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Relationships between inherited crustal structures and seismicity in the western Alps inferred from 3D structural modeling

CHRISTIAN SUE[1], PHILIPPE CALCAGNO[2], GABRIEL COURRIOUX[2], PIERRE TRICART[3], JULIEN FRECHET[4] and FRANÇOIS THOUVENOT[5]

Key-words. – Western Alps, GéoFrance3D, 3D crustal structures, Structural modeling, Active tectonics, Alpine seismicity.

Abstract. – We developed a 3-D structural model of a key area in the southwestern Alps, at the boundary between the external and internal zones. Six geological bodies are analyzed: internal and external basements, Briançonnais and Piemontais zones (internal sedimentary cover nappes), exotic flyschs, and external sedimentary cover. 3D volumes of each geological body are modeled using the structural map of the area projected on the Digital Elevation Model (DEM) and 5 cross-sections. The global model is interpolated from the map, DEM, and cross sections, using the potential field method, and represented by a Voronoï diagram. The final 3D-model is used as a structural frame to plot the earthquakes of the GéoFrance3D database, allowing to precisely and quantitatively investigate the relationships between crustal structures and current seismic activity of the belt. The boundary between external and internal zones corresponds to the so-called Crustal Penninic Thrust (CPT), which is a former Oligocene major thrust. Our model establishes that this former thrust represents the western limit of the seismic activity along the Briançonnais seismic arc, currently undergoing extensional tectonics.

Relations entre structures crustales héritées et sismicité dans les Alpes occidentales : apport de la modélisation structurale 3D

Mots-clés. – Alpes occidentales, GéoFrance3D, Structures crustales 3D, Modélisation structurale, Tectonique active, Sismicité alpine.

Résumé. – Nous avons développé un modèle structural 3D d'une zone clé des Alpes sud-occidentales, à la limite entre les zones externe et internes. Six unités géologiques ont été analysées : socles externe et interne, zones Briançonnaise et Piémontaise (nappes de couverture sédimentaire internes), flyschs exotiques, et couverture sédimentaire externe. Les volumes 3D de chacune de ces unités géologiques ont été modélisées à partir du schéma structural projeté sur le modèle numérique de terrain (MNT), et de 5 coupes. Le modèle général est interpolé à partir de la carte, du MNT, et des coupes, en utilisant la méthode du champ de potentiel, et représenté par un diagramme de Voronoï. Le modèle 3D final est utilisé comme un cadre structural pour localiser les séismes de la base de données GéoFrance3D, afin d'analyser précisément et quantitativement les relations entre les structures crustales et l'activité sismique de la chaîne. La limite entre les zones externe et internes correspond au Front Pennique Crustal (CPT), un chevauchement Oligocène majeur. Notre modèle montre que cet ancien chevauchement limite à l'ouest l'activité de l'arc sismique briançonnais, actuellement caractérisé par une tectonique extensive.

INTRODUCTION AND GEOLOGICAL SETTING

The Western Alps result from the converging motion between the Europe and Africa plates, to the front of the Apulo-Adriatic indenter, since the Upper Cretaceous [*e.g.* Coward *et al.*, 1989; Schmid and Kissling, 2000]. They include two imbricated arcs (see inset in fig. 1) [Frey *et al.*, 1999]: (i) the internal arc is a collision prism made of high grade metamorphic rocks and built during the Paleogene after the subduction of the Tethys ocean; (ii) the external arc is a younger prism made of less metamorphosed rocks, and showing weaker deformations. The external arc has mainly been built during the Neogene. It concentrates most of the shortening due to the global plate convergence [see a review in Lemoine *et al.*, 2000].

The boundary between the external and internal arcs is a main lithospheric discontinuity (the Crustal Penninic Thrust, CPT), developed along former faults of the Tethys rifting [Lemoine *et al.*, 1986]. Along the ECORS-CROP seismic profile, the CPT is underlined by a crustal thrust-ramp [Mugnier *et al.*, 1990]. In the southern branch of the Alpine arc, this thrusting was active during Oligocene times [Tricart, 1984]. To the southeast of the

1. IUEM-UBO-UEB-UMR6538, Place Copernic, 29280 Plouzané. Tel: 02 98 49 88 91. Fax: 02 98 49 87 60. Email: christian.sue@univ-brest.fr. Now at UMR 6249, Univ. de Franche-Comté, 25030 Besançon cedex. christian.sue@univ-fcomte.fr
2. BRGM, 3 av. C. Guillemin, 45060 Orléans cedex
3. LGCA, BP 53, 38041 Grenoble cedex
4. IPG, 5, rue Descartes, 67084 Strasbourg cedex
5. LGIT, BP 53, 38041 Grenoble cedex
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Pelvoux massif, the CPT has subsequently been reactivated as an extensional detachment [Sue and Tricart, 1999], associated to a regional-scale multi-trend extensional tectonics in the internal arc [Sue and Tricart, 2002; Sue and Tricart 2003; Sue *et al.*, 2007a]. The extensional reactivation of the CPT began during early Miocene [Tricart *et al.*, 2001]. Using a seismotectonic approach, Sue *et al.* [1999] have shown that the regional extensional tectonics is still active and actually affects the whole internal western Alps. This active extension has been confirmed by other seismotectonic studies [*e.g.* Kastrup *et al,* 2004; Delacou *et al.,* 2004] and by several local-scale and alpine-scale geodetic campaigns [*e.g.* Sue *et al.*, 2000; Calais *et al.*, 2000; Vigny *et al.*, 2002; Calais *et al.,* 2002; Delacou *et al.,* 2008]. The thrusting of the internal arc onto the external arc along the CPT linked to the alpine compression, then the extensional reactivation of the CPT linked to the extensional tectonics in the internal arc, are key events in the alpine history at the Paleogene-Neogene limit [Tricart *et al.*, 2006]. The external crystalline massifs that underline the crest-line of the belt and currently present a thick crust, underwent a recent (Mio-Pliocene) and rapid uplift [*e.g.* Ménard, 1988; Fügenschuh *et al.*, 1999]. This uplift, just in front of the zone undergoing active extension, points out an increasing uncoupling between the external and internal arcs in this part of the western Alps.

This polyphased tectonic evolution results in a complex 3D-geometry of the alpine structures along the boundary between external and internal zones. In this paper we propose to model this complex geometry and its relationships with the active tectonics (seismicity), using a 3D approach. We chose to build the 3D structural model of a key zone in the core of the western Alpine arc, at the boundary between the external and internal zones (fig. 1).

3D STRUCTURAL MODELING

Environment and methods

3D structural modeling was performed using the GeoModeller software developed by the BRGM (French geological survey). This interactive software is useful to mix all geometrical, geological, and geophysical data available in a same 3D space to complete a geometric 3D–model. This method allows to manage data such as a digital elevation model (DEM), geological maps and cross sections. The geometrical coherence of geological interpretations can be checked and insured with this software in 3D. Interpolation of the data is performed using the potential field geostatistical method [Lajaunie *et al.*, 1997]. This method computes (i) positions of the interfaces between geological bodies known on the map and sections and (ii) dips of the geological body limits measured on the field. These geometrical data and the geological history of the formations (Erod and Onlap relations, fig. 2) are combined to achieve the geological model. The result consists in scalar functions (isopotential surfaces) describing the whole 3D space. Visualization of the isopotential surfaces coming from the interpolation is achieved by the Voronoï diagram method applied to geological objects [Boissonnat and Nullans, 1996; Courrioux *et al.* 2001]. This method transforms isopotential surfaces into discrete sites, which are used to partition 3D space in adjacent cells containing a unique site. Cells are then merged to construct 3D volumes of the geological objects. Either volumes of the geological formations or geological interfaces surfaces can be extracted from these scalar functions [Calcagno *et al.*, 2008]. The modelling process is designed to be applied to various geological contexts [Martelet *et al.*, 2004; Maxelon and Mancktelow, 2005; Calcagno *et al.*, 2006; Marquer *et al.*, 2006; Baujard *et al.*, 2008; Joly *et al.*, 2008]. Finally, the geological model can be used for geophysical forward or inverse modelling [Guillen *et al.*, 2008] or exported for further computations.

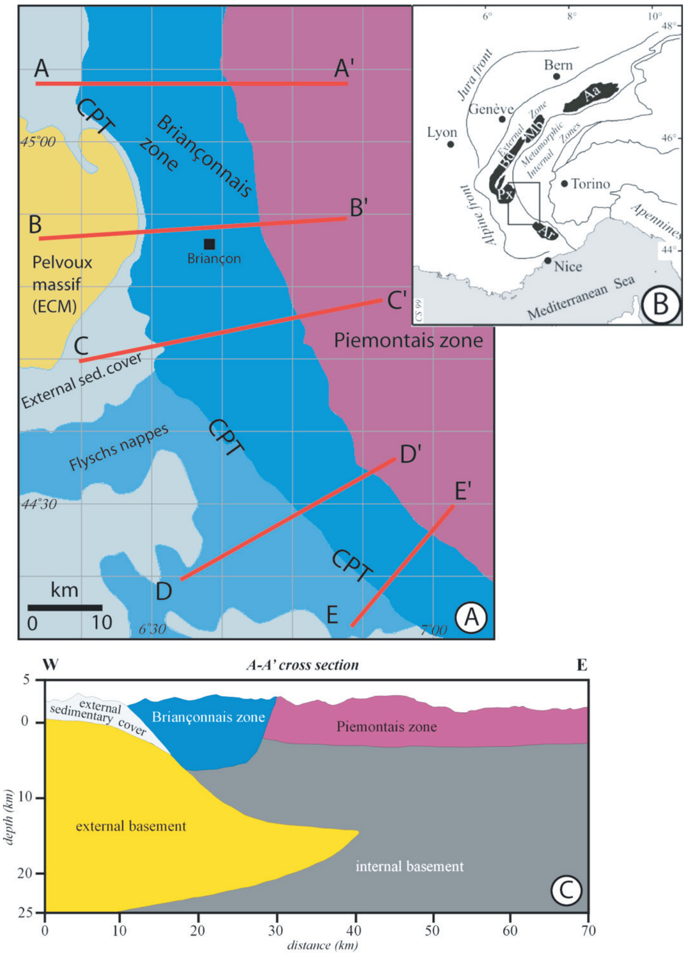

FIG. 1. – (A) Simplified structural map of the studied area; Location inside the Alpine belt is shown by the square in inset B (external crystalline massifs in black : Aa, Aar; Mb, Mont-Blanc; Bd, Belledonne; Px, Pelvoux; Ar, Argentera). The 5 cross-sections used to compute the 3D model are drawn in red (A-A' to E-E'). CPT : Crustal Penninic thrust. (C) Example of a basic E-W cross-section in the north of the studied area (section A-A'). Our 3D structural model is constructed using 5 equivalent and quite similar cross-sections distributed in the whole area.

FIG. 1. – (A) *Schéma structural simplifié de la zone d'étude. Sa localisation dans l'arc alpin est indiquée par le rectangle dans la carte des Alpes (insert B, massifs cristallins externe en noir :* Aa, *Aar ;* Mb, *Mont-Blanc ;* Bd, *Belledonne ;* Px, *Pelvoux ;* Ar, *Argentera). Les 5 coupes utilisées pour le calcul du modèle 3D sont tracées en rouge* (A-A' to E-E'). CPT *: Front Pennique crustal.* (C) *Exemple d'une coupe de base au nord de la zone d'étude (section* A-A'*). Notre modèle structural 3D est construit à partir de 5 coupes équivalentes et assez similaires distribuées dans l'ensemble de la zone.*

Data

In order to use a single 3D space to build the model, all data must share the same georeference. Data and ensuing 3D model are referenced in the Lambert 2 projection [Cuenin, 1972]. The top boundary surface of the model is the DEM of the area. It is constructed by merging data provided by the *Institut Géographique National* (IGN, France) for the French part of the zone and by the *Centro di Studi sulla Geodinamica delle Catene Collisionali* (CNR, Italy) for the Italian part of the zone. The final DEM gives a geo-referenced elevation at each point of a 200 m-resolution grid. The simplified structural map (fig. 1) comes from geological maps [Barféty *et al.*, 1996; Debelmas and Lemoine, 1966; Gidon *et al.* 1994] and our own field data. Six geological bodies have been modeled: (i) internal basement (Briançonnais), (ii) external basement (Dauphinois), (iii) Piemontais zone, (iv) Briançonnais zone, (v) exotic flyschs and (vi) external sedimentary cover. To describe our interpretation of the main geological structures, we used 5 cross-sections distributed along the whole study area. Figure 1 shows an example of these cross-sections (section AA'), which is representative of the other ones, as the 5 sections are quite similar. These cross-sections have been built using the GeoModeller software to ensure their coherence with the structural map and the topography. They take into account field data such as dip measurements.

In terms of deep structures, to perform 3D-modelling, we had to simplified the complex geometries of the tectonic contacts between our modeled geological bodies. Our purpose is to examine the relationships between active seismicity and crustal structures, mainly the CPF, and not the detailed deep structures [see for instance Schmid and Kissling, 2000; Lardeaux *et al.*, 2006). Indeed, the upper CPF's vergence to the East is the main feature, as it corresponds to the seismogenic zone. The lower part of the model shows a west-dipping CPF, reproducing the so-call "crocodile-like" structures, proposed by several authors [*e.g.* Schmid and Kissling, 2000]. Anyhow, alternative structural interpretations are as well as valuable [*e.g.* Lardeaux *et al.*, 2006], and this amazing topic remains a matter of debate far beyond the scope of this paper.

Modeling process

Structural map and cross-sections (fig. 1) have been digitized and their 3D geometrical coherence checked. We added field dip measurements of the geological structures to constrain the interpolation of the model. The model of the zone has been constructed using the potential field method on the data. The geological history and relationships chosen are, in chronological order: (i) internal basement (Erod), (ii) external basement (Erod), (iii) Piémontais zone (Erod), (iv) Briançonnais zone (Onlap), (v) exotic flyshs and (vi) external sedimentary cover (Onlap). Once the interpolation is complete, the geological body is constrained at any point of the studied volume. This knowledge forms the final 3D structural model. Figure 3 shows two views (figure 3a toward NW, figure 3b toward SE) of this model visualized using the Voronoï method.

STRUCTURES AND SEISMICITY

The GéoFrance3D experiment

The aim of this work was to constrain the relationships between the microseismicity of the area and its inherited structures. We used the GéoFrance3D earthquake database [Paul *et al.*, 2001] to plot the seismicity of this area in our 3D structural model. It corresponds to a microseismicity campaign performed during the July/December 1996 period in the southwestern Alps. Seismicity was monitored using a temporary network of 67 portable seismographs, which complemented the 59 permanent stations of the Grenoble, Nice and Genova universities. Thus, the average inter-station distance decreased to 10-15 kilometers. This experiment aimed at studying the current strain field of the area from precise earthquake locations and focal solutions [Bethoux *et al.*, 2007], and to image the upper crust 3D structure using local earthquake tomography [Paul *et al.*, 2001; Bethoux *et al.*, 2007]. Around a thousand local earthquakes were recorded, with local magnitude between –0.5 and 4.2. 730 of them were located reliably using an updated version of the HYPO71 program [Lee and Lahr, 1975], which takes station elevations into account. 235 of these earthquakes have been localized in the investigated area. The location error is about 1 kilometers both vertically and horizontally, mainly thanks to the high density of seismic stations.

Tectonic and seismotectonic framework

Two important issues are risen up by our approach. Firstly, we assume that the microseismicity recorded during the GéoFrance3D experiment is representative of the average

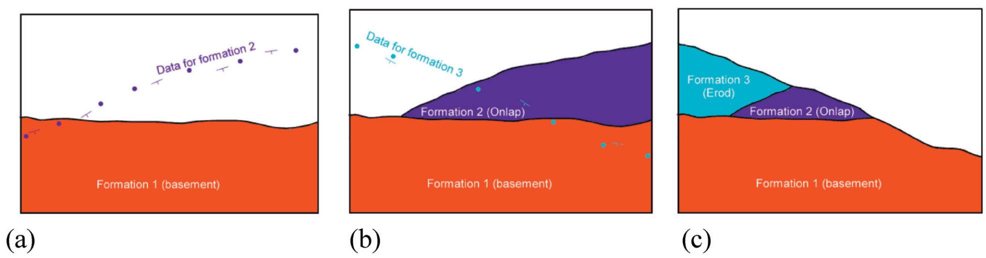

FIG. 2. – Illustration of the multipotential fields method, allowing "Onlap" and "Erod" relations between interfaces. (a) Interpolated formation 1 (basement). Data for potential field of formation 2 in violet blue. (b) Formation 2 interpolated with onlap relation. Data for potential field of formation 3 in light blue. (c) Formation 3 interpolated with erod relation.

FIG. 2. – *Illustration de la méthode des champs multipotentiels, autorisant les relations "onlap" et "erod" entre interfaces.* (a) *Formation 1 interpolée (socle). Les données pour le champ potentiel de la formation 2 sont en bleu-violet.* (b) *Formation 2 interpolée avec une relation "onlap". Les données pour le champ potentiel de la formation 3 sont en bleu clair.* (c) *Formation 3 interpolée avec une relation "erod".*

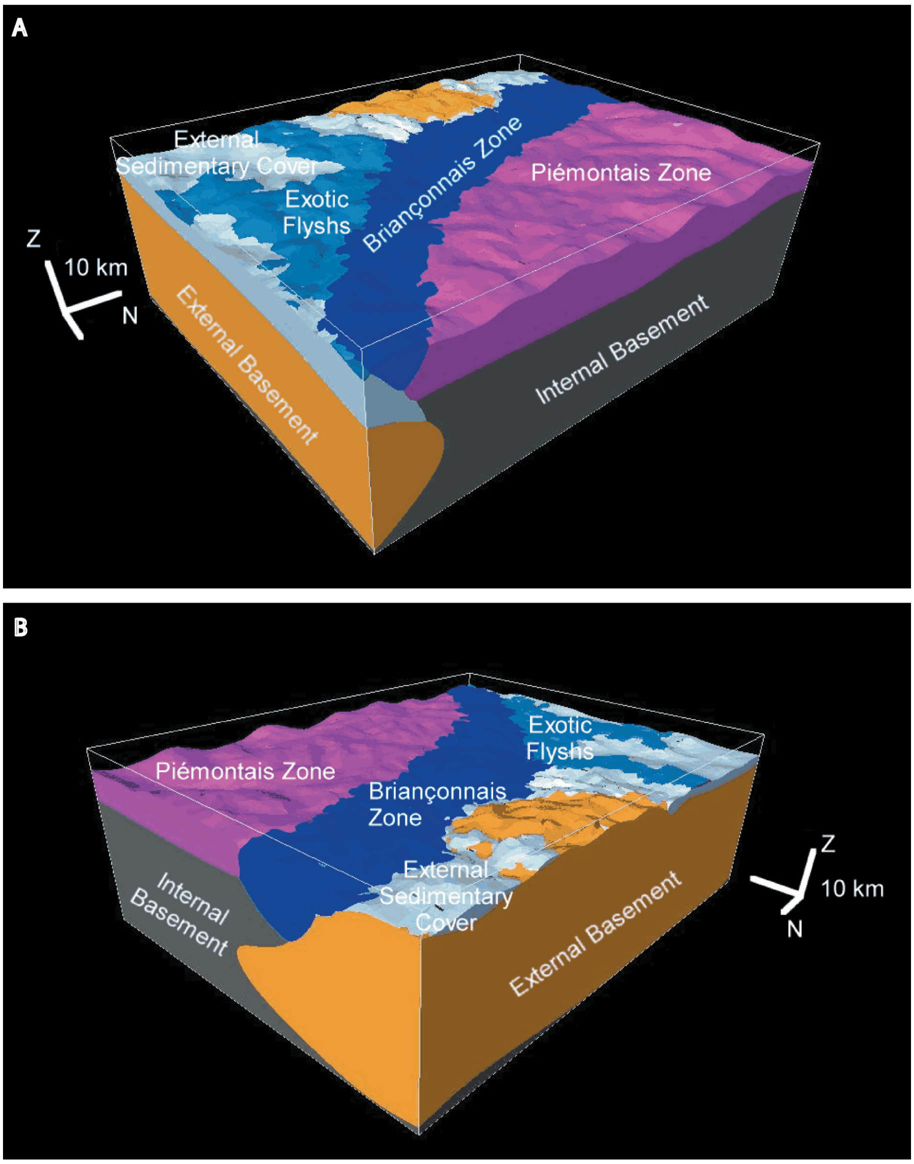

FIG. 3. – Two views of the final 3D structural model of the study area (Briançonnais zone and adjacent areas), view toward the northwest (a) and toward the southeast (b).
FIG. 3. – *Deux illustrations du modèle structural 3D final de la zone d'étude (zone briançonnaise et régions adjacentes), vu vers le nord-est* (a) *et le sud-ouest* (b).

seismic activity of the area, which is supported by the comparison between the focal mechanisms computed using the GéoFrance3D database and the already available focal mechanisms [Sue, 1998; Bethoux *et al.,* 2007]. Secondly, we assume that the seismic activity is relevant for the current tectonic activity of the belt on a longer time scale. Actually, it appears that the seismotectonic regime is very homogeneous in local sub-areas of the belt. Thus, and following the results of Amelung and King [1997], it has been proposed that the seismic activity is representative of the present tectonic activity [Sue *et al.,* 1999; Delacou *et al.,* 2004], although the magnitudes of recorded earthquakes are quite small. We discard here the discussion about seismic *vs.* aseismic deformation [see discussion in Sue *et al.*, 2007b]. Moreover, the analysis of faulting in the Briançon region shows a good coherency between the late Alpine brittle tectonics (Mio-Pliocene to Quaternary times) and the seismicity [Sue, 1998; Sue and Tricart, 2003]. Figure 4 presents a global synthesis of the late-Alpine and still active tectonics in the southwestern Alps, revealing the coherency of the fault systems and the seismically active areas. The studied area is located at the southern tip of the Briançonnais seismic arc (BSA, fig. 4), the seismically most active area in the French Alps. From a neotectonic viewpoint, this specific area is characterized by a recent and still active extensional to transtensional tectonic regime [Sue *et al.*, 1999; Sue and Tricart, 2003; Sue *et al.*, 2007a]. This result has been strengthened by re-measurement of a local geodetic network [Sue *et al.,* 2000] showing active E-W extension. In a broader tectonic context, the Briançonnais seismic arc follows roughly the Crustal Penninic Thrust (CPT). To the west, the seismic activity in the external zone is quite diffuse or absent (*e.g.* Pelvoux massif), except under the flyschs Nappe, to the southwest of our modeled zone. To the east, the Piemontais seismic arc (PSA, fig. 4) is another very active seismic zone [Sue *et al.,* 2002]. The tectonic behavior of the Piemontais seismic arc is also mainly extensive. To the front of the belt, in the

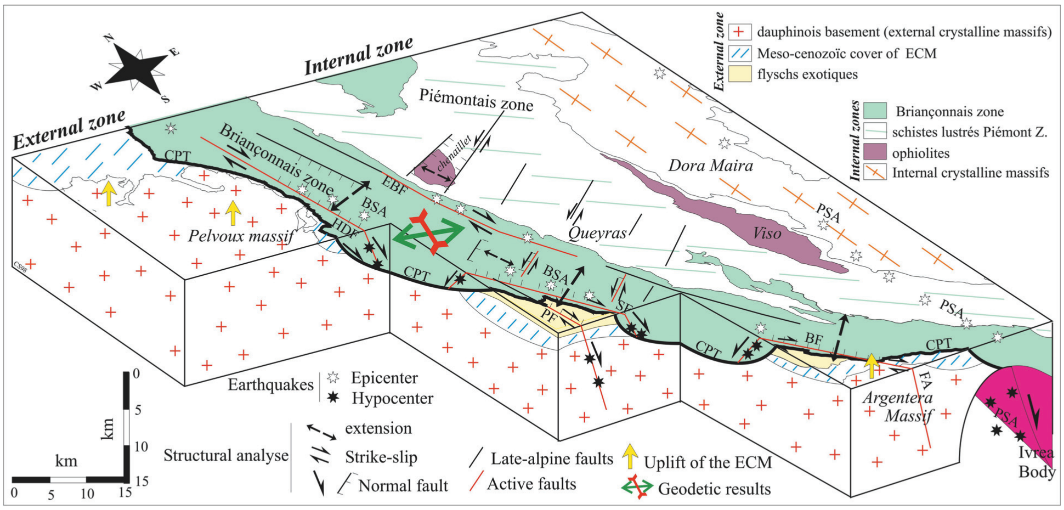

FIG. 4. – Synthetic neotectonic block-diagram of the southwestern Alps. The seismicity of the Briançonnais and Piemontais seismic arcs (BSA and PSA respectively) is symbolized by stars [Sue *et al.*, 1999; Sue *et al.*, 2002]. In the hanging wall of the Crustal Penninic thrust (CPT, the late-alpine and still partly active fault system is drawn with black and red lines respectively. Black arrows symbolize the extensive/transtensive deformations observed on these faults [Sue and Tricart, 2003]. Red/green arrows give the main results of a local geodetic network [after Sue *et al.*, 2000]. Yellow arrows show the uplift of the external crystalline massifs [*e.g.* Ménard, 1988]. Abbreviations: BF: Bersézio fault; EBF: East Briançonnais fault; FA: Argentera fault; HDF: High Durance fault; PF: Parpaillon fault [after Sue and Tricart, 2003]. BSA: Briançonnais seismic arc, PSA: Piemont seismic arc. The southernmost part of the block-diagram artificially shows the Ivrea Body and the PSA.

FIG. 4. – *Bloc diagramme néotectonique synthétique des Alpes sud-occidentales. La sismicité des arcs sismiques briançonnais et piémontais est symbolisée par les étoiles [Sue* et al.*, 1999; Sue* et al.*, 2002]. Le système de failles tardi-alpines encore partiellement actives est tracé en rouge et noir dans le toit du Front pennique crustal (CPT). Les flèches noires symbolisent les déformations extensives/transtensives observées sur ces failles [Sue et Tricart, 2003]. Les flèches rouges et vertes illustrent le résultat majeur d'une campagne géodésique locale [Sue* et al.*, 2000]. Les flèches jaunes montrent la surrection des massifs cristallins externes [e.g. Ménard, 1988]. Abréviations :* BF *: faille de Bersézio ;* EBF *: faille Est-Briançonnaise ;* FA *: faille de l'Argentera ;* HDF *: faille de la Haute Durance ;* PF *: faille du Parpaillon [d'après Sue et Tricart, 2003].* BSA *: arc sismique briançonnais,* PSA *: arc sismique piémontais. L'extrémité sud du bloc diagramme laisse apparaître artificiellement le coprs d'Ivrée et le PSA.*

external zone, the seismotectonic analysis shows mainly transcurrent motions and some reverse faulting [Sue *et al.*, 1999; Delacou *et al.,* 2004]. In this broader neotectonic frame, the current activity of the studied area (southern tip of the Briançonnais seismic arc) is controlled by the late Alpine fault network, made of dextral longitudinal faults parallel to the alpine structures and sinistral transverse faults [Sue and Tricart, 2003].

To summarize, a good coherency appears between: (i) the late Alpine tectonics and the current seismic activity; and (ii) the GéoFrance3D earthquake database and the global Alpine seismotectonics analyzed using permanent Alpine seismic networks (Sismalp, IGG, Swiss Seismological service). These correlations justify the use of the GéoFrance3D earthquake database as an indicator for the present-day alpine tectonic activity.

Seismicity and 3D structural modeling

The association of the 3D-structural model with the earthquake database allows to investigate the relationships between the inherited structure and the present-day tectonic activity. The main tectonic structure imaged in our 3D structural model is the Crustal Penninic thrust (CPT). It represents the main Oligocene thrust of the internal Briançonnais zone onto the external (Dauphiné) zone. In order to check the relation between the CPT and the earthquakes of the GéoFrance3D database, the seismicity is plotted on the 3D structural model in figure 5. From a qualitative viewpoint, it appears that the current tectonic activity along the Briançonnais seismic arc is located mainly in the hangingwall of the CPT, or in its close vicinity. Actually, part of the seismicity potted in our 3D-model is located rather far and westward of the CPT. These events are mainly located in the southern sector of the model, which corresponds to the Flyschs nappe, where a quite important, but diffuse seismic activity is documented. The most interesting area in our model, in term of relationships between earthquakes and alpine structures, is actually the central sector where earthquakes belonging to the Briançonnais seismic arc are effectively well located in the hanging wall and close to the CPT.

One of the main interests of 3D structural modeling is to provide a quantified geometry of the geological structures. For instance, our 3D geometric model allows to calculate the distance between epicenters and the modeled CPT interface. This analysis shows that 77% of the referenced earthquakes (182 out of 235) have their hypocenter closer than 10 kilometers from the CPT (fig. 6). Taking into account that part of the database is made of earthquakes outside the Briançonnais seismic arc (in the Flyschs nappe for instance), this quantification strengthens the observation that the CPT plays an important role to localize the seismicity in its vicinity, and in the close volume corresponding to the Briançonnais zone.

DISCUSSION

The 3D model built in this study allows to localize the seismicity of a key area in the western Alps with respect to the large-scale crustal structures. We find a general agreement

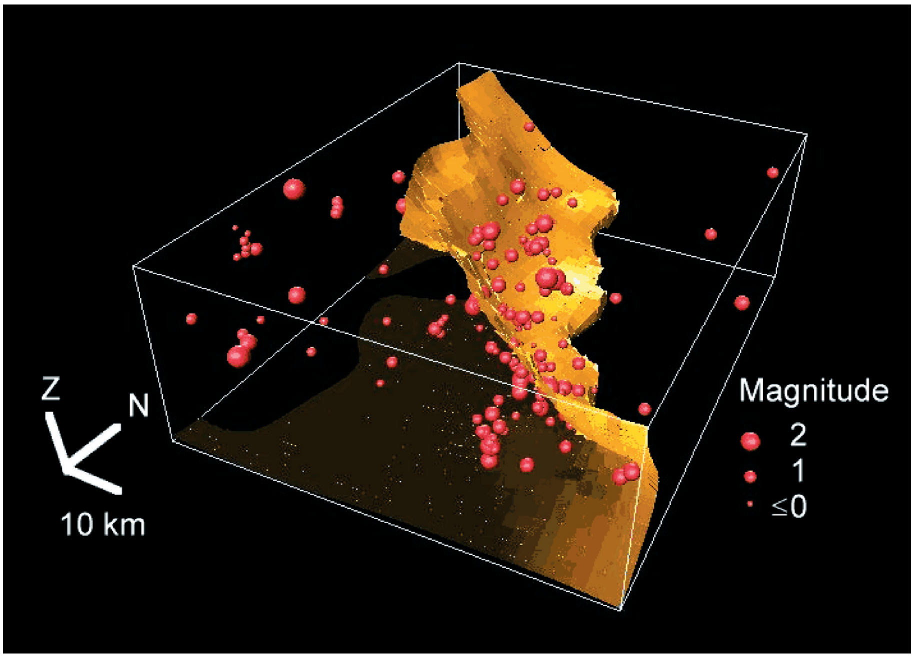

FIG. 5. – Earthquake hypocenters located with respect to the 3D model of the CPT (GeoFrance3D database). Each earthquake is plotted as a sphere located at the hypocenter with a radius proportional to the magnitude.
FIG. 5. – *Hypocentres des séismes de la base de données GéoFrance3D localisés par rapport au modèle 3D du CPT. Chaque séisme est symbolisé par une sphère proportionnelle à la magnitude.*

with former seismological and seismotectonic studies [see a review in Sue *et al.*, 2007a]. Although our model depends on the basic cross-sections that we have drawn, it provides a new and precise 3D-view of the seismicity in the studied area. A limitation of our approach is due to the small number of earthquakes used. Nevertheless, we establish that the active extensional tectonics mainly affects the volume of the Briançonnais zone close to the CPT. The seismicity along the Briançonnais seismic arc itself is very well bounded to the west by the CPT. This work also agrees with the field work study led by Sue and Tricart [1999] from a structural viewpoint. They showed that, at the scale of the outcrop and along a natural cross section (2D approach), the late alpine normal faulting close to the CPT remains located above the CPT, and does not affect the external zone. This late alpine faulting is still active in the more internal Briançonnais zone, particularly along the high Durance fault [Sue *et al.,* 2007a]. The main result of this paper is to draw a precise and quantified 3D structural model of the area, which allows to precisely establish the relationships between the seismicity and the CPT. This former Oligocene thrust seems to work as an important mechanical boundary, as it localizes the earthquakes of the Briançonnais seismic arc at its vicinity, and mainly within the volume of the Briançonnais zone. As the hypocenters are not exactly located on the CPT itself, it would not work as an active fault *sensu stricto*, although the Briançonnais seismic arc follows the CPT at the scale of the western Alps. We propose that seismicity concentrates along this major discontinuity in the alpine crust due to inherited fractures associated to the emplacement of the CPT.

A 3D model highly depends on the primary cross sections, and thus remains dependent of geological interpretation. It is for instance possible to slightly change the shape of the CPT. Nevertheless, the positions of the earthquakes globally above the CPT, as well as the change of stress regime documented by Sue *et al.* [1999] (extensive in the Briançonnais zone and transpressive in the outer zone) argue for an important role of the CPT in the current tectonics of the western Alps as a major mechanical discontinuity. The current reactivation of this old Oligocene thrust at the regional scale seems to control the activity of the Briançonnais seismic arc.

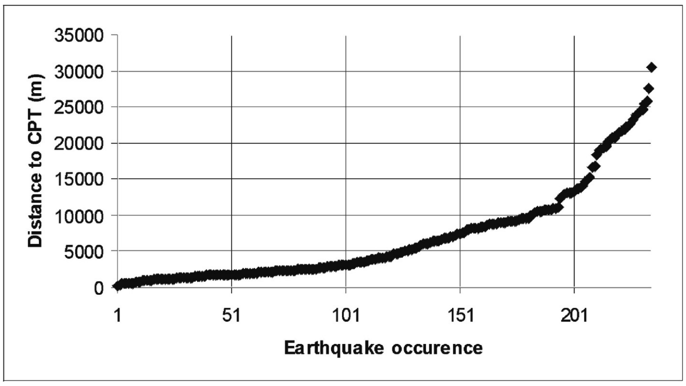

FIG. 6. – Diagram of distances between the 235 earthquakes of the Géo-France3D database and the modeled CPT.
FIG. 6. – *Distribution des distances entre le CPT modélisé et les 235 séismes de la base de données GéoFrance3D.*

To go further in our investigations, several fruitful research ways may be developed. A larger 3D-modeling of the alpine crustal structures (*e.g.* covering the whole western Alps, or in key areas, such as the Mont-Blanc massif, or the Swiss Valais area…), associated to 3D-locations of available seismological data, should provide a large-scale view of the relationship between structures and seismicity. A more precise modeling of the structures and faults, by combining 3D-modeling, structural analysis, and relocation of earthquakes, may also provide an accurate 3D-view of active faulting.

CONCLUSION

The 3D-structural approach developed using the GeoModeller of the BRGM allowed us to propose a 3D structural model of a key area in the western Alps. The seismicity plotted in this model clearly shows that the present-day seismic deformation (in extension) mainly affects the Briançonnais zone volume and is quite well bounded by the CPT to the west. This result leads us to propose that the CPT is a major mechanical discontinuity in the present-day kinematics of the western Alps. The seismicity concentrates along this major discontinuity of the alpine crust, probably due to inherited fractures associated to the CPT emplacement. During Oligocene times, the CPT worked as a major crustal thrust. It is currently reactivated as a crustal extensional detachment at the scale of the belt, and it bounds to the west most of the active extension associated to the Briançonnais seismic arc. In this context, the 3D modeling approach appears as a major tool to investigate tectonic problems related to a complex geometry.

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