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Geochemical and isotopic (Sr, Nd and Pb) evidence on the origin of the anorthosite-bearing anorogenic complexes of the Aïr Province, Niger *

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ABSTRACT

Abundant leucogabbro and anorthosite associated with other felsic rocks occur in seven high-level ring complexes of Ofoud-type in central Aïr. The leucogabbroic rocks are plagioclase cumulates, whereas troctolites and melatroctolites in the Meugueur-Meugueur ring dyke are olivine cumulates. The plagioclase cumulates are strongly laminated but generally unlayered and have positive europium anomalies. Fine-grained marginal gabbros and monzogabbros without europium anomalies are interpreted as having been close to magmatic liquids, as are the other felsic rocks, which have complementary negative europium anomalies. The fine-grained basic rocks are mildly alkaline with a troctolitic tendency with high Ti, P and incompatible elements and low transition elements. Cumulus mineral compositions ($\sim An_{65}$ and $\sim Fo_{65-55}$) are moderately differentiated. The felsic syenites and granites are alkaline to rarely peralkaline. Strontium isotopic initial ratios (Sr_i) in the leucogabbroic rocks, calculated assuming ages for each intrusion based on whole rock isochrons for felsic rocks, range from 0.7035 to about 0.707, whereas $\epsilon_{Nd}(t)$ varies sympathetically from +2.6 to −4.2. Although there is a spread in values, each intrusion has a distinct isotopic signature, Bous and the marginal facies of Meugueur-Meugueur having the highest $\epsilon_{Nd}(t)$ and lowest Sr_i, whereas rocks from the others have lower $\epsilon_{Nd}(t)$ and higher Sr_i. Sr_i in the felsic rocks obtained from isochrons (ages in the range 400–490 Ma) are considerably larger and vary from 0.7084 for Abontorok and Tagueï to 0.7138 for Bous; $\epsilon_{Nd}(t)$ varies from −7.5 to −14.4. The initial lead isotopic ratios for the leucogabbroic rocks show a narrow range of values ($^{206}Pb/^{204}Pb$: 16.7–17.75; $^{207}Pb/^{204}Pb$: 15.45–15.53) while the felsic rocks have less radiogenic ratios, down to $^{206}Pb/^{204}Pb$: 16.4 and $^{207}Pb/^{204}Pb$: 15.32. The parental basic magma fractionated olivine and (ortho)pyroxene but not plagioclase, which must have accumulated prior to intrusion at moderately shallow depths. The inferred parental magma probably had characteristics suggesting an origin by minor contamination of a slightly depleted OIB-type source. The other felsic rocks are not comagmatic and could have arisen by crustal contamination of a residual felsic melt. The Ofoud-type complexes are similar to Labrador-type massif anorthosites.

1. Introduction

The origin of Proterozoic massif-type anorthosites has always posed a major problem in igneous petrology, because of the large differences in composition between the rocks and common basic magmas and of the low normative plagioclase contents of possible mantle sources. A consensus appears to have been reached recently concerning the possible parental magmas [1–4], which are now generally thought to be basaltic and of mantle origin; see [5] for a review of the earlier literature. If the large volumes of true anorthosite were ever close to being liquid, they must have formed from a parental magma of unusually feldspathic composition or from a magma of more normal composition by some unusual differentiation process. Field evidence appears to confirm the existence, at least locally, of highly feldspathic *magmas* in Labrador-type [3] anorthosites, either as

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chilled margins or as dykes [1,6,7], which are of leucotroctolitic, leuconoritic or anorthositic composition. However, this does not necessarily imply the existence of anorthositic *liquids*, because of their unreasonably high liquidus temperatures [8] and the probable presence of small to moderate amounts of plagioclase crystals.

Anorthosites and related leucogabbroic rocks also occur in significant amounts in certain anorogenic ring complexes of Paleozoic age, the most well known being those in the Aïr Province, Niger [9–16], and it was felt that they might shed light on the anorthosite problem. The Aïr massif (Fig. 1) consists of three main geological units: a Precambrian basement composed of highly deformed medium- to high-grade metamorphic rocks cut by numerous granite batholiths of Pan-African age, approximately 30 ring complexes which intruded the basement during a major Paleozoic magmatic event, and recent volcanic cones and flows. The

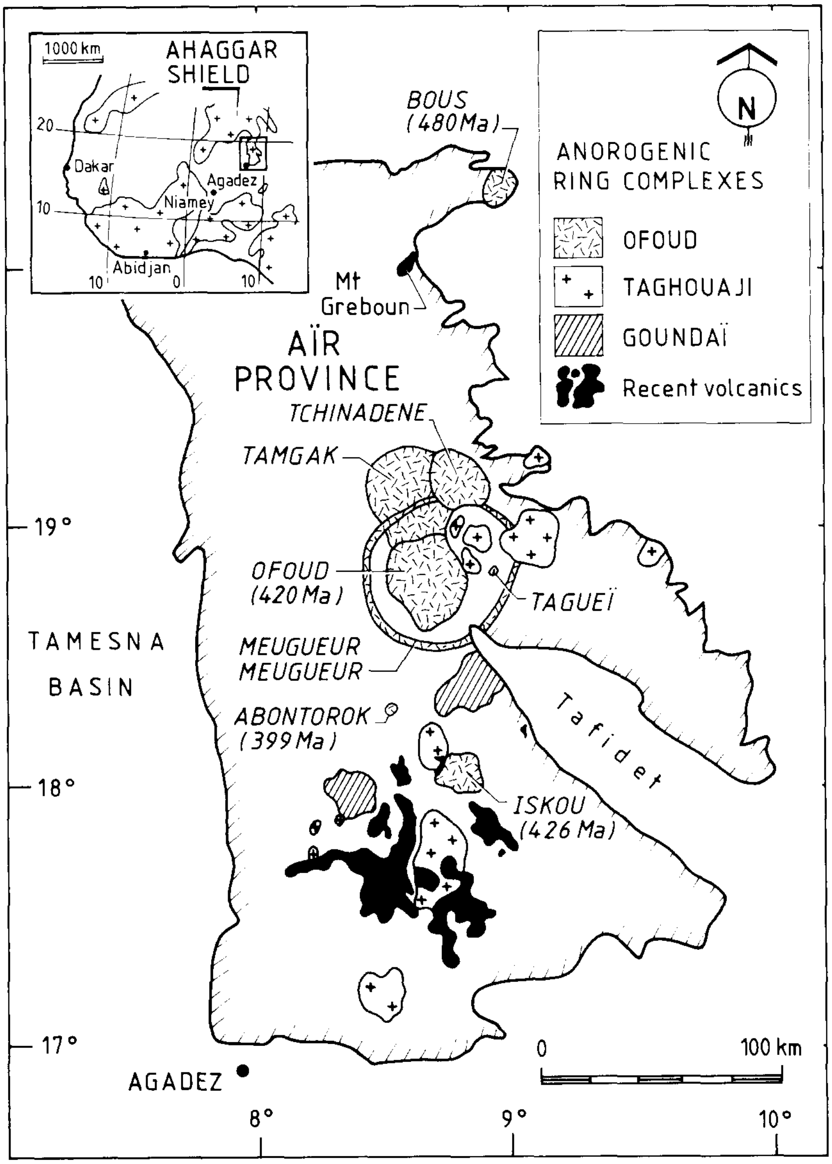

Fig. 1. Sketch map of the Aïr region (Niger) with the different types of ring complexes. Inset shows position of Aïr in western Africa.

ring complexes have been divided into three main types [15,16] depending on the nature and abundance of the rocks:

(1) a *volcanic* or *Goundaï type* comprising mainly rhyolitic tuffs and ignimbrites with a few microsyenite ring dykes;

(2) a *granitic* or *Taghouaji type* consisting of peralkaline syenites and granites, associated in places with peraluminous biotite granites accompanied by W and Sn mineralization. Basic rocks are absent at the present exposure levels;

(3) a *leucogabbroic* or *Ofoud type* characterized by a large proportion of basic rocks varying from troctolitic gabbros and leucogabbros to true anorthosites, intruded by mildly alkaline to peralkaline syenites and granites.

Seven ring complexes of *Ofoud type* exist in the Aïr Province. They have been studied from a geological, structural, petrological and mineralogical point of view [9–16]. The evidence is strongly in favour of an origin from mildly alkaline leucotroctolitic parental magmas (with the possible exception of Meugueur-Meugueur) which arose at depth by fractionation of olivine and pyroxene and accumulation of plagioclase crystals to different degrees, prior to intrusion at shallow level in the crust where consolidation of the plagioclase-bearing magmas occurred. In the Meugueur-Meugueur ring dyke the magma was more primitive (possibly mildly tholeiitic) and olivine was the main cumulus phase. Except for the scale, the Ofoud-type complexes are very similar to Labrador-type massif anorthosites [2]. This paper attempts to constrain possible sources for the basic rocks and to determine the origin and possible contamination of the intermediate to acid rocks

TABLE 1

Area and types of rocks in Ofoud-type ring complexes

Name	Area and form	Leucogabbroic Group (area and rock types)	Felsic Group (area and rock types)
Bous	100 km^2 elliptical	40 km^2 of basic rocks: 70% troctolitic layered gabbro, 30% microgabbro 10 km^2 of monzonite and cpx-opx-amph-bearing monzogranite	50 km^2 20% quartz-micromonzonite 70% alkaline and peralkaline granite; 10% late felsic rocks
Tamgak (Tchinadène)	1000 km^2 circular	20 km^2 of troctolitic leucogabbro with anorthosite enclaves	100 km^2 rhyolite 880 km^2 alkaline and peralkaline granite
Ofoud	900 km^2 circular	450 km^2 70% anorthosite, 25% leucogabbro, 5% gabbroic rocks 45 km^2 90% micro-monzogabbro, -syenite, monzo-anorthosite 10% ferrosyenite	405 km^2 45% amph–cpx syenite; 45% sodi-calcic amph granite 10% microgranite
Meugueur-Meugueur	40 km^2 ring dyke	36 km^2 of troctolitic melagabbro with enclaves (anorthosite, gabbro, leucogabbro, dunite, etc.) 1 km^2 of monzosyenite	3 km^2 subalkaline and alkaline syenite and granite (reworked basement?)
Tagueï	0.5 km^2 circular	0.2 km^2 95% leucogabbro, 5% chilled marginal gabbro 0.2 km^2 monzo-anorthosite	0.1 km^2 30% alkaline granite 70% quartz-monzonite
Abontorok	5 km^2 circular	4 km^2 40% anorthosite, 55% leucogabbro, 5% chilled marginal gabbro and monzogabbro	1 km^2 30% alkaline granite 60% Qz alkaline syenite 10% endogenic breccia
Iskou	150 km^2	45 km^2 leucogabbro with enclaves (anorthosite, troctolite, norite, etc.)	15 km^2 ferrosyenite 90 km^2 peralkaline syenite and granite aluminous granite

making use of trace-element and radiogenic (Sr, Nd and Pb) isotopic data.

2. Field relationships and summary of mineralogy and petrology

The seven ring complexes of Ofoud type (Fig. 1, Table 1) vary in size, shape and field occurrence and are described briefly in order, from North to South. They range in size from a very small pipe (Tagueï) through a funnel-shaped intrusion (Abontorok) and a large massif-type body (Ofoud) to a relatively thin ring dyke 65 km in diameter (Meugueur-Meugueur). Anorthosite occurs in different ways in all seven, varying from rare thin gently dipping layers in a stratiform intrusion (Bous) through a steeply laminated but unlayered type (Abontorok) to something resembling a Proterozoic massif-type (Ofoud). These complexes were emplaced during the Paleozoic but detailed geochronological data are still lacking, only felsic rocks having been dated for all the intrusions (see [15]). Two independent Rb/Sr whole-rock isochron ages have been obtained for Adrar Bous: 420 ± 4 Ma [17] and 487 ± 7 Ma [18]. In a more recent discussion of the ages in the Niger–Nigeria province, Bowden and Karche [19] favoured an age of 487 Ma for the intrusion which fits better with the N–S younging suggested by these authors. A minimum age for the Ofoud intrusion is given by that of 421 ± 15 Ma of the associated Agaragueur granite septum [17]. Tamgak and Iskou have been dated at 455 Ma and 426 Ma respectively [19]. The granites and syenites of Abontorok gave an age of 399 ± 10 Ma [14,16].

Bous, the most northerly complex, consists of a layered series of basic rocks (~ 40% by area) ranging from troctolite and troctolitic gabbro to leucogabbro alternating with thin layers of anorthosite. They are intruded by medium-grained monzonite to quartz monzonite and later alkaline and peralkaline granites.

Tamgak (Tchinadène) consists mainly of alkaline and peralkaline granite with small areas especially to the northeast occupied by troctolitic leucogabbro and anorthosite, very similar to rocks from Ofoud.

Ofoud covers ~ 900 km^2 much of which (~ 50% by area) consists of anorthosite and associated leucogabbro cut by micromonzogabbro dykes. The rest of the complex consists of later alkaline syenite and granite.

Meugueur-Meugueur, the largest ring dyke on the Earth, is 200–400 m thick and 65 km in diameter. It consists almost entirely of troctolite and melatroctolite with small very rare cognate enclaves of anorthosite and dunite [13,20].

Tagueï, the smallest complex, is an 800 m diameter pipe consisting of marginal leucogabbro grading into an unusual central rock called monzo-anorthosite, which has been interpreted as a hybrid composed of cumulus plagioclase and infiltrated intercumulus granitic material [12]. It is cut by rare thin granite dykes.

Abontorok is a 2.6-km diameter funnel-shaped intrusion, composed of a steeply internally dipping laminated but not layered central anorthosite varying outwards continuously to leucogabbro (~ 80% by area), and cut by a later central syenite and syenitic breccia and by syenite and granite ring dykes [14].

Iskou shows a variety of rocks including leucogabbro associated with monzogabbro and ferrosyenite with abundant anorthosite, leuconorite and leucotroctolite enclaves, cut by thick arcuate intrusions of peralkaline syenite and of peralkaline or peraluminous granite [11].

The general petrography of each of the complexes (Table 1) is similar, although in detail there are differences both in the early basic and associated rocks (called Leucogabbroic Group in Table 1; there is no simple term for such rocks, because anorthosites are not strictly gabbroic and are often not basic with $SiO_2 > 52\%$) and in the later syenites and granites (Felsic Group). Bous is the only complex with a layered basic series; it displays strong similarities with other layered intrusions throughout the world [21–23]. It lies well to the North of the other complexes in central Aïr, was intruded at the boundary of the Precambrian basement with its Paleozoic cover and may be significantly older [17–19]. The layered rocks comprise in decreasing order of abundance olivine gabbro, leucogabbro and only rare thin anorthosite layers; the layered series is transitional to mildly alkaline, whereas the syenites and granites are strongly peralkaline. The leucogabbroic rocks of the other complexes are not layered (although some of them may be strongly laminated, Abontorok). Cumulate textures are more or less well developed in the rocks of all the complexes, the main cumulus mineral being plagioclase with olivine in the Meugueur-Meugueur troctolites and melatroctolites. The rocks of the complexes of central Aïr have a troctolitic tendency; monzogabbros occur in Abontorok and Iskou. Ofoud is the only complex in which massive anorthosites occur (~ 35% of the total area), and Ofoud and Tagueï the only ones in which the anorthosite locally contains abundant quartzo-feldspathic material in the interstices (monzo-anorthosite). Anorthosite occurs only as enclaves in Meugueur-Meugueur and Iskou, and the latter is the only one to contain leuconorite enclaves. The syenites and granites are generally peralkaline, although peraluminous granites occur at Iskou and those of Ofoud are only mildly alkaline.

The mineralogy of the complexes is similar. Mineral compositions and modal abundances are given in [16]. All the leucogabbroic rocks contain abundant plagioclase, generally labradorite cores (although bytownite occurs in Bous) with thin zoned rims, the zoning reaching progressively more Ab-rich compositions in the sequence anorthosite-gabbro-monzogabbro. Augite may only locally be more abundant than olivine, the latter being more Fo-rich in Meugueur-Meugueur and Bous. Although most of the leucogabbroic rocks are rich in total iron as Fe–Ti oxides, they are not ferrogabbroic as the ferromagnesian silicates are not iron-rich. The syenites and granites contain abundant alkali feldspar and are almost exclusively hypersolvus, but have suffered strong to very strong deuteric alteration [24]; the alkali feldspars are now a cloudy film to patch perthites with numerous micropores [25]. The ferromagnesian minerals are also often altered and ragged; they range from hornblende and biotite in the peraluminous rocks to aegirine and sodium-rich amphiboles in the peralkaline ones.

3. Analytical methods

Major and trace-element concentrations in the whole-rock samples were determined by ICP atomic emission spectrometry [26] and FeO by wet chemistry at the CRPG. Precision on the REE determinations is in the range of 2 to 6% [26]. Wave-length-dispersive electron-microprobe data on the minerals were obtained with Camebax and SX 50 probes at the University of Nancy I. Operating conditions were generally 15 kV accelerating voltage, 15 nA beam current, beam size ~ 1 μm, counting time 10 s. Oxides and natural silicates were used as standards. Data reduction was performed using the MBXCOR-ZAF corrections of [27].

Isotopic analyses were carried out at the Laboratoires Associés Géologie–Pétrologie–Géochronologie of the Université Libre de Bruxelles. The sample was processed following standard chemical separation procedures (i.e., HF–$HClO_4$ dissolution and anion exchange column separation of the different elements following the method described in [28]). ^{84}Sr and ^{85}Rb spikes were added to part of the solution for determination of Rb and Sr concentrations by isotope dilution when the concentrations are lower than 30 ppm. The blanks for the columns were below 3 ng Sr, while the total blanks for the whole procedure were below 6 ng for Sr and below 2 ng for Nd and Rb for usually between 200 and 500 mg of sample. These blanks are then negligible relative to the concentrations in the samples. For Pb isotopes, the samples were processed separately in a clean over-pressurized (> 3 mm Hg) laboratory, using sub-boiled reagents. Pb was separated on anion-exchange columns in an HBr–HCl medium, following a method derived from [29]. Pb and U concentrations were measured on the same sample solution (aliquots were split before loading on columns and spiked with a ^{235}U–^{206}Pb mixed spike). U was separated in an HNO_3 medium.

Sr isotopic compositions and Rb and Sr concentrations by the isotope-dilution method were measured on double Re filaments with a Finnigan MAT 260 mass spectrometer. Between-run precisions are better than 5×10^{-5}. The Rb and Sr concentrations as well as the ^{87}Rb/^{86}Sr ratios are given with a precision better than 2%. The measured values were normalized to $^{86}\mathrm{Sr}/^{88}\mathrm{Sr} = 0.1194$. Twenty aliquots of NBS 987 analyzed during the same time period as the Aïr samples yielded ^{87}Sr/^{86}Sr of 0.71022 ± 1 ($2\sigma_m$). Nd isotopic compositions were measured on double Re filaments with the same Finnigan MAT 260. Thirteen analyses of the nNdβ [30] yielded $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.511910 \pm 13$ and $^{145}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.348436 \pm 11$ ($2\sigma_m$). Nd is run as a metal and for each run, the 146, 145, 144 and 143 isotopes are measured with all values normalized to $^{146}Nd/^{144}Nd = 0.7219$. $^{147}Sm/^{144}Nd$ ratios are given with a precision of minimum 5%.

Pb isotopic compositions and Pb and U concentrations by isotope dilution were measured on single Re filaments with a Finnigan MAT 260 mass spectrometer, using the H_3PO_4-silica gel technique [31]. All the results were corrected for mass fractionation (0.13 ± 0.04% per a.m.u.) on the basis of 72 analyses of the NBS 981 Pb standard [32] for a temperature range of 1090–1200°C. Between-run precision is better than ~ 0.1% for the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios and ~ 0.15% for the $^{208}Pb/^{204}Pb$ ratios. The Pb and U concentrations are given with a precision of better than 2%. Total blank values for Pb for the whole chemical procedure were below 2 ng.

4. Major and trace-element geochemistry

The major-element compositions of the *plagioclase-rich* cumulates cannot be used easily to determine the nature of the magmatic series. The marginal facies of some of the intrusions are however fine-grained gabbros or microgabbros grading progressively and rapidly towards the center of the intrusion to coarser-grained plagioclase-rich rocks (gabbros and leucogabbros or leucotroctolites). These marginal facies can be interpreted as being close to chilled magmatic liquids. Major element compositions of these rocks are given in [14] for Abontorok and in [16] for the other massifs. In a ($Na_2O + K_2O$)–SiO_2 diagram (Fig. 2), these inferred liquids with 40.8–50.8% SiO_2 plot distinctly in the alkaline field or close to the boundary line between the alkaline and subalkaline fields of Miyashiro [33], except for the chilled facies of the Meugueur-Meugueur ring dyke (only one sample analysed). It also appears that samples from Abontorok and Ofoud are more alkaline than the microgabbros from the Bous layered intrusion which plot close to the boundary line. An alkaline affinity is confirmed by the high TiO_2 (2–6.3%) and P_2O_5 (0.3–1.3%) contents of most of the samples, except for the marginal facies from Tagueï and Meugueur-Meugueur which have less than 2% TiO_2 and 0.3% P_2O_5. The Al_2O_3 content is moderate to high (14–18.2%) in most such samples, but may be very high (19.3–21.6%) in microgabbros from Bous. Most of the gabbros have high Fe contents, 100 MgO/(MgO + FeO_{tot}) ratios falling in the range 22–30, except for the marginal facies of Tagueï (50) and Meugueur-Meugueur (45).

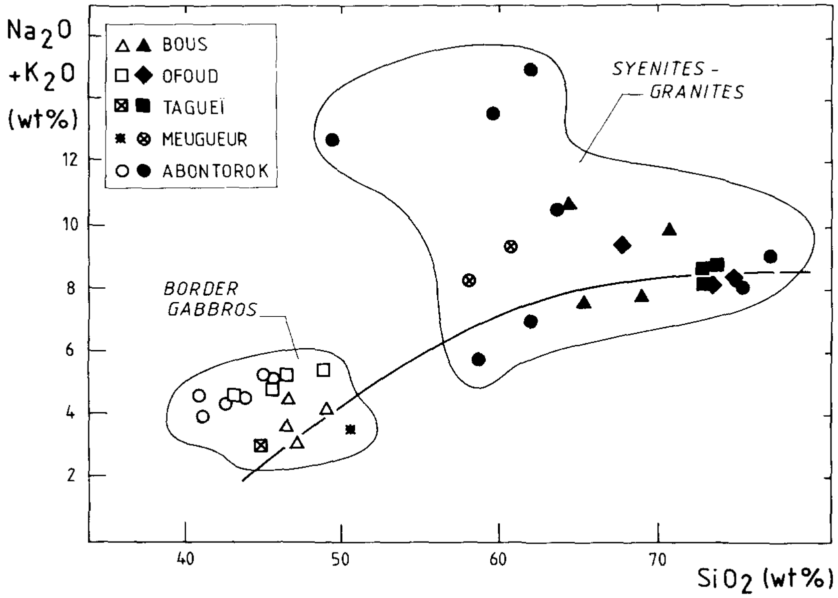

Fig. 2. Total alkalies versus silica diagram for the inferred chilled gabbroic liquids (border gabbros, empty symbols) and felsic rocks (granites and syenites, filled symbols). The line separating the alkaline (above) and subalkaline (below) fields is from Miyashiro [33].

Most of the intermediate and acid rocks — *syenites and granites* — spatially associated in the field with the gabbroic and anorthositic cumulates occur as arcuate intrusions, plugs, sheets or ring dykes which crosscut the basic cumulates; their fine-grained nature and their field occurrence suggest that they were intruded as magmatic liquids. They display alkaline affinities, although some of them are close to the alkaline–subalkaline boundary (Fig. 2). K_2O is largely dominant over Na_2O except in syenites from Meugueur-Meugueur. K_2O is very high (up to 15%) in the syenite breccia at Abontorok. These rocks have high FeO/MgO ratios and very low MgO contents (< 0.1%) and can be classified chemically as A-type granites [34].

The general trace-element chemistry of the anorthosite-bearing complexes of central Aïr is only summarized here (see [16]). Detailed data for the Abontorok intrusion are given in [14]. Representative analyses are given in Table 2.

(1) Transition-element concentrations are low in gabbros from Abontorok and Ofoud with low $100\ MgO/(MgO + FeO_{tot})$ ratios: 30–130 ppm Ni, 50–120 ppm Cr and 38–70 ppm Co. In gabbros with higher $100\ MgO/(MgO + FeO_{tot})$ ratios, such as the marginal facies of Tagueï and Meugueur-Meugueur and sample Bo 78 from Bous, the concentrations are higher: up to 340 ppm Ni and 330 ppm Cr.

(2) The plagioclase-rich cumulates and related leucogabbroic rocks have low K_2O (< 1%) and Rb (usually < 10 ppm) concentrations, with high K/Rb ratios in the range 400-800-some values as high as 2000 were obtained for samples from Ofoud. The alkaline syenites and granites have higher K_2O (4.8 ± 1%) and Rb (150 ± 50 ppm) contents, except for the syenite breccia at Abontorok which is very rich in both (up to 14.5% K_2O and 400 ppm Rb).

(3) The gabbros have high Sr contents (> 600 ppm) except for the marginal facies (border) of Meugueur-Meugueur (300 ppm). The plagioclase-rich cumulates have still higher Sr contents (700–1040 ppm), whereas the layered gabbros from Bous have significantly lower ones (300–600 ppm).

TABLE 2

Trace-element contents (ppm) of representative samples from the different intrusions [1]

	Ofoud						Bous			
	anorthosite OF 2.2	leucogabbro OF 100b	microgabbro OF 15′d	microgabbro AG4	monzogranite AG3	microgranite OF42	anorthosite BO 7741	leucogabbro BO 28e	gabbro BO 60j	microgabbro 28a
Rb	6.4	3.1	11.6	10.5	104	115	1	<1	9.5	<1
Sr	925	878	695	540	81.2	39	480	462	334	698
Ba	407	913	1078	154	922	203	737	87	105	189
Zr	134	150	211	207	306	875	nd	109	137	159
Y	6.1	9.9	24.9	23.6	42.8	82	nd	8.9	24	20.4
Ni	67	36	65	131	26	18	<10	137	104	124
Cr	39	139	102	61	63	nd	154	396	197	168
Co	44	23	45	77	13	<10	<10	79	56	56
La	5.2	12.5	20	18.5	89	119	1.50	3.9	8.4	11.1
Ce	12.2	24	42	44	165	202	3.0	10.5	22	26
Nd	5.0	11.7	25	23	63	101	1.53	5.0	13.7	16.9
Sm	1.08	2.7	5.7	5.3	11.8	20	0.36	1.43	4.1	4.4
Eu	1.17	3.0	1.84	2.1	1.42	1.23	0.29	0.80	1.31	1.74
Gd	1.06	2.1	4.6	4.5	8.9	15.6	0.48	1.39	3.8	4.2
Dy	0.62	1.58	4.2	3.8	7.2	15.1	0.36	1.06	3.8	3.5
Er	0.33	0.82	1.94	1.83	3.8	7.7	0.16	0.69	1.90	1.73
Yb	0.29	0.58	1.83	1.69	3.8	1.9	0.14	0.42	1.70	1.36
Lu	0.05	0.09	0.28	0.28	0.57	1.15	0.02	0.11	0.27	0.24
(La/Yb)N	10.9	12.9	6.7	6.6	13.8	8.9	6.4	5.5	2.9	5.1
Eu/Eu*	3.4	3.8	1.10	1.30	0.42	0.21	2.2	1.80	1.00	1.20

[1] Data for the Abontorok intrusion are given in [14].

The syenites and granites have much lower Sr contents, < 200 ppm down to 30 ppm in the peralkaline granites.

(4) Chondrite-normalized [35] trace-element diagrams for one or two marginal facies samples of each intrusion are given in Fig. 3. Although data for Th, Nb and Ta are lacking for many samples, useful information can be deduced from this diagram. All analysed gabbros are rich in incompatible elements: most elements have normalized abundances between 10 and 70, which are comparable in general to many continental basalts, whatever their geochemical affinities [36,37]. In detail, the spider-diagrams show some specific features: (a) Ba is much more enriched than Rb, which is the opposite to what is commonly observed in continental flood basalts. (b) Most samples, except for the gabbros from Meugueur-Meugueur, show rather high normalized Sr values of about 60. (For Tag 35, the high Sr value probably results at least partially from slight plagioclase accumulation as suggested by its positive Eu anomaly, see Fig. 4.) (c) Gabbros from Ofoud and Abontorok are rich in Ti, a characteristic commonly observed in gabbros related to massif-type anorthosites.

The rare-earth element (REE) abundances were measured in more than 60 samples covering a large variety of rock types: plagioclase-rich cumulates (anorthosite, leucogabbro, leucotroctolite), marginal gabbros and microgabbros, syenites and granites. Representative analyses and chondrite-normalized plots for 21 samples are given in Table 2 and Fig. 4 respectively. The anorthosites and related leucogabbros and leucotroctolites have REE patterns characteristic of rocks formed by accumulation of plagioclase crystals: (a) light REE enrichment, the average $(La/Yb)_N$ ratio being close to 8.5 for most samples, except for those less fractionated from Bous which have $(La/Yb)_N$ values in the range 2.9–7.5. (b) moderate REE contents, Σ_{REE} varying from 28 to 110 ppm, except for samples from Bous which have Σ_{REE} from 9 to 60 ppm. (c) positive europium anomalies (Eu/Eu* > 1), the value decreasing from 3 to near 1 with increasing total REE content, which may be re-

		Tagueï				Meugueur-Meugueur				
micro-monzonite 57a	alkaline granite 7828	leuco-gabbro Tag 18	monzo-anorth. Tag 1	gabbro Tag 35	granite Tag 32a	anortho-site MG34	leuco-troct. MG52	gabbro MG11	syenite MG25	syenite MG5
73	nd	4.7	43	2.7	141	nd	2.9	7.2	0.3	0.4
252	nd	749	721	636	149	nd	724	299	160	103
1016	27	230	442	176	nd	nd	305	164	466	163
342	nd	175	195	137	280	nd	80	125	137	203
44	nd	12.3	18.2	10.7	27.8	nd	13	17.5	68	39
21	175	145	66	336	nd	nd	303	182	110	10
77	83	89	122	45	nd	nd	356	260	86	8
63	nd	55	26	nd	nd	nd	nd	nd	nd	nd
50	24	9.5	15.2	8.4	33	8.3	9.5	14.9	40	36
100	67	21	32	18.0	70	17.8	22.3	40	130	80
47	32	12.9	16.3	9.6	31	7.7	12.8	17.4	46	41
9.6	7.2	2.6	3.2	2.1	6.2	1.73	2.7	5.3	12.6	9.3
2.0	1.09	1.36	1.38	1.13	0.90	0.77	1.54	1.70	1.94	2.9
8.4	6.1	2.6	2.6	1.66	4.7	1.60	2.3	5.6	11.7	7.8
7.5	5.5	2.1	2.4	1.46	4.6	1.21	2.1	4.1	12.4	7.3
3.9	2.9	1.17	1.38	0.79	2.4	0.65	0.91	2.1	6.71	3.6
4.0	3.0	0.84	1.08	0.65	2.4	0.68	0.80	1.48	7.5	3.2
0.66	0.56	0.12	0.15	0.14	0.33	0.19	0.09	0.26	1.27	0.52
7.5	4.8	6.8	8.5	7.7	8.1	8.2	8.0	6.8	3.6	7.6
0.71	0.55	1.60	1.40	1.90	0.50	1.40	1.90	1.00	0.50	1.00

lated to increasing amount of trapped intercumulus liquid. The fine-grained gabbros typically display smooth, high light-REE patterns (La_N from 25 to 35 for Bous, 60 to 90 for Ofoud) with no or only a small positive Eu anomaly. In each massif except Tagueï, the gabbros have typically higher REE contents than the associated plagioclase cumulates. These data show that such fine-grained gabbros can be interpreted as chilled magmatic liquids which have neither fractionated nor accumulated significant amounts of plagioclase. In view of its REE distribution trend, Tag 35 is considered as a plagioclase cumulate and not as a true chilled facies.

The syenites and granites usually show high total REE contents (Σ_{REE} varying from 160 ppm in Bous up to 650 ppm in the syenite breccia from Abontorok) with moderate to high $(La/Yb)_N$ ratios in the range 7 to 11, similar to those of the plagioclase-rich rocks and large negative Eu anomalies (Eu/Eu* from 0.7 to 0.21). These rocks can be interpreted as residual liquids after extensive feldspar fractionation or as partial melts which were in equilibrium with residual feldspar in the source.

5. Isotope geochemistry

Rb–Sr and Sm–Nd isotopic data for the different anorthosite-bearing anorogenic complexes of the Aïr are given in Tables 3 and 4. Sr data for the Abontorok intrusion can be found in [14]. The Sr and Nd isotopic initial ratios for the plagioclase cumulates and gabbros were calculated, from the measured ratios, assuming for each intrusion an age similar to that deduced from the Rb–Sr whole-rock isochron for the associated syenites and granites. A few samples of granitic gneisses from the Precambrian basement near the Meugueur-Meugueur ring dyke were also analysed.

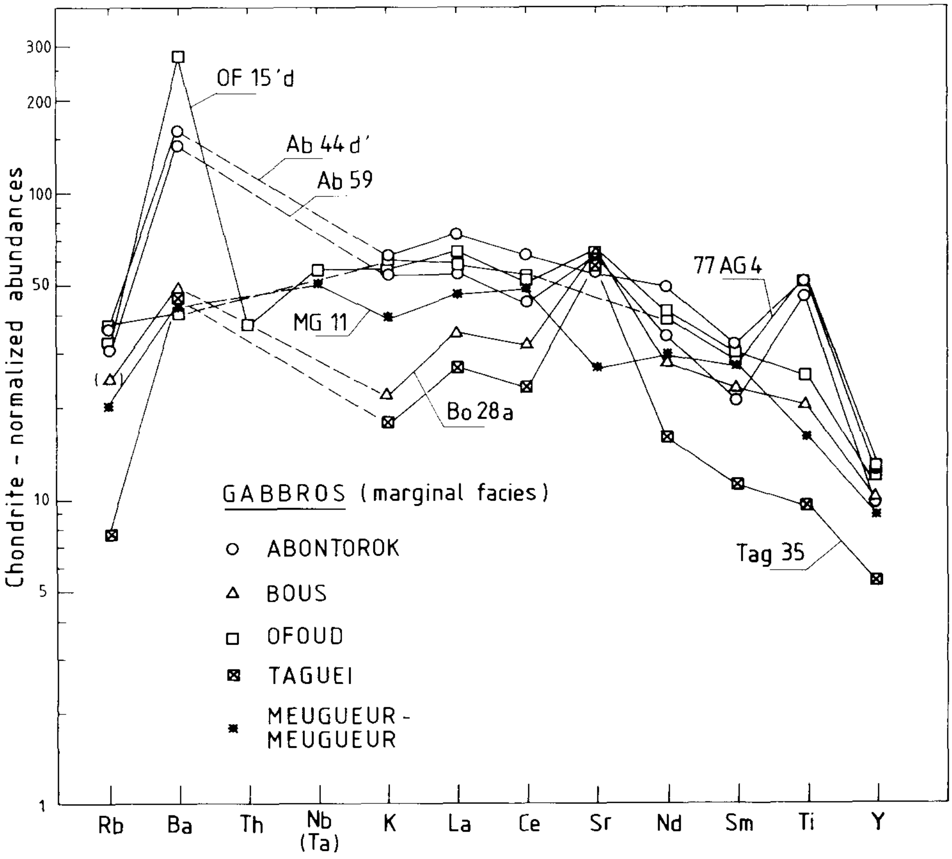

Fig. 3. Chondrite-normalized [35] abundances of trace elements for fine-grained gabbroic border facies.

The Sr isotopic initial ratios obtained for the gabbroic and cumulate rocks are plotted versus age for each intrusion (Fig. 5); the values obtained for the Proterozoic massif-type anorthosites in the North Atlantic province, for the Sept-Iles intrusion, Quebec and for the Tertiary Mboutou layered complex, Cameroon are plotted for comparison [3,22,38].

Taken together, the Aïr data show a large spread of values but the basic rocks of each intrusion have a distinct Sr and Nd isotopic signature (Fig. 6). The Bous layered intrusion and the gabbroic marginal facies of the Meugueur-Meugueur ring dyke have the lowest $(^{87}Sr/^{86}Sr)_i$ ratios, close to 0.7035 and the highest $\epsilon_{Nd}(t)$ values up to +1.0 (or +2.6 if one considers the anorthosite with a very large 2σ error on the measurement) for Bous gabbro. Rocks from the other intrusions have higher Sr and lower Nd initial ratios: 0.7048 for Tagueï with $\epsilon_{Nd}(t)$ +0.6 for the marginal facies; 0.7058 for Abontorok and $\epsilon_{Nd}(t)$ in the narrow range −1.1 to −2; 0.705–0.707 for Ofoud and Iskou and for the troctolites and melatroctolites from Meugueur-Meugueur with $\epsilon_{Nd}(t)$ of −2.4 for a leucogabbro and down to −4.2 for a troctolite from the latter. As a general observation, the $\epsilon_{Nd}(t)$ values for the basic rocks range from slightly positive for the intrusions with initial Sr

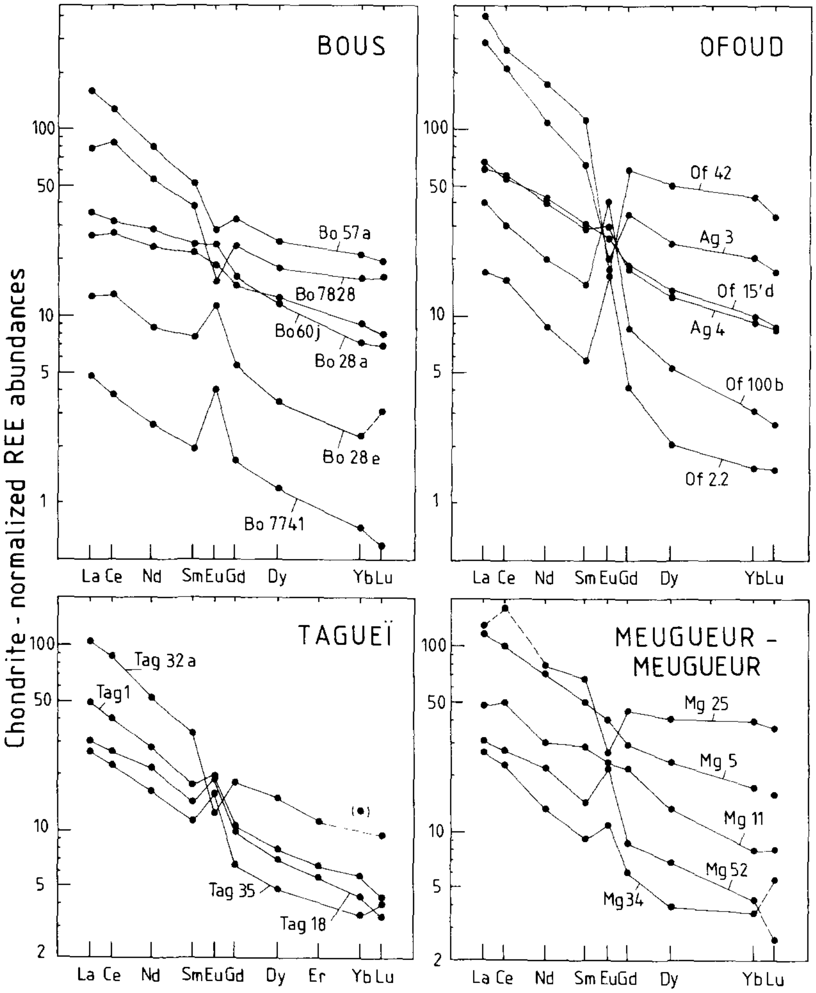

Fig. 4. Chondrite-normalized REE patterns for selected representative samples of basic (plagioclasic cumulates, gabbroic marginal facies) and felsic (granites, syenites) rocks from Bous, Ofoud, Tagueï and Meugueur-Meugueur. Data for Abontorok have been published in [14].

ratios < 0.705 to slightly negative for those with initial Sr ratios > 0.705. The monzo-anorthosites from Tagueï have significantly more negative values (-5 and -7.9) than the basic rocks.

The felsic rocks have even higher Sr initial ratios (deduced from whole-rock isochrons) and more negative $\epsilon_{Nd}(t)$ values: $(^{87}Sr/^{86}Sr)_i$ of 0.7084 for Abontorok and Tagueï [14,16], 0.7098 for Iskou and 0.7138 for Bous [18], with $\epsilon_{Nd}(t)$ from -7.5 for syenites from Abontorok down to -10 and -14.4 for the syenitic and granitic dykes of Tagueï, Abontorok and Bous. No Nd data are available for felsic rocks from Ofoud and Iskou. At the time of intrusion of the anorogenic com-

TABLE 3

Selected Rb-Sr isotopic data for the Aïr ring complexes [a]

Samples	Rb ppm	Sr ppm	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	$2\sigma m$	$(^{87}$Sr/^{86}Sr$)_i$		
Bous	*487 Ma*							
Basic rocks								
7741	1.00	480	0.060	0.70333	5		0.70331	
78 Bo 60a	1.20	309	0.0112	0.70381	1		0.70373	
78 Bo 55B	4.40	394	0.0323	0.70455	4		0.70433	
77 Bo 26′	1.00	534	0.0054	0.70356	3		0.70352	
Felsic rocks [b]							0.7138	
Ofoud	*420 Ma*							
Basic rocks								
76OF2.2	6.4	925	0.0200	0.70705	7		0.70693	
76OF15′D	11.6	695	0.0483	0.70624	3		0.70595	
78OF84	4.80	259	0.0536	0.70759	18		0.70727	
77OF57D	17.8	554	0.093	0.70590	5		0.70534	
Felsic rocks [b]							0.713	
Tagueï	*400 Ma*							
Basic rocks								
76 Tag 11	4.60	806	0.0165	0.70474	2		0.70465	
78 Tag 1	43	721	0.173	0.70659	12		0.70534	
85 Tag 35	2.70	636	0.0123	0.70486	2		0.70479	
85 Tag 34	40	707	0.164	0.70638	5		0.70544	
Felsic rocks [b]							0.7084	
Meugueur	*420 Ma*							
Basic rocks								
MG11	7.2	299	0.070	0.70353	3		0.70311	
MG85-14a	<1	1167	0	0.70547	5		0.70547	
MG14	2.30	635	0.0105	0.70555	5		0.70549	
MG52	2.90	724	0.0116	0.70562	3		0.70555	
Iskou [c]	*426 Ma*							
Basic rocks							≈ 0.707	
Felsic rocks [b]							0.7098	
Basement near Meugueur-Meugueur						*400 Ma*	*420 Ma*	*487 Ma*
MG9	263	218	3.50	0.73889	8	0.71895	0.71795	0.71459
MG19	159	236	1.94	0.72714	5	0.71606	0.7155	0.71364
MG36	175	282	1.81	0.72337	1	0.71309	0.71257	0.71084
MG46	251	169	4.31	0.74533	3	0.72078	0.71955	0.71542

[a] Data for Abontorok are given in [14]; [b] Initial ratios from Rb–Sr whole-rock isochrons; [c] Data in [18].

TABLE 4

Nd and Pb isotopic data for the Aïr ring complexes

Samples	Rock type	Sm ^{a} (ppm)	Nd ^{a} (ppm)	^{147}Sm/ ^{144}Nd	^{143}Nd/ ^{144}Nd	$\epsilon_{Nd}(t)$	Pb ^{b} (ppm)	U ^{b} (ppm)	^{206}Pb/ ^{204}Pb	^{207}Pb/ ^{204}Pb	^{208}Pb/ ^{204}Pb	^{238}U/ ^{204}Pb	(^{206}Pb/ ^{204}Pb)$_i$	(^{207}Pb/ ^{204}Pb)$_i$
Tagueï	*420 Ma*													
TAG 11	leucogabbro	3.1	14.9	0.124	0.51253 ± 3	1.8	1.55	0.35	18.472	15.579	38.526	8.11	17.505	15.526
TAG 35	microgabbro	2.1	9.5	0.132	0.51249 ± 4	0.6	0.79	0.14	18.407	15.562	38.737	8.09	17.647	15.520
TAG 1	monzo-anorth.	3.2	16.3	0.120	0.51217 ± 6	−5.0	7.2	2.7	18.052	15.488	38.573	8.02	16.457	15.400
TAG 34	monzo-anorth.	3.8	16.9	0.136	0.51207 ± 2	−7.9	7.3	1.0	18.184	15.494	38.716	8.00	17.599	15.462
TAG 32a	granite dyke	6.2	31	0.123	0.51181 ± 3	−12.2	23.8	4.1	18.114	15.492	38.547	8.00	17.381	15.452
Abontorok	*400 Ma*													
AK 24	anorthosite	2.6	14.5	0.109	0.51235 ± 8	−1.1	2.3	0.25	17.924	15.544	38.549	8.10	17.485	15.520
AK 36	leucogabbro	7.8	40	0.118	0.51237 ± 4	−1.2	3.9	0.54	18.095	15.535	38.580	8.07	17.534	15.504
AK 59	gabbro	4.1	20.4	0.120	0.51236 ± 3	−1.5	2.7	0.36	18.059	15.542	38.704	8.09	17.518	15.512
AK 107	gabbro border	5.3	25	0.129	0.51236 ± 3	−1.9	2.0	0.33						
AK 15	alkaline granite	6.5	37	0.108	0.51167 ± 4	−14.4	17.5	4.6	18.309	15.595	39.903	8.15	17.221	15.535
AK19	syenite	15.4	79	0.118	0.51205 ± 3	−7.5	28.4	3.8	17.780	15.507	38.788	8.05	17.239	15.477
AK 101	syenite (xenolith)	10.3	57	0.110	0.51178 ± 4	−12.3	31.9	3.7	17.763	15.508	39.009	8.06	17.293	15.482
Bous	*487 Ma*													
BO 26′	anorthosite	0.34	1.5	0.133	0.51257 ± 17	2.6	0.48	0.03	17.886	15.547	38.012	8.11	17.579	15.530
BO 60a	gabbro	1.64	4.1	0.241	0.51283 ± 2	1.0	0.8	0.2	17.934	15.561	37.910	8.14	16.706	15.491
BO 57a	micromonzonite	9.6	47	0.123	0.51187 ± 3	−10.4	11.2	1.8	17.439	15.370	38.449	7.86	16.651	15.325
Meugueur	*420 Ma*													
MG14	troctolite	3.4	13.1	0.160	0.51232 ± 7	−4.2	1.5	0.17	17.786	15.489	38.445	8.02	17.306	15.463
MG52	leucogabbro	2.7	12.8	0.130	0.51233 ± 3	−2.4	1.7	0.4	17.763	15.499	38.493	8.05	16.767	15.444
Basement near	*Meugueur-Meugueur*					*range 487–400 Ma*							*range 487–400 Ma*	
MG9	granitic gneiss	11.4	56	0.121	0.51159 ± 3	range −15.8 to −16.6	49.8	5.8	17.948	15.552	39.180	8.11	17.366 to 17.473	15.519 to 15.526
MG46	alaskitic gneiss	11.5	62	0.111	0.51151 ± 3	range −16.7 to −17.7	47.2	6.7	17.966	15.538	40.145	8.09	17.247 to 17.380	15.497 to 15.506

$\lambda^{147}Sm = 6.54 \cdot 10^{-12}\ y^{-1}$

ϵ_{Nd} calculated relative to BE at $^{143}Nd/^{144}Nd = 0.512638$; $^{147}Sm/^{144}Nd = 0.1967$

[a] ICP analysis (CRPG, Nancy); [b] isotope dilution (ULB, Bruxelles).

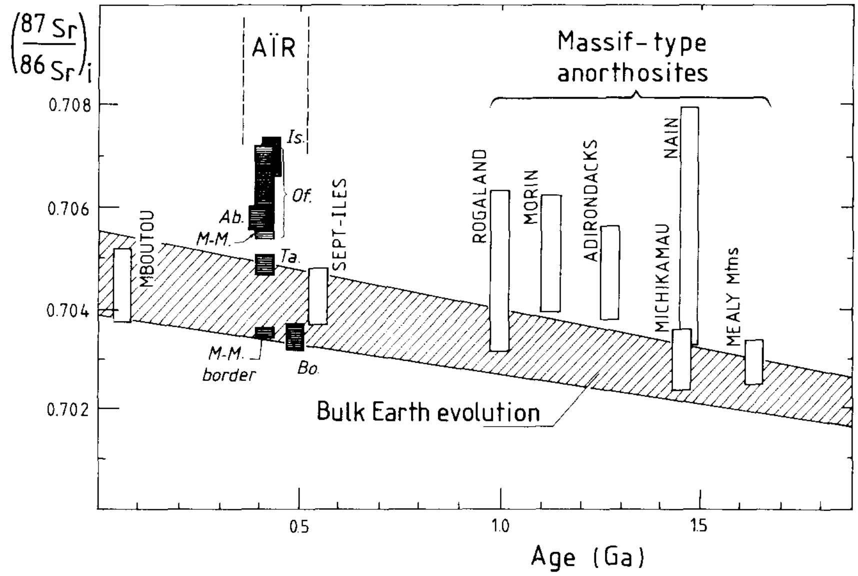

Fig. 5. Initial strontium isotopic ratios of the basic rocks (calculated on the basis of the whole-rock-isochron ages of the felsic rocks) vs. time for complexes in Aïr. *Bo*: Bous; *M-M*: Meugueur-Meugueur (border = gabbroic marginal facies); *Ta*: Tagueï; Ab: Abontorok; *Of*: Ofoud; *Is*: Iskou. Comparison with North Atlantic Proterozoic massif-type anorthosites (from [3], modified) and the Tertiary Mboutou intrusion, Cameroon [22].

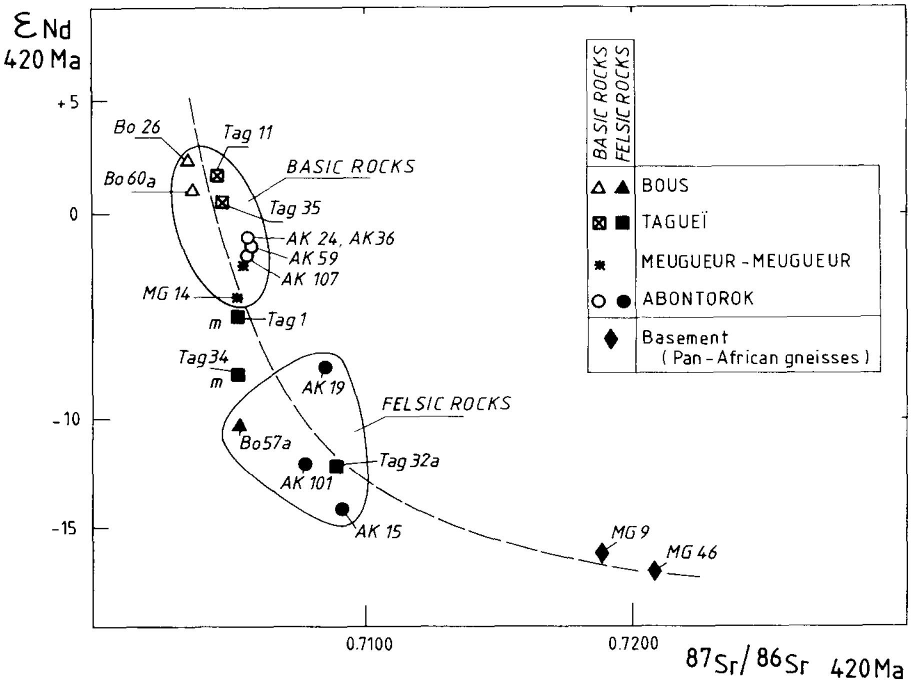

Fig. 6. $\epsilon_{Nd}(t)$ versus initial strontium isotopic ratios of the leucogabbroic and felsic rocks from Aïr compared to two samples of Pan-African basement from near the Meugueur-Meugueur ring dyke. *m* corresponds to the Tagueï monzo-anorthosites. The dashed line represents an hypothetical mixing hyperbola between a slightly-depleted mantle-derived magma and crustal material (Pan-African gneisses).

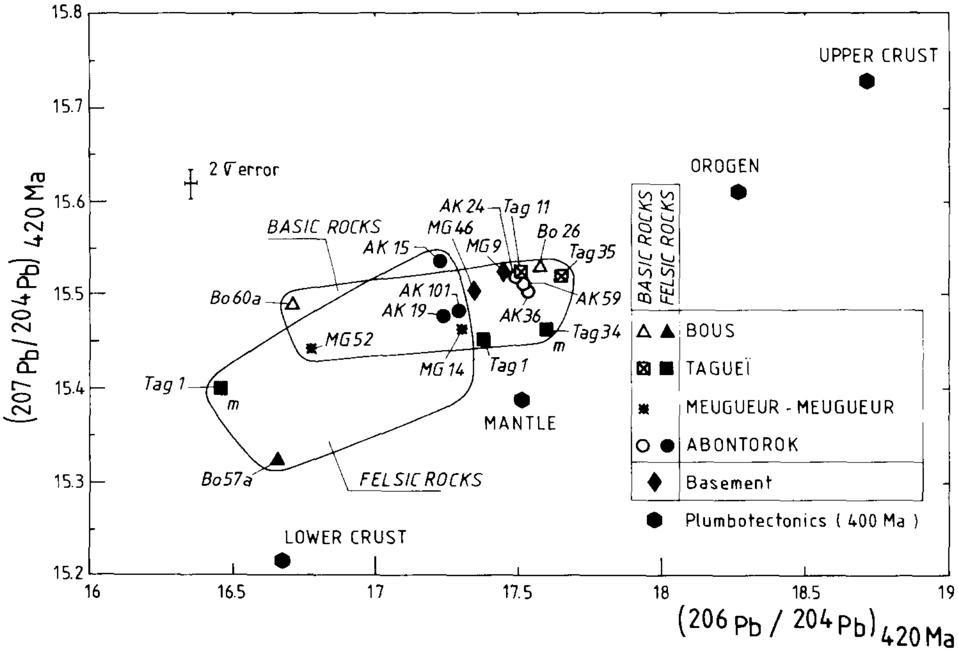

Fig. 7. $(^{207}Pb/^{204}Pb)_i$ versus $(^{206}Pb/^{204}Pb)_i$ isotopic initial ratios calculated at −420 Ma for the basic and felsic rocks from Aïr compared with points for upper crust, lower crust, mantle and orogen from the Plumbotectonics model [45].

plexes (400–487 Ma), the $\epsilon_{Nd}(t)$ values of the surrounding granitic gneisses would have been even more negative: -17 ± 1.

The measured Pb isotopic compositions, as well as the U and Pb concentrations determined by isotope dilution, are given in Table 4. The measured compositions for the basic rocks fall in the range: $^{206}Pb/^{204}Pb$: 17.76 to 18.47; $^{207}Pb/^{204}Pb$: 15.49 to 15.59; $^{208}Pb/^{204}Pb$: 37.91 to 38.74. The initial Pb compositions for the basic rocks plot within a narrow range with $(^{206}Pb/^{204}Pb)_i = 16.7$ to 17.8 and $(^{207}Pb/^{204}Pb)_i = 15.45$ to 15.53 (Fig. 7). The initial Pb isotopic compositions of felsic rocks spread towards less radiogenic values down to 16.4 and 15.3 for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, respectively.

6. Discussion

Field relationships and petrographic and geochemical data show unambiguously that the anorthosites and related leucogabbros and leucotroctolites are cumulate rocks, plagioclase being the only cumulus mineral, except in the troctolites and melatroctolites of Meugueur-Meugueur where it is olivine. Chilled gabbroic to microgabbroic facies have been found sporadically at the contacts of each intrusion. The alkaline affinity of these gabbros is shown by the alkali/silica ratios, the absence of low-Ca pyroxene (except for Meugueur-Meugueur), high TiO_2 (> 0.8% in most samples) and P_2O_5 (usually > 0.5%) contents and the general richness in incompatible trace elements. These possible congealed liquids have rather low MgO contents, in the range 3.5 to 9% (except for the facies from Tagueï with 11% MgO) and consequently low 100 MgO/(MgO + FeO_{tot}) values, usually lower than 30. Transition-element contents are also low (< 150 ppm Ni, < 120 ppm Cr). If the primary parental magmas which gave rise to the anorogenic complexes were in equilibrium with typical upper mantle minerals, the low Mg, Cr and Ni contents imply that the analysed gabbros were not primary liquids, but must have already fractionated large amounts of olivine and pyroxene [8]. Moreover, the high Al_2O_3/CaO ratios (1.8–2.4) of these samples (except for the marginal rocks from Tagueï and Meugueur-Meugueur and one sample from Bous) combined with their high Sr contents (> 600 ppm) and the lack of a negative Eu anomaly clearly demonstrate that plagioclase was not among the first minerals to fractionate, or did not fractionate at all.

Although some overlapping occurs, it appears that each intrusion has a distinct isotopic signature, as shown by the Nd–Sr isotopic data (Fig. 6) for the basic rocks (cumulates and marginal gabbros), which could have been produced from distinct batches of mantle-generated magma, each with its own isotopic composition. This could result:

(1) either from heterogeneities of the source region which could have had OIB-type characteristics: slightly depleted with $(^{87}Sr/^{86}Sr)_i < 0.705$ and positive (+2.6 to +0.6) $\epsilon_{Nd}(t)$ values for Bous and Tagueï, to slightly enriched with $(^{87}Sr/^{86}Sr)_i$ values of 0.705–0.707 and negative (−1 to −4.2) $\epsilon_{Nd}(t)$ values for Abontorok, Ofoud and Meugueur-Meugueur;

(2) or from various degrees of crustal contamination of a slightly depleted mantle-derived OIB-type magma. The second hypothesis is favoured because these high-level (subvolcanic) intrusions were emplaced in a 30–35 km thick Precambrian crust [39,40]. Moreover, Nd and Sr isotopic data on late Tertiary to Quaternary alkali basalts, basanites and nephelinites from the Ahaggar shield [41] and from the Cameroon Line [42] show that the mantle beneath the northwestern portion of the African Continent had depleted features with $(^{87}Sr/^{86}Sr)_i$ in the range 0.7029–0.7035 and positive (+2 to +7) ϵ_{Nd} values at those times. In addition, the Tadhak alkaline ring complex (Mali) has an initial $(^{87}Sr/^{86}Sr)_i$ ratio of 0.70457 at 270 Ma together with mantle Pb signatures [43]. The mantle beneath the Aïr province, which is the southeastern extension of the Ahaggar shield, may also have shown this slightly depleted signature during the Paleozoic.

The isotopic composition of the Bous magma, especially the low Sr initial ratio $[(^{87}Sr/^{86}Sr)_i = 0.7035]$ and the positive $\epsilon_{Nd}(t)$ values, is thus compatible with a slightly depleted mantle source region without significant crustal influence. It is interesting to observe that this most northerly intrusion of the Aïr province was intruded at the boundary between the Precambrian basement and its Paleozoic cover. Moreover, the Bous area is characterized by a well defined positive gravity anomaly (25 to 30 mgals [44]), which has been related to the existence of ultramafic rocks close to the main Aïr fault. For the other intrusions, the contamination process is not progressive during the differentiation process. Indeed, the Sr isotopic initial composition of 10 cumulates from the Abontorok laminated intrusion is constant at 0.70582 ± 0.00004 (2σ) [14] and the $\epsilon_{Nd}(t)$ values are also constant at -1.5 ± 0.5. Thus, an assimilation-fractional crystallization (AFC) process did not operate during the crystallization of the plagioclase-rich rocks.

The monzo-anorthosites from Tagueï deserve special attention. Two whole-rock samples were analysed: their initial Sr isotopic composition (0.7054) and their $\epsilon_{Nd}(t)$ values (−5 and −7.9) are significantly higher and more negative, respectively, than those of the other basic rocks from the same intrusion (0.7048 and +0.6 to +1.8). These isotopic values are intermediate (see Fig. 6) between those of the gabbro and the granitic dyke (−12.2). The same type of relation is observed for the Pb isotopic data. These monzo-anorthosites may be interpreted as hybrid rocks with cumulus plagioclase and an infiltrated granitic intercumulus liquid, as suggested by [12] on textural, petrological and trace-element geochemical data.

Initial Pb isotopic compositions of the basic rocks do not show a large spread in a $(^{207}Pb/^{204}Pb)_i$–$(^{206}Pb/^{204}Pb)_i$ diagram. The $^{238}U/^{204}Pb$ (μ_1) values deduced from these compositions fall in a narrow range 7.99–8.15 which is very close to model mantle values at 400 Ma. However, the average $(^{207}Pb/^{204}Pb)_i$ ratio is close to 15.5 which is slightly higher than the 400 Ma mantle value (15.39) of the Plumbotectonics model [45]. This slightly higher value might reflect the influence of an old crustal component; it is interesting to observe that the Pb isotopic composition, at 400 Ma, of the two analysed granitic gneisses are comparable to those of the basic rocks.

The syenites and granites (some of them are peralkaline) have high Sr isotopic initial ratios, from 0.7084 up to 0.7138 and strongly negative $\epsilon_{Nd}(t)$ values (−7.5 down to −14.4) which means that these rocks are not purely comagmatic with the basic rocks. Such isotopic compositions reflect a strong crustal influence. However, the presently exposed metamorphic country rocks display more extreme isotopic composition, with $(^{87}Sr/^{86}Sr)_{400\ Ma}$ of ~0.720 and $\epsilon_{Nd}(t)$: −17. They cannot be considered as suitable source

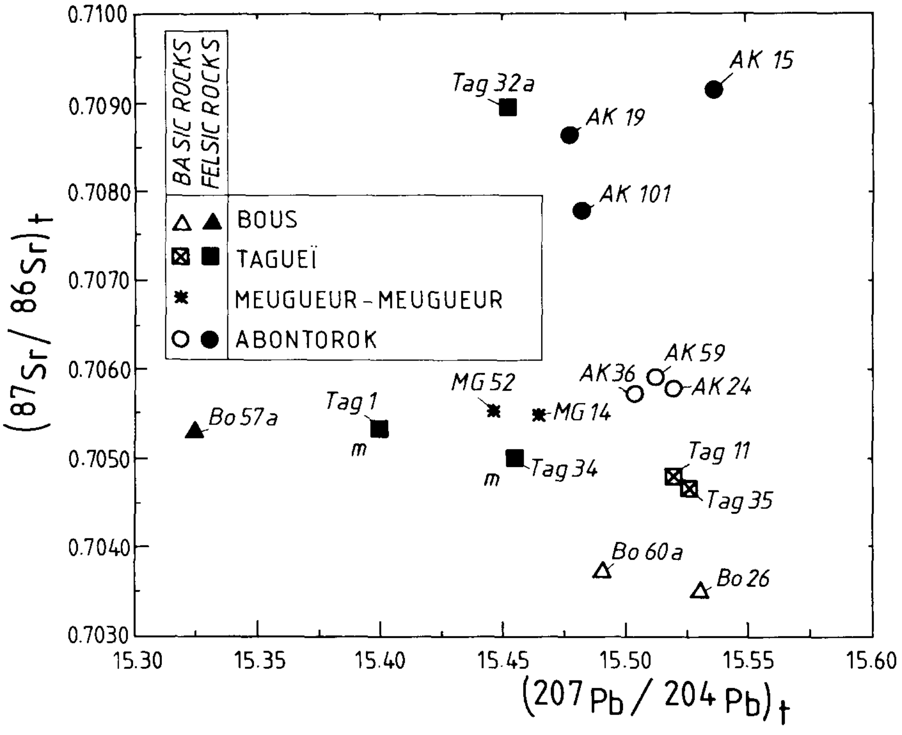

Fig. 8. ($^{207}Pb/^{204}Pb$) versus ($^{87}Sr/^{86}Sr$) initial ratios for the different intrusions suggesting two possible contamination trends.

material to generate the granites and syenites by partial melting. In an Nd–Sr diagram, data points for Abontorok and Tagueï define mixing hyperbolae, the extreme members being the basic rocks on the one hand and the country rocks on the other hand. However, with our data alone, one cannot rule out the possibility that the basic rocks themselves have already been contaminated. In that hypothesis, the primary uncontaminated basic magma would have a more depleted isotopic signature. The granites and syenites could then tentatively be interpreted as resulting from the mixing of the residual liquid of the basic magma and an anatectic crustal melt. Alternatively, if, as suggested by [34], A-type granites result from partial melting of F- and/or Cl-rich dry granulite-facies rocks, the Aïr granites and syenites could be interpreted as anhydrous partial melts generated at deep levels in the continental crust.

In a Pb–Pb diagram (Fig. 7) the syenites and granites show less radiogenic compositions than the basic rocks, with ($^{206}Pb/^{204}Pb)_i$ and ($^{207}Pb/^{204}Pb)_i$ ratios down to 16.4 and 15.3, respectively. These data show the influence of U-depleted, relatively unradiogenic lower crustal material. The analysed gneisses do not represent a suitable source material for the granites and the syenites.

In an initial $^{207}Pb/^{204}Pb$–$^{87}Sr/^{86}Sr$ diagram (Fig. 8), the samples from Abontorok, Tagueï and Bous roughly display negative correlations, that is decreasing ($^{207}Pb/^{204}Pb)_i$ for increasing ($^{87}Sr/^{86}Sr)_i$. These correlations could indicate contamination trends of a basic magma with U-depleted lower crustal material for Bous and Tagueï and less depleted (both in U and Rb) material for Abontorok.

7. Conclusions

The anorogenic ring complexes of the Aïr are characterized by the abundance of plagioclase cumulates (anorthosite, leucogabbro and leucotroctolite) with subordinate amounts of syenite and granite occurring as thin ring dykes, central plugs or septa at the contact with country rocks. The general petrography and geochemistry of these rocks are similar to those of Proterozoic massif-type anorthosites, the importance of olivine and the An content (67–56) of the cumulus plagioclase in the Aïr anorthosites–leucotroctolites making them more comparable to the Labrador type (leucotroctolite dominant) than to the Grenville type which is characterized by orthopyroxene and a less basic plagioclase near An_{50} (leuconorite) [2].

A high-level emplacement (subvolcanic environment) was demonstrated for the Abontorok intrusion [14] and, by extension, is probably applicable to all the other intrusions: the main arguments are the very thin (0.1 m) thermal aureole around the small Abontorok intrusion (2.6 km diameter), the high Ca and Mn (0.3 to 0.7%) contents of the olivine and the composition and type of feldspars. The pressure was estimated to have been 1.2 ± 0.5 kb. Contact metamorphism is slightly greater around the large intrusions like Ofoud, which may have induced slight brittle to ductile deformation of the contact rocks [10]. On a regional scale a Caledonian (?) uplift occurred in the Aïr massif which produced erosion of the Ordovician cover and transgression of the lower Devonian onto the basement [46,47]. The emplacement of the ring complexes can be considered to have occurred just after the uplift during distension related to a transtensional regime with rejuvenation of Precambrian structures [48]: this interpretation implies strong structural control of the crust during emplacement. The anorogenic mode of emplacement of the Aïr ring complexes and their undeformed nature make them more comparable to the Labrador-type than to the Grenville-type massif anorthosites. The mineralogical differences between Ofoud- and Grenville-types could possibly be related to a pressure difference at the final emplacement level [2].

The alkaline affinity of the Aïr magmatic differentiation series has been demonstrated on the basis of the mineralogical, petrographical and geochemical (alkali/silica ratios, abundance of incompatible trace elements, etc.) features of the gabbroic chilled facies. The mineralogical composition (cumulus and intercumulus minerals) of the Aïr basic rocks, in particular their troctolitic affinity (plag + ol; plag + ol + cpx) is comparable to the cumulus assemblages [49] for the gabbroic Tugtutôq giant dyke of the Gardar Province (South Greenland), which resulted from the fractional crystallization of an alkali magma at different stages (alkali olivine basalt, hawaiite, mugearite).

The isotopic signature of the most primitive intrusion (the Bous layered complex), especially the low Sr initial ratio [$(^{87}Sr/^{86}Sr)_i = 0.7035$] and the positive $\epsilon_{Nd}(t)$ values, implies a slightly depleted mantle source, comparable to an OIB source or a more depleted source if the basic rocks were already contaminated. The Pb isotopic composition (a slightly high $^{207}Pb/^{204}Pb$ ratio) might indicate that this magma had interacted with crustal material. The other intrusions (the small Abontorok and Tagueï bodies, the large Ofoud massif and the Meugueur-Meugueur mega ring dyke) all show obvious signs of crustal contamination with $(^{87}Sr/^{86}Sr)_i$ as high as 0.707 and $\epsilon_{Nd}(t)$ down to -4.2. For the basic-rocks, the samples showing the highest crustal contamination are also the ones with the strongest alkaline affinity. The mantle-derived magma could have experienced extensive fractionation of olivine and pyroxene which reduced its Mg number, probably in the lower crust or at the crust–mantle interface, during an early stage of magma ponding. Alternatively, Olson and Morse [50] proposed that the Fe enrichment in gabbros and troctolites associated with the Adirondack anorthosites reflects an Fe-rich source. Contamination may have taken place when the already differentiated magma (low Mg number) rose through the continental crust to its final emplacement level. Extensive crystallization of plagioclase probably started during uprise of the magma and its accumulation took place at a higher level in the crust. The alkali syenites and granites, whatever their exact mode of formation, were intruded after the more or less complete crystallization of the plagioclase-rich cumulates, along the same conduits as the ones used by the basic magmas.

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