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

Grégory Bièvre, Eric Mercier

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Grégory Bièvre (1,2,*) and Éric Mercier (3)

1. Centre d'Études Techniques de l'Équipement de Lyon, Laboratoire Régional d'Autun, BP 141, 71404 Autun cedex, France.

2. Laboratoire de Géophysique Interne et Tectonophysique, Université de Grenoble, BP 53, 38041 Grenoble cedex 9, France

3. Laboratoire de Planétologie et Géodynamique, Université de Nantes, Géodynamique, CNRS, 2 rue de la Houssinière, BP 92208, 44322 Nantes cedex 3, France.

* Corresponding author (gregory.bievre@equipement.gouv.fr ; Tel: +33-385-86-67-90)

Abstract

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

Keywords: Jura mountains, "fault-fold", décollement tectonics, balanced cross- sections, forward modelling.

28

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 the observed tectonics of the Jura mountains and, more specifically, external Jura. The latter consists of kilometer-wide strips (called bundles) which are densely folded and faulted. Relatively tabular sections (called plateaus) are found on both sides of these bundles, with the topographically higher ones 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 in figure 2. According to him, a pre-existing normal fault (inherited from a previous distension phase) would have elevated the eastern bloc (relative to the western bloc). 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 field-trip to the Jura that took place in 1951, 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. Later authors such as Caire (1963), Chauve and Perriaux (1974), Chauve (1975) then worked on these sections and further detailed them, thus helping to make the "Bois du Peu" area the reference location for the concept of "fault-folding".

The concept of "fault-folding" remained quite popular for a long time in French geological literature. Several reference books applied the concept to the Jura mountains without discussion (Aubouin 1973, Mattauer 1973, Foucault and Raoult 1980, Dercourt et al. 2006). The concept remained dominant for the Jura mountains until at least the end of the 1980s (Chauve 1987).

During the same period, however, the anglophone (in the sense of non-francophone) community completely ignored the fault-fold concept. Since the end of the 1960s, their approach to the tectonics of the external zones has been based on 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-folding". Moreover, Madritsch et al. (2008, 2010) recently proposed that the Besançon zone is affected by

58   thin-skinned tectonics only.

59

60   De facto, even if this concept has never been strongly discussed in the literature, it appears inconsistent with the

61   principle of balanced cross-sections and therefore must be abandoned. Since Glangeaud's work (Glangeaud

62   1951), the "Bois du Peu" area has never been reinterpreted. Geological study and civil engineering works

63   conducted for the Besançon higway by-pass project provide new outcrops and subsurface drillings (corings and

64   tunnels) in the "Bois du Peu" area. This new data provides a good opportunity to re-examine and re-interpret this

65   reference location.

66

67   The aim of this paper is first to re-examine the concept of "fault-fold" and to show why it is inconsistent with the

68   concept of balanced cross-sections. The implications of this on Glangeaud's concept will be re-examined.

69   Secondly, new data concerning the "Bois du Peu" area will be presented. This data allows a new detailed

70   geological map to be created. Finally, it will be proposed that a new fault-related fold model is consistent with

71   field observations.

72

73   2   Geological context of the study area

74   The Jura is an arched moutain belt located NW of the Swiss molasse basin (Fig. 1a). The study zone is located

75   in the outer Jura chain and is mainly made of Jurassic carbonate formations (Fig. 3). These sedimentary strata

76   are arranged in relatively tabular plateaus separated by severely folded and faulted narrow elongated bundles

77   (Fig. 1b). This arrangement is the result of the "multi-phased" tectonic history of the area, where two main phases

78   can be distinguished. The first phase was extensional, with an E-W sense and has an Oligocene age. This

79   resulted in a general westward downstepped blocks geometry which corresponds to the present-day look of the

80   massif. The second phase was compressive, directed towards the NW and is Miocene. The deformation related

81   to the compressive phase was principally located at the boundaries between the plateaus, thus generating

82   bundles, characterized by folds and thrust faults (Glangeaud 1951, Caire 1963, Bergerat et al 1990, Guellec et al

83   1990, Lacombe and Angelier 1993, Martin and Mercier 1996, Homberg et al 1999). Furthermore, the major

84   oligocene-inherited meridian faults induced a leftward strike-slip motion which allowed the panels to slide.

85   According to palaemoagnetic recordings, this translation movement did not induce significant rotation of the

86   structures (Gehring et al 1991).

87

88　The Besançon bundle constitues one of the narrow strips. In the study area, this bundle is oriented SW-NE and

89　is about 4 km wide. It is bounded by the Besançon/Thise plateau to the NW and by the topographically higher

90　Montrond plateau to the SE (Fig. 1b). At the outcrop, this bundle is made of two parallel antinclines. To the NW,

91　the Citadel anticline shows a symetric or slightly SE overturned geometry. To the SE, the Mercureaux anticline is

92　strongly dyssimetric and overturned towards the NW (Fig. 1b). It is the Mercureaux anticline, along with its

93　associated Montfaucon fault (Dreyfuss and Kuntz 1968), which have been interpreted as one of the best

94　examples for the "Fault-fold" structure by Glangeaud (1951).

95

96　The local geological series consists of alternating soft (clay and marls) and hard levels (limestones, dolomites

97　and sandstones) and is shown in figure 3. The main decollement level is located within the Triassic gypsum-rich

98　strata. Secondary decollement levels may be found within soft Jurassic strata (Fig. 3): Pliensbachian-Aalenian,

99　Oxfordian sensu stricto-Argovian and middle Sequanian. Regional sub-stages denominations (Dreyfuss and

100　Kuntz 1968) have been kept to distinguish between the mechanically variable strata.

101

102　The Besançon highway by-pass (Maurin 2001, Bièvre 2007) crosses the Mercureaux anticline in the "Bois du

103　Peu" area. The geological complexity of the site lead to dense prospectings: several kilometers of boreholes, and

104　logging (gamma-ray, microseismics, digital camera) as well as mechanical in situ and laboratoray tests.

105　Furthermore, a reconnaissance gallery has been drilled that crosses the base of one of the bundles. The

106　integration of these new data allow to detail the orientation and dip of faults as well as the lithology of the bedrock

107　underlying the top-soil layer, especially along the Mercureaux anticline axis (Fig. 1b) made of soft clayey and

108　marly formations. The data allows the construction of a detailed geological map of the area as well as an original

109　synthetic cross-section of the bundle which was crossed by the reconnaissance gallery.

110

111　3 The concept of "fault-fold" in the light of balanced cross-sections theory

112　The theory of balanced cross-sections is based on the assumption that thanks to the law of conservation of

113　matter, the amount of material remains constant during tectonic deformations. In faults and folds belts, it is often

114　possible to work on cross-sections (see complete discussion in Marshak and Woodward (1988) for example)

115　and, in this way, to transform the law of conservation of matter into a law of conservation of surfaces (i.e. during

116　deformation, the surface of each bed remains constant). To verify this conservation, it is necessary to set

117　boundaries on the system studied and, consequently, to discuss the conditions of these boundaries.

118

119 Figure 4 shows that surface conservation requires that, during the growth of a "fault-fold", the boundaries of the

120 system undergo differential simple shear. This diagram shows that only the upper layers of the upper block suffer

121 simple shear during horizontal shortening. More specifically, only the beds which are in elevation over the top of

122 lower block after the first deformation (normal fault) suffer simple shear. This is problematic because, obviously,

123 the boundary conditions are controled by rear area deformation conditions and not by internal parameters

124 (normal fault offset) as the figure might falsely imply.

125 Furthermore, Figure 5 shows that the deformations are amortized into the structure and are not transfered

126 forward from one block to another. Accordingly, this model fails to explain the succession of several "fault-fold"

127 strutures on a unique cross-section as is the case in the Jura (Chauve 1987).

128

129 A high proportion of authors who recently worked on the Jura (see above), appear to have abandoned the

130 concept of "fault-fold". None of these authors have justified this abandonment however, and the concept of fault-

131 folding therefore goes unmentioned. We have shown that the concept of "fault-folding" is incompatible with the

132 theory of balanced cross-sections, this incoherence being the reason for the abandonement. The "Bois de Peu

133 "area, the reference location for the concept of "fault-folding", therefore has to be explained otherwise. The

134 following sections show that it is possible to reinterpret this structure using the concepts of "fold and fault-belts"

135 tectonics.

136

137 4 Results

138 4.1 Geological field data

139 Surveys conducted for the highway by-pass study provided a large amount of geological data (Maurin 2001,

140 Bièvre 2007). Combined with detailed field observations, these data allow us to produce a new geological map

141 based on a previously established one (Dreyfuss and Kuntz 1968). There is no fundamental change between the

142 two maps, but the one that is proposed here is much more detailed (Fig. 6) due to new available data. In

143 combination with these field observations, a reconnaisance gallery was drilled through the base of one of the

144 "Bois du Peu" thrust sheets and an interpretative cross-section was built (Fig. 7; modified from CETU 1999).

145

146 The proposed cross-section for this work is located one km SW of the reference location. The geological map

147 reveals that fault F2 dips towards the SE (as it has been revealed by corings and gamma-ray logging; Maurin

148   2001). Fault breccia was found in corings conducted along the road project to define the dip of F3 (Bièvre 2007).

149   Along with the gamma-ray logging in surrounding drillings, this reveals that the F3 fault (Montfaucon fault of

150   Dreyfuss and Kuntz 1968) slighlty dips towards the SE (Fig. 6). These two faults were previsously considered to

151   be subvertical (Fig. 8a; Glangeaud 1951, Caire 1963, Chauve and Perriaux 1974, Chauve 1975). Moreover, the

152   Mercureaux anticline axis is located a few hundred metres SE of F3 (Fig. 6; Bièvre, 2007). These two initial

153   observations are inconsistent with the "fault-fold" interpretation of the area ".

154

155   A vast outcrop composed of Triassic strata is present in contact with F3 along the road project, 200 m SE of the

156   tunnel (location on Fig. 6). This Triassic outcrop is bordered by Pliensbachian strata (Belemnites as well as

157   Ammonite Amaltheus margaritatus were found in corings). Associated with the presence of fault breccia,

158   cartography and orientations of dips, these elements allow this Triassic outcrop to be considered as a tectonic

159   flake forced against the Montfaucon fault (F3). The presence of such a flake constitutes an important argument to

160   interpret F3 like a thrust fault seated within Triassic strata (Fig. 8b).

161

162   The hinge and inverted limb, situated NW of the Mercureaux anticline overthrust the very competent Jurassic

163   beds. In first approximation, despite some irregularities (Fig. 7 and Fig. 8), this thrust is parallel to the autochton

164   stratification. Previous authors had considered implicitly (compare Fig. 3 and Fig. 8a) or explicitly that the thrust

165   surface was the Pontian topographic surface (surface of "Montrond"; Dreyfuss and Glangeaud 1950). This

166   hypothesis is discussed further in section XXX.

167

168   Thrust F1 is not the only one to be locally parallel with the stratification. For example, thrust F2 is, from NW to

169   SE, successively sub-parallel, oblique and again sub-parallel with the stratification(Fig. 8b). These particular

170   relations refer to the ramp geometry. This observation, along with previous works on other bundles in the Jura

171   (Endignoux and Mugnier 1990, Zoetemeijer and Sassi 1992, Martin and Mercier 1996, Meyer 2000), lead us to

172   propose a kinematic scheme characterized by the development of folds-related ramps for the "Bois de Peu" area.

173

174   4.2 Kinematic modelling

175   Cross-section balancing has become a standard method for testing viability and admissibility of hypothetical

176   deep geometry. Many theoretical and applied works have focused on this method in thrust and fold belts. Several

177   approaches have been developed but, according to most of the authors, in the Jura, the "forward" method is the

178 most appropriate (Endignoux and Mugnier 1990, Zoetemeijer and Sassi 1992, Martin and Mercier 1996).

179 Martin and Mercier (1996) proposed a comprehensive discussion on the application of this method to a bundle of

180 the Jura. To summarise, this method provides a viable and admissible kinematic pathway between an initial state

181 (undeformed) and a final state (deformed). The need to respect the law of conservation of matter (1) between

182 initial stage and final stage, and (2) between each kinematic step, strongly limits the number of possible

183 solutions.

184

185 In practice, a trial and error process was used to build an image of the finite deformation which is consistent with

186 field data. With this kind of problem solving process, there is a risk of neglecting alternative solutions. Hence,

187 many tests were carried out to assess the influence of changes in calibration parameters.

188

189 In this study, we chose to work on an "average" cross-section. This section can be considered as representative

190 of the whole area, and allows the elimination of local variations that can not be taken into account by modelling.

191 The numerical solution is shown in figure 9.

192

193 Steps a, b and c: a "fault-propagation fold" (in the sense of Suppe 1985) gradually grows over a ramp deeply-

194 seated in a decollement level located at the top of the Triassic strata. It has long been known (e.g. Glangeaud

195 1951, Caire 1963) that the Jura bundles are the result of the superposition of an Oligocene tectonic distension

196 and a Miocene tectonic compression. Previous modelling works (Martin and Mercier 1996) showed that in the

197 bundle, ramp initiation occurs systematically at the intersection between a decollement level and inherited normal

198 faults. Surprisingly, there are no arguments in these works to link the initiation of the ramp with a normal fault.

199

200 Step d: the fault-propagation fold suffers a standard late evolution: transport on the flat (Mercier 1992; Mercier

201 et al 1997). Usually, such evolution occurs when the ramp can no longer propagate upwards (when the ramp

202 crosses very competent beds, for example), and seeps into an interbed level. It does not seem to be the case

203 here, the very competent Jurassic series is already crossed and the Cretaceous series, thin and weakly

204 competent, can not stop the propagation of the ramp. The simplest is to assume that the allochton slept upon the

205 paleo-surface topography ("Montrond" surface; Dreyfuss and Glangeaud 1950).

206

207 Step e: The transport on the flat becomes increasingly difficult (friction increasing, blocking on local micro-

208 topography) and the mechanical conditions in autochton change because of the tectonic overload. A new thrust

209 plane is established.

210 The movement over this thrust creates a duplex which is transported under the fold. Modeling suggests that this

211 duplex is deep-seated in a secondary detachment level in the Oxfordian-Argovian strata. This hypothesis is fully

212 consistent with mechanical properties of these levels (Fig. 3) and field data (Fig. 6).

213

214 Step f: After a significant displacement, this new thrust is blocked in turn. Out-of-sequence thrusts occur from the

215 existing ramps and through weakened areas of the structure (Mercier and Mansy 1995). The northern out-of-

216 sequence fault corresponds to the "forelimb breakthrough" of fault-propagation folds (Mercier 1992). It isolates,

217 between F1 and F3, a small thrust sheet with reverse polarity. We suggest that this thrust sheet is torn into

218 several elements that are more or less carried forward in reponse to the movement of the allochton.

219 Finally, synchronically or not, growth of the Citadel anticline, located just NW of the section studied, affects the

220 whole structure which is partly integrated into its SE limb. The final bending is not really taken into account by our

221 modeling. The surface topography drawn in figure 9f is distorted from reality, but this adjustment imprecision

222 does not affect the principle and the conclusions of our model. In fact, it only introduces an uncertainty on the

223 geometric modeling of the out-of-sequence faults F4 and F4'.

224

225 The total shortening, of about 50 % (4 km), is significantly higher than what was calculated on the sections

226 located further north accross the same bundle (Martin and Mercier 1996). This difference suggests small

227 rotations of the plateaus during deformation.

228

229 5 Discussion and conclusions

230 Major geological reconnaissance for the Besançon by-pass took place in the reference location for the concept of

231 "fault-folding" ("Bois du Peu" area; Glangeaud 1951). It provides firstly an opportunity to discuss this concept of

232 "fault-folding", and to show its incompatibility with the theory of balanced cross-sections. Secondly, it allows us to

233 propose a new structural evolution for this area (Fig. 8b and Fig. 9).

234

235 We show that available field data are consistent with a typical scenario of folds and thrust belt evolution,

236 particularly characterized by the growth and evolution of fault-related folds deeply seated within Triassic strata.

237 This is very similar to scenarios already proposed for other Jura bundles (e.g. Guellec et al 1990, Martin and

238 Mercier 1996, Meyer 2000). In particular, we note the combination of various folding modes (fault-related folds
239 with late evolution, duplex, etc.) in the same sector. This work, among many others, confirms the utility of the
240 "forward" method in the study of the Jura tectonics. However, without syntectonic sedimentary markers, the
241 sequence of deformation proposed remains, in the study case as elsewhere, poorly constrained. In the study
242 area, the shortening is about 50% which is higher than what is known in other bundles. Finally, we note the
243 importance of earlier morphological evolution in the development of some thrust faults wich slip onto a paleo-
244 erosion surface.

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249 6 References

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320

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322

323   Figure 1: Location of the study area and strutural map of the Besançon area. a) Strutural map of the Jura

324   mountains around Besançon showing the organization in plateaus and bundles (simplified from Madritsch et al.

325   2008). b) Detailed structural map of the study area (location on Fig. 1a) showing the main faults and folded

326   structures (adapted from Dreyfuss and Kuntz 1968). CA: Citadelle anticline; MA: Mercureaux anticline; MF:

327   Mercureaux fault; TF: Trochatey fault.

328

329   Figure 2: The kinematics of a "fault-fold" according to Glangeaud (1944).

330

331   Figure 3: Synthetic lithologic log of the Besançon area showing the alternation of clays/marls soft levels with hard

332   limestone layers. The main decollement level is located within the upper Keuper layers; Pliensbachian-Aalenian,

333   Oxfordian-Argovian and middle Sequanian layers may serve as secondary décollement levels. Oxf. s.s.:

334   Oxfordian sensu stricto. Arg.: Argovian. Raur.: Rauracian. Seq.: Sequanian.

335

336   Figure 4: An attempt to integrate the concept of "fault-fold" in a balanced cross-section. To balance the structure

337   (same as step b on Fig. 2), layers have to be subject to a simple shear whose characteristics depend on the

338   inherited fault net slip.

339

340   Figure 5: Non-balanced cross-section showing that a "fault-fold" is unable to transmit forward the deformation

341   necessary to the growth of a second "fault-fold". Examination of this diagram shows that the upper part of the

342   central flat can not undergo at the same 1) a moderate shear resulting from the deformation coming from the

343   back and 2) a significant shear necessary to generate the forward (left) structure.

344

345   Figure 6: Geological map of the study area, location of the road works (bold dashed black line) and of the "Bois

346   du Peu" tunnel (black rectangle). Coordinates are metric according to the French Lambert II system. BdP.T.: Bois

347   de Peu tunnel and cross-section of figure 7. faults are named after Dreyfuss and Kuntz (1968). F1 to F5: faults.

348   Map adapted from Dreyfuss and Kuntz (1968) and Bièvre (2007).

349

350   Figure 7: Geological cross-section of the "Bois du Peu' tunnel. Faults are labelled in the same manner as in

351   Fig. 6. Modified from CETU (1999).

352

353   Figure 8: Cross-sections of the "Bois du Peu" area. a: Interpretation in terms of a "fault-fold" (according to

354   Glangeaud 1951, Chauve and Perriaux 1974). Faults are labelled in the same manner as in Fig. 6. The fault

355   associated to the "fault-fold" structure corresponds to F1 and to the lower part of F3. The uppert part of F3 would

356   be the result of a late reactivation Chauve (1975). b: Proposed interpretation according to new data and balanced

357   cross-sections. Position of Figure 7 is indicated. See text for details.

358

359   Figure 9: Kinematic evolution of the Besançon bundle in the study area based on balanced cross-sections and

360   using a forward modelling approach. Faults are labelled in the same manner as in Fig. 6. M.A.: Mercureaux

361   anticline. BdP.T.S.: "Bois du Peu" thrust sheets. Step a to f: see text for details.
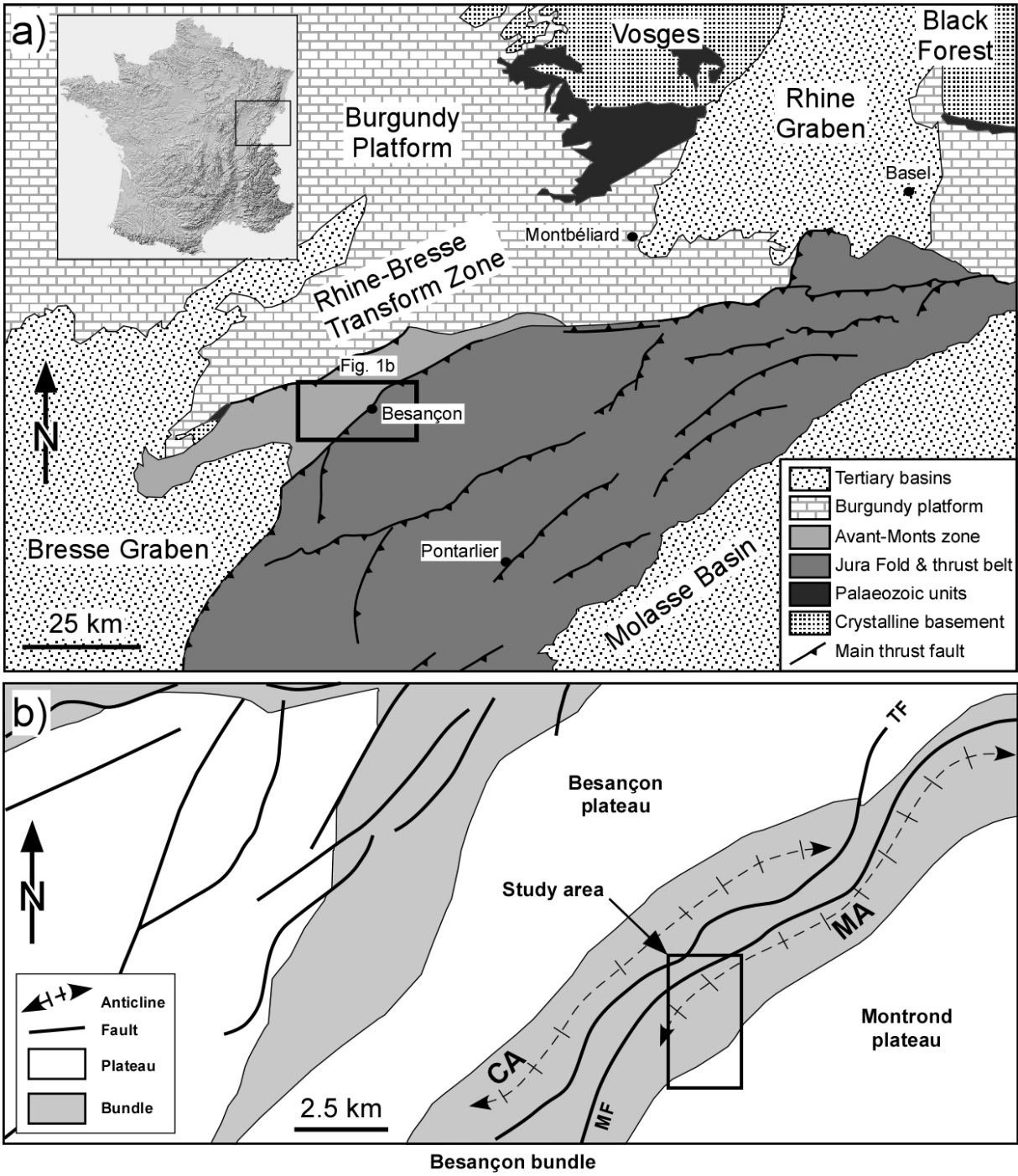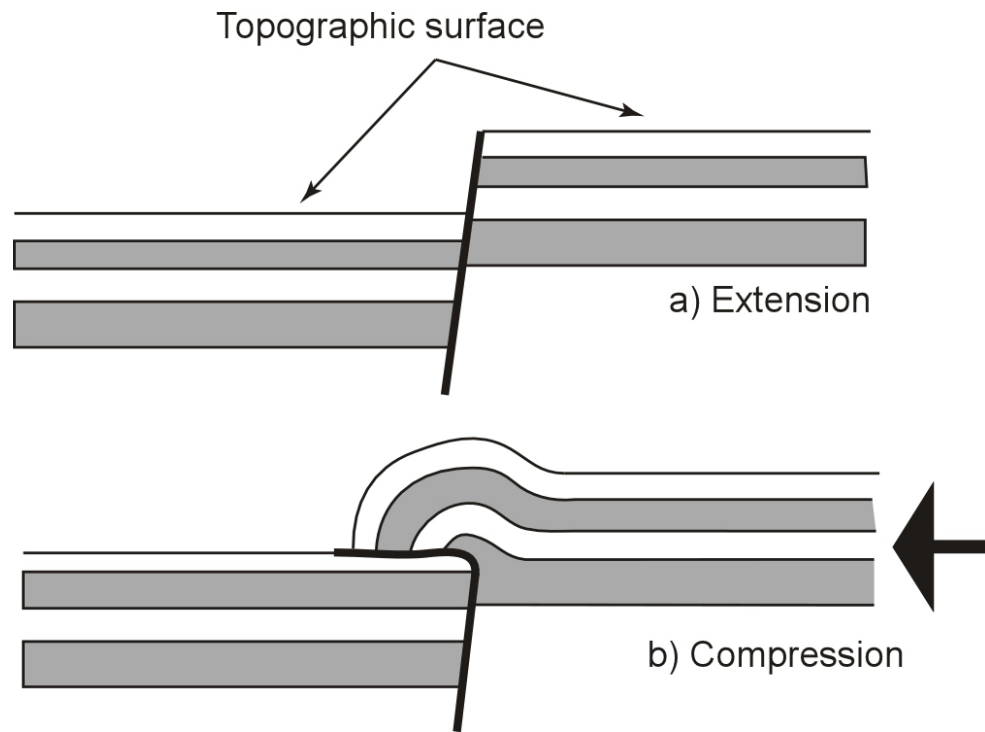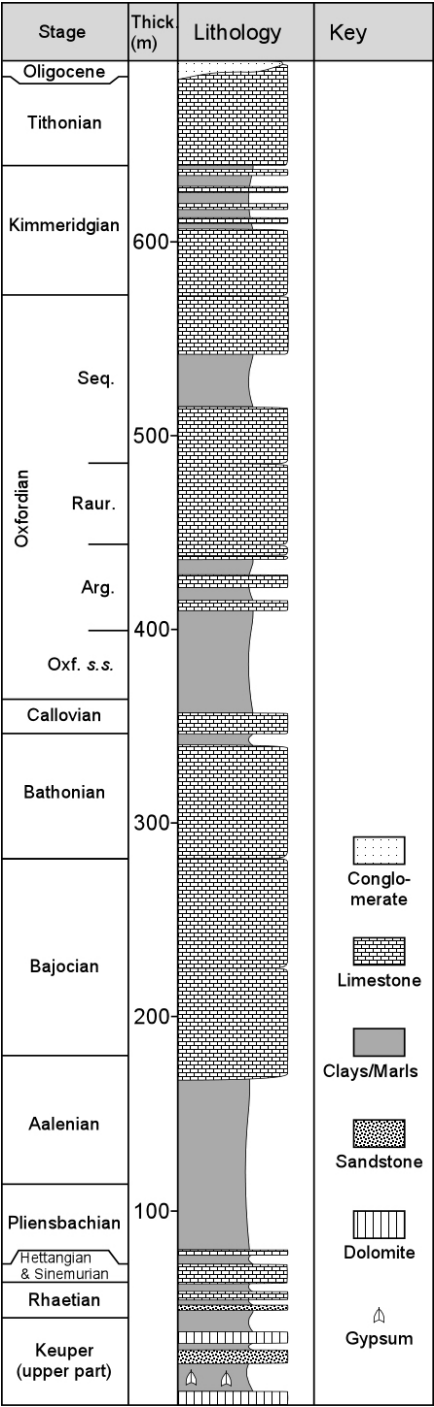
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365
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367
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Figure 1

1

Topographic surface

a) Extension

b) Compression

Figure 2

Stage	Thick (m)	Lithology	Key

Oligocene
Tithonian
Kimmeridgian
Oxfordian
Seq.
Raur.
Arg.
Oxf. *s.s.*
Callovian
Bathonian
Bajocian
Aalenian
Pliensbachian
Hettangian & Sinemurian
Rhaetian
Keuper (upper part)

Conglo-merate
Limestone
Clays/Marls
Sandstone
Dolomite
Gypsum

Figure 3

379

a)

Simple shear

b)

380
381
382
Figure 4
383
384
385
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?

388
389
Figure 5
390
391
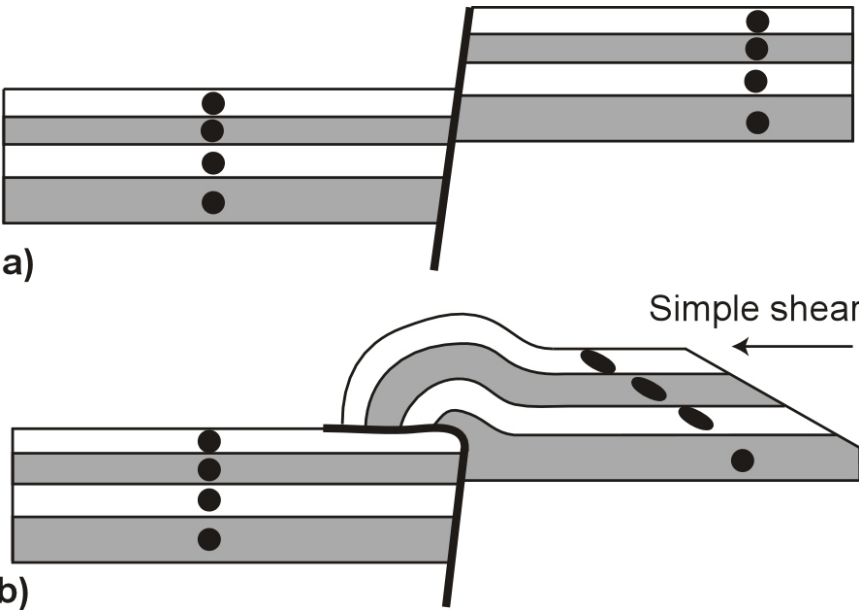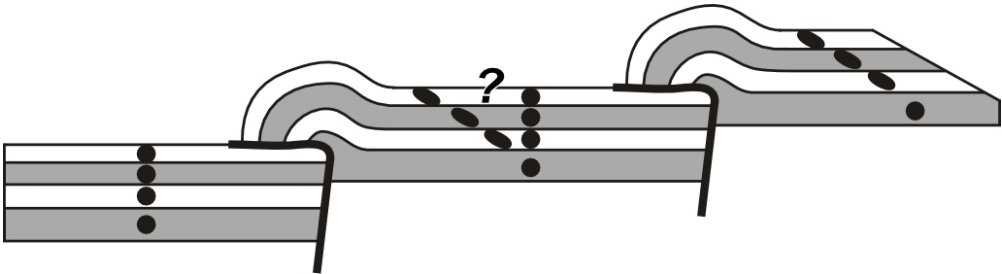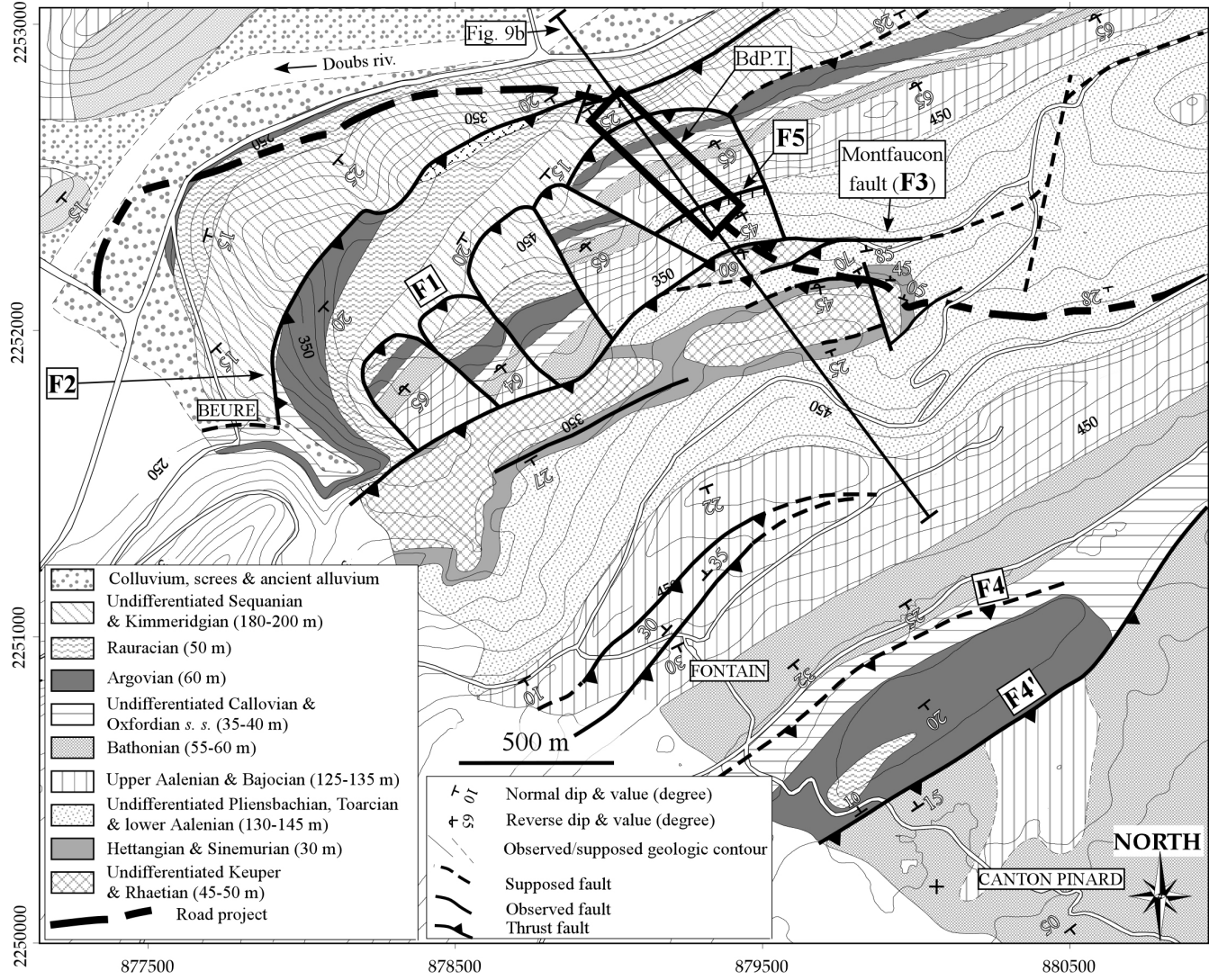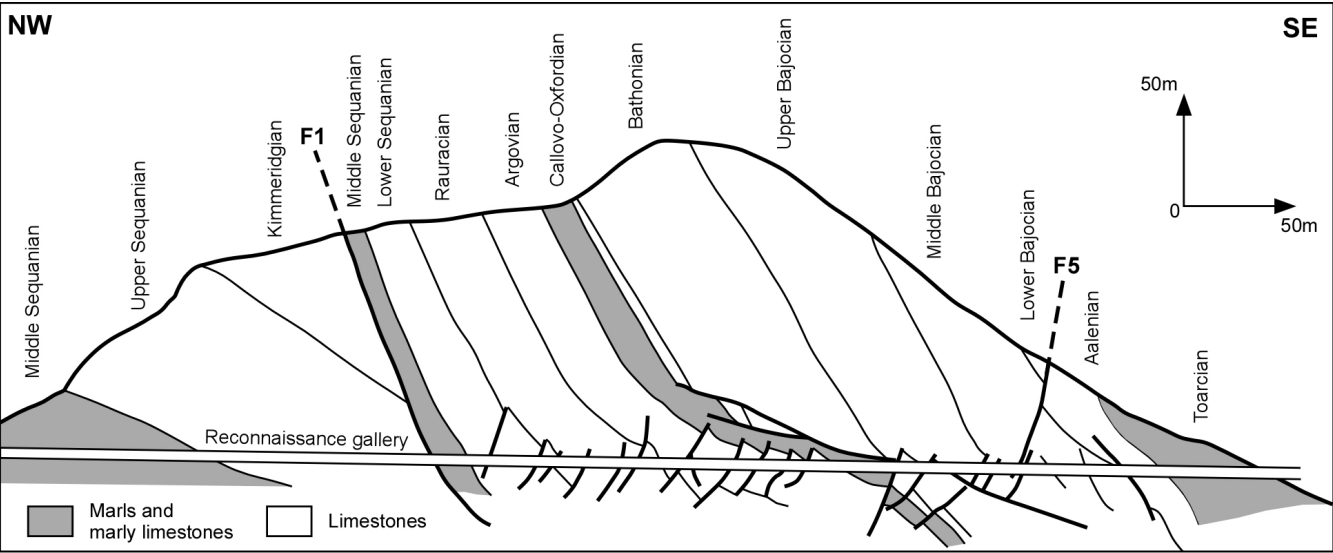
Figure 6

Figure 7

398
399
400
401
402
403

Figure 8

409

North　　　　　　　　　　　　　　　　　　　South

1)

2)

3)

4)

1 km

5)

Kimmeridgian & 'Sequanian'
'Rauracian'
'Argovian'
Oxfordian *s.s.* & Callovian
Bathonian
Upper and Lower Bajocian

Upper Aalenian
Lower Aalenian, Toarcian
& Pliensbachian
Sinemurian
Hettangian and Rhaetian
Upper Keupper

M.A.

F1
F3
F2
F4
F4'

6)

Present-day
topography

BdP. T.S.

410
411
412
413

Figure 9

2