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Structure and U–Pb dating of the Saint-Arnac pluton and the Ansignan charnockite (Agly Massif): a cross-section from the upper to the middle crust of the Variscan Eastern Pyrenees

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Abstract: In the Agly Massif (Pyrenees), two Variscan plutons, the Saint-Arnac pluton and the Ansignan charnockite, intrude different levels of a *c.* 10 km thick crustal section. The Saint-Arnac pluton intrudes through upper crustal rocks and the Ansignan charnockite cuts mid-crustal country-rocks. A structural study of these plutons based on the anisotropy of magnetic susceptibility technique, combined with a kinematic study of the country-rocks, shows that the structures and emplacement modes of the plutons are compatible with those of the other plutons of the Pyrenees emplaced during the D_2 transpressive phase. U–Pb dating on zircons from the Saint-Arnac pluton yields a 308.3 ± 1.2 Ma age for a diorite and a 303.6 ± 4.7 Ma age for a granodiorite. The charnockite was previously dated at 315 Ma. The emplacement ages of these two intrusions are thus separated by at least 5 Ma. First, numerous sills and laccoliths, such as the Ansignan laccolith, were injected in the middle crust, and this induced heating and thickening. Subsequently, the large Saint-Arnac pluton was injected in the upper crust at the beginning of formation of a gneissic dome.

Many plutons are exposed along the Variscan chain of the Pyrenees, both in the Axial Zone and in the North Pyrenean Zone (Fig. 1a). Petro-structural studies have been performed recently on most of them, generally by means of the anisotropy of magnetic susceptibility (AMS) technique; plutons studied recently include the Quérigut (Auréjac *et al*. 2004), Bielsa (Román-Berdiel *et al*. 2004) and Bordères (Gleizes *et al*. 2006) plutons. These bodies are intrusive at different levels of the crust and display various structural features. In spite of these differences, several features (S-sigmoids and HT reverse dextral movements in the granites; systematic east–west-trending dextral senses of shear in the country-rocks) have been used to support an interpretation that the emplacement of all these plutons was coeval with a dextral transpressive event (Leblanc *et al*. 1996; Druguet & Hutton 1998; Gleizes *et al*. 1998*b*), the so-called D_2 main phase. Recent U–Pb dating of zircon from several plutons has shown that they were emplaced in the 312–301 Ma time span (Fig. 1a): Bassiès at 312 ± 3 Ma (Paquette *et al*. 1997); Quérigut at 307 ± 3 Ma (Roberts *et al*. 2000); Mont-Louis at 305 ± 3 Ma (Maurel *et al*. 2004); Cauterets at 301 ± 7 Ma and Eaux-Chaudes at 301 ± 9 Ma (Ternet *et al*. 2004), and Bordères at 309 ± 4 Ma (Gleizes *et al*. 2006).

In the Agly metamorphic dome (Eastern Pyrenees) several granitic bodies crop out, the main two being the Saint-Arnac pluton to the north and the Ansignan charnockitic pluton to the south (Fig. 1b and c). The Saint-Arnac pluton intrudes greenschist- to amphibolite-facies country-rocks, whereas the Ansignan charnockite has granulite-facies country-rocks. The study of the structure of these plutons and their country-rocks is thus interesting in that it offers, over a restricted area, a cross-section of at least 10 km thickness of the Variscan crust of the Pyrenees.

Previous U–Pb zircon ages from the charnockite (*c*. 315 Ma, Respaut & Lancelot 1983) and from a granitic sill that crops out in the gneissic core of the Agly Massif (317 ± 3 Ma, Olivier *et al*. 2004) indicate emplacement ages older than those given above for most of the plutons of the Pyrenees. Therefore, it appeared necessary to date also the Saint-Arnac pluton, to determine the chronological relationships between the various granites of the Agly Massif, and, more generally, with the other granites of the Pyrenees. On the other hand, a structural study of the charnockite (Althoff *et al*. 1994) concluded that it was emplaced in an extensional regime, whereas the Saint-Arnac granite, emplaced later, would have recorded the end of this extension. These conclusions are at odds with those of more recent studies (Auréjac *et al*. 2004; Román-Berdiel *et al*. 2004) showing that the emplacement of most of the plutons of the Pyrenees took place in a transpressive regime. The aims of this paper are: (1) to present a detailed structural study, using the AMS technique, of both the Ansignan and Saint-Arnac granites; (2) to date precisely the latter; (3) to specify the relationships between granite emplacement and gneissic dome formation.

Geological setting

The Agly Massif is the easternmost Variscan massif of the North Pyrenean Zone (Fig. 1a). It is located between the Aptian–Albian formations constituting the Saint-Paul-de-Fenouillet and Agly synclines to the north and the Boucheville syncline to the south, which are all east–west-trending (Fig. 1b). This massif forms a N110°E-trending half-dome, split by many N110°E-trending Alpine faults that display systematically down-dip lineations corresponding to vertical or reverse movements, related to the uplift of this dome and its northward thrusting on the Saint-Paul-de-Fenouillet syncline. The Agly Massif is formed

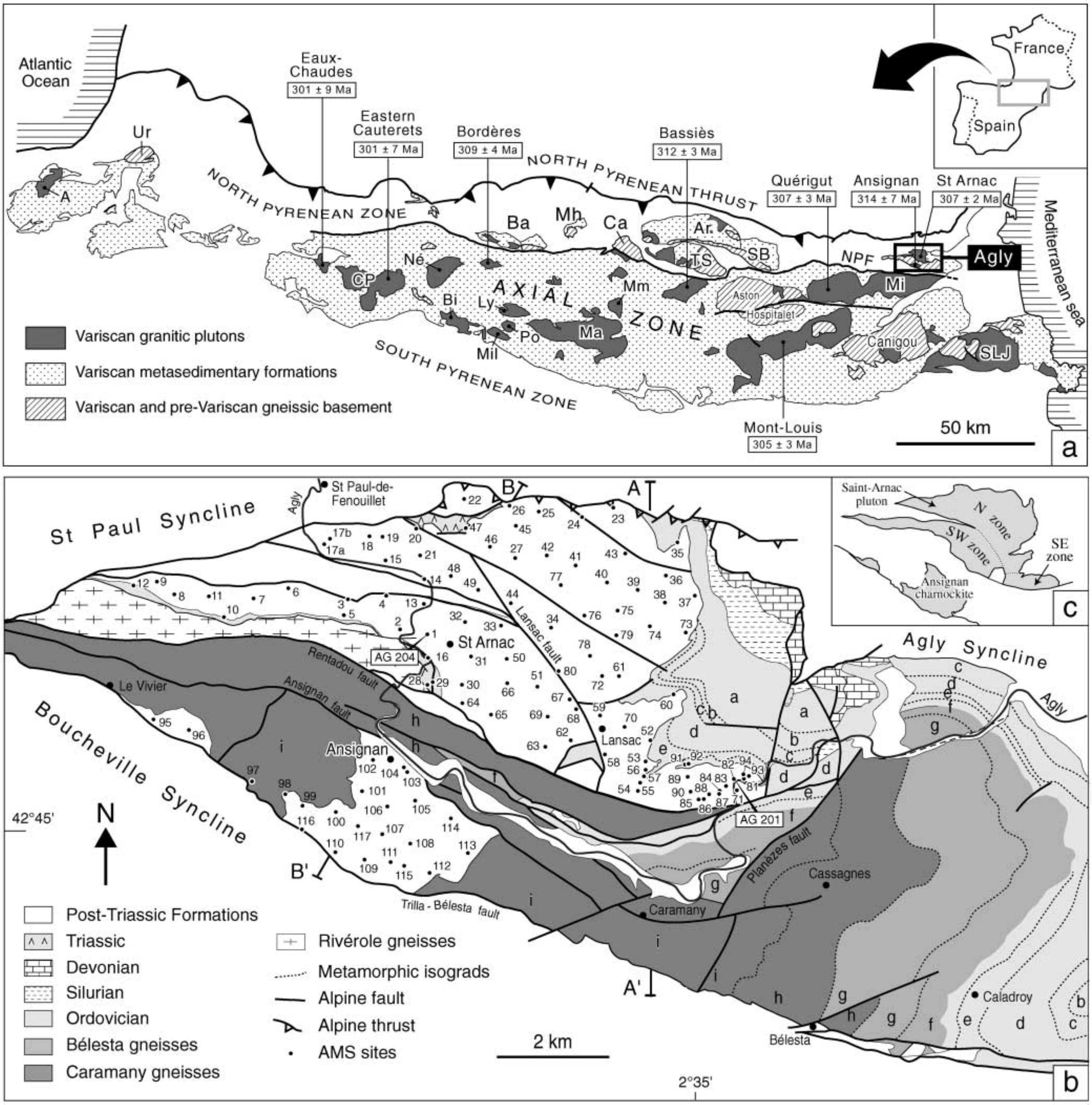

Fig. 1. The Agly Massif in the Variscan Pyrenees. (**a**) Structural sketch of the Pyrenees showing from west to east: (1) the North Pyrenean massifs (Ursuya (Ur), Barousse (Ba), Milhas (Mh), Castillon (Ca), Arize (Ar), Trois-Seigneurs (TS), Saint-Barthélémy (SB) and Agly); (2) the main granitic plutons of the Axial Zone (Aya (A), Eaux-Chaudes, Cauterets–Panticosa (CP), Néouvielle (Né), Bielsa (Bi), Bordères, Millares (Mil), Posets (Po), Lys–Caillaouas (Ly), Maladeta (Ma), Marimanha (Mm), Bassiès, Mont-Louis, Quérigut, Millas (Mi) and Saint Laurent–La Jonquera (SLJ)). NPF, North Pyrenean Fault. (**b**) Geological sketch-map of the Saint-Arnac and Ansignan plutons (after Delay 1990; Fonteilles *et al*. 1993, modified): a, chlorite zone; b, biotite zone; c, cordierite zone; d, andalusite zone; e, sillimanite zone; f, sillimanite + K-feldspar zone; g, cummingtonite zone; h, hypersthene + hornblende zone; i, hypersthene zone; A–A′ and B–B′ are the cross-sections shown in Figure 5b. Location of the 117 oriented sampling sites measured for the AMS study of the Saint-Arnac and Ansignan plutons is shown. AG 201 and AG 204 are samples dated by U–Pb on zircons in this study. (**c**) The three petro-structural zones of the Saint-Arnac pluton.

of a granulitic gneissic core (Belesta and Caramany gneisses), considered to be a late Proterozoic basement, and a conformable amphibolitic to weakly metamorphic cover, essentially consisting of micaschists, of Ordovician to Devonian age (Berger *et al*. 1993). This massif has been much studied for its high-temperature–low-pressure (HT–LP) metamorphism characterized by a particularly strong geothermal gradient, which is locally higher than 100 °C km^{-1} (Fonteilles 1976; Vielzeuf 1984; Delay 1990).

The Saint-Arnac pluton (25 km^2) was injected into Ordovician metapelites (Fig. 1b). Along its eastern border a contact metamorphic aureole, oblique to the regional isograds, may be observed. The present position of the pluton, with metamorphic conditions of its country-rocks increasing to the south, indicates that (1) the southern boundary corresponds to the floor of the pluton, intrusive in more or less anatectic sillimanite-bearing micaschists to the SW and in gneisses with sillimanite + K-feldspar ± garnet corresponding to P–T conditions estimated at 2.5–3 kbar and 650–700 °C (Vielzeuf 1996) to the SE, and (2) the northern part of the pluton is close to its roof, intruding into greenschist-facies metapelites. Such relationships between the metamorphic country-rocks and the pluton imply a northward tilt after its emplacement. As the observed thickness of the pluton is about 5 km from the floor to the highest part in the north, the pressure conditions near the roof may be estimated at 1–1.5 kbar. The base of the pluton is formed to the west by granodiorites and tonalites and to the east by granodiorites and a 1 km thick sheet of diorites (Tournefort diorite). The core and the roof of the pluton are made up of monzogranites.

The charnockitic pluton of Ansignan (5 km^2) crops out in the deepest part of the Agly Massif, as a 1 km thick laccolith (Fig. 1b). A smaller charnockitic body (0.5 km^2) appears to the west. The laccolith is composed of biotite- and orthopyroxene-bearing porphyritic granodiorites representing the main part of the pluton, 1–100 m thick levels of orthopyroxene- and biotite ± clinopyroxene-bearing norites, and a border facies of garnet ± orthopyroxene-bearing leucogranite. These parageneses are stable and in thermal and barometric equilibrium with the paragneissic country-rocks metamorphosed in the hypersthene zone of the LP granulites facies (Fonteilles 1976). They allowed the estimation of the P–T conditions at 5 ± 0.5 kbar and 700–800 °C (Vielzeuf 1984). The main charnockitic body is separated to the north from the Saint-Arnac pluton by a 1 km wide, N110°E-trending band of gneisses metamorphosed in the hypersthene + hornblende zone. This band, where the P–T conditions are estimated at 3.5–4 kbar and 650–700 °C (Vielzeuf 1984), is bounded by the Rentadou and Ansignan N110°E-trending faults, to the north and south, respectively (Fig. 1b).

AMS study of the Saint-Arnac and Ansignan plutons

The now classical AMS technique applied to granitoids has been described in many publications (e.g. Borradaile & Henry 1997; Bouchez 1997) and we will recall here only the points useful for understanding the present study. Susceptibility measurements of oriented samples allow the calculation of the mean axes of the AMS ellipsoid $K_1 \geqslant K_2 \geqslant K_3$ of a site. Various parameters are then deduced: the mean magnetic susceptibility K_m, the magnetic lineation K_1, the magnetic foliation (which is the plane normal to K_3), the total anisotropy ratio P_{para}% and the shape parameter T.

For this study, the distance between the sampling sites varies from 0.5 to 1 km, except in the southeastern zone of the Saint-Arnac pluton, where the sites are 0.1 km apart. A total of 117 sites were drilled (Fig. 1b). The results of the AMS study are given in Table 1. Because the Saint-Arnac pluton has zones with very different petro-structural features, we have subdivided this pluton into three zones: northern, southwestern and northeastern (Fig. 1c).

Magnetic susceptibility and petrography

The values of $K_m = (K_1 + K_2 + K_3)/3$ (Fig. 2 and Table 1) are generally low ($<500 \times 10^{-6}$ SI), indicating that these rocks are dominantly paramagnetic, like most plutons of the Pyrenees (Gleizes *et al*. 1993). However, three sites displaying high susceptibilities ($>1000 \times 10^{-6}$ SI), located in hydrothermalized and fractured areas of the northern zone of the Saint-Arnac pluton, correspond to rocks with a ferromagnetic component; this was found to be magnetite, as demonstrated by K_m v. temperature measurements made at site 43, which displayed a Curie point at about 580 °C. Petrographic types determined from thin sections show a good correlation with K_m values.

In the Saint-Arnac pluton, the three zones display a wide range of magnetic susceptibilities (Fig. 2). The northern zone consists of three types of monzogranite: to the south, the two-mica and microcline Lansac granite ($(120–150) \times 10^{-6}$ SI); to the north, a biotite porphyritic granite ($(100–200) \times 10^{-6}$ SI); and a central two-mica granite ($(40–100) \times 10^{-6}$ SI). The southwestern zone is almost entirely formed of biotite-bearing porphyritic granodiorites ($(200–250) \times 10^{-6}$ SI), passing into tonalites ($(250–350) \times 10^{-6}$ SI) with abundant flattened basic enclaves near the pluton floor. In the southeastern zone, the highest susceptibilities ($(350–550) \times 10^{-6}$ SI) correspond to the Tournefort diorite and the lowest values ($(200–350) \times 10^{-6}$ SI) correspond to biotite ± hornblende granodioritic to tonalitic types.

In the Ansignan charnockite, the norite layers have relatively high susceptibilities ($(350–750) \times 10^{-6}$ SI). The biotite and orthopyroxene porphyritic granodiorites forming the main part of the laccolith have intermediate values ($(150–350) \times 10^{-6}$ SI) and the garnet leucocratic type located on the borders of the laccolith has weaker susceptibilities ($(50–150) \times 10^{-6}$ SI).

AMS directional data

Magnetic foliations. As a test of the reliability of the magnetic measurements presented below, field measurements have also been performed on the mineral foliations in the strongly foliated southern border of the Saint-Arnac pluton and in the Ansignan charnockite, where the magmatic foliations are well defined by the K-feldspar megacrystals. These field measurements are very similar to the corresponding AMS measurements (Table 1).

In the Saint-Arnac pluton, the three zones display different patterns of planar fabrics (Fig. 3a). The northern zone is divided into compartments by several NW–SE-trending Alpine faults, which interrupt the foliation trajectories. The stereonet corresponding to this zone shows that the foliations are rather scattered but there is a clear tendency to a northeastward dip (mean foliation 122°NE45°). The southwestern zone is characterized by foliations with generally northeastward steep dips (mean foliation 123°NE79°), the trajectories forming an arc of a circle parallel to the pluton floor. In the southeastern zone, the foliations are roughly east–west-trending and subvertical (mean foliation 84°N83°) with trajectories outlining a vertical-axis large fold truncated to the south by the Rentadou fault.

The Ansignan charnockite is characterized by shallowly dipping foliations (mean foliation 67°NW11°, Fig. 3a). The foliation trajectories show that the laccolith has a synformal shape, predominantly conformable with the country-rocks, with dips to the SW on the northern border and dips to the NW on the southern border.

Magnetic lineations. In the Saint-Arnac pluton, the northern and southern halves of the pluton display very different structural patterns (Fig. 3b). In the northern zone the stereographic projection of the lineations shows that they are dominantly grouped in the northeastern quadrant with a moderate plunge (mean lineation 049°/45°) but, as for the foliations, the trajec-

Table 1. *AMS measurements, field foliations and petrographic types of the Saint-Arnac (sites 1–95) and Ansignan (sites 96–117) plutons*

Site	Type	K_m (10^{-6} SI)	P_{para}%	T	Magnetic fabrics (deg)		Field foliations (deg)	Site	Type	K_m (10^{-6} SI)	P_{para}%	T	Magnetic fabrics (deg)		Field foliations (deg)
					Lineation	Foliation							Lineation	Foliation	
1	gd	256	5.8	0.21	256/82	109 S 86	104 S 88	59		69	2.9	0.15	56/38	149 E 35	
2	gd	229	5.5	0.58	46/85	116 N 84	107 N 71	60	mg2m	49	2.1	−0.29	11/67	51 N 72	
3		235	5.5	0.45	23/57	82 N 31		61		138	2.0	0.64	279/36	65 N 53	
4	dq	386	5.3	0.77	331/71	90 N 74		62	gd	168	5.6	−0.02	356/65	152 E 79	
5	gd	222	10.4	0.59	51/60	77 N 74	95 N 70	63	gd	191	6.5	−0.25	56/61	118 N 66	130 N 70
6		203	4.2	0.25	173/86	89 S 85	95 N 80	64	gd	256	7.4	0.41	86/81	176 E 81	160 E 80
7		227	3.2	0.61	310/76	96 N 75		65	gd	222	5.3	0.22	8./80	146 E 83	
8		338	9.2	0.53	293/45	105 N 82	108 N 80	66		83	1.8	0.64	5./69	128 N 76	
9	ton	247	7.0	0.31	260/67	91 S 86	90 S 80	67		262	2.8	0.01	8./67	179 E 90	
10	ton	300	10.4	0.83	66/62	91 N 78	90 N 80	68		207	5.3	−0.4	142/60	0 E 70	170 E 80
11	gd	251	3.9	0.43	216/47	85 S 62		69		216	4.8	−0.05	64/69	143 E 69	
12	ton	296	7.3	0.43	29/41	100 N 43	93 N 57	70		106	4.7	−0.04	73/61	118 N 69	
13		249	5.7	0.21	306/74	107 N 85	115 90	71		357	10.1	0.24	126/80	151 E 86	
14	mg2m	67	1.8	−0.01	35/30	147 E 55		72	mg	74	2.3	0.29	45/52	111 N 52	
15	mg	149	1.6	−0.19	74/39	131 E 49		73		186	1.7	0.31	21/51	70 N 58	
16	gd	203	9.2	0.56	350/61	150 E 79	150 E 70	74		169	0.9	−0.45	39/52	34 SE 55	
17a		32	0.7	−0.13	164/32	53 S 41		75		151	1.9	0.29	23/31	164 E 45	
17b		129	0.5	−0.03	288/69	57 N 68	52 N 70	76		153	1.1	−0.13	28/45	98 N 46	
18		120	1.3	−0.06	254/84	105 S 88		77		141	1.9	0.46	54/26	153 E 32	
19	mg2m	119	1.7	0.12	66/9	52 S 67		78		74	1.3	0.4	21/50	92 N 49	
20		141	3.4	0.06	69/3	70 N 78		79		87	1.7	0.1	78/43	126 N 50	
21		162	1.3	0.15	95/14	119 N 35		80		72	1.4	0.00	91/81	101 N 88	
22		166	1.6	0.29	43/2	33 E 22		81	d	498	8.4	0.43	184/66	144 W 73	
23		154	2.8	−0.15	39/40	175 E 52		82	d	505	6.1	0.04	247/83	110 S 83	
24	mg	3813	–	0.21	148/42	138 W 72		83	d	432	8.2	0.33	167/79	82 S 80	
25		149	1.4	0.18	39/8	112 N 7		84	d	540	16.0	0.35	333/55	103 N 62	
26		212	2.2	0.04	286/3	104 N 82		85	d	508	–	0.13	254/57	65 N 84	
27		182	1.0	0.31	286/30	103 S 67		86	gd	313	7.7	−0.24	229/66	15 W 76	
28	Rg	172	13.9	0.58	93/60	143 E 66	155 E 65	87	gd	316	7.2	0.13	–	79 N 84	
29	ton	361	8.5	0.36	33/68	162 E 72	170 E 80	88	gd	394	11.3	0.16	331/65	92 N 68	
30	ton	249	6.1	0.38	351/62	139 E 73	150 E 80	89	gd	259	7.8	−0.08	236/70	82 S 80	
31	gd	224	4.8	0.19	123/73	102 S 85	105 S 80	90	gd	334	9.6	0.05	258/62	68 N 84	
32		273	5.1	0.16	190/78	125 S 79	120 90	91	gd	276	10.9	−0.26	354/87	56 N 87	
33		91	2.6	0.12	108/59	106 S 90	110 90	92	gd	230	9.1	−0.31	335/71	60 N 71	
34		59	1.6	−0.27	89/29	96 N 76		93	gd	299	9.6	0.23	352/71	141 E 81	130 N 85
35	mg	34	1.0	0.65	311/12	108 N 29		94	d	372	10.3	0.07	247/52	113 S 60	120 S 60
36		157	1.4	0.3	14/53	168 E 88		95		296	8.8	−0.30	58/43	127 N 43	
37		163	2.3	−0.14	4/81	–		96		922	32.9	−0.09	24/18	21 E 73	
38		163	1.4	0.39	356/29	149 E 65		97		113	1.2	−0.04	259/30	98 S 55	
39		153	1.3	−0.08	44/43	145 E 44		98		224	2.6	−0.13	227/5	30 W 15	
40	mg	1389	1.4	−0.06	38/18	152 E 20		99		274	11.1	0.28	238/16	18 W 23	
41		139	1.3	0.23	12/31	119 N 31		100	gd	219	7.1	0.12	51/4	71 N 16	
42		142	1.9	0.15	69/33	162 E 34		101		154	7.5	0.32	251/20	149 W 17	
43		4656	5.8	0.46	–	–		102		241	8.5	0.06	228/5	56 S 17	

44		58	1.8	0.25	279/52	87 N 87		103		484	19.6	−0.02	238/41	120 S 43
45		146	1.4	0.14	200/2	–		104		706	10.8	0.11	245/64	91 S 79
46		154	1.9	0.25	–	143 E 21		105	gd	496	11.9	−0.06	249/25	22 W 31
47	mg	102	2.1	0.34	19/40	148 E 49		106		190	8.1	0.21	39/11	156 E 16
48		46	1.6	0.2	93/24	144 E 47		107		67	7.2	0.35	47/7	135 E 8
49		44	1.9	−0.03	93/ 5	53 S 5		108		396	5.4	0.37	258/1	68 N 6
50	mg	218	2.3	−0.01	119/75	146 E 83		109		167	10.1	0.21	273/5	91 N 32
51	gd	218	3.7	−0.14	17/78	155 E 82	135 E 80	110	gd	204	4.8	0.35	241/0	75 N 22
52	mg	132	8.0	0.2	116/62	101 S 46		111		251	5.4	−0.03	43/12	80 N 19
53	mg	138	5.1	0.11	226/48	23 W 70	50 W 70	112	gd	237	10.7	0.39	49/26	95 N 35
54	gd	215	8.3	0.21	342/66	100 N 69	95 N 75	113		148	3.2	0.32	30/44	88 N 49
55	gd	217	8.8	0.08	278/82	81 N 86	70 90	114		261	6.9	0.25	223/8	148 W 7
56	gd	243	8.1	−0.09	266/87	58 N 88	65 S 80	115	n	709	18.1	0.13	52/8	73 N 26
57	gd	358	11.3	0.16	313/68	98 N 77	75 N 60	116		96	5.2	0.44	35/0	33 W 9
58		147	3.7	−0.07	280/44	143 W 53	150 W 65	117		167	4.4	0.33	226/2	51 N 15

Petrographic types listed in column 2 were determined in thin sections. d, diorite; gd, granodiorite; Rg, Rivérole orthogneiss; mg, biotite monzogranite; mg2m, two-mica monzogranite; ton, tonalite; n, norite.
A dash indicates ill-defined data.

tories are interrupted by the Alpine faults. In both the southwestern and southeastern zones the lineations are systematically subvertical (mean lineations 029°/80° and 279°/79°, respectively).

The Ansignan charnockite displays subhorizontal lineations strongly grouped along a NE–SW direction (mean lineation 233°/1°). Because of the synclinal structure of this laccolith, the lineations are southwestward plunging on the northern border and northeastward plunging or horizontal in the southern half.

Anisotropy of the magnetic susceptibility and shape of the AMS ellipsoid

The anisotropy ratio used in this study is $P_{para}\% = [(K_1 - D)/(K_3 - D) - 1] \times 100$, where D is the diamagnetic contribution ($c.$ -14.6×10^{-6} SI) (Rochette 1987).

In the Saint-Arnac pluton, $P_{para}\%$ values range from 0.5 to 16.0 (Table 1 and Fig. 4), the mean being 4.8. Overall, the anisotropy increases from north to south; that is, from the roof to the floor of the pluton. In detail, the three zones are contrasting. The northern zone generally displays weak anisotropies ($P_{para}\%$ <2 for 64% of the sites, mean 2%) with a noticeable increase to 4.7% towards the southeastern zone. Site 43 shows an 'abnormal' $P_{para}\%$ of 5.8 as a result of the ferromagnetic contribution (see above). The southwestern zone displays a well-marked zonation of the anisotropy parameter, which increases regularly from the core of the pluton ($P_{para}\%$ <3) towards the floor, where the values may exceed 10%. The southeastern zone is characterized by high anisotropies (mean 10.3%): 8–11% for the granodiorite, and 6–16% for the Tournefort diorite.

The Ansignan charnockite displays generally high values of $P_{para}\%$ (mean 9.4; Fig. 4). The lowest values (3–7%) are located in a central east–west-trending band, whereas the highest values ($>10\%$) are located near the northern and southern borders of the laccolith, generally corresponding to basic rocks.

These $P_{para}\%$ values show a good correspondence to the microstructural types (Fig. 4) observed in thin-sections. The anisotropies $<2\%$ correspond to magmatic microstructures and the 2–5% values correspond to a weak submagmatic deformation. The anisotropies $>5\%$ correspond to different microstructures: (1) for the Ansignan charnockite they correspond to magmatic and subsolidus states; (2) for the southwestern zone of the Saint-Arnac pluton, there is a continuum of deformation in the HT subsolidus deformation increasing towards the tonalite that forms the floor of the pluton; (3) in the southeastern zone of this pluton the granodiorite and the Tournefort diorite show an important solid-state deformation resulting in gneissic to mylonitic textures developed in the stability domain of biotite and amphibole, in a high- to mid-temperature continuum; the thin-sections cut in the *xz*-plane (parallel to the stretching lineation and perpendicular to the foliation) systematically indicate a downward displacement of the northern compartment.

The T parameter ($T = \ln[K_2^2/(K_1 \times K_3)]/\ln(K_1/K_3)$) characterizes the shape of the AMS ellipsoid (Jelinek 1981), which is prolate when $-1 < T < 0$ and oblate when $0 < T < 1$. For the Saint-Arnac pluton, T values range from -0.46 to 0.83 (Table 1); the prolate fabrics are essentially located in the core of the pluton and along the southwestern border of the northern zone. The T parameter shows a conspicuous zonation in the southwestern zone from east to west: the fabrics, which are fully linear in the granodiorite, become gradually planar–linear, then planar, and finally very planar in the granodiorites and tonalites near the pluton floor. For the Ansignan charnockite, T is less variable ($-0.23 < T < 0.39$) and the fabric is dominantly oblate except

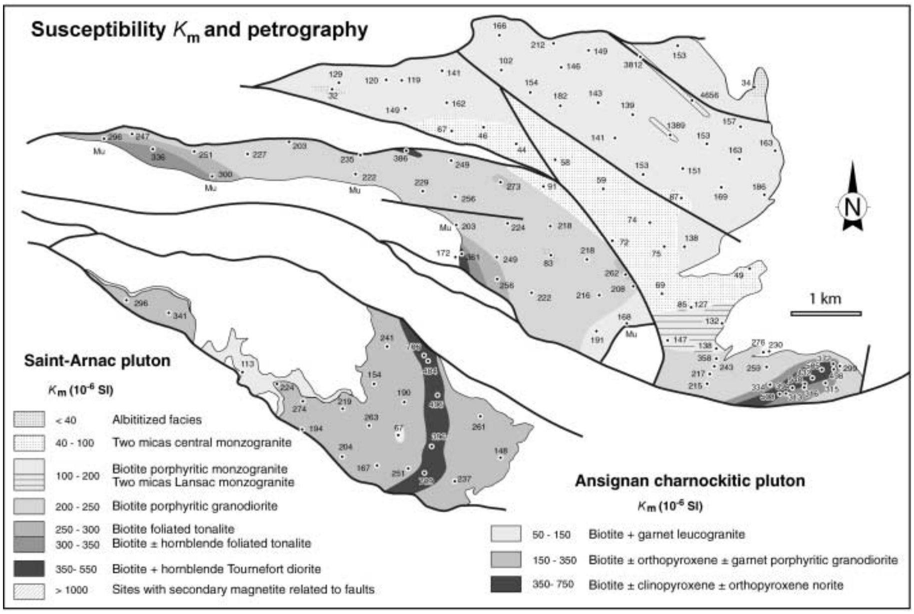

Fig. 2. Contour map of magnetic susceptibility magnitude K_m in the plutons of the Agly Massif and corresponding petrographic types. Mu, secondary muscovitization in granodiorite and tonalite of the floor of the Saint-Arnac pluton.

in the noritic layers, or close to them, where it is linear and planar–linear.

Structure and kinematics of the country-rocks of the Agly plutons

The metamorphic rocks that crop out around the Saint-Arnac and Ansignan plutons have been studied thoroughly from a structural and kinematic point of view (Fig. 5). For ease of presentation, the country-rocks are subdivided into three main zones: (1) the Saint-Arnac block, itself subdivided into three subzones (micaschists close to the pluton floor, Rivérole orthogneisses, eastern sector); (2) a gneissic band located between the Saint-Arnac pluton and the Ansignan charnockite; (3) the Ansignan block.

The Saint-Arnac block

The micaschists underlying the Saint-Arnac pluton were deformed together with the neighbouring foliated granodiorites, forming a 100 m thick interlayered unit. The mean foliation and lineation are 108°N82° and 039°/74°, respectively (Fig. 5a). The deformation corresponds essentially to a flattening regime and no sense of shear was determined in *xz*-plane thin sections.

The Rivérole orthogneisses form a *c*. 1000 m thick band located directly to the south of these micaschists. They are two-mica- and microcline-bearing orthogneisses. The mean foliation and stretching lineation are 135°NE57° and 049°/50°, respectively, corresponding to an obliquity of 35° for the foliations and 24° for the lineations with respect to the micaschists. The pervasive deformation in these gneisses is dominantly planar but the shear criteria show a tendency to a top-to-the-south movement.

The eastern border micaschists are roughly parallel to the border of the pluton. The foliations are subvertical (mean 119°/90°), similar to the foliations of the micaschists underlying the pluton floor. These foliations correspond to a highly flattened regime. The few stretching lineations observed are subvertical (mean 301°/82°) and did not yield a sense of shear. However, close to the Tournefort diorite, the deformation is strongly non-coaxial and the shear senses show a downward displacement of the northern compartment (Fig. 5a).

The Camp de l'Argent–La Menère gneissic band

This band is mainly formed of alternating orthogneisses, anatectic paragneisses and several 1–10 m thick granitic sills. These rocks have regular structures with a mean foliation and lineation at 110°N58° and 030°/52°, respectively (Fig. 5a). Two types of deformation are observed: (1) an early pervasive deformation D_1, slightly non-coaxial with a top-to-the-south sense of shear; (2) a superimposed deformation localized along mylonitic bands characterized by a continuum from high to medium temperatures and a strongly non-coaxial top-to-the-north sense of shear.

The Ansignan block

The deformation regime in this block was dominantly flattening, both in the hanging wall and in the underlying formations. The foliations are subhorizontal, conformable with the boundaries of the laccolith, and display a 132°SW21° mean orientation (Fig. 5a). A stretching lineation is locally observed (mean 208°/18°) but no sense of shear could be determined.

U–Pb dating of the Saint-Arnac granodiorite and the Tournefort diorite

Conventional isotope dilution thermal ionization mass spectrometry U–Pb zircon dating was performed according to the techniques described by Paquette & Pin (2001) on two samples of granitoids from locations shown in Figure 1b. Sample AG 201 corresponds to the Tournefort diorite located in the southeastern zone of the Saint-Arnac pluton, near its floor. Sample AG 204 corresponds to a granodiorite located near Saint-Arnac village. In thin section, AG 201 displays a weak subsolidus deformation whereas AG 204 shows a rather strong solid-state deformation developed in a continuum from high to medium temperature.

Individual analyses were performed on the least magnetic (2° forward and side tilt at 2.2 A using a Frantz isodynamic magnetic

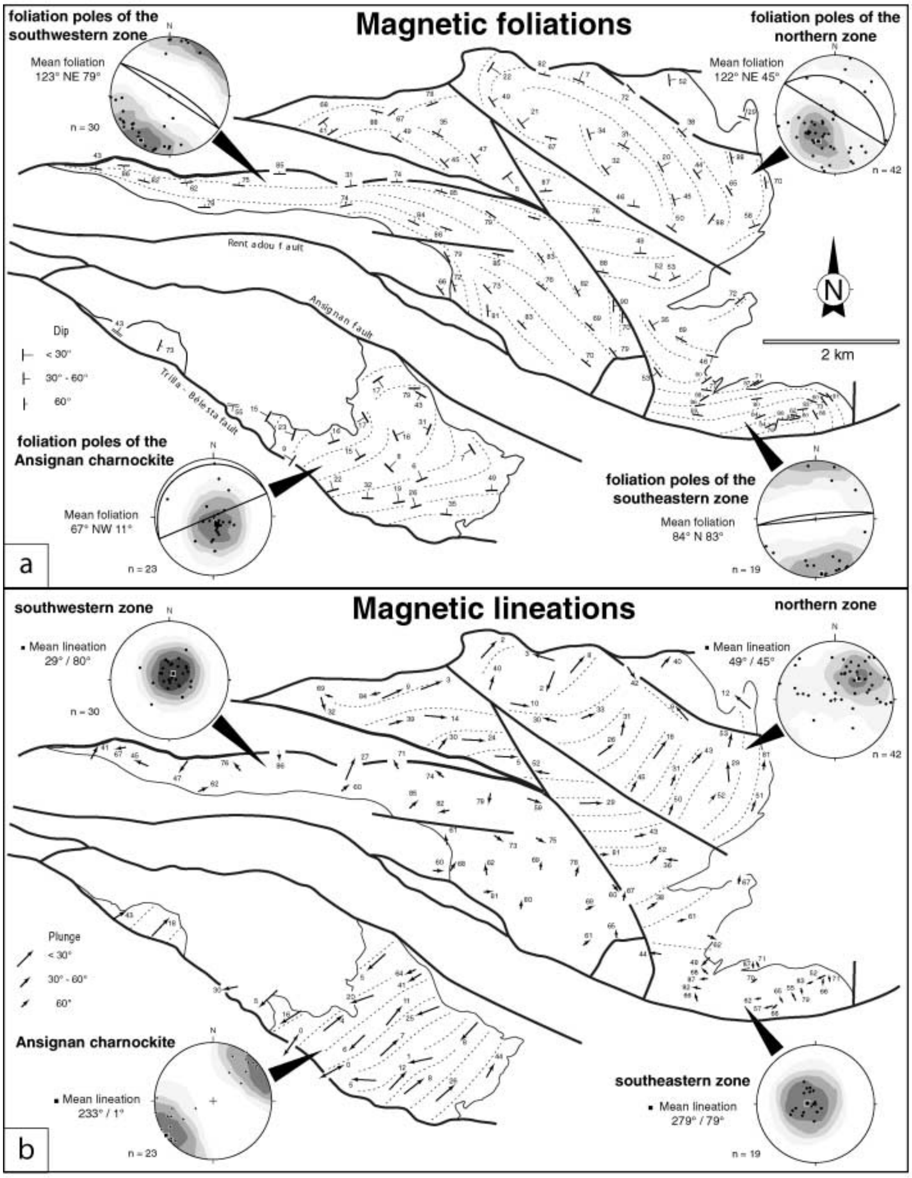

Fig. 3. Magnetic foliation (**a**) and lineation (**b**) maps of the Saint-Arnac pluton and the Ansignan charnockite. Schmidt lower hemisphere stereonets have contours of 2, 4, 6 and 8%.

barrier separator), euhedral and crack-free zircon grains. The isotopic ratios were corrected for mass discrimination ($0.1 \pm 0.015\%$ per a.m.u. for Pb and U), isotopic tracer contribution and analytical blanks: 6.5 ± 2.5 pg for Pb and 1 pg for U. Initial common Pb was determined for each fraction containing 3–10 zircons by using the Stacey & Kramers (1975) two-step model.

In both samples, two types of zircon occur: (1) short-prismatic euhedral and pale yellow grains, sometimes containing inherited cores; (2) strongly elongated or needle-shaped colourless to pale yellow crystals. All grains are inclusion-free and very translucent despite the high U content often associated with metamictization.

In AG 201 diorite, three of the four abraded fractions are concordant and yield an age of 308.0 ± 0.3 Ma. The fourth abraded fraction indicates inheritance of at least a 0.8 Ga crustal component. The three fractions representing unabraded needle-shaped zircons plot on a discordia line indicating an upper intercept at 307.3 ± 1.9 Ma (MSWD $= 0.014$), which is equivalent within error limits to the age obtained on the abraded fractions. Consequently, we pooled all uncontaminated fractions, which plot on a discordia line specifying an upper intercept at 308.3 ± 1.2 Ma (MSWD $= 0.38$) (Fig. 6 and Table 2), with a $^{207}Pb/^{206}Pb$ weighted mean age of 308.1 ± 0.6 Ma (MSWD $=$ 0.36). This age is interpreted as the age of crystallization of the zircons in the magma.

In AG 204 granodiorite, all abraded short-prismatic crystals are affected by both crustal inheritance and Pb loss. Consequently, these data cannot be used to precisely define the age of the granodiorite emplacement but only indicate complicated polygenic crustal contamination at least between 1.3 and 2.0 Ga. In such a case, the use of needle-shaped zircons can be useful (Bussy & Cadoppi 1996; Paquette *et al*. 1999). Four fractions of representative elongated zircons plot on a discordia line defining an upper intercept age of 303.6 ± 4.7 Ma (MSWD $= 1.4$) (Fig. 6 and Table 2), with a $^{207}Pb/^{206}Pb$ weighted mean age of 304.2 ± 0.9 Ma (MSWD $= 0.94$). This age is interpreted as dating the crystallization of the zircons.

In conclusion, and taking into account the $^{207}Pb/^{206}Pb$ ages

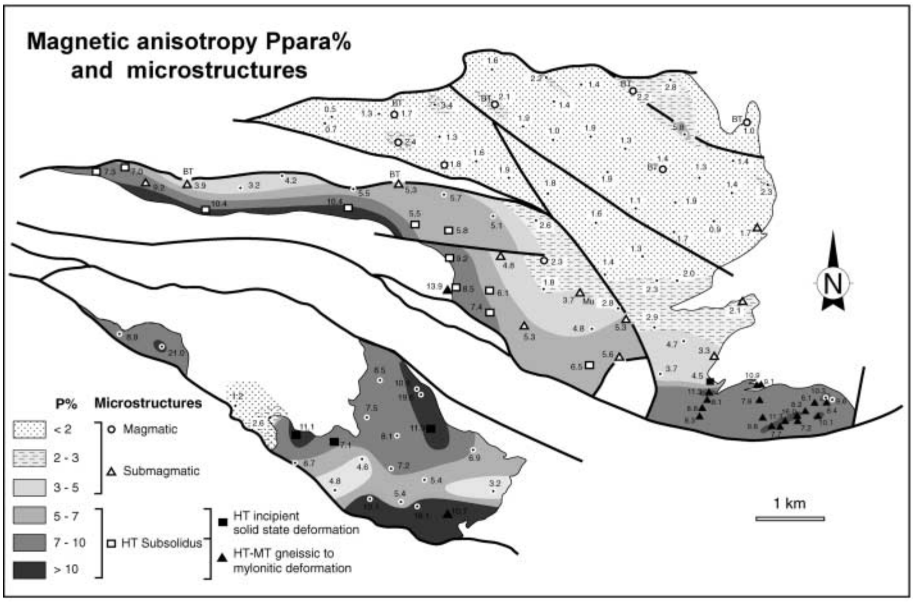

Fig. 4. Magnetic anisotropy map of the Saint-Arnac pluton and the Ansignan charnockite.

and related errors, it appears that the diorite and granodiorite emplacement ages may be separated by about 3 Ma.

Discussion

Structural relationships between the Agly Massif plutons and their country-rocks

The micaschists of the country-rocks were deformed together with the Saint-Arnac pluton both near its floor and at its eastern border, pointing to deformation during the same tectonic event. The emplacement of the pluton has caused reorientation of the surrounding regional main foliation, which may be observed far from the pluton to the NE, with an east–west-trending and moderate to steep northward dip corresponding to the S_1 foliation of the northern limb of the dome. It should be noted that the Rivérole orthogneisses, which have been considered as belonging to the southwestern part of the pluton floor (Fonteilles 1976), show a *c*. 30° obliquity between their structures and the micaschist structures that may result from a differential movement along the Alpine faults generally separating both formations. These structural data show that the emplacement of the Saint-Arnac pluton was post-D_1, but by themselves do not allow its attribution to a precise event.

For the Ansignan block, we consider that the lineations of the country-rocks, which are oriented 208°/18° with a southward sense of shear (Fig. 5a), were acquired during the D_1 phase, because Olivier *et al*. (2004) have demonstrated that throughout the Agly Massif the stretching lineations associated with D_1 are oriented on average at 203°/8° with a top-to-the-south tangential movement. The mean lineations and foliations of the charnockitic laccolith (233°/1° and 67°NW11°, Fig. 3) display a *c*. 30° obliquity with respect to the lineations and foliations of the country-rocks (208°/18° and 132°SW21°, Fig. 5a). This obliquity points to emplacement of the charnockite in a stress regime with a different orientation from that which prevailed during the deformation of its country-rocks in the D_1 tangential phase. The charnockite emplacement at *c*. 315 Ma could thus be related to the transition between the D_1 and D_2 phases.

Geodynamical context prevailing during the emplacement of the plutons and the formation of the Agly dome

The structural data described above lead us to consider that the charnockite and probably the other sills of the Agly middle crust were emplaced in a compressive to transpressive regime. This interpretation is at odds with that of Althoff *et al*. (1994), who proposed that the charnockite was emplaced in an extensional regime on the basis of the observation of some magmatic shear bands acting as normal faults. No other argument allows the confirmation of this point of view. For the Saint-Arnac pluton, the new ages presented in this paper, 308.3 ± 1.2 Ma for a diorite from the base of the pluton and 303.6 ± 4.7 Ma for a granodiorite emplaced higher in the crust, show that its emplacement was coeval with that of the other plutons of the Pyrenees, which were emplaced during the D_2 transpressive phase (see introduction).

Previous models proposed that the Agly thermal dome was formed in an extensional regime. Bouhallier *et al*. (1991) have interpreted the HT–LP gradient, up to 100 °C km^{-1} near the boundary between the gneissic core and the micaschist cover, as being the result of a late Variscan crustal thinning along a major northward detachment. Paquet & Mansy (1991) proposed a similar model but with a deeper major detachment, of Cretaceous age. Olivier *et al*. (2004) have shown that there is no major detachment in the Agly dome, and that the formation of this dome may be related to the D_2 dextral transpression. The extensional structures, such as the HT–MT mylonitic normal shear zone described here at the base of the Saint-Arnac pluton, may be interpreted either as local thinning on the limbs and roof of this dome in an overall transpressive regime, or as the result of a regional change of the stress regime that became extensional after formation of the dome.

*Position of the Agly plutons by the end of the Late Carboniferous (*c. *300 Ma)*

At present, the three tectonic blocks described above display, from north to south, a progressive evolution of their structures (Fig. 5): subvertical in the Saint-Arnac pluton floor, steeply to

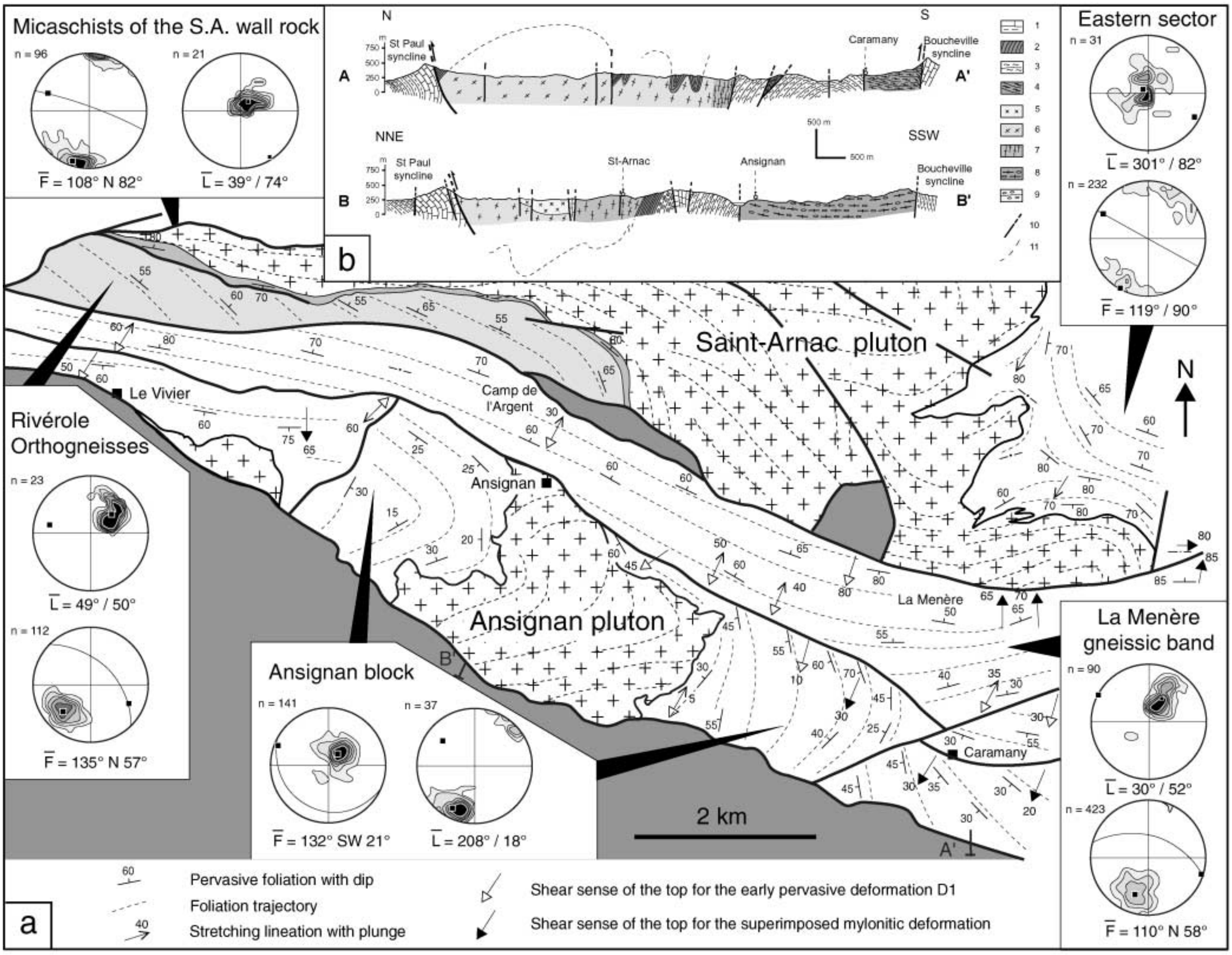

Fig. 5. (**a**) Structural map and kinematics of the country-rocks of the Saint-Arnac and Ansignan plutons. Schmidt lower hemisphere stereonets have contours of 1%, 2%, 3%, etc. (**b**) Cross-sections through the Saint-Arnac and Ansignan plutons. Location of cross-sections is shown in (a) and Figure 1. 1, Post-Palaeozoic formations; 2, Ordovician micaschists; 3, La Menère gneissic band; 4, paragneisses and charnockitic sills of the Ansignan block; 5, two-mica central monzogranite; 6, biotite porphyritic monzogranite; 7, foliated granodiorite to diorite; 8, Ansignan charnockite; 9, Rivérole orthogneiss; 10, Alpine faults and thrusts; 11, supposed boundary of the Saint-Arnac pluton.

moderately northward dipping in the gneissic band, and subhorizontal in the Ansignan block. Although this part of the Agly Massif is split by WNW–ESE-trending subvertical Alpine faults, these structures correspond to a general disposition in a half-dome, whose eastern periclinal termination may be observed to the east of the Planèzes fault (Fig. 1b). A thorough structural study of this part of the Agly Massif was presented by Olivier *et al*. (2004), who determined a N115° subhorizontal axis for the dome. The Ansignan block corresponds to the core of the dome, the depth of which was close to 18 km during the charnockite emplacement. The gneissic band, the initial depth of which was about 12–15 km, corresponds to the middle part of the northern flank of the dome and the Saint-Arnac block represents the northernmost part of this flank. The dioritic and granodioritic floor of the Saint-Arnac pluton has been injected into metapelites at an initial depth of about 10 km and then, as the pluton grew, the monzonitic magmas were emplaced to less than 5 km depth.

How can the attitude of the Saint-Arnac pluton before the Alpine tilting be reconstituted? As the post-Hercynian sedimentary cover of this pluton is generally faulted, it does not allow the precise estimation of this tilting, but indirect arguments may be used. It is now established that the Variscan plutons of the Axial Zone of the Pyrenees, which have not undergone Alpine rotation, display subhorizontal NE–SW-trending magmatic lineations (e. g. Bassiès, Gleizes *et al*. 1991; Cauterets, Gleizes *et al*. 1998*a*). We consider that the coeval Saint-Arnac pluton had the same characteristics before the Alpine tilting. As its roof structures display at present a northeastward plunge of 45° (Fig. 3), the position of the pluton by the end of the Variscan time with horizontal lineations may be restored by a southward untilting of about 45° around a N115°-trending horizontal axis, which corresponds to the mean zone axis of the Agly dome. The result of the same rotation for the pluton floor leads to 30–40° NNE-dipping foliations and plunging lineations.

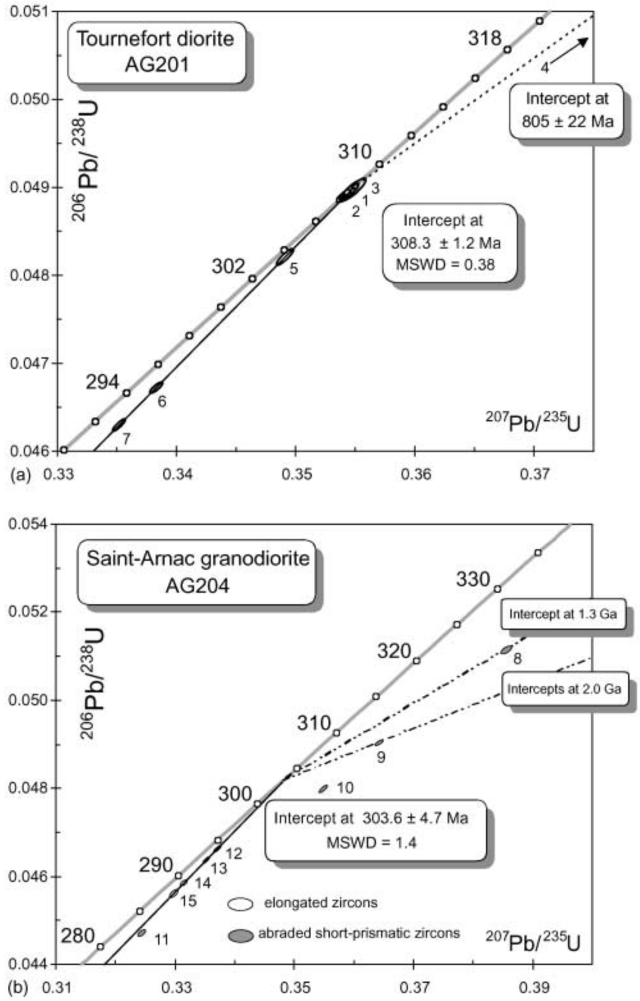

Fig. 6. Concordia diagrams of two samples of the Saint-Arnac pluton. (**a**) Tournefort diorite (AG 201) in the southeastern part of the pluton. (**b**) Granodiorite (AG 204) close to the Saint-Arnac village in the southwestern part. Location of these samples is shown in Figure 1b. Data-point error ellipses are 2σ. Individual fraction ellipse errors and regression calculations were determined using the PbDat 1.24 and Isoplot/Ex 2.49 programs, respectively (Ludwig 1993, 2001).

Evolution of the plutonism and dome formation in the Agly Massif

From the previous data it is possible to propose the following reconstitution of the magmatic and tectonic history of the Agly metamorphic dome.

(1) Sill emplacement in the middle crust. The Ansignan charnockite (314 ± 6 Ma, Respaut & Lancelot 1983) and a granitic sill (317 ± 3 Ma, Olivier *et al*. 2004) from the gneissic formations deeper than 12 km are the oldest dated Variscan granitoids of the Agly Massif. In fact, there are numerous 1–10 m thick sills probably also emplaced around 315 Ma in this gneissic series (Fig. 7a) whose cumulative thickness would be >1 km. This accumulation would have produced a thickening of the middle crust in this region, heated the middle crust and consequently weakened it, which probably facilitated the formation of the dome.

(2) Second magmatic episode and initiation of the gneissic dome. A second magmatic stage, which occurred at least 5 Ma

Table 2. *U/Pb analyses on zircons of two specimens of the Saint-Arnac pluton*

Sample number	Fraction (μm)	Weight (mg)	U (ppm)	Pb rad (ppm)	Atomic ratios					Apparent ages (Ma)			Correl. coeff.
					$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	
AG 201													
1	tr.ye.sp.ab. [4]	0.051	1369	64.2	16082	0.062	0.04895 ± 8	0.3546 ± 6	0.05253 ± 4	308	308	309	0.91
2	tr.ye.sp.ab. [4]	0.069	610	28.8	12067	0.0714	0.04891 ± 7	0.3542 ± 6	0.05252 ± 6	308	308	308	0.79
3	tr.ye.sp.ab. [6]	0.077	784	37.2	4985	0.0722	0.04887 ± 11	0.3548 ± 9	0.05254 ± 7	308	308	309	0.87
4	tr.ye.sp.ab. [4]	0.108	705	37.0	20123	0.0778	0.05396 ± 10	0.4053 ± 8	0.05449 ± 4	339	346	391	0.93
5	tr.ye.nd.un.[2]	0.062	1171	56.4	6520	0.1068	0.04822 ± 7	0.3491 ± 6	0.05250 ± 4	304	304	307	0.91
6	tr.ye.nd.un.[10]	0.123	581	26.1	7761	0.0659	0.04672 ± 5	0.3383 ± 5	0.05251 ± 4	294	296	308	0.85
7	tr.el.nd.un.[6]	0.089	993	44.1	8541	0.0592	0.04630 ± 5	0.3353 ± 4	0.05252 ± 3	292	294	308	0.91
AG 204													
8	tr.ye.sp.ab.[3]	0.038	569	28.6	5852	0.087	0.05114 ± 7	0.3852 ± 7	0.05463 ± 7	322	331	397	0.73
9	tr.ye.sp.ab.[4]	0.055	1017	48.5	19573	0.079	0.04905 ± 6	0.3640 ± 5	0.05382 ± 4	309	315	364	0.86
10	tr.ye.sp.ab.[3]	0.038	1040	49.1	17532	0.0918	0.04801 ± 7	0.3547 ± 6	0.05358 ± 4	302	308	353	0.87
11	tr.ye.sp.ab.[3]	0.027	1080	46.6	9600	0.0702	0.04476 ± 6	0.3244 ± 6	0.05257 ± 6	282	285	310	0.74
12	tr.el.nd.un.[4]	0.086	913	41.6	14003	0.083	0.04663 ± 6	0.3371 ± 5	0.05244 ± 3	294	295	305	0.92
13	tr.el.nd.un.[4]	0.049	1243	58.7	3574	0.1236	0.04638 ± 5	0.3351 ± 4	0.05241 ± 4	292	293	303	0.86
14	tr.el.nd.un.[3]	0.037	978	44.9	2815	0.1029	0.04583 ± 6	0.3315 ± 6	0.05245 ± 6	289	291	305	0.76
15	tr.el.nd.un.[2]	0.021	1189	69.7	4103	0.0812	0.04563 ± 6	0.3299 ± 7	0.05244 ± 8	288	289	304	0.65

The errors refer to the least significant digits of the corresponding ratios and are given at the 2σ level. Number in brackets is number of grains per fraction. The decay constants used for the U–Pb system are those recommended by the IUGS (Steiger & Jäger 1977). rad, radiogenic; tr., translucent; ye., pale yellow; nd., needle-shaped; el., elongated; sp., short prismatic; ab., mechanically abraded (Krogh 1982); un., unabraded.

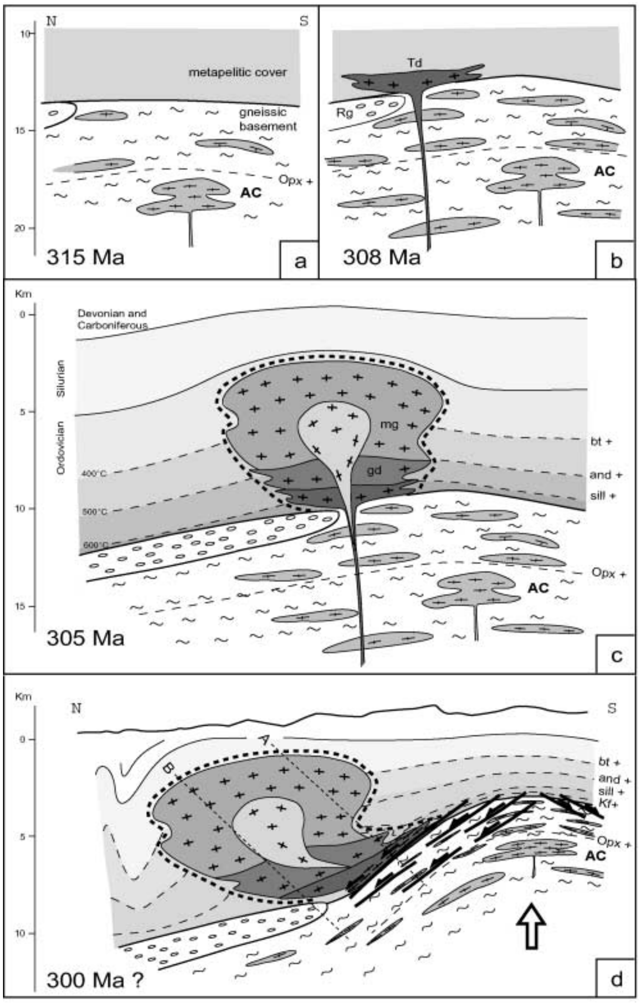

Fig. 7. Schematic cross-sections through the middle and upper crust of the Agly Massif during the late Carboniferous. (**a**) Emplacement of the Ansignan charnockitic laccolith (AC) at 315 Ma. (**b**) Emplacement of the Tournefort diorite (Td) at 308.3 ± 1.2 Ma. Rg, Rivérole orthogneiss. (**c**) Emplacement of the granodiorite (gd) and monzogranites (mg) of the Saint-Arnac pluton at 303.6 ± 4.7 Ma. (**d**) Doming of the Agly Massif, resulting in a top-to-the-north shearing solid-state deformation of the floor of the Saint-Arnac pluton, from high to medium temperature, at about 300 Ma. Lines A and B correspond to the approximate present level of erosion (i.e. cross-sections A–A′ and B–B′ of Fig. 5b), after the Alpine tilting of about 45° to the north.

later, was characterized by the emplacement of the Saint-Arnac pluton, at a depth between 10 and 5 km. This stage began with the intrusion of a subhorizontal dioritic sill near the gneiss–micaschist boundary at *c*. 308 Ma (Fig. 7b), corresponding to the first magma that crossed the entire gneissic pile. Gradually, the production of more differentiated magmas increased and these magmas reached the upper crust through the same conduit; first the granodiorite at about 305 Ma, then the biotite monzogranite and, finally, the central two-mica monzogranite (Fig. 7c). At this stage the doming was slight and was essentially linked to the accumulation of magmas in the gneissic basement.

(3) Doming of the Agly Massif. As the doming developed, the northern limb of the dome became progressively steeper and the pluton floor underwent a northward normal shearing leading to the HT solid-state deformation of the granodiorite and diorite (Fig. 7d). With the temperature decrease during uplift of the dome, the deformation became more localized, creating numerous normal MT mylonitic to ultramylonitic bands.

Conclusion

The structural study of the Saint-Arnac and Ansignan plutons and their metamorphic country-rocks yields an exceptional cross-section of an initial thickness of at least 10 km from the middle to the upper crust. The structural relationships between the plutons and the country-rocks allow both the understanding of the link between the magmatic injections and the formation of a gneissic dome, and the specification of the origin of the especially high thermal gradient characterizing the Agly dome and its micaschist cover by the combination of several magmatic intrusions and a local crustal thinning.

Furthermore, this study shows that the plutonism lasted at least 10 Ma with, first, the emplacement of small-volume sills in the middle crust and then the emplacement of large plutons in the upper crust, their roofs being less than 5 km deep. The formation of these large plutons could have lasted several million years, as suggested by the $^{207}Pb/^{206}Pb$ weighted mean ages of the Saint-Arnac pluton: 308.1 ± 0.6 Ma for the diorite and 304.2 ± 0.9 Ma for the granodiorite.

Although this general scheme seems to be well established, complementary age dating is necessary to determine: (1) whether the plutonism was more or less continuous in the 317–300 Ma time span or, conversely, whether there is a lull in the plutonism between the emplacement of the sills and of the large plutons; (2) whether there is a vertical polarity in the emplacement of the various sills or whether they are randomly distributed in the middle crust.

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