Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Tectonophysics 382 (2004) 117–128
TECTONOPHYSICS
www.elsevier.com/locate/tecto

Integrated 3D geophysical and geological modelling of the Hercynian Suture Zone in the Champtoceaux area (south Brittany, France)

G. Martelet[a,*], P. Calcagno[a], C. Gumiaux[b], C. Truffert[a], A. Bitri[a], D. Gapais[b], J.P. Brun[b]

[a] BRGM-CDG/MA, 3 av. Claude Guillemin, BP6009, 45060 Orléans Cedex 2, France
[b] Géosciences Rennes, UMR 6118 CNRS, Université de Rennes 1, Campus de Beaulieu, 35042 Rennes Cedex, France

Received 16 January 2003; accepted 17 December 2003

Abstract

This paper combines geological knowledge and geophysical imagery at the crustal scale to model the 3D geometry of a segment of the Hercynian suture zone of western Europe in the Champtoceaux area (Brittany, France). The Champtoceaux complex consists of a stack of metamorphic nappes of gneisses and micaschists, with eclogite-bearing units. The exhumation of the complex, during early Carboniferous times, was accompanied by deformation during regional dextral strike–slip associated with a major Hercynian shear zone (the South Armorican Shear Zone, SASZ). Dextral shearing produced a km-scale antiformal structure with a steeply dipping axial plane and a steeply eastward plunging axis. Armor 2 deep seismic profile shows that the regional structure was cut by a set of faults with northward thrusting components. Based on the seismic constraint, direct 2D crustal-scale modelling was performed throughout the Champtoceaux fold on seven radial gravity profiles, also using geological data, and density measurements from field and drill-hole samples. The 3D integration of the cross-sections, the digitised geological map, and the structural information (foliation dips) insure the geometrical and topological consistency of all sources of data. The 2D information is interpolated to the whole 3D space using a geostatistical analysis. Finally, the 3D gravity contribution of the resulting model is computed taking into account densities for each modelled geological body and compared to the Bouguer anomaly. The final 3D model is thus compatible with the seismic and gravity data, as well as with geological data. Main geological results derived from the modelling are (i) the overall 3D geometry of the south dipping thrust system interpreted on the seismic profile emphasises northward thrusting and folding of the Champtoceaux complex which was coeval with strike–slip along the South Armorican Shear Zone; (ii) the gravity modelling suggests the presence of a relatively dense body below the Champtoceaux complex that could be interpreted as a result of relative uplift of midcrustal material during thrusting along the E–W trending wrench–thrust system; (iii) the northern limb of the Champtoceaux anticline is a relatively shallow feature; and (iv) Vigneux synkinematic granitic body is a laccolith sheared and rooted along the southern branch of the SASZ and spreads away from the strike–slip zone within weak country-rocks.

Keywords: 3D modelling; Gravity; Champtoceaux; Armorican massif; Hercynian belt

* Corresponding author. Tel.: +33-2-38-64-47-32; fax: +33-2-38-64-33-34.
E-mail address: g.martelet@brgm.fr (G. Martelet).

0040-1951/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2003.12.009

1. Introduction

Geological structures are often noncylindrical and can result from complex deformation histories. Therefore, their analysis and tectonic interpretation generally require a 3D structural model. In most cases, available data are limited to surface geology and interpreted cross-sections. More favourable situations are those where geophysical data, such as deep seismics, gravity, or magnetics, are also available, allowing a better constraint on the interpretation of geological structures (e.g., Torné et al., 1989; Truffert et al., 1993; Tsokas and Hansen, 1997).

In the present study, based on such geophysical constraints, we achieve the 3D modelling of a crustal-scale segment of the Hercynian belt of western Europe: the Champtoceaux complex, south Brittany, France (Fig. 1). This metamorphic complex is part of a major suture zone marked by a strong deformation history involving burial of continental units down to at least 50 to 60 km (Ballèvre and Marchand, 1991, Ballèvre et al., 1989, Bosse et al., 2000), exhumation in the upper crust, and folding associated with wrench–thrust tectonics. This latter event produced a complex noncylindrical structure of crustal-scale.

Beside a well-constrained surface geology, available data in the area comprise gravity data, detailed aeromagnetic data (Truffert et al., 2001), and a deep seismic reflection profile (Bitri et al., 2003). From the input data (geological maps and cross-sections, structural dips, 2D geophysical information, drill-holes), a geostatistical interpolation produces a 3D model divided into geometrical bodies representing different lithologies. In order to compute the 3D gravity or magnetic contributions of the model, physical parameters (density, magnetic susceptibility) can be attributed to each representative lithology. An interactive comparison between modelled and measured potential

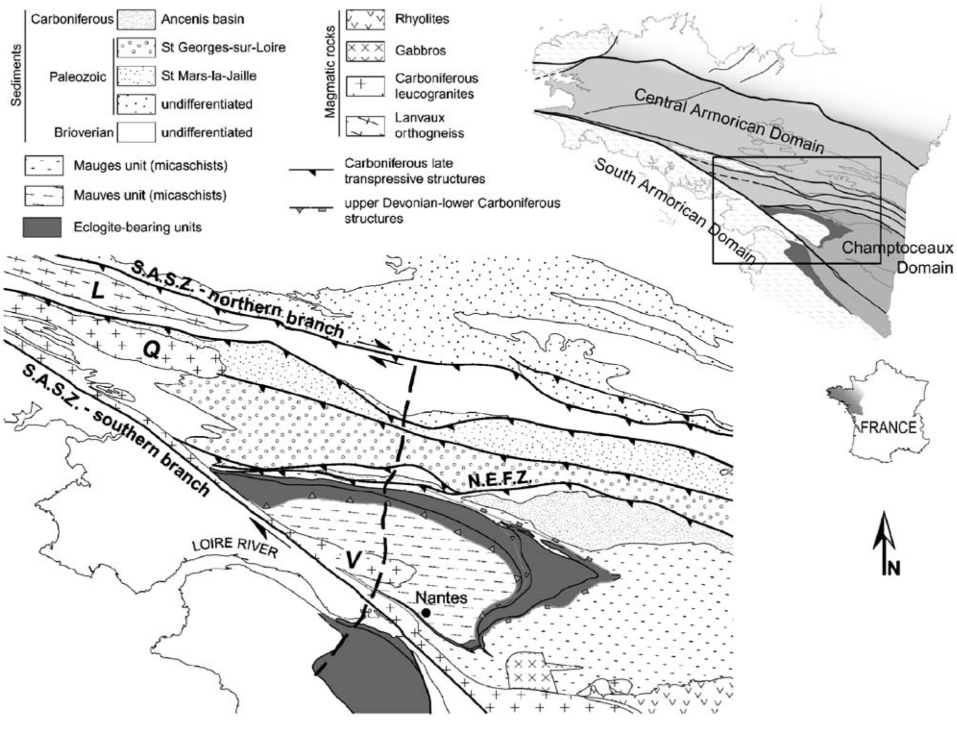


Fig. 1. Simplified geological map of the Champtoceaux area in the Hercynian belt of Brittany. SASZ, South Armorican Shear Zone; NEFZ, Nort-sur-Erdre Fault Zone; Q, Questembert granite; L, Lanvaux orthogneiss; V, Vigneux granite. Black rectangle shows limits of the 3D modelling area; thick dashed line is the location of the Armor 2 seismic profile (Fig. 2).

fields provides a best-fit adjustment of the model geometry. The final model is therefore compatible with the different sets of input data.

The study (i) provides a methodology for integrating multidisciplinary information into a realistic geological 3D model, (ii) emphasises the usefulness of 3D modelling to ensure an overall consistency between geological interpretations and geophysical data, and (iii) provides new constraints for geological and kinematic interpretations of the Champtoceaux area.

2. Geological data

The Champtoceaux Domain (Fig. 1) is bounded to the north by the Nort-sur-Erdre Fault Zone (NEFZ) and to the south by the southern branch of the South Armorican Shear Zone (SASZ; Berthé et al., 1979; Jégouzo, 1980). In this domain, a piling up of strongly deformed eclogite-bearing gneisses witness to a segment of the Hercynian suture zone (Marchand, 1981; Ballèvre et al., 1994; Bosse et al., 2000). The eclogitic units of the Champtoceaux Domain were exhumed and thrust onto lower-grade units (Mauves units; Fig. 1) during the early Carboniferous (Bosse et al., 2000). Further details concerning the early history of the Champtoceaux complex can be found in Marchand (1981), Ballèvre et al. (1989, 1994) or Bosse et al. (2000). Here, we mainly focus on the deformation events occurring after the exhumation. During the upper Carboniferous (Ballèvre et al., 1994), the area was affected by dextral strike–slip along the SASZ, which produced a km-scale noncylindrical antiformal structure, with a steeply dipping axial plane and a steeply eastward plunging axis (Fig. 1). During dextral shearing along the SASZ, the Vigneux leucogranite emplaced within the core of the antiform (Fig. 1) and induced thermal contact metamorphism within the Mauves unit. To the north and to the east of the antiform, the top of the high-pressure units is affected by normal faulting (Fig. 1). The hanging wall of the fault zone consists of low-grade upper crustal sediments, the early Carboniferous Ancenis basin (Beaupère, 1973; Cavet, 1978) and the Late Proterozoic Mauges unit (Wyns and Le Metour, 1983).

The area north of the northern branch of the SASZ is the Central Armorican Domain (Fig. 1). It is mainly made of Upper Proterozoic to Lower Devonian sediments affected by low-grade metamorphism (Le Corre, 1977). The overall ductile deformation of the area results from dextral strike–slip of Carboniferous age (Gapais and Le Corre, 1980; Percevault and Cobbold, 1982; Gumiaux et al., in press), with EW-striking upright folds associated with a subvertical cleavage and a subhorizontal stretching lineation (Le Corre, 1978; Gapais and Le Corre, 1980). Along the northern branch of the SASZ, and south of it, folds tend to become asymmetric as a result of northward thrusting components, locally marked by minor thrusts (Le Corre, 1978; Ledru et al., 1986; Cartier et al., 2001).

To the south, the South Armorican Domain shows a complex structural pattern. Upper units are marked by high-pressure metamorphic histories (Godard, 1988; Bosse et al., 2000; Le Hébel et al., 2002). They are thrust onto a metasedimentary pile marked by Barrovian metamorphic conditions associated with crustal thickening (Iglesias and Brun, 1976; Brun and Burg, 1982). During the upper Carboniferous, crustal thickening was followed by pervasive extension (Gapais et al., 1993).

3. Geophysical data

3.1. Deep seismics

Armor 2 deep seismic profile (Bitri et al., 2003) provides a 2D image of crustal-scale relationships between the Central Armorican, the Champtoceaux and the South Armorican Domains (see profile location on Fig. 1). Fig. 2 is a line drawing (after Bitri et al., 2003) of the profile that crosscuts the whole Champtoceaux Domain. Only the strongest groups of reflections are represented, and a geological cross-section is superimposed on the upper part of the profile. The profile shows an overall strong reflectivity throughout the entire crust. In the upper crust, many reflections are directly correlated with mapped faults or unit boundaries. The following paragraphs summarises the seismic interpretation of Bitri et al. (2003), and focuses on deep reflections and large-scale structures that are critical to constrain our gravity modelling of the Champtoceaux Domain.

Below the Central Armorican Domain, the lower crust exhibits a moderate reflectivity, marked by

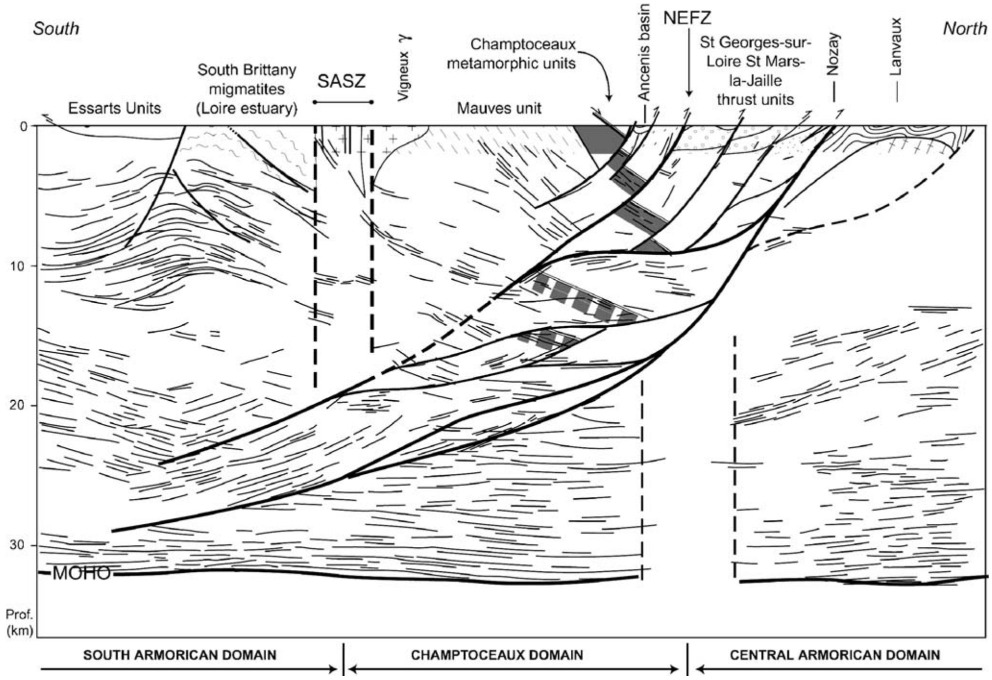


Fig. 2. Interpretation of the Armor 2 seismic profile (located on Fig. 1) (modified after Bitri et al., 2003). Major interpreted structures are highlighted by black lines; less constrained structures and interruptions of reflections are underlined by dotted lines. SASZ, South Armorican Shear Zone; NEFZ, Nort-sur-Edre Fault Zone. Surface geological units as on Fig. 1. See text for detailed description.

horizontal reflections, between 25 and 32 km. In contrast, it is slightly more reflective and a bit thicker below the Champtoceaux Domain, between 22 and 32 km. Below the South Armorican Domain, the lower crust remains reflective but is substantially thinner (27–28 to 31 km) and cut by south dipping reflections. The Moho is slightly deeper below the Champtoceaux and Central Armorican Domains (32 km) than in the southern part of the profile (31 km).

In the Champtoceaux Domain, the upper crust is strongly reflective, with numerous groups of north dipping reflections that correlate toward the surface with the overall attitude of the metamorphic layering, as observed in the field in the Mauves and Champtoceaux units (Fig. 2). In the first 10 km, a set of localised south dipping reflections offsets the north dipping set and outlines a north verging thrust system that brings the upper part of the Champtoceaux Domain onto the southern border of the Central Armorican Domain (Bitri et al., 2003). Some of these reflections can be clearly correlated, in the field, with faulted unit boundaries. At depth, the thrusts join a group of south dipping reflections that interrupt the flat reflections of the lower crust.

3.2. Gravity data

Gravity data used in this study come mainly from the French gravity database (Grandjean et al., 1998). They are heterogeneously distributed throughout the area, with a minimum average sampling spacing of about 1 km^{-2} (Fig. 3). In order to reduce effects of sampling heterogeneity, we acquired 200 additional measurements. The whole data set has been tied to the CGF65 French gravity reference network and reduced to the Hayford 1930 ellipsoid. We chose a Bouguer reduction density of 2600 kg/m^3, comparable to the density of granites that crop out in the study area. The terrain corrections were computed out to 167 km (Martelet et al., 2002). The whole data set was krigged (Chilès and Guillen, 1984), which yielded an interpolated 500 m Bouguer anomaly grid. The gravity modelling extends down to the Moho, constrained by the interpreted seismic profile (Fig. 2) and by

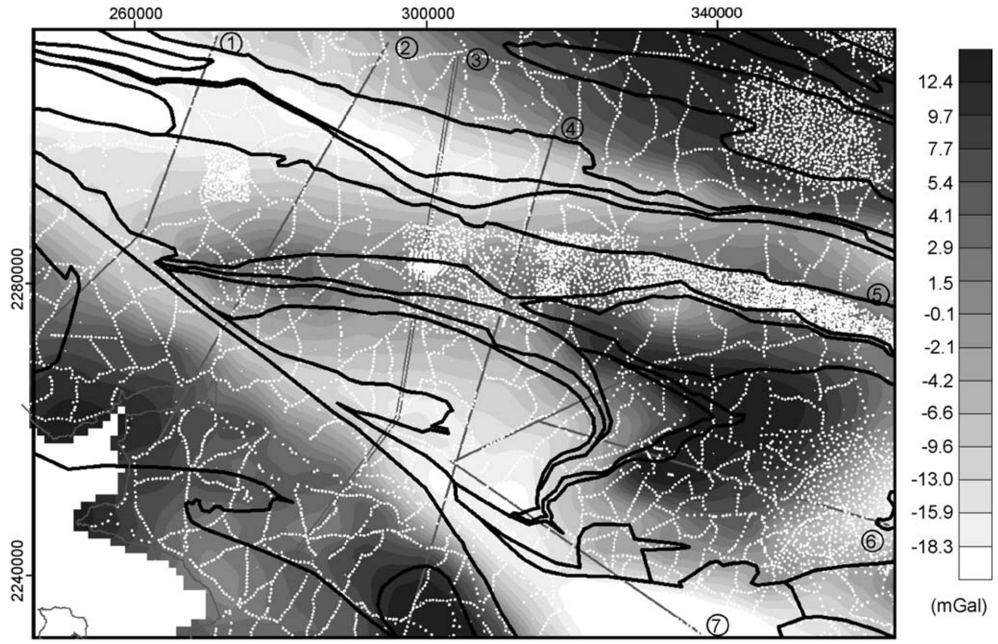


Fig. 3. Bouguer anomaly map in the Champtoceaux area (see location on Fig. 1). White dots are locations of available gravity data. Black thin lines indicate locations of the seven gravity cross-sections used in the modelling. Profile 3 coincides with the Armor 2 seismic profile (Fig. 2). Black thick lines correspond to simplified geological contours used for modelling.

geological information (Fig. 1). We further assumed that possible sources located in the asthenosphere induce gravity anomalies of wavelengths longer than the size of the study area. Therefore, we did not remove any regional component from the gravity signal and modelled directly the Bouguer anomaly.

The Bouguer anomaly map (Fig. 3) displays three main positive anomalies separated by two elongate gravity lows. The southern gravity low, which trends N125° along the southern branch of the SASZ, can be attributed to syntectonic leucogranites that mark-out the southern branch of the SASZ (Fig. 1; Jégouzo, 1980). The northern gravity low trends N105° along the northern branch of the SASZ (Fig. 1). It is also associated to granitic bodies: the pretectonic Lanvaux orthogneiss and the syntectonic Questembert leucogranite that crop out west of the study area and are buried at shallow depth toward the east, south of the northern branch of the SASZ (Weber, 1967). According to the geological data (Fig. 1), the three positive gravity anomalies correspond, from south to north to (i) the South Armorican Domain, marked by the occurrence of migmatites that contain substantial amounts of amphibolites (Cogné, 1953), (ii) the Champtoceaux Domain with a strong positive anomaly partly related to the occurrence of mafic eclogites, and (iii) the Central Armorican Domain which exhibits a positive anomaly of intermediate wavelength and of unknown source.

4. 3D geometrical modelling

4.1. Methodology

The 3D geometrical model is built on the basis of the geological map, cross-sections, and a digital elevation model (DEM). To construct the 3D volumetric bodies, we used the Geological Editor, an original software developed at the BRGM (French geological survey; Lajaunie et al., 1997, Calcagno et al., 2002), and especially devoted to geological modelling. In this software, lithological units are described by a pseudostratigraphic pile, intended to image the geology and structural relationships as best as possible. Compared with other existing 3D solid modelling approaches (e. g. Boissonnat, 1988; Bertrand et al., 1992), a major original feature of this modeller is that the 3D description of the geological space is achieved through a potential field formulation in which geological boundaries are iso-potential surfaces, and their dips are represented by gradients of the potential. The model is built in a geo-referenced system; it takes into account (i) a DEM, (ii) a simplified geological map (lithological contact information), (iii) foliation dips measured within the different units (local gradient information), and (iv) gravity cross-sections.

A few crustal-scale geological sections have first been drawn. The interpretation of the seismic profile has been used to constrain the geometry of the structures at depth. On this basis, the geometry of the lithological boundaries was adjusted performing 2D gravity modelling along the geological sections. In the next step, integration in the 3D geometrical modeller produces consistency between all cross-sections and the geological map. Based on a specific geostatistical interpolation procedure (Lajaunie et al., 1997), the Geological Editor interpolates the local input data to the whole 3D space. Finally, using the densities reported in Fig. 4, the gravity contribution of the resulting 3D model is computed and compared with the Bouguer anomaly. When discrepancies between computed and observed gravity fields are identified, the geology is locally reinterpreted, the model being interactively adjusted in 3D. Instead, a 3D stochastic inversion could have been performed, following the work by Guillen et al. (2000).

4.2. 2D gravity modelling

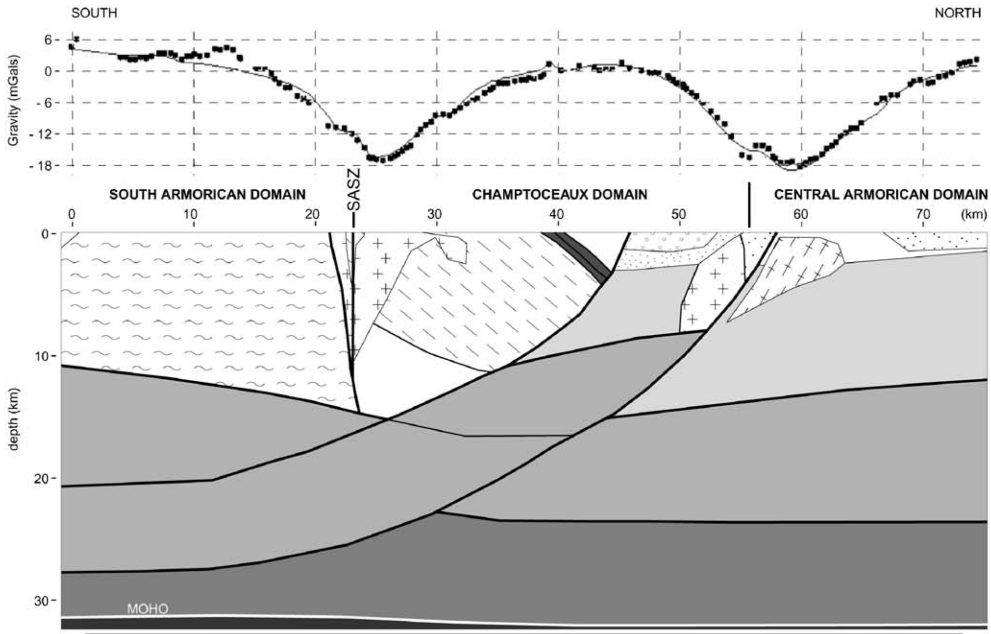
Gravity modelling has been performed along seven crustal-scale cross-sections subperpendicular to the Champtoceaux structure (locations on Fig. 3). The gravity profiles were extracted along the roads where gravity data have been preferentially collected (Fig. 4, upper part). Densities of rocks (Fig. 4, lower part) derive from field samples (Weber, 1973) and borehole samples (Ogier, 1984) collected in the area. For the upper and lower crust, we have converted RMS velocities of the seismic profile to densities using the empiric law of Nafe and Drake (1963). A middle and a lower crust have been distinguished according to their different reflectivity pattern and RMS velocities (i.e., densities). In Fig. 4, we show the gravity model of profile n°3, located along the seismic line. The three main positive anomalies identified on the profile correspond to those observed on the gravity map (Fig. 3).

In the South Armorican Domain (Fig. 4), the southward increase of the gravity anomaly is related to the southward thickening of the intermediate crust deduced from the occurrence of north dipping seismic reflections. Superimposed short-wavelength anomalies are attributed to high-density material locally present within the high-grade rocks (migmatites) that characterise this domain (Cogné, 1953). However, for the modelling, we chose to apply a homogeneous density to the South Armorican Domain.

In the Champtoceaux Domain (Fig. 4), the positive anomaly is composed of short and long wavelengths. The anomaly cannot be entirely explained by a prolongation at depth of the rocks cropping out in the high-pressure complex. Indeed, the crustal-scale fault system revealed by the seismic profile limits the extension of the Champtoceaux structure to a depth of about 10 km. Furthermore, the local occurrence of Champtoceaux-type mafics at depth are not sufficient to account for the observed anomaly. Therefore, the gravity modelling suggests the presence of a deep dense body below the Champtoceaux complex. Locating the top of this dense body within the thrust system at a depth of around 10 km yields a good fit with the gravity anomaly. This geometry suggests that some middle crust material could have been thrust into the upper crust.

In the Central Armorican Domain (Fig. 4), the positive anomaly is attributed to a gentle uplift of the upper/middle crust interface. This interpretation is consistent with the occurrence of south dipping reflections within the middle crust. Short-wavelength anomalies can be related to superficial lithological contrasts (e.g., slates versus quartzites).

Gravity lows separating the three long wavelength-positive anomalies are due to granitic intrusions associated with the southern and northern branch of the SASZ. The Vigneux leucogranite, which crops out along the southern branch of the SASZ (Fig. 1), is imaged as a laccolith rooted at about 10–15 km depth within the shear zone. Along the northern branch of the SASZ, the Questembert leucogranite and the



Lithology	Formation / Unit	Density (kg/m³)
Carboniferous leucogranites	Questembert, Vigneux, Mortagne	**2620**
Ordovician orthogneisses	Lanvaux	**2590**
Orthogneiss, paragneiss, micaschists	Southern Armorican metamorphic units	2750
Micaschists and metagrauwackes	Mauves-sur-Loire	**2735**
Micaschists and metagrauwackes	Mauges	**2750**
Carboniferous sediments	Ancenis basin	**2700**
Slates and volcanites	S[t] Georges-sur-Loire	**2755**
Sandstones and slates	S[t] Mars-la-Jaille	**2730**
Sanstones and slates	Undiffenratiated Paleozoic sediments	**2710**
	Nozay (sanstones, schists,ampelites)	**2680**
schists (mainly)	Brioverian sediments	2800
Champtoceaux metamorphic complex	Drain unit	**3100**
	Champtoceaux unit	**2800**
	Désert unit	**2650**
	Le Cellier unit	**2820**
gabbro and diorite	Pallet massif	**2860**
rhyolites, ignimbrites, anatectic paragneiss	Choletais unit	2750
undifferenciated upper crust		2750
Middle crust		2850
Lower crust		2950
Mantle		3300

Fig. 4. Direct 2D gravity modelling along profile 3 (see location on Fig. 3). The interpretation of Armor 2 seismic section (black thick lines) constrains the geometry of mid to lower crust units. The model gravity effect (thin black curve on upper window) has been fitted to Bouguer anomaly data (black dots on upper window) using surface geology (lithologies and structural data) and available shallow seismic reflections. A good fit of the central midwavelength-positive anomaly necessitates the occurrence of a dense body underneath the Champtoceaux complex. A possible candidate can be a relative uplift of middle crust along the crustal-scale south dipping shear zone system deduced from seismics (see Fig. 2). The different units (symbols as on Figs. 1 and 2) and corresponding densities used in the modelling are listed (sample or well-logging density measurements are in bold).

Lanvaux orthogneiss are shallowly rooted along the south dipping thrust structure. They do not crop out along profile n°3. However, their gravity signatures attest to their extensions at shallow depth, down to 6–8 km.

4.3. From 2D to 3D

Based on the geological knowledge, six other profiles have been modelled (see location on Fig. 3). Their geometries have been adapted from the seismically constrained cross-section, assuming that the deep structures follow the SASZ regional trend. Three of the profiles are oblique to deep structural trends (Fig. 3), and their integration in 3D is critical to ensure a good geometrical and topological consistency between all modelled structures. The 3D gravity effect of the model has been computed (Fig. 5) using rock densities (Fig. 4), and a routine derived from Okabe (1982). Reducing slight discrepancies between the computed and the observed gravity anomalies allowed to improve the accuracy of the geological model. In particular, the geometry of the Vigneux laccolith, as well as the precise positioning of the dense body below the Champtoceaux complex, have significantly benefited from this procedure. The comparison between Figs. 3 and 5 shows a rather satisfying correlation between the model gravity effect and the Bouguer anomaly. The average difference between both grids is -1.38 ± 10.1 mgal, and a histogram of this difference is shown on Fig. 5. Because the modelling was focussed on the Champtoceaux units and the main surrounding thrusts, only minor discrepancies exist in the central part of the model. Main discrepancies between data (Fig. 3) and model (Fig. 5) are located in the NE and SW parts of the map where possible lateral effects of deep sources might not have been taken into account.

5. Discussion

Although certainly nonunique, the 3D model we propose has an internal geometrical consistency, is

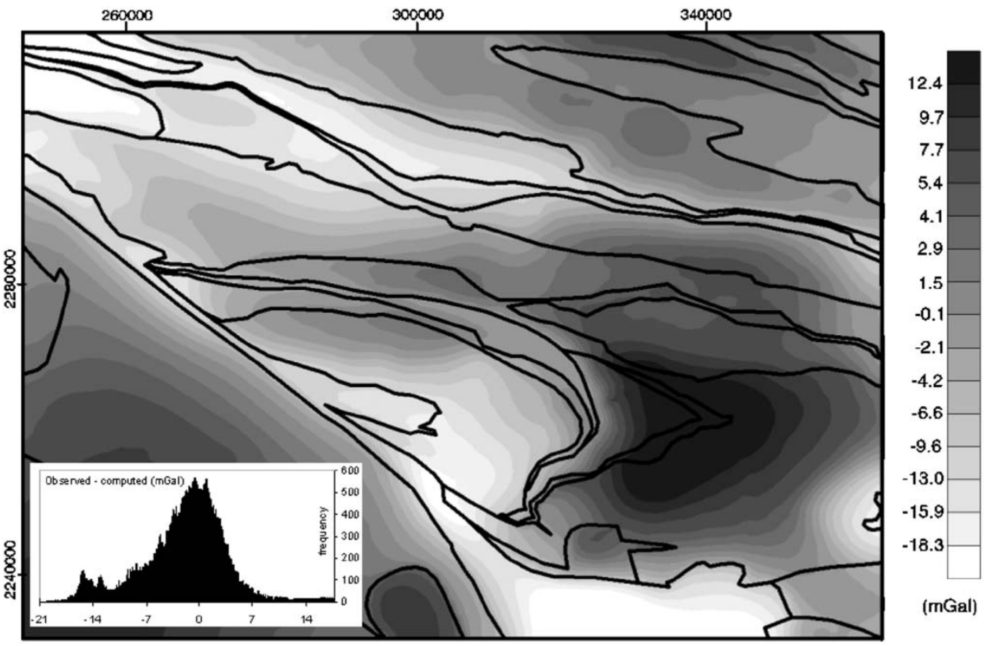


Fig. 5. Computed 3D gravity effect of the 3D model, using densities reported in Fig. 4. A good consistency is obtained between this model gravity map and the Bouguer anomaly map (Fig. 3), which is confirmed by the discrepancy histogram. In particular, middle- to short-wavelength anomalies located between the two branches of the SASZ fit the measured anomaly fairly well.

compatible with available geophysical data (seismics and gravity), and integrates the present-day geological knowledge at a regional scale. On this basis, some important implications of the modelling can be further discussed.

The gravity model suggests the occurrence of a relatively dense body below the Champtoceaux complex. The 3D model allows to extend this body at midcrustal level, approximately in the E–W direction, within the south dipping crustal thrust system interpreted from the seismic profile. This deep dense body accounts for the intermediate wavelength-positive gravity anomaly observed over the Champtoceaux Domain. It can be interpreted as a result of relative uplift of midcrustal material during thrusting along the E–W trending wrench–thrust system.

The modelling also allows to infer the 3D geometry of granitic massifs that were emplaced along the SASZ branches. The Vigneux syntectonic leucogranite appears as a laccolith sheared and rooted along the southern branch of the SASZ. The modelling suggests that it is not rooted deeper than 10–15 km along the SASZ, which is consistent with previous works (Vigneresse and Brun, 1983; Bayer and Hirn, 1987). The laccolithic shape develops in the core of the Champtoceaux complex, where the granite appears as a thin sheet with a much broader extension than its map contours (Fig. 6). This geometry is compatible with the spreading of upper crustal synkinematic intrusions within weak country-rocks that has been modelled in analogue experiments and used to interpret the shape of granites along the northern branch of the SASZ (Roman-Berdiel et al., 1997).

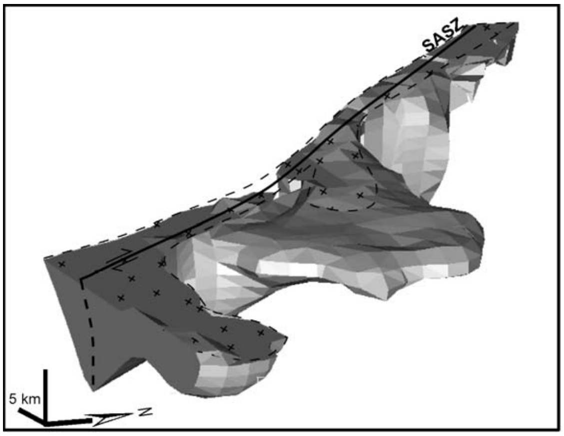


Fig. 6. 3D view from the SE of the leucogranites which have been sheared along the southern branch of the SASZ. Black dotted lines show the outcropping limits of granites. The shape of the Vigneux granite (centre of the figure) clearly exhibits its laccolithic nature.

To the north of the Champtoceaux Domain, the Questembert syntectonic leucogranite and the pretectonic Lanvaux orthogneiss are elongate along an E–W trend (Fig. 1), with significant buried volumes (Weber, 1967). Our model evidences that the Lanvaux orthogneiss extends for more than 150 km along the south dipping wrench–thrust system. The gravity signature of the orthogneiss suggests that it is shallowly rooted, with a tube-type shape (as shown by the intersection of this granite with the three cross-sections of Fig. 7). Furthermore, its overall shape, with a south dipping lower boundary, is consistent with the interpretation of the seismic profile (Fig. 2). This feature is in agreement with some reverse components along the northern branch of the SASZ (Figs. 2 and 4; Le Corre, 1978).

Modelling the 3D geometry of a south dipping shear band spatially related to the SASZ and Champtoceaux complex is one of the most important results of this study. The 3D block diagram and the cross-sections of Fig. 7 illustrate the geometry of this crustal-scale structure. Cross-sections confirm the roughly E–W trending antiformal shape of the Champtoceaux complex and illustrate the interruption of the northern limb of the fold against the south dipping thrust system. The model shows that the south dipping fault system, initially interpreted in the seismic profile, can be extrapolated along a N100–110° direction. This is consistent with the geological map where tectonic boundaries, as well as internal structures (foliations), have this direction (Fig. 1; Le Corre, 1978; Ledru et al., 1986; Cartier et al., 2001). Cross-sections extracted from the 3D model (Fig. 7) show that the south dipping thrust system becomes vertical toward the west when approaching the SASZ (Fig. 7). This feature outlines that interactions occurred between thrusting along the northern boundary of the Champtoceaux Domain and wrenching along the SASZ. The geological map shows that unit boundaries within the Champtoceaux Domain, most corresponding to thrusts imaged on the seismic profile, are interrupted by the southern branch of the SASZ (compare Figs. 1 and 2). On the other

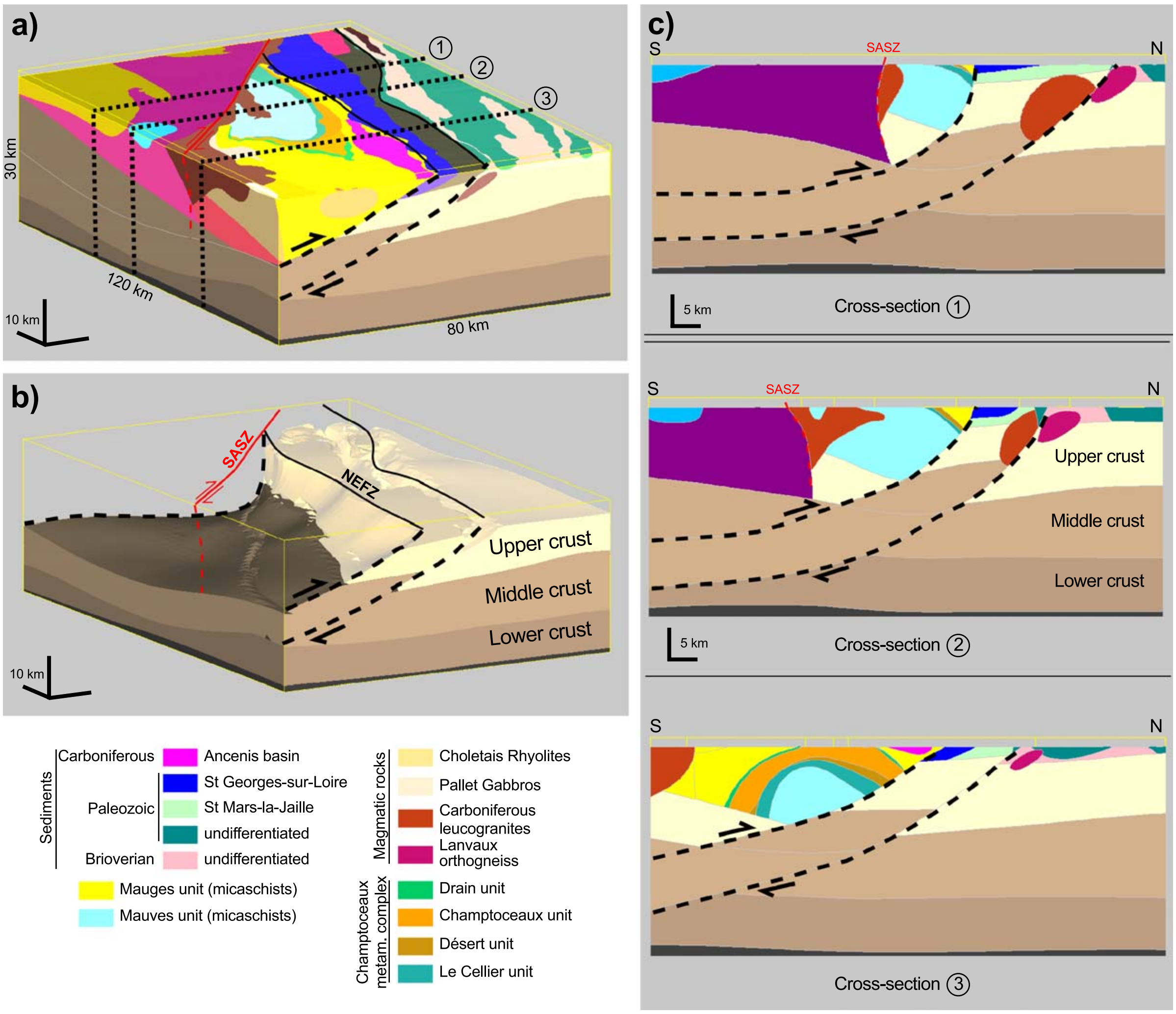


Fig. 7. (a) View from the SE of the 3D block modelled in Champtoceaux area, with location of the three cross-sections shown in (c). The south dipping crustal-scale shear zone is highlighted by black dotted lines. (b) View of the middle to lower crustal interfaces beneath the Champtoceaux complex after removal of more superficial units. The south dipping crustal-scale shear zone becomes subvertical at the vicinity of the SASZ (in red). (c) Extraction of three parallel cross-sections from the 3D model, outlining the evolution of the Champtoceaux Domain from west to east. To the south, this Domain is sheared along the SASZ, and to the north, it is folded (orange and blue in cross-section 3) above the crustal-scale shear zone. The three cross-sections also illustrate the elongate shape of granitic bodies (Questembert and Lanvaux) that extend in subsurface, perpendicular to the cross-sections, along the south dipping wrench–thrust system.

hand, the Champtoceaux fold is cut by the thrust system. This led Bitri et al. (2003) to propose that strike–slip along the SASZ and thrusting of the Champtoceaux Domain should be partly coeval. Our 3D modelling confirms that folding of the Champtoceaux metamorphic complex and its northward thrusting occurred during strike–slip movement along the SASZ.

6. Concluding remarks

The above study emphasises the need of 3D modelling in a highly noncylindrical geological context such as in Champtoceaux area. It also reassesses the need of an integrated geological and geophysical approach to improve the understanding of crustal-scale tectonic processes. To build a regional-scale

3D geometrical model, original 2D geophysical and geological data are processed together and interpolated to the whole 3D space. At any stage during the model construction, refinements can be interactively introduced to ensure the consistency between original data, so that a relevant 3D geometry can be produced. In the model, lithological units are volumes to which physical properties (density, susceptibility) are attributed. The 3D gravity or magnetic contribution of the model can thus be calculated and compared to the measured potential fields for further interactive adjustment of the model geometry. The result is a 3D model that respects constraints imposed by geological and geophysical data, and can be further used to interpret and discuss crustal-scale structures.

Concerning the Champtoceaux Domain, the modelling has shown that tectonic inferences made from geological data and the seismic profile could be extended to 3D using 2D gravity modelling. In particular, the primary geometry of the suture zone appears obliterated by a late E–W striking thrust system that brings the Champtoceaux Domain on the southern part of the Central Armorican Domain. In addition, the modelling emphasises that the Champtoceaux Domain was affected by a crustal-scale north verging thrust system that developed during regional scale strike–slip along the SASZ.

Acknowledgements

We thank reviewers J.P. Busby and V. Bosse who allowed us to significantly improve the original manuscript. Geophysical maps and 2D gravity modelling were achieved using Geosoft—GM-SYS package. This contribution was financed by BRGM Research Division and has benefited from the interpretation of seismic data acquired during the Armor 2—GeoFrance3D research program (CNRS–BRGM).

References

Ballèvre, M., Marchand, J., 1991. Zonation du métamorphisme éclogitique dans la nappe de Champtoceaux (Massif armoricain, France). Comptes Rendus de l'Académie des Sciences, Paris 312, 705–711.

Ballèvre, M., Pinardon, J.L., Kiénast, J.R., Vuichard, J.P., 1989. Reversal of Fe–Mg partitioning between garnet and staurolite in eclogite-facies metapelites from the Champtoceaux nappe (Brittany, France). Journal of Petrology 30, 1321–1349.

Ballèvre, M., Marchand, J., Godard, G., Goujou, J.C., Wyns, R., 1994. Eo–Hercynian events in the Armorican massif. In: Keppie, J.D. (Ed.), Pre-Mesozoic Geology in France and Related Areas. Springer-Verlag, Berlin, pp. 183–194.

Bayer, R., Hirn, A., 1987. Données géophysiques sur la structure profonde de la croûte hercynienne dans l'arc ibéro-armoricain et le Massif central français. Bulletin de la Société Géologique de France III-3, 561–574.

Beaupère, C., 1973. Contribution à l'étude de la flore fossile du "Culm" du synclinal d'Ancenis. Thèse de troisième cycle, Université Paris VI. 111 pp.

Berthé, D., Choukroune, P., Jégouzo, P., 1979. Orthogneiss mylonite and non coaxial deformation of granites: the example of the South Armorican Shear Zone (France). Journal of Structural Geology 1, 31–42.

Bertrand, P., Dufour, J.F., Françon, J., Lienhardt, P., 1992. Modélisation volumique à base topologique. Actes MICAD92, vol. 1. Hermès, Paris, pp. 59–74.

Bitri, A., Ballèvre, M., Brun, J.P., Chantraine, J., Gapais, D., Guennoc, P., Gumiaux, C., Truffert, C., 2003. Seismic imaging of the Hercynian collision zone in the south–eastern Armorican Massif (Armor 2 project/Géofrance 3D Program). Comptes Rendus. Géoscience, Paris 335 (13), 969–979.

Boissonnat, J.D., 1988. Shape reconstruction from planar cross-sections. CVGIP. Graphical Models and Image Processing 44, 1–29.

Bosse, V., Féraud, G., Ruffet, G., Ballèvre, M., Peucat, J.J., De Jong, K., 2000. Late Devonian subduction and early-orogenic exhumation of eclogite-facies rocks from the Champtoceaux complex (Variscan belt, France). Geological Journal 35, 297–325.

Brun, J.P., Burg, J.P., 1982. Combined thrusting and wrenching in the Ibero–Armorican arc: a corner effect during continental collision. Earth and Planetary Science Letters 61, 319–332.

Calcagno, P., Martelet, G., Gumiaux, C., 2002. Apport de la modélisation géométrique 3D à l'interprétation géologique du complexe de Champtoceaux (massif armoricain). 19ème RST, Nantes, p. 79 (abstract).

Cartier, C., Faure, M., Lardeux, H., 2001. The Hercynian orogeny in the South Armorican massif (St-Georges-sur-Loire unit, Ligerian domain, France): rifting and welding of continental stripes. Terra Nova 13, 143–149.

Cavet, P., 1978. Carte géol. France (1/50,000), feuille d'Ancenis (452), Ed. BRGM, Orléans, France.

Chilès, J.P., Guillen, A., 1984. Variogrammes et krigeages pour la gravimétrie et le magnétisme. Sciences de la terre. Série Informatique Géologique 20, 455–468.

Cogné, J., 1953. Schistes cristallins et granites en Bretagne méridionale: l'anticlinal de Cornouaille. Bulletin de la Société Géologique de France 6, 785–806.

Gapais, D., Le Corre, C., 1980. Is the Hercynian belt of Brittany a major shear zone? Nature 288, 574–576.

Gapais, D., Lagarde, J.L., Le Corre, C., Audren, C., Jégouzo, P., Casas Sainz, A., Van den Driessche, J., 1993. La zone de cisaillement de Quiberon: témoin d'extension de la chaîne varisque en Bretagne méridionale au Carbonifère. Comptes Rendus de l'Académie des Sciences. Série II 316, 1123–1129.

Godard, G., 1988. Petrology of some eclogites in the Hercynides: eclogites from the Southern Armorican massif, France. In: Smith, D.C. (Ed.), Eclogite and Eclogite-Facies Rocks, 451–519. Amsterdam.

Grandjean, G., Ménnechet, C., Debéglia, N., Bonijoly, D., 1998. Insuring the quality of gravity data. EOS Transactions-American Geophysical Union 79, 217–221.

Guillen, A., Delos, V., Ledru, P., 2000. A new method to determine lithology and geometry in depth: 3D litho-inversion of potential fields. European Geophysical Society, 25th General Assembly, Katlenburg–Lindau, Federal Republic of Germany (DEU). abstract.

Gumiaux, C., Brun, J.P., Gapais, D., in press. Strain removal within the Hercynian Shear belt of Central Brittany (western France). Methodology and tectonic implications. Geological Society of London Special Publication.

Iglesias, M., Brun, J.P., 1976. Signification des variations et anomalies de la déformation dans un segment de la chaîne Hercynienne (les séries cristallophylliennes de la Vendée littorale, Massif Armoricain). Bulletin de la Société Géologique de France 18, 1443–1452.

Jégouzo, P., 1980. The South Armorican Shear Zone. Journal of Structural Geology 2, 39–47.

Lajaunie, C., Courrioux, G., Manuel, L., 1997. Foliation fields and 3D cartography in geology: principles of a method based on potential interpolation. Mathematical Geology 29, 571–584.

Le Corre, C., 1977. Le Briovérien de Bretagne centrale: essai de synthèse lithologique et structurale. Bulletin du BRGM 1 (3), 219–254.

Le Corre, C., 1978. Approche quantitative des processus synschisteux. L'exemple du segment Hercynien de Bretagne Centrale. Thèse d'état, université de Rennes 1. 382 pp.

Ledru, P., Marot, A., Herroin, Y., 1986. Le synclinorium de St-Georges-sur-Loire: une unité Ligérienne charriée sur le domaine Centre-Armoricain. Découverte de la métabasite à glaucophane sur la bordure sud de cette unité. Comptes Rendus de l'Académie des Sciences, Paris, Série II 303, 963–968.

Le Hébel, F., Vidal, O., Kienast, J.R., Gapais, D., 2002. Les "Porphyroïdes" de Bretagne méridionale: une unité de HP–BT dans la chaîne hercynienne. Comptes Rendus. Géoscience 334, 205–211.

Marchand, J., 1981. Ecaillage d'un "mélange tectonique" profond: le complexe cristallophyllien de Champtoceaux (Bretagne méridionale). Comptes Rendus de l'Académie des Sciences, Paris, Série II 293, 223–228.

Martelet, G., Debéglia, N., Truffert, C., 2002. Homogénéisation et validation des corrections de terrain gravimétriques jusqu'à la distance de 167 km sur l'ensemble de la France. Comptes Rendus Géoscience 334, 449–454.

Nafe, S.E., Drake, C.L., 1963. Physical properties of marine sediments. In: Hill, M.N. (Ed.), The Sea. Interscience Publishers, New York, pp. 794–819.

Ogier, M., 1984. Analyse des densités mesurées sur les carottes du sondage SC2 AN PAN de Pannece (Loire Atlantique). Rapport BRGM 86GPH067. 17 pp.

Okabe, M., 1982. Analytical expressions for gravity due to homogeneous revolutional compartments in the Gaussian divergence approach. Geophysical Prospecting 30, 166–187.

Percevault, M.N., Cobbold, P.R., 1982. Mathematical removal of regional ductile strains in central Brittany: evidence for wrench tectonics. Tectonophysics 82, 317–328.

Roman-Berdiel, T., Gapais, D., Brun, J.P., 1997. Granite intrusion along strike–slip zones in experiment and nature. American Journal of Science 297, 651–678.

Torné, M., de Cabissole, B., Bayer, R., Casas, A., Daignières, M., Riveiro, A., 1989. Gravity constraints on the deep structure of the Pyrenean belt along ECORS profile. Tectonophysics 165, 105–116.

Truffert, C., Chamot-Rooke, N., Lallemant, S., De Voogd, B., Huchon, P., Le Pichon, X., 1993. A crustal-scale cross-section of the western Mediterranean Ridge from deep seismic data and gravity modelling. Geophysical Journal International 114, 360–372.

Truffert, C., Gumiaux, C., Chantraine, J., Perrin, J., Galdeano, A., Gapais, D., Ballèvre, M., Asfirane, F., Guennoc, P., Brun, J.P., 2001. Levé géophysique aéroporté dans le Sud-Est du Massif armoricain (programme GéoFrance 3D Armor 2). Magnétisme et radiométrie spectrale. Comptes Rendus de l'Académie des Sciences, Paris 333, 263–270.

Tsokas, G., Hansen, R., 1997. Study of the crustal thickness and subducting lithosphere in Greece from gravity data. Journal of Geophysical Research 102, 20585–20597.

Vigneresse, J.L., Brun, J.P., 1983. Les leucogranites armoricains marqueurs de la déformation régionale: apport de la gravimétrie. Bulletin de la Société Géologique de France XXV (3), 357–366.

Weber, C., 1967. Le prolongement oriental des granites de Lanvaux d'après la gravimétrie et l'aéromagnétisme. Mémoires du BRGM 52, 83–89.

Weber, C., 1973. Le socle antétriasique sous la partie Sud du bassin de Paris. Bulletin du BRGM 3–4 (Section II), 219–343.

Wyns, R., Le Metour, J., 1983. Le Précambrien du massif vendéen. Etude détaillée de deux coupes de référence (coupe de l'Evre et coupe de la Divatte) et synthèse des données récentes. Documents du BRGM 68 (60 pp.).