Late Hercynian leucogranites modelling as deduced from new gravity data: the example of the Millevaches massif (Massif Central, France)

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Key words. — Gravimetry, Density, Laccolith, Millevaches massif, Crustal structure.

Abstract. — The Millevaches granitic complex, located in the northern part of the French Massif Central, is elongated in a N-S direction, perpendicular to the main E-W trend of the Hercynian belt. It is affected on its limits and in its core by several ductile shear zones that have necessarily played a great role in the emplacement and exhumation of the massif. Based on gravity modelling and recent field observations, this study intends to highlight the massif structure at depth and discuss its mode of emplacement and relations with the surrounding terrains.

The new gravity and density measurements on the north-east part of the Millevaches massif improve the gravity coverage of the northern Limousin. Using these new data we model the deep structure of the Millevaches plateau. The density measurements made on the different types of granites of the massif, and on the surrounding terrains improve the interpretation of the Bouguer anomaly. Analysis and inversion of the residual Bouguer anomaly in the area show that the Millevaches massif is 2 to 4 km-thick, from north to south and from west to east, locally rooting down to about 6 km deep in its eastern and southern terminations. These two zones coincide with porphyritic plutons and, because of the complex composite structure of the massif, cannot be definitively interpreted as feeding zones. In the field, the N-S-oriented Pradines vertical fault affects the core of the massif on 4 to 5 km width. Microstructural observations evidence that the faulting is contemporaneous of the granites emplacement. We suggest that this tectonic lineament could have triggered the migration of the magma, although it is not related to a clear gravity anomaly. AMS measurements in the north-central part of the Millevaches massif suggest that the magnetic foliation and lineation display a general sub-horizontal pattern. Moreover, on the western border of the Millevaches massif, the Argentat deep seismic profile shows sub-horizontal layering of gneisses and micaschists and evidences normal faulting offset of this layering along Argentat fault. This agrees fairly well with the gravity results, suggesting that (i) the Millevaches massif would be at a high structural level in the crust, (ii) the exhumation of the massif would have been favoured along the Argentat normal fault. As a whole, the massif can be described as a laccolith, 2 to 4 km-thick, emplaced as a “magmatic lens” into the sub-horizontally foliated gneisses and micaschists.

Modélisation des leucogranites tardi-hercyniens à partir de nouvelles données gravimétriques : l’exemple du massif de Millevaches (Massif central)

Mots-clés. — Gravimétrie, Densité, Laccolithe, Massif de Millevaches, Structure crustale.

Résumé. — Le massif granitique de Millevaches orienté N-S est transverse aux grands chevauchements de la chaîne hercynienne. Il est affecté en son cœur et au niveau de ses bordures par de grandes zones de cisaillement ductiles. On propose que ces accidents aient joué un rôle significatif dans la mise en place et dans les mécanismes d’exhumation du massif. Sur la base d’une modélisation gravimétrique et d’observations de terrain, cette étude est destinée à mieux comprendre la structure en profondeur du massif, son contexte de mise en place et ses relations avec l’encaissant.

Afin d’améliorer la couverture gravimétrique régionale, de nouvelles données gravimétriques ont été acquises sur la partie nord-est du Millevaches et permettent de modéliser la structure profonde du massif. En complément, des mesures de densité ont été effectuées sur l’ensemble des granites du plateau de Millevaches, ainsi que sur les formations encaissantes pour affiner la lecture de l’anomalie gravimétrique. L’observation de l’anomalie résiduelle et de son inversion, permettent de modéliser ce massif granitique comme un laccolithe dont le plancher se situe entre 2 et 4 km de profondeur du nord vers le sud et de l’ouest vers l’est. Deux zones d’épaississement bien marquées (épaisseur supérieure à 5 km) sont mises en évidence, à l’est, à l’aplomb du granite de Meymac et à l’extrémité sud du Millevaches. Elles sont toutes deux superposées au faciès porphyroïde et compte tenu de la structure complexe du massif elles ne peuvent être considérées avec certitude comme zones d’alimentation de l’ensemble du massif.

L’analyse microstructuraire de la zone de cisaillement des Pradines parallèle à l’orientation N-S du massif et qui l’affecte au centre sur une largeur de 4 à 5 km, met en évidence des textures sub-solidus dans les granites qui indiquent une mise en place synchrone de ces derniers. Comme hypothèse de travail, nous proposons que cet accident décrochant représente une zone de faiblesse ayant joué un rôle dans la migration des magmas. Cette structure qui n’est que faiblement marquée en gravimétrie pourrait néanmoins avoir favorisé la migration des magmas.

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L’acquisition de données d’anisotropie de susceptibilité magnétique effectuées dans la partie nord du massif de Millevaches mettent en évidence des directions préférentielles de fluidalité magmatique sub-horizontales.

En accord avec le modèle gravimétrique, ces résultats indiquent que les granites du Millevaches se seraient mis en place dans la foliation horizontale préexistante des gneiss et des micaschistes. Par ailleurs, le profil de sismique réflexion Argentat qui recoupe la bordure ouest du Millevaches indique une structuration en lames horizontales de l’encaissant formé par les gneiss et micaschistes. Il montre également une remontée de ces structures et du plancher du Millevaches à l’est de la faille d’Argentat démontrant le rôle important joué par celle-ci dans les mécanismes d’exhumation du massif.

INTRODUCTION

The Variscan Massif Central, France, is known to be a collision belt which first experienced crustal stacking and thickening [Matte, 1986], followed by extension and thinning [Mattauer et al., 1988 ; Faure, 1989 ; Van den Driessche and Brun, 1989 ; Faure et al., 1990 ; Bour et al., 1990 ; Faure, 1995]. Syn- or post-tectonic leucogranite plutons related to the post thickening thermal event crop out over large areas within the Massif Central hiding the earlier crustal structures. Some authors propose that leucogranites were emplaced during the Carboniferous post-collision crustal thinning episode [Faure, 1989 ; Faure and Pons, 1991]. Most Hercynian leucogranites are bounded by ductile shear zones which probably played a significant role in magma emplacement and/or subsequent exhumation of the massifs. Relationships between magmatism and deformation in orogenic belts are a large question. Indeed, close spatial and temporal relationships between faults and plutons have been recently described [Tikoff and St Blanquat, 1997]. Based on observation of geological maps several authors propose that magma ascent and emplacement is controlled by faults [Hutton, 1988 ; D’Lemos et al., 1992]. Others show that magmatic processes can produce regional deformation [Tikoff et al., 1999]. During their emplacement, large and hot magma volumes induce thermal heterogeneities that may disturb the regional deformation field. Shear zones can result from the instability propagation and in this case the pluton is closely related to their development [Holm, 1995]. The knowledge of depth processes is crucial for an overall understanding of phenomenon and requires using the geophysical tools. It is now well accepted that gravity modelling is appropriate to get a 3D image of geological bodies, and especially of granitic plutons [e.g. Vigneresse and Brun, 1983 ; Améglio, 1998 ; Martelet et al., 1999]. The gravity modelling complements the structural study that is restricted to the surface interpretation compared to the inferred thickness of granitic plutons. In this study, the gravity modelling is performed using simple assumptions in order to bring a first overview of the Millevaches massif geometry at depth. Together with other structural and geophysical data, this brings new constraints to investigate the relationships between the massif and the host rocks as well as its mode of emplacement. This could be related to large ductile shear zones which affect the Millevaches massif on its boundaries and in its centre. Trying to detect a possible negative anomaly along the fault, evidence of close relationships between fault and magma, the gravity associated with the kinematics study will help us to understand the fault impact on the magmas emplacement and on the mechanism of exhumation. To infer the 3D shape of several plutons in the Hercynian belt, several authors performed gravity modelling [Martelet et al., 1999 ; Audrain et al., 1989 ; Dumas et al., 1990 ; Améglio et al., 1994]. These studies allowed to raise questions in some cases about the bubble shape of plutons in orogenic belts. According to Vigneresse [1995] the granites emplaced during extensional deformation are thin with many root zones whereas the ones emplaced in context of shear deformation or compression are more deeply rooted with only one or a few roots. We will compare the Millevaches massif shape with others surrounding Hercynian plutons.

GEOLOGICAL SETTING

This study focuses on the Millevaches granitic complex, located on the northwestern part of the Massif Central, France (fig. 1). The Millevaches massif is 160 km-long, it follows a N-S trend and is sub-perpendicular to the E-W to WNW-ESE main thrusts of the Hercynian belt. On its western side, the Millevaches plateau is separated from the Limousin metamorphic units [Floc’h, 1983] by the ductile and brittle Argentat fault ; to the north, it is separated from the Guéret granitic massif by the “St Michel de Visse” dextral wrench fault, and in the east it is separated from cor-diere anatexesites and biotite-sillimanite paragneiss units by the Felletin - la Courtine shear zone, followed southward by the Ambrugeat fault (fig. 1). The massif is affected in its central part by the N-S Pradines ductile dextral wrench fault. Understanding the general kinematics of these major shear zones, their relations with plutonism and their role in the exhumation of the granitic massif is essential to better apprehend the transition between compressive, wrench and extensional tectonics in the Hercynian belt.

The Millevaches massif is composed of several porphyritic biotite granites and leucogranites plutons hosted in micaschists, forming N-S or NW-SE elongated stripes (fig. 1). Whole rock Rb/Sr isochrones give late Visean ages between 332 and 336 Ma [Augay, 1979 ; Monier, 1980] for the leucogranites emplacement. Furthermore, 40Ar/39Ar step-heating age spectra performed on muscovites of leucogranites give ages between 335 and 337 Ma [Roig et al., 2002]. According to Donnot [1965] the different magmas were emplaced at the same time. Other authors propose two generations of granites ; the porphyritic biotite granite resulting from melting of the lower crust are thought to be early compared to later leucogranites [Mouret, 1924 ; Raguin, 1938 ; Lameyre, 1966]. According to Monier [1980], the south of the Millevaches is composed of distinct plutons, each corresponding to a different melting event.
In the northern part of the Millevaches, three main domains can be distinguished according to magnetic susceptibility anisotropy [Jover, 1986]. The earliest porphyritic biotite granites, related to cordierite-garnet granites, show N-S sub-horizontal magnetic lineation and vertical magnetic foliation planes, parallel to granulite lenses. These formations are cut by later leucogranites parted in two groups by the author [Jover, 1986]: the former having NW-SE vertical foliations and sub-horizontal lineations, the latter having E-W to NW-SE sub-horizontal lineations and foliations.

GRAVITY DATA

Data acquisition

In order to get sufficient gravity stations to model the deep structures of the Millevaches massif, we had to complete the regional gravity coverage. In addition to the data from the French Gravity Database (white dots on figure 2), we measured 200 new gravity stations in the northeastern part of the Millevaches massif (black dots on figure 2). In most parts of the 450 km$^2$ surveyed area, we sampled 0.5 km$^{-2}$.
gravity measurements. The data were measured with a Scintrex CG3-M micro-gravimeter which had been calibrated along the Sèvres-Orléans baseline. In the field, the measurements were tied to the CGF 65 French gravity base network. Stations were positioned with about 1 metre accuracy in altitude using bench marks from the Institut Géographique National. Latitude and longitude were obtained using simple mode GPS positioning, with an accuracy of a few meters. The positioning was finally converted to the NTF French geodetic system using the WGS84 – Clarke 1880 transformation and projected into the Lambert II étendu projection, the altitude reference being at sea level.

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Data reduction and integration

The gravity anomaly was computed with respect to the theoretical value of g on Hayford–1930 ellipsoid. In order to obtain the complete Bouguer anomaly, we successively performed standard free air, plate and terrain corrections. For the two latter, a 2.6 g/cm³ Bouguer reduction density was chosen, close to the expected density of the granites. Terrain corrections were computed up to 167 km to ensure a good consistency of the new dataset with the French Gravity Database [Martelet et al., 2002]. Up to 53 m, terrain corrections were estimated in the field using Hammer charts [Hammer, 1939]. Beyond that distance, they were computed numerically using three DTM with grid sizes of 50 m, 250 m and 1 000 m, within annular zones of radius respectively 53 m-3 km, 3-10 km and 10-167 km. The error in the terrain correction is mostly due to the altitude offset between the DTM and the gravity stations: it varies from 0.1 to 0.6 m.Gal depending on the roughness of the topography. The mean quadratic error on the complete Bouguer anomaly due to the measurement, positioning and terrain corrections is 0.7 m.Gal.

Residual Bouguer anomaly

In order to highlight the short wavelengths of the gravity map, we have computed a residual Bouguer anomaly map (fig. 2) by removing a degree 3 polynomial computed at the scale of the Massif Central and representing the regional trend. The resulting residual anomaly (fig. 2) (i) has apparently lost all regional trend, (ii) is consistent with the geology (negative anomalies are related to granites, and positive ones to gneissic units), (iii) fits fairly well with the outcropping limits of the Millevaches massif. Using the density measurements results (table 1), the residual Bouguer anomaly map is consistent with the location of lithotectonic units: negative gravity anomalies are found to coincide with the granites (average density 2.62), whereas positive anomalies are related to the heavier gneissic or micaschists units (average density respectively 2.78 and 2.74). Hence, the Brâme, St Sylvestre, and St Goussaud granitic complexes are related to clear negative anomalies which are persistent to the southwest and strengthen under the Blond porphyritic plutons. North of the massif, the negative anomaly decreases, suggesting northward thinning of the granite. Close to the Guéret granitic massif, the anomaly even becomes positive probably due to the presence of nearby high density cordierite anatexites that would underlie the Guéret massif. In order to give quantitative estimates of these interpretations, the variations in thickness of the Millevaches have been computed performing an inversion of the gravity field.

GRAVITY INVERSION

The gravity field is inverted in terms of depth to the bottom of the granite using IBIS code [Chenot and Débéglia, 1990]. Prior to the inversion, the average depth of the modelled interface is calculated using Spector and Grant [1970] spectral analysis method. Then, assuming a density contrast of 0.11 (2.73-2.62) between the granite and the host rocks, the interface is iteratively deformed and its gravity effect compared to the Bouguer anomaly until the misfit between both is considered small. Figure 3 shows the geometry of the obtained granite/micaschists interface. Average thickness of the granite ranges between 2 and 4 km, with a maximum of about 6 km, which is in good agreement with estimations published on nearby massifs [e.g. Audrain et al., 1989], or on massifs with comparable extension [e.g. Pétrequin, 1979 ; Talbot, 2003]. Uncertainties attached to the modelled geometry of the pluton floor are mainly related to the uncertainty on densities. We have chosen a constant density contrast between the granites and the surrounding rocks in order to keep the modelling as simple as possible. Indeed, we have considered neither depth-dependent densities, nor varying densities of the pluton basement, since we have poor constraints on these parameters. Moreover, in accordance with results obtained in comparable conditions for the Sidobre pluton [Améglio et al., 1994], our tests show that uncertainties of 0.01 to 0.02 g/cm³ on the density contrast used for the inversion shifts the average depth of the pluton floor by about 250 to 500 m, without significantly altering its shape. As previously suggested in the residual Bouguer anomaly map, the bottom of the massif is deeper in its eastern, and southern parts, with thickness reaching 5 to 6 km. In the south, this deep-rooting could be associated

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Table I. – Density measurements.

Density measurements were obtained by double weighing method with an average uncertainty on each sample of 0.01 g/cm³. Several calibrations using heavy liquids allowed to verify the accuracy of the density measurements.

Mesures de densité réalisées par la méthode de la double pesée, avec une incertitude moyenne de 0.01 g/cm³ sur chaque échantillon. Plusieurs calibrages aux liquides denses ont permis de s’assurer de la justesse des densités établies par pesée.

<table>
<thead>
<tr>
<th>N° Ech.</th>
<th>D (g/cm³)</th>
<th>Type lithologique</th>
<th>Localisation</th>
<th>N° Ech.</th>
<th>D (g/cm³)</th>
<th>Type lithologique</th>
<th>Localisation</th>
</tr>
</thead>
<tbody>
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<td>2.58</td>
<td>granite à 2 micas porphyroïde</td>
<td>Meymac</td>
<td>D66</td>
<td>2.67</td>
<td>granite à Bt porphyroïde</td>
<td>massif de Millevaches</td>
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<tr>
<td>D3</td>
<td>2.59</td>
<td>granite à 2 micas porphyroïde</td>
<td>Meymac</td>
<td>D65</td>
<td>2.65</td>
<td>leucogranite mylonitique</td>
<td>Fellein-La Courtoire</td>
</tr>
<tr>
<td>D4</td>
<td>2.64</td>
<td>granite à 2 micas porphyroïde</td>
<td>Meymac</td>
<td>D68</td>
<td>2.67</td>
<td>leucogranite mylonitique</td>
<td>Fellein-La Courtoire</td>
</tr>
<tr>
<td>D5</td>
<td>2.64</td>
<td>granite à Bt porphyroïde</td>
<td>massif de Millevaches</td>
<td>D69</td>
<td>2.61</td>
<td>granite à Bt type Guéret mylonitique</td>
<td>Fellein-La Courtoire</td>
</tr>
<tr>
<td>D6</td>
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<td>gneiss anatexique un peu altéré</td>
<td>Sornac</td>
<td>D70</td>
<td>2.66</td>
<td>granite type guéret</td>
<td>Fellein-La Courtoire</td>
</tr>
<tr>
<td>D7</td>
<td>2.73</td>
<td>gneiss anatexique</td>
<td>Sornac</td>
<td>D71</td>
<td>2.67</td>
<td>leucogranite très frais</td>
<td>Peyrat-le-château</td>
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<tr>
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<td>2.7</td>
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<td>leucogranite très frais</td>
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<tr>
<td>D9</td>
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<td>Sornac</td>
<td>C</td>
<td>2.64</td>
<td>leucogranite très frais</td>
<td></td>
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</table>

with the Glénat porphyritic granite rather than with the shallow leucogranites that mark out the Argentat fault (Roig, personal communication). Related to the easternmost negative anomaly, mining work in the Meymac area revealed the occurrence of a buried late granite [Burnol et al., 1980]. It is however difficult to know whether the anomaly is due to the Meymac porphyroid granite or to the late leucogranite body. Figure 4 presents a geological cross-section (profile A’A’) through the Millevaches granitic massif.

In the central part of the massif strongly affected by the Pradines shear zone, the gravity does not detect any large anomaly. The N-S oriented Pradines fault affects leucogranites and porphyritic biotite granites of the Millevaches massif in a 4 to 5 km-wide corridor. The N-S
trending vertical foliation and sub-horizontal lineation define a consistent pattern associated with the emplacement of granites during dextral shearing. Indeed, from south to north within the shear zone, the leucogranites are typical biotite-muscovite C-S orthogneisses, and mylonites that indicate a dextral sense of shear (fig. 5). Furthermore, the microstructural study of Pradines dextral wrench fault mylonites shows sub-solidus deformation textures (fig. 6): rectangular grain boundaries shape form a reticular or mosaic-like pattern indicating extensive grain boundary migration, typical of high temperature sub-solidus deformation [Gapais et al., 1986; Tommasi and Vauchez, 1994]. These observations suggest a synchronous emplacement of leucogranites with the Pradines fault activity. Vertically foliated gneiss xenoliths prolongate the Pradines fault to the north. This occurrence advocates that the fault could have locally weakened the crust and favoured the migration of magmas.

Eastward and close to the leucogranite mylonites, the porphyritic biotite granites show magmatic textures with a N-S to NNW-SSE preferential orientations of the (010) plane in K-feldspars which become NW-SE south-eastwards [Mezure, 1980]. According to field relationships at the regional scale [Lameyre, 1966] the porphyritic biotite granite could have been emplaced at the same time as the leucogranites or more likely just before. We propose that the trend of this NW-SE foliation recorded strain field during the Pradines fault activity. In this last case the magma should not crystallise everywhere to record the effects of the dextral wrench Pradines fault.

DISCUSSION

Following Améglio et al. [1997] gravity and structural results for several plutons show that magma emplacement is largely controlled by the anisotropy and rheology of the

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FIG. 3. – Map of the depth to the granite/micaschists interface, obtained by inversion of the gravity anomaly using the IBIS code. A A’ : Cross-section, fig. 4.

FIG. 3. – Carte de profondeur de l'interface granite/encaissant obtenue par inversion de l'anomalie gravimétrique à l'aide du logiciel IBIS. A A' : coupe de la figure 4.

FIG. 4. – Sketch geological cross-section. (see location on fig. 3).
Fig. 5. – Typical C-S structures developed in the leucogranites of the Pradines fault indicating a dextral sense of shearing.

Fig. 6. – Quartz microstructures within foliated granite showing rectangu-
lar contours forming a reticular or mosaic-like pattern typical of high tem-
perature deformation.

crust, in particular around the brittle-ductile transition. Local
dilatancy of the brittle crust may be achieved under ei-
 ther compressive or extensive regime, but dominated by
transcurrent movements. These authors differentiate
“flat-shaped” and “wedge-shaped” plutons on geometrical
criteria and related tectonic regime criteria: (i) flat-shaped
plutons have much broader horizontal than vertical exten-
sion and would spread parallel to the pre-existing tectonic
layering of the crust, whereas, (ii) wedge-shaped plutons
would infill more or less vertical fractures in the brittle
crust. In addition, relations between plutons and the tec-
tonic structures is generally evidenced: whether these rela-
tions are genetic or related to the exhumation is often less
clear. This is illustrated in the Limousin area, where several
plutonic complexes were emplaced during the late-Hercynian period. The leucogranitic complex of la
Brâme – St Sylvestre dated at 318 ± 5 Ma and 324 ± 4 Ma
by U-Pb method [Holliger et al., 1986] has a flat-shaped ge-
ometry, with a rather low thickness of about 2 km [Audrain et al., 1989], and an overall flat foliation. Likewise, the
Sidobre granite located in the Montagne Noire (SW Massif
central) was emplaced at 304 ± 8 Ma [Pin, 1991], and ap-
ppears as a 2 to 3 km thick sill, the emplacement of which
was favoured by normal faults that also certainly played a
role of feeding zone [Améglio et al., 1994]. On the oppo-
site, the plutons of the Aigurande plateau are rather of the
wedge-shaped type. The Crevant leucogranitic massif is
dated at 312 ± 6 Ma [Petitpierre and Duthou, 1980] by
Rb/Sr on whole rock and Crozant and Orsennes at
312 ± 20 Ma [Rolin et al., 1982] by the same method. The
bodies are rooted southward around 3 km depth and spread
laterally [Dumas et al., 1990]. Owing to their close relations-
ships, their emplacement is certainly linked with the
Marche senesral wrench fault. These plutons could be com-
pared with those of the South Armorican Shear Zone, such
as the Mortagne pluton [Guineberteau et al., 1987], which
was emplaced between 300 and 360 Ma [Hamner et al.,
1982; Le Corre et al., 1991], deeply rooted into the shear
zone and extrusive beyond the surface toward NE.

The Millevaches massif is the largest one. It was
emplaced during the same late Hercynian period. Our model
shows a large and rather thin batholith that can be classified
in the “flat-shaped” type. In the context of the Hercynian
orogeny, a wealth of geological considerations, synthesised
by Faure and Pons [1991] document the emplacement of
such type of plutons in a late-orogenic extensional tectonic
environment.

Other tabular Hercynian granites have been recognized
in western Europe and NW Africa. The idea of magma
injection through fault and lateral expansion has already been
discussed by Lagarde et al. [1990] about the late Carbonif-
erous plutons of the Moroccan Meseta. To explain the em-
placement of granitic plutons within high structural levels
along crustal faults and their tabular shape, he suggests that
fauls collect melts at depth and control sites of emplace-
ment within shallow crustal levels in which rheology permit
the lateral expansion of magma [Lagarde et al., 1990]. Sim-
ilarly, the Itaporanga pluton in the northeast of Brazil is an
example of granite that emplaced into a shear zone and
spread out laterally as a sill [Archanjo et al., 1999]. Accord-
ing to Hutton [1996], the Itaporanga pluton presents a
syntectonic emplacement because of the magmatic and
magnetic fabrics which are coherent with the country rock
deforestation. Relationships between faulting and granitic
ascent have also been described in the Himalayas with em-
placement of leucogranites along the North Himalayan Det-
achment [Burg and Brunel, 1984; Searle, 2003]. This fault
zone behaves like a barrier to the magma ascent and con-
trols the pluton emplacement in an extensional shear zone
[Guillot et al., 1995].

Owing to its overall tabular shape and geometric rela-
tionship with the surrounding terrains, the emplacement of
the Millevaches massif can apparently be explained by this
process: once it has reached the upper crust, the magma
spreads laterally into the sub horizontal micaschist foliation
(profile AA’, figure 4). Lately, its exhumation is favoured
along several faults that bound its limits and especially the
Argentat normal fault. In the present state of knowledge, as
a working hypothesis, we propose to interpret the
Millevaches as a laccolitic intrusion driven and emplaced
above a N-S trending vertical lineament.

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However, the question of the magma feeding process still needs investigations since only a weak negative anomaly is expressed along the N-S Pradines shear zone. According to Fyfe [1973], or Reches and Fink [1988], we imagine the magma conduits as very narrow, jagged and instable pipes that disapper at the end of the magma transfer and give in consequence a weak anomaly.

CONCLUSION
During the Hercynian orogeny large amounts of magmas resulting from the partial melting of the pre-Variscan basement [CuneY et al., 1990] were produced, as can presently be observed in the Limousin area (Massif central, France). The process of magma segregation, their ascent and emplacement mechanisms, as well as their relationships with the regional tectonics are still debated. Gravity modelling combined with structural analysis yield a first overview of the Millevaches massif geometry at depth. Together with other structural and geophysical data, this brings new constraints that help investigate the relationships between the massif and the host rocks, as well as its mode of emplacement.

New gravity and rock densities have been measured which improve the gravity knowledge of the northern Limousin. Analysis and inversion of the residual Bouguer anomaly in the area show that the Millevaches massif is 2 to 4 km-thick, from north to south, rooting down to about 6 km depth in its eastern and southern terminations. These two zones coincide with porphyritic plutons but, because of the complex composite structure of the massif, cannot be definitively interpreted as feeding zones for the whole massif. Independent AMS and seismic results are in good agreement with the overall flat-lying geometry we derive from gravity modelling. These geophysical constraints also suggest, in agreement with field observations, that the exhumation of the massif was achieved along several boundary faults and especially the Argentat normal fault. The scenario of emplacement of the massif as a laccolith at a high crustal level and its exhumation in relation with tectonic structures seems compatible with previously recognised situation for other batholiths in the late-Hercynian extensional context.

We further suggest that the Pradines shear zone, which is oriented parallel to the massif length and affects its core on a 4 to 5 km-wide corridor, could have triggered the migration of the magma (profile AA’, figure 4). However, the question of the magma feeding process requires further investigations, since only a weak negative anomaly is expressed along the N-S Pradines fault. In the field, throughout the shear corridor in the leucogranites along the Pradines fault, typical C-S structures indicating a dextral sense of shear have been confirmed. Moreover, in this zone, quartz microstructures showing rectangular contours forming a mosaic-like pattern are typical of high temperature sub-solidus deformation creval with leucogranite cooling.

Combining new geochronology (40Ar/39Ar method on the Pradines shear zones, together with the U-Pb method to determine the crystallization age of leucogranites), microstructural and AMS data, will be essential to further understand the internal magmatic processes, as well as the geodynamic context of the Millevaches massif emplacement.

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