The ”Bois du Peu” thrust sheets (external French Jura mountains):re-examining the concept of ”Fault-Fold”

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The "Bois du Peu" thrust sheets (external French Jura mountains): a flash-back on the concept of "fault-fold"

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Abstract Significant reconnaissance field work along a road project which crosses the site of "Bois du Peu" thrust sheets (near Besançon, Eastern France), provides us the opportunity to re-examine the concept of "fault-fold" (faille-pli) which was introduced by Glangeaud (1944). In theoretical point of view, we put in obvious that this concept is incompatible with general principles of balanced cross-sections and have to be rejected. We show that in the "Bois de Peu" area, data fit with a deformation model associating several modes of fold (fault-propagation fold and fault-bend fold). The décollement level related to these folds is located into Keuper strata, Oxfordian-Argovian levels being used locally as secondary decollement level.

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1 Introduction

The concept of "faille-pli" (in english "fault-fold"; not to be mistaken with the french term of "pli-faille" which means fault-related fold) was introduced by Glangeaud (1944) to account for observations about tectonics of the Jura mountains and, more specially, external Jura. This last is made of kilemetric-wide strips which are densely folded and faulted: the bundles. Relatively tabular sections (named plateaus) are found on both sides of these bundles, with the higher topographical one lying to the East (Fig. 1).

Glangeaud (1944) proposed that the bundles in these carbonate strata resulted from a process he named "fault-fold" and which is illustrated on figure 2. Following him, a pre-existing normal fault (inherited from a previous distension phase) would have elevated the eastern bloc (relative to the western one). Then, during the following compression phase, this eastern bloc covered the topographic surface below on the hanging wall block. Hence, the normal fault turns into a thrust fault and the distorted strata draw a fold structure which spills in the direction of the deformation.

Following a fild-triep that took place in 1951 in the Jura, this morpho-structural concept became very popular in the French geological community. Glangeaud (1951) illustrated his proposed concept on the cross-sections of the Besançon bundle in the "Bois du Peu" area, 2 km south of the city of Besançon. Some following authors (*e.g.* Caire, 1963; Chauve and Perriaux, 1974; Chauve, 1975) worked on these sections and further detailed them, thus contributing to make the "Bois du Peu" area the reference location for the concept of "fault-fold".

The concept of "fault-fold" remained quite popular for a long time in the French geological literature. Some reference books (*e.g.* Aubouin, 1973; Mattauer, 1973; Foucault and Raoult, 1980; Dercourt et al, 2006) illustrate this concept applied to the Jura mountains without any discussion. This concept remained dominant for Jura mountains until, at least, the end of the 1980's (Chauve, 1987).

At the same time, the anglophone (in the sense of non-francophone) community totally ignore that concept. Since the end of the 1960's, their approach of the tectonics of the external zones was renewed by the concept of balanced cross-sections (Wilson and Stearns, 1958; Bally et al, 1966; Dahlstrom, 1969, to cite only a few pioneering works). Applying this concept, some authors (Laubscher, 1961; Mugnier and Vialon, 1986; Endignoux and Mugnier, 1990; Zoetemeijer and Sassi, 1992; Martin and Mercier, 1996; Meyer, 2000) proposed balanced cross-sections of the Jura bundles without taking into account the concept of "fault-fold". *De facto* and even if this concept has never been strongly discussed in the literature, it appears inconsistent with the principle of balanced cross-sections and has to be abandoned.

Since Glangeaud's works (Glangeaud, 1951), the "Bois du Peu" area has never been reinterpreted. Geological study and civil engineering works conducted for the Besançon higway by-pass project provide new outcrops and subsurface drillings (corings and tunnels) in the "Bois du Peu" area. These new data give us a good opportunity to re-examine and re-interpret this reference location.

The aim of this paper is first to re-examine the concept of "fault-fold" and to show why it is inconsistent with the concept of balanced cross-sections. This re-examination of Glangeaud's concept will be limited to this only point. Secondly, new data concerning the "Bois du Peu" area will be presented. They allow to build a new detailed geological map. Finally, it will be proposed that a new fault-related fold model is consistent with field observations.

2 Geological context of the study area

The Jura is an arched moutain belt located NW of the Swiss molasse basin (Fig. 1a). The study zone is located in the outer Jura chain and is mainly made of Jurassic carbonate formations (Fig. 3). These sedimentary strata are arranged in relatively tabular plateaus separated by severely folded and faulted narrow elongated bundles (Fig. 1b). This arrangement is the result of the "multi-phased" tectonic history of the area, where two main phases can be distinguished. The first phase was extensional, with an E-W sense and has an Oligocene age. This resulted in a general westward downstepped blocks geometry which correspond to the present-day look of the massif. The second phase was compressive, directed towards NW and is Miocene. The deformation related to the compressive phase was principally located at the boundaries between the plateaus, thus generating bundles, characterized by folds and thrust faults (Glangeaud, 1951; Caire, 1963; Bergerat et al, 1990; Guellec et al, 1990; Lacombe and Angelier, 1993; Martin and Mercier, 1996; Homberg et al, 1999). Furthermore, the major oligocene-inherited meridian faults induced a leftward strike-slip motion which allowed the panels to slide. According to palaemoagnetic recordings, this translation movement did not induce significant rotation of the structures (Gehring et al, 1991).

The Besançon bundle constitues one of the narrow strips. In the study area, this bundle is oriented SW-NE and is about 4 km wide. It is bounded by the Besançon/Thise plateau to the NW and by the topographically higher Montrond plateau to the SE (Fig. 1b). At outcrop, this bundle is made of two parallel antinclines. To the NW, the

Citadel anticline shows a symetric or slightly SE overturned geometry. To the SE, the Mercureaux anticline is strongly dyssimetric and overturned towards the NW (Fig. 1b). It is the Mercureaux anticline, along with its associated Montfaucon fault (Dreyfuss and Kuntz, 1968), which have been interpreted as one of the best example for the "Faul-fold" structure by Glangeaud (1951).

The local geological series is made of an alternation of soft (clay and marls) and hard levels (limestones, dolomites and sandstones) and is shown on figure 3. The main décollement level is located within the Triassic gypsum-rich strata. Secondary décollement levels may be found within soft Jurassic strata (Fig. 3): Pliensbachian-Aalenian, Oxfordian *sensu stricto*-Argovian and middle Sequanian. Regional sub-stages denominations (Dreyfuss and Kuntz, 1968) have been kept to distinguish between the mechanically variable strata.

The Besançon highway by-pass (Maurin, 2001; Bièvre, 2007) crosses the Mercureaux anticline in the "Bois du Peu" area. The geological complexity of the site lead to dense prospectings: several kilometers of coring, diagraphies (gamma-ray, microseismics, digital camera) as well as mechanical in situ and laboratoray tests. A reconnaissance gallery has been drilled that crosses the base of one of the bundles. These new data allow to detail the orientation and dip of faults as well as the lithology of the bedrock underlying the top-soil layer, especially along the Mercureaux anticline axis (Fig. 1b) made of soft clayey and marly formations. The whole data allow to propose a detailed geological map of the area as well as an original synthetic cross-section of the bundle which was crossed by the reconnaissance gallery.

3 The concept of "fault-fold" in the light of the balanced cross-sections theory

The theory of balanced cross-sections is based on the assumption that thanks to the law of conservation of matter, the material amount remains constant during tectonic deformations. In faults and folds belts, it is often possible to work on cross-sections (see complete discussion in Marshak and Woodward, 1988, for example) and, in this way, to transform the law of conservation of matter into a law of conservation of surfaces: during deformation, the surface of each bed remains constant. To verify this conservation, it is necessary to set boundaries on the system studied and, consequently, to discuss these boundaries conditions.

Figure 4 shows that surfaces conservation requires that, during the growth of a "fault-fold", the boundaries of the system undergo differential simple shear. This diagram shows that only the upper layers of the upper block are those who will suffer the simple shear during horizontal shortening. More specifically, the only beds which are in elevation over the top of lower block after the first deformation (normal fault) suffer the simple shear. This is problematic because, obviously, the boundaries conditions are controled by rear area deformation conditions and not by internal parameters (normal fault offset) as the figure might falsely believe.

Furthermore, Figure 5 shows that the deformations are amortized into the structure and are not transfered forward from one block to another one. Accordingly, this model fails to explain the succession of several "fault-fold" strutures on a unique cross-section as it is the case in the Jura (Chauve, 1987).

A large part of recent authors who worked on the Jura (see above), have already abandoned the concept of "fault-fold". More precisely these authors do not take account of this concept because none of them has really justified this abandonment. We have shown that the concept of "fault-fold" is incompatible with the theory of balanced cross-sections. This short demonstration largely justifies abandonment. So, the "Bois de Peu "area, the reference locality for the "fault-fold" concept has to be explained otherwise. As we shall see in the following parts, it is possible to reinterpret this structure with concepts of "folds and faults belts" tectonics.

4 Results

4.1 Geological field data

Prospectings conducted for the highway by-pass study provided a large amount of geological data (Maurin, 2001; Bièvre, 2007). Combined with detailed field observations, these data allow us to produce a new geological map based on a previously established one (Dreyfuss and Kuntz, 1968). There is no fundamental change between the two maps, but the one that is proposed here is much more detailed (Fig. **??**) due to new available data. In combination with these field observations, a reconnaisance gallery was drilled through the base of one of the "Bois du Peu" thrust sheets and an interpretative cross-section was built (Fig. 7; modified after CETU, 1999).

The proposed cross-section for this work is located one km SW of the reference location. The geological map reveals that fault F2 dips towards SE (as it has been revealed by corings and gamma-ray logging; Maurin, 2001). Fault breccia was found in corings conducted along the road project to define the dip of F3 (Bièvre, 2007). Along with gamma-ray logging in surrounding drillings, this reveals that the F3 fault (Montfaucon fault of Dreyfuss and Kuntz, 1968) slighlty dip towards SE (Fig. **??**). These two faults were previsously considered to be subvertical (Fig. 8a; Glangeaud, 1951; Caire, 1963; Chauve and Perriaux, 1974; Chauve, 1975). Moreover, the Mercureaux anticline axis is located a few hundreds of m SE of F3 (Fig. **??**; Bièvre, 2007). These two observations are already inconsistent with the interpretation of the area in terms of "fault-fold".

A vast outcrop composed of Triassic strata is present in contact with F3 along the road project, 200 m SE of the tunnel (location on Fig. **??**). This Triassic outcrop is bordered by Pliensbachian strata (Belemnites as well as Ammonite *Amaltheus margaritatus* were found in corings). Associated with the presence of fault breccia, cartography and orientations of dips, these elements permit to consider this Triassic outcrop like a tectonic flake forced against the Montfaucon fault (F3). The presence of such a flake constitute an important argument to interpret F3 like a thrust fault seated within Triassic strata (Fig. 8b).

The hinge and inverted limb NW of the Mercureaux anticline overthrust the very competent Jurassic beds. In first approximation, despite some irregularities (Fig. 7 and Fig. 8), this thrust is parallel to the autochton stratification. Previous authors had considered implicitly (compare Fig. 3 and Fig. 8a) or explicitly that the thrust surface was the Pontian topographic surface (surface of "Montrond"; Dreyfuss and Glangeaud, 1950). We will mention again this hypothesis.

Thrust F1 is not the only one to be locally parallel with the stratification. For example, thrust F2 is, from NW to SE, successively sub-parallel, oblique and again sub-parallel with the stratification(Fig. 8b). These particular relations refer to the ramp geometry.

This observation, along with previous works on other bundles in the Jura (Endignoux and Mugnier, 1990; Zoetemeijer and Sassi, 1992; Martin and Mercier, 1996; Meyer, 2000), lead us to propose a kinematic scheme characterized by the development of folds-related ramp for the "Bois de Peu" area.

4.2 Kinematic modelling

Cross-section balancing became a standard method for testing viability and admissibility of hypothetical deep geometry. Many theoretical and applied works have focused on this method in thrust and fold belts. Several approaches have been developed but, according to most of the authors, in the Jura, the "forward" method is the most appropriate (Endignoux and Mugnier, 1990; Zoetemeijer and Sassi, 1992; Martin and Mercier, 1996).

Martin and Mercier (1996) proposed a comprehensive discussion on the application of this method to a bundle of the Jura. To summarize, this method provides a viable and admissible kinematic way between an initial state (undeformed) and a final state (deformed). The need to respect the law of conservation of matter (1) between initial stage and final stage, and (2) between each kinematics step, strongly limits the number of possible solutions.

In practice, a trial and error process led us to build an image of the finite deformation witch is consistent with field data. With this kind of problem solving process, there is a risk of neglecting some other possible solutions. Hence, many tests have to be carried out to assess the influence of changes in calibration parameters.

In the case studied here, we chose to work on an "average" cross-section. This section can be considered as representative of the whole area, and allow to eliminate local variations that can not be taken into account by modelling. The numerical solution is shown in figure 9.

Steps a, b et c: a "fault-propagation fold" (in the sense of Suppe, 1985) gradually grows over a ramp deeply-seated in a décollement level located at the top of the Triassic strata. It has long time been known (*e.g.* Glangeaud, 1951; Caire, 1963) that the Jura bundles are the result of the superposition of an Oligocene tectonic distension and a Miocene tectonic compression. Previous modelling works (Martin and Mercier, 1996) showed that in the bundle, ramps initiation occur systematically at the intersection between a décollement level and inherited normal faults. Surprisingly, there are no arguments here to link the initiation of the ramp with a normal fault.

Step d: the fault-propagation fold suffers a standart late evolution: transport on the flat (Mercier, 1992; Mercier et al, 1997). Usually, such evolution occurs when the ramp can no longer propagate upwards (when the ramp crosses very competent beds, for example), and seeps into an interbed level. It does not seem to be the case here, the very competent Jurassic series is already crossed and the Cretaceous, thin and weakly competent, can not stop the propagation of the ramp. The simplest is to assume that the allochton slept upon the paleo-surface topography ("Montrond" surface; Dreyfuss and Glangeaud, 1950).

Step e: The transport on the flat becomes increasingly difficult (friction increasing, blocking on local micro-topography) and the mechanical conditions in autochton change because of the tectonic overload. A new thrust plane takes place.

The mouvement over this thrust creates a duplex wich is transported under the fold. Modeling suggests that this duplex is deep-seated in a secondary detachment level in the Oxfordian-Argovian strata. This hypothesis is fully consistent with mechanical properties of these levels (Fig. 3) and field data (Fig. **??**).

Step f: After a significant displacement, this new thrust is blocked in turn. Out of the sequence thrusts occur from the existing ramps and through weakened areas of the structure (Mercier and Mansy, 1995). The northern out-of-sequence fault corresponds to the "forelimb breakthrough" of fault-propagation folds (Mercier, 1992). It isolates, between F1 and F3, a little thrust sheet with reverse polarity. We suggest that this thrust sheet is torn into several elements that are more or less carried forward in reponse to the movement of the allochton.

Finally, synchronically or not, growth of the Citadel anticline, located just NW of the section studied, affects the whole structure which is partly integrated into its SE limb. The final bending is not really taken into account by our modeling. The surface topography drawn in figure 9f is distorted from reality. But this adjustment imprecision does not affect the principle and the conclusions of our model. In fact, it only introduces an uncertainty on the geometric modeling of the out-of-the sequence faults F4 and F4'.

The total shortening, of about 50 % (4 km), is significantly higher than what was calculated on the sections located further north accross the same bundle (Martin and Mercier, 1996). This difference suggests small rotations of the plateaus during deformation.

5 Discussion and conclusions

Major geological reconnaissance in the reference locality for the concept of "fault-fold" ("Bois du Peu" area; Glangeaud, 1951) provide an opportunity, first, to discuss the concept of fault-fold, and to show its incompatibility with the theory of balanced cross-sections. Secondly, it allows to propose a new structural evolution for this area (Fig. 8b and Fig. 9).

We show that available field data are consistent with a typical scenario of folds and thrust belts evolution. This scheme is particularly characterized by growth and evolution of fault-related folds deeply seated within Triassic strata. This is very similar to scenarii already proposed for other Jura bundles (*e.g.* Guellec et al, 1990; Martin and Mercier, 1996; Meyer, 2000). In particular, we note the combination of various folding modes (fault-related folds with late evolution, duplex, etc.) in the same sector. This work, among many others, confirms the usefulness of the "forward" method in the study of the Jura tectonics. However, without syntectonic sedimentary markers, the sequence of deformation proposed remain, in the study case as elsewhere, poorly constrained. In the study area, the shortening is about 50% which is higher than what is known in other bundles. Finally, we note the importance of earlier morphological evolution in the development of some thrust faults wich slip onto a paleo-erosion surface.

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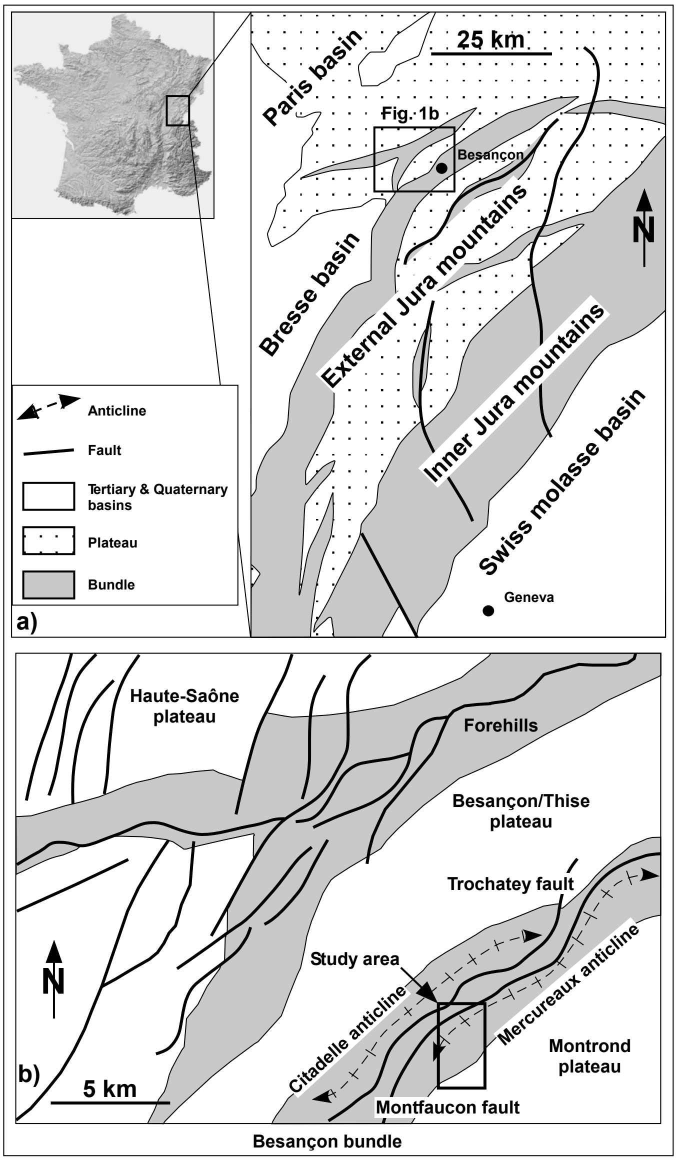

Fig. 1 Location of the study area and strutural map of the Besançon area. a) Strutural map of the Jura mountains around Besançon showing the organization in plateaus and bundles. b) Detailed structural map of the study area showing the main faults and folded structures (adapted from Dreyfuss and Kuntz, 1968).

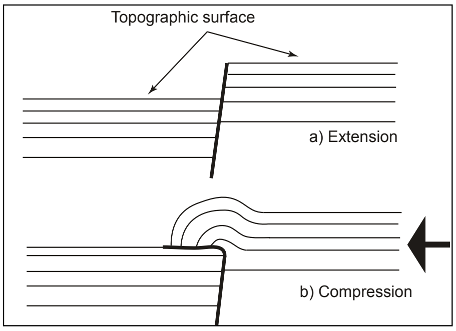

Fig. 2 The kinematics of a "fault-fold" after Glangeaud (1944).

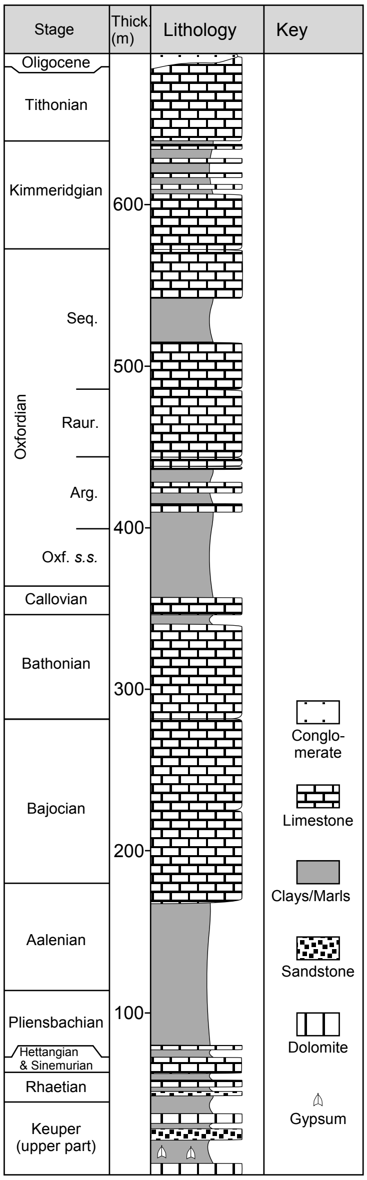

Fig. 3 Synthetic lithologic log of the Besançon area showing the alternation of clays/marls soft levels with hard limestone layers. The main décollement level is located within the upper Keuper layers; Pliensbachian-Aalenian, Oxfordian-Argovian and middle Sequanian layers may serve as secondary décollement levels. Oxf. *s.s.*: Oxfordian *sensu stricto*. Arg.: Argovian. Raur.: Rauracian. Seq.: Sequanian.

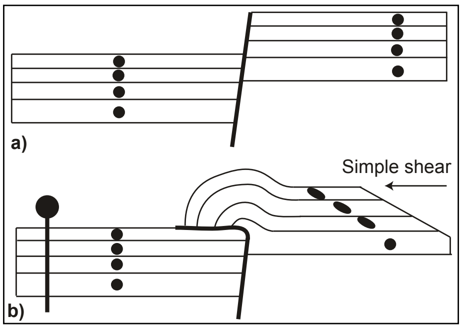

Fig. 4 An attempt to integrate the concept of "fault-fold" in a balanced cross-section. To balance the structure (same as step b on Fig. 2), layers have to be subject to a simple shear which characteristics depend on the inherited fault net slip.

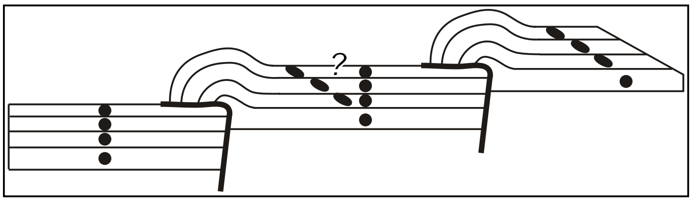

Fig. 5 No-balanced cross-section showing that a "fault-fold" is unable to transmit forward the deformation necessary to the growth of a second "fault-fold". Examination of this diagram shows that the upper part of the central flat can not undergo at the same 1) a moderate shear resulting from the deformation coming from the back and 2) a significant shear necessary to generate the forward (left) structure.

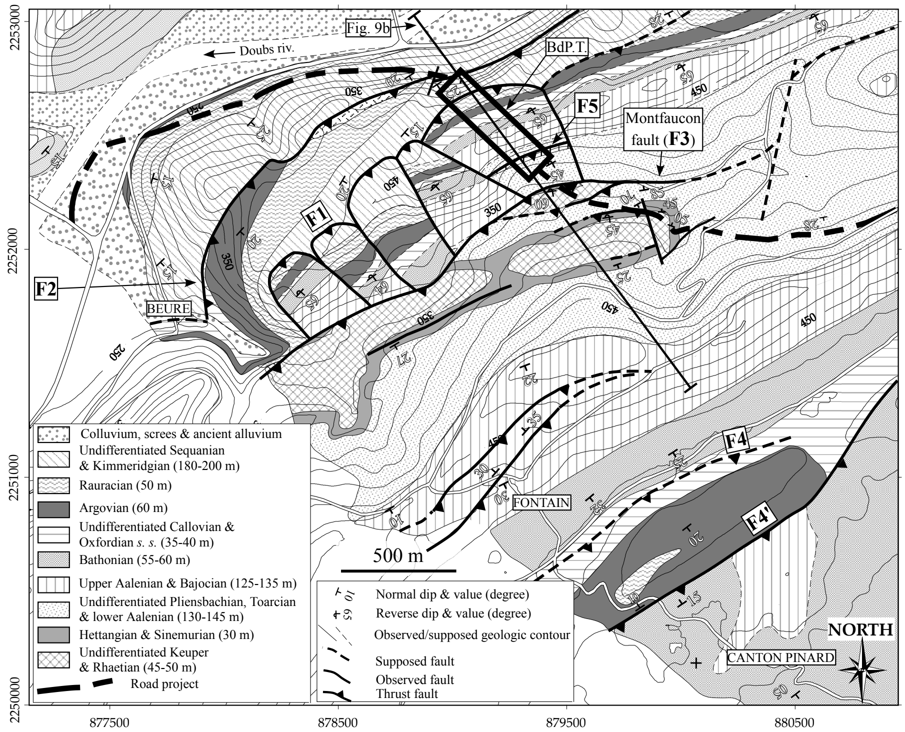

Fig. 6 Geological map of the study area, location of the road works (bold dashed black line) and of the "Bois du Peu" tunnel (black rectangle). Coordinates are metric according to French system Lambert II. BdP.T.: Bois de Peu tunnel and cross-section of figure 7. faults are named after Dreyfuss and Kuntz (1968). F1 to F5: faults. Map adapted from Dreyfuss and Kuntz (1968), Guttierez (2000) and Bièvre (2007).

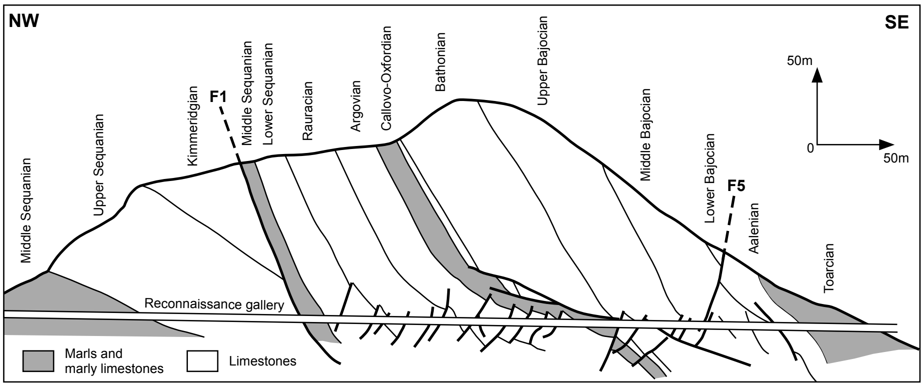

Fig. 7 Geological cross-section of the "Bois du Peu' tunnel. Same label for faults as in Fig. **??**. Modified after CETU (1999).

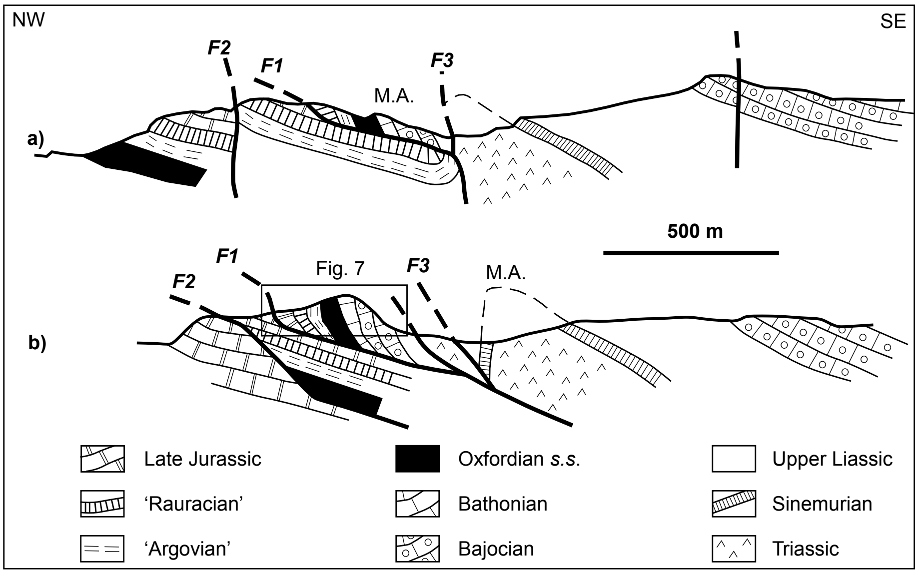

Fig. 8 Cross-sections of the "Bois du Peu" area. a: Interpretation in term of "fault-fold"(after Glangeaud, 1951; Chauve and Perriaux, 1974). Same label for faults as in Fig. **??**. The fault associated to the "fault-fold" structure corresponds to F1 and to the lower part of F3. The uppert part of F3 would be the result of a late reactivation (Dreyfuss in Chauve, 1975, p. 54). b: Proposed interpretation according to new data and balanced cross-sections. See text for details.

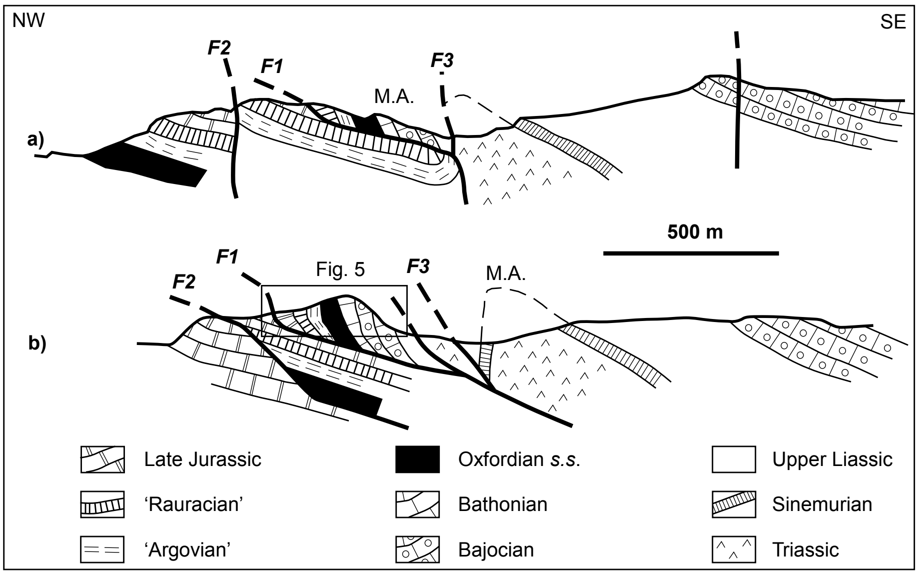

Fig. 9 Kinematic evolution of the Besançon bundle in the study area based on balanced cross-sections and using a forward modelling approach. Same label for faults as in Fig. **??**. M.A.: Mercureaux anticline. BdP.T.S.: "Bois du Peu" thrust sheets. Step a to f: see text for details.