Contrib Mineral Petrol (1990) 104:163–172

Contributions to Mineralogy and Petrology

Meta-igneous origin of Hercynian peraluminous granites in N.W. French Massif Central: implications for crustal history reconstructions

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Abstract. Seventy samples of Hercynian peraluminous granites (Guéret, Millevaches and Saint Sylvestre massifs) and metamorphic units of the Limousin area were analysed for Rb – Sr and Sm – Nd. The source rocks of the peraluminous granites can be found in the metamorphic rocks of Limousin, among them meta-igneous rocks were largely predominent over meta-sedimentary rocks in the source of the three granites. Millevaches and Guéret granites were generated by the partial melting of rocks comprising meta-volcanics and meta-sediments, whereas the Saint Sylvestre granite was produced exclusively by the melting of late Precambrian granites. This leads to confusing T_{DM}^{Nd} values, the confusion being amplified by the segregation of monazite during the petrogenetic evolution of the peraluminous granites, which leads to dramatic fractionation in Sm/Nd ratios. The data of the present study tend to demonstrate that peraluminous granites do not give a good representation of isotopic mean crustal estimates. Late Precambrian time seems, however, to have been a period of extensive crustal generation in Western Europe.

Introduction

Peraluminous granites are generally considered to be generated through partial melting of upper crustal rocks, especially during continent-continent collisional events (e.g. Le Fort 1975, 1981), but also occur at active margins. By reference to the S-type of Chappel and White (1974), the genesis of such granites in intra-continental situations is attributed to the melting of pelitic sediments, and, by analogy with the shale geochemical model (e.g. Taylor and McLennan 1984), peraluminous granites may be tentatively considered to sample a mean isotopic estimate of the continental crust. This point of view seems to be widely accepted by isotope geochemists, contrasting with the problem of I-type granite genesis, which in most aspects remains problematic (e.g. McCulloch and Chappel 1982; Hensel et al. 1985; Liew and McCulloch 1985; Juteau et al. 1986).

This apparent simplicity needs, however, to be assessed by a case study investigating both aluminous granites and their possible source rocks in a well-known area. Pelitic sediments are not so common in the upper crust, and the partial melting of meta-igneous rocks could equally well generate peraluminous melts. The ubiquitous presence of ophiolitic and calk-alkaline granitoid remnants within collisional orogens indicates that most of these orogens were preceded by active margin episodes, and thus peraluminous rocks can be considered as having been "contaminated" by segments of newly accreted crust in the form of igneous rocks. This contamination could lead to an apparent rejuvenation of isotopic charcteristics of upper crustal granitoids, consequently the question of how representative peraluminous granitic magmas are as "mean crust samplers" could be considered.

This problem is particularly well illustrated in the Hercynian orogen. Hercynian peraluminous granites generally have low initial $^{87}Sr/^{86}Sr$ (compared with the evolution of the $^{87}Sr/^{86}Sr$ ratios of potential source rocks, the so-called Sr paradox; Vidal et al. 1981) and high $^{143}Nd/^{144}Nd$ ratios, but their Pb isotope patterns are indicative of a long residence time for their source rocks, and they sometimes contain zircons which yield Archean to mid-Proterozoic upper intercept ages (e.g. Michard-Vitrac et al. 1981; Bernard-Griffiths et al. 1985; Kober and Lippolt 1985; Peucat et al. 1988). Liew and Hoffmann (1988) and Peucat et al. (1988) proposed regional evolution models involving crustal accretion at approximately 1.8 Ga, and subsequent mixing of the products of this accretion with an Archean crust (approx. 2.5 Ga) and lower Paleozoic crust (approx. 0.5 Ga), but the "mixing" mechanisms are not considered.

In a comprehensive study of the South Mountain Batholith (Nova Scotia), Clarke et al. (1988) reported isotopic "incompatibility" between the aluminous granitoids and their enclosing flyschoid rocks; they identified a "juvenile" component in the source of the granites. The general problem is then summarized: Hercynian granitoids have "paradoxical" isotopic characteristics in the sense that there seems to be a decoupling between the different isotopic systems, and this situation is probably due to some kind of "mixing" between reservoirs, as initially proposed by Allègre and Dars (1965).

The present study aims to identify the source rocks which possibly generated peraluminous granites, and to determine the significance of their crustal Nd residence time. It focuses on Rb – Sr and Sm – Nd systematics of the late Hercynian peraluminous granites and the enclosing metamorphic units of the Limousin area, in the North Western part of the French Massif Central. The outcropping metamorphic units comprise both meta-igneous and meta-sedimentary rocks which have locally reached anatexis.

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Geological setting

The metamorphic series of Limousin consists of the stacking of five units (Floc'h 1983), respectively from bottom to top: (a) the "Dronne" unit, with predominent metapelites and subordinate metagranites; (b) the "Lower gneiss unit", with abundant metagranites dated at 530–450 Ma (data and references in Duthou et al. 1984) and meta-graywackes/meta-pelites; (c) The "Upper gneiss unit", consisting of meta-graywackes including eclogite and granulite remnants, and locally ultramafic slices; (d) the "Thiviers-Payzac" unit, which comprises calcalkaline volcanics and sediments metamorphosed in mesozonal conditions; (e) the epizonal "Genis" unit characterized by marine sediments associated with tholeiitic volcanic rocks. The three lower units have undergone anatexis in Eastern Limousin and may represent important contributors to the protolith of the peraluminous granites. The peraluminous granites (Fig. 1) appear as flat shearing, slab-shaped bodies, sometimes rooted in migmatitic zones. The structural study by Bouchez and Jover (1986) emphasizes the parallelism between syn-magmatic and regional fabric in late Hercynian times (predominance of flat foliations and E–W directed linear structures).

The major element geochemistry of the peraluminous granites of the French Massif Central has been investigated in detail by La Roche et al. (1980). They defined an "alumino-cafemic" (AlC), biotite- and plagioclase-rich type with cordierite, and an "alumino-potassic" (AlK), biotite-poor, muscovite-bearing type. In the present study, we focused attention on three important massifs in which both AlK and AlC types are present.

The Guéret granitic complex (4500 km^2), dated by Rb–Sr on whole rocks at approximately 355 Ma (initial $^{87}Sr/^{86}Sr = 0.7098$, Berthier et al. 1979), mainly comprises AlC types (La Roche et al. 1980; Vauchelle 1987), from granodioritic to granitic composition (SiO_2 content ranges between 60 and 70 wt.%), and locally small AlK bodies. Contrasting with typical S-type granitoids, the peraluminous character of this granite increases with differentiation. The zircon typology indicates a dominantly crustal origin (Pupin 1985).

The Millevaches massif (1000 km^2) comprises both AlC and AlK types. A biotite-sillimanite bearing granitic facies (AlC) yielded a Rb–Sr whole rock age of 357 ± 11 Ma (Augay 1979), and Rb–Sr whole rock ages at 332 ± 25 Ma were proposed for several two mica (AlK) facies (Augay 1979; Monier 1980). These measurements of dates are, however, not convincing: they present considerable scatter, and the isochron at 357 Ma could well be a mixing line if one considers the very low initial $^{87}Sr/^{86}Sr = 0.7054 \pm 0.0004$. Nevertheless, it appears from field relationships that granites of different ages are present within this complex, so the scope of our study has been restricted to the most recently emplaced two-mica subtypes and to biotite-sillimanite subtypes shown to have undergone the same deformational events (Jover 1986); samples are only from the best studied northern part of the Millevaches complex.

In the Saint-Sylvestre massif (500 km^2), the AlK type is widely predominant, AlC types occur locally. The coarse-grained two micas facies (γ_1) have been dated by U-Pb on zircon at approximately 325 Ma (Holliger et al. 1986); locally, the γ_1 granite contains cordierite in place of muscovite, and is then called γ_{1b}. AlC fine-grained granites (γ_2) are dated at approximately 310 Ma (Duthou, Leroy and Cuney, personal communication); they are biotite-rich and show magmatic contacts with γ_1. Leucocratic fine-grained granites (γ_3) sharply crosscut γ_1 and γ_2. In the vicinity of these fine-grained intrusions, mineralogical transformations such as muscovite crystallization and Li, F, Sn, U and Be enrichment appear as halos on the scale of hectometres (Friedrich et al. 1987; Monier 1987). An important characteristic of the Saint Sylvestre granite is that it contains economic U-ore hydrothermal deposits. the Millevaches complex contains small U deposits or showings, whereas no uranium deposit has yet been discovered in the Guéret massif.

Anatectic gneisses can be found as large xenoliths (kilometre-sized) in the Saint Sylvestre and Millevaches massifs, or as windows of the basement in the Guéret massif. In the Saint Sylvestre and the Guéret massifs, these gneisses have been identified as belonging to the "Lower gneiss unit" of Limousin (see above).

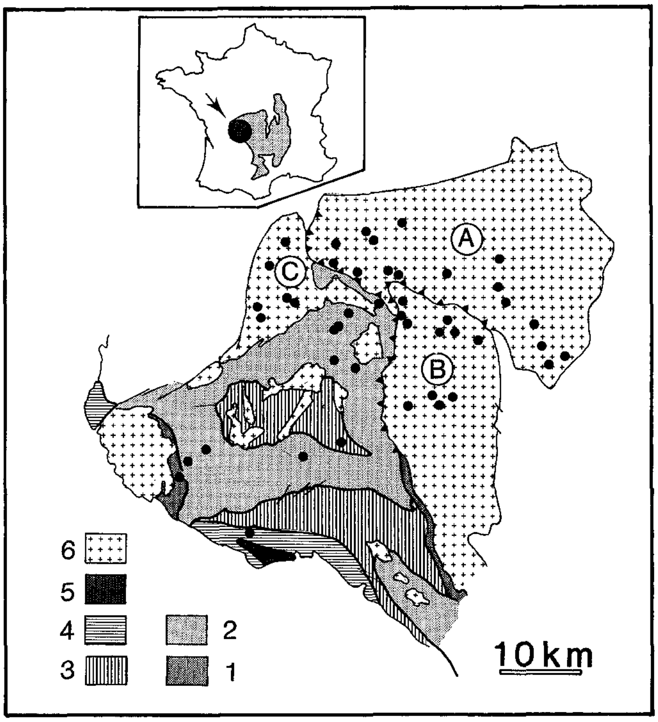

Fig. 1. Sketch map (modified after Floc'h 1983) showing the studied area and the sample locations. 1: "Dronne" Unit (unit 1); 2: "Unité des gneiss inférieurs", i.e. lower gneiss unit (unit 2); 3: "Unité des gneiss supérieurs", i.e. Upper gneiss unit (unit 3); 4: "Thiviers-Payzac" unit (unit 4); 5: "Génis" series (unit 5); 6: Hercynian granites. *A*, Guéret, *B*, Millevaches, *C*, Saint Sylvestre

Sample selection and analytical procedures

The Guéret and Millevaches granites were sampled so as to cover wide but petrographically homogeneous areas, representative of the emplacement dynamics (E–W flat magmatic structures; Jover 1986; Jover and Bouchez 1986). Small drill cores previously used for magnetic susceptibility anisotropy measurements were ground in agate mills, and in addition, seven samples of Guéret were selected from their major element characteristics so as to cover as wide a range of geochemical variation as possible. Saint Sylvestre samples were selected on the basis of a larger sampling by their major and trace element geochemical characteristics: they are designated as "two-mica coarse-grained" (γ_1), "biotite-cordierite coarse-grained" (γ_{1b}), "biotite-rich fine-grained" (γ_2) or "leucocratic fine-grained" (γ_3) (Table 1). Some of the gneiss samples were collected within the granitic bodies where they outcrop either as large xenoliths (10–100 m) or as showing evidence of having been partially molten. The other metamorphic rock samples come from the different thrust units and comprise ortho- and meta-sedimentary gneisses and schists. The metamorphic rock samples have been selected from 600 samples studied for their major and trace element characteristics by Bourguignon (1988) on their ability to produce significant amounts of minimum-melt magmas in upper crustal melting conditions: amphibolites, for instance, were discarded.

Analytical procedures are those described in Turpin et al. (1988), with the exception of the following points: all the samples were digested in closed Teflon vessels using a CEM micro-wave digestion oven (Fisher 1986). This procedure was checked by duplicating some measurements using non-destructive neutron activation analysis, and was shown to ensure a complete dissolution of REE-bearing accessory minerals; all the Nd and most of the Sr isotope compositions were determined on a 5-collector VG SECTOR mass spectrometer, which gave absolute external reproducibilities of $8.10^{-6} (2\sigma)$ on $^{143}Nd/^{144}Nd$ measurements as determined from 18 standard runs (a Johnson-Matthey Nd batch) during the course of this study, and of 2.10^{-5} (external, 2σ) on $^{87}Sr/^{86}Sr$ (NBS SRM 987=0.710283). ^{149}Sm and ^{150}Nd tracers were calibrated using reference solutions prepared from REACTON sublimed metal chips, weighed under Ar flux to avoid uptake of atmospheric nitrogen; during preparation of these reference solutions, we calculated that the correction for buoyancy is greater than 1‰ on 1 l of 2 M HCl solution, which implies that claims on 0.5‰ (or lower) absolute accuracy in Nd or Sm concentration determinations must take into account this correction. Th was determined at the C.R.P.G. (Nancy) by ICP-AES (Govindaraju et al. 1987).

Results

The analytical results are given in Table 1. Initial isotopic ratios have been calculated at 325 Ma for Saint Sylvestre γ_1 and Millevaches samples, 310 Ma for Saint Sylvestre fine-grained granites samples, and at 355 Ma for Guéret samples. The use of 325 Ma to correct the Millevaches data will be justified below. Concerning metamorphic samples, the $^{143}Nd/^{144}Nd$ and ε_{Nd} values calculated at 325 Ma are reported in Table 1, but the initial $^{87}Sr/^{86}Sr$ ratios, subject to more important variations in small time intervals, are not given. Meta-sedimentary gneisses have low, homogeneous ε^T_{Nd}, near -12, while meta-igneous gneisses have higher ε^T_{Nd}, between -2.2 and -8. All the granite samples give ε^T_{Nd} intermediate between these two ranges, but close to the ortho-gneiss characteristics. Crustal residence times, given as T^{Nd}_{DM} are between 1.08 and 1.77 Ga; their significance will be discussed below. Concerning the Saint Sylvestre results, we emphasize the high Nd and Sm abundances (up to 117 ppm Nd) in samples of the γ_2 facies, and also the large absolute variation of Nd and Sm contents. In the granite samples, $^{147}Sm/^{144}Nd$ ratios range between 0.07 and 0.13, and between 0.0986 and 0.1364 in all the gneiss samples. In granites, the $^{87}Rb/^{86}Sr$ ratios cover a wide range between 1.2 and 104.

Discussion

The problem of age correction

In spite of the care taken in sample selection, samples as old as 300 Ma may well have been subject to geochemical changes, especially those affecting the Rb/Sr ratio, which may have been modified by sub-solidus fluid migration linked, in the example of Saint Sylvestre, to the fine-grained granite intrusions at 310 Ma, or lamprophyre injection and hydrothermal alteration at approximately 300 Ma (Turpin et al., in press). Such modifications that can alter the calculation of initial $^{87}Sr/^{86}Sr$ ratios must be kept in mind when examining the results. Partly for this reason, some authors have focused on the Sm−Nd system (e.g. Patchett and Arndt 1986; Liew and Hoffmann 1988), but this may involve loss of information: the geochemistry of the Rb−Sr system is controlled by major mineral phases during granitoid genesis, and thus its evolution is closely related to the petrogenetic processes.

Limousin gneisses as possible source rocks

Peraluminous granitic magmas are generally produced by crustal anatexis. The petrogenesis of such magmas is known from experimental data either in wet melting (e.g. Winkler et al. 1975) or "dry" melting (e.g. Vielzeuf and Holloway 1988) conditions. In a comprehensive study of the Macusani glasses, Pichavant et al. (1988) demonstrated that a $_{H_2O}$ is internally controlled during the genesis of peraluminous effusive melts. Therefore, potential source rocks producing Al-rich melts must themselves be Al- and H_2O-rich: pelitic sediments may be considered to be ideal source rocks, but metagranites which occur in the Lower gneiss unit of Limousin can equally well fit petrogenetic modelling of peraluminous granites (Friedrich et al. 1988; Bourguignon 1988). Initially meta-aluminous, these granites became peraluminous, especially during green-schist facies metamorphism by Ca and/or alkali leaching (Bourguignon 1988; Marquer 1987). Moreover, these meta-granites have compositions close to that of the minimum melt, which, provided an external water supply, favours melting and magma extraction.

Figure 2 shows the Sr vs Rb contents of all the samples analysed in the present study. Partial melting paths of either meta-igneous or meta-sedimentary gneisses fit the data for all of the Saint Sylvestre samples, and most of the Millevaches samples: only a few data points for biotite granites from Millevaches and most of the Guéret samples, both of which have high Sr contents, require the participation of the fractional crystallization and crystal segregation of plagioclase and biotite, as suggested by Vauchelle (1987).

Sr and Nd isotopic data

Isotopic ratios $^{143}Nd/^{144}Nd$ (in the form of ε_{Nd} notation) and $^{87}Sr/^{86}Sr$, corrected for in situ decay, are presented in Fig. 3. At 355 Ma, meta-granites, meta-volcanic rocks and meta-sediments plot within three different, well-delimited fields: metagranites have fairly constant ε_{Nd} between -6 and -8 (with the exception of a plagioclase-rich orthogneiss at -2.4), and $^{87}Sr/^{86}Sr$ ratios dispersed toward highly radiogenic values, due to the abundance of Rb relative to Sr commonly observed in evolved granitic rocks. Meta-sediment data plot at low ε_{Nd} (-13 to -12) and medium $^{87}Sr/^{86}Sr$ (0.715–0.722). Meta-volcanic rocks have comparatively high $\varepsilon_{Nd}(\cong -2$ to $-5)$ and low $^{87}Sr/^{86}Sr(\cong 0.707)$. These fields are slightly displaced at 325 and 312 Ma, but keep their relative positions due to similar Sm/Nd ratios and moderate Rb/Sr ratios. The data from Downes and Duthou (1988) on metamorphic rock samples collected from a wider area also evidence this difference between ortho- and meta-sedimentary rocks.

The correction of Millevaches data at approximately 330 Ma yields scattered points, but when corrected at 325 Ma (the same age as Saint Sylvestre Massif) the data fit a near-hyperbolic distribution suggestive of mixing between a meta-volcanic rock and a meta-sedimentary component (Fig. 3), except for one sample (MLA 47) which plots in the meta-granite field. As this sample was run in duplicate, the result cannot be considered as an artefact, and the existence of a meta-granite component as the source of Millevaches granite cannot be excluded. Both biotite granite and cordierite-garnet granite data are randomly distributed along the hyperbole, which rules out the possibility of a batch mixing between two different magmas: the different facies are probably produced by different melting conditions of a mixed source.

The Guéret data, corrected at 355 Ma, plot in an intermediate field between a meta-volcanic and a meta-sedimentary component. Data points are more tightly grouped than in the case of Millevaches, but they also define a kind of

Table 1. Rb–Sr and Sm–Nd results

No.	Nature	Th	Rb	Sr (ppm)	Sm	Nd	$^{87}Rb/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{87}Sr/^{86}Sr$		$^{143}Nd/^{144}Nd$		T_{DM}^{Nd} (Ga)
									p.d.	initial	p.d.	ε_{Nd}^{i}	
Saint Sylvestre													
8643	γ_3	6.8	532.9	20.45	1.336	6.57	78.00	0.1231	1.055300	0.708962[a]	0.512118	−7.25[a]	1.53
3132	γ_3	2.2	313.8	78.25	1.026	4.94	11.67	0.1269	0.760485	0.709000[a]	0.512287	−4.13[a]	1.32
1354	γ_2	35	548.0	86.65	8.300	64.46	18.44	0.0787	0.784321	0.702443[a]	0.512042	−6.96[a]	1.14
1355	γ_2	61	432.6	115.27	13.380	116.80	10.92	0.0700	0.757383	0.708896[a]	0.512005	−7.34[a]	1.11
B61	γ_1	4.6	361.0	66.00	1.978	9.17	15.97	0.1305	0.805471	0.731599	0.512010	−9.54	1.83
3134	γ_1	27	446.9	75.06	6.070	33.31	17.37	0.1114	0.787470	0.707122	0.512139	−6.23	1.34
8130	γ_1	6	502.9	14.45	1.786	8.36	104.16	0.1292	1.181750	0.699941	0.512137	−7.01	1.60
8185	γ_1	10.5	551.3	44.05	2.732	13.58	37.05	0.1221	0.874179	0.702798	0.512113	−7.18	1.52
3133	γ_1	42	431.9	64.54	7.111	45.45	19.54	0.0956	0.794568	0.704182	0.512019	−7.91	1.32
8229	γ_1	11	353.6	56.04	3.472	19.06	18.68	0.1102	0.792051	0.705644	0.512136	−6.24	1.33
8166	γ_1	21	353.9	54.91	5.450	27.26	19.08	0.1209	0.793311	0.705053	0.512222	−5.00	1.34
3137	γ_1	43	196.8	86.68	11.900	63.33	6.721	0.1137	0.760956	0.729867	0.512120	−6.69	1.40
C4	γ_1	48	–	–	8.498	50.86	10.22	0.1011	0.756223	0.708949	0.512103	−6.50	1.27
B33	γ_1	51	474.0[b]	106.00[b]	9.760	62.76	12.98	0.0941	0.775586	0.715545	0.512073	−6.80	1.24
L12-11	γ_1	50	324.0[b]	90.00[b]	10.09	57.43	10.44	0.1063	0.755260	0.706968	0.512122	−6.35	1.31
L12-6	γ_1	46	317.8	97.90	8.260	49.35	9.44	0.1048	0.757418	0.713742	0.512148	−5.78	1.26
8190	γ_1	75	364.0[b]	103.00[b]	11.800	75.81	10.29	0.0942	0.754121	0.706523	0.512179	−4.73	1.11
84-101	γ_{1b}	–	347.5	142.04	7.248	35.91	7.24	0.1221	0.739697	0.706207	0.512173	−6.01	1.43
84-102	γ_{1b}	–	201.1	140.50	6.029	28.19	4.24	0.1294	0.732315	0.712702	0.512142	−6.92	1.60
Saint Sylvestre enclaves:													
L342	Orthogneiss	10.5	248.4	79.59	1.940	10.12	9.27	0.1160	0.760758	0.717878	0.512197	−5.29	1.32
83-127	id.	–	270.6	93.81	4.397	21.77	8.57	0.1222	0.751381	0.711739	0.512178	−5.92	1.43
84-100	id.	–	257.7	164.80	3.856	19.86	4.63	0.1174	0.729504	0.708087	0.512154	−6.18	1.40
82-49	id.	13.4	383.0	86.44	9.179	45.57	13.12	0.1218	0.767048	0.706359	0.512134	−6.76	1.49
86-50	id.	19	334.5	98.91	3.534	17.95	10.01	0.1191	0.754606	0.708303	0.512131	−6.70	1.45
82-138	id., biotitic restite	108	341.6	126.30	12.917	80.89	8.01	0.0966	0.746018	0.708966	0.511947	−9.36	1.42
84-103	Paragneiss	–	164.5	104.70	6.944	37.92	4.65	0.1108	0.738621	0.717112	0.511832	−12.20	1.75
Guéret													
30A	Biotite granite	–	216.4	364.40	5.830	31.17	1.72	0.1131	0.717664	0.708849	0.512163	−5.39	1.33
101A	id.	–	217.1	239.20	4.940	29.77	2.63	0.1004	0.724490	0.711011	0.512103	−5.98	1.27
43A1	id.	–	235.0	224.70	5.140	31.76	3.03	0.0979	0.724830	0.709301	0.512114	−5.65	1.23
28A	id.	–	181.4	397.00	3.290	23.87	1.32	0.0833	0.717581	0.710816	0.511962	−7.96	1.26
38-76	id.	–	208.3	337.60	5.261	33.91	1.79	0.0938	0.718952	0.709778	0.512044	−6.83	1.27
86B2	id.	–	96.8	133.50	3.485	20.00	2.10	0.1054	0.721481	0.710718	0.512092	−6.42	1.33
5	id.	–	159.4	281.90	5.335	30.90	1.638	0.1044	0.719337	0.710942	0.512080	−6.61	1.34
94	id.	–	233.2	206.80	4.560	26.79	3.268	0.1030	0.726425	0.709676	0.512098	−6.20	1.30
33	id.	–	248.6	274.20	5.100	31.39	2.628	0.0983	0.722069	0.708600	0.512116	−5.63	1.23
H87	id.	–	205.1	411.10	7.335	43.63	1.477	0.1017	0.717616	0.710046	0.512103	−6.04	1.28
H89	id.	–	192.7	354	6.12	35.96	1.613	0.1029	0.717344	0.709077	0.512114	−5.88	1.28
H100	id.	–	212.5	219.8	4.059	21.59	2.86	0.1137	0.724980	0.710322	0.512087	−6.90	1.44
H101	id.	–	223.2	213.6	4.48	24.52	3.095	0.1105	0.725509	0.709648	0.512081	−6.87	1.41
H148	id.	–	166.1	260.8	5.67	32.05	1.887	0.1070	0.720261	0.710590	0.512020	−7.90	1.45
H211	id.	–	175.9	326.4	7.16	42.35	1.596	0.1023	0.718500	0.710320	0.512059	−6.93	1.34
H216	id.	–	214.2	116.86	2.695	14.53	5.428	0.1122	0.737323	0.709504	0.512049	−7.57	1.48

Millevaches													
47	Biotite granite	–	236.5	287.64	7.642	48.35	2.386	0.0956	0.732812	0.721775	0.512150	−5.36	1.16
56	id.	–	208.6	158.95	4.366	27.32	3.806	0.0967	0.727129	0.709524	0.512136	−5.68	1.19
106	id.	–	167.5	398.00	4.093	26.26	1.219	0.0943	0.714309	0.708670	0.512171	−4.89	1.12
121A1	id.	–	232.4	157.17	2.180	10.50	4.293	0.1256	0.735759	0.715901	0.512050	−8.56	1.68
179	id.	–	280.9	188.22	8.877	50.25	4.329	0.1069	0.729421	0.709396	0.512114	−6.53	1.32
21C	id.	–	243.4	213.02	3.904	22.11	3.313	0.1068	0.725838	0.710513	0.512115	−6.51	1.32
11	Cordierite-garnet gr.	–	163.5	189.14	2.907	17.33	2.508	0.1015	0.730728	0.719127	0.511963	−9.25	1.45
24	id.	–	150.5	115.97	4.050	24.05	3.793	0.1019	0.729653	0.712108	0.512082	−6.94	1.31
52	id.	–	182.8	109.90	2.382	13.34	4.827	0.1080	0.734620	0.712292	0.512067	−7.49	1.40
97	id.	–	254.0	38.62	0.464	2.29	19.20	0.1224	0.793903	0.705090	0.512118	−7.10	1.52
146	id.	–	202.0	184.43	3.552	21.08	3.175	0.1019	0.724458	0.709772	0.512147	−5.68	1.23
Mi92	Kinzigite	–	314.2	165.40	6.035	39.16	5.64	0.0932	0.741863	0.715774	0.511919	−9.77	1.41
Gneiss units													
Me6	Paragneiss, unit 1	14.1	154.5	94.65	9.009	52.79	4.831	0.1032	0.744906	–	0.511947	−9.64	1.49
122	Paragneiss, unit 2	–	152.8	83.98	7.995	49.07	5.387	0.0986	0.742744	–	0.511791	−12.49	1.63
B17	id.	–	108.8	191.45	5.501	31.77	1.683	0.1044	0.723645	–	0.511769	−13.16	1.74
A16	id.	17.9	165.9	201.67	9.045	54.46	2.439	0.1005	0.727482	–	0.511857	−11.28	1.57
γ63	id.	9.8	129.1	127.90	5.369	28.88	2.990	0.1124	0.729821	–	0.511839	−12.13	1.77
γL12	id.	14.1	121.3	251.62	2.630	14.69	1.427	0.1083	0.722490	–	0.511839	−11.96	1.71
151	Orthogneiss, unit 2	–	121.4	184.36	9.650	53.57	1.949	0.1090	0.721561	–	0.512058	−7.71	1.42
152	id.	–	160.5	78.21	5.098	24.40	6.073	0.1264	0.748181	–	0.512124	−7.14	1.58
755	id.	34.8	233.1	61.49	11.980	64.91	11.22	0.1116	0.771812	–	0.512140	−6.22	1.34
1157	id.	25	206.3	54.12	4.730	22.13	13.534	0.1293	0.792152	–	0.512139	−6.97	1.60
γ150	Orthogneiss, unit 3	10.2	103.0	270.90	2.708	13.73	1.126	0.1193	0.713234	–	0.512350	−2.44	1.13
80-11	Meta-tuff, unit 4	–	41.2	158.99	2.966	15.79	0.770	0.1136	0.711325	–	0.512349	−2.22	1.08
15	id.	13.5	115.6	74.35	5.142	22.80	4.604	0.1364	0.727540	–	0.512256	−4.98	1.52
13	Meta-sediment, unit 5	17.2	176.5	151.04	7.903	50.48	3.459	0.0947	0.735320	–	0.511830	−11.57	1.53

Saint Sylvestre, Millevaches, gneiss units: isotopic ratios corrected back to 325 Ma excepted: [a] corrected back to 310 Ma and Guéret (corrected back to 355 Ma). Abbrevations: *gr*, granite; γ_1, γ_{1b}, γ_2, γ_3 refer to the classification described in the text. Gneiss units quoted from 1 to 5: see Fig. 1. [b] Isotope dilution determination by Duthou (unpubl.)

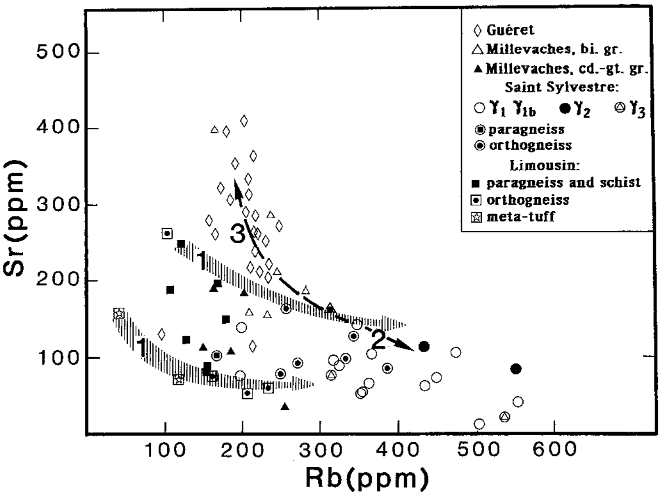

Fig. 2. Sr — Rb distribution. Arrows denoted 1 are equilibrium partial melting paths; arrows 2–3 fractional crystallization paths (2: evolution of the melt; 3: evolution of the residual solid), partition coefficients taken from Hanson (1978). Data from Berthier et al. (1979) have been added. Discussion in text

mixing trend. Batch mixing calculations indicate that the meta-igneous terms was predominant over the meta-sedimentary term at the source of this granite.

Saint Sylvestre data show a restricted range in ε_{Nd}, near -7, and a dispersion in $^{87}Sr/^{86}Sr$, a distribution which overlaps the field defined by meta-granite data, both from the present study and from Downes and Duthou (1988). Although metasedimentary xenoliths ($\varepsilon_{Nd} \cong -13$, sample 84–103) are present in the Western part of the massif, none of the investigated samples have initial $\varepsilon_{Nd} < -8$. An additional problem comes from the reworking of the Rb — Sr system at approximately 310 Ma in relation with the intrusion of γ_2 and γ_3 granites, which leads to an additional scatter in apparent initial Sr isotope ratios. The crystallization of phengite has been observed in some samples (indicated by arrows in Fig. 3), and this probably caused a partial redistribution of the Rb — Sr system.

If the dispersion in $^{87}Sr/^{86}Sr$ could be in part attributed to this event, it is possible that the initial ratios of some samples were as high as 0.730, indicative of source rocks having had high Rb/Sr ratios. The study of metamorphic rocks shows that only meta-granites have $^{87}Sr/^{86}Sr$ ratios compatible with those observed in Saint Sylvestre, and also a restricted range in ε_{Nd} (between 6.2 and 7.7) in good agreement with the range defined by Saint Sylvestre samples.

The characteristics of the three aluminous granite massifs investigated can be summarized as follows: meta-igneous components have been identified in the sources of these three massifs, possibly acid meta-volcanics in Millevaches and Guéret, meta-granites in Saint Sylvestre. Metasediments also participated in the genesis of Millevaches and Guéret, but not in Saint Sylvestre. As suggested by their strong isotopic heterogeneity, Millevaches and Saint Sylvestre magmas were not homogenized before emplacement, as observed in the Manaslu granite of the Himalaya by Deniel et al. (1987). From the isotopic measurements of the present study, it appears that the three granitic complexes may have been generated through partial melting of upper crustal rocks similar to those which outcrop in the Limousin, which is consistent with the regional reconstruction proposed by Friedrich et al. (1988).

The data from the present study also emphasize the poor reliability of the Rb — Sr isotopic chronometer: Saint Sylvestre and Millevaches granites appears as strongly heterogeneous in initial $^{87}Sr/^{86}Sr$, and additional disturbance problems occurred in the Saint Sylvestre massif.

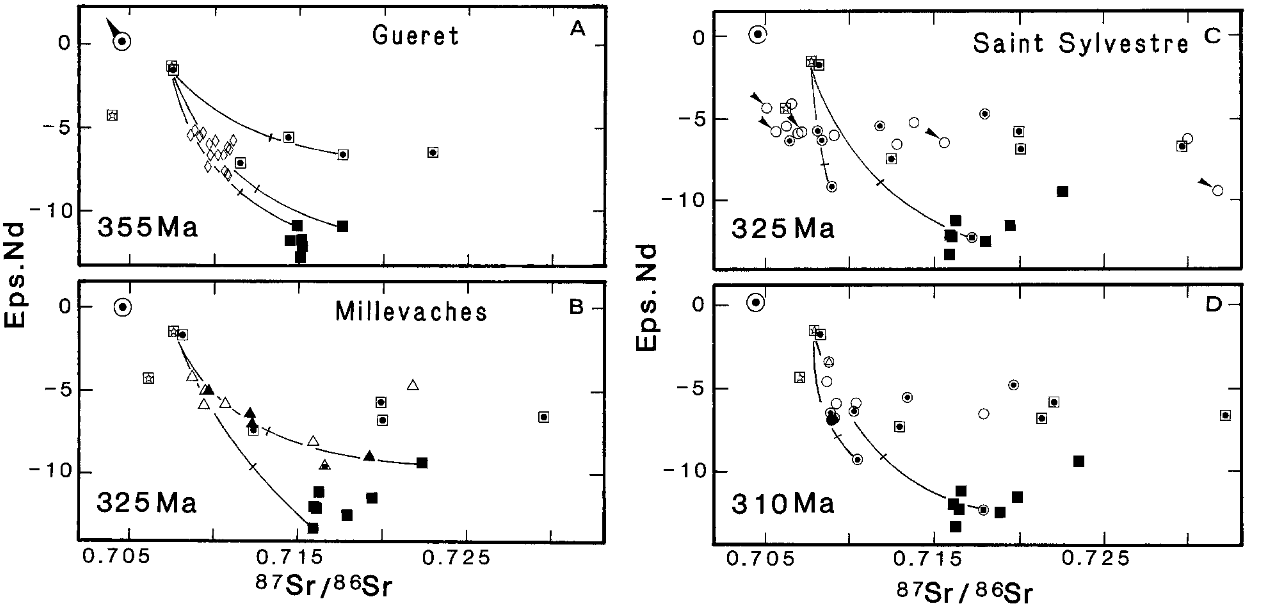

Fig. 3. Initial $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios (same symbols as in Fig. 2). Lines are computed mixing hyperbola, with *tick marks* indicating 1:1 contribution from the quoted end-members. *Small arrows* indicate Saint Sylvestre samples suspected to have undergone disturbance at approximately 310 Ma (from petrographical and geochemical examination, see text): some of the points plot outside of the limits of the diagram. None of the analysed granites may have been dominantly generated by partial melting of metasedimentary gneisses. See discussion in the text

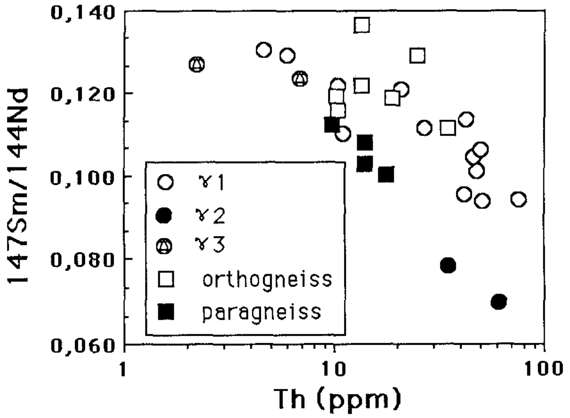

Fig. 4. Plot of $^{147}Sm/^{144}Nd$ ratio vs Th content for Saint Sylvestre samples (same symbols as in Fig. 2). See text for discussion

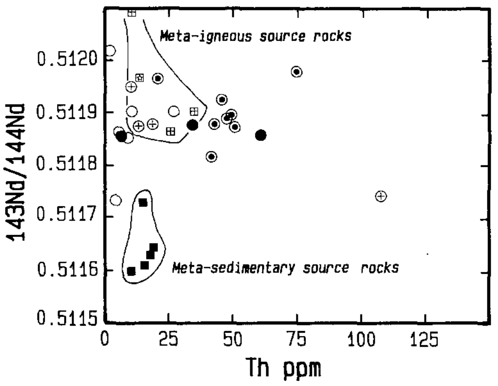

Fig. 5. Plot of initial $^{143}Nd/^{144}Nd$ ratio vs Th content for Saint Sylvestre samples (same symbols as in Fig. 2). The predominance of orthogneisses as source rocks is clearly evidenced. See text for discussion

Sm–Nd geochemistry: REE fractionation during petrogenesis

A fundamental feature of peraluminous granites is that almost the totality of light REE and Th is contained in monazite (Cuney and Friedrich 1987). Below 800° C, however, the solubility of monazite in peraluminous melt is rather low (Montel 1986), and consequently LREE behave as compatible elements during the petrogenetic evolution of such melts (e.g. Mittlefehldt and Miller 1983; Friedrich 1984; Le Fort et al. 1987). In the case of the Saint Sylvestre granite, the Nd content of γ_2 fine-grained granites, typically monazite-rich, is as high as 120 ppm, but is as low as 5 ppm in a γ_3 aplitic sample. A consequence of this phenomenon is that the Sm/Nd ratio is dramatically fractionated during the petrogenetic evolution of peraluminous granites, irrespective of their SiO_2 content. In the example of Saint Sylvestre, $^{147}Sm/^{144}Nd$ ratios range between 0.07 in γ_2 fine-grained granites and 0.13 in some γ_3 facies. Evolved peraluminous granites from Brittany have $^{147}Sm/^{144}Nd$ ratios up to 0.16 (Bernard-Griffiths et al. 1985). Figure 4 shows the general negative correlation relation between Th and $^{147}Sm/^{144}Nd$ in Saint Sylvestre samples: cafemic facies have higher Th and lower $^{147}Sm/^{144}Nd$ than leucocratic facies. Compared with potential source rock data, γ_2 and γ_3 facies respectively have higher and lower Th content, indicating either fractionation or accumulation of monazite. The plot of initial $^{143}Nd/^{144}Nd$ vs Th content (Fig. 5) shows a close identity in Nd isotope ratios between meta-igneous rocks and Saint Sylvestre data, as outlined in the previous section.

Nd crustal residence time (T_{DM}^{Nd})

T_{DM}^{Nd} is Nd "model age", i.e. the time T which elapsed from the segregation of a crustal segment (C) from depleted mantle (DM). It is commonly calculated from present day characteristics as follows:

$$T_{DM}^{Nd}=\frac{1}{\lambda}\cdot \mathrm{Ln}\left(1+\left(\frac{(^{143}Nd/^{144}Nd)_{DM}-(^{143}Nd/^{144}Nd)_{C}}{(^{147}Sm/^{144}Nd)_{DM}-(^{147}Sm/^{144}Nd)_{C}}\right)\right). \quad (1)$$

In the present study, $(^{143}Nd/^{144}Nd)_{DM}=0.513114(\varepsilon=+8.7)$, and $(^{147}Sm/^{144}Nd)_{DM}=0.222$. As a first order approximation, the fractionation in Sm/Nd during the crustal history may be considered as minor, relative to the fractionation between the depleted mantle and the upper crust which occurred at the time of crustal growth (e.g. DePaolo 1981; Taylor et al. 1983; O'Nions et al. 1983). This approximation is generally satisfied through earth history by fine-grained sediments whose Sm/Nd $\cong 0.197$ ($^{147}Sm/^{144}Nd \cong 0.119$) (e.g. Taylor and McLennan 1984). The accuracy of T_{DM}^{Nd} determination is, however, rather poor: a sample having $^{147}Sm/^{144}Nd=0.119$, $^{143}Nd/^{144}Nd=0.5121$ would give $0.96 < T_{DM}^{Nd} < 1.7$ Ga assuming the present-day $^{143}Nd/^{144}Nd$ variability observed in East Pacific Rise and North Mid-Atlantic Ridge N-MORB $\cong 0.51275$ to 0.51325, calculated with $(^{147}Sm/^{144}Nd)_{DM}=0.222$.

Additionally, the fractionation in Sm/Nd due to monazite (or any LREE-rich mineral phase) separation has dramatic consequences on T_{DM}^{Nd} determination. Figure 6 shows initial $^{143}Nd/^{144}Nd$ ratios of all the samples investigated in the present study plotted against $^{147}Sm/^{144}Nd$, and the iso-T_{DM}^{Nd} lines. The $^{143}Nd/^{144}Nd$ ratios of most of the granites from the present study are between 0.5118 and 0.51195, which at a constant $^{147}Sm/^{144}Nd \cong 0.11$ would give a T_{DM}^{Nd} variation of $\cong 0.2$ Ga; in fact, the extreme dispersion in $^{147}Sm/^{144}Nd$ leads to T_{DM}^{Nd} values difference of more than 0.5 Ga, i.e. between 1.1 and 1.6 Ga. Including the aplite 3132 from Saint Sylvestre, the difference is between 1.1 and 1.9 Ga. This effect is still more pronounced in Vendée-Brittany granites, whose T_{DM}^{Nd} plot between 1.4 and 2.2 Ga, for initial $^{143}Nd/^{144}Nd$ ratios $=0.51185 \pm 0.0005$. A common way to eliminate this effect in T_{DM}^{Nd} calculation is to arbitrarily assume a constant $(^{147}Sm/^{144}Nd)_C=0.12$ (e.g. Peucat et al. 1988; Liew and Hofmann 1988), but metamorphic rocks from the present study have $0.095 < {}^{147}Sm/^{144}Nd < 0.13 \cdot T_{DM}^{Nd}$ values calculated with this approximation, combined with the approximation on the depleted mantle characteristics, suffer a non-negligible error propagation, which hampers their use as precise quantitative data.

As outlined in the sections above, Fig. 6 emphasizes the importance of meta-igneous rocks as source rocks of peraluminous granites. This, in addition to the $^{147}Sm/^{144}Nd$ variations observed during the petrogenetic evolution of these granites, leads to an apparent rejuvenation of T_{DM}^{Nd}: the peraluminous granites from the present study cannot be considered as "mean crustal samplers", and in any "historical" study of Western European crust, T_{DM}^{Nd} values of such granites should be considered cautiously.

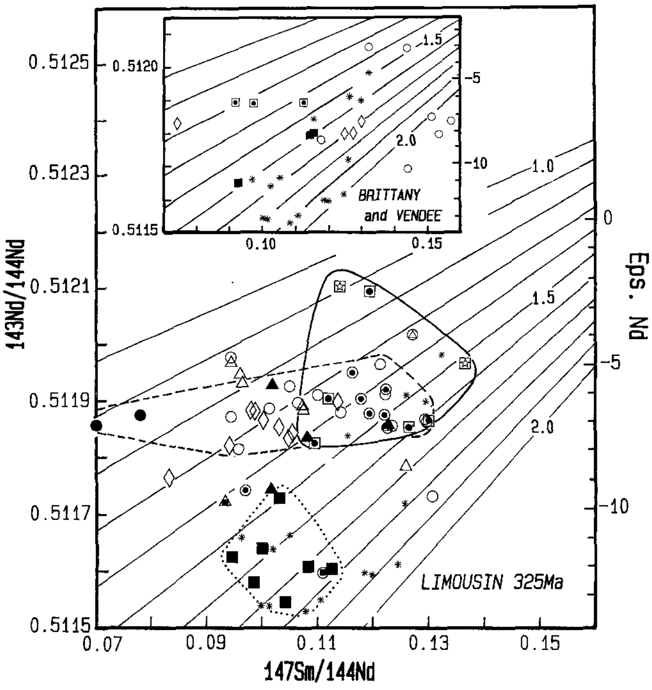

Fig. 6. Plot of initial $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$ ratios for all the samples from this study (same symbols than in Fig. 2). *Inset* shows peraluminous granites (*diamonds*) and metamorphic rocks (*squares*) from Vendée: *filled squares*, metasediments; *dotted squares*, orthogneisses (Respaut, unpublished data) and Brittany peraluminous granites (*open circles*, Bernard-Griffiths et al. 1985) and sediments. All sediment data are represented by *stars* and are taken from Michard et al. 1985. Potential source rocks are enclosed within *encircled areas*. See text for discussion

The crustal evolution of N.W. French Massif Central

Historical reconstruction studies need reliable U – Pb zircon ages (e.g. Patchett and Arndt 1986). The compilation of the available U – Pb zircon ages in Western Europe indicates: (1) ages of 2.3 – 1.7, either from direct dating of metamorphic terrains or detrital zircons in N. Brittany, Spain and Massif Central (e.g. Gebauer and Grünenefelder 1976; Calvez and Vidal 1978; Guerrot et al. 1987; unpublished work by Lancelot, quoted in Downes and Duthou 1988) or from upper intercept memory in granite or metamorphic rock dating (e.g. Pin 1981; Priem and Den Tex 1984; Lancelot et al. 1985; Bernard-Griffiths et al. 1985); (2) scarce mid-Proterozoic ages (approx. 1.2 Ga), only as upper intercept memory in granite or eclogite dating (e.g. Priem and Den Tex 1984; Peucat et al. 1982; Bernard-Griffiths et al. 1985); (3) abundant upper-Precambrian/lower-Paleozoic ages (approx 600 – 500 Ma), with evidence of oceanic crust generation attest by dating of mafic gneisses and amphibolites in Brittany, Massif Central, Spain and the Alps (work of Rennes and Montpellier laboratories, e.g. Peucat et al. 1981; Vidal et al. 1984; Lafon 1984; Lancelot et al. 1985; Lévèque 1985; Pin and Carme 1987; Ménot et al. 1988; Galibert et al. in press).

Crustal material accreted during upper Precambrian times can be expected to have had isotopic characteristics close to those observed in present-day arc-type components which generally have $\varepsilon_{Nd} \cong +4 \mp 7$ and thus apparent "T_{DM}^{Nd}" $\cong 0.6$ Ga, so continental crust newly accreted at approximately 0.6 Ga would yield T_{DM}^{Nd} in the range 1.0–1.2 Ga: for example, mafic amphibolites from the deep drilling G.P.F.-Couy (N.E. Massif Central), dated at 495 Ma (Galibert et al., in press) and having trace element features close to arc-type material, yield T_{DM}^{Nd} close to approximately 1.2 Ga (Turpin and Quenardel, unpublished work). Assuming that the $^{147}Sm/^{144}Nd$ ratios of primary sources of peraluminous granites were between 0.10 and 0.13, their T_{DM}^{Nd} values would be in the range 1.2–1.6 Ga, i.e. identical to South Brittany peraluminous granites (Peucat et al. 1988). This range overlaps the orthogneiss range (Downes and Duthou 1988; this study), while meta-volcanic rocks of Limousin have $T_{DM}^{Nd} \cong 1.1$ Ga. Following the 2-component (Archean/upper Precambrian) mixing model proposed by Liew and Hofmann (1988), and the supposition that peraluminous granites represent a mean estimate of the bulk crust, this leads to the conclusion that in Western Europe, more than 50% of the crust would have been accreted at approximately 600 – 500 Ma, i.e. at Pan-African time.

This estimation could readily explain the "Sr paradox" pointed out by Vidal et al. (1981) which is that given the mean $^{87}Sr/^{86}Sr$ and Rb/Sr ratio of granites and enclosing rocks, the bulk Sr in most of the Western European granites cannot have a crustal residence time older than 700 Ma. More than 50% seems, however, an exageration: T_{DM}^{Nd} values are biased by the fact that peraluminous granites were more efficient samplers of late Precambrian igneous rocks than sediments. In the area considered in the present study, the importance of uppermost Precambrian meta-igneous rocks (meta-volcanic rock and meta-granites) in the genesis of the peraluminous granites makes them mimic Nd isotope characteristics of upper Precambrian igneous rocks. This, together with the considerable bias due to monazite separation, contributes to the scrambling of isotopic data, especially T_{DM}^{Nd} values, but also $^{87}Sr/^{86}Sr_i$. Additionally, Sawka et al. (1986) indicate that at the mineral scale, the Sm – Nd system could be not chemically homogenized by weathering or metamorphic and magmatic processes.

Conclusions

The present study demonstrates that source rocks of Hercynian peraluminous granites may plausibly be analogous to the thrust metamorphic units of Limousin. Among the metamorphic units, meta-igneous formations of uppermost Precambrian to early Paleozoic age extensively participated in the genesis of peraluminous granites, and exclusively in the case of the U-enriched Saint Sylvestre granite. Fine-grained meta-sediments did not play an important role in the genesis of the three peraluminous complexes investigated.

This has two major consequences. First, combined with the fact that Sm/Nd ratios are extensively fractionated along their petrogenetic evolution, cautions use has to be made of T_{DM}^{Nd} values in tectonic models: the $^{143}Nd/^{144}Nd$ characteristics of the Saint Sylvestre granite are those of a Precambrian granite. Second, the I – S classification does not clearly apply to such granites, since peraluminous granites can be produced by melting of peraluminous igneous material.

In spite of the difficulties in interpreting T_{DM}^{Nd} values, and of the decoupling of the Rb – Sr system from the Sm – Nd system, it seems than an extensive crustal accretion occurred in late Precambrian time in Western Europe, i.e. during the Pan African events.

Acknowledgements. This study is part of the CEA/CREGU (Commissariat à l'Energie Atomique – Centre de Recherche sur la Géologie de l'Uranium) common programs, and has been supported by CEA-DAMN. All the people who participated in some way to the discussions are gratefully thanked, especially J.L. Duthou and C. Pin. P. Bratt from VG Isotopes is also responsible for the analytical quality of Saclay's SECTOR. J.P. Respaut contributed to this paper as a data provider during a stay in Saclay. The English was improved by T. Hinckley.

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Received January 25, 1989 / Accepted September 9, 1989
Editorial responsibility: J. Touret