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Gneiss domes and granite emplacement in an obliquely convergent regime: New interpretation of the Variscan Agly Massif (Eastern Pyrenees, France)

Ph. Olivier*
G. Gleizes
CNRS-UMR 5563 LMTG, Université Paul Sabatier, 38 rue des Trente-Six-Ponts, 31400, Toulouse, France

J.L. Paquette
CNRS-UMR 6524 Magmas et Volcans, Université B. Pascal, 5 rue Kessler, 63038 Clermont-Ferrand, France

ABSTRACT

Like the metamorphic core complexes of the Basin and Range (United States), the gneiss domes of the west European Variscan range have been associated with large-scale extension. In particular, the development of the Agly Massif, a gneiss and micaschist dome in the eastern Pyrenees (France), has been related to N-S–directed, late Variscan or Cretaceous extension. However, new microstructural and kinematic investigations in the Agly Massif demonstrate that (i) there is no major detachment, (ii) the pervasive deformation associated with the early metamorphism indicates a southward vergence, and (iii) the numerous mylonitic bands observed at different levels of the section acted as gently dipping normal faults and display opposite shear senses on both northern and southern flank of the dome. Shearing on these bands caused a multi-kilometer–scale thinning distributed across the whole lithologic column.

Two new U-Pb zircon analyses yielded an age of 317 ± 3 Ma for a deformed granite from the core of the dome, and an age of 307 ± 0.4 Ma for a deformed granite emplaced in the micaschist cover. This suggests that two phases of magmatism occurred in the Agly Massif, the first prior to doming and the second during doming and the emplacement of the main Pyrenean plutons associated with a dextral transpressive phase. Therefore, the Agly gneiss dome formed in a transpressive regime and not in a late Variscan or Cretaceous extensional regime related to the collapse of a previously thickened crust.

Keywords: gneiss dome, granite emplacement, transpression, Variscan Pyrenees, Agly.

INTRODUCTION

Gneiss domes from the west European Variscan Range have been interpreted by many authors (e.g., Echtler and Malavieille, 1990; Gibson, 1991; Musumeci, 1992; Malavieille, 1993; Brun and Van den Driessche, 1994; Vanderhaeghe et al., 1999) in a comparable way to the metamorphic core complexes (MCCs) from the western United States (e.g., Lister and Davis, 1989; King and Ellis, 1990; Foster, 1994; Lister and Baldwin, 1993; Foster and John, 1999). Domes are thought to be the result of a post-collision generalized extension, allowing the uplift and exhumation of the ductile crust under major detachments.

*E-mail: olivier@lmtg.obs-mip.fr.

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The Pyrenees are an Alpine intracontinental belt, located between Spain and France (Fig. 1A), and show a segment of the west European Variscan Orogen. They are characterized by many gneissic domes and granitic plutons. The state of knowledge about the Variscan orogen in the Pyrenees has been synthesized in Barnolas and Chiron (1996), but this study leaves unresolved many essential problems, especially the age and geodynamic conditions of emplacement of the plutons or the origin of gneiss domes and the associated high temperature–low pressure (HT-LP) metamorphism. These authors list the different geodynamic models that have been proposed concerning the Variscan evolution of the Pyrenees:

- a process of continental rifting leading to the intrusion of mantle-derived magmas and to the HT-LP metamorphism and anatexis (Wickham and Oxburgh, 1985, 1987);
- a compressional regime leading to the thickening of the crust during south-directed thrusting, followed by a more coaxial N-S compression (Matte and Mattauer, 1987; Marshall, 1987);
- a tectonic regime first in compression, then in extension leading to crustal thinning and the development of flat structures observed in the cores of gneiss domes (Van den Eeckhout and Zwart, 1988);
- early crustal thinning and partial melting of the mantle leading to overall anatexis, followed by shortening and thrusting, inducing the uplift of granulitic gneisses, the formation of domes, and the diapiric emplacement of granitoids (Soula et al., 1986);
- shortening by thrusting in the deep levels of the crust producing subhorizontal foliations, while transpressional folding in the upper crust might have been coeval with the formation of gneiss domes and plutons emplacement, without any possibility to separate the two events (Carreras and Capella,1994).

Concerning the gneiss domes in the Pyrenees (Fig. 1A), the most studied areas in the Axial Zone are the Aston-Hospitalet dome (Van den Eeckhout, 1986; Vissers, 1992) and the Canigou dome (Gibson, 1991; Ayora et al., 1993) and, in the North-Pyrenean Zone, the Agly Massif (Fonteilles, 1976; Delay, 1990; Vielzeuf, 1996). For the Agly Massif, it has been proposed that the crustal thinning and associated HT-LP metamorphism were the result of an extension of either late Variscan (Bouhallier et al., 1991), or Cretaceous age (Paquet and Mansy, 1991). More recently, Kornprobst (1994) proposed the following model: (i) continental collision with underthrusting of crustal units, (ii) slow isostatic uplift with mantle magmatic injections, (iii) formation of a dome piercing its pelitic cover during a post-collision phase, and development of HT-LP metamorphism around this dome.

These interpretations need to be reconsidered in the light of new data obtained on the Pyrenean Variscan plutons and their country rocks. Indeed, (i) magmatic fabrics in the plutons (Gleizes et al., 1998a; Olivier et al., 1999, Gleizes et al., 2001), and (ii) U-Pb isotopic ages of zircon between 305 and 312 Ma (Paquette et al., 1997; Romer and Soler, 1995; Roberts et al., 2000) show that pluton emplacement was coeval with a phase of transpressive deformation (Leblanc et al., 1996; Gleizes et al., 1998b). This conclusion matches best the model proposed by Carreras and Capella (1994).

In this paper, we present a reinterpretation of the Agly dome based on a detailed kinematic study and on new U-Pb dating of zircons from two variably deformed granite bodies, one located in the gneissic core and the other located in the micaschist cover.

GEOLOGICAL SETTING

The North Pyrenean Massifs are generally characterized by a granulitic basement and a Paleozoic pelitic cover. The Agly Massif is the easternmost massif (Fig. 1A), WNW-ESE–trending and ~35 km long. Its maximum width is ~8 km near Belesta (Fig. 1B). The massif is bounded by large Alpine faults that separate it from three synclines cored by Cretaceous strata: the Saint-Paul-de-Fenouillet and Agly synclines to the north and the Boucheville syncline to the south (Fig. 1).

The Agly Massif consists of a gneiss core and a micaschist cover. The gneiss is considered Precambrian (Vitrac-Michard and Allègre, 1975) and is subdivided into two parts: the Caramany gneisses in the deepest part (hypersthene and hypersthene + hornblende zones), and the Belesta gneisses forming the upper part (cummingtonite and sillimanite + K-feldspar zones). The micaschist cover consists mainly of Ordovician to mid-Devonian metapelitic units that have recorded a HT-LP metamorphism. Metamorphic zones range upward from sillimanite + K-feldspar + incipient anatexis to the chlorite zone. Near the contact with the gneiss core, the metamorphic isograds are compressed (Fig. 1B), displaying a gradient at ~125 °C/km (Barnolas and Chiron, 1996). Granitoids were emplaced at different levels of this massif such as the charnockitic granite of Ansignan, located at the base of the Caramany gneisses, and the Saint-Arnac granite pluton in the cover.

The Agly Massif is split into several compartments (Fonteilles, 1976; Vielzeuf, 1984; Delay, 1990; Fonteilles et al., 1993). The western part displays E-W to N120°-trending bands, several kilometers long and a few hundred meters to 2 km wide. The eastern part consists of a half-dome cut by Alpine faults to the south and the west. This study focuses mainly on this eastern part because it contains the most complete lithologic column of the massif, all the metamorphic zones from the hypersthene zone to the chlorite zone are present, and most of the mylonitic bands cutting these metamorphic rocks are exposed.

CHARACTERIZATION OF DEFORMATION

The metamorphic rocks of the Agly Massif have undergone two main Variscan deformation events, the first one pervasive and ubiquitous, the second one corresponding to the formation of localized mylonitic bands.

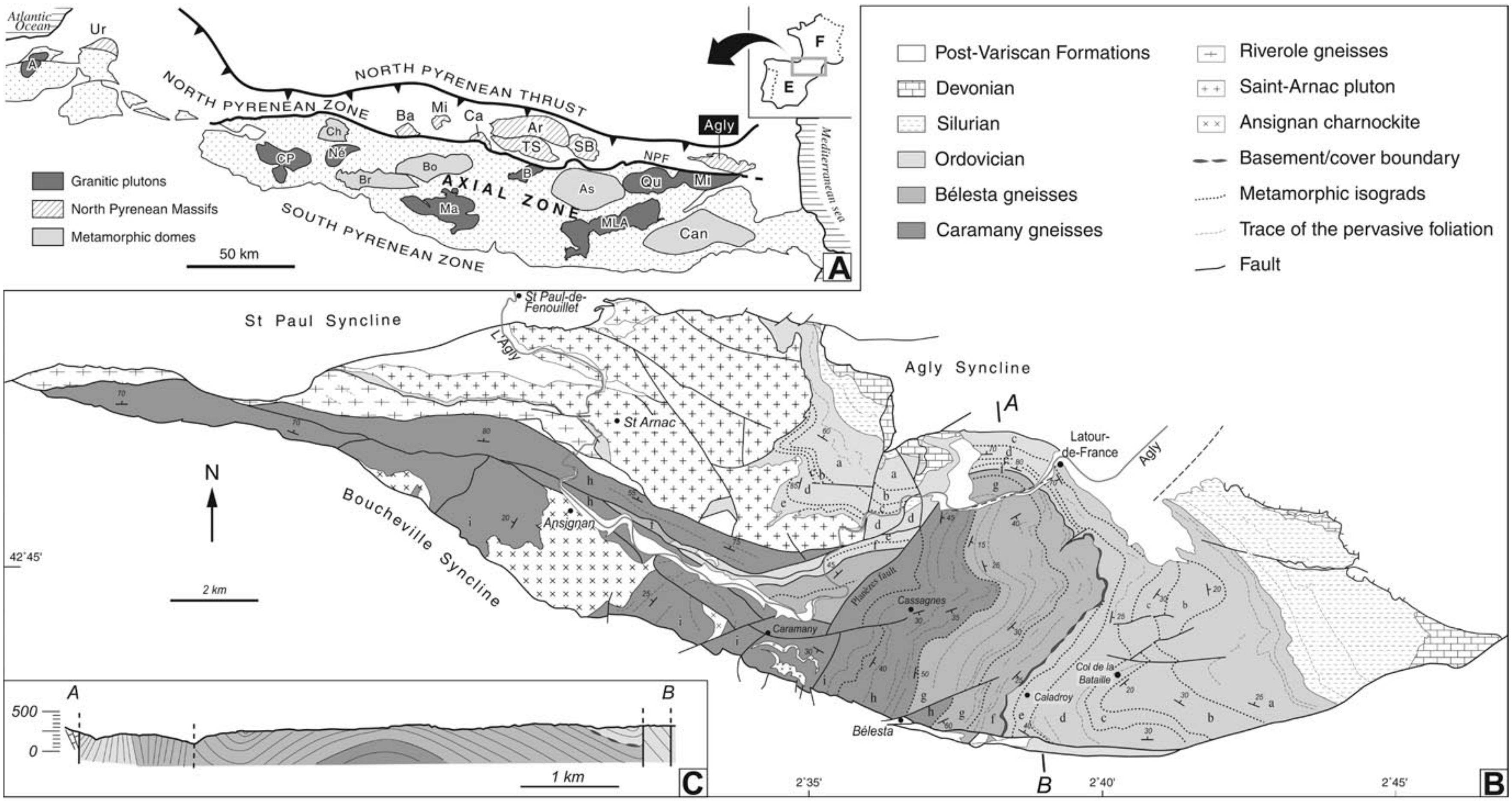


Figure 1. The Agly Massif in the Oriental French Pyrenees. (A) Location in the Pyrenees from east to west of the North-Pyrenean Massifs (Agly; SB—Saint-Barthèlèmy; Ar—Arize; TS—Trois-Seigneurs; Ca—Castillon; Mi—Milhas; Ba—Barousse; Ur—Ursuya), of the main domes (Can—Canigou; As—Aston; Bo—Bosost; Br—Barroude; Ch—Chiroulet) and of the main Hercynian plutons (Mi—Millas; Qu—Quèrigut; MLA—Mont Louis Andorre; B—Bassiës; Ma—Maladeta; Nè—Nèouvielle; CP—Cauterets-Panticosa; A—Aya). NPF—North Pyrenean Fault. (B) Geological sketch-map of the Agly Massif (after Delay, 1990 and Fonteilles et al., 1993 modified). (C) schematic North-South cross-section shown in B. a—chl zone; b—bt zone; c—cd zone; d—and zone; e—sill zone; f—sill + FK zone; g—cumm zone; h—hyp + hb zone; i—hyp zone.

Pervasive Deformation

This deformation is characterized by a conspicuous foliation defined by phyllosilicate minerals. This foliation is generally parallel to lithologic surfaces (Fig. 1B), whatever the origin of the rock: paragneiss such as calcsilicate-bearing gneiss, marble, or felsic and mafic orthogneiss. In general, the foliation is parallel to the metamorphic isograds. A well-defined stretching lineation is generally associated with this foliation, except where flattening strain dominates, particularly in the western part of the massif. In thin section (Figs. 2C and 2D), this foliation appears to be either synchronous or late with respect to the growth of peak metamorphic minerals.

Mylonitic Deformation

The mylonitic bands are distributed throughout most of the Agly Massif but are especially common in the eastern compartment of the dome. The bands are easily observable in orthogneissic rocks and are less well defined in metapelites. The outcrop conditions generally do not allow one to observe the longitudinal and/or lateral prolongations of these bands or to measure accurately their density. Nevertheless, we have observed higher densities of mylonite bands, for instance in the Belesta gneisses to the South of Latour-de-France, or in the Caramany gneisses, one kilometer to the northwest of Cassagnes (Fig. 1B). Conversely, we have not observed a high density of mylonitic bands near the basement/cover boundary as stated by Bouhallier et al. (1991), or at the boundary between Belesta and Caramany gneisses as mentioned by Delay and Paquet (1989).

The mylonitic deformation is characterized by bands of a few centimeters to a few decimeters thick locally cutting the pervasive foliation. The mylonitic foliation and associated stretching lineation are always conspicuous, but deformation is more-or-less penetrative and intense according to proximity to mylonitic bands. A strong gradient of deformation is observable within a given band. Near the borders, some quartz ribbons appear parallel or oblique with respect to the main foliation and in the core of the band, the minerals of the first foliation are strongly fragmented and transformed, producing ultramylonite (Fig. 2E).

Deformation of the minerals in the mylonitic bands observed in the gneiss core of the dome indicates temperature conditions around 500 °C (Figs. 2A and 2B) based on microfabric and metamorphic criteria: quartz ribbons show a preferred orientation of C-axes consistent with prism <a> slip; quartz micrograins recrystallized into mosaic textures with numerous triple-junction grain boundaries; biotite crystallized in garnet fractures that developed during mylonitic deformation, and there is a lack of chlorite growth.

Geometry and Kinematics

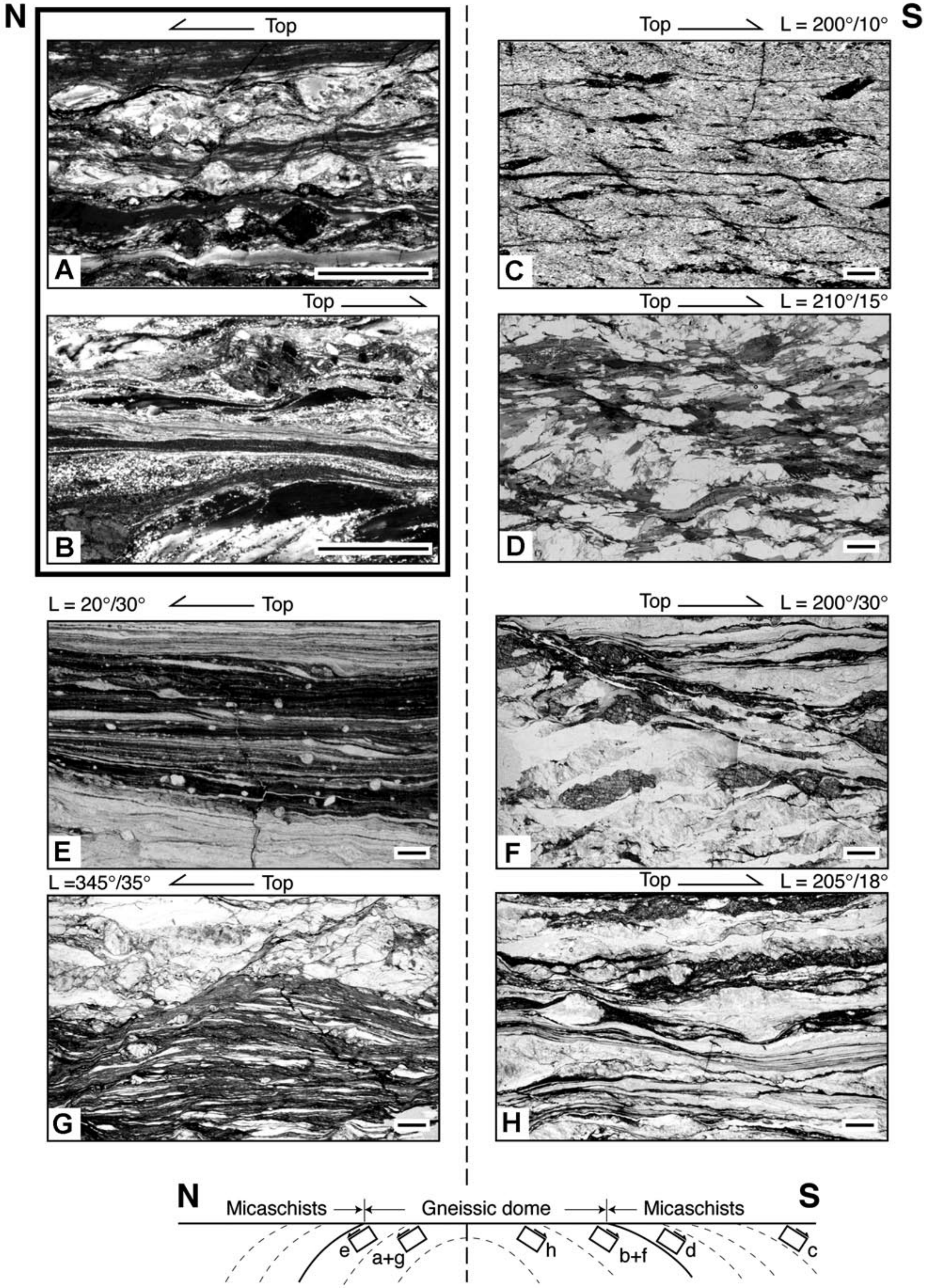
The Variscan structures of the Agly Massif have been affected variably by the Alpine orogeny. The western region is more affected than the eastern region where the half gneiss dome is preserved. The boundary between the two regions corresponds to the Planèzes fault (Fig. 1B). Concerning the pervasive deformation, we present separately the data from both parts. By contrast, as the data concerning the mylonitic deformation were mainly obtained in the eastern part of the massif, we have not separated these data into two sets.

For the kinematic study of the Agly Massif, 150 thin sections were cut in the plane parallel to stretching lineation and perpendicular to foliation (XZ sections). Sense of shear, which is unambiguous for about 55% of the thin sections, was determined by using standard criteria: C/S relationships, S- or Z-shaped drag folds, asymmetry of pressure shadows, σ-and δ-type porphyroclasts, and obliquity of quartz crystallographic fabric. Most samples studied are from the eastern part of the massif where Alpine deformation is weak.

Pervasive Deformation

In the western part of the Agly Massif, the main foliation displays different orientations (Fig. 1B): (i) subhorizontal or shallowly dipping in the southern compartment where the sill-like charnockitic granite of Ansignan crops out, (ii) roughly W-E

Figure 2. Microphotographs of oriented thin sections of rocks from the Agly Massif. All thin sections are cut in the XZ plane. The upper part of each photograph corresponds to the upper part of the sample. Photographs a and b are taken in crossed nicols, the other ones in plane polarized light. Scale bar = 1 mm for all photographs. A and B are magnifications of G and F, respectively. They show microstructures in the mylonitic bands from the gneiss core of the dome. (A) Note long quartz ribbons between the different K-feldspars porphyroclasts which are very fragmented with typically sinistral synthetic shear planes. (B) Numerous quartz grains with polygonized boundaries indicate a recrystallization under very high stress and high temperature (at least 500 °C). The very well-grouped fabric of quartz grains, sigmoids in the quartz and pressure shadows around the porphyroclasts clearly indicate a dextral sense of shear. C and D correspond to samples from the micaschist cover, in the SE flank of the dome, showing the pervasive main foliation. C comes from the beginning of the biotite zone, D from the base of the cover, in the sillimanite zone. For both samples, the shearing is dextral, i.e., top to the south, as shown by pressure shadows around porphyroclasts, sigmoids of foliation and C□ planes. (E to H) Mylonites from the gneissic part of the dome, showing top to the North in the northern flank (E and G) and top to the South in the southern flank (F and H). G and H come from the deepest parts of the gneisses, E and F from the highest parts of the dome. All these thin sections show a strong deformation, the strongest being represented by ultramylonites (E).


N
Top
A
Top
B
S
Top
L = 200°/10°
C
Top
L = 210°/15°
D
L = 20°/30°
Top
E
L =345°/35°
Top
G
Top
L = 200°/30°
F
Top
L = 205°/18°
H
N
Micaschists
Gneissic dome
Micaschists
S
e
a+g
h
b+f
d
c

to WNW-ESE–trending and steeply dipping to the north in the central compartments, or (iii) subvertical at the base of the Saint-Arnac granite. Foliation and lineation measurements in this part of the massif indicate that the poles to foliation are distributed on a girdle whose axis is oriented 114°/0°, the mean foliation being at 115N61 (Fig. 3A). Lineation, which is observed only on about one third of the measured foliation surfaces in this part of the massif, is distributed on a girdle whose pole is at 299°/3° with a mean at 034°/52° (Fig. 3B).

In the eastern part of the massif, the trajectories of the main foliation describe an arc with a convexity facing ENE, defining the shape of the half-dome (Figs. 1B and 1C). The northern flank of this dome is steep while the southeastern flank is gently dipping. Foliation and lineation measurements in this part of the massif indicate that the poles of this foliation are rather well grouped and generally shallowly dipping, the mean foliation being 036SE25. The corresponding zone axis is at 112°/24°, but the foliation does describe a part of a small circle as would be expected from a dome. The lineations are rather well grouped around the mean at 204°/9° (Fig. 3D). The pole of the best-fit plane containing these lineations is at 110°/22°.

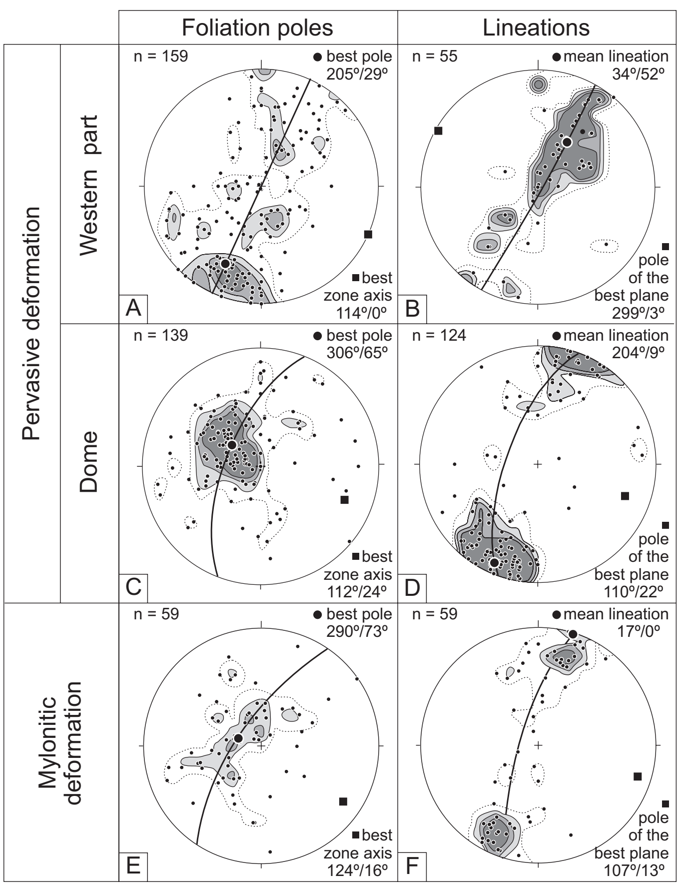


Figure 3. Stereonets (Schmidt, lower hemisphere, 1% area contours). (A) Poles of the major pervasive foliation and its associated stretching lineation for all the Agly Massif. (B) Poles of the mylonitic foliation and its associated stretching lineation for all the Agly Massif.

In both parts of the massif, the pervasive foliation and lineation are distributed around the same axis (~N110E), but this axis is horizontal in the western part and plunges ~20E in the eastern part. This direction corresponds to the orientation of the main Variscan structures in the Pyrenees, but also to the orientation of Alpine structures. Because only the dip and plunge of these pervasive foliations and lineations change from the western to the eastern part, it may be considered that the influence of the Alpine orogenesis in the Agly Massif is just represented by block tilting along an axis more-or-less parallel to the Variscan direction. Consequently, the eastern part of the massif with its present shape in a half dome may represent the almost unmodified periclinal termination of a Variscan anticline trending 110, while the western part may represent the central part of this anticline strongly affected by Alpine tilting but with its original Variscan direction essentially preserved. Before Alpine tectonics, the Agly Massif would have been an elongated dome at least 35 km long, like the Aston or Canigou domes in the Axial zone, which are also roughly E-W-trending (Fig. 1A).

Thirty-six XZ thin sections yielded a reliable sense of shear. The stereonet of the corresponding lineation measurements (Fig. 4) shows that lineation is distributed on a girdle whose pole is at 294°/2° and is more-or-less grouped around the mean 203°/8°. These directions are very comparable to those obtained for the whole massif, indicating that this smaller data set is representative of the massif. The few values that depart from the general trend generally correspond to sites located near Alpine faults. Most of the samples (92%) display a top-to-south displacement of the lithologic stack, irrespective of the plunge of lineation either to the north or to the south, and whatever the structural level considered.

Mylonitic Deformation

Fifty-nine mylonitic bands were studied in the whole massif but mostly from the eastern part. The stereonets (Figs. 3E and 3F) corresponding to foliation and lineation measured in these bands show that: (i) the mylonitic foliation is generally subhorizontal to shallowly dipping, with, however, a slight distribution of the poles in a zone around a 124°/16° axis. The mean foliation is 020°E17°; (ii) the lineation is rather well grouped with a tendency, however, to be distributed on a girdle around a 107°/13° axis. The mean lineation is oriented 017°/0°.

This kind of structure indicates that mylonitic foliations and lineations are "wrapped" around an axis oriented at ~110°/15°. It is interesting to note that the stereonets concerning these mylonitic structures and the pervasive structures are similar and that both types of structures are distributed around subparallel axes of rotation.

Most XZ thin sections (83%) from the mylonitic bands yielded a reliable sense of shear. The corresponding lineations are grouped around the mean lineation (018°/1°) but display a

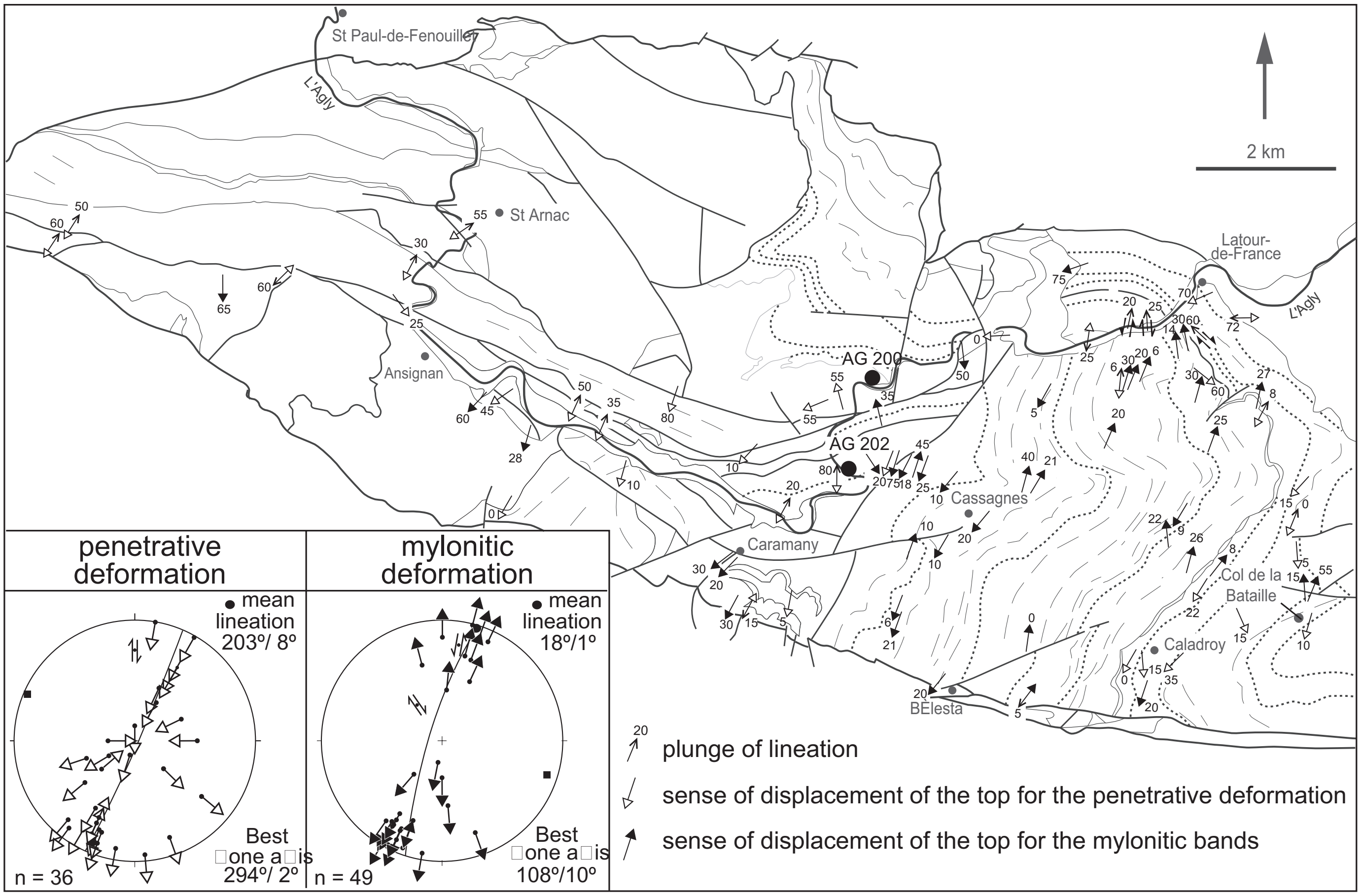


Figure 4. Map of the lineations corresponding to unambiguous senses of shear, for the pervasive and the mylonitic deformations, determined on XZ thin sections. Stereonet (Schmidt, lower hemisphere, 1% area contours) of the foliation poles and of the lineation for both deformations. AG 200 and AG 202: location of the deformed granites dated in this paper.

slight distribution on a girdle around an axis oriented 108°/10° (Fig. 4). The mylonitic lineations are in most cases shallowly plunging and carried by shallowly dipping foliations. However, some sites, especially in the center of the dome, show steep foliations and lineations. All shear senses corresponding to the northward plunging lineations are top to north (Figs. 2E, 2G, and Fig. 4), and almost all shear senses corresponding to the southward-plunging lineations show top to south (Figs. 2C, 2D, 2F, 2H, and Fig. 4) irrespective of structural level (see schematic cross section at the bottom of Fig. 2). At some sites, both senses of shear correspond to conjugate foliations with opposite dip.

Geochronology

Conventional ID-TIMS (isotope dilution–thermal ionization mass spectrometry) U-Pb zircon dating was performed according to the techniques described in Paquette and Pin (2001) on two specimens of variably deformed granitoids (sample localities in Fig. 4). The first specimen, AG 202, corresponds to a monzogranite intrusive in the upper part of the Belesta gneisses. This monzogranite is a 1-m-thick sill parallel to the main foliation, and displays, in thin section, high-temperature solid-state deformation and secondary muscovite growth. The second specimen, AG 200, corresponds to a granodiorite in the micaschist cover, located near the base of the Saint-Arnac pluton. Thin section observations reveal a rather strong deformation developed progressively under high to low temperature.

In sample AG 202 of monzogranite, two types of euhedral zircons occur: translucent and colorless needle-shaped prismatic grains and colorless to pale yellow, short to medium length prismatic grains. Five fractions of the latter were analyzed (Table 1, fractions 8–12). Four of the five points plot on a linear array, which intercepts the concordia curve at 306 ± 2 Ma and 1.42 ± 0.03 Ga (Fig. 5A). Inherited cores occur in short prismatic zircon grains from this sample and are documented by the upper intercept at 1.42 Ga. The isotopic ages calculated in the case of nonzero lower intercepts are considered to be reliable when: (i) one or several analytical points are concordant, and/or (ii) the regression is good, and/or (iii) there is no suspicion of Pb-loss in the zircons. In the case of short prismatic grains from

TABLE 1. ANALYSES OF TWO SPECIMENS OF GRANITOIDS OF THE AGLY MASSIF

Sample	no.	Fraction (µm)	Wt. (mg)	U (ppm)	Pb rad (ppm)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	correl. coeff.
atomic	ratios	apparent	ages											
AG200	1	tr.ye.ab. [6]	0.046	830	41.7	4384	0.1384	0.04887 ± 7	0.3539 ± 6	0.05253 ± 5	308	308	308	0.81
	2	tr.ye.ab. [7]	0.050	715	37.3	3262	0.1824	0.04879 ± 6	0.3532 ± 6	0.05250 ± 6	307	307	307	0.78
	3	tr.ye.ab. [7]	0.054	853	43.6	8528	0.1645	0.04876 ± 6	0.3530 ± 5	0.05250 ± 4	307	307	307	0.83
	4	tr.ye.ab. [6]	0.050	665	33.7	7094	0.1562	0.04886 ± 9	0.3538 ± 10	0.05252 ± 11	308	308	308	0.68
AG202	5	tr.cl.nd.un. [26]	0.048	1867	83.0	3367	0.0439	0.04680 ± 10	0.3406 ± 7	0.05279 ± 3	295	298	320	0.96
	6	tr.cl.nd.un. [11]	0.025	793	34.6	2903	0.0423	0.04606 ± 7	0.3352 ± 7	0.05278 ± 7	290	294	319	0.79
	7	tr.cl.nd.un. [22]	0.022	1443	67.4	3391	0.0383	0.04950 ± 8	0.3599 ± 7	0.05273 ± 5	311	312	317	0.87
	8	tr.cl.el.ab. [10]	0.037	518	26.7	431	0.1253	0.04736 ± 6	0.3669 ± 7	0.05618 ± 8	298	317	460	0.68
	9	tr.cl.sp.ab. [4]	0.038	1301	60.5	16305	0.0510	0.04905 ± 7	0.3570 ± 6	0.05279 ± 5	309	310	320	0.83
	10	tr.cl.sp.ab. [6]	0.034	945	45.1	2122	0.0561	0.04968 ± 9	0.3660 ± 11	0.05343 ± 12	313	317	347	0.67
	11	tr.ye.sp.ab.[7]	0.036	1068	51.4	3749	0.0374	0.05120 ± 8	0.3876 ± 9	0.05491 ± 9	322	333	409	0.70
	12	tr.ye.sp.ab. [4]	0.025	855	57.4	6580	0.0669	0.06919 ± 13	0.6319 ± 17	0.06624 ± 12	431	497	814	0.73

Note: Individual analyses were performed on the least magnetic (2° forward and side tilt at 2.2 A using a Frantz Isodynamic magnetic barrier separator), euhedral and crack-free zircon grains. The isotopic ratios are corrected for mass discrimination (0.1 ± 0.015% per amu 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 is determined for each fraction in using the Stacey and Kramers (1975) two-step model. The errors refer to the last significant digits of the corresponding ratios and are given at the 2σ level. Number in brackets is number of grains in fraction. Individual fraction ellipse errors and regression calculations were determined using the PbDat 1.24 and Isoplot/Ex 2.49 programs respectively (Ludwig, 1993 and 2001). The decay constants used for the U-Pb system are those recommended by the IUGS (Steiger and Jäeger, 1977). Abbreviations: rad = radiogenic; tr. = translucent; cl. = colorless; ye. = pale yellow; nd. = needle-shaped; el. = elongated; sp. = short prismatic; ab. = mechanically abraded (Krogh, 1982); un. = unabraded.

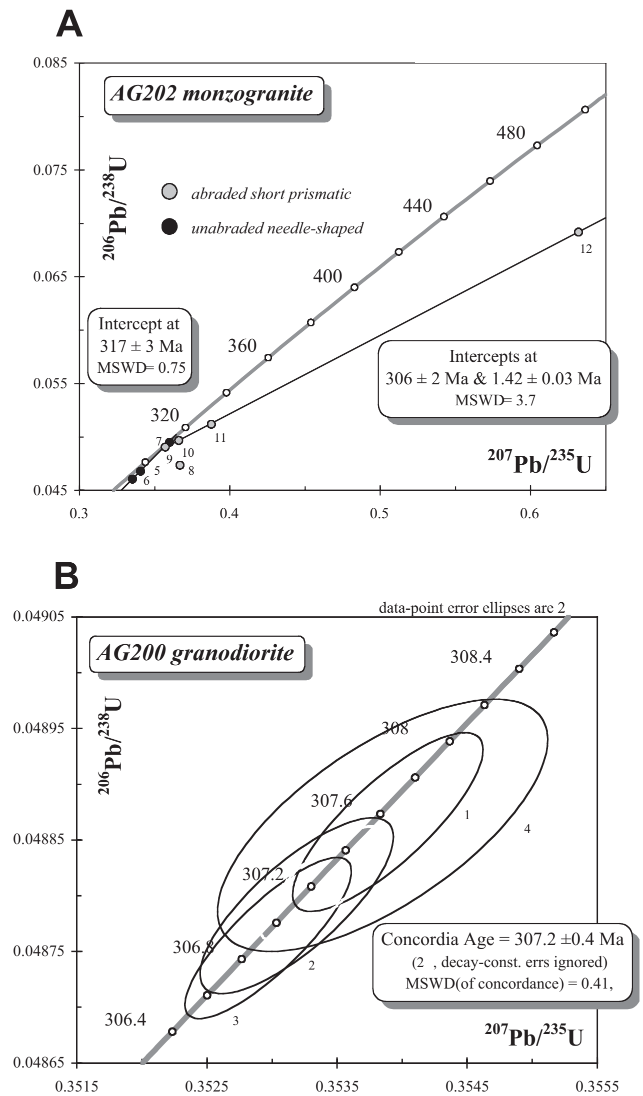


Figure 5. Concordia diagrams of two samples of deformed granites of the Agly Massif. (A) Monzogranite of the gneissic core of the dome. (B) Granodiorite of base of the Saint-Arnac pluton intruding the micaschist cover. Locations of these samples are given on Figure 4.

sample AG202, there is no concordant point, the mean square of weighted deviates is poor in spite of the large spreading of the analytical points, and point 8 is clearly affected by Pb loss and the other (nonconcordant) points may also be disturbed. Consequently, the lower intercept at 306 Ma cannot be considered meaningful; this age is discarded on analytical grounds. For this reason, and to better constrain the age of magmatism, we also analyzed three fractions of needle-shaped zircons (Table 1, fractions 5–7). Indeed, in granites, such zircons generally do not contain inherited cores and crystallize rapidly, but they are rare and small (Paquette et al., 1999). Consequently, the upper intercept at

317 ± 3 Ma, with a lower intercept being at the origin, yielded by these three fractions (Fig. 5A), is unambiguous and we consider that it represents the true age for magma crystallization.

In sample AG 200, the zircon grains are euhedral, translucent, short to medium prismatic, and light yellow in color. The four abraded zircon fractions (Table 1) yield a concordant intercept age at 307.2 ± 0.4 Ma (Fig. 5B). This latter is equivalent to the mean $^{207}Pb/^{206}Pb$ age of 307.6 ± 1.2 Ma. Consequently, this age is interpreted as the primary crystallization of the AG 200 granodiorite at 307 Ma. The possible occurrence of inherited cores inside zircon crystals was neither analytically nor optically found.

DISCUSSION

The main pervasive foliation present in all the lithologies of the Agly Massif is the oldest observable foliation. It is generally shallowly dipping and corresponds to a displacement of the top of the metamorphic stack to the SSW. Such a foliation and associated kinematics are characteristic of the gneiss domes of the Pyrenees, in the Axial Zone as well as in the North-Pyrenean massifs. However, this foliation has been interpreted in the past in different ways: synmetamorphic S1 foliation developed during an early tangential phase (e.g., Matte and Mattauer, 1987; Carreras and Capella, 1994), or S2 foliation superimposed on a S1 foliation (e.g., Soula et al., 1986), or late S3 foliation linked to a post-collision extension (e.g., Van Den Eeckhout and Zwart, 1988; Vissers, 1992). In the Agly Massif, this main foliation was interpreted as S1 (Bouhallier et al., 1991), which our observations support.

The mylonitic foliation cuts the pervasive foliation generally at a low angle. Sense of shear criteria unambiguously indicate top to NNE on the north-dipping mylonitic foliation and top to SSE on the south dipping foliations. These results contradict the only two kinematic studies previously performed on the mylonitic bands of the Agly Massif (Bouhallier et al., 1991; Paquet and Mansy, 1991). These authors considered that the upper part of the series was systematically northward displaced, leading to models in extension, either late Variscan (Bouhallier et al., 1991) or Cretaceous (Paquet and Mansy, 1991). It is noteworthy that some movements to the south were mentioned by Bouhallier et al. (1991) but were not taken into account in their model. Similar mylonitic bands have been described in the North Pyrenean massif of Saint-Barthèlèmy (Saint Blanquat, 1993) with a sense of shear top to the South. As a consequence, the hypothesis of an overall collapse of the North Pyrenean massifs to the North is indefensible.

The stretching lineations carried by both types of foliations are subparallel but correspond to different events. The first deformation, D1 was necessarily achieved in a noncoaxial regime, prior to doming, considering the unique sense of shearing to the south observed on both flanks of the gneiss dome. The doming event deformed S1 and L1 around a subhorizontal N110°-trending axis without creating a new foliation. We only observed a partial retrograde metamorphism of the paragenesis related to D1 in the gneissic core of the dome and a prograde evolution in the micaschist cover.

The mylonitic deformation developed under rather high temperature conditions, only slightly less than the temperature of the D1 deformation. The lineation trend perpendicular to the dome axis and the sense of shear opposite and symmetrical about this axis indicate a dome-up relationship.

Interpretation of the Metamorphic Gradients

Different studies on the thermodynamic conditions suffered by the Agly formations show that there are three types of gradients: medium pressure, HT-LP and finally very high temperature localized at the base of the micaschist cover.

Medium Pressure Gradient

Some authors mentioned that medium pressure relict minerals such as kyanite and staurolite are locally preserved in the gneiss domes of the Axial Zone (Besson, 1974) and of the North Pyrenean massifs (Roux, 1977; Vielzeuf, 1980), especially in the Agly gneisses (Fonteilles and Guitard, 1971). These observations led them to argue for an early Variscan medium pressure metamorphism, developed during a phase of thickening related to a continental collision (Azambre and Guitard, 2001). However, there is no proof for the age of these relict paragenesis, which could be pre-Variscan. Indeed, U-Pb dating of zircon recently obtained from the Canigou orthogneiss (Fig. 1A) yielded an age of 475 ± 10 Ma (Deloule et al., 2002), demonstrating the existence of the Caledonian orogenesis in the Pyrenees.

The HT-LP Gradient

Several authors have estimated the P-T conditions of this metamorphism in the deepest part of the series, near the charnockitic granite of Ansignan: 6 ± 1 kbar, 750° ± 50 °C (Andrieux, 1982); 4 kbar, 700–800 °C (Barbosa and Fonteilles,1986); 5 ± 0.5 kbar, 800 ± 100 °C (Vielzeuf, 1996). These estimations are rather poorly constrained but, whatever the authors considered, the mean thermal gradient is high (~40–50 °C /km). In all the models trying to explain this HT-LP gradient, heat was considered to be provided, at least partly, by injections of mafic magmas in the lower crust, the type of geodynamic evolution being either an early thinning of the crust during the Early Carboniferous (Soula et al., 1986), or a slow isostatic uplift following a medium pressure metamorphism (Vielzeuf, 1996).

Very High Temperature Gradient

The metamorphic conditions at the base of the micaschists are estimated as having been between 2.5 and 3 kbar (Vielzeuf, 1996), with temperatures ~650–700 °C based on the observation that this level is located in the zone of sillimanite and has suffered incipient anatexis. This corresponds to a mean gradient of ~60–75 °C/km. However, this gradient is not homogeneously distributed in the series, the isograds of temperature being very narrow at the base of the micaschists close to the contact with the Belesta gneisses, where they indicate a very high gradient of ~125 °C/km (Barnolas and Chiron, 1996, p. 569). Such a prograde gradient displays all the features of a contact metamorphism caused by the exhumation of the gneiss dome that simultaneously registered a retrograde evolution. A comparable gradient developed around the Saint-Arnac pluton with strongly compressed isograds seemingly matching the compressed isograds that surround the gneiss dome.

No Major Detachment in the Agly Massif

Different studies in the Agly Massif postulated a thinning of at least 10 km, essentially localized along a main subtractive detachment. Nevertheless, the different authors do not agree about the location of this detachment, either at the boundary between the Caramany and Belesta gneisses (Paquet and Mansy, 1991), or at the boundary between the gneissic basement and the micaschist cover (Bouhallier et al., 1991).

On the basis of the most recent barometric data (Vielzeuf, 1996), it is possible to better evaluate the thinning of the Agly series: (i) considering the pressure difference between the deepest gneisses (5 ± 0.5 kbar) and the base of the cover (2.5–3 kbar), the initial thickness of the gneisses was around 8 km. The present thickness of these gneisses being 2.5 km, the thinning of this part of the series would have been ~5–6 km; (ii) considering the pressure at the base of the cover, its initial thickness would have been ~10 km, including the Upper Devonian–Lower Carboniferous strata that are not exposed in this area; however, in regions of the eastern Pyrenees where these strata are exposed, their thickness never exceeds a few hundred meters. The present cover series being 2.5 km thick, it is also necessary to admit ~7 km of thinning for this cover. Then, the total thinning of the metamorphic stack may be estimated at ~12–13 km. This calculation is in good agreement with the estimation mentioned above. However, the hypothesis of a major subtractive detachment is not compatible with our data, whatever the location proposed by the different authors:

We have observed numerous mylonitic bands with variable spacing and thicknesses, but these are rather uniformly distributed across the whole section (Fig. 4).

The micaschist cover does not display evidence of lithologic gap. The stratigraphic column is complete from the lower Ordovician to the middle Devonian. Moreover, a marble strata, stretched but quite continuous (Fig. 1), is considered as the base of the Ordovician series (Fonteilles et al., 1993). Consequently the thinning by two thirds of this cover was uniformly distributed in all the series.

Concerning the metamorphism, no juxtaposition of units with very different P-T conditions was observed. Conversely, there is continuity between the gneisses and their cover, because all the isograds are present from the hypersthene zone to the chlorite zone (Fig. 1B). The main difference across the gneiss-micaschist contact is that the metamorphism is retrograde in the gneisses while it is prograde in the cover at the same time.

The Agly Massif displays some features commonly described in metamorphic core complexes, such as exhumation of granulitic rocks, a high temperature gradient, and the presence of thick mylonite zones. Nevertheless, our data show fundamental differences with a core complex. Indeed, core complexes are characterized by the juxtaposition of low-grade upper crustal units and high-grade metamorphic rocks along a major shear zone (Crittenden et al., 1980; Armstrong, 1982; Coney, 1987). In particular, a "detachment system" combining décollement levels - shear zones that are localized in specific lithologies or at the boundary between two rheologically contrasted levels and detachments (ramps that cross-cut lithologic contacts) ranging from ductile shear zones to brittle faults (e.g., Gans, 1987; Vanderhaeghe and Teyssier, 2001). We have shown that in the Agly Massif there is no juxtaposition of low-grade with high-grade metamorphic rocks along a major detachment, but numerous mylonitic bands accounting for distributed thinning throughout almost all the series. Moreover, there is no décollement localized within specific levels.

Chronology of the Magmatism

The dating at 317 ± 3 Ma of a deformed granitic sill intruded in the Belesta gneisses, i.e., in the upper part of the gneiss series, is very close to the previous ages of 314 ± 6 Ma (Respaut and Lancelot, 1983) or 315 ± 5 Ma (Postaire, 1984) obtained on the Ansignan charnockite. The sill, several hundred of meters thick and concordant with its country rock, is intrusive in the deepest part of the dome. This result indicates that the numerous sills, more-or-less deformed, that intruded all levels in the gneissic series, are coeval and were emplaced relatively early during the Variscan orogenesis of the Pyrenees which began ca. 325 Ma and ended ca. 300 Ma (Barnolas and Chiron, 1996). Moreover, all authors admit that the granulitic metamorphism, the pervasive regional deformation, and the emplacement of the charnockite are coeval events. Consequently, we argue that these ages of ca. 315 Ma date the thermal peak of metamorphism during the tangential phase D1, prior to doming and retrograde metamorphism in the gneisses.

The dating at 307 ± 0.4 Ma of the deformed granodiorite located at the base of the Saint-Arnac pluton, intruded in the micaschist cover, is similar to other dates obtained previously on plutons emplaced at comparable structural levels, e.g., Mont-Louis-Andorra pluton (305 ± 5 Ma; Romer and Soler, 1995) or Quérigut complex (307 ± 2 Ma; Roberts et al., 2000). Therefore, the magmatism corresponding to the emplacement of the plutons in the micaschist cover represents a distinct event from the emplacement of the deep sills. However, in the absence of more dating, one cannot discard that magmatic bodies (sills, dikes, small stocks) were also emplaced in the core of the gneiss dome during the formation of this dome.

The Agly Massif in the Variscan Pyrenees

In order to interpret the formation of the Agly dome, it is necessary to take into account the data concerning all the Variscan Pyrenean range. This belt is characterized by an "infrastructure" and a "superstructure" whose characteristics are very different: (i) The infrastructure roughly corresponds to the gneiss domes (Fig. 1), metamorphosed in the amphibolite facies or even in the LP granulite facies in the North-Pyrenean massifs. This infrastructure is characterized by shallowly dipping foliations. (ii) The superstructure corresponds to the cover metamorphosed in the greenschist facies. It is characterized by N110°E-trending folds, with subhorizontal axis, a steeply dipping axial-planar foliation, and stretching lineations subparallel to the fold axis and associated with dextral shearing.

Moreover, results recently obtained from studies on the Pyrenean granites and their country rocks have demonstrated that the large plutons were emplaced in the superstructure during the D2 main phase (e.g., Gleizes et al., 1998b, 2001; Olivier et al., 1999; Auréjac et al., 2004). This phase corresponds to a dextral transpressive regime, as shown by, on one hand, the magmatic structures in these plutons (shear bands with reverse displacements, steep foliations, N 60° to 100° E-trending subhorizontal lineations oblique with respect to the long axis of the range), and on the other hand, the shear sense determined in the country rocks.

We interpret the differences between the infrastructure and the superstructure as a strain partitioning due to the transpressive nature of the D2 main phase. So, the domes are seen as large scale anticlines, with N110°-trending axes, S1+2 composite shallowly dipping foliations, allowing the exhumation of deep rocks. Contemporaneously, in the cover preserved in between these domes, isoclinal folds with subvertical S2 axial-plane cleavage were formed. Because the Agly dome is comparable to the other Pyrenean domes, and because the Saint-Arnac granite is coeval with the other plutons of the belt, it is very likely that the formation of this dome was also the consequence of D2 transpression.

Model of the Agly Dome Formation

The data and discussion mentioned above allow us to propose a model different from the previously published models (Bouhallier et al., 1991; Paquet and Mansy, 1991; Kornprobst,1994).

D1 Tangential Phase of N-S Convergence (Fig. 6A)

This deformation might have been initiated as soon as 325 Ma, at the beginning of the compression in the Variscan Pyrenees (Barnolas and Chiron, 1996), in a noncoaxial regime, without significant crustal thickening. D1 was responsible for the main pervasive flat foliation and the associated SSW vergent movements. The HT gradient (~45 °C/km) developed during this phase was linked to an accumulation of basic magmas in the lower crust and to injections of sill-like granitoids such as the charnockite and monzogranite AG 202 at ca. 315 Ma.

D2 Transpression and Formation of the Dome (Fig. 6B)

A transpressive regime, acting as soon as ca. 310 Ma, followed continuously the tangential phase D1, without important change in the orientation of the strain field which shows roughly N-S contraction. This transpression induced the antiformal bending and uplift of the deep gneissic parts of the series, which recorded a retrograde metamorphism without developing a new foliation. The volume of magma that accumulated under the dome was more and more important during this phase, was involved in the dome uplift, and caused the emplacement of the Saint-Arnac pluton in the micaschist cover. Heat was advected upward, inducing in the cover the superimposition of a prograde metamorphism with a high temperature gradient comparable to a contact metamorphism with compressed isograds.

Development of the Mylonites during a Late Extensional Event (Fig. 6C)

The mylonitic band development in the gneisses and micaschists and the deformation at the base of the Saint-Arnac pluton would have appeared by the end of the formation of the dome. The mylonitic lineations being perpendicular to the dome axis means that transpression had ceased. At least on the dome apex, an extensive regime caused an important thinning in the upper part of the gneisses and in the lower part of the micaschist cover. This deformation further compressed the isograds, leading to the present gradient of 125 °C/km.

Alpine Deformations (Fig. 6D)

Alpine tectonics corresponds to "cold" structures in the Agly Massif, like the dissection of the massif into compartments that suffered northward rotations around a roughly E-W–trending horizontal axis. Steepened foliations and lineations observed on the northern border of the massif may correspond to such tilting to the north, linked to the formation of the large synclines made up of cretaceous strata which enclose the massif to the north and to the south. Some reactivation of the mylonitic bands might have happened at that time.

CONCLUSIONS

This new study of the Agly Massif allows us to propose an original model calling for a Variscan transpressional regime to explain the formation of this thermal dome. This model contradicts the previous models that called for a generalized extension and a unique and thick northward major detachment, either late Variscan or even Cretaceous in age, to explain the main characteristics of this dome, especially the presence of mylonitic bands and the apparent contradiction between the thermobarometric data obtained near the base of the series and the present thickness of this series. Our model is constrained by the fact that there is no

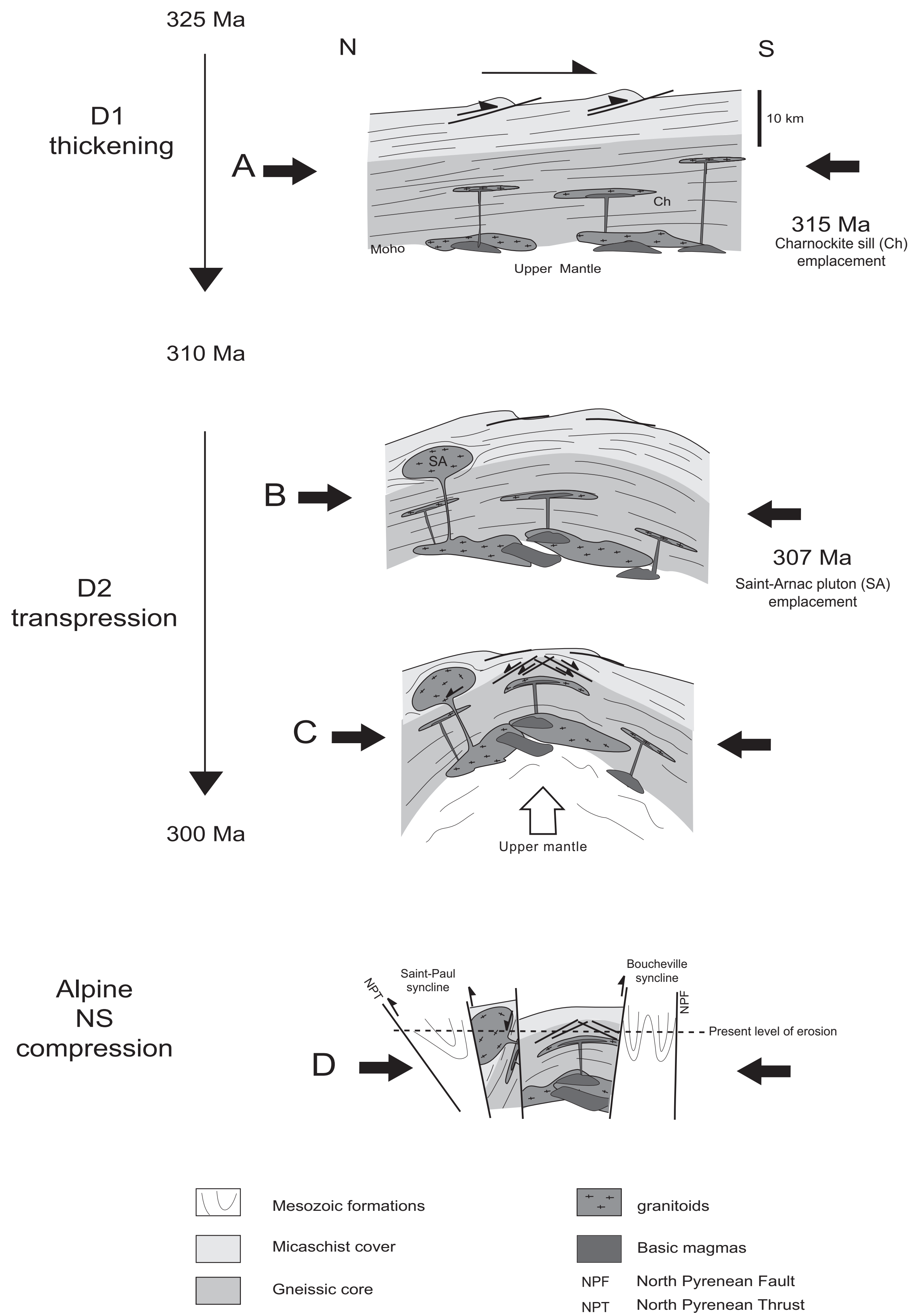


Figure 6. Model of formation of the thermal dome of the Agly Massif in a transpressive regime.

major detachment in the series and that the kinematics associated to the mylonitic bands formed by the end of doming indicates opposite senses of shear on the northern and southern sides of the dome.

The HT-LP metamorphism is related to the first D1 phase corresponding to SSW-vergent movements with no or slight thickening of the crust. The formation of the dome is contemporaneous with the transpressive main D2 phase which followed without discontinuity the D1 event.

New dating of two deformed granites allows us to better evaluate the timing of plutonism in the Agly Massif. A first magmatic event ca. 315 Ma corresponds to sill emplacement of basic and granitic magmas, which is coeval with D1 and the HT-LP metamorphism. A second event, ca. 307 Ma, coeval with D2, allowed granitic magmas to ascend in the upper crust where they formed the large Saint-Arnac pluton. This difference of 8–10 Ma between both magmatic events poses the following question: were there really two separate events of melting of the crust or just one with a continuous production and stocking of magmas at the base of this crust during all this period? Was the softening of the crust that favored the formation of the dome a continuous or discrete process?

These results, which are important for understanding the geodynamics of the Variscan Pyrenees, may probably be applied to other North-Pyrenean massifs which also display a HT-LP metamorphism and mylonitic bands acting as normal faults. Several problems are still unresolved, especially the differences between these domes and those located in the Axial Zone which do not display late mylonitic bands nor granulitic gneisses.

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