

Characterization of wrench tectonics from dating of syn- to post-magmatism in the north-western French Massif Central

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Abstract This work establishes the relative timing of pluton emplacement and regional deformation from new dating and structural data. (1) Monazite and (2) zircon dating show Tournaisian ages for the Guéret granites [Aulon granite 352 ± 5 Ma (1), 351 ± 5 Ma (2) and Villatange tonalite 353 ± 6 Ma (1)] and Viseo-Namurian ages for the north Millevaches granites [Chavanat granite 336 ± 4 Ma (1), Goutelle granite 336 ± 3 Ma (1), Royère granite 323 ± 2 Ma (1) and 328 ± 6 Ma (2), Courcelles granite 318 ± 3 Ma (1)]. The Guéret and Millevaches granites are separated by the N110 Arrènes-la Courtine Shear Zone (ACSZ), composed from West to East by the Arrènes Fault (AF), the North Millevaches Shear Zone (NMSZ) and the la Courtine Shear Zone (CSZ), respectively. Tournaisian Guéret granites experienced a non-coaxial dextral shearing (NMSZ) recorded by the Villatange granite while the Aulon granite (Guéret granite) cuts across this dextral shear zone which thus stopped shearing during Tournaisian time. Visean to Namurian Millevaches granites experienced a coaxial deformation. Therefore, low displacements along the NMSZ and the CSZ

occurred at the emplacement time of Chavanat and Pontarion-Royère granites (336–323 Ma). The structural analyses of Goutelle granite emphasizes a deformation related to the dextral Creuse Fault System (CFS) oriented N150–N160. From 360 to 300 Ma, the Z strain axis is always horizontal inferring a wrench setting for these granite emplacements. During this tectonic evolution, the Argentat zone acted as a minor normal fault and is related with a local Middle Visean (340–335 Ma) syn-orogenic extension on the western border of the Millevaches massif.

Keywords French Massif Central · Monazite · Zircon · Dating · Displacement · Granite deformation

Introduction

Collision tectonic in the Hercynian belt is characterized by the stacking of syn-collisional nappes (Matte 1986) followed by syn- to post-tectonic granite intrusions (Duthou 1984; Lagarde et al. 1992) and marked by the development of large crustal scale shear zones (Gumiaux et al. 2004). These orogenic granites are of importance in the understanding of the kinematics of highly strained zones in collision belts (Hutton and Reavy 1992). Dating syn- to post-orogenic granites allows the timing of regional deformation to be determined. This methodology is applied in the western part of French Massif Central, more precisely in the Guéret and Millevaches massif (Cuney et al. 2002; Gébélín 2004; Roig et al. 2002; Scaillet et al. 1996).

New geochronological ages on monazite and zircon are first presented. Then, the main deformation zones which affected the dated granites with the support of

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cartographic data (Cartannaz et al. 2006b; Rolin et al. 2006) and a careful analysis of the structures in the granitic plutons are described. In the inner part of the Variscan chain, this study on high strained zones allows to propose a new geodynamic evolution for the Guéret and Millevaches massifs during Carboniferous time.

Geological and tectonic setting

The Guéret and Millevaches massifs are composed of several granites (Ranchin 1971; Stussi and Cuney 1993; Vauchelle et al. 1988). They belong to the north-western part of the French Massif Central, in the inner zone of the Variscan belt. These granites intrude a reverse pile of metamorphic nappes, overthrust and deformed during the Silurian-Carboniferous convergence between Gondwana and Laurasia (Matte 1986). The inner zone experienced a post-collisional extension during the Late Viséan (Burg et al. 1994; Faure 1995; Faure et al. 2002). Large crustal wrench zones deform the metamorphic nappe pile at the end of the collision from western Brittany to the French Massif Central (Gumiaux et al. 2004; Rolin and Colchen 2001). One of these main crustal shear zones, the “Arrènes-la Courtine” shear zone (ACSZ) divides the study area into two granitic domains, the north Guéret massif mainly composed of peraluminous cordierite-bearing granites and the south Millevaches massif mainly composed of peraluminous muscovite-bearing granites (Fig. 1).

The Guéret massif is one of the largest granitic domain (4,500 km²) in the French Massif Central. The massif is delimited by the Marche Shear Zone (MSZ) and the ACSZ, at the northern and southern borders, respectively. The Bussière-Madeleine Shear Zone (BMSZ) and the Sillon Houiller Fault (SH) delimit the massif at the western and eastern borders, respectively (Fig. 1). This domain is mainly constituted by peraluminous cordierite-bearing granites (ASI > 1) (Downes et al. 1997). With respect to their petrological facies and geochemistry, the massif is composed of four main types, induced by fractional crystallization (Vauchelle 1988). Their structural relationships and the relative chronology deduced by new field mapping (Rolin et al. 2006) allow to consider these different facies as separate bodies: the Villatange granodiorite-tonalite, the Saint-Martial-Saint-Fiel granodiorite-monzogranite, the Chénérailles-Peyrabout monzogranite and the Aulon leucomonzogranite. New gravimetric data (Gébelin 2004) and the Créchat-les-Sibieux deep drill-hole (Laurent 1988) evidence a migmatite-granite lithological contact at a shallow depth (ca. 500 m) and

emphasize the laccolite shape of the whole granitic Guéret massif. The Peyrabout monzogranite was previously dated, by Rb-Sr whole rock method, at 356 ± 10 Ma with an initial isotopic ratio $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7098 ± 4 (Berthier et al. 1979).

The paragneisses of the northern part of the Millevaches massif are intruded by the Pontarion-Royère magmatic complex (Razafimahefa 1987). Imbricated structures at magmatic stage (cauliflower and lobed structures) suggest a coeval emplacement. The northern border of the Millevaches massif is intruded by elongated leucogranites, localised along the ACSZ (Fig. 2). Several granites are distinguished: the biotite +/- muscovite-sillimanite Chavanat granite, the two micas Courcelles leucogranite, the foliated Bourgneuf leucogranite, along the Argentat Fault, and the coarse-grained Chasselines-Goutelle granite, on the NE border of the massif.

The Guéret and Millevaches granites are separated by the N110-N120 ACSZ, composed from west to east by the Arrènes Fault (AF), the North Millevaches Shear Zone (NMSZ, also called Saint-Michel-de-Veisse Fault) and the la Courtine Shear Zone (CSZ), respectively. The ACSZ is disrupted by the N-S Argentat Fault, west of the Millevaches massif and the N150 Creuse Fault System (CFS) and the N020 Fellestin-Ambrugeat Fault System (FAFS) at the eastern border of the Millevaches massif (Fig. 2). West of the Millevaches massif, the Limousin domain constitutes a large metamorphic area resulting from thrust-nappe stacking during early Devonian times (Burg and Matte 1978; Costa et al. 1993; Floc'h 1983; Ledru et al. 1989). East of the Millevaches massif, the Ussel unit is mainly composed of a metamorphic nappe complex.

Geochronological results

Guéret massif

Villatange granodiorite (CJ 51) The Villatange granodiorite was sampled within the elongated granodiorite body deformed by the NMSZ, close to the NW border of Millevaches massif (Fig. 2). Eleven monazite grains were investigated: 93 analyses indicate significant variation of Th/U ratio (Table 1) making the $\text{Th}/\text{Pb} = f(\text{U}/\text{Pb})$ diagram suitable for mean age calculation. The calculated MSWD of 1.2 makes the regression line, calculated from the 93 data points, statistically in agreement with a single age (Fig. 3a). The intercept ages are rather well defined (U-Pb age: $325 + 48$ –51 Ma and Th-Pb age: 360 ± 12 Ma) and similar within the errors. A mean age of 353 ± 6 Ma was calculated at the centroid of the population.

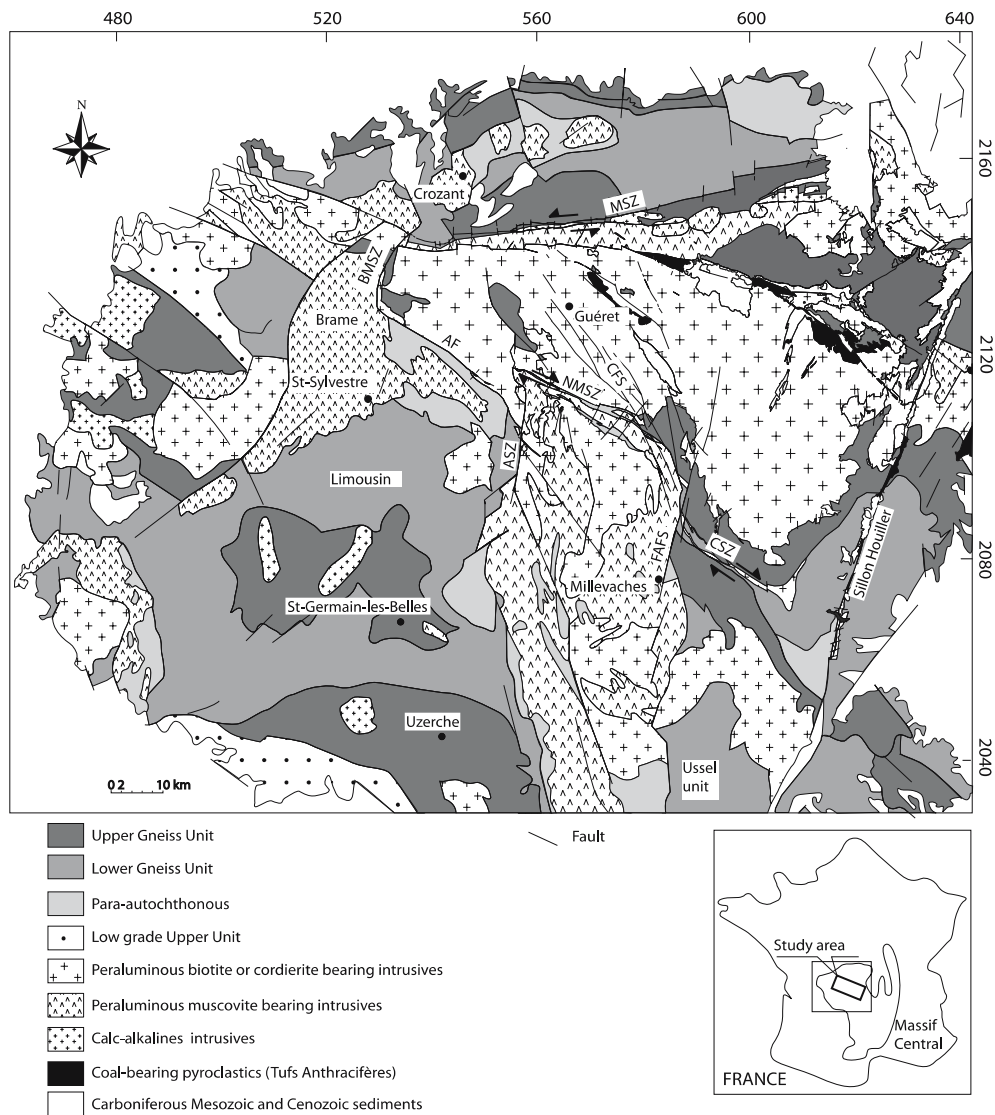


Fig. 1 Location of the studied area (north-western part of French Massif Central). AF Arrènes Fault, ASZ Argentat Shear Zone, BMSZ Bussière-Madeleine Shear Zone, CFS Creuse Fault System, CSZ la Courtine Shear Zone, FAFS Felletin-Ambrugeat

Fault System, NMSZ North Millevaches Shear Zone, MSZ Marche Shear Zone. Arrènes-la Courtine Shear Zone (ACS-Z) = AF + NMSZ + CSZ

Aulon leucomonzogranite (LB 92) Both methods were used to date this leucomonzogranite. Seven *monazite* grains were investigated: 81 analyses indicate a very similar U and Th composition as that of Villatange granodiorite (Table 1). Using the $\text{Th/Pb} = f(\text{U/Pb})$ diagram, the calculated MSWD of 0.69 makes the regression line, calculated from the 81 data points, statistically in agreement with a single age (Fig. 3b). The intercept ages are well defined (U–Pb age: $317 \pm 37\text{--}39$ Ma and Th–Pb age: 360 ± 10 Ma) and similar within the errors. A mean age of 352 ± 5 Ma was calculated at the centroid of the population.

The *zircons* in this rock are quite numerous and relatively large, usually $> 200 \mu\text{m}$. Most of them are

euhedral but show many inclusions. They mainly show a characteristic S2–S6–S12 type silhouette according to the morphological typology of Pupin (1980). The average population index $\text{I.}\bar{\text{A}}, \text{I.}\bar{\text{T}} = 333\text{--}384$ corresponds to the area of crustal anatexis. About 50 grains were mounted in polished section. Twelve spot analyses from 12 different grains were obtained (Table 2). Nine out of them are perfectly concordant in agreement with the lack of common-Pb observed in the Tera and Wasserburg concordia diagram (Fig. 4a). Two discordant analyses (6.1 and 2.1) indicate a significant contribution of common-Pb. One of them (2.1) also seems slightly affected by partial radiogenic Pb (Pb^*) loss, so it was not taken into account for

Fig. 2 Sample dating location. *AF* Arrèrès Fault, *ASZ* Argentat Shear Zone, *CFS* Creuse Fault System, *CSZ* la Courtine Shear Zone, *FAFS* Felletin-Ambrugeat Fault System, *NMSZ* North Millevaches Shear Zone, *SMVF* Saint-Michel-de-Verisse Fault. CJ51: Villatange granite, LB92: Aulon granite, LA48: Chavanat granite, CJ41: Chasselines-Goutelle granite, CJ47: Royère granite, CJ53: Courcelles granite

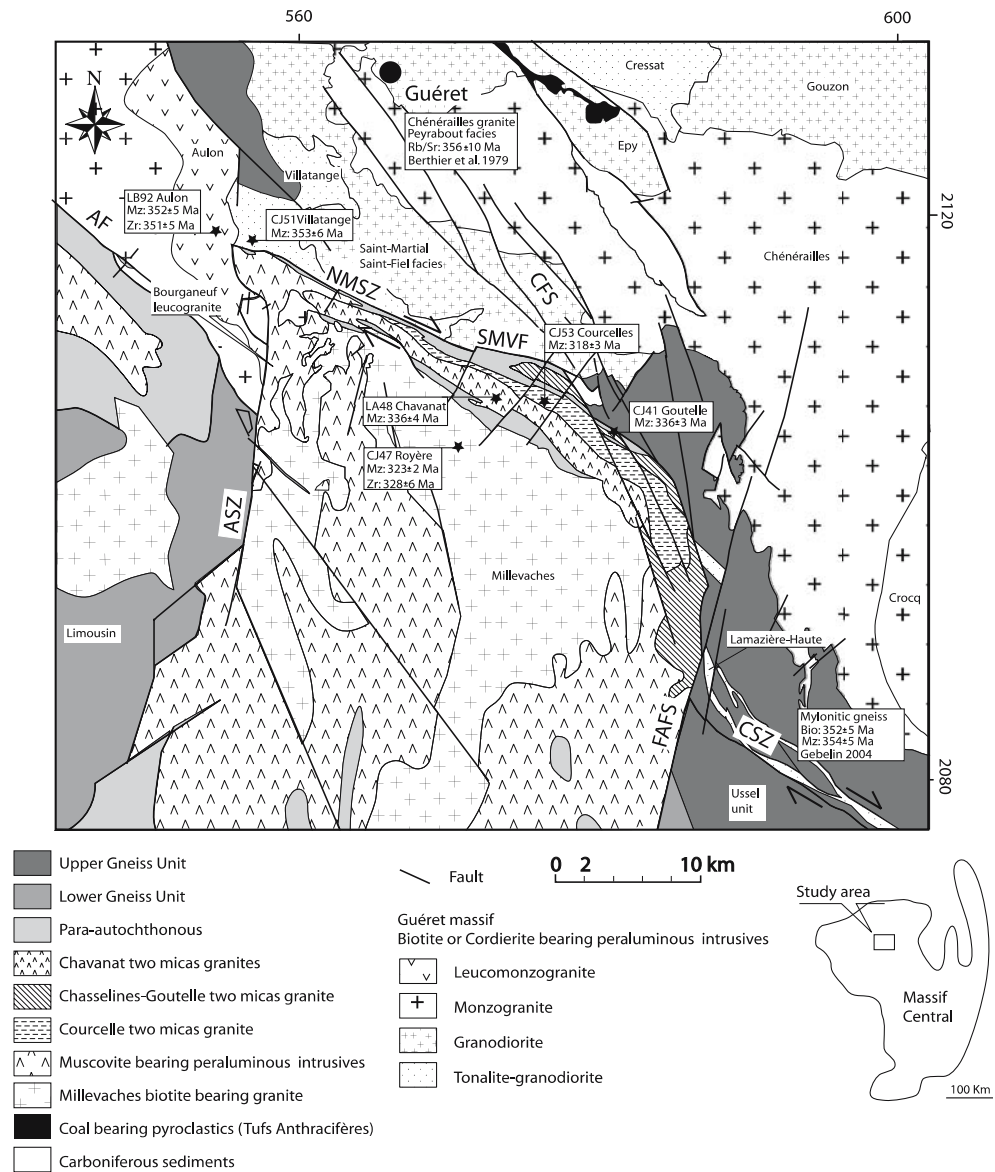


Table 1 Summary of electron microprobe data for analysed monazites from French Massif central

	Pb (ppm)	$\pm \sigma$	U (ppm)	$\pm \sigma$	Th (ppm)	$\pm \sigma$	Th/U	$\pm \sigma$	Isochron age (Ma $\pm 2\sigma$)	<i>n</i>
Villatange granodiorite (CJ 51)	822	114	2,831	1,564	43,646	6,197	31.3	14.4	353 $\pm$ 6	93
Aulon leucomonzogranite (LB 92)	872	132	3,164	1,958	44,801	6,070	22.6	15.7	352 $\pm$ 5	81
Chavanat two mica granite (LA 48)	1,669	470	13,181	7,266	69,733	23,234	7.5	5.8	336 $\pm$ 4	84
Goutelle leucogranite (CJ 41)	1,376	462	10,077	5,179	59,410	20,545	7.2	4.6	336 $\pm$ 3	83
Royère granite (CJ 47)	1,565	275	14,095	5,184	63,219	5,311	6.1	4.9	323 $\pm$ 2	82
Courcelles leucogranite (CJ 53)	1,724	363	13,463	8,299	78,175	10,932	10.6	10.9	318 $\pm$ 3	95

Average Pb, U and Th concentrations and corresponding standard deviations are given as well as the calculated mean isochron ages and related uncertainty at 2σ level. *n* denotes the number of individual analyses taken into account for isochron age calculation

average age calculation. Two analyses show obvious inherited contribution (10.1 and 11.1) despite the unusual reverse discordancy of the data for 11.1 spot

analysis. The major event was dated by means of eight clustered and one discordant analysis (6.1) whose 2σ ellipse error is located on the common-Pb mixing

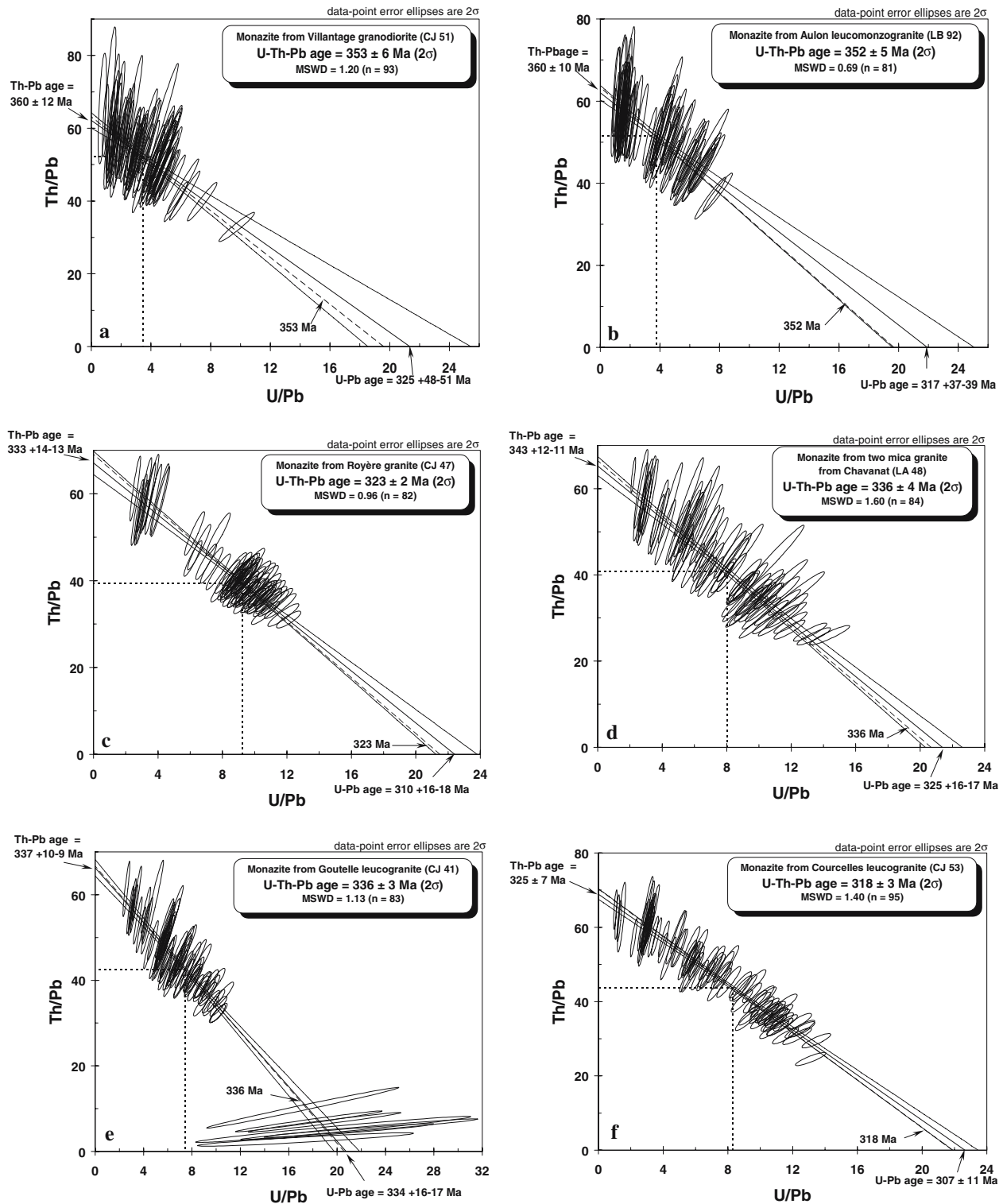


Fig. 3 U/Pb versus Th/Pb isochron diagrams for monazite from analysed granitoids from western part of French Massif Central. All errors are quoted at 95% confidence level and error ellipses are plotted as 2σ . The regression line calculated from the data (full line) is compared to the theoretical isochron (heavy dashed line). The error envelop is formed by two hyperbolas (light dashed line). For a simple monogenetic monazite the theoretical

isochron must be located in between those two hyperbolas. The mean age is calculated at the centroid of the data population, where the error is minimum. **a** CJ51: Villatange granite, **b** LB92: Aulon granite, **c** CJ47: Royère granite, **d** LA48: Chavanat granite, **e** CJ41: Chasselines–Goutelle granite, **f** CJ53: Courcelles granite

Table 2 Summary of SHRIMP U–Pb zircon results for granitoids from French Massif Central

Grain spot	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total				Radiogenic			Age (Ma)	
							²³⁸ U/ ²⁰⁶ Pb ±	²⁰⁷ Pb/ ²⁰⁶ Pb ±	²⁰⁶ Pb/ ²³⁸ U ±	²⁰⁶ Pb/ ²³⁸ U ±					
<i>Aulon leucomonzogranite (LB 92)</i>															
1.1	1,208	338	0.28	60	0.000031	< 0.01	17.36	0.25	0.0532	0.0003	0.0577	0.0008	361.3	5.2	
2.1	788	181	0.23	36	0.000809	1.65	18.57	0.27	0.0663	0.0013	0.0530	0.0008	332.6	4.8	
3.1	1,085	95	0.09	52	0.000027	0.06	17.85	0.28	0.0540	0.0004	0.0560	0.0009	351.2	5.4	
4.1	1,424	57	0.04	67	0.000013	< 0.01	18.19	0.26	0.0528	0.0004	0.0550	0.0008	345.2	4.8	
5.1	619	157	0.25	30	0.000141	0.14	18.01	0.26	0.0546	0.0005	0.0554	0.0008	347.8	4.9	
6.1	1,020	282	0.28	49	0.001508	2.68	17.84	0.27	0.0749	0.0010	0.0545	0.0009	342.4	5.3	
7.1	1,099	140	0.13	52	0.000032	< 0.01	18.02	0.26	0.0533	0.0004	0.0555	0.0008	348.2	4.9	
8.1	1,009	265	0.26	49	0.000048	< 0.01	17.55	0.25	0.0536	0.0004	0.0570	0.0008	357.4	5.0	
9.1	3,165	108	0.03	155	0.000024	< 0.01	17.55	0.25	0.0533	0.0002	0.0570	0.0008	357.4	5.0	
10.1	1,255	59	0.05	64	0.000079	0.04	16.76	0.29	0.0544	0.0005	0.0596	0.0010	373.4	6.3	
11.1	2,421	1,133	0.47	146	0.000052	< 0.01	14.22	0.25	0.0533	0.0003	0.0705	0.0013	439.5	7.5	
12.1	564	217	0.38	27	0.000091	< 0.01	18.08	0.31	0.0533	0.0006	0.0553	0.0009	347.1	5.8	
<i>Royère granite (CJ 47)</i>															
1.1	1,260	150	0.12	60	0.001947	3.42	18.06	0.27	0.0807	0.0023	0.0535	0.0009	335.9	5.3	
2.1	3,125	17	0.01	136	–	0.02	19.80	0.28	0.0529	0.0003	0.0505	0.0007	317.5	4.4	
3.1	3,019	18	0.01	127	0.000009	0.10	20.48	0.29	0.0533	0.0002	0.0488	0.0007	307.0	4.3	
4.1	570	103	0.18	23	0.000601	1.11	21.35	0.31	0.0610	0.0009	0.0463	0.0007	291.8	4.3	
5.1	253	72	0.29	11	0.000952	0.89	19.05	0.32	0.0601	0.0012	0.0520	0.0009	326.9	5.4	
6.1	2,936	10	0.00	132	0.000008	< 0.01	19.13	0.27	0.0530	0.0002	0.0523	0.0007	328.4	4.5	
7.1	369	133	0.36	19	0.006874	12.28	16.68	0.28	0.1518	0.0015	0.0526	0.0014	330.3	8.3	
8.1	3,711	287	0.08	177	0.000026	< 0.01	17.96	0.25	0.0529	0.0002	0.0557	0.0008	349.5	4.8	
9.1	2,274	33	0.01	95	0.000225	0.43	20.60	0.30	0.0559	0.0003	0.0483	0.0007	304.3	4.4	
10.1	3,972	380	0.10	177	0.000732	1.34	19.26	0.27	0.0636	0.0002	0.0512	0.0007	322.0	4.5	
11.1	2,282	103	0.05	111	0.000004	< 0.01	17.59	0.27	0.0527	0.0004	0.0569	0.0009	356.9	5.3	
12.1	702	824	1.17	32	0.000155	0.24	18.68	0.27	0.0551	0.0005	0.0534	0.0008	335.5	4.8	

Uncertainties are given at one σ level. Error due to standard calibration (FC 1) is included in the above uncertainties. f_{206} % denotes the percentage of ²⁰⁶Pb that is common-Pb. Correction for common Pb made using the measured ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb following Tera and Wasserburg (1972) as outlined in Williams (1998). In *italics*, data not included in the average age of the zircons from a given rock sample

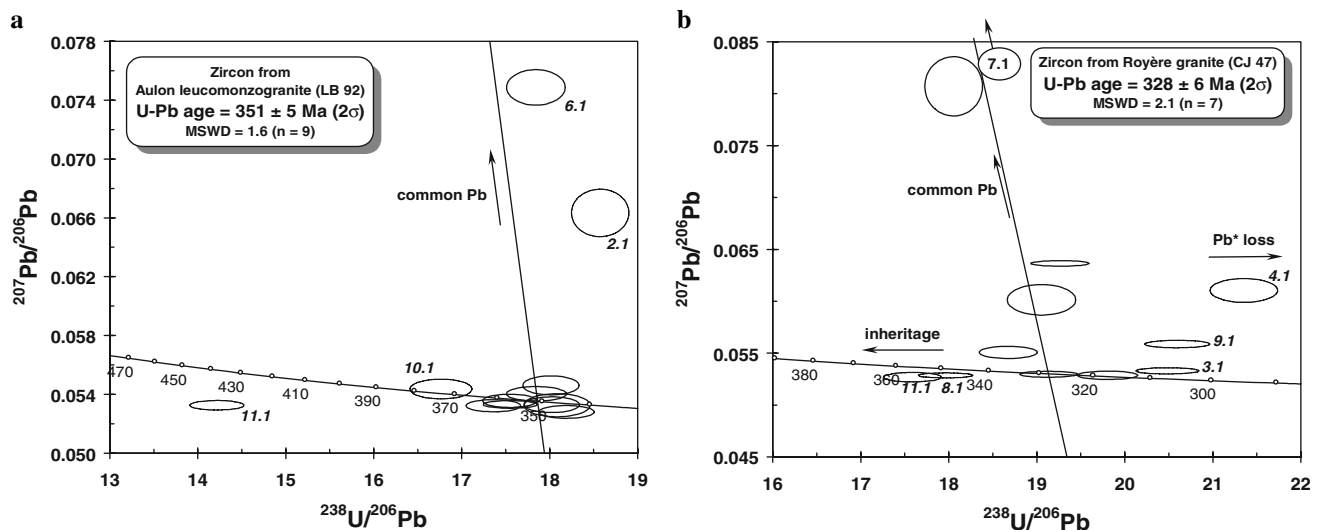


Fig. 4 Common-Pb uncorrected Tera and Wasserburg diagram for data obtained with SHRIMP II on zircons from western part of French Massif Central. *Dashed ellipsoids* are not taken into

account for average age calculation. Data error ellipses are at 1 σ , calculation done 2 σ . **a** LB92: Aulon granite, **b** CJ47: Royère granite

line. The average $^{206}\text{Pb}^*/^{238}\text{U}$ age, given by the intercept of the mixing line with the common-Pb and the population of nine analyses, was therefore well defined at 351 ± 5 Ma. The regression line is statistically validated by an MSWD value at 1.6.

Thus, the U–Pb age of closure of zircon is similar to the U–Th–Pb chemical age calculated on monazite. It is interpreted as corresponding to the emplacement age of this leucomonzogranite (LB 92).

Millevaches massif

Royère granite (CJ 47) Both methods were used to date this leucogranite located in the Millevaches massif.

Six monazite grains were investigated among the less altered and less broken ones: 82 analyses indicate a very constant Th composition around 6.3 wt% (Table 1). On the contrary, U concentration range is rather wide: from 0.3 to 3.0 wt% yielding a large variation for Th/U ratio very suitable for getting a precise age using the $\text{Th/Pb} = f(\text{U/Pb})$ diagram. The calculated MSWD of 0.96 makes the regression line statistically in agreement with a single age (Fig. 3c). The intercept ages are well defined (U–Pb age: 310 ± 16 – 18 Ma and Th–Pb age: 333 ± 14 – 13 Ma) and similar within the errors. A mean age of 323 ± 2 Ma was calculated at the centroid of the population.

The zircons in this rock are usually large (200–400 μm) and relatively numerous. Most of them are euhedral but they show many inclusions, cracks and other defaults. They mainly show a characteristic S1–S2–S6–S7 type silhouette according to the morphological typology of Pupin (1980). The average population index $\text{I.A.}, \text{I.}\bar{\text{T}} = 263\text{ndash};359$ corresponds to the area of the crustal anatexis. About 60 grains were mounted in polished sections. Twelve spot analyses from 12 different grains were obtained (Table 2). Uncommonly numerous spot analyses are discordant in the Tera and Wasserburg concordia diagram (Fig. 4b). This is indicated by the scatter of the data according to $^{207}\text{Pb}/^{206}\text{Pb}$ axis as an evidence of variable and significant amount of common-Pb contribution. On the other hand, a scatter of the data is also observed according to the $^{238}\text{U}/^{206}\text{Pb}$ axis. Such scattering is quite common for zircon grains extracted from leucocratic rocks of crustal origin (Cocherie et al. 2004) while zircon grains of high crystallization temperature used to give concordant data (Cocherie et al. 2005b). We interpret the scatter according to the $^{238}\text{U}/^{206}\text{Pb}$ axis as a result of both processes: (1) Pb^* loss (3.1, 9.1, 4.1) and (2) inheritance (8.1, 11.1). Despite the number of grains available and an especially careful selection of the studied area we

could not get more concordant analyses. By chance, some discordant analyses fits relatively nicely (at 2σ level) along a mixing line from the age intercept, we are looking for, and the $^{207}\text{Pb}/^{206}\text{Pb}$ composition of common-Pb during Variscan time (Stacey and Kramers 1975). Thus, using seven spot analyses we calculated an age intercept at 328 ± 6 Ma (Fig. 4b), statistically validated by the MSWD (2.1).

To sum up, we observed that the U–Pb age closure of the zircon system (328 ± 6 Ma) is similar to the “chemical” U–Th–Pb age of the monazite system (323 ± 2 Ma). However, we prefer to favour an emplacement age for the Royère granite at 323 ± 2 Ma (monazite age) because of the complex scattering of the isotopic analyses of the zircon.

Chavanat two-mica granite (LA 48) Nine monazite grains were investigated: 84 analyses indicate very high U concentration for some domains (up to 3.2 wt%) associated with “normal” Th concentration (~ 5.7 wt%), meanwhile other domains show huge Th concentration (up to 19.4 wt%) associated with ordinary U concentrations (~ 0.7 wt%). As a result, we observe large variation of Th/U ratio (Table 1) making the $\text{Th/Pb} = f(\text{U/Pb})$ diagram especially efficient for calculating a precise mean age. The calculated MSWD of 1.6 makes the regression line, calculated from the 84 data points, statistically in agreement with a single age (Fig. 3d). The intercept ages are precisely defined (U–Pb age: 325 ± 16 – 17 Ma and Th–Pb age: 343 ± 12 – 11 Ma) and similar within the errors. A mean age of 336 ± 4 Ma was calculated at the centroid of the population.

Chasselines–Goutelle leucogranite (CJ 41) Seven small monazite grains ($< 150 \mu\text{m}$) were investigated: 83 analyses indicate contrasting U and Th contents. Most of the grains are characterized by “normal” Th concentrations (5–8 wt%) and a large range variation for U concentration (0.4–2.0 wt%) associated with normal Th concentration (5–8 wt%). This induces extensive Th/U variation and relatively small error ellipses. About less than 10% of the analyses are uncommon: they show ordinary U concentration (0.5–0.7 wt%) and uncommonly low Th concentration (0.1–0.2 wt%, only). The lack of Th seems to be chemically equilibrated by higher light rare-earth element concentrations, so that the total oxide content remains close to 100%. The amount of Pb^* produced is very low (250–400 ppm) and the related data plotted in the $\text{Th/Pb} = f(\text{U/Pb})$ diagram as large ellipses close to the U/Pb axis, while all other data plot nicely, in the upper part of the diagram (Fig. 3e). As a consequence, the

regression line is especially well defined and the error envelop is very narrow. The question remains to control the cogenetism of both spot analysis types. To do that, we calculate, as usual, the intercept ages on the two axes: they are very similar within the error (U–Pb age: 334 ± 16 – 17 Ma and Th–Pb age: 337 ± 10 – 9 Ma). In addition, the theoretical isochron calculated at the age of the mean age is similar to the regression line. Therefore, the mean age can be calculated at the centroid of all the population at 336 ± 3 Ma, with a good MSWD of 1.13.

Courcelles leucogranite (CJ 53) This pluton intruded the NMSZ, crosscutting the shear structures but being weakly affected by these structures themselves.

Monazite grains from this leucogranite are about 170 – 230 μm in size. They show large unaltered domains without any cracks or inclusions; in addition, growth structures are visible, making the grains suitable for detailed investigations. Ten monazite grains were studied: 95 analyses indicated a quite high and constant Th composition around 7.8 wt% (Table 1). On the contrary, U concentration changes in a wide range, from 0.2 to 3.0 wt%, yielding a large variation in Th/U ratio, very suitable for getting a precise age using the $\text{Th/Pb} = f(\text{U/Pb})$ diagram (Fig. 3f). The error envelop is especially narrow, and subsequently, the intercept ages are very well defined at 307 ± 11 Ma (U–Pb age) and 325 ± 7 Ma (Th–Pb) and similar within the errors. An acceptable MSWD of 1.40 is achieved. A mean age of 318 ± 3 Ma was calculated at the centroid of the population.

Dextral ductile Arrènes–la Courtine shear zone

The ACSZ is divided into three segments which run from east to west: the Courtine Shear Zone (CSZ), the North Millevaches Shear Zone (NMSZ) and the Arrènes Fault (AF).

The Courtine Shear Zone

The CSZ is a 2 km wide deformed zone mainly composed of well-developed mylonitic biotite–sillimanite paragneisses separating the Guéret massif from the Ussel unit (Fig. 2). The syntectonic mineralogical assemblage is mainly composed of quartz, plagioclase, K-feldspar, biotite, sillimanite, muscovite, cordierite $\pm$ garnet (Gébelin 2004). The N90–N110 regional mylonitic foliation is subvertical and affected by N120–N130 vertical shear bands (Fig. 5a, b). A horizontal mineral stretching lineation is present on the shear

bands and shear-sense indicators emphasise a bulk dextral sense of shear during retrograde metamorphic conditions under greenschist facies. The high-grade metamorphism recorded by the mylonitic gneisses was dated at 354 ± 5 Ma using the U–Th–Pb monazite method and at 352 ± 5 Ma using ^{40}Ar – ^{39}Ar biotite ages (Gébelin 2004).

The tonalite and granodiorite intrusions (labelled Lamazière-Haute on Fig. 2), located in the mylonitic biotite–sillimanite paragneisses, exhibit dextral C/S structures (average direction: N120 S plane and N150 C plane) associated with a horizontal stretching lineation on vertical planes. The study of quartz lattice preferred orientation shows high-grade metamorphic conditions (450 – 700°C) related to the dextral syntectonic shearing of these intrusions (Gébelin 2004).

North Millevaches Shear Zone

The NMSZ is a N120 zone of intense ductile deformation of about 3–6 km wide. The northern Millevaches paragneisses and the Villatange intrusion are affected by this shear zone.

The metamorphic assemblages of the Millevaches paragneisses are mainly constituted by quartz, plagioclase, K-feldspar, biotite, cordierite, sillimanite, muscovite $\pm$ garnet (Rolin et al. 2006). The mylonitic foliation is oriented N90–N120 and is affected by N120–N130 shear bands. The shear bands and the mylonitic foliation are subvertical or dipping 60° – 70° toward the south. The pitch of the mineral stretching lineation dips from 10° to 45° toward the south-east on the shear bands. These microstructures reflect a dextral to reverse-dextral shearing under high-grade metamorphic and retromorphic conditions.

The Villatange granite, dated at 353 ± 6 Ma, exhibits vertical C/S microstructures (Fig. 5c) (average direction: N100 S plane and N130 C plane) related to retromorphic conditions ending in greenschist facies. The pitch of the mineral stretching lineation dips from 10° toward the SE on the C planes.

Lower metamorphic conditions (chlorite zone) in the NMSZ are present in a narrow corridor of 1 km width, along the Saint-Michel-de-Visse fault (SMVF). Breccia and cataclasites occur on a width of about 10–20 m along the SMVF. The mylonitic paragneisses are affected by faulting with NW–SE fault planes dipping 30 – 60° toward the SW and associated with striations plunging toward the SW. Asymmetrical microfolding (axes 10/N140) in mylonitic paragneisses and kinematic indicators on fault planes reveal a late superimposed reverse faulting toward the NE of the northern border of the Millevaches massif.

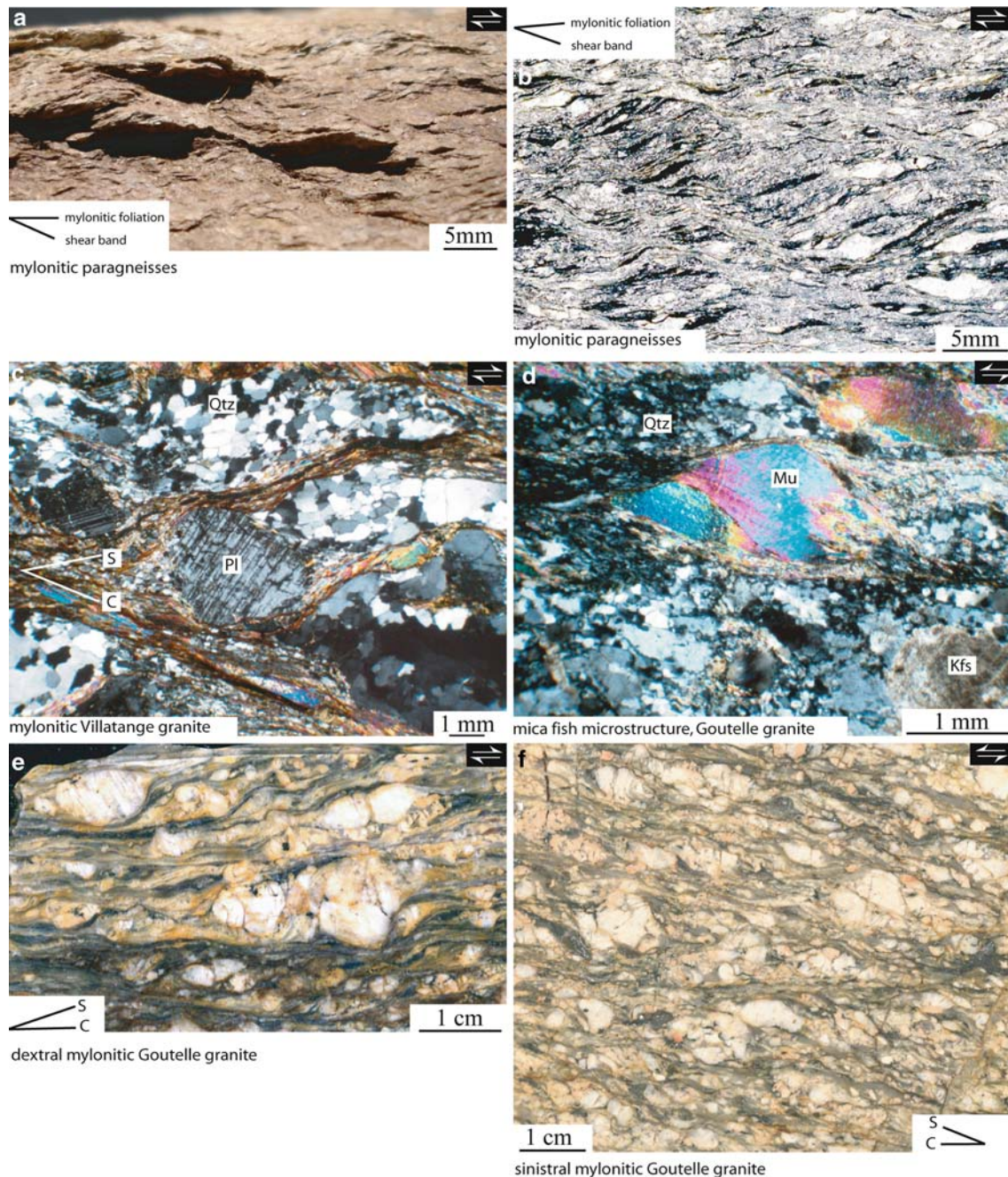


Fig. 5 Samples and microstructural observations of deformed rocks of ACSZ, observed in the *XZ* plane of the finite strain ellipsoid. **a** and **b** Dextral shear bands in the mylonitic paragneisses; **c** thin section of dextral C/S fabrics developed in

the deformed Villatange granites; **d** thin section of mica fish microstructure in the Goutelle granite; **e** and **f**: dextral and sinistral C/S fabrics developed in the Goutelle granite

Arrènes Fault

The Arrènes Fault (AF) separates the Guéret massif from the Limousin area. Field observations highlight the occurrence of a 50 m wide cataclastic zone and the absence of dextral ductile deformation in the Guéret granite and Limousin paragneisses. Furthermore,

the Limousin paragneissic high-grade metamorphic foliation, oriented N150/160, is broadly oblique related to the N140 fault direction (Fig. 2) (Arène et al. 1972). Thus, the AF displays a different tectonometamorphic evolution and deformation mechanisms in comparison with the ductile NMSZ and CSZ. At map scale, the NMSZ is crosscut by the Aulon granite and the

Saint-Martial granite (Fig. 2). The prolongation of the NMSZ could be located below the Guéret massif in the north of the Arrènes Fault. Therefore, the AF could not be directly correlated with the NMSZ and the CSZ.

In the western part of the studied area, the AF deformation is coeval with syntectonic Brame granite (324 ± 5 Ma) (Holliger et al. 1986).

Deformation of Visean magmatic intrusions

In the northern Millevaches massif, the Chavanat leucogranite (336 ± 4 Ma), the Chasselines–Goutelle leucogranite (336 ± 3 Ma), the Courcelles leucogranite (318 ± 3 Ma) and the Pontarion–Royère complex (323 ± 2 Ma) constitute time-markers for the post 340 Ma deformation history of the crustal ACSZ.

The Chavanat granite (336 ± 4 Ma) is heterogeneously deformed and locally shows a vertical N115/130° foliation with scarce subhorizontal lineations. Field observations mainly show symmetrical deformation of feldspar and quartz aggregates and the absence of shear bands and emphasise a low non-coaxial component during the granite deformation. The Chavanat granite hosts several xenoliths, originated from north Millevaches mylonitised paragneisses. In these xenoliths, structures corresponding to the mylonitic foliation and dextral shear bands related to the NMSZ are locally recognizable. These features indicate an emplacement of the Chavanat granite posterior to the main dextral shear in the NMSZ.

In the Pontarion–Royère magmatic complex (323 ± 2 Ma), only the porphyroid Pontarion granite is located close to the NMSZ. Here on 300–500 m width, a vertical slight N115–N130 post-solidus foliation is underlined by quartz and deformed feldspar. Conjugate C planes, developed under greenschist metamorphic conditions, occur symmetrically around the schistosity and testify to a ductile coaxial deformation at pluton scale (Fig. 6). At the scale of the Pontarion–Royère magmatic complex, the treatment of C planes, stretching lineations and local kinematic indicators (Faulking method: Allmendinger et al. 1989) reveals a subhorizontal N16-oriented shortening axis *Z*, perpendicular to the NMSZ, and a horizontal N285-oriented stretching axis *X* (Fig. 6). On the north-eastern and western parts, the Pontarion–Royère magmatic complex is affected by the CFS and the Argentat Shear Zone (ASZ), respectively.

The Courcelles leucogranite ($318 \pm$ Ma) is weakly deformed and mainly shows an isotropic structure

except in the south-eastern part where a vertical slight post-solidus foliation, oriented N130, occurs with a stretching mineral lineation plunging 20° toward the SE. In this part of the leucogranite, the absence of observed shear indicators does not allow to make any kinematic interpretation.

Ductile–brittle disruption of the ACSZ

After 350 Ma, the ACSZ was disrupted by the Argentat Fault and CFS, located, respectively, at the western and eastern borders of the Millevaches massif.

Argentat Fault Zone

The N10 Argentat Fault Zone (AFZ) occurs at the western border of the Millevaches massif. In fact a ductile fault (ASZ) and a brittle fault can be described:

Argentat Shear Zone

This zone corresponds to a normal-dextral fault responsible for the ductile deformation of the Bourgneuf leucogranite (see location in Fig. 2) under greenschist metamorphic conditions. On the western edge of the Millevaches, the Bourgneuf leucogranite experiences a mylonitic deformation characterised by C/S structures with S and C planes weakly to moderately dipping westward. Schistosity and C planes are oriented N–S and dipping 20W and 30–50W, respectively. They are associated with a stretching mineral lineation oriented around N300–N320. The asymmetry of the C/S structures shows a top to the west–northwest sense of shear, indicating normal faulting. A seismic profile (Bitri et al. 1999) reveals a 4 km vertical offset along the ASZ. The emplacement of the syntectonic Bourgneuf leucogranite occurs between 341 and 331 Ma (Roig et al. 2002).

Argentat Fault s.s

Post 325 Ma, this fault corresponds to a nearly vertical cataclastic fault which crosscuts the Argentat Shear Zone (ASZ) (Bitri et al. 1999; Labernardière 1970). The kinematics on the cataclastic fault is poorly defined. Previous studies regarded it as a sinistral fault responsible for the offset between the Arrènes Fault and the SMVF (Labernardière 1970; Faure 1995). The sinistral sense of displacement is compatible with pull-apart deposits in Carboniferous basins along the Argentat Fault.

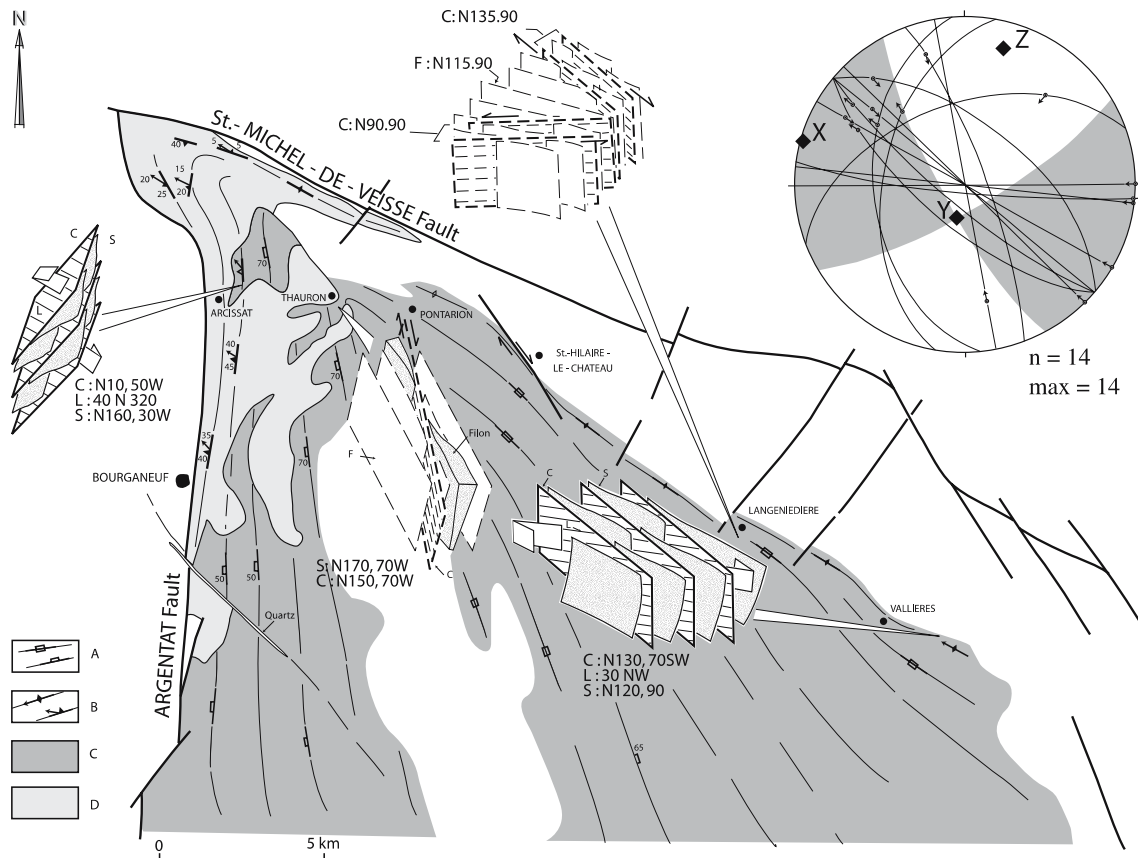


Fig. 6 Pontarion-Royère magmatic complex map and structural observations of C/S structures. *A* magmatic foliation, *B* tectonic foliation, *C* Pontarion-Royère granite, *D* Bourganeuf leucogranite. Faultkin analysis of C planes (Wulff projection, lower hemisphere)

Creuse Fault System and Felletin-Ambrugeat Fault System

Two families of brittle–ductile faults delimit the north-eastern edge of the Millevaches massif. The most important set corresponds to the CFS. The N140/160 CFS, shifts the NMSZ to the CSZ with a 5 km offset dextral displacement. The second set, FAFS, is oriented N15/20 and lately crosscuts all the structures with a brittle dextral sense of shear.

Creuse Fault System

The CFS consists of a set of brittle faults inside the Guéret massif, oriented N140/160. Furthermore, at 335 Ma calc-alkaline coal-bearing pyroclastic deposits (tuf anthracifère) are unconformable on the Guéret massif which outcrops at the surface at the time (Hottin et al. 1991).

In the Millevaches massif, these faults developed in ductile conditions in the Chasselins–Goutelle (Fig. 7) granite (336 ± 3 Ma). The Chasselins–Goutelle granite outcrops with a NE convexity. It underwent a

ductile dextral faulting related to the CFS (oriented N160) (Fig. 7). All the granites are affected by C planes (Fig. 5d–f) developed under greenschist facies metamorphism. Statistical analysis (Allmendinger et al. 1989) of C planes geometry and kinematics reveals a 20/N201 shortening strain axis *Z*, perpendicular to the NMSZ, and a 39/N091 stretching strain axis *X* (Fig. 7). Three samples of Chasselins–Goutelle mylonites are dated by $^{40}\text{Ar}/^{39}\text{Ar}$ on white micas (Gébelin 2004). These $^{40}\text{Ar}/^{39}\text{Ar}$ white mica's ages range between 325 and 304 Ma and are interpreted as a dextral deformation still acting until Namurian–Westphalian times (Gébelin 2004).

Felletin-Ambrugeat Fault System

The FAFS crosscuts the eastern part of the Millevaches massif. These faults are oriented N015–N020 and striations on fault planes are sub-horizontal. They are evidenced by the occurrence of decametrical fault-gouge. The dextral sense of shear is deduced from the displacement of structural markers as the cartographic shape of the Lamazière-Haute granitic intrusion

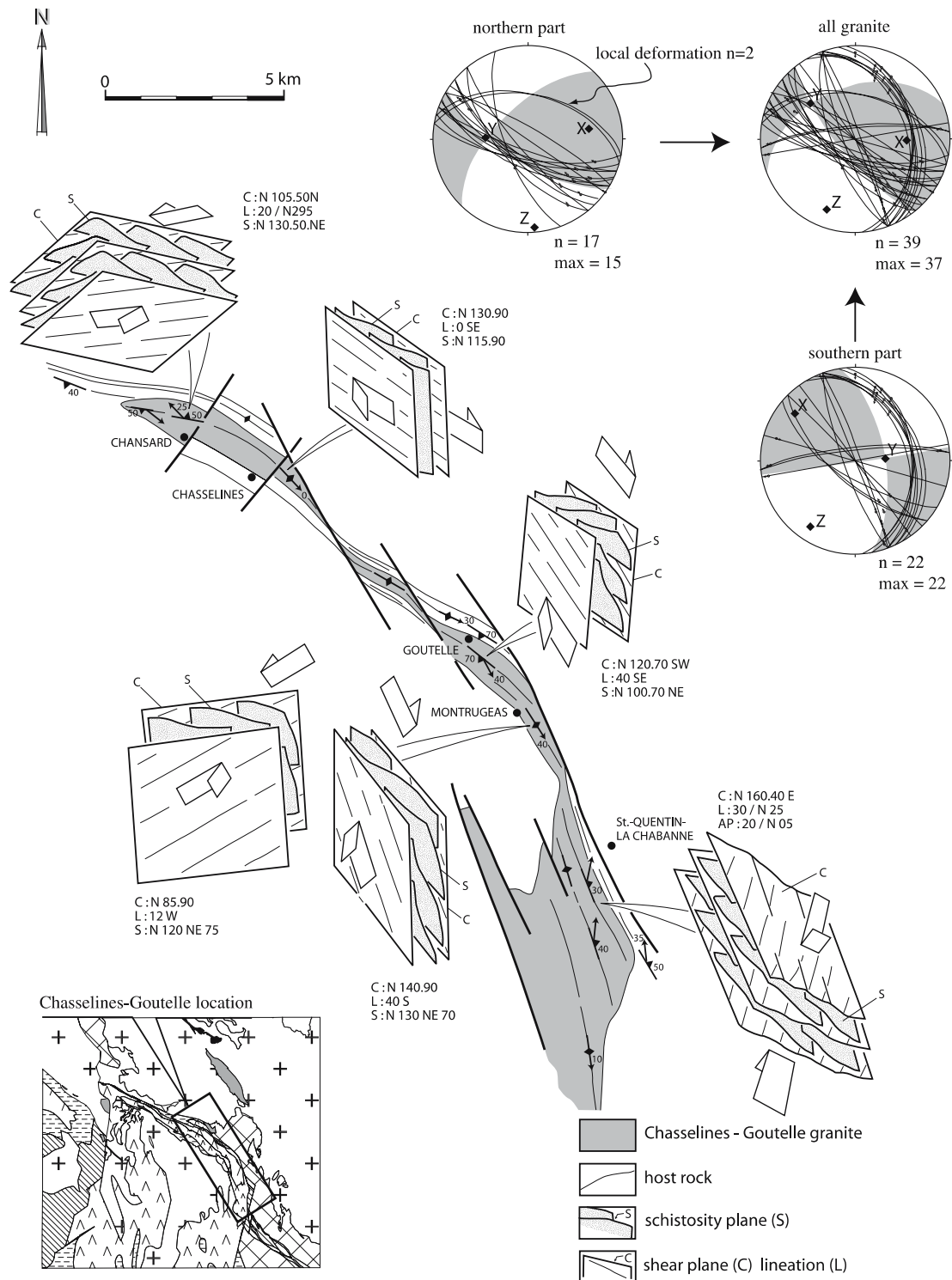


Fig. 7 Chasselins-Goutelle map and structural observations of C/S structures. Faultkin analysis of C planes (Wulff projection, *lower hemisphere*)

(Fig. 2). Undeformed microgranites and rhyolites are observed along these faults. They are related to Permian dykes and post-date the brittle dextral deformation (Bazot 1970). The first stage of activity is

posterior to 315 Ma because the FAFS crosscuts under brittle condition the Courcelles granite dated 318 ± 3 Ma. The cumulative offset on the FAFS is approximately 5 km.

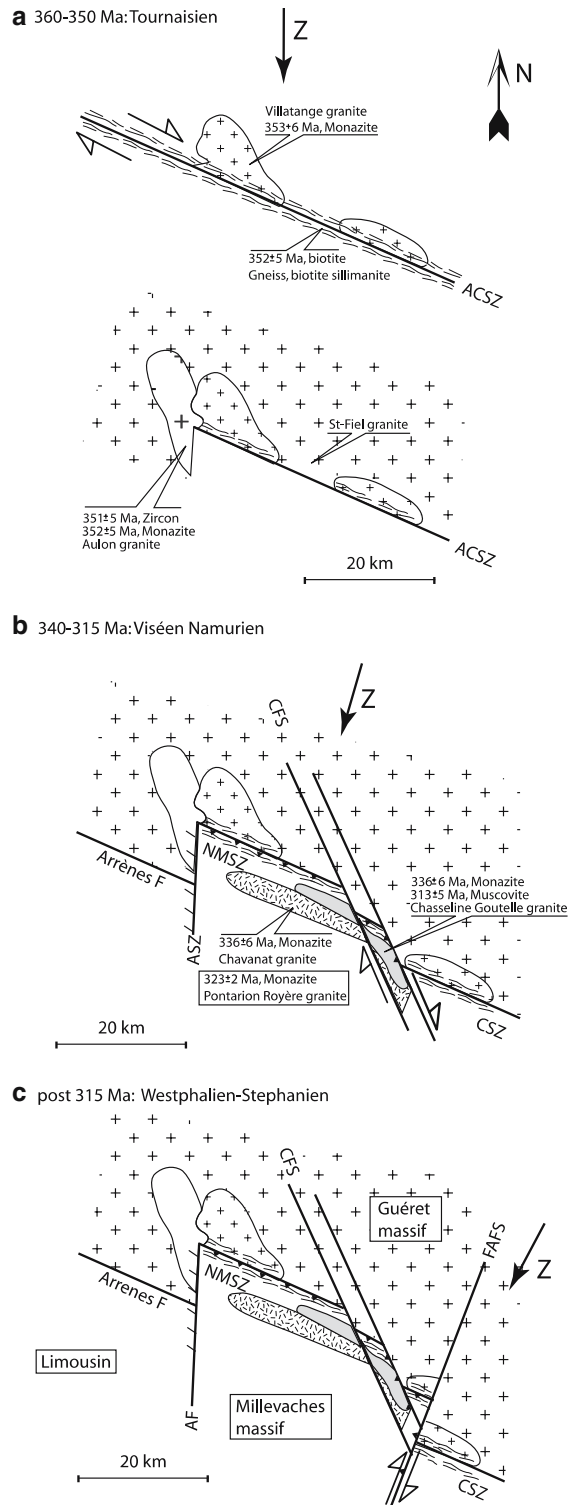


Fig. 8 Schematic Arrènes–la Courtine Shear Zone tectono-magmatic evolution during Carboniferous time (360–300 Ma). *AF* Arrènes Fault, *ASZ* Argenta Shear Zone, *CFS* Creuse Fault System, *CSZ* la Courtine Shear Zone, *FAFS* Felletin-Ambrugeat Fault System, *NMSZ* North Millevaches Shear Zone, *UGU* Upper Gneiss Unit, *LGU* Lower Gneiss Unit, *PU* Paraautochthonous Unit

Interpretation and discussion

A model for the tectonic evolution of ACSZ between 360 and 300 Ma is proposed mainly based on investigated deformations in newly dated granites. The tectonic evolution of the north Millevaches and the Guéret massifs can be described in three main stages, during Tournaisian, Viséan–Namurian and Westphalian times (Fig. 8).

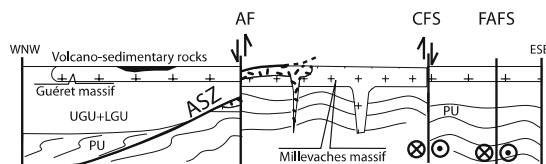
Tournaisian (360–350 Ma)

During the Late Devonian and Tournaisian times the CSZ and NMSZ corresponded to the same crustal scale shear zone with a dextral shear sense (ACSZ) (Fig. 8a). The metatectic paragneisses of north Millevaches and la Courtine are deformed under amphibolite facies condition (Rolin et al. 2006). At around 355 Ma, the first syntectonic Guéret granites (Villatange) were deformed under a greenschist facies metamorphism with a dextral kinematics suggesting a NS trending shortening axis Z. This dextral shearing is sealed at around 350 Ma by the post-tectonic Aulon-Guéret granite. Thus, no large amount of displacement is recorded on the N110 dextral la Courtine Shear Zone (CSZ) and NMSZ after 350 Ma. Inception of the right-lateral offset along the ACSZ occurred immediately after the Late Devonian regional anatexis event dated at 378–368 Ma and most of the offset was achieved at the end of the Tournaisian (Cartannaz et al. 2006a).

Middle Viséan–Namurian (340–315 Ma)

Two tectonic regimes can be inferred for middle Viséan–Namurian times, corresponding to (1) vertical shortening, thinning and exhumation of the Millevaches massif during 340–335 Ma and (2) dextral shearing along the CFS between 335 and 315 Ma.

Between 340 and 335 Ma, a local extensional regime occurs during the synkinematic granite emplacements in the western part of the Millevaches massif (e.g. Bourgneuf leucogranite) close to the ductile normal ASZ. Hydrothermal muscovites from the Bourgneuf leucogranite are dated between 341



and 331 Ma by the $^{40}\text{Ar}/^{39}\text{Ar}$ method (Roig et al. 2002).

An extension tectonics was also argued by Faure et al. (2002) and Roig et al. (2002). They proposed a south-eastwards displacement of the Guéret massif related to the sinistral Marche Shear Zone (MSZ; Fig. 1) and dextral faulting on the ACSZ (Dumas et al. 1990; Faure 1995) from 330 to 310 Ma. In the case of Guéret massif, this tectonics occurs certainly before Middle Viséan because of its near-surface position at this period (Hottin et al. 1991) proved by the volcano sedimentary strata deposited at its surface (Bazot 1970). Moreover, our new results emphasize that the dextral displacements along N110 ACSZ are restricted during Middle and Late Viséan. Consequently, we propose only a local extensional regime along the ASZ during Early Viséan (340–335 Ma).

Between 335 and 315 Ma, a wrench regime occurs along faults oriented N150 in the eastern part of the studied area where the NMSZ and CSZ were disrupted by the dextral CFS (Fig. 8b). The CFS, coeval to Chavanat sillimanite leucogranite and Chasselins–Goutelle leucogranite emplacements, is not affected by the normal ASZ proving the end of extensional regime. The leucogranites underwent a coaxial deformation with a horizontal shortening axis Z oriented N20. Biotite granites, like the Pontarion-Royère granites (ca. 324 Ma), and a new generation of two mica granites, like the Courcelles leucogranite (ca. 318 Ma), also intrude the metamorphic Millevaches massif under a coaxial deformation with N20 trending shortening axis. Locally, the N20 shortening induces reverse faulting on the SMVF, progressively moving the deep-seated Millevaches close to its actual position with respect to the Guéret massif.

Post 315 Ma

The last stage of deformation of this segment corresponds to the dextral movement along the FAFS oriented N15/N20 (Fig. 8c). This movement occurred after the emplacement of the Courcelles granite dated 318 ± 3 Ma and before undeformed rhyolitic dykes, probably of Permian age. During that time, the Millevaches massif was still uplifted with respect to the Guéret massif.

This multi-stage deformation of the ACSZ allows us to explain the cartographic shape of the north-eastern part of the Millevaches massif which does not correspond to the single fault envisaged by several authors (Chantraine et al. 1996; Forestier 1965; Gébelin 2004; Lameyre 1982).

Conclusion

New dating by chemical method on monazite and zircon proposes a new geodynamic evolution which refines more precisely the wrench frame in a crustal shortening during Carboniferous times in the Northern French Massif Central. The first emplacement of the Guéret granite occurred during non-coaxial deformation along N110 dextral shear zone (ACSZ) which stopped its major displacement at around 350 Ma with the emplacement of the undeformed Aulon-Guéret granite. Inception of the movement of these high-strain zones began before the Tournaisian (Cartannaz et al. 2006a). This N110 major dextral shear zone (ACSZ) was disrupted by the beginning of wrench regime along the dextral CFS. A final stage consists in brittle faulting along two meridian major zones (AF, FAFS) that cut across the two previous shear zones, resulting in the final cartographic pattern of the studied area.

New results also lead to refine the extensional frame in space and time in this area. The syntectonic leucogranite Bourganeuf experienced syncollisional extension during Middle Viséan time (335–340 Ma). The end of this local extensional regime took place at 335 Ma. The kinematic analysis in the studied area emphasizes a strong horizontal displacement along N110 fault before Tournaisian times (370–350 Ma) and weak horizontal displacement during Viséan–Namurian times (350–315 Ma) along the N110 ACSZ.

Acknowledgments This work was supported by the mapping program of BRGM. The constructive comments by D. Gapais helped us to clarify our understanding of the Variscan tectonic frame. O. Fabbri is thanked for his remarks on the manuscript and S. Andre for Pontarion and Goutelle drawing. Prof. Van den Driessche and an anonymous reviewer are thanked for their helpful reviews.

Appendix 1: Analytical procedure

EPMA dating

The electron probe microanalyzer (EPMA) is becoming increasingly popular for determining Th–U–Pb_{tot} ages on monazite because it provides a true in situ high spatial resolution method and because it is a non-destructive method. The monazite mounted in resin and polished to obtain cross-sections of the grain was analysed using a Cameca SX 50 electron microprobe. The analytical procedure for monazite was detailed in Cocherie et al. (1998, 2005a). The interference of $\text{YL}\gamma$ on $\text{PbM}\alpha$ is subtracted offline by applying a coefficient of interference to the value of Y . The

different interference corrections have been validated by dating several monazite samples using this method and conventional isotopic methods (Cocherie et al. 1998). An acceleration voltage of 20 kV was considered while a beam current of 200 nA is now applied. According to this procedure, the calculated detection limits (2σ) are 110 ppm for Pb, 105 ppm for U and 130 ppm for Th, whereupon the absolute error is taken as 110, 105 and 130 ppm, respectively. A systematic relative error of 2% is considered for Th (whose concentration is generally above 6,500 ppm) and also for U concentrations above 5,250 ppm in order to avoid an unrealistic low error for U-enriched grains (Cocherie and Legendre 2006). For monazite the standards were galena (PbS) for Pb, uraninite (UO₂) for U, thorite (ThO₂) for Th, endmember synthetic phosphates (XPO₄) for each rare-earth element (REE) and Y, apatite for P and andradite for Si and Ca.

If two or more homogeneous age domains are separated by a gap that is lower than the analytical error on each individual spot analysis age, these can be identified by suitable isochron diagrams (Cocherie and Albarède 2001; Cocherie et al. 1998; Suzuki and Adachi 1991). A recent study shows how to provide precise ages of ± 5 to 10 Ma (2σ) using the most suitable isochron diagram according to the geochemistry of the studied grains (Cocherie et al. 2005a).

With an obvious need for a program to simplify individual age and isochron mean-age calculations, we created *EPMA dating*, a Microsoft Excel add-in program for determining U–Th–Pb_{tot.} ages from EPMA measurements (Pommier et al. 2002). All the parameters needed to calculate mean and intercept ages are computed, ready to be plotted using the *ISOPLOT* program (Ludwig 1999) in order to obtain statistics from suitable diagrams. Finally, *EPMA dating* produces (1) the age and error from the slope of the Pb versus Th* diagram, (2) the U–Th–Pb age at the centroid of the best-fit line and (3) the Th–Pb age (intercept with Th/Pb axis) and the U–Pb age (intercept with U/Pb axis) from the Th/Pb versus U/Pb diagram. All calculations were done at 2σ level. A special care was taken on the MSWD (mean squared weighted deviation) which must be below $1 + 2/(2/f)^{0.5}$ (f : degree of freedom = number of analyses – number of dated events) in order to validate age calculation (Wendt and Carl 1991) for a single age population.

The three starting assumptions are: (1) common Pb is negligible as compared to the amount of thorogenic and uranogenic lead; (2) no radiogenic Pb loss has occurred since system closure; (3) a single age is involved at the size level of each individual spot analysis. After comparison with conventional isotopic U–Pb age

determinations, it is now accepted that EPMA resolution allows to avoid inclusions and altered domains that could potentially contain common Pb. Systematic BSE study was performed to investigate monazite micro-texture for all mounted grains.

SHRIMP dating

Zircons were dated using the ion microprobe (SHRIMP II) of the Australian National University, Canberra, according to the procedure described by Williams (1998). The areas analysed ($\sim 25 \mu\text{m}$) were selected after studying images of the grains obtained by cathodoluminescence and by transmitted light microphotography. The determination of the $^{238}\text{U}/^{206}\text{Pb}$ ratio necessitated the external calibration of the measurements with the aid of a particularly homogeneous standard zircon of known composition: the Duluth Gabbro (Paces and Miller 1993). In general, areas very rich in U ($> 2,000$ – $3,000$ ppm) were not selected in order to avoid, first, moving away from the area of validity of the U–Pb calibration line and, secondly, the risk of losses of radiogenic Pb, in relation to the metamictisation. For the relatively recent zircons ($< 1,000$ Ma), the imprecision of the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio becomes critical; one then uses the Concordia diagram of Tera and Wasserburg (1972), modified by Compston et al. (1992), in which one plots the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ ratios, not corrected for common Pb. In the absence of common Pb, the analyses of areas not affected by thermal events subsequent to the crystallisation of the zircon or by inherited cores are spread along this Concordia (Williams 1998). Although the variable quantities of common Pb adversely affect the values of the two ratios, these kinds of points form a straight line passing through the composition of common Pb ($^{207}\text{Pb}/^{206}\text{Pb}$) at the estimated age of the system given, in a first approximation, by the average $^{238}\text{U}/^{206}\text{Pb}$ ages stemming from the concordant analyses. The extrapolation of this line on the Concordia defined the sought age. This is what is called a correction of common Pb by the ^{207}Pb method and not by the ^{204}Pb method, as in the case of the conventional diagram. Using this correction method, one calculates the $^{206}\text{Pb}^*/^{238}\text{U}$ (Pb^* = radiogenic Pb) ratios for each point.

Whatever analytical approach was used, all the calculations were made at 2σ (95% confidence limit) using the *ISOPLOT* program (version 2) of Ludwig (1999). On the other hand, in the case of the data obtained using the SHRIMP, the uncertainties are given at 1σ in the corresponding table and, in the same way, the error ellipses are given at 1σ in order to make the figures easier to read.

Appendix 2: Sample location

Sample	X Lambert 2	Y Lambert 2	Locality	Rock type
CJ 51	554.95	2,116.76	Villatange	Granodiorite
LB 92	552.21	2,119.63	Aulon	Leucomonzogranite
LA 48	571.38	2,105.92	Chavanat	Two-mica granite
CJ 41	582.42	2,101.76	Goutelle	Leucogranite
CJ 47	569.45	2,102.36	Royère	Garnet, cordierite granite
CJ 53	576.38	2,105.20	Courcelles	Leucogranite

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