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A tectonic model for the location of Palaeozoic ring complexes in Aïr (Niger, West Africa)

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Abstract

The Aïr region in Niger is one of the largest peralkaline granite provinces in the world. In addition to the granites, some plutons are characterized by an abundance of plagioclase-rich cumulates (gabbros, troctolites and anorthosites), with subordinate metaluminous granites and quartz syenites. These anorogenic ring complexes were intruded along a 400 km zone near the 9°E meridian. The province formed during a major magmatic event, newly dated at around 407 ± 8 Ma, and comprises 28 plutons, which range from 0.8 to 65 km in diameter and show no correlation between distribution and age. Remote sensing over the whole Aïr massif demonstrates the existence of two main trends of faults or lineaments: N50°E–N90°E and N120°E–N150°E. Autocorrelation analysis of the ring complexes reveals three large, parallel, high-density strips orientated N20°E. Based on the structural and geological setting, coupled with map analysis, a new tectonic model for the location of the complexes is presented. We propose a dextral N5°E shear zone model, where the emplacement of the ring structures is controlled by N20°E dextral Riedel shear (*R*) with a secondary N50°E tensional gash (*T*). This tectonic model implies a control by lithospheric structures for the emplacement of the ring complexes, as well as a relationship between a transtensional tectonic regime and intra-plate alkaline magmatism. The new geochronological data on the Aïr massif allow us to derive a Silurian–Devonian palaeomagnetic pole (representative for Gondwana) which fits data for the other continents better than previous estimates.

1. Introduction

Several explanations have been proposed for the mode of emplacement and the structural setting of anorogenic ring complexes, as well as for their relationship with the dynamic environment. In any model, it is important to distinguish the processes which generate the magma at deep levels, from the mechanisms of emplacement at high levels in the crust.

In the classical study of Glen Coe, Scotland, Clough et al. (1909) explained the emplacement of ring structures by a cauldron subsidence process resulting from magma intrusion. Anderson (1936) further explained the mechanics of the successive intrusions (cone sheets and ring dykes) on the basis of strain distribution related to the pressure of an ellipsoidal magma chamber. Those concepts have been used to explain the emplacement for the provinces of Nigeria (Jacobson et

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al., 1958) and Niger (Black et al., 1967). Roberts (1970) and W.S. Phillips (1974) improved the previous model, assuming a spherical magma chamber.

Bonin (1982) gave an extensive review of the different models proposed for the mode of emplacement of ring structures. Lameyre et al. (1984), Black et al. (1985) and Black and Liégeois (1993) emphasized the importance of lithospheric control. Tectonic events control the distribution and the emplacement of within-plate magmatism. Breaking of the lithosphere and deep tension gashes induce a pressure release which can initiate melting of the mantle. Thinning of the lithosphere and crustal doming occur successively and sometimes rifting subsequently appears. Today, one of the most interesting hypothesis to explain rapid regional extension is lithospheric delamination (Kay and Kay, 1993), which implies that thermal expansion generated density changes. Black and Liégeois (1993) suggested that a large amount of continental lithospheric mantle delamination during the Pan-African movement would have provided the mantle upwelling needed to explain the isotopic composition of ocean island basalts, and possibly of the Palaeozoic alkaline magmatism of the Aïr as well.

This paper presents new structural and geochronological data for the Aïr province and proposes a model for the location of the anorogenic ring structures. In this province, 28 Palaeozoic subvolcanic plutons and ring complexes have been identified and mapped (Black et al., 1967). Their petrology and geochemistry have been described previously (Black et al., 1967; Moreau, 1982, 1987; Moreau et al., 1986, 1987a, 1991; Demaiffe et al., 1991a,b). Black et al. (1967) indicated that the granites and syenites which commonly occur as ring dykes and/or cone sheets are typically high-level intrusions, whereas Moreau (1982, 1987) demonstrated that the gabbro–anorthosites occur in lopoliths.

Recently, an original tectonic model (Moreau et al., 1987b; Déruelle et al., 1991) has been proposed on the basis of LANDSAT imagery and autocorrelation analysis for the Tertiary anorogenic province of the Cameroon Line. In order to test that model, a similar approach has been used for the Aïr province.

2. Geological setting of Aïr

2.1. *The Tuareg shield*

The Aïr massif is the southeastern extension of the Tuareg shield, which forms the Trans-Saharan segment of the Pan-African belt (Cahen et al., 1984). As described by Lelubre (1952), Caby (1968), Vitel (1975) and Bertrand and Caby (1978), this belt displays many blocks elongated N–S and separated by strike-slip shear zones, resulting from the Pan-African collision of the West African Craton with the eastern mobile belt at the end of a Wilson cycle (Bertrand and Caby, 1978; Black et al., 1979; Caby et al., 1981). Some of these strike-slip shear zones, however, are supposed to have a complex history (Caby, 1968) and to represent the limits of accreted terranes (Boullier, 1991; Liégeois et al., 1994).

Many shear zones have been studied in detail in the Algerian Hoggar. For example, the Pan-African Tiririne belt along the 8°30′ meridian (Fig. 1) separates the central polycyclic Hoggar from the 730 Ma old Taffassasset domain (Bertrand et al., 1978). This fault acted first as a thrust zone then as a dextral shear zone, the movement along the fault had ceased by 580 Ma (Bertrand et al., 1986).

No detailed study is available in Algeria on the N–S-trending fault along the 7°50′ meridian which affects the Phanerozoic cover and corresponds to the northern extension of the Arlit flexure to the west of the Aïr basement. This fault joins the Tiririne belt and may indicate the edge of a terrane older than the central polycyclic Hoggar (Boullier, 1991).

Brittle deformation, revealed by conjugate NE–SW-trending dextral faults and NW–SE-trending sinistral faults, also affected the Tuareg shield during the later stage of the Pan-African collision (Ball, 1980). Furthermore, many authors (Fabre, 1976, 1988; Guiraud et al., 1987; Bellion, 1989) have pointed out the polyphase activity of

N–S-trending shear zones and associated NE- and NW-trending conjugate faults during the Phanerozoic in the Tuareg shield and its surrounding sedimentary basins. For example, the 4°50′ shear zone has been reactivated several times during the Phanerozoic.

In summary, N–S-trending lineaments are the major structural feature of the basement and sedimentary cover of the Tuareg shield and correspond to Phanerozoic zones of weakness in the lithosphere.

2.2. Aïr massif (Fig. 2a)

The Aïr Precambrian basement was mapped by Black et al. (1967) and, in the southeastern part, by Kehrer et al. (1973). Recently, new structural and geochronological data have allowed us to describe the tectonic history of the whole Precambrian Aïr province, which appears to be composed of three N–S elongated terranes: Aouzegueur, Barghot and Assode (Liégeois et al., 1994; Fig. 2b). In the southeastern part of the Aïr massif, the limit between the Aouzegueur and Barghot domains is a thrust, which brought the central gneissic domain onto the eastern basement (Cosson et al., 1987; Boullier et al., 1991). Highly serpentinized ultramafics constitute an upper Proterozoic suture (Boullier et al., 1991) which has been dated at around 680–670 Ma (Black et al., 1991).

The Barghot domain is made of medium- to high-grade metasediments and gneisses; the recumbent isoclinal folds of the first phase were deformed by a second phase of N170°E folds (Boullier et al., 1991), themselves cross-cut by a 664 ± 8 Ma granite (Black et al., 1991). Therefore, this domain strongly differs from the Alge-

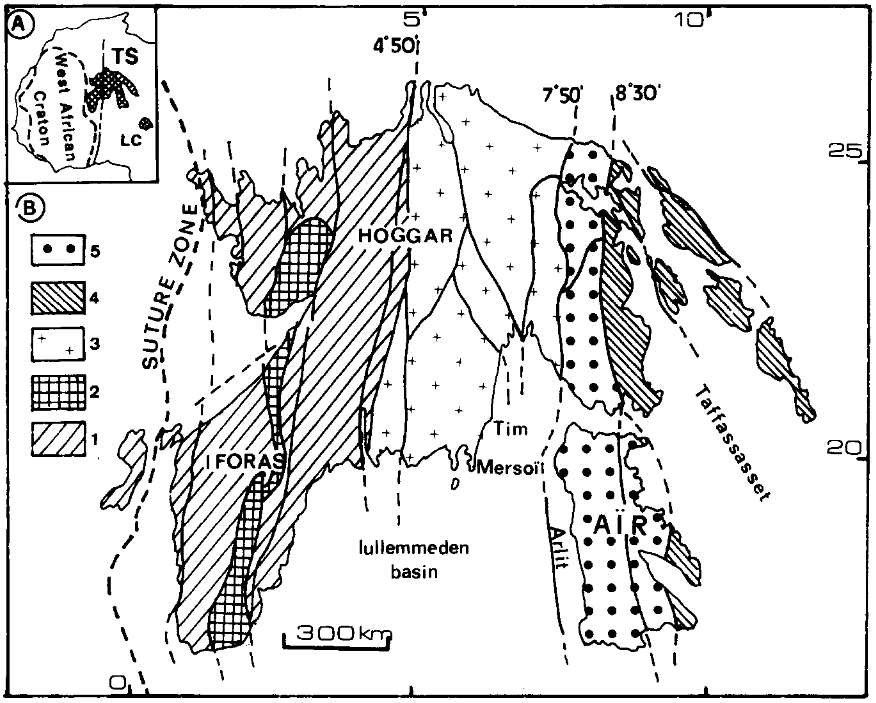

Fig. 1. (a) The Tuareg shield (*TS*) in West Africa. *LC* = Lake Chad. (b) Schematic geological map of the Tuareg shield. *1* = upper Proterozoic low-grade rocks; *2* = Iforas and In Ouzzal Eburnian granulitic rocks; *3* = Central Polycyclic Hoggar; *4* = upper Proterozoic (East Saharan Craton); *5* = Eastern Hoggar and Aïr Proterozoic formations.

rian polycyclic central Hoggar, in which thrust tectonics and granite emplacement have been dated at 615–580 Ma (Bertrand et al., 1986).

The Barghot and Assode domains are separated by the Raghane N–S-trending dextral strike-slip shear zone, which contains remnants of

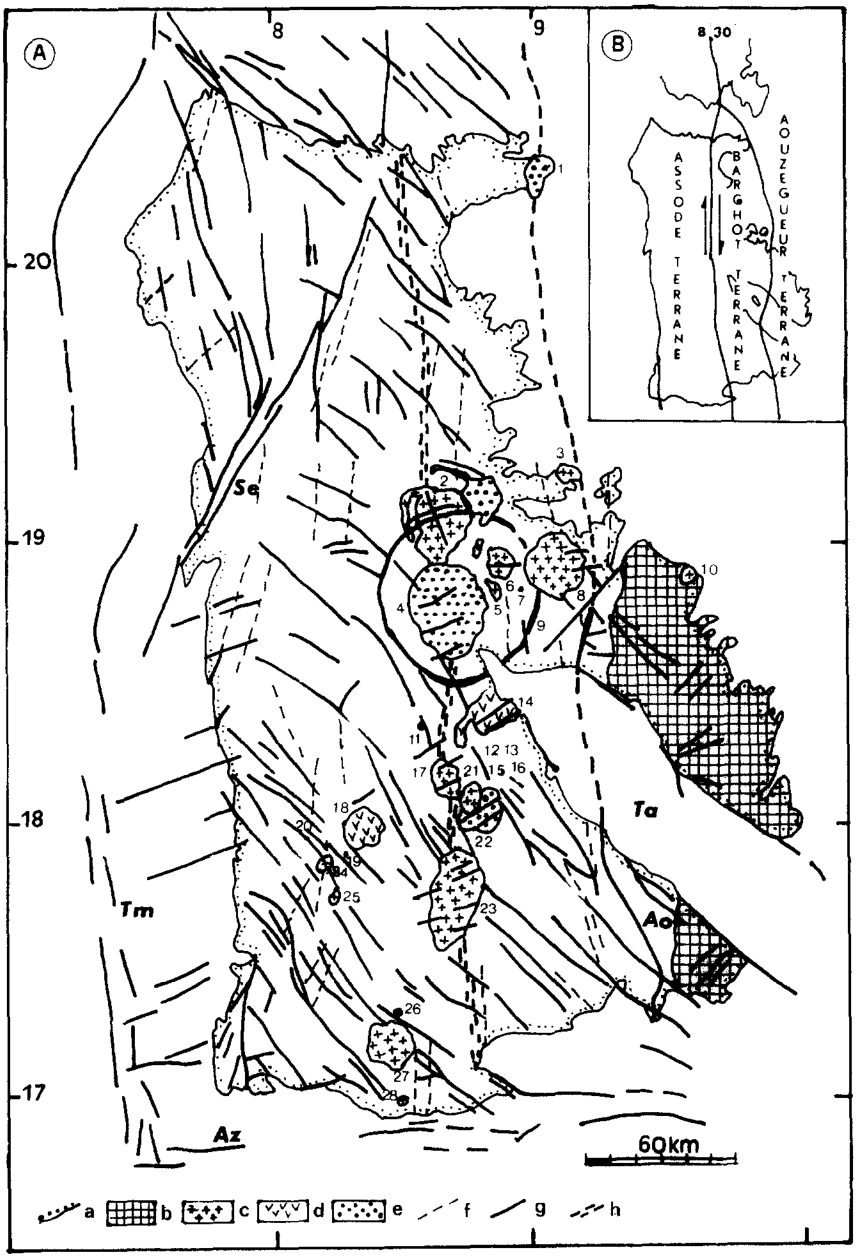

Fig. 2. (a) Geological sketch map of Aïr. *a* = geographical limit of the Aïr massif; *b* = Proche-Ténéré Formation; *c* = Taghouaji type ring complexes; *d* = Goundaï type ring complexes; *e* = Ofoud type ring complexes; *f* = foliation trend in gneissic basement; *g* = lineaments and faults; *h* = Raghane shear zone; *Ao* = Aouzegueur belt; *Az* = Agadez Town; *Se* = Serchouf lineament; *Ta* = Tâfidet graben; *Tm* = Tim Mersoï basin. The Aïr ring complexes are numbered from 1 to 28 (see Table 1 for description and explanation). (b) Aïr terranes (after Liégeois et al., 1994).

ultramafics, and which was first recognized by Liégeois et al. (1994). This shear zone extends over more than 1000 km and is probably connected to the Pan-African Tiririne shear zone along the 8°30′E meridian (Fig. 2b).

The Assode domain is characterized by the intrusion of young Pan-African (645–580 Ma) granites, which were emplaced during a dextral strike-slip movement of the Raghane shear zone (Liégeois et al., 1994). The authors interpret the southwestern Tchilit palaeorift as a collapse structure or as a pull-apart basin.

Brittle tectonics have been responsible for a system of sinistral strike-slip faults, trending N135°E, which are sealed by quartz veins. Black and Girod (1970) suggested that, after uplift of rigid blocks and isostatic equilibrium, a new tectonic regime prevailed, with NW-trending sinistral wrench faults accompanied by NE-trending dextral faults. During that stage, the main direction of compression was N80°E (considered as equivalent to the E–W direction of Black and Girod, 1970), which was responsible for the late fracturing of the Tuareg shield at the end of the Pan-African collision. This N80°E direction is also the main orientation of the Guinea–Nubian

Table 1
Ring complexes in the Aïr massif

No.	Name	Location		Area (km^2)	Form	Type	Age (Ma)	References
		N lat.	E long.					
1	Bous	20°20′	9°00′	100	Elliptical	III	420 ± 40	Bowden et al. (1976)
							487 ± 7	Karche and Vachette (1978)
							406 ± 11	This paper
2	Tamgak	19°03′	8°40′	1000	Circular	III	455 ± 19	Karche and Vachette (1978)
							414 ± 9	This paper
3	Chiriet	19°16′	9°09′	70	Circular	I		
4	Ofoud + Agueraguer	18°49′	8°43′	900	Circular	III	409 ± 12	This paper
							421 ± 15	Bowden et al. (1976)
5	Tchin-Tajat	18°42′	8°40′	20	Rectangular	I		
6	Imaghlane	18°50′	9°55′	80	Circular	I		
7	Taguei	18°49′	8°59′	0.5	Circular	III		
8	Taghmert	18°58′	9°06′	500	Circular	I		
9	Meugueur-Meugueur	18°49′	8°49′	40	Ring dyke	III		
10	Arakaou	18°57′	9°36′	80	Circular	I		
11	Abontorok	18°23′	8°35′	6	Circular	III	399 ± 10	Brown et al. (1989)
12	Tibougouene	18°22′	8°31′	3	Circular	I		
13	Tagha	18°12′	8°31′	5	Circular	I		
14	Goundai	18°24′	8°54′	150	Elliptical	II		
15	In Tainok	18°12′	8°54′	15	Circular	I		
16	Manouaroun	18°10′	8°54′	8	Circular	I		
17	Egalah	18°10′	8°42′	180	Circular	I	435 ± 8	Karche and Vachette (1978)
18	Bilet	18°	8°23′	100	Circular	II		
19	Agadao	17°54′	8°18′	2	Circular	I		
20	Rouraouet	18°04′	8°07′	3	Circular	I		
21	Aroyan	18°06′	8°48′	60	Semicircular	I	426 ± 6	Karche and Vachette (1978)
22	Iskou	18°04′	8°52′	160	Semicircular	III	426 ± 8	Karche and Vachette (1978)
23	Bagzane	17°45′	8°44′	600	Elliptical	I		
24	Guissat	17°52′	8°14′	8	Circular	I		
25	Elmecki	17°45′	8°18′	12	Circular	I		
26	In Tajet	17°18′	8°32′	4	Circular	I		
27	Taghouaji	17°12′	8°30′	292	Circular	I	407 ± 6	Karche and Vachette (1978)
							401 ± 5	Karche and Vachette (1978)
28	Tcheemanassene	17°	8°28′	4	Circular	II		

I = Taghouaji type; II = Goundaï type; III = Ofoud type.
For location see Fig. 2a.

lineaments (Guiraud et al., 1987), along which movements occurred during the Lias. Further movements are also known at the end of the Cretaceous and during the upper Eocene. Recent reactivation along the same direction gave rise to earthquakes in Guinea and in the Aswan region.

Caledonian uplift led to erosion of the Cambrian–Ordovician cover so that Lower Devonian series now overlie the basement (Joulia, 1959; Black and Girod, 1970; Fabre, 1988).

Evidence for the reworking of N–S-trending shear zones in the Tuareg shield is found in many places: in the thickness of the unconformable cover (Beuf et al., 1971; Fabre, 1976, 1988; Moussine-Pouchkine, in Ball, 1980) and the faulting and folding of the cover (Karpoff, 1958). Even recent earthquakes in Ghana, Togo and Benin may be due to the southern extension of those shear zones (Bellion, 1989).

3. Anorogenic ring complexes

The anorogenic ring complexes cut across all the previously described structures of the basement and were emplaced during a major Palaeozoic magmatic event along the 9°E meridian, which is close to the Raghane shear zone.

The Aïr province is typically alkaline, with abundant alkaline and peralkaline syenites and granites, accompanied by subordinate metaluminous granites and quartz syenites, as well as by plagioclase-rich cumulates (leucogabbro, leucotroctolite and anorthosite) in some complexes. In total, 28 complexes have been recognized (Black et al., 1967; Moreau, 1982, 1987; Demaiffe et al., 1991a; Moreau et al., 1991). They differ greatly in their shape, internal structures and petrographic associations. For example, the largest cone sheet in the world (Meugueur-Meugueur, 65 km in diameter, Moreau et al., 1986) and one of the smallest intrusions (Tagueï, 0.8 km in diameter) occur in this province. Most intrusions have a circular shape, but some are elliptical or semicircular (Table 1).

The anorogenic ring complexes have been divided into three main types (Table 1), depending on the nature and abundance of rock types (Moreau et al., 1991; Demaiffe et al., 1991a):

(1) *the Taghouaji type*, composed mainly of alkaline and peralkaline syenites and granites, with, in some cases, metaluminous granites (eighteen complexes);

(2) *the Goundaï type*, composed mainly of acid volcanic rocks (rhyolitic tuffs and ignimbrites) with quartz syenite ring dykes (three complexes);

(3) *the Ofoud type*, characterized by a large proportion of basic rocks, varying from troctolites and leucogabbros to true anorthosites, intruded by mildly alkaline to peralkaline syenites and granites (Demaiffe et al., 1991a) (seven complexes).

Structural studies (Moreau, 1982) in the northernmost ring complex (Adrar Bous) have shown that granophyric dykes were emplaced along the fracture zones trending N40°E and N130°E. In the Ofoud complex vertical shear zones 1 cm wide and trending N80°E have been observed in the monzogabbros and in the external leucogabbros: these are mylonites consisting of cataclastic plagioclases in a fined-grained (recrystallized) matrix. These are interpreted as postdating the emplacement of these rocks; N55°E- and N145°E-trending fractures are also observed on aerial photographs of the same massif (Moreau, 1982) and indicate that preexisting fractures have been reworked after the emplacement of the Ofoud ring complex. The Goundaï–Bilet (and probably Arakaou) ring complexes are aligned along a prominent NE–SW direction, which is oblique to the main alignment of the other ring complexes.

Faults trending N45°E, N–S and N20°E (Serchouf) have also controlled the geometry of the Palaeozoic and Cretaceous sedimentary basins (Raulais, 1958; Moreau, 1982). The N–S and N20°E faults affected the western part of the Aïr province and the Tim Mersoï Palaeozoic sedimentary basin (Joulia, 1963; Bigotte and Obellianne, 1968; Forbes, 1989). Finally, volcanic activity, with alkaline affinity, occurred much later, during the Cenozoic to Quaternary.

Large-scale gravity data are available for the entire Aïr massif (Louis, 1970). A new interpretation of these gravity data was recently proposed by Jallouli (1989); he explained the lack of symmetry and the displacement of the high gravity anomalies with respect to the topography as resulting from the flexure of a fractured continental lithosphere, with the axis close to 9°30′. The thickness of the elastic lithosphere is estimated to be 20–30 km, which is rather thin for a continental environment and is more comparable to what is commonly observed in rift zones. The reduced thickness has been related to an extension process associated with a thermal asthenospheric plume. This plume was active during the Palaeozoic (emplacement of the ring complexes) and the Cenozoic (recent volcanic activity). The gravity signature is similar to that of other parts of the Trans-Saharan Pan-African belt (Bayer and Lesquer, 1978; Ly et al., 1984; Fairhead and Okereke, 1987).

4. Radiometric dating of Aïr ring complexes

The Palaeozoic age of the ring complexes of the Aïr province was established by Bowden et al. (1976) and Karche and Vachette (1978). However, there were large discrepancies between the ages (Rb–Sr whole-rock isochrons) obtained by the two groups for the same intrusion. For example, the Adrar Bous intrusion was dated at 420 ± 40 Ma by Bowden et al. (1976) and 487 ± 7 Ma by Karche and Vachette (1978). In a more recent synthesis, Bowden and Karche (1984) chose the old age (487 Ma) for Bous and suggested that there had been a N–S age migration in the Aïr province from Adrar Bous, in the north, to Taghouaji (407 ± 6 Ma), in the south. They even extended their space–time migration model further to the south, to the Zinder area in South Niger, where intrusion ages were in the 330–260 Ma range and to the Mesozoic 'Younger granites' province of the Jos plateau (Nigeria). This age migration was related by Bowden and Karche to "a local thermal anomaly in the mantle" (p. 173); that is, to a hot spot.

We were puzzled by the above-mentioned discrepancy and also by the fact that, on Karche and Vachette's isochron for Adrar Bous, all the petrographic types (gabbro–leucogabbro, monzonite and peralkaline granites) plotted on the same line, which gave a high $^{87}Sr/^{86}Sr$ initial ratio (0.7138 ± 0.0009). To resolve this discrepancy, we measured the same samples (same powders) as those of Karche and Vachette (1978). The new Rb–Sr analytical data are given in Table 2 and on Fig. 3a. The six peralkaline granites define a good isochron (MSWD = 0.61), which yields an age of 406 ± 11 Ma (2σ), with an initial isotopic ratio of

Table 2
Rb, Sr isotopic data for Adrar Bous, Tamgak and Ofoud

Samples	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ
Bous					
B1	74.0	235.1	0.911	0.71332	0.00003
B2	86.6	204.5	1.226	0.71432	0.00004
B3	14.3	323.2	0.128	0.70484	0.00003
B5	7.0 *	474.6	0.043	0.70417	0.00002
B6	77.2	206.0	1.085	0.71311	0.00004
B8	95.6	10.4 *	27.011	0.86748	0.00025
B10	150.0	22.1 *	19.873	0.83011	0.00005
B11	100.8	61.3	4.774	0.74292	0.00006
B12	76.8	15.9 *	14.097	0.79696	0.00016
B14	86.8	15.7 *	16.155	0.80935	0.00055
B21	124.8	10.9 *	33.795	0.91394	0.00012
Tamgak					
T26	117.9	22.7 *	15.159	0.79762	0.00001
T23	164.3	87.9	5.426	0.74244	0.00005
T28	105.3	23.7 *	12.957	0.78882	0.00003
T30	124.6	155.0	2.329	0.72382	0.00005
T41	162.9	10.1 *	47.964	0.99249	0.00007
T42	156.9	8.5 *	54.914	0.99632	0.00003
T16	133.9	6.3 *	63.749	1.08276	0.00050
T7	192.4	8.3 *	69.689	1.10726	0.00003
T8	165.8	68.6	7.020	0.74703	0.00012
Ofoud					
OF-26	136.6	39.3	10.114	0.76630	0.00002
OF-32	133.3	46.4	8.350	0.75427	0.00002
OF-33	74.7	146.3	1.478	0.71559	0.00001
OF-63	45.2	149.8	0.874	0.71543	0.00002
FA-5a	130.0	60.8	6.208	0.74369	0.00002
OF-42	119.5	12.7 *	27.443	0.87109	0.00002
OF-48	35.0	136.2	0.744	0.71419	0.00002

The Rb and Sr concentrations were determined by X-ray fluorescence spectrometry, except for the samples marked with * which were determined by isotope dilution–mass spectrometry. The $^{87}Sr/^{86}Sr$ ratios were measured on a Finnigan MAT 260 mass spectrometer (Centre Belge de Géochronologie). The isotopic ratios were normalized to $^{88}Sr/^{86}Sr = 8.3752$.

0.7153 ± 0.0016. The micromonzonites (samples B1, B2, B6) and the gabbros (samples B3, B5) have low ^{87}Rb/^{86}Sr ratios (< 1.3) and plot distinctly below the isochron. The gabbros also have low ^{87}Sr/^{86}Sr ratios, around 0.704; these are normal values for basic cumulates and are comparable to those of the basic rocks in the other ring complexes of the province (Demaiffe et al., 1991b).

A seven-whole-rock isochron was obtained for the granites and syenites (Moreau's collection) of the small Abontorok intrusion in Central Aïr. This gives an age of 399 ± 10 Ma (2σ) with a MSWD value of 1.77 (Brown et al., 1989).

These two new age determinations do not confirm the age migration model from north to south of Bowden and Karche (1984). To strengthen our data, we analyzed the Tamgak intrusion again, for which Karche and Vachette obtained an age of 455 ± 19 Ma (4 points isochron). The new measurements on alkaline and peralkaline granites on the same powders (Table 2) give a good 6 point isochron (MSWD = 0.95), yielding a younger age of 414 ± 9 Ma (Fig. 3b). For an unknown reason sample T42 (peralkaline granite) plots below the isochron and was not used for the regression calculation, nor were the T7 and T8 samples (dykes) whose relationship with the peralkaline granite are unclear.

From the field relationships it is evident that the Meugueur-Meugueur cone sheet is younger than the Tamgak intrusion. The new age obtained for Tamgak (414 ± 9 Ma) thus poses a problem, because it is younger than the ^{40}Ar/^{39}Ar plateau age (431 ± 4 Ma) obtained for one biotite of the Meugueur-Meugueur (Hargraves et al., 1987) (actually, the mica in the Meugueur-Meugueur is a phlogopite with $0.78 < X_{Mg} < 0.65$, rather than a biotite). This discrepancy can be explained, however, because it is well known (i.e. Hess and Lippolt, 1986) that "some biotites yielded total Ar and plateau ages significantly older than conventional K–Ar and Rb–Sr data" (Hess and Lippolt, 1986; p. 223).

Two mechanisms have been proposed to explain these high ^{40}Ar/^{39}Ar biotite ages:

(1) partial ^{39}Ar loss during neutron activation in the reactor: this is particularly true if a low-K phase (chlorite) is present as an alteration product of the biotite (see experimental evidence of Hess and Lippolt, 1986; and Lo and Onstott, 1989);

(2) excess argon (^{40}Ar) contamination: this has been observed in mantle-derived minerals (i.e. phlogopite: D. Phillips and Onstott, 1988).

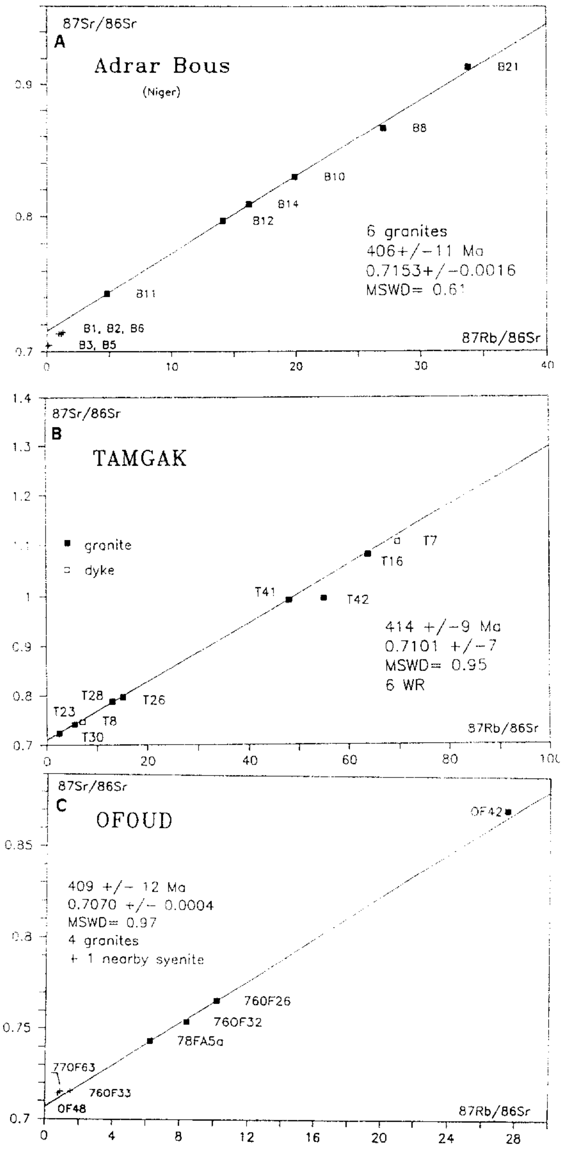

Fig. 3. Rb–Sr whole-rock isochrons. (a) Adrar Bous. (b) Tamgak. (c) Ofoud.

These two mechanisms could have played a role in the Meugueur-Meugueur: (1) even if the phlogopite crystals appear to be fresh under the optical microscope, they may contain thin (~ 100 Å) layers of chlorite (Hess and Lippolt, 1986); (2) moreover, the parental magma of the Meugueur-Meugueur intrusion is presumably of mantle origin (Demaiffe et al., 1991b) and so could contain excess Ar.

For the large Ofoud intrusion, four granites of the central part of the intrusion and a nearby syenite (new samples) crosscutting the anorthosite–gabbro sequence plot on an isochron (MSWD = 0.97) giving an age of 409 ± 12 Ma and an initial $^{87}Sr/^{86}Sr$ isotopic ratio of 0.7070 ± 0.0004 (Fig. 3c). Two syenites (Of 63 and Of 48) plot slightly above the isochron: they were sampled close to the western and eastern contacts, respectively, and their alkali feldspars have suffered deuteric alteration, which may have disturbed the Rb/Sr isotopic system. Bowden et al. (1976) obtained an age of 421 ± 15 Ma for the large Agueraguer granitic intrusion along the southern border of the Ofoud intrusion. The age relationship between the Agueraguer granite and the Ofoud central granites and syenites are unknown because the do not come into contact.

In summary, the new radiometric Rb/Sr data give good isochrons and yield an average age of 407 ± 8 Ma (i.e., close to Silurian–Devonian boundary or the lowest Early Devonian).

5. Lineaments determined from LANDSAT imagery (Fig. 4)

The Aïr massif is cut by a dense network of faults and lineaments. These are mapped in Fig. 4, drawn from a visual study of LANDSAT MSS7 image assemblages. It appears that the lineaments are shorter but more numerous in central Aïr than in the northern and southern parts of the massif. Directional distribution of about 1320 lineaments was analyzed and is shown in rose diagrams of cumulative length. For the Aïr massif as a whole, the diagram (Fig. 4d) displays two main broad trends: N50°E to N90°E (31%) and N120°E to N150°E (about 28%), with N70–80°E and N130–140°E maxima.

Lineament distributions are different in northern, central and southern Aïr (Fig. 4a–c): the N130–140°E direction is dominant in the north, while N70–80°E is the main trend in the centre; both are present in the south. Furthermore, the northern Aïr diagram shows a third significant N–S- to N30°E-striking fracture system which is also present, but of lesser importance, in the central and southern zones.

The N120–150°E-trending lineaments, which coincide with a system of NW–SE-trending quartz veins, have a prominent role in the northwestern part of the Chad sedimentary basin (Taffassasset, eastern Niger). There, evidence for narrow and elongate troughs was found by mapping (Faure, 1966; Tâfidet graben) or by gravity survey (Louis, 1970; Taffassasset grabens). These troughs are attributed to the rejuvenation (as normal faults) of N120–150°E-trending lineaments during a regional extensional regime with a N50°E trend. The troughs have subsided since the Lower Cretaceous (no earlier than the Barremian) and are filled with at least 7000 m of Mesozoic–Cenozoic sediments (Bellion, 1989; Guiraud and Maurin, 1992).

The N50°E- to N90°E-trending lineament system, which is seen in LANDSAT imagery, is locally underlined by rhyolite dyke swarms and gabbro dykes (southwest Iferouane; Black et al., 1967). However, this system and the N–S- to N30°E-trending lineaments have had a great influence on the history of the western sedimentary cover (Joulia, 1957, 1959, 1963; Greigert, 1966; Valsardieu, 1971; Cazoulat, 1985; see also Bellion, 1989; Forbes, 1989). In the Tim Mersoï area, recurrent basement faulting trending N–S, N30° and N80°E controlled thinning or wedging-out of sedimentary units during the Lower Carboniferous, Mesozoic and Cenozoic (Valsardieu, 1971). These faults are also responsible for the development of basement highs (e.g., Ibadanane and Afasto; Valsardieu, 1971) or drag folds affecting the Palaeozoic and Mesozoic cover in the eastern part of the Iullemmeden basin (e.g., drag folds with a N30°E axial trend superimposed on the N–S-trending Arlit flexure fault) and fault systems trending N80°E (Joulia, 1957; Valsardieu, 1971). The N80°E direction, called the Guinea–Nubian lineament (Guiraud et al., 1987), is a very important lineament all over West Africa where it can be followed from the Senegal–Guinea margin to the Red Sea.

Finally, the continuity of this fault network in the entire Tuareg shield is emphasized. The variations and/or deformations of the sedimentary cover, the basement highs and the magmatism must be interpreted as being the results of the reworking of basement faults (especially faults

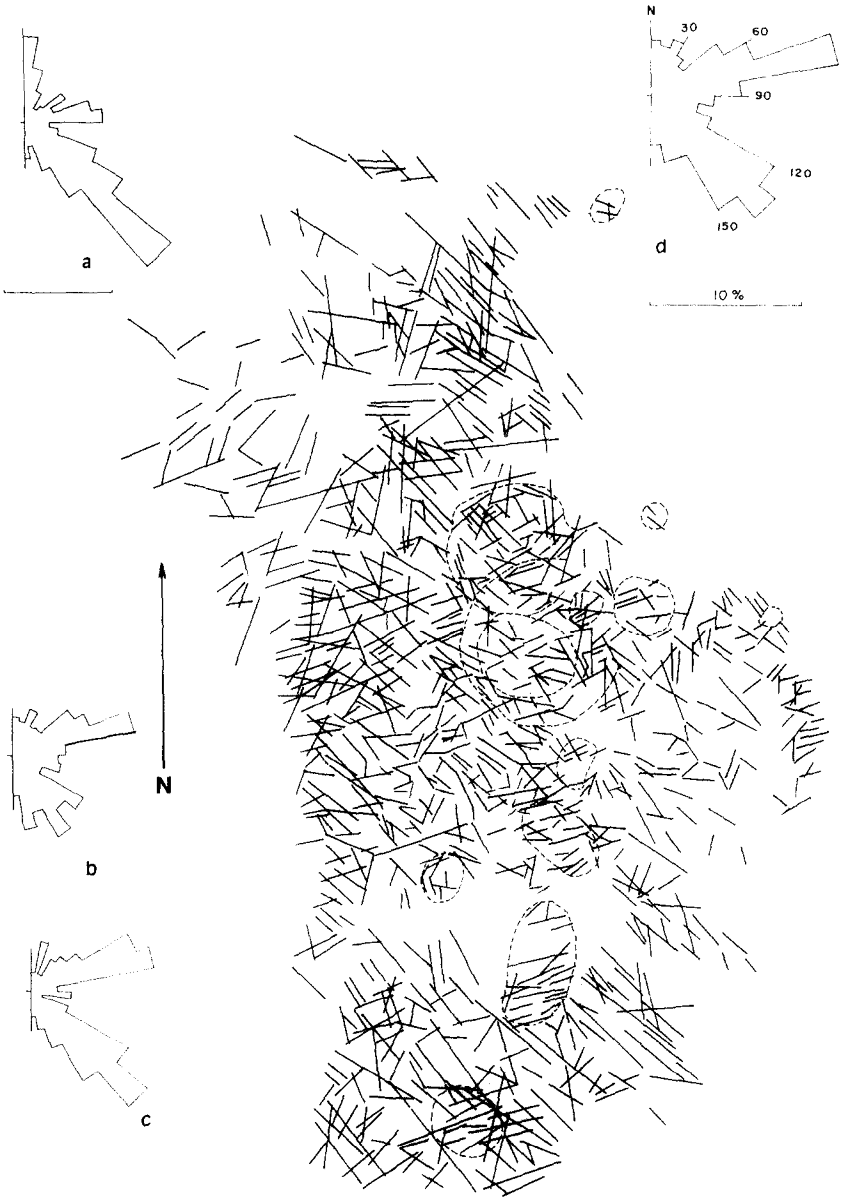

Fig. 4. Map of the lineaments in the Aïr massif. Rose diagrams represent cumulative lengths of lineaments in (a) the northern, (b) the central and (c) the southern parts of the massif and (d) in the entire massif.

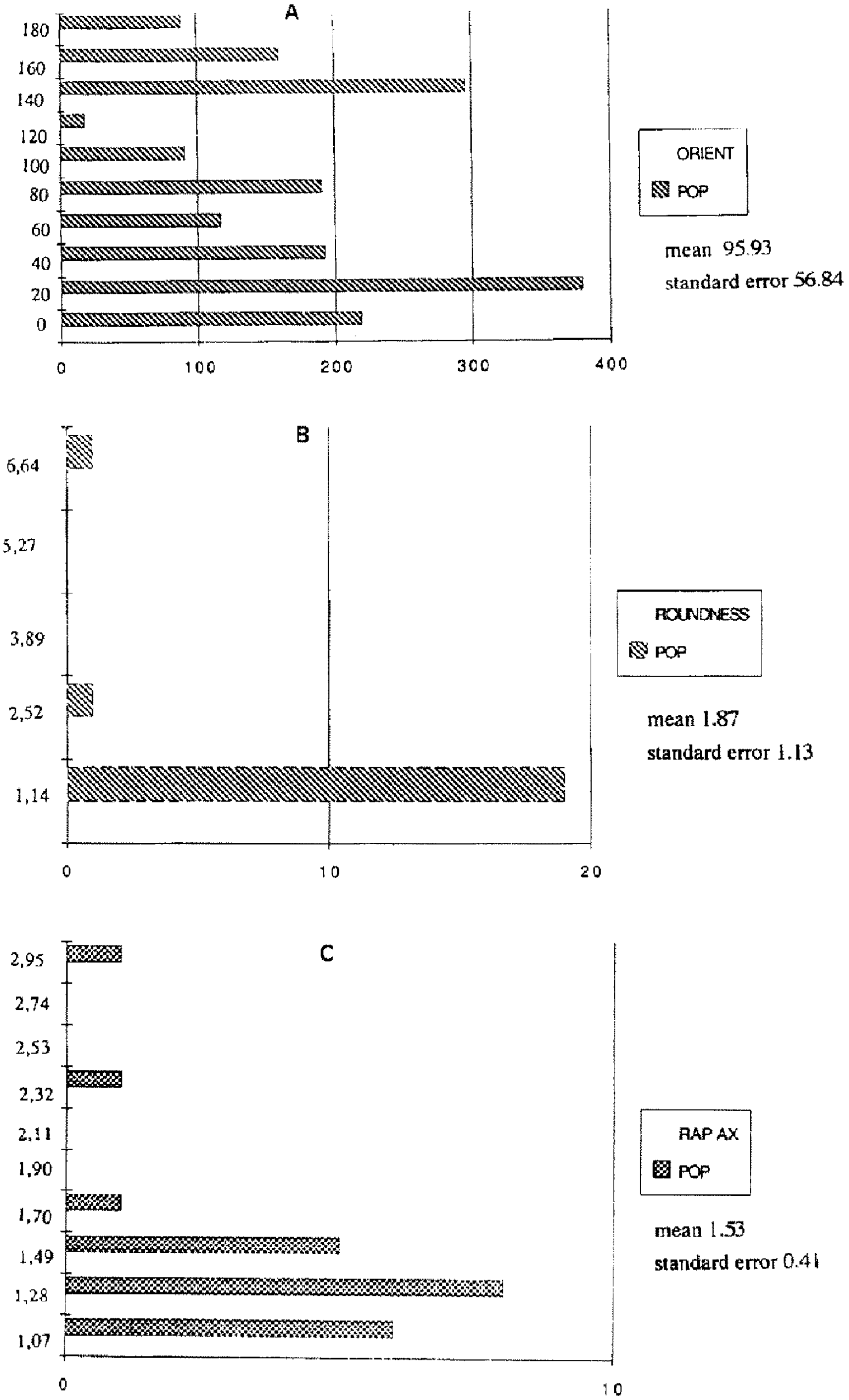

Fig. 5. Histograms of the shape analysis of the ring complexes. (a) Orientation of the great axis. (b) Roundness. (c) Axial ratio.

striking N50°E to N80°E) from the Pan-African orogeny until the present.

6. Geological map analysis (Fig. 5)

In order to complete the geometrical information about the ring complexes of the Aïr, as mapped by Black et al. (1967), we have used an interactive video analyzer (CRPG, Nancy), associated with computer programs applied to structural geology and strain analysis (Lapique et al., 1988). This analysis gives a quantitative appreciation of the shape and orientation of the ring complexes on a horizontal plane (erosion surface).

The Aïr ring complexes greater than 2 km^2 in area were digitized from the geological map. The main results (shape of the ring complexes and elongation axis) are shown on three histograms (Fig. 5). The first histogram indicates that more than half of the complexes have their major axis orientated N20°E, one third N160°E and only five have other orientations. The second histogram expresses the roundness (or sphericity) parameter of the intrusions (i.e. $P^2/4\pi S$, where $P =$ perimeter and $S =$ surface): more than two-thirds of the complexes have a roundness of less than 1.2, which means that they are nearly circular (the roundness of a circle is 1, that of an ellipse with $a = 2b$ is 1.25). The third parameter examined is the axial ratio (great axis/small axis): more than half of the complexes have an axial ratio of less than 1.5 and only 4 have an axial ratio larger than 1.7.

These results show that most of the Aïr complexes have a nearly circular shape (ellipse of low eccentricity) and they are mainly orientated along two conjugate directions: N20°E and N160°E. Only five complexes have a different shape and orientation, which will be discussed later.

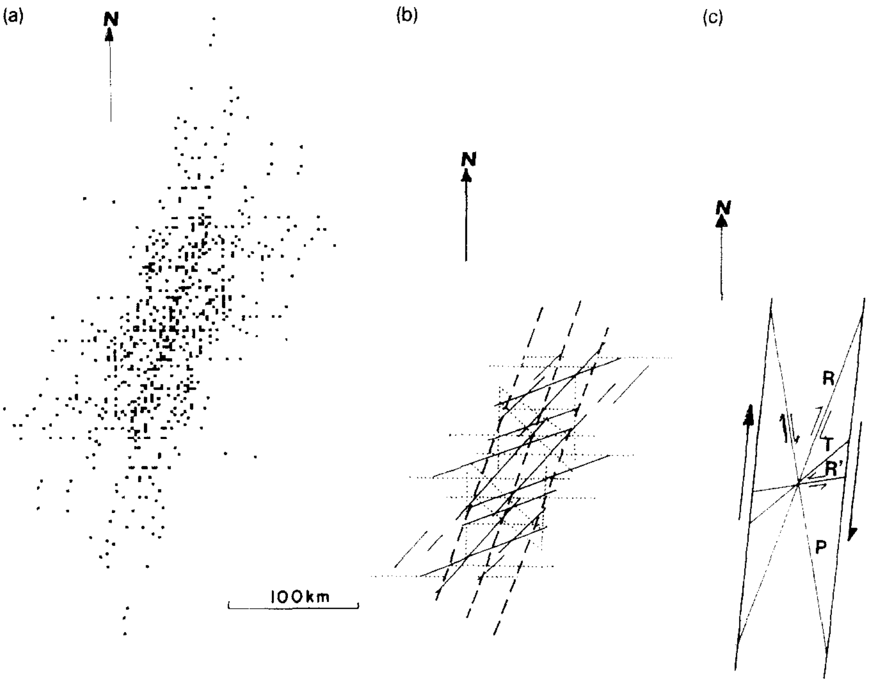

Fig. 6. Autocorrelation graph. (a) Graphic image of the computed data (autocorrelation program). (b) Interpretation of the graph. (c) Theoretical Riedel model proposed to explain the autocorrelation graph: N5°E dextral shear with dextral Riedel shear ($R =$ N20°E) and sinistral shear ($R' =$ N80°E), tension gash ($T =$ N50°E) and dextral shear ($P =$ 170°E).

7. Autocorrelation analysis

The autocorrelation analysis involves an analog calculation method known as the convolution product or square correlation (Leymarie, 1970). It was first solved using an optical method (Robertson, 1943; Leymarie, 1968; Cottard, 1982). In this method, a function $f(\phi,\rho)$, which can only be equal to 1 or 0, is associated with each set of geographical coordinates (ϕ,ρ). The geological objets studied (the ring complexes in our case) are assimilated to barycentric bodies, represented by the geographical coordinates of their barycentre. Then autocorrelation of the point distribution can be analyzed by analog calculation. This method has been computerized (Leistel et al., 1984), adapted by the authors and completed by statistical tests applied to graphs according to the Lutz method (Lutz, 1986). The result of the autocorrelation is a graph that can be considered as a statistically significant spatial distribution of the bodies. The dimensions of the graph are double those characterizing the initial document, because the autocorrelation is a square correlation. However, the results may be reported at the same scale to compare graph and map. Several high-density strips usually appear on the graph, which correspond, by construction (Leymarie, 1970), to one or two source structures (Moreau et al., 1987b).

Autocorrelation analysis thus provides information complementary to the remote sensing, confirms field data and can reveal deep structural elements which are not directly visible in the field or in the imagery. It allows a recognition of linear arrangements in a population of geological objects. The spatial distribution of volcanic or subvolcanic complexes from the Cameroon Line has already been tested with this method (Moreau et al., 1987b).

The distribution of points on the graph (Fig. 6) represents the spatial arrangement of the Aïr ring complexes through their autocorrelation. Points are included in a parallelogram envelope with a N10°E elongation axis. The graph clearly shows three large parallel high-density strips orientated N20°E. Thin N45°E and N90°E lineaments are less apparent. The N90°E direction displays a slight shift in density westwards, from north to south. The high density of points in the middle part of the graph is linked to the high density of anorogenic ring complexes in central Aïr.

8. Interpretation: a tectonic model

The autocorrelation graph and the geometrical analysis provide constraints for any interpretative model. The three N20°E alignments on the graph represent one or two source structures but their narrow spacing, their length and symmetrical arrangement more likely suggest a deep origin along a single structure. It has been quoted before that N–S- to N10°E-trending lineaments are important structural discontinuities of the Tuareg shield that have been reactivated at the time of emplacement of the ring complexes. The late Pan-African faults trending N135°E, which are obvious on the map (Black et al., 1967) and on the LANDSAT imagery (this work), are not so obvious on the autocorrelation graph. Therefore, they do not seem to have been a significant direction at the time of emplacement of the ring complexes. On the other hand, the geometrical analysis shows a weak elongation of the complexes, with a major axis which is preferentially orientated to N20°E and to a lesser extent to N170°E.

Considering the geometrical and the timing relationships between the faults and the ring complexes in the Aïr massif, a tectonic model may be proposed in which the N20°E direction represents the Riedel direction (*R*) of a N5°E dextral shear zone on the scale of the whole province. The N5°E dextral shear zone can now be assimilated to the Raghane shear zone recently discovered by Liégeois et al. (1994). The N50°E, N90°E and N170°E trends could correspond to the *T* (compressional axis), *R'* sinistral and *P* dextral directions, respectively. Following this model, the N20°E elongation direction of the ring complexes should correspond to a 'domino' opening along the N20°E (*R*) direction, which is parallel to the Serchouf lineament. The secondary elongation along the N170°E direction should be related to a minor 'domino' opening along the *P* direction. In such a N50°E-trending compressional regime, the late Pan-African faults, trending N135°E, were nearly perpendicular to the compression axis and, therefore, should not have been reactivated.

9. Discussion

In a previous comparable study of the Cameroon Line, Moreau et al. (1987) envisaged three types of tectonic environment to explain the distribution of the anorogenic ring complexes:

(1) emplacement along a tension gash under a regional transtensional regime;

(2) space–time migration of the magmatic activity, due to a local tensional regime related to lithospheric uplift above a hot spot or thermal doming;

(3) emplacement during a transtensional regime along an active fault zone.

The model of a stationary (or fixed) hot spot beneath a moving lithospheric plate seems plausible, if a space–time migration of the anorogenic ring complexes can be demonstrated. In contrast, in a transtensional regime, the magmatic activity is controlled by the regional tectonic events and, therefore, does not involve a space–time migration.

During the 1970s, available geochronological data on the Aïr ring complexes were interpreted by some authors in terms of a space–time migration model (see review in Bowden and Karche, 1984) due to a mantle plume (i.e. hot spot), which periodically pierced the African lithosphere during its northwards displacement. Our new age determinations obtained on the northernmost intrusion of the province (Adrar Bous) and on three massifs of the central Aïr (Abontorok, Tamgak and Ofoud) do not confirm this model. They show that most of the magmatic activity took place during a rather short time span (around 20 Ma), contemporaneous with the Caledonian phase (ca. 410 Ma), during which the major Pan-African fractures were reactivated and subsidence and uplift movements occurred. Such a magmatism of mantle origin (Demaiffe et al., 1991b) can be associated with, and be a consequence of, a lithospheric delamination (Kay and Kay, 1993) but more constraints (in particular thermal modelling) are needed to confirm this model.

The age migration model has thus to be abandoned, at least for the Aïr province. The emplacement of the ring complexes appears to be controlled by lithospheric structures. This was discussed previously by Black and Girod (1970) and confirmed by Moreau (1982, 1987) and Black et al. (1985).

Following the structural model proposed above, the location of the Aïr ring complexes is essentially controlled by the N20°E *R* dextral shear and, to a lesser extent, by the N50°E *T* compressional axis of a N–S- to N10°E-trending regional dextral shear. Such an orientation is parallel to the Raghane dextral shear zone, which is a major structural feature of the Aïr Precambrian basement, and may be of lithospheric scale (remnants of ultramafic rocks in mylonites). The finite strain associated to the ring complex location and related to the dextral shear probably was of low amplitude, as no large horizontal displacement could be detected on a map scale. The main effect of this NE-trending compressional event could have been a large-scale doming of the Aïr massif between the Ordovician and Carboniferous. This doming probably migrated southwards with time, as shown by younger ages of the Palaeozoic transgression from north (Lower Devonian) to south (Namurian) on the western margin of the massif (Joulia, 1963).

The tectonic model proposed here for the Aïr ring complexes, on the basis of new structural and geochronological data, has important consequences for the palaeomagnetic evolution of Gondwana during the Ordovician–Carboniferous. Palaeomagnetic data (Hargraves et al., 1987) show that ten of the twelve sites measured display a similar polarity and pole position, confirming the penecontemporaneity of magnetisation. Hargraves et al. (1987) proposed a pole position located southwest of Cape Town and a 435 Ma age for that pole (average $^{40}Ar/^{39}Ar$ age on 3 biotites: two from Ofoud and one from Meugueur-Meugueur). However, this age is probably too old (see discussion earlier). Two recent syntheses of palaeomagnetic data for Gondwana during the Palaeozoic (Bachtadse and Briden, 1990; Kent and Van Der Voo, 1990) stressed that " the validity of the apparent polar wander path... depends crucially on the Aïr pole and on the correct determination of its age" (Bachtadse and Briden, 1990, p. 46). With these data, Gondwana should have to move northward at the extremely high drift rate of 23 cm a^{-1}. In these two papers, the authors wondered if such surprisingly rapid motions are reasonable. Our new radiometric data suggest a more representative age of 407 ± 8 Ma (average of the 4 new isochron ages) for the Aïr ring complexes. This age and the corresponding pole position are in better agreement with the Snowy River pole, southeastern Australia (Schmidt et al., 1987), used by Kent and Van Der Voo (1990) to derive a mean Silurian–Devonian pole representative for Gondwana.

Structural data are still scarce on the basement of the Tuareg shield as a whole, but detailed studies of the kinematics of the large-scale shear zones would be of great interest to constrain the Phanerozoic intracontinental evolution of the northwest African mobile zone more closely.

10. Conclusions

The fault network in the Tuareg shield, including the Aïr province of Niger, is dominated by N–S shear zones which control: (1) the variation in thickness and/or deformation of the sedimentary cover; (2) the location of basement topographic highs; and (3) the location of the magmatic activity. Tectonic reactivation occurred several times during the Phanerozoic in the Aïr massif, resulting in the emplacement of the ring complexes, the Cretaceous rifting, the formation of the Tâfidet trough and the Cenozoic to Recent volcanism. Fracturing resulted in the N50°E to N90°E (Guinea–Nubian lineament) and N120°E to N150°E fault directions, which may be related to reworking of N-S-trending shear zones by successive stress fields.

New radiometric data (Rb–Sr whole-rock isochrons) obtained from four ring complexes (Bous, Ofoud, Tamgak and Abontorok) give an intrusion age of about 407 ± 8 Ma. This age grouping allows us to reject the model of age migration from north to south proposed by several authors. Isotopic data (Demaiffe et al., 1991b) show that the anorthosite-bearing anorogenic complexes are derived from a slightly depleted mantle source region (comparable to the OIB-type source), but sometimes contaminated by crustal material.

Detailed structural analysis (autocorrelation method, lineament distribution from LANDSAT images) and geometrical information about ring complexes (nearly circular shape, major-axis orientation) allow us to propose a new tectonic model for their location. The major N20°E direction represents the Riedel *R* direction, which corresponds to an 'en échelon' opening; this *R* direction resulted from the N5°E dextral shear zone, which can be included in the Raghane shear zone, proposed by Liégeois et al. (1994) as one of the major shear zones of the Aïr basement.

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