Fig. 7): a prograde stage taking place at a pressure of 10–11 kbar characterized by a rise in temperature from 800 to 1050 °C, followed by a decompression from 9 to 5 kbar at temperatures close to 900–1000 °C (Ouzegane, 1987; Bertrand et al., 1992; Ouzegane and Boumaza, 1996). The prograde stage led to the development of high-temperature metamorphic conditions. It is characterized by the significant growth of a number of minerals and the formation of characteristic mineral associations such as sapphire–quartz and sapphire–spinel–quartz. The metamorphism during decompression is characterized by the formation of increasingly fine-grained symplectites with cordierite, sapphire, orthopyroxene and spinel.

4.1. Prograde stage

This early stage, illustrated particularly in the system FeO–MgO–Al$_2$O$_3$–SiO$_2$ (FMAS), is characterized by the equilibrium of primary parageneses such as orthopyroxene–corundum–garnet, orthopyroxene–corundum, garnet–spinel, garnet–spinel–corundum, garnet–quartz–sillimanite–orthopyroxene, orthopyroxene–sillimanite and orthopyroxene–sillimanite–quartz. In the more complex chemical systems, occur variable amounts of biotite, potassic feldspar, plagioclase and rutile. The evolution of parageneses in the quartz-bearing Al–Mg granulites of In Ouzzal can be represented in a pressure–temperature grid adapted to the FMAS system (Fig. 7). This diagram is established using the Thermocalc software, which includes data on sapphire (V 2.75 Holland and Powell, 1998). Ouzegane et al. (2003) modified the sapphire enthalpy calculated by Holland and Powell (1998) in order to fit the curves calculated by Thermocalc to the slopes of experimental curves determined for reactions such as pyrope + corundum + spinel $\Rightarrow$ sapphire (Ackermann et al., 1975). Fig. 7 shows the position of the invariant points [Sp] and [Opx] cal-
culated with a H$_2$O values of 0.3 and 0.5. In this case, the calculated spinel invariant point (9–10.5 kbar, 1050 °C) is compatible with the experimental data of Hensen and Green (1973), Bertrand et al. (1991) and Harley and Motoyoshi (2000). These authors give the following conditions for the invariant point: 10.1 ± 1 kbar at 1020 °C, 9.5 ± 1 kbar at 1030 °C and 10.5 ± 1 kbar at 1050 °C, respectively. In quartz-bearing Al–Mg granulites, the earliest reaction is garnet + quartz $\Rightarrow$ orthopyroxene + sillimanite (Fig. 7). The conditions of crystallization during this early stage are estimated at around 9.5–11.5 kbar and 1000 °C, using the calibration of the garnet–hypersthene–sillimanite–quartz equilibrium as a geobarometer (Bertrand et al., 1992); this result is in agreement with the T–X diagram calculated by “Thermocalc” at a pressure of 10.5 kbar (Fig. 8A). At 10 kbar and low fO$_2$ conditions, the metamorphic peak temperature is expressed by the association sapphire–quartz. Bertrand et al. (1991) show that this association is stable above 1050 °C. This paragenesis can be formed due to the crossing of the univariant reaction orthopyroxene + sillimanite $\Rightarrow$ garnet + sapphire + quartz (Rahmani, 1992; Bertrand et al., 1992; Adjerid et al., 2002; Adjerid, 2002). These symplectites appear to develop in chemically distinct microdomains, since reaction products involving garnet are richer in iron than those lacking garnet (Fig. 8A). On the P–T grid (Fig. 7), associations with sapphire + quartz appear to the right of the [Sp] invariant point, thus reflecting the highest temperatures attained in the granulites.

During the sequence of early prograde reactions, garnet becomes enriched in iron (X$_{\text{Mg}}$ decreasing from 0.64 to 0.50) and the Al$_2$O$_3$ content of the orthopyroxene increases. The Al$_2$O$_3$ content of sapphire decreases in relation to a substitution of the type MgSi$\Rightarrow$AlAl (Ouzegane, 1987; Bertrand et al., 1992; Ouzegane et al., 2003). These observations, combined with thermodynamic calculations and the topological constraints, clearly demonstrate that the high-pressure stage (10–11 kbar) is accompanied by a significant increase in temperature (from 800 to 1050 °C and Fig. 7) under isobaric conditions (Bertrand et al., 1992; Ouzegane and Boumaza, 1996). During formation of the sapphire + quartz association, the temperature is extreme as shown by the low value of K$_d$ between hypersthene and garnet (K$_d$: 2.06–1.99), the high Al$_2$O$_3$ content of the orthopyroxene (which reaches 11.8%) and the high pyrope content in the garnet (maximum at 50–55 mol%).
Thermometry based on the Fe–Mg exchange equilibrium and the solubility of alumina between garnet and orthopyroxene yields temperatures close to 970 ± 70 °C at 10 ± 1.5 kbar (Bertrand et al., 1992). This is compatible with the association sapphirine–quartz and the grids calculated by Thermocalc. In addition, the Al–Mg granulites of Ihouhauene show reactions involving phlogopite at very-high-temperature (900–1000 °C) without partial melting in a liquid-absent KFMASH system (Mouri et al., 1993; Mouri, 1995). One of the hypotheses proposed by Mouri et al. (1996) to explain the stability of the phlogopite + quartz assemblage at very high temperature—without melting—is the presence of fluorine, which stabilizes biotite under extreme granulite-facies conditions as shown by the experimental work of Carrington and Harley (1995). Indeed, biotites in the Al–Mg granulites of In Ouzzal have high fluorine contents attaining 2–4%.

In Al–Mg granulites with corundum or spinel, the earliest reactions lead to the development of sapphirine in large crystals (1–10 cm). The corundum is separated from the orthopyroxene by a double corona of sapphirine armouring the corundum and sillimanite, thus suggesting the reaction orthopyroxene + corundum → sapphirine + sillimanite (Ouzegane, 1987; Bertrand et al., 1992; Ouzegane et al., 2003). At 9 kbar, the association hypersthene–corundum–sapphirine–sillimanite provides temperatures of 795 °C for magnesian assemblages and 850 °C for assemblages richer in iron (Bertrand et al., 1992), which seems to indicate an increase in

Fig. 8. T–X pseudosections calculated in the FMASH system. Prograde paths for (A) quartz-bearing Al–Mg granulites and (B) corundum-bearing Al–Mg granulites according to their X_Mg bulk composition. See text for discussion.
temperature of 55 °C under isobaric conditions. All the prograde reactions are characterized by equilibrium mineral growth and textures with triple points. A number of very rare prograde reactions (Ouzegane, 1987; Bertrand et al., 1992; Ouzegane et al., 2003) can proceed until the complete disappearance of corundum. These include the reactions: orthopyroxene + corundum ⇒ garnet + sapphire + sillimanite (Fig. 8B), garnet + corundum + spinel ⇒ sapphire and garnet + spinel ⇒ sapphire + orthopyroxene. The prograde stage can also be recognized in the scapolite marbles of Ihouhaouene: in the system CaO-Al2O3–SiO2–Vapour (CASV), the growth of wollastonite takes place at the expense of calcite + quartz via the reaction calcite + quartz ⇒ wollastonite + CO2. This reaction occurs in response to an increase in temperature from 800 up to 1000 °C at a pressure of around 10–11 kbar (Benyaibia, 1996; Ouzegane et al., 2002). In the banded iron formation of Ihouhaouene, the most extreme conditions of pressure and temperature are represented by the association corundum–quartz, with equilibrium conditions estimated at 12 kbar and 1100 °C (Guiraud et al., 1996).

4.2. Decompression stage

All primary and intermediate associations developed during the prograde stage are destabilized during a metamorphic evolution characterized by a significant drop in pressure down to 5 kbar (Ouzegane, 1987; Bertrand et al., 1992; Mourdi et al., 1996; Ouzegane and Boumaza, 1996; Adjerid, 2002; Ouzegane et al., 2003). A P–X diagram was constructed in the FMAS system using the program Thermocalc (Holland and Powell, 1998). This diagram proves particularly useful in describing the evolution of the various assemblages as a function of X\text{Mg} in the rocks during a lowering of pressure. We fixed an \(d_{\text{H}_{2}\text{O}}\) value of 0.3 for the calculation of this diagram (Fig. 9), thus taking account of the low water activities encountered in granulite-facies rocks. Fig. 9 shows the successive parageneses found in Al–Mg granulites without garnet (X\text{Mg} of the rock >0.80), granulites with garnet (X\text{Mg} ranging between 0.50 and 0.80) and Al–Fe granulites (X\text{Mg}: 0.30–0.40). In the most magnesian Al–Mg granulites with quartz (X\text{Mg}>0.80, Fig. 9), the orthopyroxene, sillimanite and quartz are systematically isolated by a corona of cordierite, suggesting the reaction orthopyroxene + sillimanite + quartz ⇒ cordierite. This reaction occurs at a pressure around 9 kbar at a temperature of 950 °C. This is in agreement with the work of Annersten and Seifert (1981), who show that magnesian cordierite can be stable up to 11 kbar at 1000 °C. However, with increasing iron in the system, this mineral can be stable up to 9 ± 0.5 kbar. The reaction orthopyroxene + sillimanite ⇒ sapphire + cordierite, which occurs in Al–Mg granulites with corundum (X\text{Mg} of the rock can reach 0.96; Ouzegane et al., 2003) as well as in the quartz-free microdomains of Al–Mg granulites, indicates pressures similar to the preceding reaction. In Al–Mg granulites richer in iron (X\text{Mg} close to 0.80), the earliest divariant parageneses are represented by garnet–sapphire–sillimanite–quartz (Fig. 9). During the fall in pressure, reactions involving garnet, such as the divariant reaction garnet + sillimanite ⇒ sapphire + cordierite, take place before the crystallization of symplectites with cordierite-spinel (Fig. 9). In the corundum-bearing Al–Mg granulites and the Al–Mg granulites with or without quartz, one of the latest reactions is orthopyroxene + sapphire ⇒ cordierite + spinel, which occurs at around 5–6 kbar (Fig. 9). In these Al–Mg granulites, various chemical microdomains appear reflecting the different X\text{Mg} in minerals. Thus, between 7 and 8 kbar, the reaction garnet + sillimanite ⇒ cordierite + sapphire is related to microdomains richer in iron than those involved in the reaction garnet ⇒ orthopyroxene + cordierite + sapphire. Al–Fe granulite textures indicate that the cordierite coronas and cordierite-spinel symplectites were formed by decompression via the following reactions: garnet + sillimanite + quartz ⇒ cordierite, garnet + sillimanite ⇒ cordierite + spinel, garnet + sillimanite ⇒ cordierite + spinel + quartz. The latest-stage reaction occurs following the growth of cordierite at the expense of spinel–quartz, in relation to a fall in temperature to 750 °C at 5–6 kbar (Kienast and Ouzegane, 1987). The marbles of In Ouzzal allow us to constrain the role of fluids such as CO2 during decompression. In the scapolite marbles, the decompression from 10 to 5 kbar is marked by the appearance of anorthite and calcite following the breakdown of meionite. The stability of parageneses with calcite–quartz–grossularite–meionite–anorthite provides evidence for XCO2 lower than 0.5 (Boureghda, 2000; Ouzegane et al., 2002). In the olivine-spinel marbles, the reaction: 2 forsterite + 4 calcite + 2CO2 ⇒ diopside + 3 dolomite takes place at XCO2 between 0.7 and 0.9 for temperatures close to 800–900 °C (Boureghda, 2000; Ouzegane et al., 2002). It appears clearly that the buffering of XCO2 is internal, in relation to the onset of various reactions at different stages in the history of these rocks. Thus, CO2 is consumed during the prograde stage in the scapolite marbles by the reaction grossularite + CO2 ⇒ 3 wollastonite + 2 calcite + meionite. On the other hand, CO2 is released during the late stages by the reaction meionite + 5 wollastonite ⇒ 3 grossularite + 2 quartz + CO2, at the same time as garnet coronas are developed in association with quartz (Benyaibia, 1996; Ouzegane et al., 2002). As in the Archaean marbles of Antarctica (Fitzsimons and Harley, 1994), there is no exchange of CO2 between the surrounding charnockitic rocks and the marbles, the latter behaving like a closed system. This is in agreement with the very heterogeneous isotopic signatures of these marbles,
which indicate they have preserved their pre-metamorphic features (Fourcade et al., 1996).

5. Interpretation and conclusion

The In Ouzzal terrane represents an Archaean block reactivated in the Paleoproterozoic, which enables us to investigate magmatic, metamorphic and structural features specific to the Archaean period and propose a model for the formation of very-high-temperature Paleoproterozoic granulites.

5.1. Archaean evolution (3.3–2.5 Ga)

Archaean geodynamic evolution can be approached primarily owing to geochemical and geochronological data obtained on the granitic rocks. The sialic material of the In Ouzzal terrane was mostly formed during the early Archaean, as shown by the \( T_{DM} \) model ages which are older than 3 Ga for all the felsic rocks of igneous origin (Allègre and Caby, 1972; Lancelot et al., 1976; Ben Othman et al., 1984; Peucat et al., 1996). The oldest rocks dated in the In Ouzzal terrane are enderbitic orthogneisses of tonalitic and trondhjemitic composition sampled from the areas of Tin Tchik Tchik and Roccan, which yield ages around 3.3–3.2 Ga (U/Pb zircon, Peucat et al., 1996). The isotopic data indicate that the igneous suites correspond to juvenile material. Such a sialic crust, made up of TTG and rocks of andesitic affinity, was probably formed by accretion of island arcs in a scenario resembling that of present-day plate tectonics (Choukroune et al., 1997; De Wit, 1998). A new suite of TTG was emplaced at 2.7 Ga. The isotopic data on these TTG suggest the reworking—at least partial—of an older crust (Nd model ages = 3.3 Ga) that could have been formed during an earlier stage. Towards 2.65 Ga, A-type granites were emplaced with the chemical signatures of rift-related granites. The mafic and ultramafic granulites of In Hihou, could also be of this age. Detrital zircons yielding ages of 2.7 Ga in the metasedimentary rocks and the formation of skarns at the contact between the marbles and the A-type granites (2.65 Ga, U/Pb zircon) make it possible to date the deposition of the metasedimentary formations at about this period.

The presence of calc-alkaline granites of type CA1 and CA2, dated at 2.5 Ga (U/Pb zircon) reflects the melting of a lower and middle crust showing a tonalitic affinity acquired during the preceding stages and transformed into granulites (Peucat et al., 1996). The development of domes and basins structures during

---

Fig. 9. P–X pseudosection calculated in the FMASH system for quartz-bearing, quartz-free Al–Mg granulites and Al–Fe granulites. The decompression paths are drawn according to \( X_{Mg} \) bulk-rock composition. See the text for discussion.
homogeneous shortening at this stage fits with the model of deformation of the Archaean crust proposed by Bouhallier et al. (1995) and Choukroune et al. (1997) for the Dharwar Craton in India.

5.2. Extreme metamorphic conditions during the Paleoproterozoic (2 Ga)

Because of the particular features displayed by the IOGU, we cannot apply the simple model of a metamorphic belt formed by continental collision as in modern mountain belts. The In Ouzzal terrane presents a number of particularities, including: very-high-temperature metamorphism up to 1100 °C (Kienast et al., 1996; Guiraud et al., 1996; Ouzegane and Boumaza, 1996; Harley, 1998), limited partial melting despite the high temperatures involved, a style of deformation comparable with that observed in Dharwar type (India) Archaean cratons, the emplacement of syn-granulite-facies carbonatites with a very peculiar geochemistry, and the presence of anorthosites. The major question posed by the development of the In Ouzzal granulitic terrane during the Paleoproterozoic, with its extreme metamorphic conditions, concerns the heat source for this very-high-temperature event. Some other questions are linked, such as the relationships that might exist between anorthosites, carbonatites and the very-high-temperature metamorphism, as well as the regional tectonic style associated with the metamorphism. The syn-granulite-facies deformation of In Ouzzal provides

Fig. 10. Cartoons showing preferred models for the tectono-metamorphic evolution and emplacement of carbonatites subsequent to delamination of lithospheric thermal barrier and uprise of asthenosphere during an Eburnean event in the In Ouzzal granulitic terrane. Evolution of P–T paths and characteristic parageneses are also shown.
evidence for a homogeneous NW–SE shortening. The structures indicate a re-activation of Archaean vertical stretching of the domes and basins, marked by the vertical foliation observed in lithologies making up these structures. The accentuation of this stretching is compatible with a homogeneous shortening, trending NW–SE on the regional scale, and accommodated by transpressive shear zone corridors. We suggest that an orogenic episode occurred at ~2.1–2.0 Ga, during which the lower crust underwent homogeneous shortening. At the same time, there was an extreme heating event related to an upwelling of the asthenosphere (Fig. 10). The study of the Paleoproterozoic granulite-facies metamorphism of In Ouzzal indicates a clockwise P–T path with an increase of temperature at constant pressure (800–1050 °C, 10–11 kbar), followed by an isothermal evolution with a significant fall in pressure (9–5 kbar). Based on these metamorphic data, we propose an evolution for the In Ouzzal terrane in three principal episodes or stages (Fig. 10).

- The first stage corresponds to a continuation of Archaean domes and basins tectonics, which became accentuated with time. During this stage, the block must undergo both shortening and thickening (Fig. 10, stage 1). The metamorphic evolution results in an increase of pressure (up to 10 kbar) for classical temperatures in the granulite-facies at the base of the crust (700–800 °C).
- From the metamorphic point of view, the following stage (Fig. 10, stage 2) is of fundamental importance, since during this episode the In Ouzzal lower crust underwent a strong reheating leading to extreme temperatures (up to 1100 °C) at constant pressure or in slight decompression. Such temperatures, even at the base of the crust, imply a considerable heat contribution from depth, most probably linked to an upwelling of the asthenosphere contemporary with an important delamination of the lithospheric mantle. To bring the lower crust at $T > 1000$ °C, this could be a result of frontal hypercollision that could remove completely the lithospheric mantle bringing the asthenosphere (1300 °C) close to the Moho (Black and Liégeois, 1993). However, the crust became dehydrated during several periods of Archaean melting. As a result, the crust is no longer fertile and cannot undergo significant partial melting. Since heat is no longer taken up by the formation of granites, the temperature is not buffered to a maximum value by melting processes around 700 °C or 800 °C. Therefore, heat will be able to diffuse without any hindrance and lead to extreme conditions of metamorphism (this mechanism was already suggested by Vielzeuf et al., 1990).
- As illustrated on Fig. 10, stage 3 represents the set of phenomena preceding the exhumation of the orogenic belt. Indeed, such an important upwelling of the asthenosphere associated with greatly enhanced heat flow is generally accompanied by extensional tectonics. Although the importance of this extension is difficult to assess in the In Ouzzal terrane, it may be expressed by the emplacement of anorthosites and carbonatites related to shear zones channelling the ascent of CO$_2$-rich fluids characteristic of the mantle. Thus, the extreme metamorphic temperatures as well as the presence of anorthosites and carbonatites would represent the effects of a phenomenon whose timing remains to be defined. However, a thermal anomaly of this magnitude is evidently unstable, which necessarily implies a return to a more normal regime characterized by a fall in temperature coupled with decompression. This stage of decompression, recorded in all the In Ouzzal formations, could correspond to the stress relaxation and isostatic re-equilibration that accompanies the recovery of the lithospheric mantle during the post-collisional post-orogenic quieter conditions, leading back to the re-establishment of a thick cratonic lithosphere and thus to the thermal equilibrium state (Black and Liégeois, 1993), that will protect the In Ouzzal terrane during the Pan-African orogeny.

Acknowledgements

We are indebted to J.P. Liégeois and M. De Wit for detailed and constructive reviews. M.S.N. Carpenter and J. Boissonnas are thanked for improving the English. This work was financed by cooperative programmes between the Universities of Algiers (USTHB), and Paris 7 (00 MDU 476 “Héritage éburnéen et structuration pan-africaine du Hoggar: étude géologique et géophysique), and by ORGM in Algeria for logistic support during field work”. We are also extremely grateful for the support of ICESA project.

References


Adjerid, Z., Ouzegane, K., Godard, G., Kienast, J.R., 2002. Les paragenèses à quartz-saphirine-spinelle, l’autre évidence d’un métamorphisme extrême en température, au cours de l’évolution


Benyahia-Boumaza, S., Ouzegane, K., Godard, G., Kienast, J.R., in preparation. Petrology of musgavrite-sapphire–pyrochlore bearing Al-Mg-Ca granulites from Alouki area (In Ouzzal terrane, NW Hoggar, Algeria).


