The Hospital coal basin (Massif Central, France): relay on the left-lateral strike-slip Argentat fault in relation to the Variscan postorogenic extension

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Key words. – Variscan belt, Massif Central, Coal basin, Late Carboniferous, Strike-slip tectonics, Argentat

Abstract. – Structural and microstructural analyses of the Argentat fault, combined with sedimentological and structural analyses of the associated Hospital basin allow us to discuss the tectonic control of coal basins by crustal-scale faults during the late Palaeozoic evolution of the Variscan lithosphere in the French Massif Central. The brittle Argentat fault zone consists of first- and second-order strike-slip faults, with dominant NNW-sinistral faults, NNE-dextral or sinistral faults and secondary ENE-dextral faults. Several experimental and theoretical models explain the observed fault patterns, like en echelon faults, A-type secondary faults, conjugate faults and Riedel shears. Strike-slip faulting is responsible for folding of the metamorphic formations characterized by N-S to NE-SW-trending axis. The regional-scale geometry of brittle faults and associated folds corresponds to a positive flower structure centered on the brittle Argentat fault, combined to a negative flower structure centered on the coal basin. Using tectonic inversion software, we show that these structures result from a left-lateral movement of the brittle Argentat fault in relation to a tectonic regime intermediate between extension and strike-slip, with a horizontal NE-SW to NNE-SSW-trending maximum stretching axis. Detailed map and cross-sections, and sedimentological interpretations of the late Stephanian Hospital basin show the occurrence of intra-basin syn-sedimentary strike-slip faults and progressive overlaying, indicating that sedimentation occurs during left-lateral strike-slip faulting and folding of basement along the Argentat fault. These data are consistent with a model of N-S to NE-SW-trending postorogenic extension proposed to account for the late Carboniferous evolution of the Variscan lithosphere. They also point out the complexity and the variety of structures developed along a regional brittle strike-slip fault zone and the necessity to take into account all the structures and the resulting geometry of the basement in order to better constrain the tectonic setting of intra-continental deposits.

Le bassin houiller de l'Hospital (Massif central, France) : un relais sur le décrochement senestre d'Argentat associé à l'extension postorogénique de la chaîne varisque

Mots clés. – Chaîne varisque, Massif Central, Bassin houiller, Carbonifère supérieur, Tectonique en décrochement, Argentat

Résumé. – Les relations géométriques et génétiques entre la faille fragile d'Argentat, accident majeur du Massif central français, et le bassin houiller de l'Hospital le long de laquelle il se localise, apportent des éléments nouveaux sur l'évolution de la chaîne varisque au Carbonifère supérieur. Ces relations sont décrites par une étude tectonique et microstructurale de la faille fragile, couplée à une analyse sédimentologique et structurale du bassin houiller. La faille fragile d'Argentat est une zone de cisaillement complexe qui associe plusieurs familles de décrochements de premier et de second ordre. Ces décrochements fragiles, NW senestres, ENE dextres et NNE dextres ou senestres, induisent des plis en relais dans les parties compétentes du socle. Décrochements et plis contrôlent la structuration du bassin dans un dispositif global de structure en fleur positive centrée sur le décrochement senestre principal, combinée à une structure en fleur négative centrée sur le bassin. Les données microstructurales montrent que ces structures sont associées à un jeu en décrochement senestre de la faille d'Argentat produit dans un régime en extension/décrochement. Ces données suggèrent une permutation entre σ_1 et σ_2 autour d'un axe σ_3 horizontal et orienté NE-SW à NNE-SSW. La géométrie du bassin montre des décrochements intra-bassins syn-sédimentaires ainsi que des discordances progressives, indiquant que la sédimentation s'est effectuée lors du plissement et de la fracturation du substratum. A l'échelle régionale, la structuration du bassin est contrôlée par le jeu en décrochement senestre de la faille d'Argentat. Ces données s'intègrent dans un modèle d'extension N-S à NE-SW post-orogénique de la chaîne varisque au Carbonifère supérieur, combinant décrochements et failles normales. Cette étude met aussi en lumière la complexité et la variété des structures développées le long des décrochements fragiles et la prise en compte des géométries induites dans le substratum pour mieux appréhender la formation des bassins sédimentaires qui les jalonnent.

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INTRODUCTION

The French Massif Central is a key outcrop of the Variscan belt that has experienced crustal-scale faulting [Arthaud and Matte, 1977], partial melting [Ledru *et al.*, 2001], a metalliferous crisis [Milési *et al.*, 1997; Becq-Giraudon *et al.*, 1999; Bouchot *et al.*, 1999], and deposition of coal and conglomerates during its late Carboniferous evolution [e.g., Becq-Giraudon, 1973]. Because of the close spatial relationships between coal basins and extension-related migmatite domes in the eastern Massif Central, coal basins are considered to reflect the N-S to NE-SW-trending postorogenic extension [Malavieille *et al.*, 1990; Echtler and Malavieille, 1990; Saint Martin, 1993; Burg *et al.*, 1994; Faure, 1995]. However, most of the coal basins are bounded by brittle strike-slip faults [Arthaud and Matte, 1977; Bonijoly and Castaing, 1986; Gélard *et al.*, 1986; Vallé *et al.*, 1988; Blès *et al.*, 1989; Mattauer and Matte, 1998] and display complex geometries differing from half grabens or roll-overs [Vetter, 1986; Genna and Debriette, 1999], providing geological arguments against the extensional model. This apparent contradiction is particularly true for the western Massif Central where small coal deposits are located along the regional Sillon houiller and Argentat faults. These basins have been interpreted as pull-apart developed during strike-slip faulting [Bonijoly and Castaing, 1986; Blès *et al.*, 1989; Faure, 1995], but their geometry is more complex than that of pull-aparts [Marest, 1985] and the kinematics of their bounded faults is suspected to be polyphased [Feybesse, 1981; Roig *et al.*, 2002]. As no attempt has been made to understand basin geometry with respect to the kinematics of regional faults and to fault-related basement deformation, the tectonic setting of late Variscan coal basins is a still matter of debate.

This paper attempts to combine various data in order to constrain the genetic link between strike-slip faults and coal basins. In our case study of the Hospital basin and the associated Argentat fault, new investigations allow us to document the geometry and kinematics of the Argentat fault, the fault-related basement deformations, the geometry of the Hospital basin, and to interpret the sedimentary infill. Thanks to the combination of all these data, we propose a tectonic model for the Hospital basin which could apply to several coal basins located along strike-slip faults of the Massif Central in the frame of the Variscan postorogenic extension.

GEOLOGICAL REGIONAL BACKGROUND

The Argentat fault is 180 km long and strikes N160°E (fig. 1). It separates the Limousin metamorphic units to the west, from the Millevaches leucogranites to the east [Mouret, 1922; Labernadière, 1967; Labernadière, 1970; Floc'h, 1983; Guillot and Feix, 1984; Feix *et al.*, 1987; Ledru and Autran, 1987; Feix, 1988; Roig *et al.*, 2002]. Stacking of the Limousin units results from a polyphased thrust tectonics ranging from early Devonian to early Carboniferous [Floc'h, 1983; Ledru *et al.*, 1994; Roig and Faure, 2000]. Thrust tectonics is responsible for a $S_{1\text{-}2}$ regional foliation, a NW-SE-trending lineation, and a northwestward shearing. From top to bottom, the Limousin units correspond to (i) the Epizonal units of Thiviers-Payzac and St.-Salvadour Units made of schist, quartzite and metabasites, (ii) the Upper Gneiss Unit, which consists of paragneiss hosting eclogitic boudins, (iii) the Lower Gneiss Unit, formed of Cambrian-Ordovician orthogneiss intruding paragneiss and micaschist, (iv) the Parautochthonous Unit, composed of quartzite and micaschist outcropping along the Argentat fault.

The Argentat fault has experienced two-deformation stages during the middle to late Carboniferous [Faure, 1995; Roig, 1997; Bellot, 2001; Roig *et al.*, 2002]. A crustal-scale ductile shear zone restrained to the micaschist-granite boundary [Bitri *et al.*, 1999; Roig *et al.*, 2002] displays a dextral/normal, northwestward movement [Ledru and Autran, 1987; Mattauer *et al.*, 1988; Bellot, 2001; Roig *et al.*, 2002] during the NW-SE synorogenic extension [Faure *et al.*, 2002; Roig *et al.*, 2002]. A fracture zone 3-4 km wide and 8 km deep [Bitri *et al.*, 1999] is superimposed on the ductile structures [Couégnas, 1920; Labernadière, 1967; Roig *et al.*, 1997; Roig *et al.*, 2002]. Late Carboniferous sediments are found near the fracture zone. From north to south, they correspond to the Hospital, Argentat, Luc and Teyssieu basins (fig. 1b) [Marest, 1985]. Because of the close spatial relationships between late Carboniferous sediments and brittle structures, it is likely that the Argentat fault experienced a late Carboniferous motion. Left-lateral kinematics have been previously proposed [Labernadière *et al.*, 1992; Faure, 1995; Genna *et al.*, 1998]. However, kinematic data were poorly documented and new investigations were undertaken in order to better constrain the movement of the brittle Argentat fault.

STRUCTURE OF THE ARGENTAT FAULT CLOSE TO THE HOSPITAL BASIN

Fault pattern

Our cartographic investigations show that the Argentat fault zone is subdivided into second-order strike-slip faults with dominant NW-SE to NNE-SSW sinistral faults and NNE-SSW dextral faults, and secondary ENE-dextral faults (figs. 1 and 2). The fault pattern strongly depends on the location of rheological boundaries inherited from ductile structures. The northern area (Treignac; station 6) is characterized by conjugate en echelon NNW-sinistral faults/NNE-dextral faults. In the central area (Lonzac; stations 2, 4 and 7), NW-SE to N-S-trending sinistral faults merge in one fault, like the A-type model of Chinnery [1966]. In the southern area (stations 1, 3 and 5), three sinistral faults are connected as in the A-type model and end at the reverse/dextral Bar fault. The eastern sinistral fault is associated with the Hospital basin and corresponds to two N-S-trending sinistral faults and second-order NW-SE-trending sinistral faults in between, similar to R shears developed in a Riedel system.

Fault-related folds

From field observations and our structural analyses (fig. 4), two post-nappe folds generations were recognized close to the Argentat fault. Early post-metamorphic folds (called P_1) display E-W- to NW-SE-trending horizontal axes. The Uzerche synform and disharmonic folds developed in its core are good examples of these upright to slightly northeastward-verging P_1 folds. They are interpreted as a result

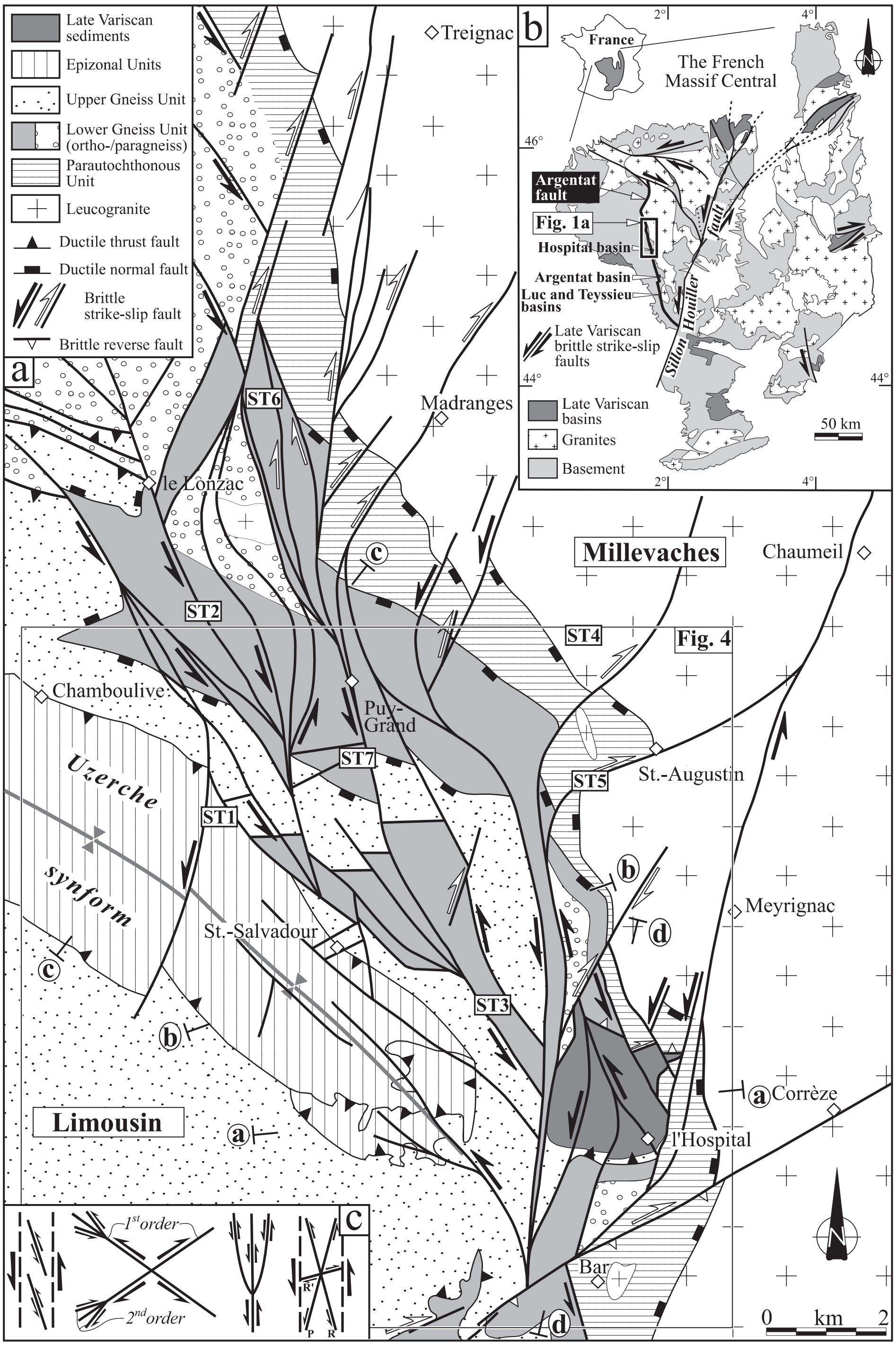

FIG. 1. – A. Simplified map of the Argentat fault focus on the Hospital basin ([Pavillon and Risler, 1970; Tempier *et al*., 1978 ; Floc'h *et al*., 1982; Labernadière *et al*., 1992] and unpublished data). Location of stereogram of figure 2, sections of figure 3 and map of figure 4. B. Location of the studied area in the context of the Massif Central, France. C. Theoretical pattern of various systems of secondary faulting observed in the area. From left to right : en echelon faults, conjugate faults, A-type secondary faults [Chinnery, 1966], and Riedel shears.

FIG. 1. – A. *Carte simplifiée de la faille d'Argentat dans le secteur de l'Hospital ([Pavillon et Risler, 1970 ; Tempier* et al.*, 1978 ; Floc'h* et al.*, 1982 ; Labernadière* et al.*, 1992] et cette étude). Localisation des stéréogrammes de la figure 2, des coupes de la figure 3 ainsi que de la figure 4.* B. *Localisation du secteur d'étude dans le Massif central français.* C. *Modèles théoriques d'agencement des failles de second ordre applicables au secteur d'étude. De gauche à droite : failles en relais, failles conjuguées, failles secondaires de type A [Chinnery, 1966] et cisaillements de Riedel.*

of the early Carboniferous collision [Floc'h, 1983] and/or the middle Carboniferous synorogenic extension [Faure, 1995; Roig, 1997; Bellot, 2001]. These folds are reworked close to brittle faults and P_2 folds.

West of the main fault, late post-metamorphic folds (called P_2) display N-S to NE-SW-trending axes that plunge gently to the north to northeast. These upright folds reworked P_1 folds. They are always encountered close to NW-SE to N-S-trending strike-slip faults but never crosscut them. Their asymmetric or en echelon patterns are in agreement with the sinistral kinematics of the fault zone (fig. 3b). In the vicinity of the coal basin, east of the main strike-slip fault, P_2 folds axes trend NNW-SSE and ESE-WNW north and south of the basin, respectively. These folds are associated with ENE-WSW-trending dextral faults (fig. 3d). Whether east or west of the main shear zone, P_2 fold geometry is always in agreement with the associated fault kinematics. P_2 folds are therefore interpreted as drag folds. It is worth noting that the fault pattern and folds geometry form a flower structure in which the Hospital basin is involved (fig. 3a, 3b, 3c). A positive flower structure is centered on the N-S-trending Argentat fault, combined to a negative flower structure centered on the basin (fig. 3a) [e.g., Harding et al., 1985;

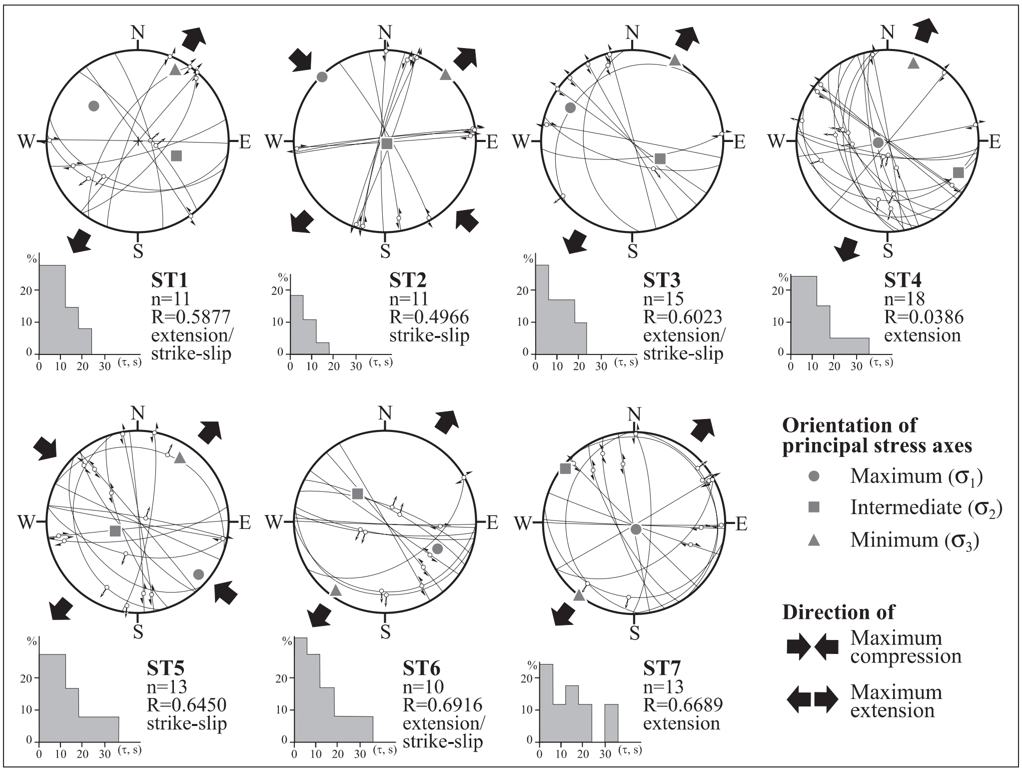

FIG. 2. – Fault-slip data and inversion obtained along the Argentat fault in the Hospital area. Stations are shown on figure 1a. Lower hemisphere, equal area stereograms. Histograms show the deviation between the striation (s) and the resolved shear stress (τ) for each fault plane. R is a stress ratio parameter defined as $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$.

FIG. 2. – *Données et résultats des inversions de populations de faille le long de la faille d'Argentat dans le secteur de l'Hospital. Les stations sont localisées sur la figure 1a. Les histogrammes montrent l'écart angulaire entre la strie mesurée (s) et la contrainte tangentielle calculée (τ) pour chaque plan de faille. R est défini par $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$.*

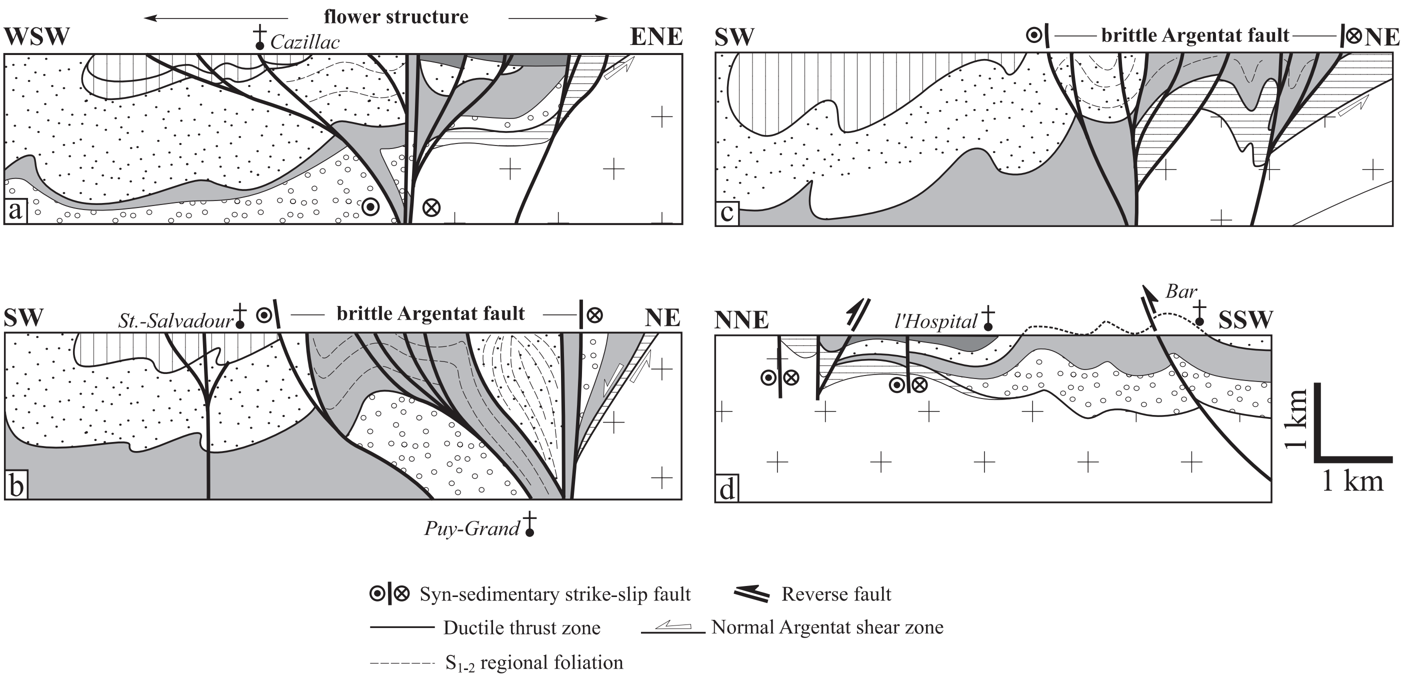

FIG. 3. – Cross-sections through the Argentat fault (see fig. 1a for location).

FIG. 3. – *Coupes à travers la faille d'Argentat (localisation en fig. 1a).*

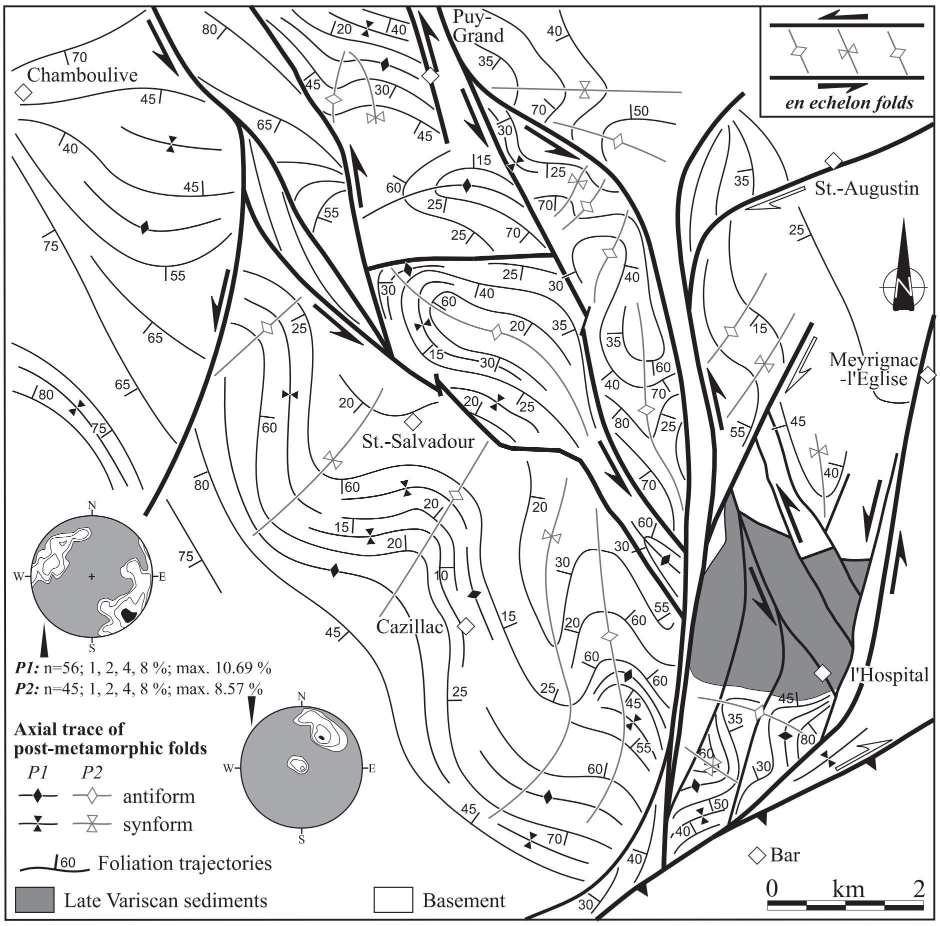

FIG. 4. – Map of S_{1-2} foliation trajectories and axial traces of two generations of post-metamorphic folds (see fig. 1a for location).
FIG. 4. – *Carte des trajectoires de la foliation métamorphique S_{1-2} ainsi que des traces axiales des plis post-foliaux (localisation en fig. 1a).*

Richard *et al.*, 1991; McClay and Bonora, 2001]. These structures imply a finite strain ellipsoid with a N-S to NE-SW-trending X-axis (maximum stretching axis) that plunges gently to the north to northeast. Y and Z axes are either vertical or horizontal and trend E-W to NW-SE.

Microstructural analysis and inversion

In order to better constrain the kinematics of the brittle Argentat fault and its related tectonic regime, a quantitative inversion of fault slip data measured on seven sites was performed (fig. 1a). This calculation provides the orientation of principal stress axes (σ_1, σ_2, σ_3), and the ratio R ($R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$) [e.g., Carey, 1979; Etchecopar *et al.*, 1981; Angelier, 1984]. Measured sites are restricted to fault segments of the flower structure previously defined in order to obtain synchronic microstructural data in different sites. Based on field observations, measured faults within each site are assumed to be coeval. Computation was made using the TectonicsFP software [Reiter and Acs, 2000]. Computed stress tensors are contrasted but all argue for a sinistral strike-slip movement along the Argentat fault (fig. 2). According to the Guiraud *et al.* [1989]'s classification, they correspond to extensional or pure strike-slip tectonic regimes, or to an intermediate behaviour. Although the minimum stress axis (σ_3) is constantly horizontal and trends regularly NNE-SSW to NE-SW, intermediate and maximum stress axes (σ_2 and σ_1) are either vertical or horizontal. It is noteworthy that the minimum stress axis is always the best defined axis, whichever of the four independent inversion methods is used. These results argue for a tectonic regime between extension and strike-slip responsible for the sinistral movement of the brittle Argentat fault.

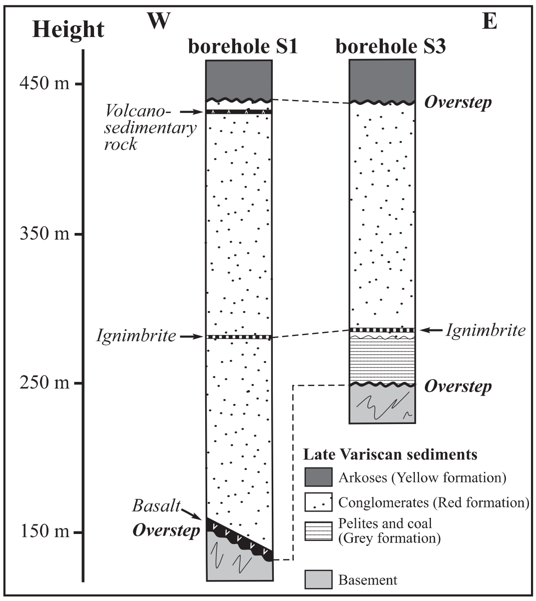

FIG. 5. – Synthetic boreholes through the Hospital basin [after Marest, 1985] (see fig. 6a for location).
FIG. 5. – *Logs synthétiques relevés le long des sondages S1 et S3 à travers le bassin de l'Hospital [d'après Marest, 1985] (localisation en fig 6A).*

STRUCTURE OF THE HOSPITAL COAL BASIN

Lithostratigraphy

Field data [Mouret, 1891; Pavillon and Risler, 1970; Marest, 1985; this study] correlated to three borehole interpretations (S1 to S3) [Marest, 1985] allow us to define three sedimentary formations in the coal basin (fig. 5). From bottom to top, they are: (i) The "grey formation" which does not outcrop. It was recognized at the base of the S3 borehole where it overlies the basement with a basal unconformity. It corresponds to grey to dark conglomerates, fine-grained arkosic sandstones, and pelites including several pyrite-bearing centimetre-thick coal levels. Based on the discovery of well-preserved flora in pelites, the base of the Hospital basin is considered to be late Stephanian in age [Marest, 1985]; (ii) the "red formation" unconformably overlies both the basement and the "grey formation". It corresponds to the main formation (275 m thick), consisting of coarse- to moderate-grained arkosic conglomerates. Ignimbrites recognized at the same level in both S1 (282.5 m) and S3 (283.8 – 285.3 m) boreholes indicate an explosive volcanic event which occurred during conglomerates deposition (fig. 5); (iii) the flat "yellow formation" unconformably overlies the "red formation". It consists of chaotic conglomerates formed of meter-scale granite blocks surrounded by an arkosic matrix.

Changes of lithology and an increase of both pebbles size and bed thickness are both progressive from the bottom to the top and associated with regular depositional pulses. These features argue for a progressive modification in depositional environment from delta-river, for the "grey" formation, to alluvial cone, for the "red" and "yellow" formations. The angular unconformities separating the three formations probably reflect major pulses during syn-sedimentary tectonics. Because of continuous sedimentation in the Hospital basin and the late Stephanian dating of its base, the whole sedimentary pile is assumed to be late Stephanian in age. Consequently, the left-lateral wrenching responsible for the tectonic control of the Hospital basin is also of late Carboniferous age.

Structure

In the southern part of the basin (Puy de Bans), conglomerates overlie the basement with a basal unconformity that strikes E-W and dips steeply to the north (fig. 6). By contrast, in the northern part, north of Mondamine and east of Boussac-Bas, the basement lies geometrically above the conglomerates (fig. 6a). Their contact corresponds to a fault plane striking N110^{o}E and dipping gently to the northeast. On the fault plane, well-defined NNW-trending slickensides are observed. Kinematic criteria indicate a reverse/dextral movement (fig. 6b, ST1). North of Enval, the basement-basin northern boundary corresponds to a right-lateral strike-slip fault striking N070^{o}E (fig. 6a). The western and eastern boundaries of the basin correspond to regional-scale left-lateral strike-slip faults that strike N-S to NNE-SSW (fig. 6b, ST2 and ST3). Close to these major faults, meter-scale normal faults striking E-W were also found (fig. 6b, ST4).

The basin structure is accessed by using lithostratigraphic correlations combined with surface structural analysis and borehole information. It corresponds to three under-basins separated near NNW-SSE-striking left-lateral strike-slip faults (figs. 6c and 7a). (1) The western under-basin has a large, symmetrical synform shape with inward

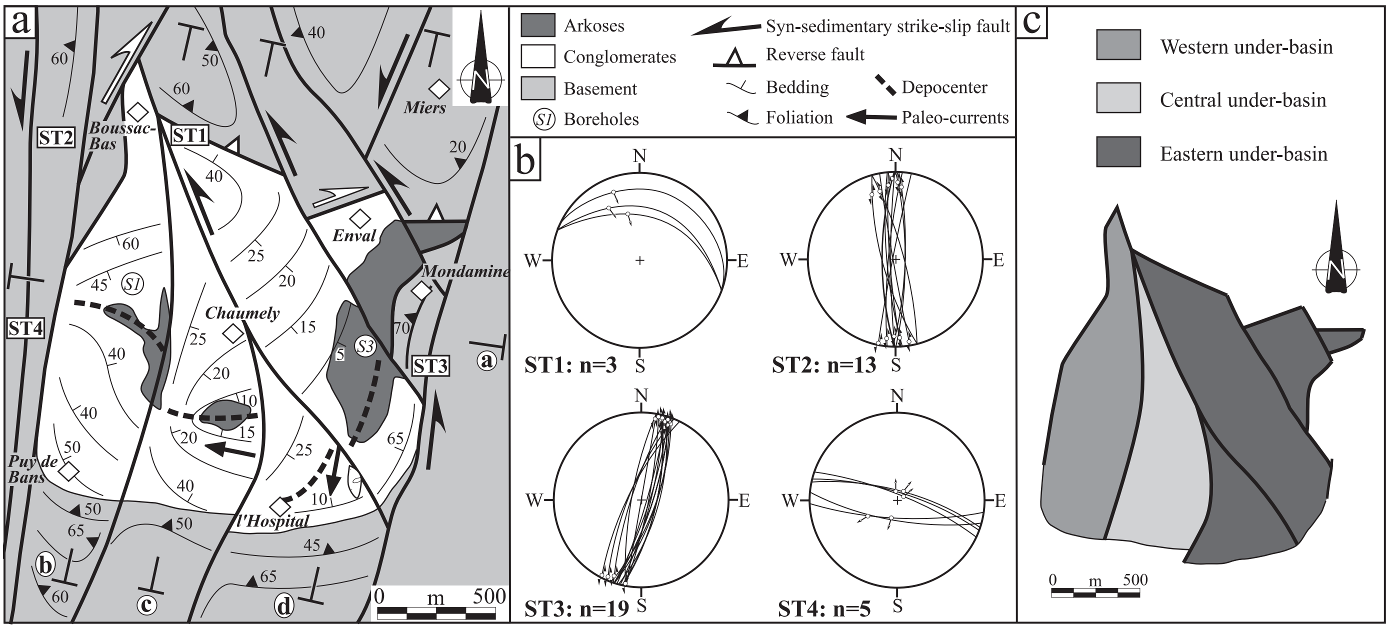

FIG. 6. – Structural data available on the Hospital coal basin and its borders. A. Structural map with bedding trajectories. Location of boreholes of figure 5, stereograms of figure 6b, and sections of figure 7. B. Microstructural data obtained on brittle fault zones that bounded the basin. Lower hemisphere, equal area stereograms (see fig. 6a for location). C. Simplified map showing the relationships between the three under-basins and NNW-SSE to NNE-SSW-trending sinistral strike-slip faults.

FIG. 6. – *Données structurales sur le bassin houiller de l'Hospital et ses alentours immédiats.* A. *Carte structurale du bassin avec trajectoires de la stratification. Localisation des forages de la figure 5, des stéréogrammes de la figure 6b, ainsi que des coupes de la figure 7.* B. *Données microtectoniques sur les failles fragiles bordant le bassin. Hémisphère inférieur, projection de Schmitt (localisation en fig. 6a).* C. *Carte simplifiée montrant les relations entre les trois sous bassins et les décrochements orientés NNW-SSE à NNE-SSW.*

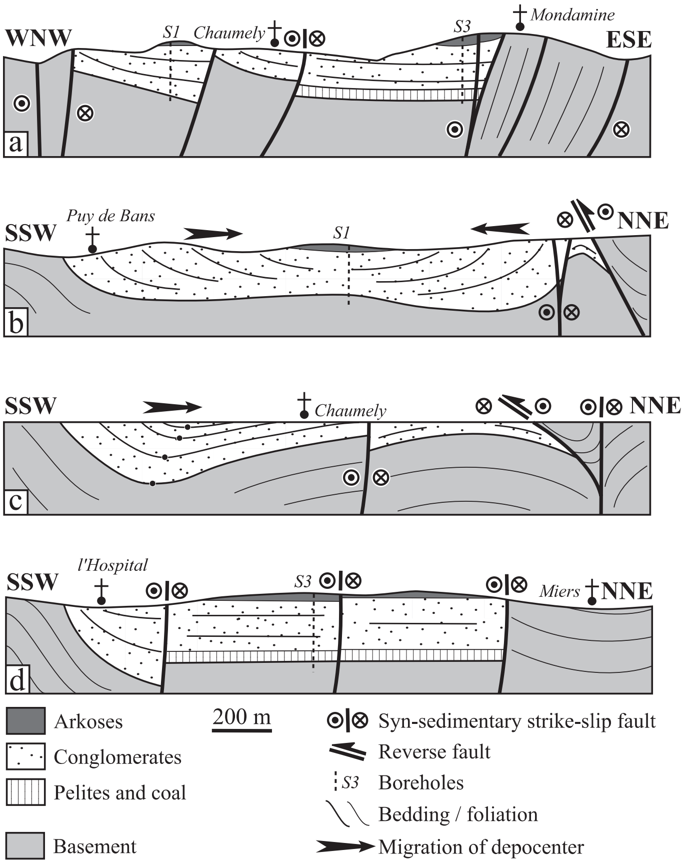

FIG. 7. – Cross-sections through the Hospital basin (see fig. 6a for location).
FIG. 7. – *Coupes à travers le bassin de l'Hospital (localisation en fig. 6a).*

progressive overlying (fig. 7b) that agrees with the E-W direction of paleo-currents derived from pebble imbrications (fig. 5a) [Marest, 1985]. (2) The central under-basin has an asymmetrical, northward-verging synform shape and displays northward progressive overlying (fig. 7c). (3) The northwestern part of the eastern under-basin has a large upright open antiform pattern. Its northern boundary corresponds to a reverse/dextral fault (fig. 7c). Other parts of the eastern under-basin display an asymmetric pattern evolving northward from "en eventail" to flat patterns (fig. 7d). Because two under-basins were formed on basement folds, conglomerates deposition and basement folding are assumed to be coeval. As each under-basin displays a specific geometry, zoning in facies-type, location and inward migration of depocenter, and orientation of paleo-currents, all of them are assumed to be developed during wrenching of their boundary faults.

DISCUSSION-CONCLUSION

The relationships between faults kinematics and basement folding show that these structures result from a single event. Moreover, we can notice the parallelism between the maximum stretching axis (x) deduced from post-metamorphic folds, and the minimum stress axis (σ_3), interpreted as an instantaneous stretching axis. There is also a good agreement between the minimum stress axis (σ_3) and the microstructural data obtained on the basin-bounded faults. Therefore, we propose that strike-slip faulting, folding of the basement, and coal and conglomerates deposition in the Hospital basin were coeval and occurred during the left-lateral wrenching of the Argentat fault in the late Carboniferous times. Strike-slip faulting and folding along the Argentat fault are both responsible for the development of positive and negative flower structures. The Hospital basin developed on the negative flower in response to faulting along R shears associated with left-lateral wrenching of the main Argentat fault. Because of its key position between the northern complex fault system and the southern single fault (fig. 1), this coal basin is considered as a relay on the Argentat fault. All these structures result from an intermediate tectonic regime between extension and strike-slip in which the extension axis is horizontal and trends NNE-SSW to NE-SW. This tectonic regime suggests local permutation between intermediate and maximum stress axes (σ_2 and σ_1).

However, the dextral/reverse ENE-trending faults, because of their location close to normal faults are not taken into account by our model. According to theoretical and analog models [Christie-Blick and Buck, 1985; McClay and Bonora, 2001], a regional strike-slip fault involved in a progressive deformation history can produce local normal, reverse and strike-slip faults without change in the tectonic regime. Therefore, dextral/reverse faults could result from early or late transpressional increments during the Argentat faulting. They are more likely due to the polyphased tectonics that have affected the study area, as examplified by the early Mesozoic reverse motion of the Bar fault (fig. 1) associated with deposition of Pb-Zn mineralization [Bril *et al.*, 1994].

Our results provide new arguments for interpreting coal basins sited along strike-slip faults in the western Massif Central as the result of the Variscan postorogenic collapse. They agree with those obtained for the eastern Massif Central where the genetic link between coal basins and postorogenic extension is more obvious [Malavieille *et al.*, 1990; Echtler and Malavieille, 1990; Burg *et al.*, 1994; Faure, 1995]. According to Faure [1995], we interpreted regional strike-slip faults in the western Massif Central as a consequence of the postorogenic extension.

As a conclusion, the Argentat fault is a crustal-scale, polyphased shear zone which experienced a late Carboniferous left-lateral movement in relation to the postorogenic extension of the Variscan belt. The tectonic regime between extension and strike-slip observed in the South Limousin is in fact widespread in the Massif Central [Arthaud and Matte, 1977; Blès *et al.*, 1989; Faure, 1995]. It reflects the late Carboniferous normal faulting of previous and/or newly formed E-W-trending faults, and wrenching along the submeridian faults, such as the Argentat and Sillon houiller faults, in response to a crustal-scale NE-SW-trending extension [Echtler and Malavielle, 1990; Lagarde *et al.*, 1994; Faure, 1995].

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