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Interpretation of seismic data using finite strain in the «Zone Houillère Briançonnaise» (French Alps)

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Abstract. Deep seismic data, paleogeographic reconstruction and tectonostratigraphic modelling, all indicate that the Pennine Front is a major lithospheric structure in the western Alps, separating external and internal domains. In France, its seismic signature is quite complex and shows a crossed pattern just below the "Zone Houillère Briançonnaise" (ZHB), the interpretation of which has not been obvious. This paper presents new structural data and a cross-section from the "vallée des Bellevilles" which differ from those previously proposed. Structural data and preliminary finite strain maps are used to interpret the geometry of the ECORS seismic reflectors and to propose a kinematic interpretation of the Pennine Front in the north of French Alps.

Riassunto. In accordo con differenti autori e con diversi metodi di studio (dati sismici profondi, ricostruzioni paleogeografiche, modelli tectonostratigrafici), il fronte Penninico appare come una struttura litosferica importante delle Alpi occidentali, che separa le unità esterne da quelle interne. In Francia la sua immagine sismica é abbastanza complessa e mostra sotto la "Zone Houillère Briançonnaise" (ZHB) un caratteristico incrocio di riflettori la cui interpretazione non é facile. Questo lavoro presenta nuovi dati strutturali della "vallée des Bellevilles" e una sezione parzialmente differente da quelle sinora proposte. Dati strutturali e carte preliminari dello strain finito sono utilizzati per discutere il significato della geometria e della cinematica associate alle riflessioni sismiche ECORS.

1. Introduction

The recent seismic profile (ECORS - CROP traverse, NICOLAS *et al.*, 1990) under the Vanoise region shows a crossed pattern of westward and eastward dipping reflectors, east of the Pennine Front (PF), which interrupts the continuity of this front at depth. The interpretation of this pattern is not straightforward and has led to several different large-scale models, none of which account for all major reflectors (BAYER *et al.*, 1987; NICOLAS *et al.*, 1990). In detail, the seismic signature of the PF shows two parallel bands of high intensity reflectors, the westernmost being related to the PF and the easternmost corresponding to the Briançonnais Front (MUGNIER *et al.*, 1993). According to MUGNIER *et al.* (1993), the Briançonnais Front (BF) lies under the "Briançonnais" units, whose westernmost part corresponds to the "Zone Houillère Briançonnaise" (ZHB). Preliminary finite strain measurements in the ZHB, between the Arc River and the Isere River ("vallée des Bellevilles", Fig. 1), have shown oblique patterns of strain intensity with respect to NS-trending previously mapped structures (FABRE *et al.*, 1958) and a gradient from prolate to slightly oblate ellipsoids. The location of the studied area on top of the BF makes it interesting to consider at map scale if the finite strain pattern above a major tectonic contact can be useful in interpreting the observed seismic patterns.

Furthermore, it became rapidly obvious that published geological cross-sections were useless (DEBELMAS, 1988) and that a more detailed structural survey was necessary. Preliminary results from this study also cast doubt on existing stratigraphic correlations (FABRE *et al.*, 1958) in the "vallée des Bellevilles". The aim of this paper is to show that mapping and measurements of finite strain, together with micro-

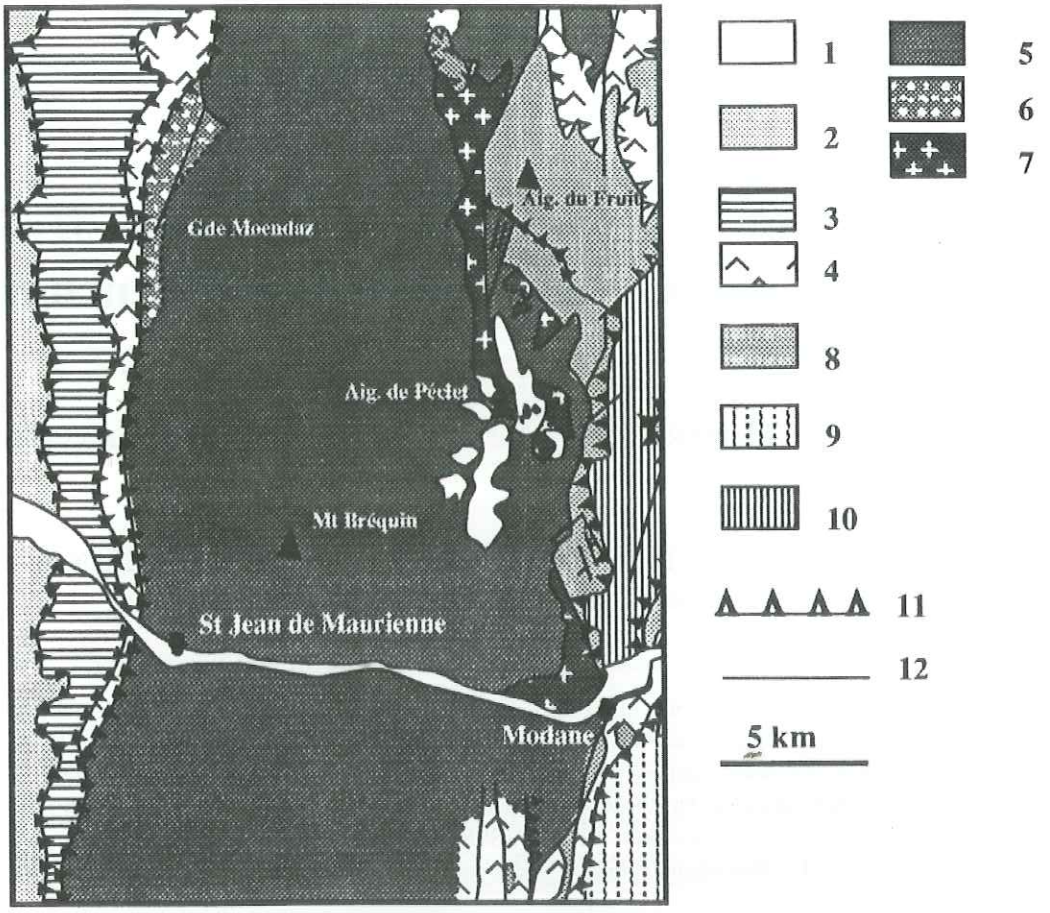

Fig. 1: Schematic structural map showing (1) Quaternary deposits, (2) "Ultradauphinois" zone, (3) "Subbriançonnais" zone, (4) gypsum outcrops between "Briançonnais" and "Subbriançonnais" domain to the west and at the bottom of the "schistes lustrés" nappe to the east, (5) ZHB (6) ZHB cover (7) Sapey gneisses, (8) Mesozoic cover of the Vanoise-Ambin zone, (9) "schistes lustrés" nappe (10) Chasseforêt basement, (11) thrusts and (12) undetermined tectonic contacts. (Modified from DEBELMAS, 1988).

Fig. 1: Carta strutturale schematica che mostra (1) depositi Quaternari, (2) zona Ultradelfinese, (3) zona Subbrianzonese, (4) affioramenti di gesso entro i domini Brianzonese e Subbrianzonese ad occidente e alla base della falda "Schistes lustrés" ad oriente, (5) ZHB, (6) copertura della ZHB, (7) gneiss del Sapey, (8) copertura Mesozoica della zona Vanoise-Ambin, (9) falda "Schistes lustrés", (10) basamento di Chasseforêt, (11) accavallamenti e (12) contatti tectonici indeterminati (modificato di DEBELMAS, 1988).

structural analysis in the field, may provide insights on the geometry at depth and may explain the high intensity of seismic reflectors located just below the ZHB.

2. Geological and tectonic setting

The study area is located in the French Alps, across the divide between the Tarentaise and Maurienne valleys (Fig. 1). It includes a complete section of the ZHB, from the BF in the west to the contact with the Sapey gneisses in the east. On its west side, the ZHB is separated from the "Subbriançonnais" domain (here represented by the Grande Moendaz unit) by the BF, the latter domain being in turn separated from the external domains ("Dauphinois" = Helvetic) by the PF (MUGNIER *et al.*, 1993). On our section, the most external part of the Pennine realm, the Valaisan domain, is lacking and is relayed by the "Subbriançonnais" (ANTOINE, 1972). If, according to recent work in Switzerland (STAMPFLI, 1993; SCHMID *et al.*, 1990), the "Valaisan" domain represents a paleo-oceanic domain, then the PF should correspond to a major alpine suture.

The two main tectonic fronts (PF and BF) show a similar seismic signature, i.e. two bands of high intensity reflectors dipping about 30° to the east, but, in the Belleville valley, the apparent dip of the BF is higher than 45° to the east (about 20 km south of the seismic profile). The westernmost and most external front (PF) does not have a marked topographic expression. It separates "Valaisan" and/or "Subbriançonnais" units from the parautochtonous "Dauphinois" domain, which rests on the external crystalline massifs, that is Variscan basement of the european plate. The PF itself is difficult to locate on the field because of lithological similarities between "Dauphinois" and "Subbriançonnais" formations. Several gypsum-outlined tectonic

contacts are possible candidates for the location of the main PF.

The trace of the easternmost front (BF) is marked by deep and steep valleys and is delineated by large gypsum outcrops. It may also correspond to a still active tectonic zone, as suggested by its morphology. The ubiquitous presence of gypsum (and/or anhydrite) along both fronts makes the direct determination of their kinematics very difficult. The kinematics can only be reconstructed by comparing the geometry of structures on both sides or by analysing small-scale secondary faults associated with the fronts. For the "Subbriançonnais" domain, SPENCER (1992) has determined a W-NW oriented transport direction from finite strain measurements on syntectonic fibres. Preliminary results concerning the the ZHB, east of the BF are shown here. Within the ZHB itself, several units can be distinguished on the basis of their very different structural behaviour. Except for the westernmost unit (see below), they are separated by thin zones of strongly schistose black shales parallel to the S1 schistosity (Fig. 2). The S1 regional schistosity is well developed and dips gently to the west, as seen on the schematic cross-section of Figure 2.

Above the "Subbriançonnais" units, three different tectonic units have been distinguished from west to east:

(1) The "Encombres" unit, in the westernmost part of the section, lies on the top of the BF which is outlined by "cargneule" and gypsum. This unit dominantly consists of arkoses and green to violet schists of assumed Permian age. It is characterized by a strong schistosity with an average eastward dip of 45°, parallel to the apparent dip of the BF. Its faulted contact with the overlying "La Masse" unit is outlined toward the north by lenses of Mesozoic formations with "Briançonnais" affinities (possibly equivalent to the "Faisceau de Salins" further north).

(2) The "La Masse" unit is characterized by a well-developed, gently westward dipping schistosity (S1) locally perturbed by hectometric F2 folds. S1 is characterized by flattened quartz pebbles and is locally refolded by F2 folds. These folds show N-S subhorizontal axes and westward dipping axial planes in the western part of the unit, while in the eastern part, the axes trend about N150°. F2 folds also show a S2

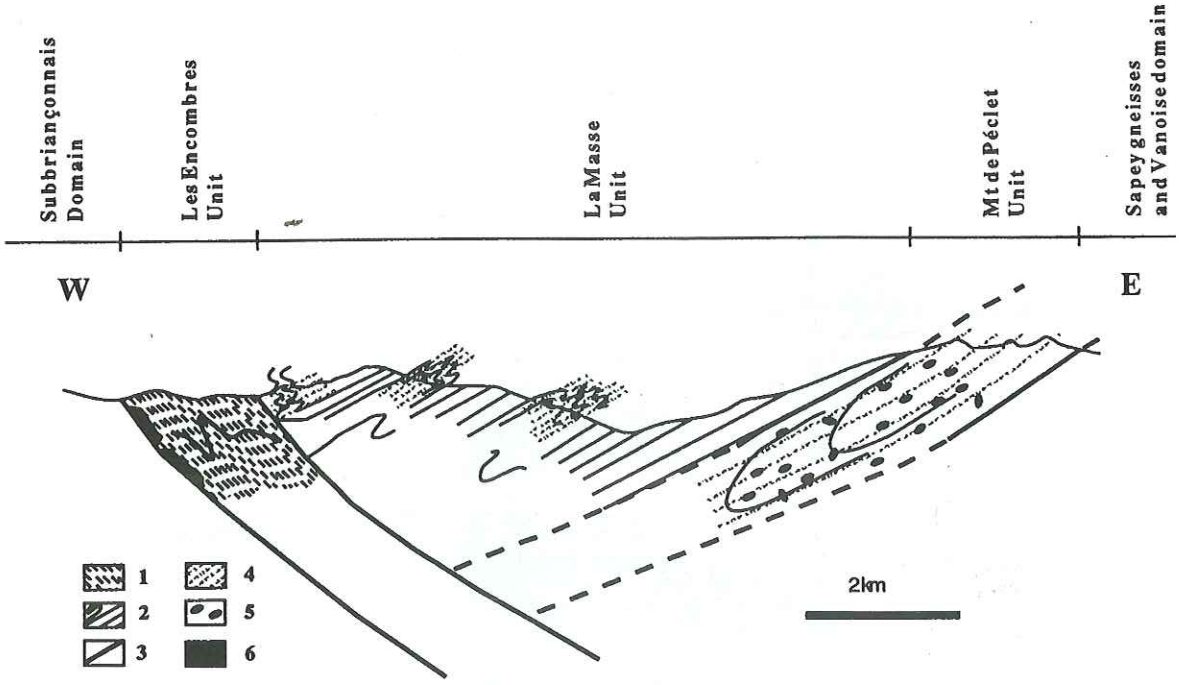

Fig. 2: Schematic cross-section of the ZHB from the BF to the Sapey gneisses. The "Mt de Péclet" consists of megaconglomeratic rocks, with pebbles showing an apparently isotropic fabric. (1) schistosity S_n in "Les Encombres" unit, (2) surface S_{n-1} in "Les Encombres" unit, (3) S1, (4) S2, (5) megaconglomeratic unit and (6) gypsum outcrops.

Fig. 2: Sezione schematica della ZHB dal BF fino agli gneiss del Sapey. Il "Mt de Péclet" é costituito da megaconglomerati, con ciottoli che mostrano un fabric isotropo apparente. (1) scistosità S_n nell'unità "Les Encombres", (2) superficie S_{n-1} nell'unità "Les Encombres", (3) S1, (4) S2, (5) unità megaconglomeratica, (6) gessi.

axial plane schistosity, which is nearly coplanar with S1 in the limbs of F2 folds when it exists and clearly cross-cuts the quartz pebbles in the fold hinges. In most cases, the observed regional schistosity may represent a combination of S1 and S2 parallel schistosities. However, large bodies of rock, the extent of which are unknown, clearly lack the S2 schistosity. F1 decametric folds have been recognized in many places (S0/S1 relationship, quartz pebbles flattened in the axial planes), and a faint EW intersection lineation is interpreted as representing L1.

(3) The "Mont de Péclet" unit shows a kilometre-scale F2 fold in the coarse-grained conglomeratic and green-violet schist formation ("assise de Courchevel" = Stephano-Permian, FABRE 1961). Axial planes dip westward while fold axes trend N150° and are subhorizontal. This unit lies on the Sapey gneisses either tectonically (DETRAZ, 1984) or stratigraphically ("Mont du Vallon" region). The significance of this eastern contact is still obscure. It may have initially been sedimentary but was probably reactivated during early-Eocene to Oligocene deformation (PLATT *et al.* 1989).

3. Finite strain measurement and maps

3.1 Finite strain determination techniques

All the measured samples are from sandstone or micro-conglomerate units. They were cut parallel to the three principal planes of strain,

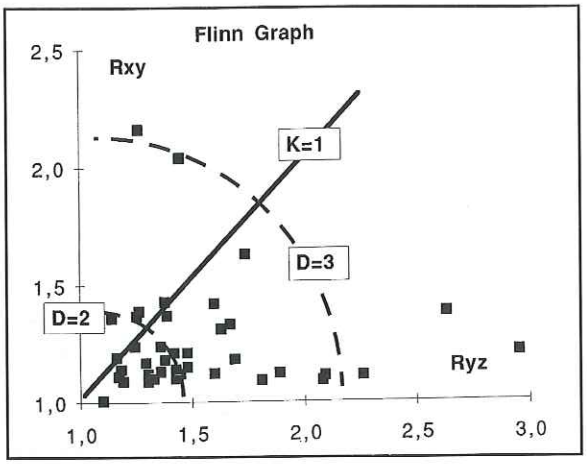

Fig. 3: FLINN plot (1962). K is the Flinn parameter and D is the intensity of strain.
Fig. 3: Grafico FLINN (1962). K é il parametro Flinn e D é la intensità dello strain.

defined with respect to S1 because S2 seems to be only developed in the F2 fold hinges: (1) XY parallel to S1, (2) XZ parallel to the faint lineation and perpendicular to S1 and (3) YZ perpendicular to S1 and to the lineation. In each plane, oriented thin sections were cut and from these sections, finite strain ellipses determined using quartz grains as strain markers. The axial ratios in each plane (R_{XY}, R_{XZ}, R_{YZ}) and the orientation of the ellipses have been calculated.

The "Féret" diameter method (LAPIQUE *et al.*, 1988) is used for determination of the finite strain ellipses. This method is based on grain-shape analysis and requires a record of the whole boundary of the quartz grains. This information is obtained using image analysis techniques on numeric images from thin sections of the micro-conglomerates (AILLERES *et al.*, in press).

Figure 3 shows a plot of the finite strain data on a Flinn diagram (FLINN, 1962).

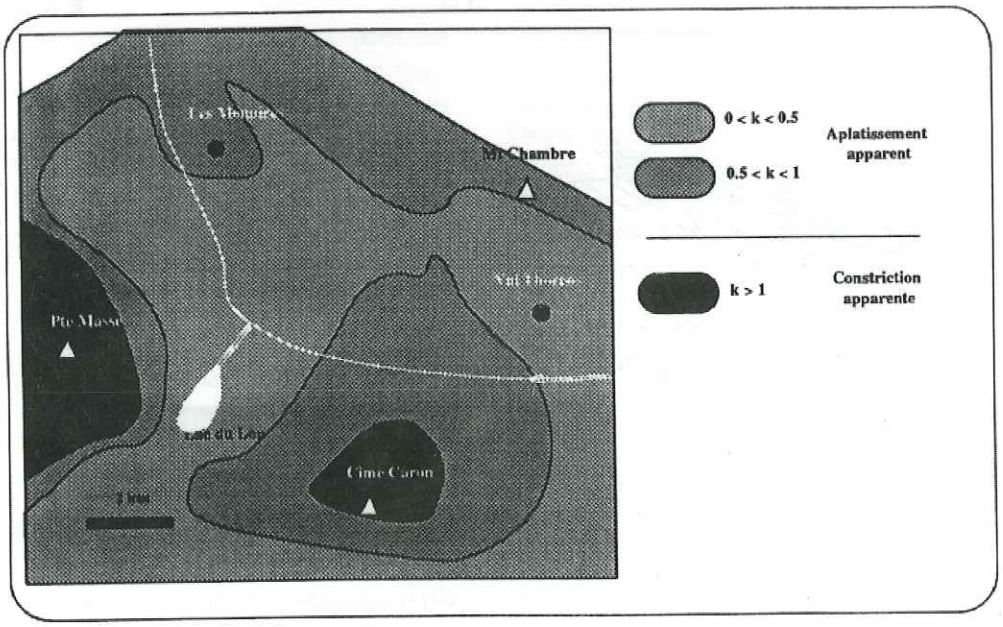

Fig. 4: Map of K Flinn parameter including the "La Masse" and "Mt de Péclet" units.
Fig. 4: Carta del parametro K-Flinn con le unità "La Masse" e "Mt de Péclet".

Most of the data plot in the field of apparent flattening (RAMSAY, 1973). RAMSAY (1967) defined a measure of the intensity of finite strain as $D = \sqrt{R_{xy}^2 + R_{yz}^2}$. This parameter has rather low values for all the samples, even for those very close to the BF (Fig. 5). As we have measured the flattened quartz pebbles lying in the S1 schistosity, this result is consistent with those of PLATT *et al.* (1989) concerning the low intensity of the early-Eocene deformation.

3.2 Maps of finite strain

These maps are only preliminary since the sampling is still too scattered and our network still has many gaps. The preliminary trends presented here have to be confirmed.

The map of K-Flinn parameter (Fig. 4) shows a wide area where apparent flattening predominates while apparent constriction is only restricted to two narrow zones. Apparent constriction is generally linked to a stretching lineation, but such a lineation has never been seen in the field, even close to the BF. Actually, the apparent constriction appears to be directly related to F2 fold hinges, where the quartz pebbles previously flattened by S1 are cross-cut and redeformed by S2, to give them a mullionned shape. The map of K-Flinn parameter thus outlines the major hinges of F2 folds. Two such hinge areas were located: (1) close to the La Masse summit, showing a N-S trend which corresponds to the measured direction of the fold in the field, and (2) in a small area around the Caron summit corresponding to the intersection of the hinge of a large F2 fold with the topography.Elsewhere, apparent flattening predominates, corresponding to zones where S1 and S2 are nearly parallel. The F2 fold axes determined using this map are well correlated with the measurements made in the field.

The X axes of the finite strain ellipses are nearly horizontal and their trends show no clear preferred orientation, as might be expected for strain ellipsoids in the apparent flattening field.

The map of the intensity of finite strain (Fig. 5) is not yet related to structural features in the field. It could correspond either to zones where a particular lithology allowed easier deformation or to tectonic contacts not yet recognized.

4. Discussion and conclusion

Results from finite strain analysis and structural observations suggest that the internal structure of the ZHB is completely unrelated to the BF structures. Within the ZHB, the large scale structures, resulting from superimposed folding, show gently westward-dipping schistosities (S_1 and S_2) and present flat lying XY planes (related to S_2) as confirmed by our finite strain analysis. Structural features observed in the ZHB are geometrically similar to those of the Vanoise adomain (PLATT *et al.*, 1989).

Our structural section show a better agreement with seismic data than previously proposed sections. The well-defined, west dipping reflectors are interpreted as related to west dipping contacts within the ZHB, *i.e.* the contact between "La Masse" and "Mont de Péclet" units and perhaps the tectonic contact between the ZHB

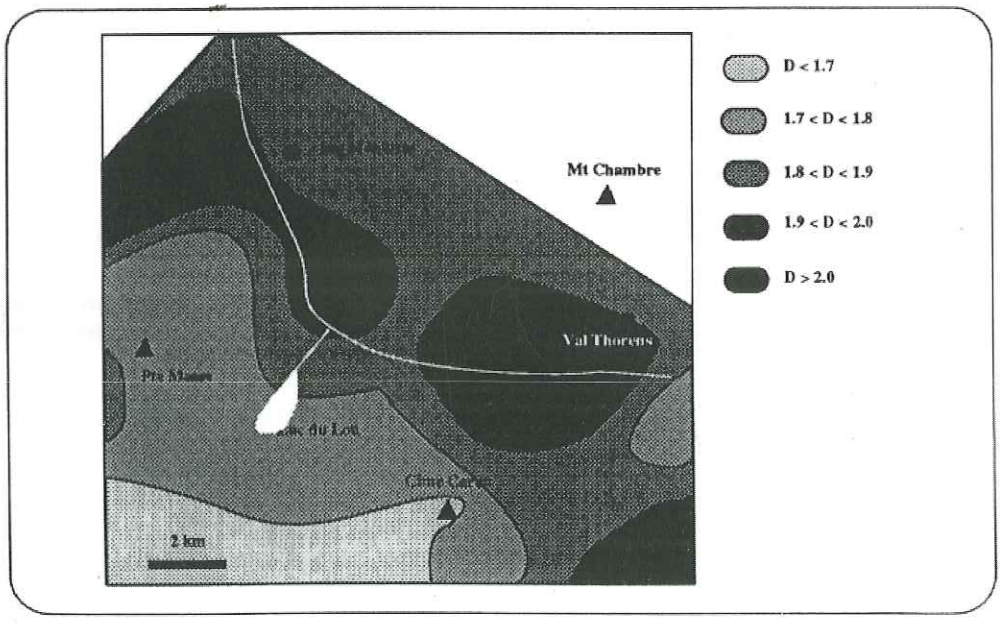

Fig. 5: Map of the intensity of finite strain.
Fig. 5: Carta della intensità dello strain finito.

and the external units of the Vanoise. The two narrow bands of east dipping reflectors are clearly related to the PF and BF (BAYER, 1987; NICOLAS, 1990; MUGNIER, 1993). They are locally outlined by a narrow zone showing an east dipping schistosity, here the "Les Encombres" unit, the relative age of which relative to S1 and S2 in the ZHB and its tectonic significance being still unknown.

Thus, the ZHB structures are sharply crosscut by the earstward-dipping BF and the overlying "Les Encombres" unit and the two domains show orthogonal relationships. This geometry suggests that the BF corresponds to a late structure with respect to the main deformation history of the ZHB and Vanoise domains.

The age and kinematics of this contact are still unknown as no direct kinematic observation may have been done so far in the brecciated and "cargneule"-invaded faulted contacts. One of the simplest interpretation, at this stage of our study is to assume a normal fault movement, moving the ZHB downward, as suggested by the observed general geometry of the contact (Fig. 2). Such an hypothesis has now to be constrained by small-scale field observations. Similar evidences for late extension along the Pennine Front are given by SEWARD & MANCKTELOW (1993, and in prep.) in the prolongation of the Simplon fault zone. The present attitude of the BF may then be the result of a late tilting of the whole crust, possibly related to the uplift of the External Crystalline Massives, which induced the steepening and reactivation of previously shallow-dipping earlier tectonic contacts such as the BF and PF.

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