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Precambrian Research 67 (1994) 59–88

Precambrian Research

Early and late Pan-African orogenies in the Aïr assembly of terranes (Tuareg shield, Niger)

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Received November 9, 1992; revised version accepted August 17, 1993

Abstract

Our study of the (60,000 km^2) Aïr massif, which comprises the southeastern extension of the Tuareg shield in the Niger Republic, has identified three major displaced terranes: Aouzegueur, Barghot and Assodé. These terranes were all affected differentially by the Pan-African orogeny during an early major phase (750–660 Ma) and a late "follow-up" phase (650–580 Ma).

The greenschist facies Aouzegueur terrane comprises an ophiolite and is intruded by a late-kinematic medium-K calc-alkaline tonalite–trondhjemite–granodiorite (TTG) suite (~730 Ma). The amphibolite facies Barghot terrane, made up of a basement and a supracrustal sequence, is intruded by late- to post-kinematic high-K calc-alkaline granitoids (715–665 Ma). Both terranes form a NNE to E-verging belt thrust (680–670 Ma) upon an unknown eastern rigid continent and are covered unconformably by an early Pan-African molasse. In contrast, the amphibolite facies Assodé terrane, composed of a basement and several supracrustal sequences, collided with the eastern rigid block without being thrust upon it. Tibetan-type crustal thickening occurred and HT–LP metamorphism proceeded to regional anatexis enhanced by widespread emplacement of anatectic granites of lower crustal origin (~670 Ma). This thermal event is attributed to the delamination of the continental lithospheric mantle and consequent rise of the asthenosphere.

The late Pan-African phase affecting mainly the Assodé terrane is marked by the intrusion of high-K calc-alkaline N–S elongated batholiths (645–580 Ma) and by right-lateral displacement along the N–S Raghane mega-shear zone, located on the edge of the eastern rigid continent. This movement along the northern extent of the rigid continent in Eastern Hoggar (8°30′E) created the Tiririne intracontinental linear fold belt made up of early Pan-African molasse. In the model proposed, we estimate that the Assodé terrane, driven by an oblique spreading ridge, moved to the north over a distance of ~1000 km during 60 Ma along the lithospheric Raghane shear zone. The latter was the subsequent locus of the Silurian–Devonian alkaline ring-complexes. The calc-alkaline granitoids are regarded as subduction-related mantle products contaminated by lower and medium-level crust. The model and mechanisms proposed can be applied to the entire Tuareg shield.

1. Introduction

The Late Precambrian orogeny has fashioned the entire Tuareg shield (Fig. 1). A striking feature is the presence of continental-scale N–S major shear zones along which important displacements have taken place (Caby, 1970). In the

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0301-9268/94/$07.00
SSDI 0301-9268(93)E0075-N

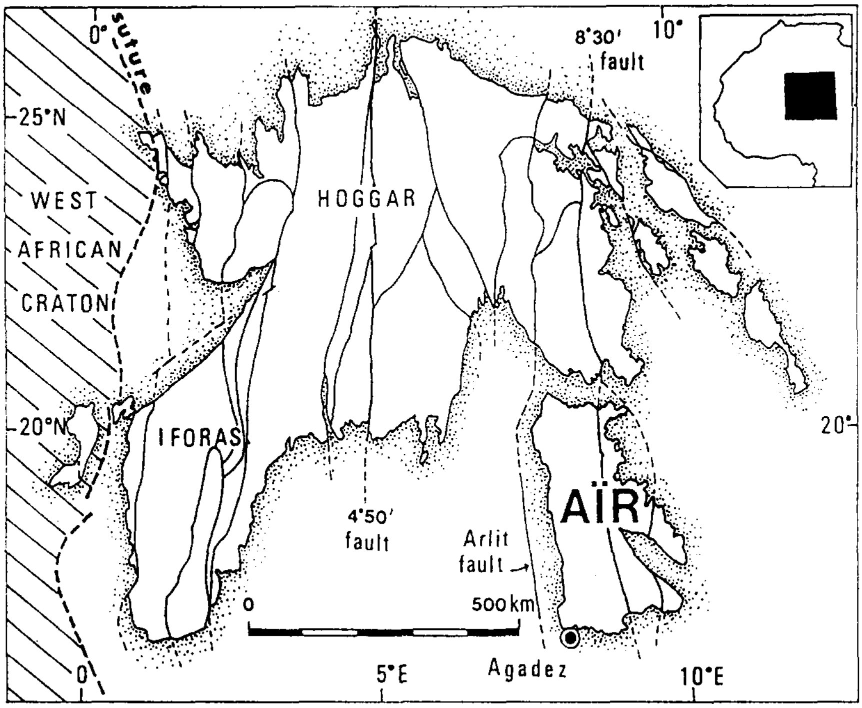


Fig. 1. Localization of the Aïr massif in the Tuareg shield (Central Sahara). Inset: the Tuareg shield in West Africa.

early literature, the 4°50′E and the 8°30′E mylonite zones have been chosen to separate respectively the Pharusian volcano-sedimentary belt from the Central Polycyclic Hoggar, and the latter from the Eastern Hoggar (for a recent synthesis, see Boullier, 1991). The Aïr massif lies astride the last two domains. If it is generally accepted that in the Tuareg shield the Pan-African orogeny has operated at 600±30 Ma (Picciotto et al., 1965; Black et al., 1979; Caby et al., 1981; Bertrand et al., 1986; Liégeois and Black, 1987), ~700 Ma events have also been recorded to the west in Iforas (Boullier et al., 1978; Caby et al., 1989) and in Eastern Hoggar (Bertrand et al., 1978; Caby and Andreopoulos-Renaud, 1987). In the latter case, these early ages coupled with the lithological particularities of the area have been the basis for separating Eastern Hoggar from the rest of the Tuareg shield and even for the notion of an East Saharan craton (Bertrand and Caby, 1978; Caby and Andreopoulos-Renaud, 1987). Our recent work in Aïr shows that the situation is more complex and that the ~700 Ma event is also present more to the West. We shall show here how the early Pan-African (~700 Ma) and the late Pan-African (~600 Ma) events can be related in a plate tectonic model.

2. General Pan-African framework

The present morphology of the Aïr massif results from Tertiary to Quaternary dome uplift related to the recent alkaline basalt–trachyte–phonolite volcanic province. The crystalline basement is surrounded and covered by subhorizontal Phanerozoic sediments (from lower Ordovician to Cretaceous and Quaternary sand dunes) and cut by the Silurian–Devonian anorthosite-bearing alkaline ring-complexes of the Niger–Nigeria Province (Black, 1965; Bowden et al., 1987; Demaiffe et al., 1991). The ring-complexes, together with the Gréboun Mountain, form the highest relief (~1900 m) and correspond to remnants of the Gondwana land surface standing 600 m above the surrounding basement.

The Precambrian basement was mapped at a scale of 1/500,000 with traverses at 1/50,000 (Black et al., 1967) and in the southeast at 1/200,000 (Barghot sheet; Kehrer et al., 1975). It has been re-examined and sampled during two expeditions in 1988 and 1990. First results have been published in Black et al. (1991). We now distinguish three terranes: Assodé, Barghot and Aouzegueur (Fig. 2B). The Assodé and Barghot terranes are separated by the major Raghane N–S shear zone lying on longitude 8°30′E and offset by later NW-trending sinistral wrench faults to 9°E in the south (Fig. 4). To the east, the amphibolite facies Barghot terrane overthrusts the greenschist facies Aouzegueur terrane (early event). Moreover, to the west the Assodé domain overthrusts the greenschist facies Tchilit palaeorift (late event).

2.1. Aouzegueur terrane

The Aouzegueur terrane (Figs. 2, 3) comprises three main lithological units. The larger and eastern one is the Eberjegui tonalite–trondhjemite–granodiorite (TTG) association whose country-rocks are here only known as enclaves and pendants of amphibolites and ultramafic rocks. It is overthrust by the Aouzegueur ophiolitic unit (Fig. 3; Boullier et al., 1991) whose serpentinites were first described by Tyrrell (1930), and by greenschist facies metasediments (Arrei unit) which contain tectonic slices of Eberjegui TTG.

These units can be followed northwards nearly 1000 km to Hoggar in Algeria where identical facies have been described (Caby and Andreopoulos-Renaud, 1987). In northern Aïr, the Coin Formation (Black et al., 1967), also NE-verging and intruded by the Eberjegui TTG, probably represents the northern equivalent of the greenschist facies Arrei unit.

2.2. Barghot terrane

This terrane (Figs. 2, 3) is composed of two high-grade gneissic groups intruded by abundant late- to post-kinematic calc-alkaline granitoids ranging from quartz-diorite to leucocratic monzogranite with predominance of porphyritic monzogranites (Dabaga-east type). These granitoids typically display quartz and K-feldspar megacryst-rich dark microgranular enclaves whose groundmass is dioritic in composition. The two gneissic groups are:

(1) The Azanguerene (Azan) Group that comprises grey, often migmatitic gneisses, amphibolites and rare calc-silicate rocks. This group is affected by complex structures and is regarded as an old basement.

(2) The Tafourfouzète (Taf) Group that is composed of abundant K-feldspar-rich leucocratic gneisses associated with quartzites, marbles, amphibolites and rare metapelites. Like the Arrei unit, which may constitute a weakly metamorphosed equivalent, the Taf Group is monocyclic even if polyphased (Black et al., 1991; Boullier et al., 1991).

2.3. The Barghot–Aouzegueur thrust belt

The Barghot and Aouzegueur terranes are associated in several nappes forming a N–S to NNW–SSE striking thrust belt displaying western to west-southwestern dips of 20° to 40° (Figs. 4, 5). The structure of this thrust belt is particularly well exposed in the south (Black et al., 1991). In the Aouzegueur terrane, the observed floor of the thrust front is the Eberjegui TTG unit, generally mylonitized, particularly beneath the thrust that displaced the ophiolitic fragment. Above, the thrust units display a metamorphism passing from greenschist facies in the tectonic slices (Arrei unit) lying upon the ophiolite to upper amphibolite facies in the overlying nappes affected by E-verging kilometric folds (Azan and Taf Groups) (Black et al., 1991). The stretching lineation related to thrusting swings from N20°E to N90°E as one goes up the nappe structure (Boullier et al., 1991).

The Dabaga-east type granitoids are late-kinematic and are involved in the nappe structure. A unique high-level circular pluton, also high-K calc-alkaline in composition but displaying a chilled margin, cuts the nappe structure (Tche-

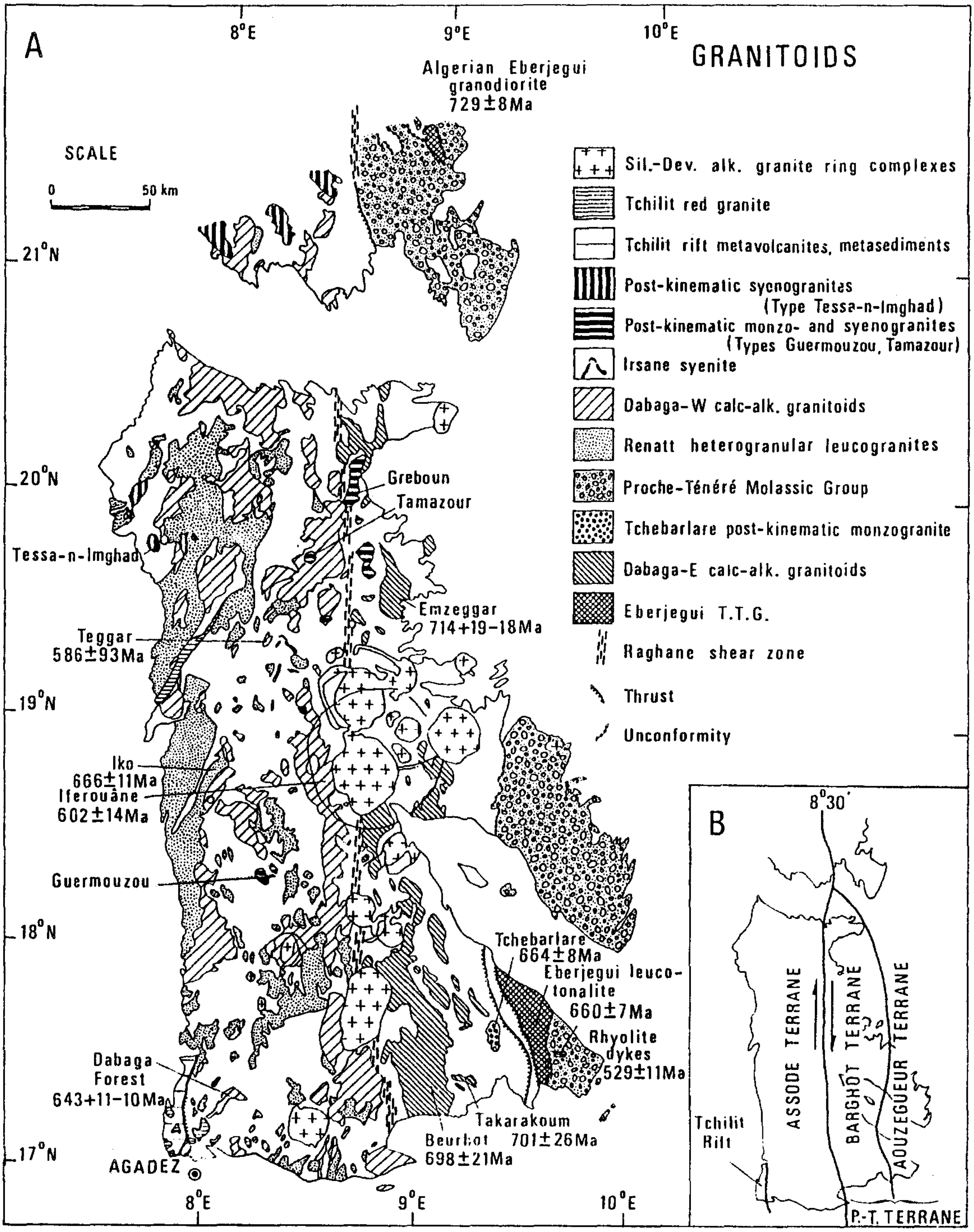


Fig. 2. (A) Geological map of the granitoids of Aïr with ages of the Pan-African granitoids. (B) The Aïr terranes.

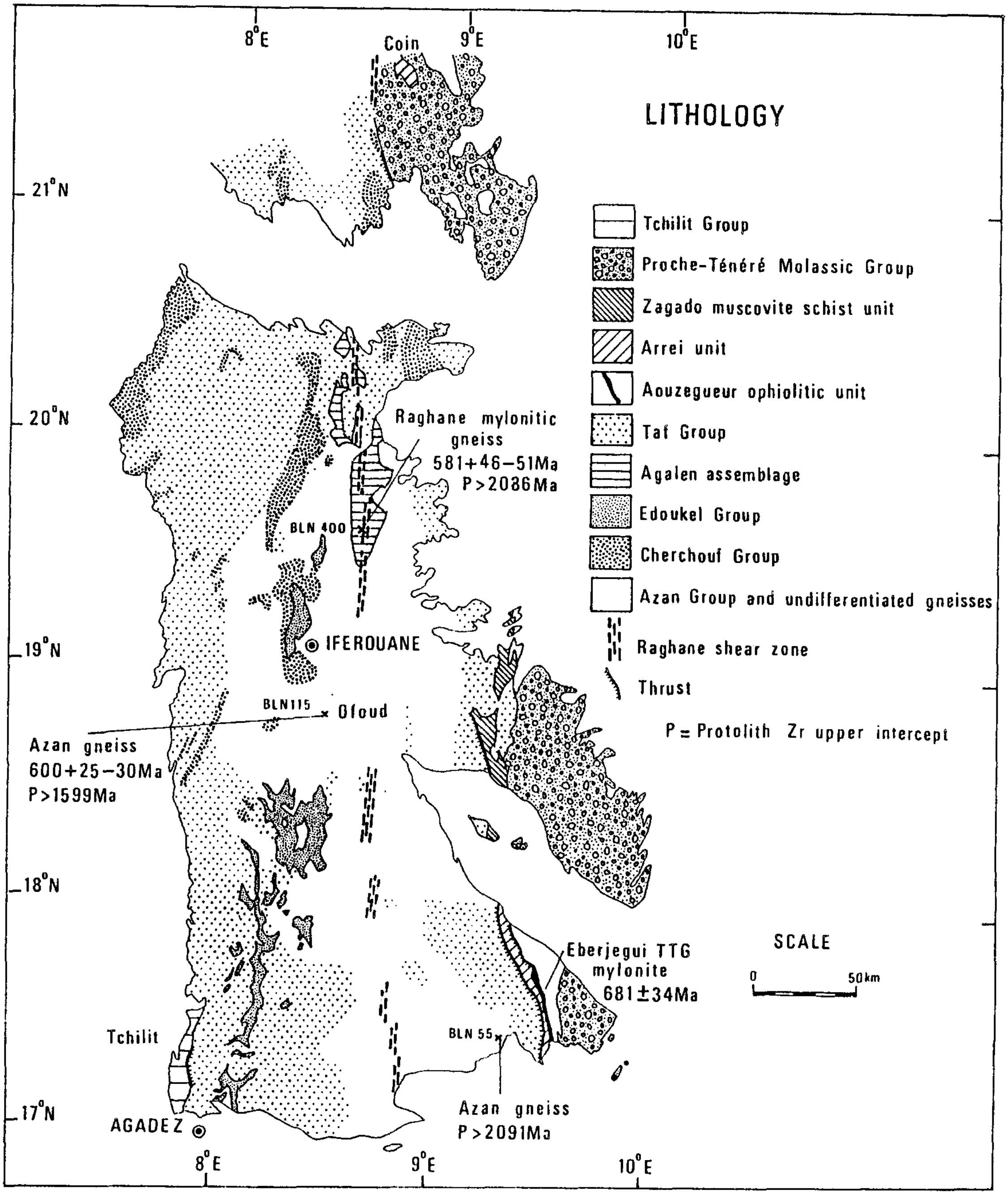


Fig. 3. Geological map of gneissic and sedimentary groups of Aïr with ages of the gneisses.

barlare pluton) (Fig. 2A): it truncates the E-verging folds of the Taf Group and a quartz-feldspar porphyry NE-oriented dyke swarm centred on the pluton that cut to the east the greenschist nappes of the Arrei unit (Kehrer et al., 1975).

After thrusting, the Aouzegueur and Barghot terranes have a common history forming the Proche–Ténéré terrane. This newly formed ter-

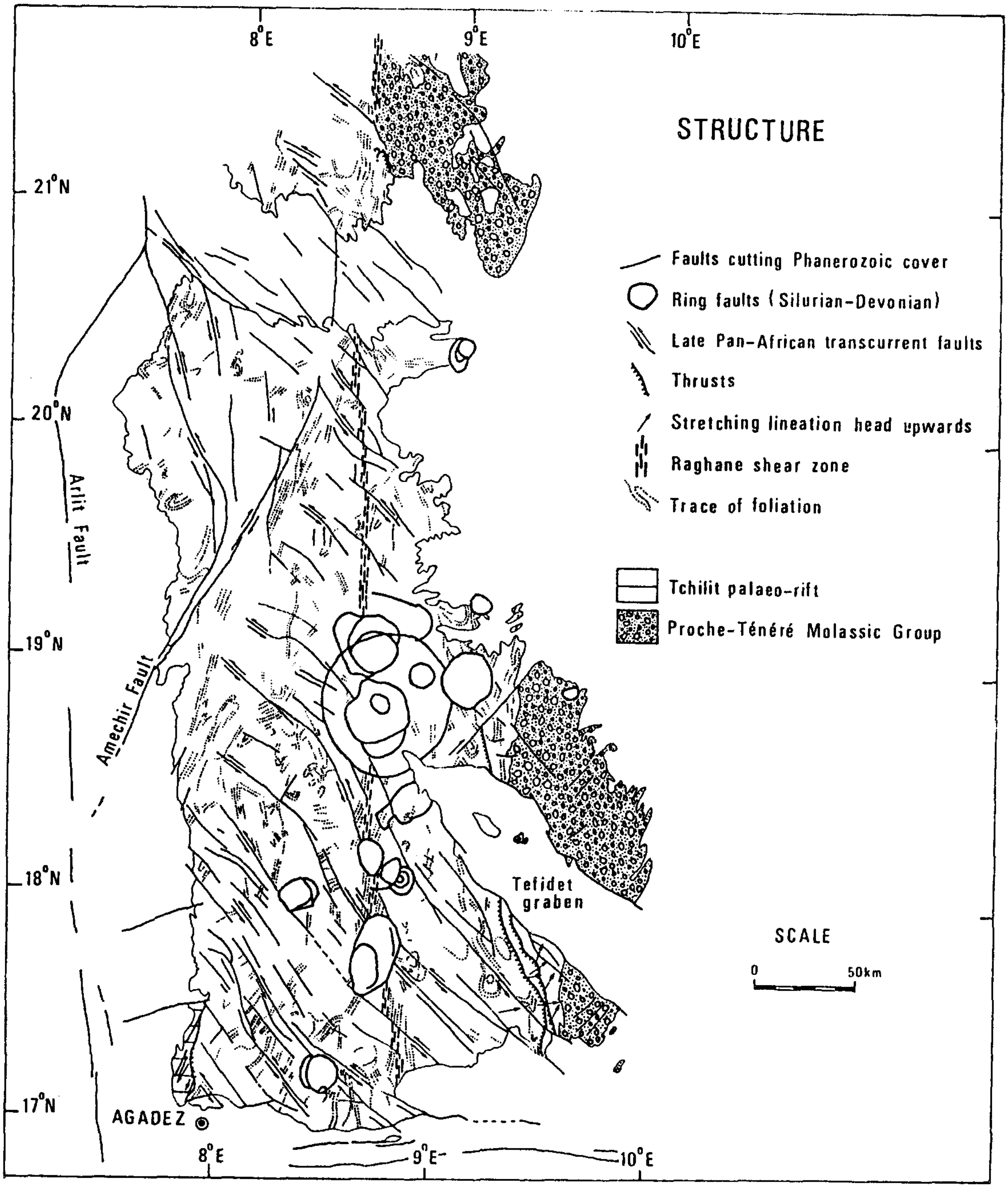


Fig. 4. Structural map of the Aïr massif.

rane is largely covered by the Proche–Ténéré Molassic Group that rests directly upon the eroded Eberjegui TTG unit in the south and the Taf Group in the north. This molasse is composed of immature sediments comprising polygenic conglomerates with horizons of pluridecimetric boulders and arkoses with rare thin pelitic intercalations. It displays an incipient subverti-

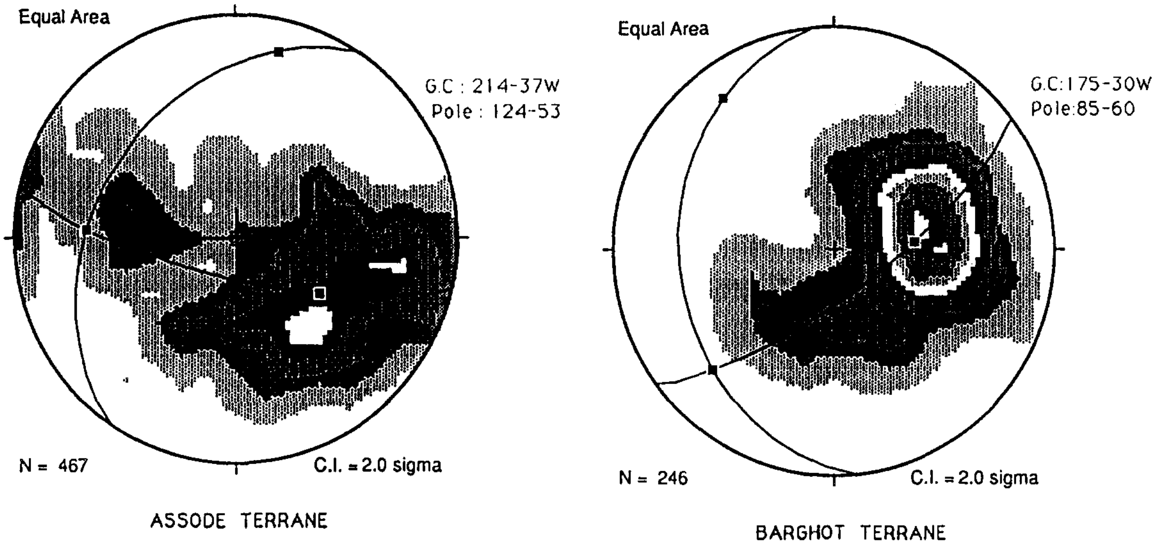


Fig. 5. Schmidt net, lower hemisphere projection of pole of schistosity planes in the Assodé and Barghot terranes. *C.I.* = contour interval; *G.C.* = great circle (using program of Allmendinger, 1988) showing the rotation of the Assodé terrane with respect to the Barghot terrane.

cal cleavage associated with widely open folds and a static greenschist metamorphic imprint suggesting an original thickness of at least 5000 m, comparable to that of the Tiririne Group, its northern extension in Hoggar (Bertrand et al., 1978). The small half graben of Proche–Ténéré sediments within the TTG unit 7 km to the NE of the Aouzegueur volcanic neck observed by Boullier et al. (1991), displays E-verging folds that we attribute to reactivation of the basement structure during the late Pan-African which elsewhere in the Proche–Ténéré Group only produced widely open folds.

2.4. *Assodé terrane*

Four lithological groups of gneisses have been recognised (Fig. 2B, 3). Two of these are the lithological equivalents of the migmatitic Azan Group and of the supracrustal Taf Group in the Barghot domain. The two others are:

(1) The Cherchouf Group that is confined to the northern and central part of Assodé terrane. It is characterised by Cpx–Hb–Kf-rich alkaline orthogneisses, biotite gneisses, amphibolites, quartzites and minor calc-silicate horizons. Migmatitic facies are frequent. The relationship of this group with the Taf Group is unknown.

(2) The Edoukel Group that forms a N–S synformal band with respect to an underlying Cherchouf Group and Taf Group in the centre of the Assodé domain. The contacts are probably tectonic. It is a pelitic sequence composed of micaschists with intercalations of calc-silicate rocks, quartzites, amphibolites and marbles.

These gneissic sequences are everywhere imbibed or invaded by granitic material at all scales: nebulitic structure, local incipient melting, lit-par-lit injection, centimetric to metric sills and dykes and finally large bodies of anatectic granitic material. The latter is a leucocratic potassic granite (Renatt-type, Fig. 2A). At the outcrop, it is heterogeneous and heterogranular, typically displaying clouds of microcline megacrysts; on the regional scale, it is very homogeneous and easily identifiable.

The heterogranular leucocratic Renatt granite, together with the gneissic sequences, is cut by numerous large composite batholiths (Iferouâne) or small plutons (Teggar) of high-K calcalkaline granitoids (Dabaga-west type) ranging from quartz-diorite to monzogranite (Fig. 2A). An apparently late pyroxene–amphibole syenite (containing ~8% K_2O) is present in the Irsane area.

The gneisses are affected by an early horizontal tectonic event phase responsible for the regional schistosity subsequently deformed to produce tight ESE-verging folds (Figs. 4, 5). The Renatt heterogranular leucocratic granite is late-kinematic with respect to this phase. At the eastern border of the terrane, Azan gneisses have been tectonically mixed with ultramafic and mafic rocks (serpentinites, peridotites, garnet amphibolites, pyroxenites) which constitute the Agalen assemblage (Fig. 3).

The later widespread emplacement of Dabaga-west granitoids occurs probably close to the brittle–ductile transition (frequent concordant contacts against the gneisses, general N–S elongated shape and presence of gneissic pendants) during a regional tectonic phase whose effects, essentially reactivation of the older structures, are enhanced by the intrusion of these granitoids. This episode of calc-alkaline magmatism ended with high-level circular plutons of leucocratic monzo- and syenogranites (Guermouzou, Tamazour, Gréboun, Tessa-n-Imghad).

2.5. Raghane boundary zone

This N–S zone of contact between the Assodé and Barghot terranes is about 5 to 10 km wide and can be followed over a distance of 400 km across the Aïr (Fig. 4). Whereas in the south it disappears below the sedimentary cover, to the north in Hoggar, it joins the 8°30′ shear zone bordering the Issalane block to the east (Bertrand et al., 1978). As we have not gone north of latitude 21°N, it is not clear for us whether the thrust indicated there (Fig. 2A) affects the Proche–Ténéré Group or is an older basement structure. On the other hand, it has been shown that the thrust structure marking the boundary between the Tiririne fold belt and Assodé–Issalane terrane (lat. 22–23°N; Fig. 12), passes progressively to the south to the 8°30′ (Raghane) dextral strike-slip fault (Bertrand et al., 1978) and has no link with the Aouzegueur thrust of southeast Aïr. The Raghane zone has an intense subvertical mylonitic fabric affecting various lithologies. Northeast of Iferouâne, it includes ultramafic–mafic rocks and Azan gneisses of the Agalen assemblage as well as some orthogneisses. Southeast of Iferouâne, it affects essentially Dabaga granites and biotite gneisses. To the south, west of the Beurhot batholith, the zone comprises Azan gneisses, and augen gneisses probably formed at the expense of Dabaga granitoids. The emplacement of the very elongated N–S Iferouâne batholith may have been guided by movements of the Raghane shear zone (Fig. 2A).

In the Agalen assemblage (Fig. 3), an orthogneiss (metatonalite) displays a strong mylonitic fabric, with a C/S angle under 5° and C surfaces defined by quartz ribbons made up of polygonal even-grained arrangement of subgrains. K-feldspar porphyroclasts, crosscut by quartz-filled veinlets, indicate a dextral shear sense.

Even if augen gneisses located to the west of the Beurhot batholith display conflicting shear criteria, our preliminary observations point to major dextral shear displacement. This is in agreement with observations made along the 8°30′ fault in Algeria (Bertrand et al., 1978). Moreover, as it will be shown below, this movement occurred, at the present exposed level, in medium amphibolite facies metamorphic climate, with no or little greenschist retrogression.

2.6. Tchilit palaeorift

In the extreme southwest of Aïr, the Tchilit palaeorift (Navez et al., 1990) is characterised by a bimodal volcanism (rhyolites, ignimbrites, basalts and mafic tuffs), badly sorted conglomerates, quartzites, purplish phyllites and a well-sorted quartz pebble conglomerate. The whole is affected by a greenschist facies metamorphism and cut by numerous small bodies of a high-level leucocratic biotite red granite. This domain is overridden by the gneisses of the Assodé terrane now acting as a rigid block. The N–S contact zone is often marked by an augen gneiss with a 50°E dipping schistosity and a stretching lineation dipping 30° to the NNE, also observed in the underlying metabasites. Although there have been lateral movements between the Tchilit domain and the Assodé terrane, we believe that the rift occurred within the Assodé terrane whose western limit is probably located further to the west and may coincide with the major Arlit fault (Fig. 4) affecting the sedimentary cover. The Arlit fault reflects the presence of the southern extension of the 7°30′ shear zone of SE Hoggar, west of which very different lithologies are found and where Renatt granites are absent (K. Baziz, written commun., 1992).

3. Post-collage Phanerozoic tectonic and magmatic events

The three main terranes (Assodé, Barghot, Aouzegueur) have been sliced by NW–SE to NNW–SSE-trending sigmoidal sinistral wrench faults filled with quartz that affect all post-tectonic Pan-African granitoids and the Raghane shear zone, but are cut by the Silurian–Devonian alkaline ring-complexes (Fig. 4). The total length of these large veins of quartz is estimated to be about 10,000 km. Rare late alkaline quartz porphyry and granite porphyry dykes cut both the Proche–Ténéré and Assodé terranes.

The spectacular alignment of the Silurian–Devonian alkaline ring-complexes broadly coincides with the Raghane boundary zone confirming its lithospheric character.

Movements that have occurred along the Amechir NNE fault zone in NW Aïr (Fig. 4), a direction also found in the Tchilit domain, affect the sedimentary cover up to the Cretaceous. The NW–SE-oriented Tefidet Cretaceous graben in southeastern Aïr (Fig. 4) is located along the NW–SE-trending late Pan-African wrench faults reactivated in this period. Vertical decametric displacements along these faults, which were also the loci of the Quaternary volcanic emission points, give a step-like structure to the recent doming. Lastly, essentially post-Variscan movements along E–W to ENE–WSW faults, active up to present, affecting the sedimentary cover and controlling locally the Aïr drainage, belong to the wide Guineo–Nubian lineament that crosses all North Africa (Guiraud et al., 1985). This direction however coincides with that of the earlier Silurian–Devonian dyke swarms associated with the ring-complexes.

4. U–Pb, Rb–Sr and Sm–Nd geochronology

4.1. Analytical techniques

Isotopic measurements have been carried out on a Fisons VG Sector 54 and on a Finnigan MAT 260 mass spectrometer.

Rb–Sr, Sm–Nd. After acid dissolution of the sample and Sr or Nd separation on ion-exchange resin, Sr isotopic compositions have been measured on Re double filament (MAT 260) or Ta simple filament (Sector 54) and Nd isotopic compositions on triple Ta–Re–Ta filament (Sector 54). Repeated measurements of Sr and Nd standards have shown that the between-run error is better than 0.00004 on the MAT 260 and better than 0.00002 on the Sector 54. These errors have been chosen in the calculations in the general cases where the within-run errors are lower. The NBS987 standard has given a value for $^{87}Sr/^{86}Sr$ of 0.710240 ± 0.000005 (2σ on the mean, 35 measurements, normalised to $^{86}Sr/^{88}Sr = 0.1198$) and the MERCK Nd standard a value for $^{143}Nd/^{144}Nd$ of 0.512740 ± 0.000005 (2σ on the mean, 26 measurements, normalised to $^{146}Nd/^{144}Nd = 0.5119$). Rb and Sr concentrations have been measured by X-ray fluorescence or by isotope dilution when concentrations were <30 ppm. The error on the Rb/Sr ratio is $<2\%$. Sm and Nd concentrations were measured by ICP-MS. The error on the Sm/Nd ratio is $<2\%$. The Rb–Sr and Sm–Nd ages have been calculated following Williamson (1968) and all the errors are given at the 2σ level. Disintegration constants used are 1.42×10^{-11} a^{-1} (^{87}Rb, Steiger and Jäger, 1977) and 6.54×10^{-12} a^{-1} (^{147}Sm).

U–Pb. The method is derived from that of Krogh (1973) and Lancelot (1975). About 2 mg of pure and homogeneous zircons are separated on ion exchange resin after acid dissolution. Pb is measured on single rhenium single filament and U on triple Ta–Re–Ta triple filament, both with silica gel. The fractionation coefficient, known at better than 0.1% is equal to 0.12% per a.m.u. Disintegration constants: $^{235}U = 9.8485 \times 10^{-10}$ a^{-1}; $^{238}U = 1.55125 \times 10^{-10}$ a^{-1} (Steiger and Jäger, 1977). The intercepts with Concordia and errors have been calculated following Ludwig (1980). For more precision, see Liégeois et al. (1991).

4.2. Results

The location of the plutons and gneisses studied here are indicated respectively on Fig. 2 and Fig. 3 together with available geochronological results.

4.2.1. Barghot–Aouzegueur thrust belt

A first set of geochronological results on southeastern Aïr has been published by Black et al. (1991). Two late-kinematic Dabaga-east granites have given similar Rb–Sr ages of ~700 Ma: Takarakoum pluton, 701±26 Ma; Beurhot batholith, 698±21 Ma. The unique post-nappe pluton (Tchebarlare) has yielded a younger U–Pb zircon age (664±8 Ma). Thrusting therefore occurred between 700±20 Ma and 664±8 Ma. This thrusting is probably responsible for the perturbation of the Rb–Sr chronometer in the TTG suite (errorchron giving 681±34 Ma). The slightly disturbed U–Pb zircon age obtained on a late leucotonalite (660±7 Ma) has been interpreted as a result of the thrust event (Black et al., 1991); however, it may correspond to the emplacement age of the pluton at the end of the thrusting. Eberjegui TTG representatives have also been mapped 450 km further north close to the frontier. Just over there in Algeria, a pluton from this suite, but unaffected by the thrust, has been dated at 729±8 Ma (zircon U–Pb, Caby and Andreopoulos-Renaud, 1987) which corresponds to its emplacement age. In the north of the Barghot terrane, a coarse-grained amphibole biotite granite from the Emzeggar batholith yields, by the U–Pb zircon method, an age of 714^{+19}_{-18} Ma (upper intercept with Concordia; lower intercept: 109^{+38}_{-39} Ma; 4 zircon fractions; Fig. 6A, Table 1). The $^{207}Pb/^{206}Pb$ ages from 629 Ma to 707 Ma (Table 1), giving minimum ages, are consistent with the upper intercept. The zircons are acicular, clear, zoned crystals without an inherited core that indicates that the 714 Ma figure corresponds to the age of the intrusion. The imperfect alignment of the fractions is reflected in the rather large error and may be due to the proximity of the younger amphibolite facies Raghane shear zone.

A migmatitic gneiss sample displaying some augen has been collected in a typical Azan outcrop (BLN 55, Fig. 3) but lying between a set of late NW–SE quartz veins. The latter may have been able to disturb the zircon U–Pb system as it gives an age of 524±7 Ma (lower intercept) and 2081^{+64}_{-63} Ma (upper intercept) (Fig. 6B, Table 1). Indeed this late Pan-African value is comparable to the age of the late Proche–Ténéré rhyolitic dykes (Fig. 2) which cut the quartz veins and which are not affected by the greenschist metamorphism: 529±11 Ma (SrIR = 0.70650±0.00030, MSWD=2.06; 5WR; with BLN201A (no particular characteristic): 531 ±11 Ma, SrIR=0.70514±0.00026, MSWD =5.33, 6WR; Table 2, Fig. 6C). The large degree of discordance shown by the zircons has probably been acquired essentially during the amphibolite facies metamorphism that preceded the thrusting and the Dabaga-east late-kinematic granitoids (700±20 Ma). The succession of events that have affected this gneiss means these two intercept ages are highly questionable and only indicate the strong Pan-African imprint on this gneiss and an age greater than 2081 Ma for the protolith.

4.2.2. Assodé terrane and Raghane boundary zone

The type locality of the large family of Dabaga-west granitoids is the Dabaga forest 40 km NNE of Agadez. The pluton there is a concordant slightly foliated porphyritic monzogranite forming a large fold in the Edoukel Group and has been regarded as one of the earliest Dabaga-west granitoids. Its zircons are elongated (length/width up to 9), clear, weakly zoned crystals (Savino, 1992). The four analysed fractions are well aligned and give an age of 643^{+11}_{-10} Ma (upper intercept, Fig. 6D, Table 1) corresponding to its emplacement age. The earliest Dabaga-west

Table 1
Zircon U–Pb data

Fraction	U (ppm)	Pb[a] (ppm)	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U^{a}$	$^{207}Pb/^{235}U^{a}$	$^{207}Pb/^{206}Pb^{a}$	t(207/206)
Emzeggar monzogranite (BLN401)							
−4°M/63–106 μm	514.4	43.4	918.1±2.0	0.0769	0.6562	0.06191	671
−5°M/63–106 μm	492.7	42.8	555.7±1.6	0.0788	0.6844	0.06297	707
−6°M/63–106 μm	458.5	40.2	1418.4±17.4	0.0793	0.6635	0.06071	629
−6°NM/63–106 μm	375.4	34.5	1525.3±3.6	0.0830	0.7087	0.06189	670
Dabaga Forest monzogranite (BLN293)							
−4°M/63–106 μm	695.7	53.1	935.4±12.9	0.0750	0.6270	0.06061	625
−5°M/63–106 μm	666.3	52.6	1223.2±5.1	0.0771	0.6460	0.06075	631
−6°M/63–150 μm	644.1	55.3	964.5±3.8	0.0791	0.6625	0.06076	631
−7°NM/63–106 μm	561.6	47.2	1573.1±13.2	0.0820	0.6871	0.06076	631
Azan gneiss (BLN55)							
1°M/63–106 μm	652.1	65.3	775.5±3.7	0.0950	0.9136	0.06972	920
−1°M/63–106 μm	597.9	60.0	982.1±6.9	0.0953	0.8984	0.06833	879
−3°M/63–106 μm	531.1	55.7	1118.6±5.8	0.1002	0.9602	0.06953	914
−3°M /106–150 μm	508.7	61.0	1395.3±9.7	0.1144	1.2897	0.08178	1240
Azan gneiss (BLN115)							
−1°M/63–106 μm	482.3	53.6	2230.3±54.9	0.1120	1.0479	0.06787	865
−3°M/63–106 μm	418.0	47.8	2979.1±74.2	0.1154	1.1054	0.06947	913
−4°M/63–106 μm	429.2	46.3	3291.8±55.2	0.1091	0.9968	0.06628	815
−5°M/63–106 μm	439.1	49.5	3066.4±57.7	0.1143	1.0682	0.06780	862
Raghane gneiss (BLN400)							
−5°M/63–106 μm	399.8	52.0	2671.6±8.8	0.1270	1.4629	0.08352	1281
−6°M/63–106 μm	345.6	46.1	1266.9±3.7	0.1299	1.5167	0.08465	1308
−7°M/63–106 μm	370.6	48.3	1926.7±7.7	0.1277	1.4678	0.08335	1277
−7°NM/63–106 μm	352.3	48.0	1122.7±3.1	0.1325	1.5737	0.08613	1341

[a]Pb = radiogenic lead; sample fractions characterized by their diamagnetism and granulometry.

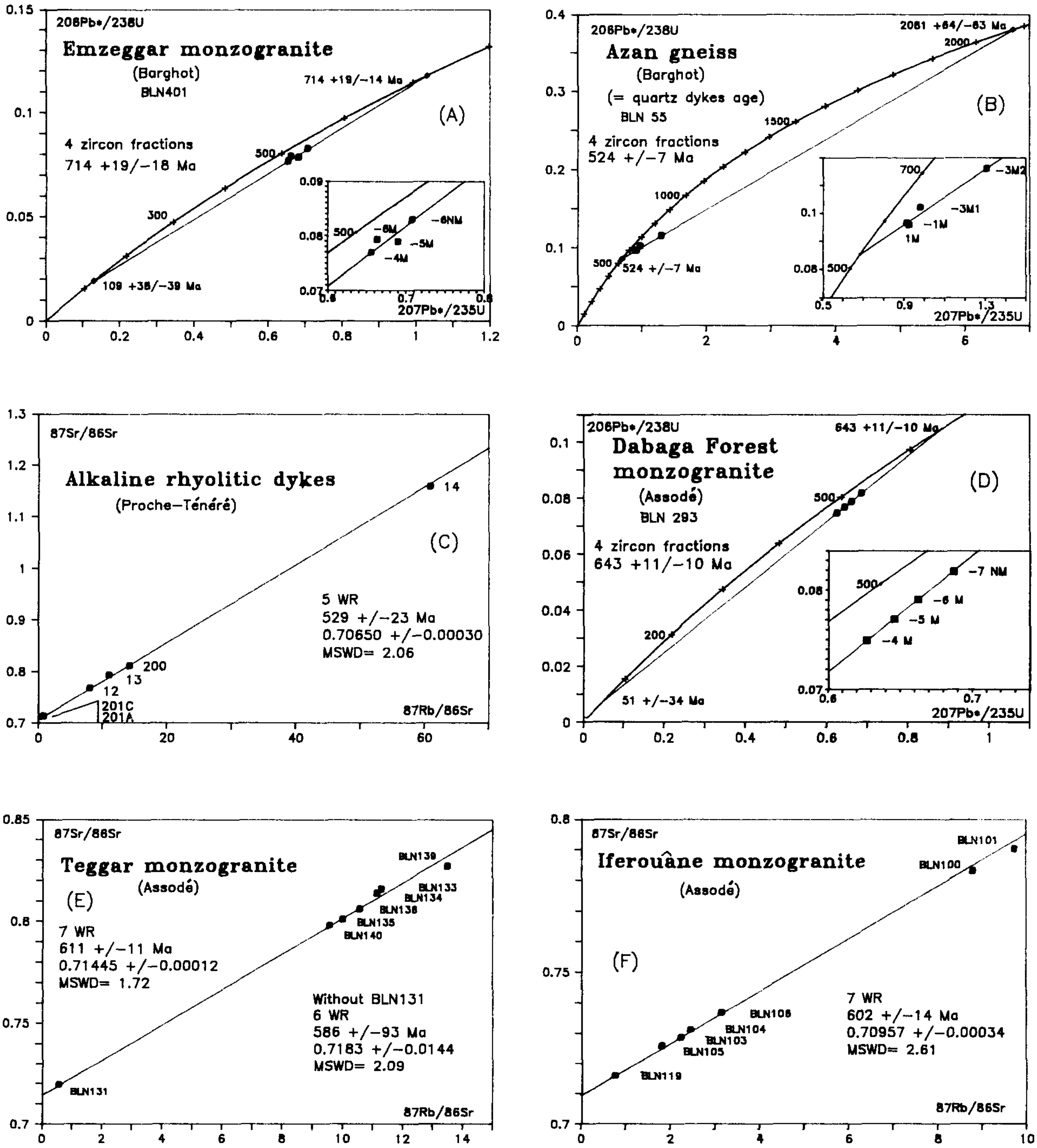
phases are then younger than the latest high-level post-kinematic Dabaga-east pluton (Tchebarlare, 664±6 Ma) of the Barghot terrane.

The sill of unfoliated fine-grained monzogranite of Teggar gives a Rb–Sr age of 586±93 Ma (SrIR=0.7183±0.0144, 6WR, MSWD=2.09; Fig. 6E, Table 2). With BLN131, a sample from an associated granodioritic sill (also found as enclave), the parameters become: 611±11 Ma (SrIR=0.71445±0.00012; 7WR, MSWD=1.72). The cogenetic character of this sample and the Teggar sill, however, has to be confirmed.

The Iferouâne batholith is composed of a number of units. Fine- to medium-grained facies have been chosen west of the Ofoud ring-complex for dating by the Rb–Sr method. The age obtained is 602±14 Ma (SrIR=0.70957±0.00031, 7WR, MSWD= 2.61; Fig. 6F, Table 2). The Iferouâne batholith is essentially unfoliated. However, it has a very elongated shape and is often concordant with the foliation of the country-rocks. This leads us to consider the Iferouâne batholith as late-kinematic and the age obtained as that of the intrusion.

A fine-grained banded gneiss of the Azan Group sampled in a 8×5 km pendant in the Iferouâne batholith has yielded four discordant zircon fractions giving a lower intercept of 600^{+25}_{-30} Ma and an upper intercept of 1599^{+215}_{-202} Ma (Fig. 6G, Table 1, BLN 115, Fig. 3). The lower intercept probably reflects heating by the Iferouâne batholith and associated regional metamorphism. The upper intercept is most likely geologically meaningless due to the multi-episode story of the rock, but indicates the existence of an old protolith.

In the Raghane shear zone a dark tonalitic gneiss (Azan type) from the Agalen assemblage is strongly affected by mylonitization (BLN 400, Fig. 3). The zircons extracted from this rock are stubby and have, following the criteria of Pupin (1980), a low-temperature metamorphic habit.



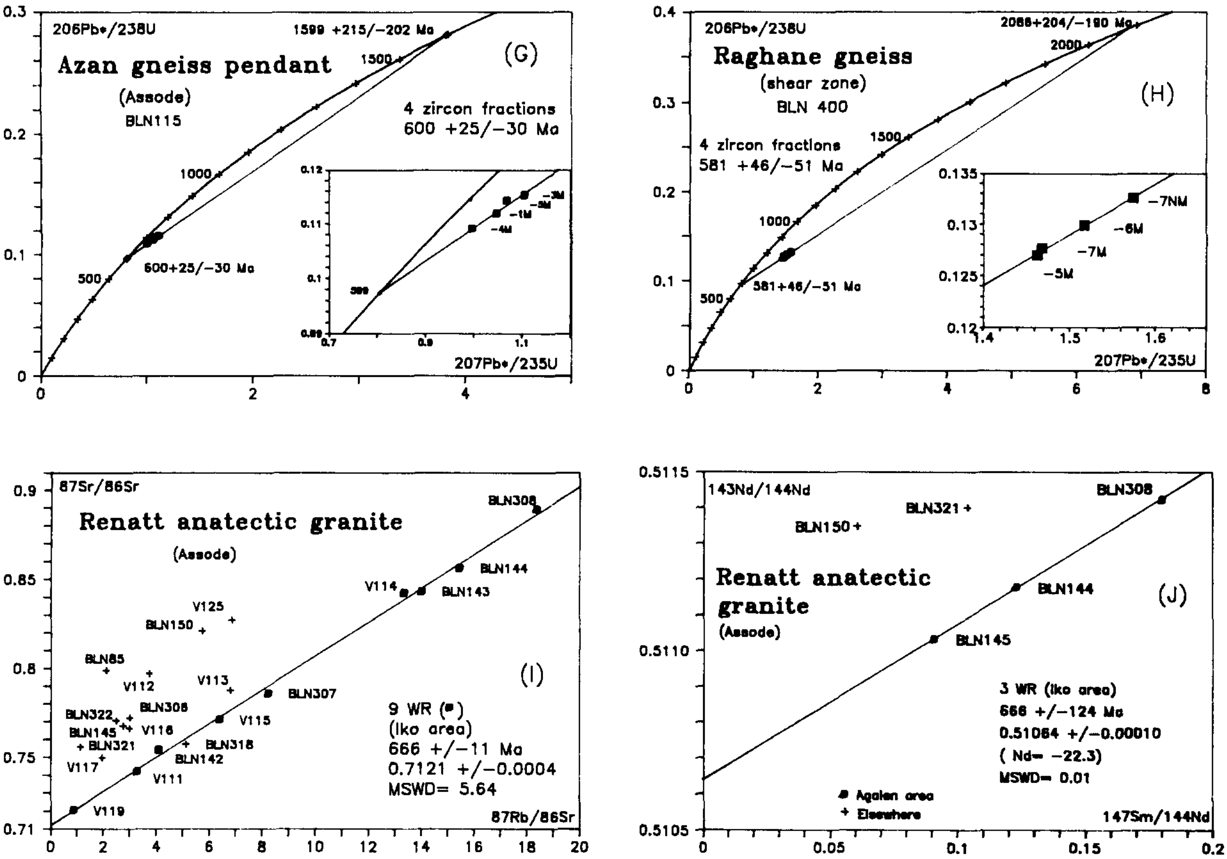


Fig. 6. New U–Pb zircon and Rb–Sr whole rock data. (A) Emzeggar late-kinematic Dabaga-east pluton (U–Pb discordia; Barghot). (B) Azan gneiss, affected by late quartz-vein hydrothermalism (U–Pb discordia, Barghot). (C) Proche–Ténéré late alkaline rhyolitic dykes (Rb–Sr isochron, Aïr). (D) Dabaga Forest late-kinematic Dabaga-west pluton (U–Pb discordia, Assodé). (E) Teggar late-kinematic Dabaga-west pluton (Rb–Sr isochron, Assodé). (F) Iferouâne late-kinematic Dabaga-west batholith (Rb–Sr isochron, Assodé). (G) Azan gneiss pendant (U–Pb discordia, Assodé). (H) Mylonitic tonalitic gneiss (U–Pb discordia, Raghane shear zone). (I) Renatt heterogranular leucocratic granite (Rb–Sr isochron, Assodé); the samples on which the isochron is based are from the Iko area, devoid of country-rock xenoliths. (J) Renatt heterogranular leucocratic granite (Sm–Nd isochron, Assodé), as for the Rb–Sr isochron, based on samples collected in the Iko area.

They have no inherited core or only an exceptionally highly resorbed one (Savino, 1992). They are largely discordant and have yielded a lower intercept of 581^{+46}_{-51} Ma and an upper intercept of 2086^{+204}_{-190} Ma (Fig. 6H, Table 1). The lower intercept is interpreted as the age of the mylonitization and the upper as indicating that the protolith is at least of Palaeoproterozoic age. In Eastern Hoggar, the post-kinematic granitic Adaf pluton that cuts the Raghane (8°30′) shear zone has been dated at 580±11 Ma (Bertrand et al., 1978).

The Renatt heterogranular leucocratic granite (Fig. 2A) contains in the south (BLN85), in the centre (BLN308) and in the north (BLN322) of Aïr similar zircons with a complex structure: a very irregular metamict core showing a leopard skin aspect with numerous inclusions (uranothorite among others) is surrounded by a homogeneous relatively thin envelope of magmatic zircon. The techniques available up to now in the laboratory have not allowed the separation of the two phases which are intergrown. The abundance of country-rock xenoliths is variable. In the Iko area, there is a zone largely devoid of gneissic xenoliths that has been sampled for the Rb–Sr

Table 2
Rb–Sr whole-rock data

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$
Proche–Ténéré rhyolites				
BLN12	165	59.2	8.111	0.767510±40
BLN13	158	41.6	11.081	0.793410±80
BLN14	274	13.6	61.000	1.159270±30
BLN200	178	36.6	14.213	0.811013±10
BLN201A	84.6	259	0.9455	0.712874±9
BLN201C	65.3	222	0.8515	0.712910±9
Teggar monzogranite				
BLN131	83.6	410	0.5906	0.719600±30
BLN133	318	82.3	11.297	0.815940±30
BLN134	312	81.8	11.150	0.813820±30
BLN135	297	86.6	10.013	0.800940±30
BLN136	351	96.9	10.581	0.806040±20
BLN139	356	77.1	13.515	0.827160±10
BLN140	320	97.7	9.560	0.797860±90
Iferouâne monzogranite				
BLN100	272	90.1	8.798	0.783240±70
BLN101	280	83.9	9.734	0.790470±50
BLN103	216	280	2.237	0.728580±30
BLN104	163	193	2.449	0.731130±40
BLN105	126	202	1.808	0.725830±30
BLN106	187	172	3.155	0.736870±40
BLN110	103	807	0.3696	0.714260±40
BLN112	145	752	0.5584	0.715700±20
BLN119	114	440	0.7502	0.715850±20
Renatt heterogranular leucocratic granite				
BLN85	105	147	2.0851	0.799280±30
BLN142	280	199	4.090	0.754520±20
BLN143	296	61.8	14.042	0.843700±30
BLN144	283	53.7	15.470	0.856740±30
BLN145	163	173	2.742	0.767790±40
BLN150	205	105	5.712	0.821800±30
BLN306	175	170	2.997	0.772622±11
BLN307	314	111	8.247	0.786134±9
BLN308	244	39.1	18.377	0.889681±11
BLN318	232	132	5.110	0.757420±11
BLN321	101	260	1.129	0.755812±15
BLN322	120	145	2.409	0.770663±9
V111	270	240	3.266	0.741780±50
V112	144	113	3.719	0.797050±50
V113	231	99	6.804	0.787790±50
V114	269	59	13.366	0.843070±50
V115	303	138	6.392	0.771140±50
V117	198	296	1.943	0.749940±50
V119	163	540	0.8744	0.720410±50
V125	248	106	6.849	0.827880±50

..ble 3
Sm–Nd whole-rock data

Sample	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma$)	ϵ_{Nd}	T_{DM}
Eberjegui (t=730 Ma)						
BLN6	6.86	35.5	0.1168	0.511755±55	−9.8	2025
BLN15	3.32	21.0	0.0956	0.511504±51	−12.7	1985
BLN16	3.84	23.7	0.0979	0.511805±9	−7.0	1627
Beurhot (t=700 Ma)						
V67	7.99	46.4	0.1041	0.511777±11	−8.5	1757
V72	2.70	15.1	0.1081	0.512199±26	−0.6	1217
V73	7.84	34.6	0.1370	0.512234±9	−2.5	1601
Takarakoum (t=700 Ma)						
BLN57	6.54	40.3	0.0981	0.511664±12	−10.2	1816
BLN58	5.00	30.6	0.0988	0.511635±15	−10.8	1865
BLN60	5.00	41.6	0.0726	0.511546±8	−10.2	1616
BLN61	7.28	37.3	0.1180	0.511857±14	−8.2	1886
Tchebarlare (t=664 Ma)						
BLN34	4.04	16.6	0.1471	0.511986±13	−8.5	2431
BLN38	1.03	5.78	0.1077	0.512121±11	−2.5	1324
V36	4.92	33.2	0.0896	0.511888±9	−5.5	1416
Renatt (t=666 Ma)						
BLN144	3.81	18.7	0.1231	0.511178±8	−22.7	3187
BLN145	3.95	26.4	0.0904	0.511032±21	−22.9	2496
BLN150	0.24	2.41	0.0602	0.511348±44	−13.6	1681
BLN308	3.60	12.4	0.1755	0.511423±24	−22.5	-
BLN321	2.71	15.8	0.1037	0.511401±39	−16.2	2279
Iferouâne (t=600 Ma)						
BLN103	6.72	57.0	0.0713	0.511391±42	−14.7	1766
BLN104	4.91	30.6	0.0970	0.511581±15	−13.0	1908
BLN110	9.94	50.1	0.1199	0.511691±51	−12.6	2200
BLN112	4.10	31.0	0.0799	0.511414±9	−14.9	1855
Teggar (t=600 Ma)						
BLN131	8.35	55.9	0.0903	0.511330±40	−17.4	2117
BLN139	4.27	19.3	0.1337	0.511987±9	−7.9	2011
Irsane (t=600 Ma)						
BLN122	13.3	67.1	0.1198	0.511513±5	−16.1	2495
BLN128	5.70	37.5	0.0919	0.511364±10	−16.8	2102

method. Most of these samples define nearly an isochron: 666±11 Ma (SrIR=0.7121±0.0004, 8WR, MSWD=5.6; Fig. 6I, Table 2). All other Renatt samples collected elsewhere in the Assodé terrane (except one, BLN318) lie above this reference line. A similar pattern exists in the Sm–Nd isotopic system: three samples from the Iko area define an isochron (3WR, 666±124 Ma, NdIR=0.51064±0.00010 or $\epsilon_{Nd}=-22.3\pm2$, MSWD=0.01; Fig. 6J, Table 3), two other samples lying above the line. This age, even if besmirched by a large error, is compatible with the interpretation of the 666±11 Ma age as that of the Rb–Sr system closure subsequent to the em-

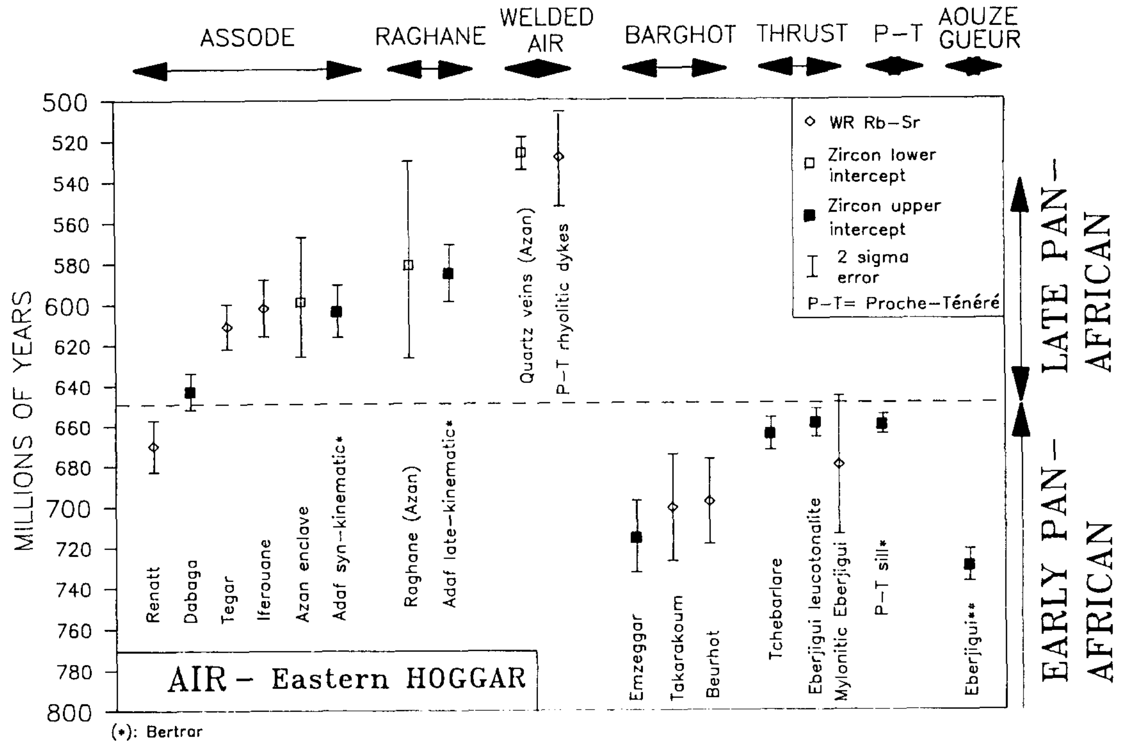


Fig. 7. Summary of the available geochronological results from Aïr and Eastern Hoggar: *Bertrand et al., 1978; **Caby and Andreopoulos-Renaud, 1987; others this paper.

placement of the clearly intrusive part of the Renatt heterogranular leucocratic granite. The case of the more radiogenic samples lying above the isochron and the relatively high MSWD value can be related to the variable abundance of country-rock xenoliths and will be discussed in Sect. 6.3 dealing with the Nd and Sr initial ratios.

A summary of all these ages, given in Fig. 7, shows the contrasting ages of magmatic events on either side of the Raghane shear zone.

5. Metamorphism

The following metamorphic data are only preliminary but are thought to be relevant to the geodynamic model which we shall propose.

5.1. Aouzegueur terrane

The ophiolitic primary parageneses are replaced by secondary greenschist minerals, the more abundant rock types being serpentinites and chlorites. Transformed gabbroic cumulates, basalts, diorites and fine-grained tonalites are also found (Boullier et al., 1991). An aluminous graphitic schist displays andalusite stretched out and retrograded to muscovite sericite during the regional greenschist dynamic metamorphism. The overlying Arrei unit comprises chlorite schists, meta-arkoses, quartzites and rare fine-grained white and pink marbles.

5.2. Barghot terrane

In the Taf Group, two metamorphic trends have been identified:

(1) In the south-southeast corner of the terrane, devoid of large batholiths, garnet gneisses display a high-pressure prograde evolution. The primary paragenesis (Qz–Pl–Kf–Chl–Ga–Ky) gave way to a secondary paragenesis of higher temperature (Qz–Pl–Kf–Bi–Ga–Ky–St). The

latter paragenesis indicates conditions of peak metamorphism at ca. 8 kbar and 680°C (following the petrogenetic grid of Holland and Powell, 1990). In this sector, striking features are the homogeneity of individual minerals and the absence of retrogression. This indicates absence of rehydration and that the secondary paragenesis has been fixed rapidly.

(2) West of the Zagado muscovite schist unit (Fig. 3) close to a large Dabaga-east batholith, garnet gneisses display a HT–LP retrograde evolution: the primary paragenesis (Qz–Pl–Kf–Ga–Bi–Cord–Sill) is followed by a lower-temperature secondary paragenesis (Qz–Pl–Kf–Ga–Chl–Mu). In one thin section, an intermediate paragenesis is characterised by the appearance of cordierite–spinel symplectites. With the exception of the Zagado muscovite schist unit where it is well developed probably due to thrust tectonics, the secondary paragenesis is limited to small patches or narrow surfaces. This leads to an estimated *P–T* evolution from 5 ± 1 kbar and 700°C to 4 ± 1 kbar and less than 600°C for the last paragenesis (following Latouche et al., 1992).

5.3. Assodé terrane

Gneisses of the Assodé terrane have been subjected to two successive metamorphic events in upper and medium amphibolite facies. The most informative parageneses are in mafic gneisses (primary: Pl–Hb^1–Ga–Qz; secondary: Pl–Hb^2–Qz) and in metapelites (primary: Qz–Pl–Kf–Cord–Bi^1–$Sill^1$; secondary: Qz–Pl–Kf–Cord–Bi^2–Mu–$Sill^2$ = fibrolite). These two successive parageneses are generally related to two deformations and by contrast to the Barghot terrane, the second metamorphism has induced notable chemical reequilibration in the primary paragenesis. Rough estimates point to 6 ± 1 kbar and 700°C for the primary paragenesis to 4 ± 1 kbar and 600°C for the secondary paragenesis. Widespread retrogression is marked by a third set of parageneses (Pl–Qz–Ep; Qz–Pl–Bi–Mu). High-pressure relicts are badly documented: kyanite has been very rarely observed in the Aïr part of Assodé but HP associations are better preserved in Issalane, the northern part of Assodé (Guérangé and Vialon, 1959; R. Caby, written commun., 1990). This could be linked to the poor quantity of Renatt granites existing to the north of Issalane.

5.4. Raghane boundary zone

Mafic–ultramafic rocks and gneisses reworked in the Raghane shear zone have recrystallized under amphibolite facies conditions. Even if they are characterised by a strong mylonitic fabric, the "annealed" appearance of individual secondary minerals, which are equigranular, with average grain size of 2 mm and the existence of peristerite in plagioclase, indicates a crystallisation under relatively high temperature (e.g. White and White, 1981). These high-grade conditions for the shear zone have allowed the preservation of clinopyroxene and Cr–spinel relicts in ultramafic rocks.

5.5. Tchilit palaeorift

In the Tchilit palaeorift, volcanic and detritic rocks are affected by a greenschist facies metamorphism. In arkosic and quartzitic horizons, the schistosity is underlined by muscovite. Some Ca–Fe-rich levels display a paragenesis with Ga–Chl–Ep–Ab–Kf–Qz (the garnet is a grossular or a hydrogrossular).

6. Description and origin of the granitoids

6.1. Petrography

The Eberjegui TTG suite characterises the Aouzegueur terrane and is found all along it. The main facies is a medium- to coarse-grained granodiorite and quartz-diorite with subidiomorphic andesine and subordinate microcline, quartz, green hornblende, biotite with apatite and titanite as accessory minerals. This rock shows a strong greenschist imprint with sericite, chlorite and epidote, giving it a green colour. Beneath the main thrust, it displays a strong mylonitic texture. Late leucocratic tonalite and trondhjemite contain small amounts of amphibole and are also mylonitic.

The Dabaga-east and Dabaga-west granitoids are petrographically similar and originally were mapped as a single composite unit (Black et al., 1967). Late-kinematic Dabaga-east and -west form generally large batholiths (e.g. Beurhot 1730 km^2; Iferouâne 1540 km^2) composed of successive intrusions with always the same relative order of emplacement: early quartz-diorite often along the outer envelope, followed by granodiorites, porphyritic monzogranites and fine-grained monzogranites and sometimes finishing with a leucocratic syenogranite.

The quartz-diorite generally displays a planar fabric and is composed of 50–70% acid andesine, 10–30% ferromagnesian minerals (green hornblende and green or rarely brown biotite) and less than 10% of interstitial quartz. Accessory minerals are abundant titanite, opaques, apatite, allanite, zircon. A slight retrogression phase composed of epidote, chlorite and calcite is often present. The porphyritic monzogranite includes megacrysts of slightly perthitic microcline with poikilitic borders. Euhedral zoned basic oligoclase is often bent or broken and quartz is present in large interstitial crystals with undulatory extinction or forming a mosaic of small grains. Green biotite associated sometimes with green amphibole may be bent. Accessory minerals are abundant titanite, apatite, zircon, opaques and rare allanite. Epidote and chlorite are present as secondary minerals.

The unique post-kinematic Dabaga-east pluton (Tchebarlare) in the Barghot terrane is a circular high-level intrusion characterised by horizontal jointing and presenting a chilled border. It is porphyritic and has a mineralogy comparable to that of the porphyritic monzogranite just described, but an isotropic fabric. The post-kinematic subcircular Dabaga-west granitoids in the Assodé terrane are more abundant; however, they are not important in volume. They are isotropic and can be subdivided in three geographically distinct subgroups: the Guermouzou-type monzogranite (four to five small plutons in the centre of Assodé), the Tamazour-type syenogranite forming five plutons intrusive in north-east Aïr in the vicinity of the Raghane shear zone apparently in both the Assodé and Barghot terranes, and the Tessa-n-Imghad-type syenogranite forming six plutons in NW Assodé, 5 to 15 km in diameter.

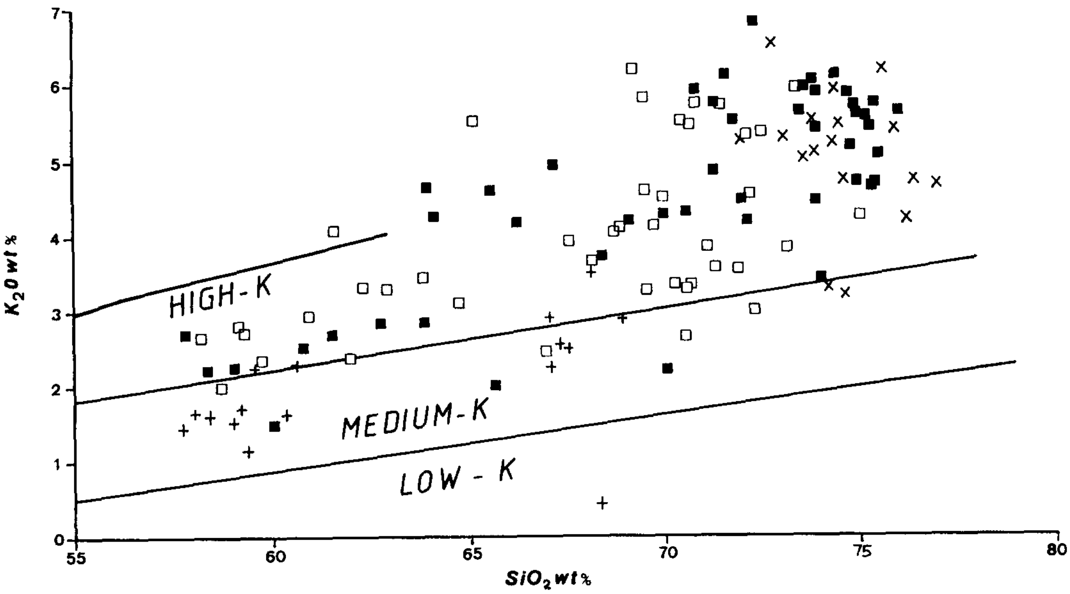
The Renatt heterogranular leucocratic granite is heterogeneous, grey to pinkish in colour, displays an allotriomorphic structure and is characterised by the presence of scattered large megacrysts of microcline attaining several centimetres in diameter, often aggregated in cloudy patches giving a pegmatitic appearance. The granite is composed of anhedral quartz in large crystals displaying undulatory extinction and small rounded grains included in the feldspars, limpid microcline sometimes slightly perthitic ($<10\%$ albite) and often poikilitic around the edges, finely twinned albite–oligoclase often with a sericitized core, myrmekite, and $<5\%$ of brown biotite altered along the cleavages to chlorite and epidote, and spongy white mica developed in the feldspars. Accessory minerals are scarce and include opaques, zircon and sometimes apatite.

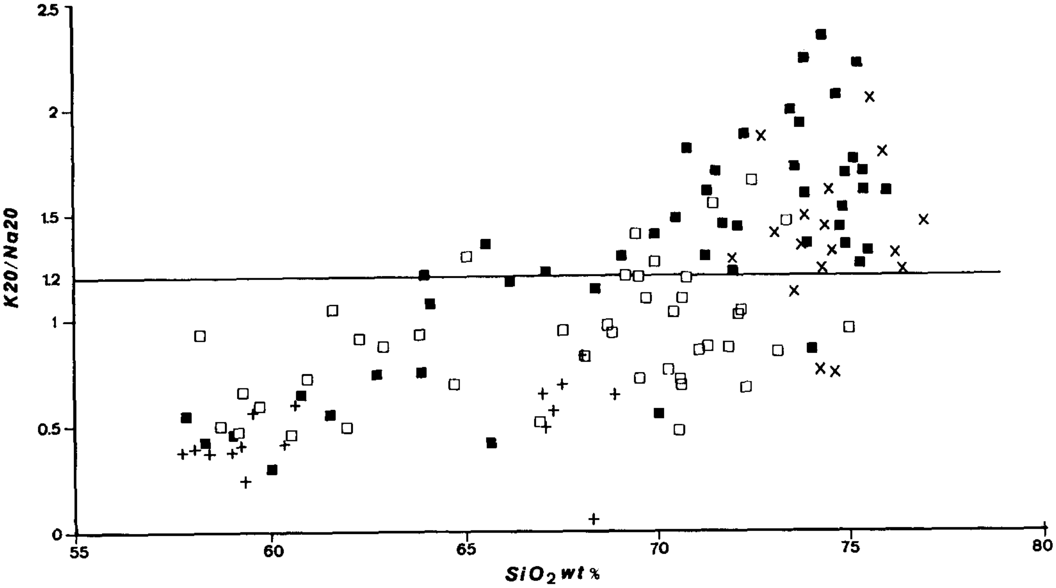
6.2. Geochemistry

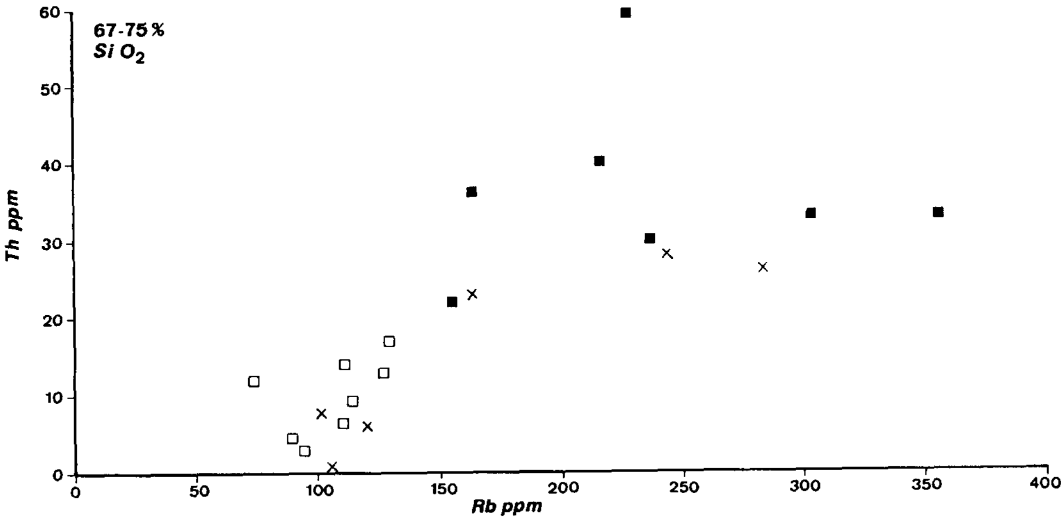
The main geochemical characteristics of the Aïr Pan-African granitoids are the following.

In the SiO_2 versus K_2O diagram (Fig. 8, upper part; Peccerillo and Taylor, 1976; Le Maître, 1989), the Eberjegui granitoids fall in the medium-K calc-alkaline field while Dabaga-east and Dabaga-west granitoids define a high-K calc-alkaline trend, the mean weight point of the Dabaga-west group being more acid and more potassic than that of the Dabaga-east group. The wide range in K_2O for a given silica content is probably due to variable K-feldspar accumulation, a phenomenon sometimes seen in the field

Fig. 8. Geochemical data of Aïr Pan-African intrusive rocks: SiO_2 versus K_2O; SiO_2 versus K_2O/Na_2O; Rb versus Th. + = Eberjegui; □ = Dabaga-east; ■ = Dabaga-west; × = Renatt.


HIGH-K
MEDIUM-K
LOW - K
K_2O wt %
SiO_2 wt %


K20/Na20
1.2
SiO_2 wt %


67-75 %
SiO_2
Th ppm
Rb ppm

south of Iferouâne. The Renatt heterogranular leucocratic granite has more than 72% SiO_2 and shows a K_2O content similar to the Dabaga-west granites.

A chemical distinction between Dabaga-west and Dabaga-east is shown by the SiO_2 versus K_2O/Na_2O diagram (Fig. 8, middle part): if the basic and intermediate rocks (up to 65% SiO_2) have similar K_2O/Na_2O ratios (from 0.25 at 57% SiO_2 to 1 at 65% SiO_2), the more acid rocks evolved divergently; most of the Dabaga-west have K_2O/Na_2O ratios higher than 1.2 by opposition to the Dabaga-east where this ratio is generally lower than 1.2. The Eberjegui granitoids have still lower ratios (<0.75) while the heterogranular leucocratic Renatt granites are in the Dabaga-west range. The other major elements of the two Dabaga groups are very similar.

Trace elements distinguish the medium-K calc-alkaline Eberjegui granitoids from the high-K Dabaga groups and from the heterogranular leucocratic Renatt granite. The two Dabaga groups can be separated by two strongly incompatible elements, Th and Rb (Fig. 8, lower part). In this diagram, the Dabaga-west group (67–75% SiO_2) are richer in both Rb and Th than the Dabaga-east group (68–75% SiO_2).

Finally, the four groups can be characterised by the REE elements (Fig. 9). The Eberjegui group shows a LREE-enriched spectrum with no Eu anomaly typical of the TTG calc-alkaline suites. The Dabaga-east group displays a wider range around similar values and a small negative Eu anomaly. The Dabaga-west group is more enriched in both LREE and HREE and has stronger Eu negative anomaly. Despite a narrow range in silica (72–76%), the Renatt heterogranular leucocratic granite presents two types of spectra. The first one has a negative Eu anomaly and LREE enrichment comparable to that of the Dabaga groups, but is more enriched in HREE ($Lu_N > 10$). The second one has a strong positive anomaly, low total abundance in REE, is moderately enriched in LREE and particularly enriched in HREE.

This brief description indicates the high-K calc-alkaline signature of both Dabaga groups. However, besides the age gap, dissimilarities exist.

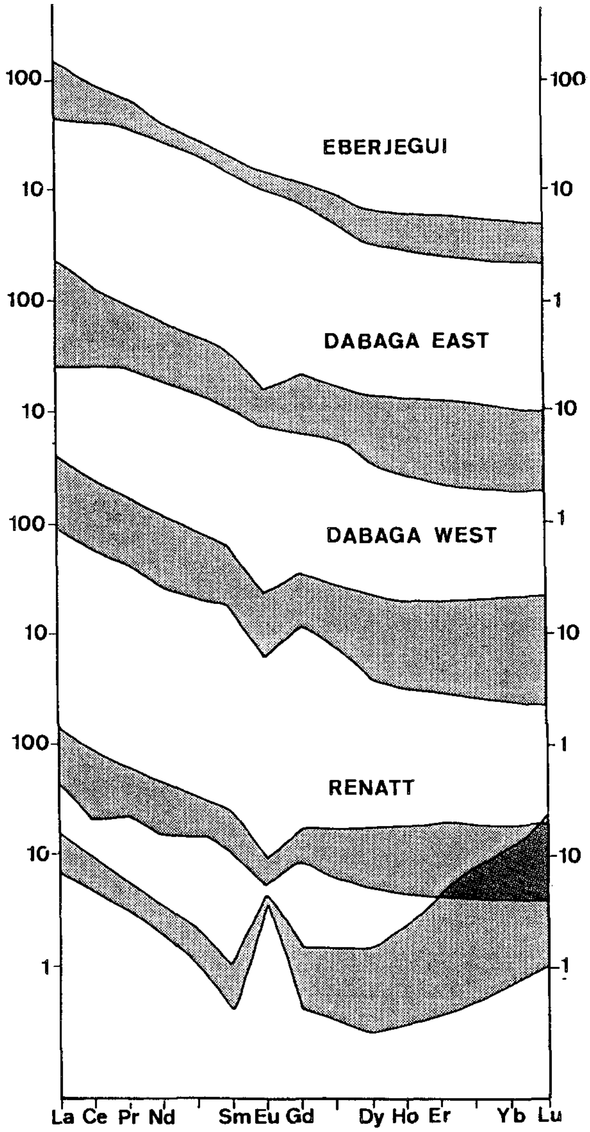


Fig. 9. Chondrite-normalized rare earth elements abundance: Eberjegui TTG (Aouzegueur terrane, 4 samples); Dabaga-east granitoids (Barghot terrane, 11 samples); Dabaga-west granitoids (Assodé terrane, 14 samples); Renatt granites (Assodé terrane, 7 samples).

The Dabaga-west series is more differentiated and enriched in some incompatible elements. Eberjegui granitoids have the characteristics of normal subduction-related plutonism. Renatt granites, whose crustal anatectic origin can be demonstrated in the field and confirmed by isotopes (see below), have not the typical peraluminous composition of S-type leucogranites derived from a wet pelitic source, but need one nearer to the bulk continental crust. Complex interactions with country-rocks probably also occurred.

6.3. Isotope geochemistry

The Renatt granites have an exclusive crustal signature in agreement with their aspect in the field and with complete absence of mafic magmatic enclaves or more mafic precursors. In the Iko zone, as already mentioned, the Renatt granite is relatively free of xenoliths and more homogeneous. Most of the samples collected there share a common Sr initial ratio (SrIR) of about 0.712 (Fig. 6I) and ϵ_{Nd} about -22.3 (Figs. 6J, 10). These values lead to interpret the Renatt granite of the Iko area as the result of partial fusion of the Assode lower crust (old lower crust: SrIR = > 0.707; $\epsilon_{Nd} < -20$, the Lewisian granulites being unique; Taylor and McLennan, 1985). The more prevalent Renatt granites, characterised by abundant more or less digested country-rock xenoliths, yield highly variable SrIR values of up to 0.780, but higher ϵ_{Nd} (-16.2 and -13.6; Fig. 10). This suggests a major input of a medium crust younger than the lower crust (to explain the less negative ϵ_{Nd} and younger T_{DM} ages; Table 3), an input likely represented by the xenoliths. Consequently, we propose that the Renatt granites originated from the regional production of high-temperature quartzo-feldspathic melts in the Assodé lower crust probably of Archaean age (T_{DM} up to 3187 Ma), such old terrains being known in northern Hoggar (Latouche and Vidal, 1974; Latouche, 1983). These melts, after upward migration, interacted variably with the amphibolite facies medium crust (2000 Ma?). Heat transfer by the Renatt granite has probably enhanced regional anatexis in the amphibolite facies medium crust.

In Fig. 10, the calc-alkaline granitoids lie between the crustal signature of the Renatt granitoids and a mantle signature such as that of the Iforas Pan-African oceanic island arc (Liégeois, 1988; Caby et al., 1989). This intermediate po-

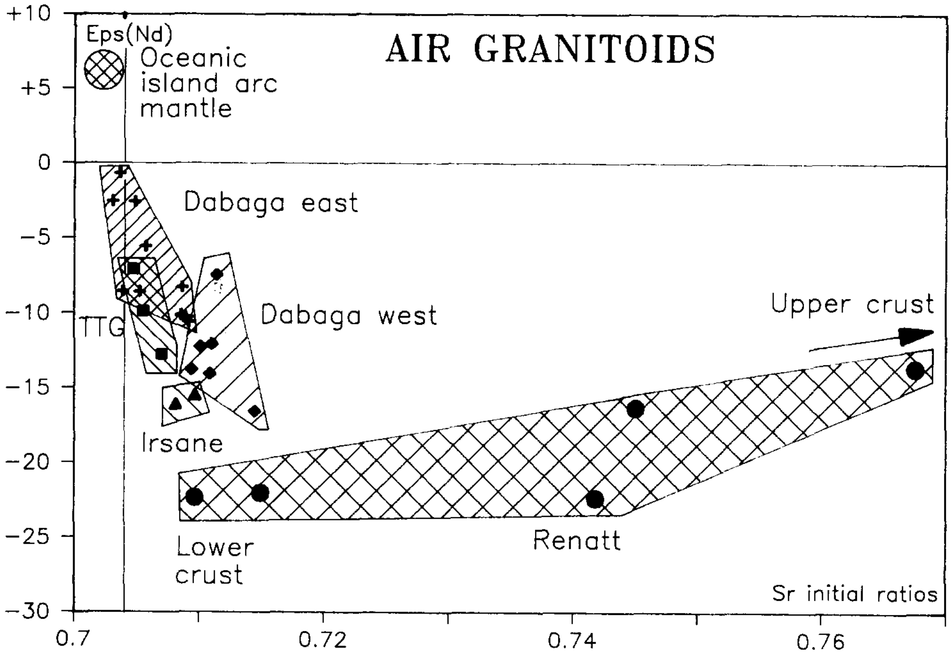


Fig. 10. Strontium initial ratios versus ϵ_{Nd}—*Eps(Nd)*—calculated at the age of each intrusion (see Sect.4.2).

sition points to a differentiating mantle magma contaminated by continental crust. This seems reasonable for the Barghot granitoids which comprise granites with Sr and Nd isotopic ratios close to mantle values (Black et al., 1991; Fig. 10) and which display a complete sequence of differentiation. The less potassic character of the Eberjegui TTG suite relative to Dabaga granitoids and the less radiogenic crustal component indicated by the TTG trend in Fig. 10, point to a contamination essentially either by a hidden lower crust or by a component derived from old sediments subducted with the oceanic crust. This last hypothesis is in agreement with the presence of only mafic and ultramafic xenoliths in this suite. The Assodé Dabaga-west calc-alkaline granitoids have a greater crustal component but are not in the Aïr crustal range defined by the Renatt granites. Moreover, concerning their petrography and major and trace element geochemistry they are similar to the Dabaga-east granitoids. We therefore also adopt a subduction-related mantle source for the Assodé Dabaga-west granitoids but with more pronounced crustal contamination. The latter can be linked to the existence of regional anatexis prior to the Dabaga-west generation (Rb–Sr isotopic system closure of the Renatt at 666 ± 11 Ma and first Dabaga-west at 643^{+11}_{-10} Ma).

The origin and significance of the Irsane syenite are not yet fully understood, but Sr and Nd initial ratios suggest an affinity with the Dabaga of the Assodé terrane.

7. The geodynamic model

The data presented in this paper coupled with the geological mapping by Black et al. (1967) in Aïr and by the Bureau de Recherches Minières de l'Algérie and Bertrand and Caby (1978) in Eastern Hoggar, and with some more recent works in the area (Bertrand et al., 1978; Caby and Andreopoulos-Renaud, 1987; Black et al., 1991; Boullier et al., 1991) allow one to propose a geodynamic model for Aïr and Eastern Hoggar in which the lithospheric mantle and large-scale displacement of terranes played a major role.

7.1. Summary of main events

Fig. 11 summarises our interpretation of the sequence of events and Fig. 12 outlines the terranes postulated in the Eastern Tuareg shield.

7.1.1. The early Pan-African orogeny (~ 700 Ma)

Aouzegueur terrane. Old basement has not been observed in this terrane. The first visible events are the deposition of the sediments of the Arrei unit and mafic–ultramafic rocks from the Aouzegueur ophiolitic unit, and as enclaves in the Eberjegui TTG suite. This assemblage was affected by a compressional period at the end of which the late-kinematic (Caby and Andreopoulos-Renaud, 1987) TTG intruded at ~730 Ma both the mafic–ultramafic rocks and the Arrei unit, the whole being finally thrust to the northeast (680–670 Ma).

Barghot terrane. The basement of this terrane comprises an old grey gneissic series (Azan, 2000 Ma?, zircon upper intercept) and a supracrustal series (Taf), both metamorphosed in a high-pressure amphibolite facies followed locally by HT–LP amphibolite facies. The high-K calc-alkaline granitoids (720–700 Ma) can be linked to the Aouzegueur subduction process. However, as they are of a late-kinematic and post- to late-HT–LP amphibolite facies metamorphism, they are quite comparable to the Pan-African batholith of Iforas (Mali). The latter has subduction characteristics but intruded at the end of a collision in a regime of transcurrent movements (Liégeois et al., 1987). Sr–Nd initial ratios indicate a mantle origin contaminated by an old continental crust. Lastly, the whole Barghot terrane is thrust to the east-northeast on the Aouzegueur terrane (>664 Ma), an event which has fixed the metamorphic parageneses.

Welded Aouzegueur–Barghot terrane: the Proche–Ténéré terrane. After the thrusting sealed by the Tchebarlare pluton (664 ± 7 Ma), the Aouzegueur and Barghot terranes have a common history characterised by a light imprint of the ~600 Ma late Pan-African events. Together they form the Proche–Ténéré terrane. Relative post-670 Ma stability of this terrane is marked by subhorizontal Proche–Ténéré sediments de-

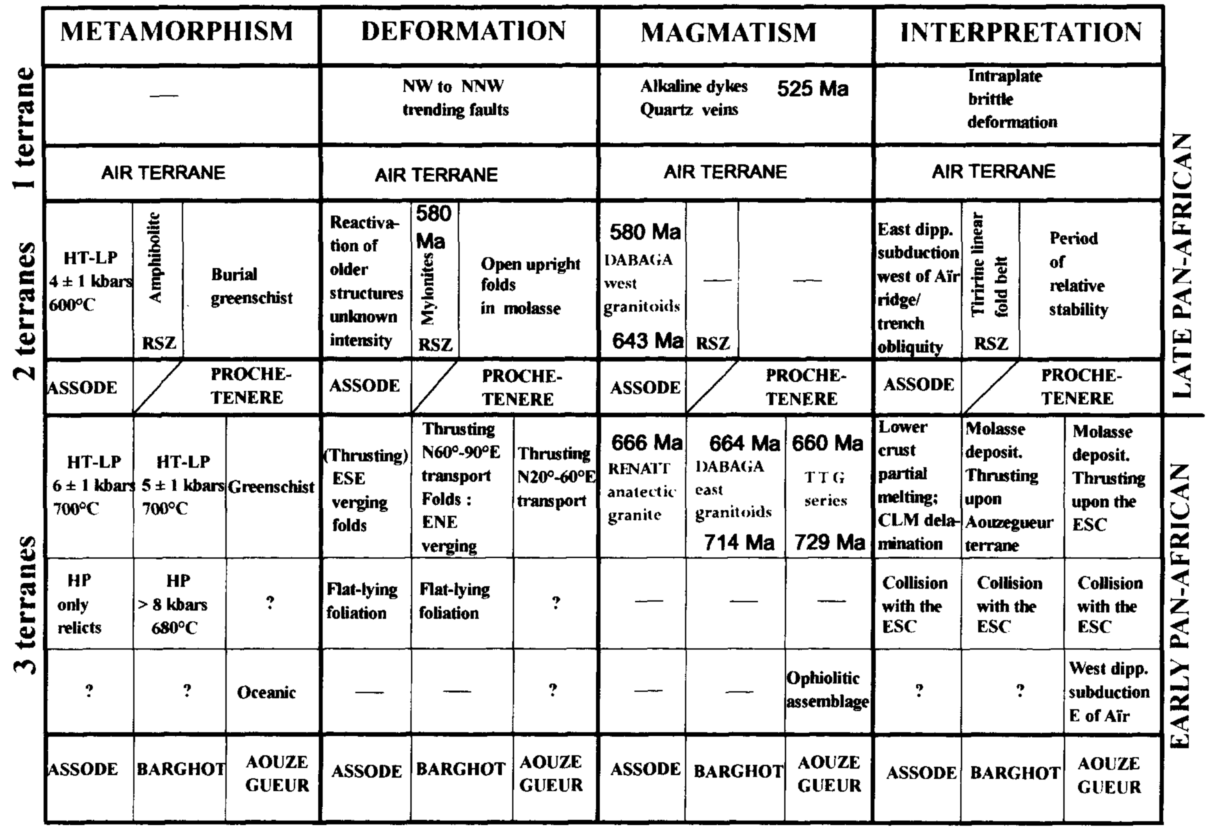


Fig. 11. Summary of the major events leading to the present terrane assembly in Aïr and Eastern Hoggar. Proposed correlations. *RSZ* = Raghane shear zone; *ESC* = East Saharan craton. See text.

posited unconformably on both the Barghot and Aouzegueur domains. These sediments and the underlying basement have only been subjected to a burial static greenschist facies (Black et al., 1967; Caby and Andreopoulos-Renaud, 1987).

Assodé terrane. First of all, note that the Dabaga-west calc-alkaline granitoids play no part in the early Pan-African orogeny as they are younger (645–580 Ma). The Assodé terrane displays an ESE-verging structure and is affected by a HT–LP metamorphism. While these conditions are arrested due to uplift associated with thrusting in the Barghot terrane, they proceed to general anatexis in the Assodé terrane with the widespread emplacement of anatectic Renatt granites (Rb–Sr isotopic closure at 666 ± 11 Ma). These granites have been observed in the Issalane block (K. Baziz, written commun., 1992), the northern extension in Algeria of the Assodé terrane, but are absent in the adjacent terranes.

7.1.2. The late Pan-African orogeny (~ 600 Ma)

Assodé terrane. The two main late Pan-African events are the intrusion of the Dabaga-west granitoids and dextral movements along the Raghane shear zone.

The first Dabaga-west pluton (643^{+11}_{-10} Ma) is younger than the last post-kinematic Dabaga-east granite (664 ± 8 Ma) and was emplaced a short time after the Rb–Sr isotopic closure of the Ren-

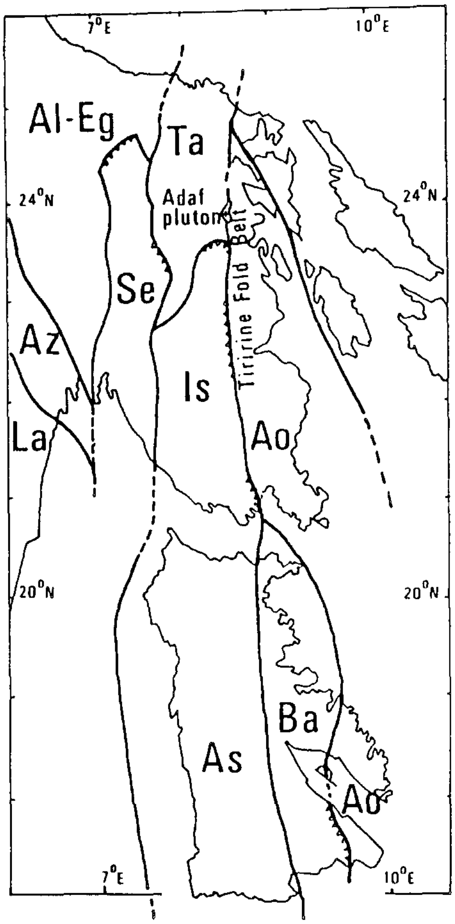


Fig. 12. Schematic terrane map of the Eastern Tuareg shield (Phanerozoic sedimentary cover has been removed). *Al-Eg*=Aleksod–Egéré terrane; *Ao*=Aouzegueur terrane; *As-Is*=Assodé–Issalane terrane; *Ba*=Barghot terrane; *Az*=Azrou-n-fad terrane; *La*=Laouni terrane; *Se*=Serouenout terrane; *Ta*=Tazat terrane.

att anatectic granite (666±11 Ma). Other Dabaga-west plutons give ages at ~600 Ma and a post-tectonic one at 580 Ma. This suggests that continuous generation of Dabaga-west granitoids probably occurred between 645 Ma and 580 Ma. Isotopic and geochemical constraints have been interpreted in terms of a mantle subduction-related origin with mixed lower and medium crust contamination. Considering that the intrusion of Dabaga-west type granitoids occurred after the regional anatexis and the closure of the oceanic domain to the east, we are led to envisage an easterly dipping subduction taking the relay to the west.

Raghane boundary zone. This major dextral shear zone delimits the eastern edge of the Assodé terrane and can be followed over a distance of 900 km. In Algeria, where its features are very similar (Bertrand et al., 1978), it is responsible for the creation of the "Tiririne intracontinental linear belt" made up of early molassic sediments (Fig. 12). West of this belt, the Issalane block (northern Assodé terrane) is affected by this shear zone over a distance of several kilometres (Bertrand et al., 1978). In Aïr, the molassic sediments lie more to the east; consequently, the Raghane shear zone affects the basement of both the Assodé and Proche–Ténéré terrane. In Hoggar, the Raghane shear zone (8°30′ mega-shear zone) is stitched by the late phase of the Adaf pluton at 580±6 Ma (Bertrand et al., 1978; Fig. 12). Further south in Aïr, the mylonitic tonalite gneiss east of Agalen has a 581^{+46}_{-51} Ma age (U–Pb zircon lower intercept) in the same range, even if imprecise.

Movements along the Raghane shear zone, which ceased at 580 Ma, probably occurred continuously over a long period of time, starting with the Dabaga-west granitoids ~645 Ma. This is based on the following observations:

(1) All three terranes (Aouzegueur, Barghot, Assodé) have collided with an unknown eastern continent but only Assodé has not been intruded by early Pan-African late- or post-kinematic calc-alkaline granitoids (Dabaga-east or Eberjegui types) and has undergone a regional anatexis. These major contrasting features indicate a different geographical position for the Assodé terrane relative to Barghot and Aouzegueur during the early Pan-African phase.

(2) The metamorphic assemblages in Assodé suggest a long metamorphic history in the upper amphibolite facies, which is also found in the Raghane shear zone.

(3) Late-kinematic Dabaga-west plutonism such as the Iferouâne batholith has an elongated shape parallel to the Raghane shear zone (Fig. 2A), suggesting that these events are contemporaneous.

(4) Post-kinematic Dabaga-west emplace-

ment coincides with the end of the life of the Raghane shear zone.

The Proche–Ténéré terrane (welded Aouzegueur–Barghot). The effect of the late Pan-African orogeny on the Proche–Ténéré terrane is weak and essentially marked by very gentle folding and incipient subvertical cleavage in the Proche–Ténéré Group, except along the Raghane shear zone (Tiririne intracontinental fold belt). The Proche–Ténéré terrane can be considered as relatively stable during the late Pan-African period.

7.1.3. Events subsequent to late Pan-African

The last major event that can be linked to the Pan-African orogeny is the Aïr NW to NNW striking transcurrent sinistral fault system that affects all the previous terranes. The age of the linked hydrothermal activity has been evaluated at ~525 Ma.

7.2. The role of the continental lithospheric mantle (CLM)

In a recent paper (Black and Liégeois, 1993), we have laid emphasis on the probable role of the mechanical boundary layer (MBL, the rigid upper part of the CLM) whose important characteristics are to be much more rigid than the crust and to be denser than the asthenosphere. That means that if the MBL is thick, the plate is very rigid (craton), and that if the MBL is weakly attached to the buoyant crust, in some circumstances, the MBL can sink into the asthenosphere (CLM delamination during hypercollision). This last phenomenon is probably a general feature of collisional orogenies leading to a paradigmal shift in plate tectonics (Nelson, 1992). An important consequence of CLM delamination is that the less dense asthenosphere rises and carries the base of the crust to a temperature >700°C inducing regional crustal melting as now in Tibet (Houseman et al., 1981; McKenna and Walker, 1990). This leaves an unrigid mobile crust. These notions are discussed in detail by Black and Liégeois (1993) and are now applied to build the Aïr model.

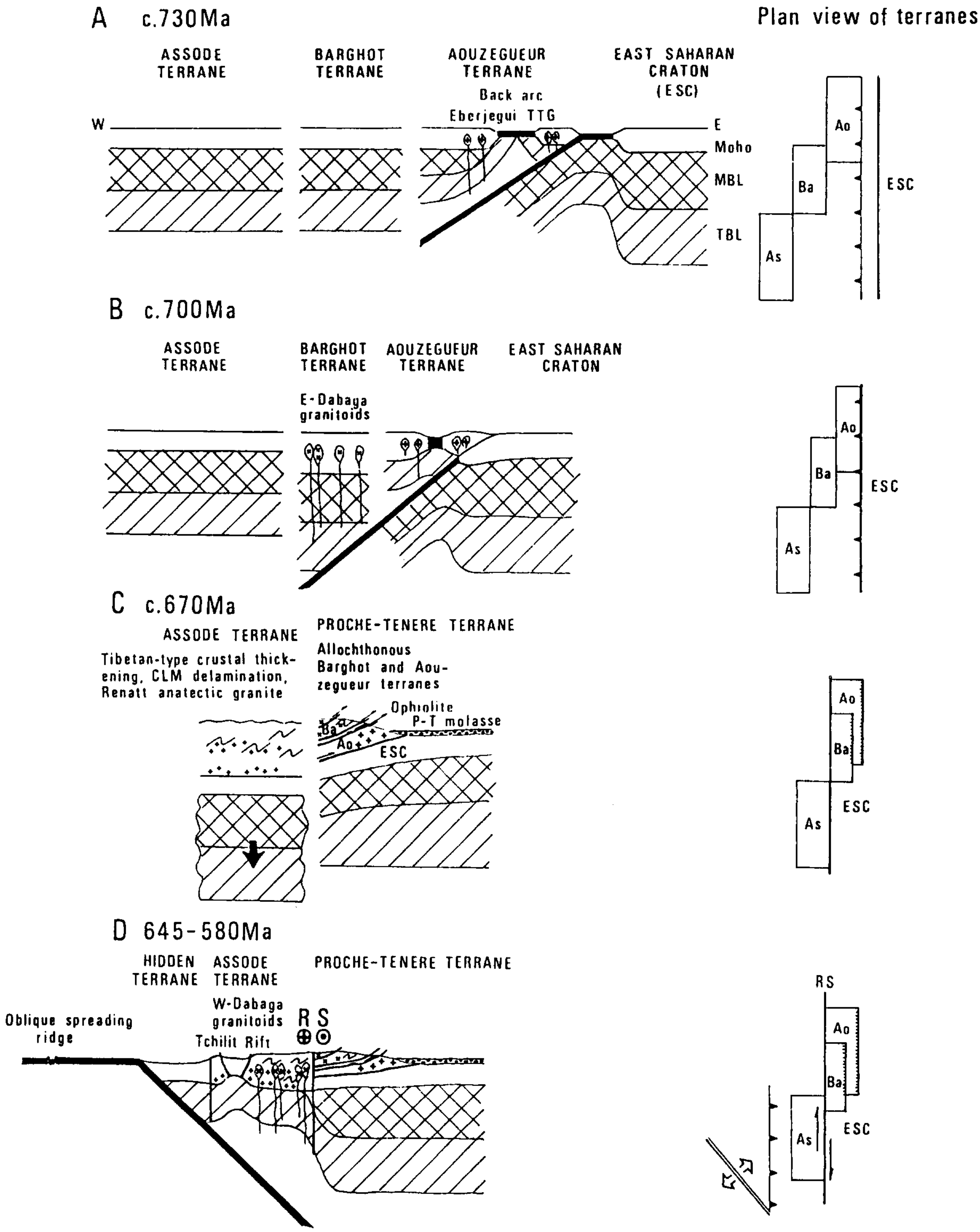
7.3. Tectonic model

Our tectonic model is illustrated in Fig. 13.

In early Pan-African times, the subduction period (>730 Ma) affected largely the Aouzegueur terrane (1000 km long), the ophiolite being interpreted as oceanic crust in a back-arc basin. The Assodé terrane at that time was located further to the south and probably at a distance from the trench with the Barghot terrane in an intermediate position (Fig. 13A).

Considering the high-pressure metamorphism found in Barghot as the collision climax and the late-kinematic granitoids accompanied by the high-temperature metamorphism as late collision events, we propose that a collision with a postulated eastern continent occurred at ~730 Ma and before in the Aouzegueur terrane (Caby and Andreopoulos-Renaud, 1987), and at ~714 Ma and before in the Barghot terrane (Fig. 13B). Thrusting upon the eastern continent of Aouzegueur followed by Barghot ended at 680–670 Ma (Rb–Sr age). This event therefore fixed the metamorphic parageneses. The thrust was followed by post-kinematic calc-alkaline plutonism (~665 Ma). The terrane that was formed (Proche–Ténéré terrane) had afterwards a relatively stable behaviour as compared with adjacent terranes. This points to an underlying old rigid eastern continental margin with thick CLM (Fig. 13C). Deposition of the Proche–Ténéré Molassic Group is subcontemporaneous with the end of the thrusting (older than 660 Ma; Bertrand et al., 1978).

The Assodé terrane is fundamentally different from the Barghot and Aouzegueur terranes, there being no ~700 Ma calc-alkaline granitoids but prevalent HT–LP metamorphism accompanied by incipient melting of the medium crust and presence of large volumes of anatectic granite (Renatt). The latter is late with respect to the metamorphism and deformation and marks the end of the early Pan-African collision (~666 Ma; Rb–Sr). These features, reminiscent of those in Tibet, suggest that CLM delamination of the Assodé terrane took place due to a vigorous confrontation with the eastern continent, which behaved as a rigid plate. This event occurred at the


A c.730Ma
Plan view of terranes
ASSODE TERRANE
BARGHOT TERRANE
AOUZEGUEUR TERRANE
EAST SAHARAN CRATON (ESC)
Back arc
Eberjegui TTG
W
E
Moho
MBL
TBL
Ao
Ba
As
ESC
B c.700Ma
ASSODE TERRANE
BARGHOT TERRANE
AOUZEGUEUR TERRANE
EAST SAHARAN CRATON
E-Dabaga granitoids
Ao
Ba
As
ESC
C c.670Ma
ASSODE TERRANE
PROCHE-TENERE TERRANE
Tibetan-type crustal thickening, CLM delamination, Renatt anatectic granite
Allochthonous Barghot and Aouzegueur terranes
Ophiolite
P-T molasse
Ba
Ao
ESC
Ao
Ba
As
ESC
D 645-580Ma
HIDDEN TERRANE
ASSODE TERRANE
PROCHE-TENERE TERRANE
W-Dabaga granitoids
Oblique spreading ridge
Tchilit Rift
R S
RS
Ao
Ba
As
ESC

same time as the Barghot–Aouzegueur thrusting (Fig. 13C).

The late Pan-African events are confined to the Assodé terrane and are characterised by large movements along the N–S-trending Raghane shear zone (ended at 580 Ma) and by the emplacement of N–S elongated calc-alkaline batholiths (Dabaga-west, 645–580 Ma). The proposed contemporaneity of these two events is best modelled with an easterly subduction zone to the west (the ocean to the east is closed) with a ridge oblique to the trench (Fig. 13D). This configuration is propitious to important strike-slip motion along shear zones parallel to the trench (transpression, Atwater, 1970; Wilcox et al., 1973; Sylvester and Smith, 1976) and to generation of a large volume of calc-alkaline plutonism (Glazner, 1991; Hutton and Reavy, 1992). A similar proposition has been recently made by Quick (1991) for the Nabitah fault system in the Arabian shield.

Contemporaneity of calc-alkaline batholith emplacement and of Raghane shear zone suggests a 60 Ma life period for this shear zone. Assuming a mean rate of 1 to 2 cm of movement per year (Jarrard, 1986) one can envisage a cumulative displacement of the Assodé terrane to the north of the order of 1000 km (Fig 13D). This would place the north of the Assodé terrane (north of Issalane), now at 25°N, beyond the southernmost visible limit of the Barghot terrane (17°N). Such a large movement could have created the shear-induced Tiririne intracontinental fold belt (Fig. 12). It would also explain the gouge shape of the northern tip of the Assodé terrane that overthrusts the Proche–Ténéré sediments (Fig. 12). The Raghane shear zone would then be located at the western limit of the postulated rigid block on which the Aouzegueur and Barghot terranes were thrust (Fig. 13D). The eastern limit of this underlying rigid block is not known; however, a deformed volcano-sedimentary belt stretching from Cameroon across western Chad to western Tibesti has yielded late Pan-African ages (Ghuma and Rodgers, 1978; Toteu et al., 1990), indicating that a craton probably did not exist there in late Pan-African times.

The movement of the Raghane shear zone ceased at ~580 Ma when high-level circular calc-alkaline plutons were emplaced. This sets an upper limit for the age of oceanic closure to the west. Traces of this ocean and of a marginal trough can be sought 800 km to the north of Agadez in the Serouenout terrane where large volumes of micaschists, ultramafic rocks and eclogites have been recorded (Guérangé and Vialon, 1959; Fig. 12).

This closure is probably also responsible for the thrusting of the rigid Assodé terrane onto the Tchilit palaeorift. We have not currently the data for choosing between the following two options: (1) the Tchilit rift is a collapse structure linked to the early Pan-African crustal thickening of the Assodé terrane which led to regional anatexis; (2) the Tchilit rift is a late Pan-African pull-apart structure contemporaneous to the Raghane shear zone.

8. Conclusions

The Aïr massif is composed of three terranes: Barghot, Aouzegueur and Assodé. The latter two can be followed to the north in Eastern Hoggar and are at least 1000 km long with a mean width of 150 km. The relative displacements of these terranes have been evaluated and their initial

Fig. 13. Model of Pan-African evolution of Aïr terranes with plan view of terranes. (A) Section indicating relative position of terranes with respect to the subduction zone prior to collision. (B) Situation at the beginning of the early Pan-African collision. It is possible that the Dabaga-east granitoids have intruded after the Barghot terrane lost its CLM, just before thrusting. (C) Situation at the end of the early Pan-African collision showing the contrast between the Tibetan-type Assodé terrane and the thrust Barghot–Aouzegueur terranes. The order of thrusting (Aouzegueur on ESC and Barghot on Aouzegueur) is not known. (D) Northern displacement of Assodé terrane (which has no rigid MBL) with respect to the Proche–Ténéré terrane. *RS* = Raghane shear zone. Circle with cross: transcurrent movement into the page; circle with dot: transcurrent movement out of the page. *MBL* = mechanical boundary layer; *TBL* = thermal boundary layer; *ESC* = East Saharan craton.

positions set with respect to a unique former active margin.

The Pan-African orogenesis, as in northeastern Africa (Schandelmeier et al., 1990), can be bracketed between 750 and 550 Ma and here comprises two periods. The early Pan-African phase is responsible for the main deformation and metamorphism of the terranes and for a first subduction-related calc-alkaline plutonism (750–660 Ma), while the ensuing late Pan-African phase (650–550 Ma), is characterised by major horizontal movements along N–S mega-shear zones and by a second subduction-related high-K calc-alkaline plutonism (Figs. 11, 13).

Note that distant effects of the West African craton (WAC, Fig. 1) are only possible in the late Pan-African period (collision WAC–Tuareg shield: 640–580 Ma), whereas in early Pan-African time the WAC could have been situated several thousands of kilometres away from the future Trans-Saharan belt.

Taking into account the major role played by the continental lithospheric mantle (CLM) in geological processes (Black and Liégeois, 1993), the behaviour of Aïr terranes during early Pan-African time suggests the existence of a hidden rigid block to the east. Its presence beneath the allochthonous Aouzegueur and Barghot terranes explains the early arrested thermal and structural evolution of these terranes and their protection during late Pan-African time. Frontal collision with it caused the delamination of the Assodé CLM allowing HT–LP metamorphism and regional anatexis in a strongly thickened crust environment. Granitoids were probably an agent for heat transfer as proposed for example in the Appalachian model (Lux et al., 1986). The major early Pan-African phase ($\sim$700 Ma) was characterised by high-grade metamorphism and the late Pan-African phase ($\sim$600 Ma) mainly by large displacements along mega-shear zones, which was made easy by early Pan-African CLM delamination. This model can be applied for interpreting the geology of the entire Tuareg shield, a collage of terranes (Black, 1978) similar in shape to those of the Aïr and comparable to the assembly of terranes bordering western North America (Coney et al., 1980). Structural studies in Nigeria (Caby, 1989; Omitogun, 1991) probably may also be interpreted following this model.

Acknowledgements

We gratefully acknowledge the help of Dr. Sadou Mammadou, Secrétaire Général du Ministère des Mines et de l'Energie du Niger, for logistic support and facilities. The Belgian FNRS and French CNRS provided financial support for field work. The C.G.R.I. (Commissariat Général aux Relations Internationales de la Communauté Française de Belgique) and the C.N.R.S. (Centre National de la Recherche Scientifique, France) are thanked for financial support during common work of the authors in Brussels and in Paris. The manuscript was improved by critical comments of J.M. Bertrand, A.M. Boullier, R. Caby, J. Fabriès, M. Guiraud and J. Sougy and by the constructive and attentive reviews of D. Demaiffe and J. Tarney. This is a contribution to IGCP 288.

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