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Kinematic models of deformation at the front of the Alps: new data from map-view restoration

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Key words: kinematics, deformation, Alps, Subalpine, map-view, restoration

ABSTRACT

Map-view restoration of the frontal part of the French Alps was done in order to test two hypotheses about the propagation of deformation. We discussed two models of the 'rooting' of the Jura-Molasse basal detachment either along basement thrusts beneath the External Basement Massifs (EBM-rooting model) or along basal thrusts of the Subalpine Chains above the External Basement Massifs (SAC-rooting model). The different sequences of deformation are described for the two models with their kinematics and geochronological constraints. The geochronological data available on the uplift timing of the External Basement Massif are then discussed. Due to their range of uncertainty, geochronological data on the exhumation of the External Basement Massifs are not decisive to discriminate between the two models. Using either the maximum or the minimum age in the range of their uncertainty allows fitting the timing constraints of both models. Interpretation of map-view restoration reveals a weakness of the EBM-rooting model linked to the fact that a sharp virgation is predicted between the two main cross sections. This does not discard this model as such virgation may be linked to paleostratigraphic or tectonic effects but this must be taken into account when using this model. Structural data are also discussed as field geology on the mechanism of uplifting of the external basement massif or geophysical data as deep seismic lines shot in the frame of the ECORS and NRP20 research programs. Such data favor one or the other model without discarding one of them. We conclude that, with the available data, both models seem possible and that the less popular one (SAC-rooting model) shows the more coherent restoration field, the reason why we favor it at the present time.

1. Introduction

Understanding the propagation of deformation in an orogen on a geological time scale is a major challenge for geoscientists. Geometrical relationships between tectonic units and data on the timing of deformation can be used to determine the kinematics of deformation. In most cases however, chronological data are sparse and do not provide decisive information. Similarly, the regional study of structures can lead to different interpretations about the kinematic relationship between tectonic units. This is particularly the case in compressive settings where deformation may propagate along blind thrusts, i.e. thrusts that do not break to the surface. In the core of mountain belts, it is not unusual that several blind thrusts occur at different structural levels. The lack of subsurface data often makes it difficult to determine the kinematic link between the different tectonic units. In this context, the restoration of geological structures Dahlstrom (1969) allows one to quantify deformations and test the strain compatibility between tectonic units, including blind thrusts. Most of the time however, it appears that a cross-section may lead to several models of deformation respecting balancing criteria. Whereas the balancing of a single cross-section usually does not bring enough constraints to determine the propagation of deformation, map-view restorations can bring some compelling evidence to determine the kinematic links between tectonic units. Map-view restorations imply that deformation be consistent along the strike of an orogen and thereby allow to rule out some hypotheses that could be considered viable in cross-section (Laubscher 1988) or at least it allows to point out a weakness of a model and to trigger new studies. Since the displacement accommodated by tectonic units is not uniform along-strike, displacement transfers from one tectonic unit to another should vary accordingly along-strike and be an indication of a kinematic link between

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these units. Thus, map-view restorations are an efficient tool to check hypotheses about the propagation of deformation in complex tectonic settings.

Map-view restoration of the frontal part of the French Alps was made in order to test two hypotheses about the kinematics of deformation in this orogen. The Alpine deformation front is formed by two main thrust systems: the Jura arcuate fold-thrust belt and the Molasse thrust. The Jura is a typical fold-thrust belt, which formed by the decoupling of a 2 km thick sedimentary cover above highly ductile Triassic salt layers. From a geodynamic point of view, the Jura basal detachment level must be connected to a blind thrust buried beneath a foredeep clastic basin and beneath klippen that were transported passively, piggy-back, in the hangingwall of the Jura floor thrust (see below, geological setting). Similarly, the Molasse tectonic unit must be connected to a blind thrust hidden beneath the molasse fill and the klippen. At the rear of these units, two Alpine tectonic units could be linked to their displacement: the crystalline basement mega-anticlines, called External Basement Massifs, or the Subalpine Chains early detached above these basement massifs. In the present paper, we discuss two hypotheses of the 'rooting' of the Jura-Molasse basal detachment either along basement thrusts beneath the External Basement Massifs or along basal thrusts of the Subalpine Chains above the External Basement Massifs.

2. Geological setting

2.1. Tectonic units

The External Alps (Fig. 1) are divided into deformational domains according to their position on the European passive margin before deformation set in. During the Alpine orogeny, this continental margin was involved in a collision with exotic terranes between the European plate and the Adria microplate. These exotic terranes, known as Penninic units, form the Internal Alps. The boundary between the Penninic nappes and the deformational domains derived from the European margin is known as the 'basal Penninic thrust' (Fig. 2.1). The basal Penninic thrust was later folded when deformation of the European margin set in and Penninic units are now found in the hangingwall of the Subalpine Chains fold-thrust belt. The present paper deals with the tectonics of the External Alps, i.e. the tectonic units found in the footwall of the Penninic units. Below the basal Penninic thrust, the External Alps are made up of five main units shown in figure 1: 1) the Ultrahelvetic nappes (these nappes are not differentiated from Penninic units on figures), 2) the Subalpine Chains, 3) the Molasse, 4) the Jura belt and 5) the External Basement Massifs.

1) The *Ultrahelvetic nappes* thrust system (Fig. 1) involved the outermost part of the European margin when collision set in. The tectonics of the Ultrahelvetic nappes is not important in the following discussion and therefore they are not differentiated from Penninic units inside the Prealpine units on figures and maps.

2) The *Subalpine Chains* thrust system (Fig. 1) forms a markedly arcuate structure in map view. On figure 1, the Subalpine Chains arc structure is evidenced by hinge point tie-lines according to Ramsay (1989) and by fold axes drawn from Gidon (1996). The deformation front of this thrust system is formed by cylindrical folds, which can be followed for tens of kilometers without significant strike-slip offset or transfer zone. In the Subalpine Chains domain, the basal detachment of the cover occurs in Liassic marls. Inside the cover, thick Valanginian marls acted as a secondary décollement horizon, decoupling strains across this level (Ferrill & Groshong 1993). Above the Valanginian detachment, the fold geometry is ruled by lower Cretaceous 'Urgonian' limestones more than 300 m thick in some places, whereas below it, Tithonian limestones play this role. Before collision, the Subalpine Chains depositional domain consisted of a set of tilted blocks forming small basins separated by basement highs at the top of tilted blocks (Gillchrist et al. 1987; Lemoine et al. 1987; Lemoine & Trümpy 1987). Normal faulting was active mainly during Liassic times and was responsible for large variations in the thickness of these deposits. Although the best records of this extensional geometry occur in the southwestern Alps (Taillefer, Rochail massifs, etc), Barféty & Gidon (1984), the same configuration is believed to have existed in the Subalpine Chains depositional area (Gillchrist et al. 1987; Lemoine et al. 1987; Lemoine & Trümpy 1987). Evidence for this mainly relies on stratigraphic observations showing large variations of sediment thicknesses across what is believed to be tilted blocks. It is generally recognized that the main stage of folding within the Subalpine Chains took place in Oligocene to Early Miocene times (Doudoux et al. 1982; Pfiffner 1986; Burkhard 1988). For more details on the broad geological setting of the Subalpine Chains, the reader is referred to Collet (1943), Pairis (1975), Pairis & Pairis (1978) and Ramsay (1981).

3) The *Molasse* tectonic unit is the internal, deformed part of a foreland basin siliciclastic wedge, which developed at the Alpine deformation front from Late Cretaceous to Upper Miocene (Fig. 1). The Molasse thrusts consist of closely imbricated thrust slices. At depth, it is not known if these thrusts are linked to the Subalpine Chains basal thrust or to deeper ramps in the crust. The timing of deformation within the Molasse is difficult to determine. It is generally accepted that deformation in the innermost part of the Molasse started in Oligocene times and reached the outermost Molasse thrusts in the Middle Miocene (Homewood et al. 1986).

4) The *Jura thrust system*, which involves 2 km-thick carbonate series detached above a basal décollement in Triassic evaporites, is found at the front of the Plateau Molasse. On figure 1, the Jura is represented by a three-dimensional model (Affolter & Gratier 2004). The arcuate structure of the Jura fold-thrust belt is mainly due to the shape of the salt basin which enabled the decoupling of the post-Triassic sedimentary cover (Lienhardt 1984; Affolter & Gratier 2004). At the front of the Jura, the Bresse Graben (Fig. 1) results from an essentially Oligocene extensional phase. The stepping-out of the deformation front from the Molasse thrust to the Jura belt is believed

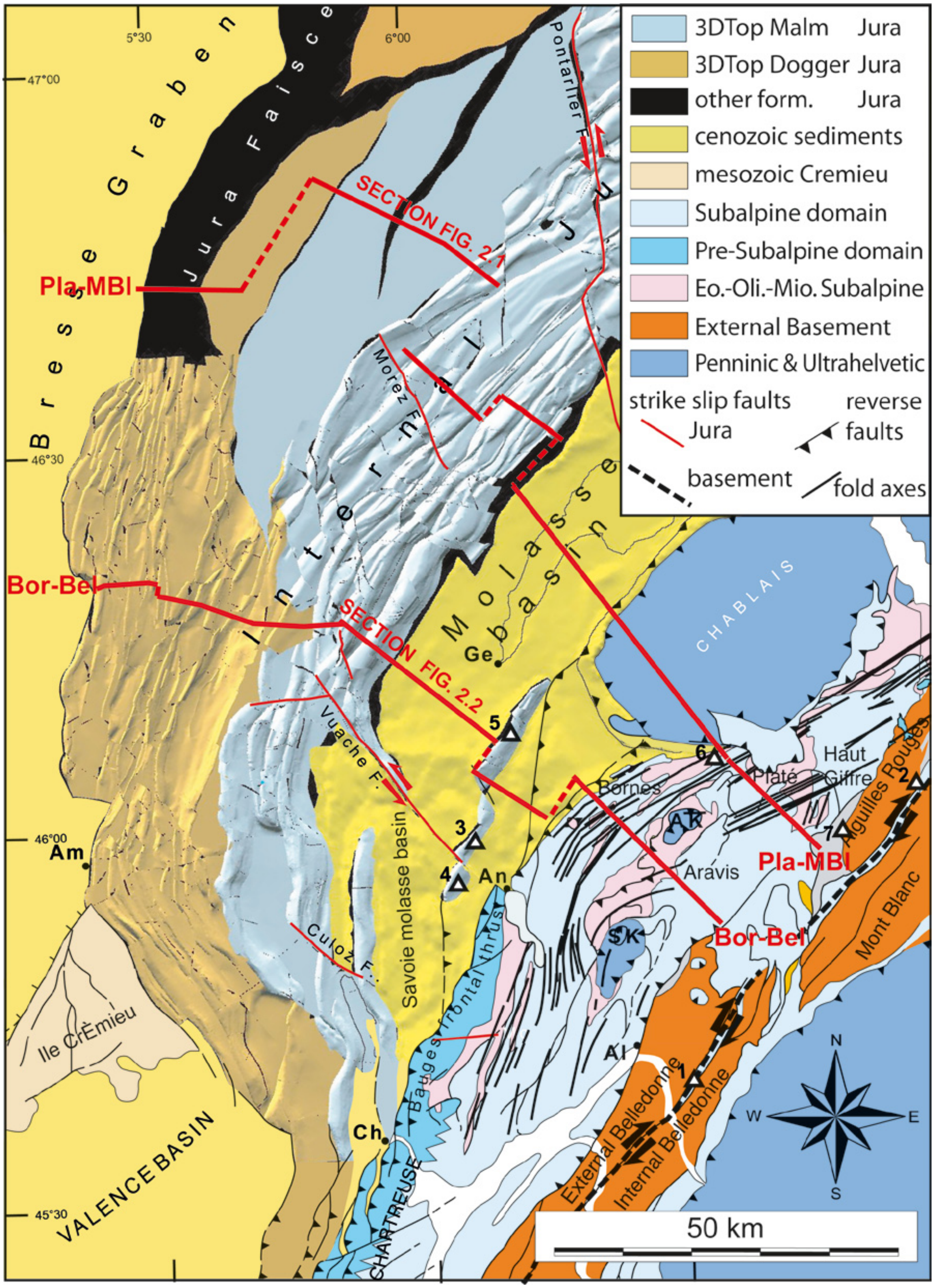


Fig 1. Tectonic map of the area of study. Structures in the Jura are shown by a three-dimensional model built for a geological target horizon [Affolter & Gratier, 2004]. The GTOPO30 digital elevation model (USGS) was used to represent the Molasse foreland basin. The location of cross-sections of figures 2.1, 2.2 is represented by thick red lines. Anticlines, synclines and a specific outcrop are represented as white triangles with specific numbers: 1. Belledonne Median syncline, 2. Chamonix syncline, 3. Mandallaz anticline, 4. Montagne d'Age anticline, 5. Salève anticline; 6. Cluses anticline, 7. Pormenaz outcrop.

to have occurred in Middle Miocene (Homewood et al. 1986; Burkhard & Sommaruga 1998,). It is now widely accepted that the Molasse basin was transported passively in the hanging-wall of the Jura basal detachment level during Jura deformations. This is consistent with the fact that the Triassic salt basin extends beneath both the Jura and the Molasse basin. In this case, the Jura detachment level must be connected to a blind thrust beneath the Molasse fill (Buxtorf 1916; Laubscher 1961; Burkhard 1990; Affolter & Gratier 2004). The late deformations of the Molasse must have been coeval with folding and thrusting within the Jura. It follows that the Jura and Molasse thrusts can be treated as a single tectonic unit, the Jura-Molasse thrusts system and that they must be connected to a common blind thrust within the Alpine orogen.

5) The *External Basement Massifs* tectonic unit (Aiguilles-Rouges, Mont-Blanc, External and Internal Belledonne massifs in the area of study) forms the most prominent tectonic feature in the French External Alps. These crystalline mega-anticlines form a structural relief of some 10 km above the regional trend of the European foreland basement (Fig. 1, 2, and 4). The results of the deep seismic profiles shot in Switzerland (Pfiffner et al. 1997a) have shown that the Moho of the European foreland is continuous beneath the External Basement Massifs, implying that these latter structures result from a thickening of the crust. The deformation mechanism, which has led to this thickening, remains a matter of debate. Different models of deformation have been proposed which can be grouped into two categories. The first group interprets the External Basement Massifs as basement imbricates or fault-bend folds formed above one or several ramps in the upper crust and transferring a significant displacement towards the Jura and/or the Molasse (Buxtorf 1916; Boyer & Elliott 1982; Burkhard 1990; Mugnier et al. 1990; Laubscher 1992 Pfiffner et al. 1997b). The second model of deformation suggests that the

Fig. 2.1

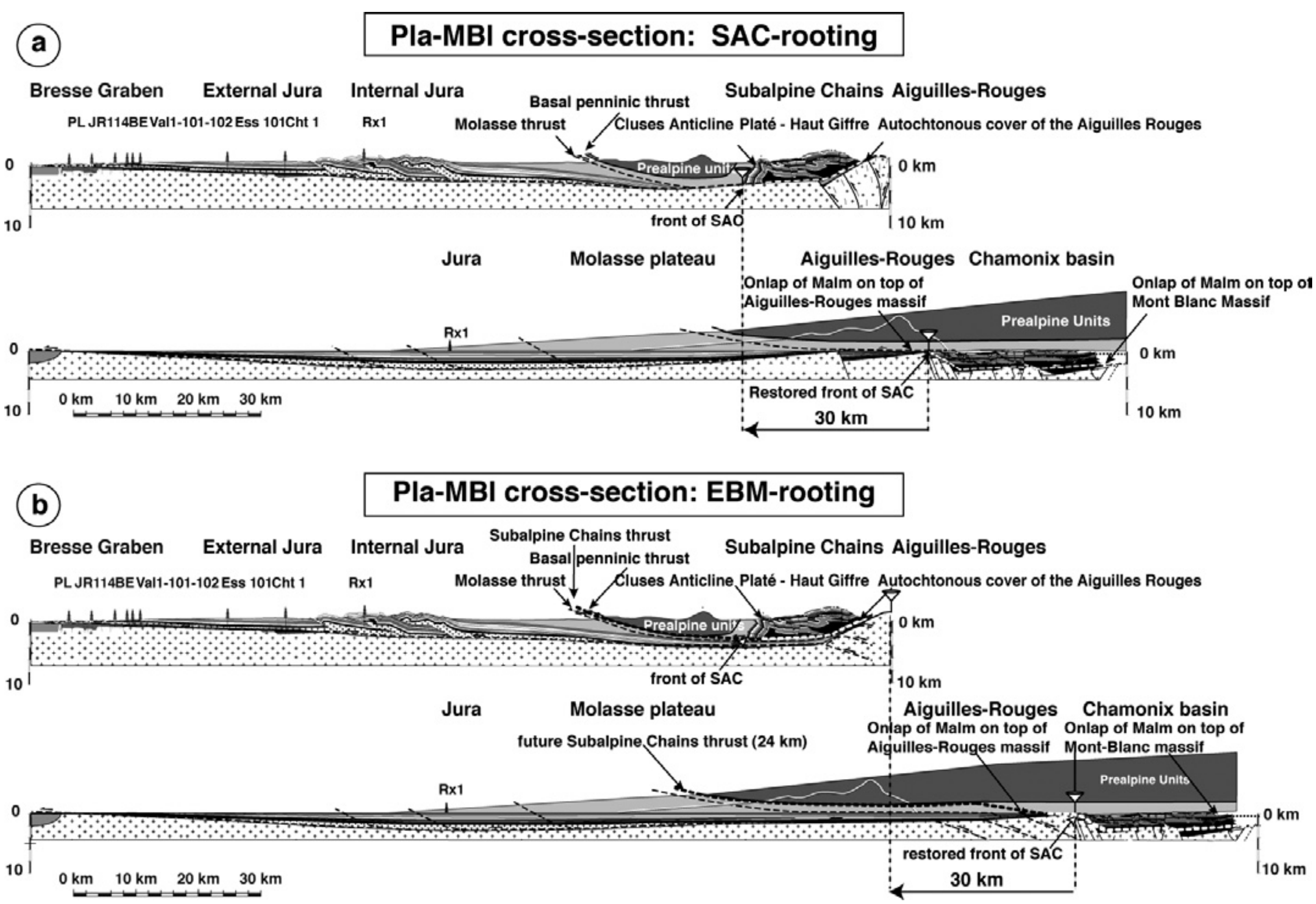
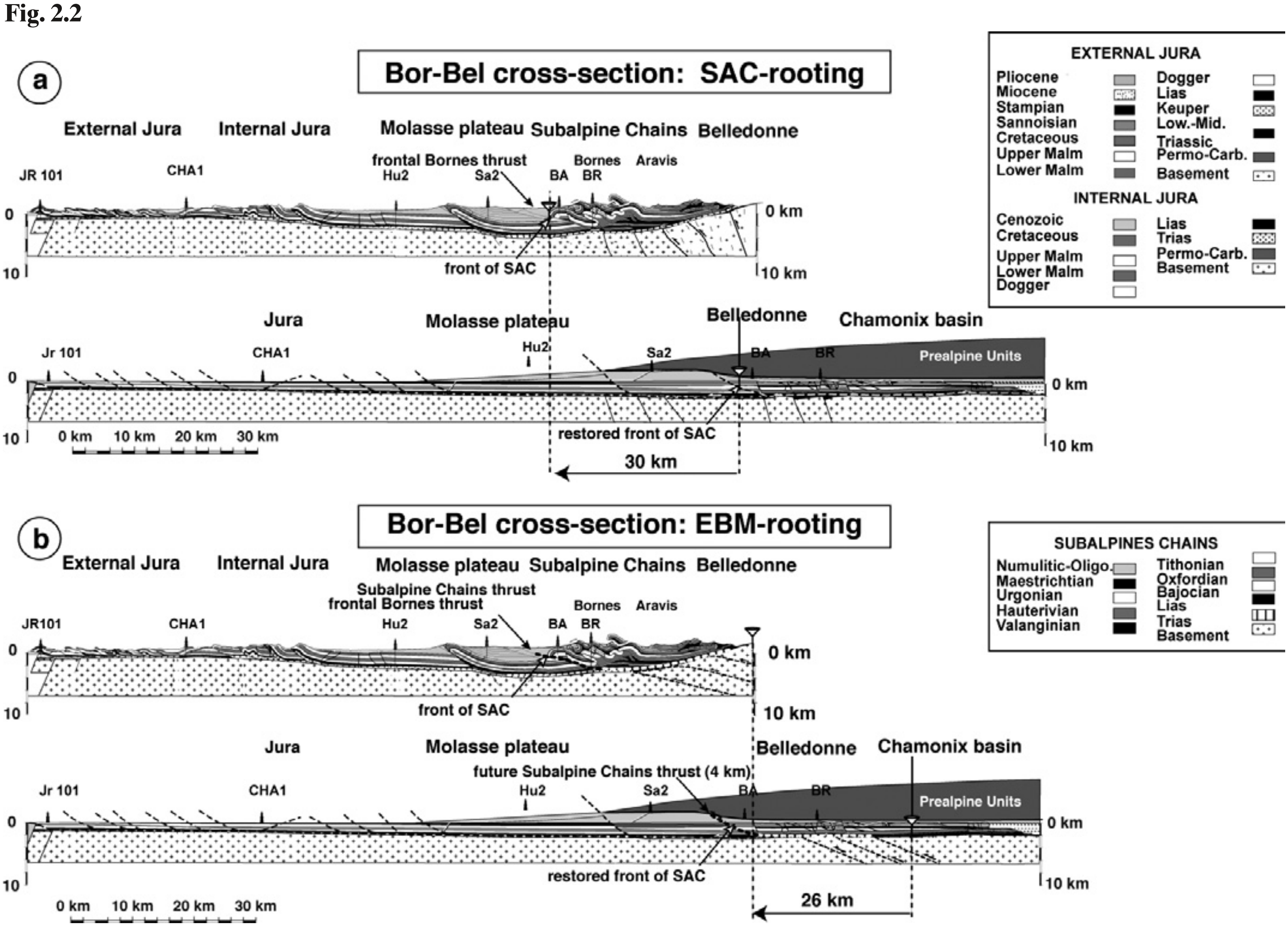


Fig. 2. The two cross-sections Pla-MBl et Bor-Bel in their present-day and restored state. Locations are given in figure 1. Both cross sections comprise two models of restoration. SAC-rooting model (2.1a and 2.2a) are drawn considering a 'rooting' of the Jura – Molasse basal detachments along the Subalpine Chains floor thrust. EBM-rooting model (2.1b, 2.2b) assumes a 'rooting' along basement thrusts beneath the External Basement Massifs. *Abbreviations:* SAC: Sub-

thickening of the crust results essentially from buckle folding of the crystalline basement above a mid-crustal detachment, without significant transfer of displacement beyond the tip of the crustal detachment (Marquer 1990; Gidon 1996). Based on microstructural observations on rock fabrics in the External Basement massifs, Marquer & Gapais (1985) and Marquer (1990) have proposed a model where a pure shear deformation takes place above a basal incipient shear zone in the crust. Shear zones analyses in the Belledonne massif (Marquer et al. 2006) reveals a bulk NW-SE contraction associated with vertical stretching at the scale of the External Basement Massifs. As far as geophysical data are concerned, interpretations of deep seismic lines shot in the frame of the ECORS and NRP20 national research programs in France and Switzerland (Roure et al. 1990; Pfiffner et al. 1997a) show that north of the Aiguilles Rouges, the Mezosoic cover is "rooting" into the basement. However, this did not bring critical information to solve the uplift mechanism problem since crystalline basement thrusts are required in both models of External Basement Massifs uplifting but with different displacement values that are difficult to deduce from geophysical studies. It must also be underlined that the External Basement Massifs coincide with a major dextral strike-slip fault zone found in the Chamonix and Belledonne Median synclines (Fig. 1, black dashed line) (Hubbard & Mancktelow 1992; Steck & Hunziker 1994). This strike-slip fault zone was initiated in Miocene times and is still active now (Seward & Mancktelow 1994; Leloup et al. 2005). Therefore the External Basement Massifs result from a transpressive deformation rather than a purely compressive one, which could explain their 'en échelon' distribution (Laubscher 1988). This might have been important in localizing the antiformal culmination of these External Basement Massifs (Seward & Mancktelow 1994).

Fig. 2.2



alpine Chains, EBM: External Basement Massifs. *Wells:* BE: Beaume-les-Messieurs, BA: La Balme, BR: Brizon, CHA1: Chatillon 1, Cht1: Charmont 1, Ess101: Essertines 101, Hu2: Humilly 2, JR101: Jura 101, JR114: Jura 114, PL: Plainoiseau, R × 1: Risoux 1, Sa2: Salève 2, SAV: Savigny, Val1–101–102: Valempoulières 1–101–102.

2.2. Kinematic models of deformations in the French External Alps

2.2.1. Existing models

A key issue regarding the sequence of deformations in the External Alps is the kinematic link of the Jura and Molasse basal detachments with more internal units. Three models have been proposed to 'root' the Jura and Molasse basal décollement (fig. 3).

1) Gravity sliding model (Gravity model)

A link of the Jura and Molasse floor thrusts with a detachment induced by denudation on top of the External Basement Massifs topographic high (Fig. 3, Gravity model) has been extensively discussed in Milnes & Pfiffner (1980) and has been shown to be a weak explanation. This model should be discarded for two reasons. First, it is well established that the Subalpine Chains emplacement is not coeval but occurred prior to the External Basement Massifs uplift. Structural studies have shown that the Subalpine Chains were tilted and deformed during the compressive deformation of the External Basement Massifs in their footwall (Burkhard 1988). This timing of deformation is visible on a tectonic map (Fig. 1) in the form of a cross-cutting relationship between the External Basement Massifs and the structural trend-lines of the Subalpine Chains: fold axes trend N60 in the Subalpine Chains whereas the crest of the External Basement Massifs strikes N40. Second, a gravitational slide of the cover on top of the External Basement Massifs necessitates a very strong extension (up to 28 km) and unroofing at the rear of the Subalpine Chains, although no such extension is documented.

2) Subalpine Chains "rooting" (SAC-rooting model)

The idea of a connection between the Jura basal thrust and the Helvetic nappes must be attributed to Laubscher (1973). This author proposed a transfer of displacement from the Morcles nappe towards the European foreland. The SAC-rooting model (Fig. 3) implies that Jura deformations occurred in a deformation involving the Subalpine Chains, so that the formation of the Jura and Subalpine arcs was coeval (see the map-view representation of deformation, Fig. 3). In this case, the deformation of the Subalpine Chains would have occurred in two stages. A first stage of deformation in Oligocene to Early Miocene times would have formed cylindrical folds (Fig. 3, SAC-rooting model, stage 1). A second stage of "passive" transport would have occurred in the Middle Miocene when the basal detachment of the Subalpine Chains propagated to the Molasse and the Jura basal thrusts, molding the initially cylindrical folds of the Subalpine Chains on the edge of the Jura salt basin and simultaneously forming both the Jura and the Subalpine Chains arcs (Fig. 3, SAC-rooting model, stage 2). The fact that the main stage of folding within the Subalpine Chains is of Oligocene to Lower Miocene age is not incompatible with a major passive transport of these thrust sheets above their basal detachment in the Middle Miocene. Finally, deformation of crystalline basement above a shear zone in the upper crust would have formed the External Basement Massifs, without significant transfer of displacement towards the foreland (Fig. 3, SAC-rooting model, stage 3).

3) External Basement Massifs "rooting" (EBM-rooting model)

A link between the Jura-Molasse thrusts and a potential thrust system in the outermost External Basement Massifs (Aiguilles-Rouges and External Belledonne) was popularized by Boyer & Elliot (1982). Burkhard (1990) and Leloup et al. (2005) later argued that apatite fission-track cooling ages documenting paleoisotherms showed an uplift of the External Basement Massifs coeval with the Jura deformations, thus supporting this EBM-rooting model and preventing a link between the Subalpine Chains and Jura basal thrusts (SAC-rooting model). This argument is in line with the conceptual models of deformation describing the External Basement Massifs as basement imbricates or mega-fault-ramp folds in the upper crust (Buxtorf 1916; Boyer & Elliott 1982; Burkhard 1990; Mugnier et al. 1990; Laubscher 1992). In this EBM-rooting model, the displacement on the External Basement thrusts over the European foreland is transferred to the Jura and Molasse basal thrust (Fig. 3, EBM-rooting model, stage 2) whereas the displacement associated with the earlier emplacement of the Subalpine Chains occurs along their basal detachment, above the External Basement Massif (Fig. 3, EBM-rooting model, stage 1). Contrary to SAC-rooting model, EBM-rooting model implies that the Jura and Subalpine Chains arcuate structures formed at different ages (see the map-view representation of deformation, Fig. 3). First the Subalpine Chains arc formed in Oligocene to Lower Miocene times (Fig. 3, EBM-rooting model, stage 1). Then, during a later deformation phase, the External Basement Massifs were thrusted over the European foreland where displacements were accommodated by the Jura arcuate fold-thrust belt and the Molasse thrust (Fig. 3, EBM-rooting model, stage 2). In the EBM-rooting model, contrary to the SAC-rooting model the parallel geometry of the two arcs structures would have been coincidental.

2.2.2. Geochronological data.

As explained above, the relative timing of formation of the Jura and of the External Basement Massifs is a critical element to determine the kinematic link between the Jura and the Alps. The uplift of the External Basement Massifs is documented by various geochronological methods that track temperature isogons from 90 °C (apatite fission-track cooling ages) to 325 °C ($^{40}Ar/^{39}Ar$ in biotite). The data are discussed in Marshall et al. (1998b) and Leloup et al. (2005). These authors underline the large distribution in ages revealing the complexity of the

External Crystalline Massifs uplift history. In such a context, the uncertainty on geochronological data is rather large due to various effects linked to multiple events, disequilibria in chronometric systems (Leloup et al. 2005), massive fluid circulations (Mullis et al. 1994; Rolland et al. 2003), uncertainties on the closing temperature (Gallager et al. 1998) and on initial PT conditions at depth and geometry of the uplifted blocks (Leloup et al. 2005). For the Mont Blanc massif, $^{40}Ar/^{39}AR$ dating of adularia and muscovite in alpine veins range from 13.4 to 15.2 Ma (Leutwein et al. 1970) for muscovite (310–370 °C), and from 9.9 Ma (Marshall et al. 1998a) to 16.7 Ma (Leutwein et al. 1970) for adularia (265–285 °C). From this point of view, the youngest adularia age seems to be more compatible with the muscovite ages than the oldest one. Older $^{40}Ar/^{39}Ar$ ages were found for biotites (300–350 °C) in mylonites (Leloup et al. 2005). Such biotites having clearly been reset by Alpine events, the problem is to link such events with the Mont Blanc uplift. Apatite and zircon fission-tracks also show a wide distribution. Ages lying from 1.4 to 5.7 Ma for apatite (60–120 °C) and from 11.2 to 11.4 Ma for Zircon (200–300 °C) were found by Seward & Mancktelow (1994). The same range of values was found by Leloup et al. (2005) using apatite (2.7 to 5 Ma). All these data indicate a mean uplift rate of about 1 mm/y with possible transitory variations from 0.5 to 3 mm/y during the uplift process (Leloup et al. 2005). The apatite fission track ages from Rahn (2001) provided similar uplift rates: for several sections crossing the External Basement Massifs, the present-day maximum elevation of the 5 Ma isochron is 2 km above sea level. If we consider that the present apatite closure depth is at 3 km below sea level, this means that the mean uplift rate was 1 mm/a during the last 5 Ma. The total amount of exhumation is another problem. It may be evaluated both from the thickness of the Subalpine cover and from thermo-barometers. The total thickness of the Subalpine cover is estimated to range from 6

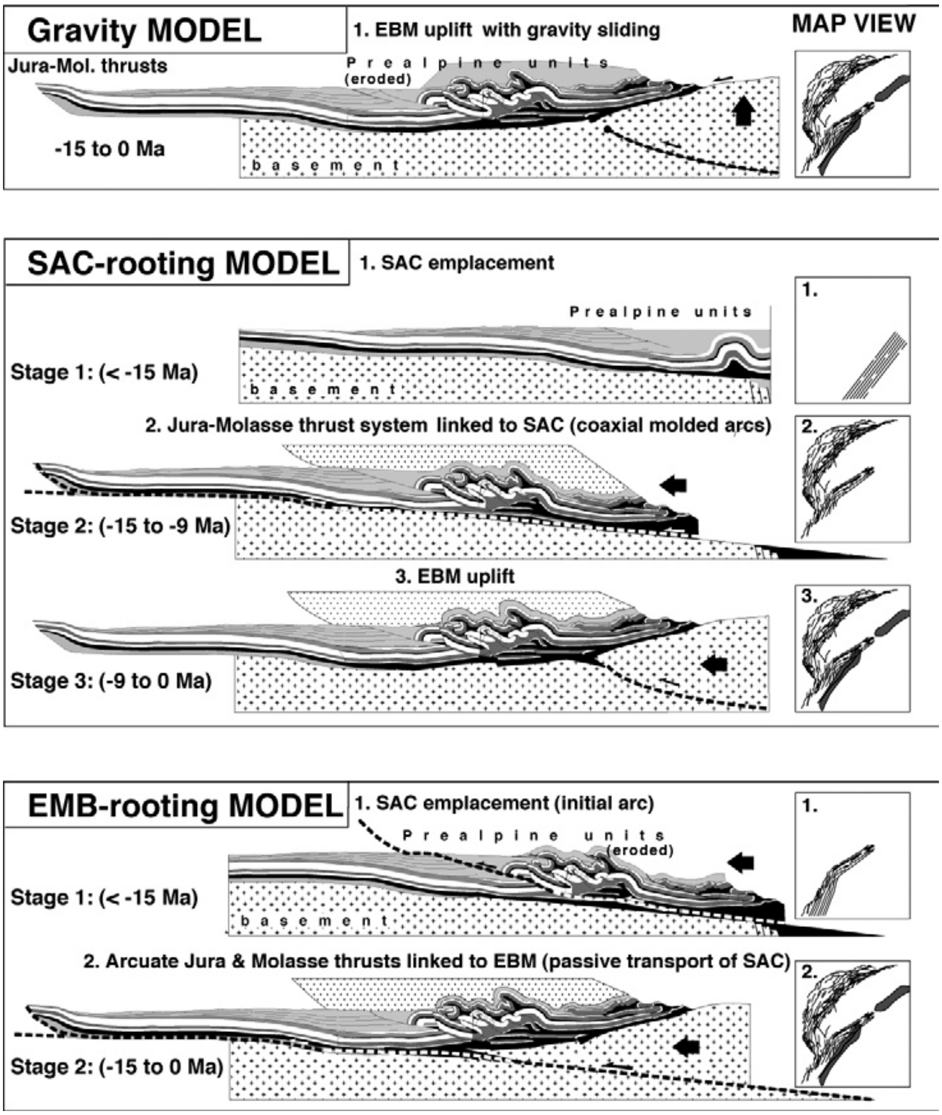


Fig 3. Schematic representation of three models for the kinematics of deformation in French External Alps: view on cross-sections on the left and map-view (in the insets) to the right.

- Gravity model: progressive emplacement by gravitational sliding of the cover on top of the External basement massifs: the emplacement of the Subalpine Chains is coeval with Jura and Molasse deformations;
- SAC-rooting model: three steps of emplacement: (i) Subalpine Chains folding, (2) Jura- Molasse thrust and deformation with and "passive" transport of the Subalpine Chains and coeval arcs formation, (iii) uplift of the External Basement Massifs;
- EBM-rooting model: two steps of emplacement: (i) Subalpine Chains thrust with initial arcuate shape (ii) basement thrusts, which progressed to the foreland to form the Jura – Molasse thrust and deformation. *Abbreviations:* SAC: Subalpine Chains, EBM: External Basement Massifs.

to 12 km (Leloup et al. 2005). From fluids inclusions studies, Poty et al. (1974) evaluated the thickness of the cover to be about 10 km, a burial depth of 10 km for the top of the External Basement Massifs is a minimum since metamorphic reactions in cover-basement interfaces indicate temperatures of about 300° C during the Oligocene (Hunziker et al. 1986). Using maximum pressure – temperature alpine conditions and mineral-equilibrium in mylonites, the total amount of exhumation was estimated to be from 15 to 20 km for the Mont Blanc massif and 10 km for the Aiguilles Rouges by Leloup et al. (2005). Difference in the uplift rates between Mont Blanc and Aiguilles Rouges is accommodated by a major steep reverse shear zone with a dextral component (Leloup et al. 2005).

With regard to the timing of Jura deformations, Deville et al. (1994) and Beck et al. (1998) have shown that deformations were initiated 15 Ma ago in the innermost part of the southern Jura (Montagne d'Age, Mandallaz and Salève anticlines, Fig. 1). As far as the end of deformations is concerned, well data show that frontal thrusts on the Bresse Graben were active as early as 9 Ma ago (Demarcq et al. 1984). However, because of a hiatus below the post-tectonic sediments (Jan du Chêne 1974), an uncertainty remains about the end of deformation on the Jura frontal thrust. We only know that thrusting came to an end between –9 and 3.3 Ma at the front of the Jura. There are several problems with such deformation history. Firstly we do not know how the deformation propagates from the inner to the outer part of the Alps: what is the dynamic of stress transfer from hinterland to foreland. Secondly, the connection between late events of the Jura deformation and External Basement thrusting is not straightforward: some of the frontal thrust on the Bresse basin has been interpreted as extensional structures (Mugnier & Vialon 1984). An alternative explanation is the reactivation of variscan faults in the Jura basement as observed in the case of the last Besançon earthquake (Conroux et al. 2004). So considering that the main Jura deformation occurs between 15 Ma (inner part) and 9 Ma (outer part), and due to the large uncertainty of both this timing and of geochronological data, the question of whether there was a significant high of basement during the Jura formation that could have prevented the mechanical connection between Jura and Subalpine massifs cannot be solved only by geochronological data. A mean uplift rate of 1 mm/y is enough to generate the required uplift of the basement-cover interface starting from a near flat basement during most of the Jura formation. This assumption remains in uncertainty range of geochronological data, but is objectively near the minimum values of both ages (9–12 Ma) and thickness (10–12 km) whereas the models that related the uplift of the External basement massifs with the Jura and Molasse thrusts (Leloup et al. 2005, for example) use data of both age (20–22 Ma) and thickness (18–20 km) that are near the maximum of the uncertainty range.

In conclusion, because of their uncertainty, geochronological data on the exhumation of the External Basement Massifs are not decisive to discriminate between SAC-rooting and EBM-rooting models of figure 3. Consequently, we also test the strain compatibility of these two models using a map-view restoration based on two regional restored cross-sections.

3. Results

3.1. Method of restoration

The restoration of geological structures consists in removing the effects of strain on rocks to determine their geometry before deformation set in. Restoration is usually applied to regional cross-sections (Dahlstrom 1969) assuming that deformation took place in the plane of section but it can also be applied in map view to generate palinspastic maps. Palinspastic maps can be determined following two techniques. The first, pseudo-three-dimensional restoration, is based on the linkage of independent balanced cross-sections along-strike (Wilkerson et al. 1991). The second, three-dimensional retrodeformation, consists in unfolding and best-fitting folded and faulted surfaces (Gratier et al. 1991; Gratier & Guillier 1993; Affolter & Gratier 2004) or volumes (Cornu et al. 2002). In the case of intensely deformed thrust sheets, total shortening results from two components: displacement above a floor thrust and sheet internal strain. Several deformation mechanisms contribute to the latter component: folding and secondary (with regard to the basal detachment) thrust faulting, grain scale brittle deformation, crystal plastic deformation and pressure solution. In this paper, we present a pseudo-three-dimensional map-view restoration of the French External Alps based on two regional restored cross-sections (Fig. 2.1 and 2.2). Cumulative displacement is determined along each cross-section and for the four main thrust systems that are found in the External Alps (see the geological setting section), namely the Jura, the Molasse, the Subalpine Chains and the External Basement Massifs thrusts. Displacement transfers between tectonic units are described and restored sections are proposed. Each cross-section was retrodeformed considering two hypotheses: a 'rooting' of the Jura-Molasse basal detachments either along the Subalpine Chains floor thrust (Fig. 3, SAC-rooting model) or along basement thrusts beneath the External Basement Massifs (Fig. 3, EBM-rooting model). For each cross-section, these two scenarios led to two different restored sections, the relative position of units being different whether SAC-root model or EBM-rooting model is considered. In a second step, the two restored cross-sections were linked to test the map-view consistency of section balancing.

3.2. Description of cross-sections and results of restoration

3.2.1. Cross-section "Cluses Anticline – Platé – Aiguilles Rouges – Mont Blanc Massifs" (Pla-MBl section)

3.2.1.1. Subalpine Chains 'rooting' (SAC-rooting model Fig. 2.1a)

Along the Pla-MBl cross-section, the displacement associated with shortening is 20 ± 3 km in the Jura (Affolter & Gratier

2004). In the Molasse zone, the resolution of seismic lines is poor (Gorin et al. 1993, Signer & Gorin 1995) and shortening cannot be determined precisely. However, structural maps published by Gorin et al. (1993) and Signer & Gorin (1995) show that west of this cross-section, the Molasse thrust separates into two branches (Fig. 1). One progressively dies out towards the Salève anticline (Fig. 1, white triangle 5), while the other joins the Bornes frontal thrust. The displacement accommodated by the Salève anticline and the Bornes frontal thrust is 5 km (Charollais et al. 1998) and 4 ± 1 km (Guellec et al. 1989), respectively. If we consider that displacement is conserved laterally from the Molasse thrust to the Salève anticline and the Bornes frontal thrust, the displacement accommodated by the Molasse thrusts along this Pla-MBl cross-section is about 10 km, compatible with the value found by Burkhard & Sommaruga (1998) in a more northern part of the Molasse basin. This displacement is evaluated with a large uncertainty (10 ± 5 km). Thus, in the case of a link between the Subalpine Chains and the Jura, a total of 30 ± 8 km must have been transferred from the floor thrust of the Subalpine Chains to the Molasse and Jura thrusts along cross-section Pla-MBl.

A key feature of figure 2.1 is that thin autochthonous series on top of the Aiguilles-Rouges basement are present. On cross-section Pla-MBl the presence of reduced series on top of the Aiguilles-Rouges basement results from a projection of the nearby Pormenaz outcrop 5 km NE of the cross-section (Fig. 1, white triangle 7). At this location, Pairis et al. (1973) and Pairis (1975) have described unconformable limestones overlying Triassic quartzites. These authors determined Turonian-Lower Senonian fauna in these limestones, which confirmed that a large unconformity exists on top of the Aiguilles-Rouges basement. In terms of shortening and displacement, the existence of an autochthonous sequence of strata with reduced thickness beneath the thick cover of the Platé massif means that these latter sediments were thrust on top of the Aiguilles-Rouges massif and must be restored at the rear of this basement massif. Based on these observations the Aiguilles-Rouges basement has formed a topographic high since the rifting of Pangea and the sedimentary record on top of it was either not deposited or condensed. These autochthonous series are in sharp contrast to the thick series of the Subalpine chains (Cluses anticline, Platé massif, Fig. 2.1). The abrupt change of thickness of the series is a key marker that is used to evaluate the displacement of the Subalpine Chains. The front of the Subalpine chains (the western limb end of the Cluses anticline, pine point Figure 2.1a) is restored up to the eastern end of the autochtonous cover of the Aiguilles Rouges. This leads to a displacement of about 24 km with an uncertainty that we estimate to ±2 km. However, this value does not take into account the late shortening of the Aiguilles-Rouges massif. We calculated this shortening using an area balance along cross-section (Fig. 4), which corresponds, for this cross section, to a shortening of 6 km with an uncertainty of ±1 km depending on the basal detachment depth (a range from 10 to 15 km is considered). Thus, if we consider that the Aiguilles-Rouges was 6 km wider before shortening, the total throw along the Subalpine Chains floor thrust is 30 ± 3 km along cross-section B. This value fits well the displacement (30 ± 8 km) associated with the shortening observed in the foreland (Jura and Molasse units).

In conclusion, in the case of a kinematic link between the Jura-Thrust Molasse and the Subalpine Chains, the 30 ± 8 km shortening associated with the Jura and the Molasse thrusts is compatible with the measured displacement of the Subalpine Chains front along its floor thrust which has a total throw of 30 ± 3 km when the late deformation of the underlying Aiguilles-Rouges massif is taken into account. It follows that the present-day front of the Subalpine Chains (pin point, Fig. 2.1a) must be restored 30 km southeast of its present location. This palinspastic position corresponds to the northwestern rim of the Chamonix basin, which was thrusted on top of the Aiguilles-Rouges reduced cover to form the Subalpine Chains.

3.2.1.2. External Basement Massifs 'rooting' (EBM-rooting model, Fig. 2.1b)

In the case of a kinematic link between the External Basement Massifs and the Jura-Molasse thrusts, the 30 ± 8 km of displacement of the Jura and Molasse along the Pla-MBl cross-section must be accommodated by basement thrusts beneath the Aiguilles-Rouges. In this case the displacement of the Subalpine Chains along their floor thrust cannot be transferred to the Jura and Molasse thrust. This assumption implies that

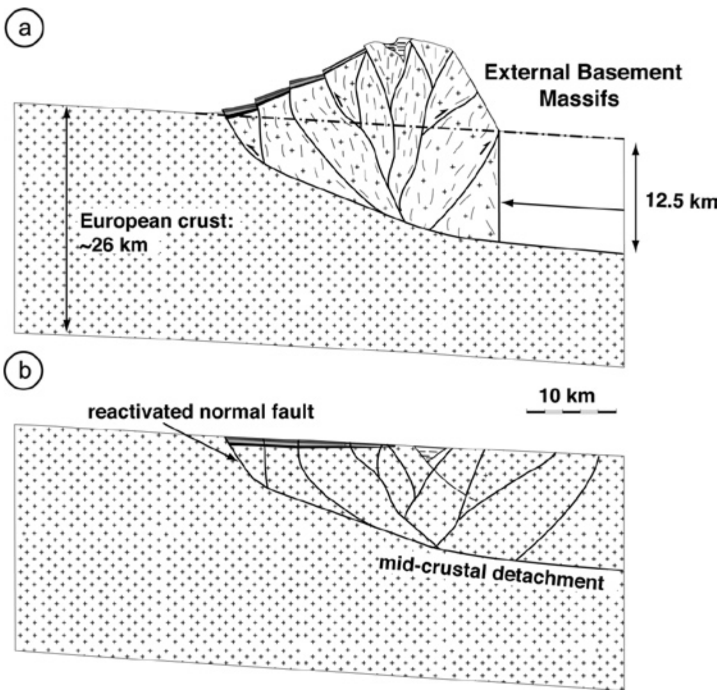


Fig. 4. Schematic deformation mechanism of the Aiguilles-Rouges External Basement Massif by a pure shear deformation above a mid-crustal shear zone, adapted from Marquer & Gapais (1985): present day (a) and restored state (b). In this model, the main crustal detachment was a normal fault before it was inverted.

this Subalpine thrust emerges at the front of the Prealpine units. The only viable solution is that this Subalpine thrust was transferred to the already existing basal Penninic thrust (Fig. 2.1b) or to any other cinematically compatible emergent thrusts. This geometry was already proposed by Burkhard & Sommaruga (1998) along their balanced cross-section. In this hypothesis, due to the active role of the External Basement Massifs, the pin point is attached to the southeastern limit of the Aiguilles-Rouges massif that must be restored 30 km of its present-day location (pin point, Fig. 2.1b). The palinspastic position of this point also defines the transition from the thin cover of the Aiguilles-Rouges massif to the thick series of the Chamonix basin. This scenario implies that the 24 ± 2 km overthrust of the Northern Subalpine Massif over the basement was transferred to the surface through the already existing Penninic thrust (Fig. 2.1b) or through any other compatible emergent thrusts.

3.2.2. Cross-section "Bornes – Aravis – Belledonne Massifs" (Bor-Bel section, Fig. 2.2).

3.2.2.1. Subalpine Chains 'rooting'
(SAC-rooting model Fig. 2.2a):

Along the Bor-Bel cross-section, displacement associated with the shortening is 26 ± 3 km in the Jura (Affolter & Gratier 2004), including the 5 km accommodated by the Salève anticline (see above). The Molasse thrust zone visible on Pla-MBl section is not present on Bor-Bel cross-section but the corresponding shortening is taken up by the Salève anticline (5 km) and the Bornes frontal thrust (4 ± 1 km, see above). Along this Bor-Bel section, the lateral equivalent of the Aiguilles-Rouges crystalline massif is known as the External Belledonne massif (Fig. 2.2). The Subalpine Chains are resting on top of this massif, above a major detachment level in Liassic marls and Triassic layers. Whereas the presence of a contrasting autochthonous cover below the Subalpine Chains makes it possible to determine the throw of the floor thrust on Pla-MBl section, no such criterion can be used in the case of Bor-Bel transect. In contrast to the Aiguilles-Rouges cover, which is devoid of Lias and Dogger, the cover resting on top of the External Belledonne basement (Fig. 1 and Fig. 2.2) is continuous. The lateral vanishing of the reduced Aiguilles-Rouges cover is well known from stratigraphers (Pairis 1975; Barféty 1988). Classically, the Aiguilles-Rouges paleogeographic area of deposition is interpreted as a paleo-high inherited from extensional tectonics in Liassic times. The transition from a thin cover in the Aiguilles-Rouges to thick series in the External Belledonne massif remains unexplained. It could be due to a transform fault bounding a tilted block laterally during the Liassic extensional stage. Although no tectonic repetition of the cover is observed above the External Belledonne massif, it is generally recognized that the base of Liassic marls (or the top of Triassic layers) forms a major detachment level as well as in the rest of the Subalpine Chains. Although the throw of the Subalpine Chains floor thrust cannot be determined directly, the hypothesis of a kinematic link with the Jura implies that it corresponds to the shortening of the Jura (26 ± 3 km) and the Bornes frontal thrust (4 ± 1 km), which corresponds to a total 30 ± 4 km.

In conclusion, in the case of a link between the Jura and Molasse thrust on the one hand and the Subalpine Chains on the other, the front of the Subalpine Chains (pin point, Fig. 2.2a) was located 30 ± 4 km southeast of its present position along Bor-Bel cross-section: 26 ± 3 km of displacement were accommodated by the Jura and 4 ± 1 km by an emergent thrust at the front of the Bornes massif.

3.2.2.2. External Basement Massifs 'rooting' (EBM-rooting model Fig. 2.2b)

In the case of a kinematic link between the External Basement Massifs and the Jura-Molasse thrust, the 26 ± 3 km of displacement observed in the Jura along Bor-Bel cross-section must have been accommodated by basement thrusts beneath the External Belledonne massif. As for Pla-MBl cross section, in this hypothesis the pin point (Fig. 2.2b) is attached to the southeastern border of the External Belledonne massif that was located 26 ± 3 km southeast of its present-day position. In this hypothesis, the palinspastic position of the Subalpine Chains front is the sum of the shortening accommodated by the basement thrusts (26 ± 3 km) and the Bornes frontal thrust (4 ± 1 km), i.e. 30 ± 4 km. It is important to notice that in this case, the relative motion between the Subalpine Chains front and the northwestern border of the External Basement Massif along this Bor-Bel section was only 4 ± 1 km when deformation took place, instead of the 24 ± 3km of displacement evaluated with this EBM-rooting model along the northern Pla-MBl section.

3.3. Map-view restoration based on restored cross-sections.

The restored Pla-MBl and Bor-Bel cross-sections can be used to generate a palinspastic map of the French External Alps. As explained in the introduction, map-view restorations based on the linkage of individual cross-sections allow testing the lateral consistency of restored cross-sections. Figure 5 shows two maps of the French External Alps where the palinspastic position of the Subalpine Chains sedimentary cover was plotted based on the restored cross-sections. On this figure 5 the pin points on these cross-sections are reported in map-view.

Figure 5a shows the palinspastic position of the Subalpine Chains sedimentary cover in the case of a kinematic link of the Jura-Molasse thrust with the Subalpine Chains (SAC-rooting model). The displacement transferred from the Subalpine Chains floor thrust to the Jura-Molasse thrust is 30 km along both sections (arrows, Fig. 5a). One must note that southwest of Bor-Bel cross-section, the displacement of the Subalpine Chains front decrease up to about 20 km (arrow), which corresponds to the shortening accommodated by the Jura at this place (Affolter & Gratier 2004). These displacement field values define the northwestern border of the Subalpine Chains front line before deformation set in. To the southeast of the

Aiguilles-Rouges massif, the palinspastic position of the Subalpine Chains sedimentary cover locates the Chamonix basin (shaded area). This basin is well defined by the palinspastic position of the Aiguilles-Rouges and Mont-Blanc massifs and has a width of about 22.5 km (Huggenberger 1985). More to the southwest, along Bor-Bel cross-section, the stratigraphic effect of Aiguilles-Rouges and Mont-Blanc tilted blocs disappear (see above) and the Subalpine Chains sedimentary cover becomes part of the Mesozoic cover, which extends towards the Jura. However, the restored sections allow reconstructing the position of the front line of the Subalpine Chains (Fig. 5a) that remains laterally smoothly continuous after restoration. As pointed out in the model description, this Subalpine Chains deformation front is in this case formed by cylindrical folds (SAC-rooting model, stage 1, Subalpine emplacement).

On figure 5b, which shows the palinspastic position of the Subalpine Chains sedimentary cover in the case of a 'rooting' of the Jura-Molasse thrust below the External Basement Massifs, the relative position of tectonic units is different. Along the Pla-MBl cross-section, the southeastern border of the Aiguilles-Rouges basement massif is restored 30 ± 8 km toward the southeast. However, the Subalpine Chain front line is restored behind (i.e. southeast of) this basement massif, 30 km more toward the southeast relative to this basement (24 ± 2 km due to the effect of the Subalpine emergent thrust and 6 ± 1 km linked to the basement deformation). So along this Pla-MBl section the Subalpine front is restored about 60 ± 12 km toward the southeast from its present position. Along the Bor-Bel cross-section, the southeastern border of the Belledone basement massif is restored 26 ± 3 km toward the southeast. The Subalpine front line remains in front of this External Belledonne massif with 4 ± 1 km of displacement (linked to the Bornes thrust) relative to the basement. So along this Bor-Bel section the Subalpine front line is restored 30 ± 4 km to the southeast from its initial position. Consequently, the EBM-rooting model results in a major inconsistency in the palinspastic map: the restored front line of the Subalpine Chains must show a sharp virgation with an offset of about 30 km between the two cross sections. Implication of such sharp lateral evolution is discussed below.

4. Discussion

Apart from restored cross-sections, few attempts have been made to propose paleogeographic reconstructions of the whole

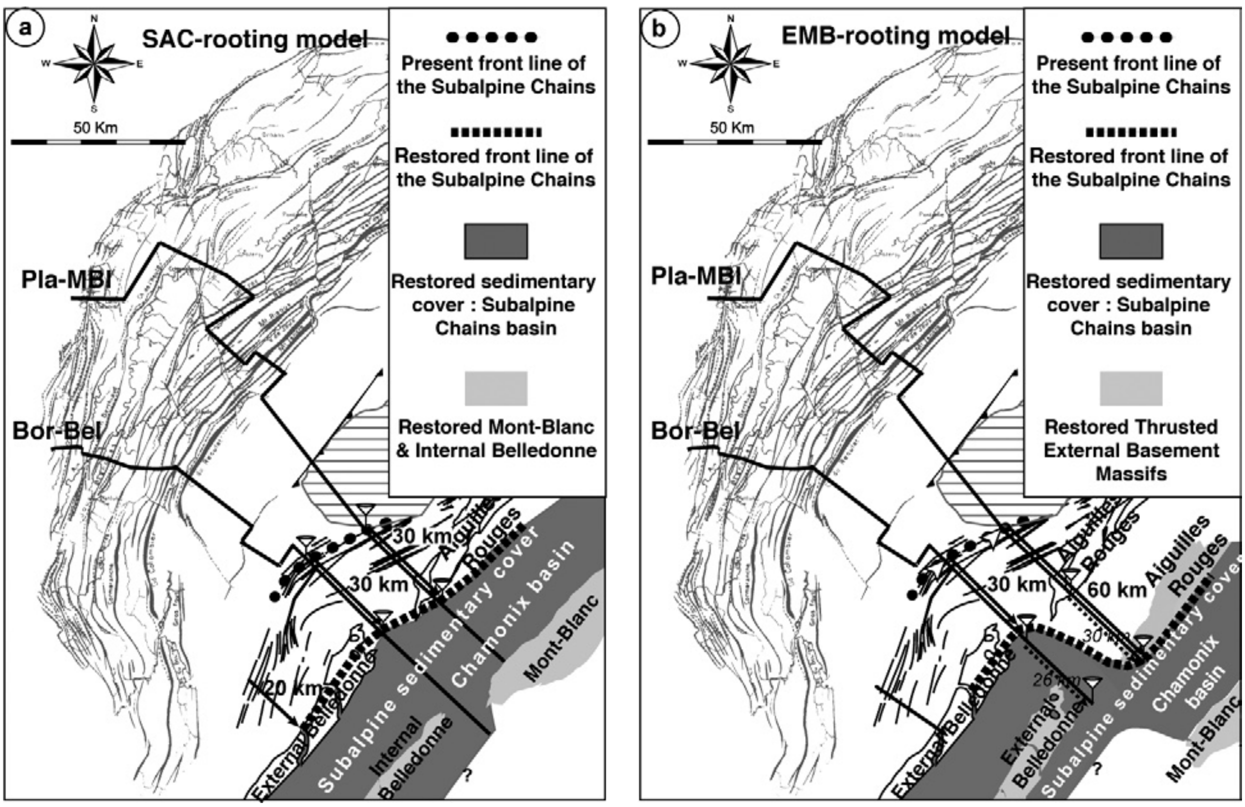


Fig. 5. Paleogeographic reconstruction of the Subalpine Chains sedimentary cover as deduced from the restoration of Pla-MBl and Bor-Bel cross-sections a) Map-view restored state in the case of a kinematic link of the Jura and Molasse thrust with the Subalpine Chains floor thrust (SAC-rooting model). b) Map-view restored state in the case of a kinematic link of the Jura and Molasse thrust with basements thrusts in the External Basement Massifs (EBM-rooting model). The pin points shown on figure 5 are the same as those represented on cross-sections of figure 2. *Abbreviations:* SAC: Subalpine Chains, EBM: External Basement Massifs.

French-Swiss External Alps (Butler 1985; Epard 1990; Wildi & Huggenberger 1993). Affolter (2003) proposed a map restoration integrating both the two cross sections discussed here and a cross section through the Jura – Swiss Helvetic nappes – French Subalpine chains. This regional setting is not discussed here since it would have implied much more detailed discussions. Moreover, the Swiss cross-section that was integrated in the Affolter thesis (2003) was found to be laterally compatible with the Pla-MBl cross-section. Therefore, from our point of view, this does not modify the discussion of the present paper.

The palinspastic map of figure 5b shows that regional cross-sections assuming a kinematic link between the Jura and the External Basement Massifs are underpinned by a major problem of lateral compatibility implying either a lateral evolution of the basin geometry or a tectonic offset. This conclusion could have been reached by comparing individual balanced cross-sections which rely on this hypothesis and which have been published in the past. For instance, a palinspastic map based on the balanced cross-section of Guellec et al. (1990) along our Bor-Bel section and on the restored profile of Burkhard & Sommaruga (1998) along a section north of the Pla-MBl one would result in a major virgation similar to the one shown on figure 5b. Guellec et al. (1990) describe the Bornes massif (Subalpine Chains in Bor-Bel section) as para-autochthonous (so with few km of displacement), although the nearby Platé and Haut-Giffre massifs (Subalpine Chains in Pla-MBl section) are clearly allochthonous (Doudoux et al. 1982; Butler 1985; Plancherel et al. 1998), i.e. with more than 20 km of displacement. Thus the EBM-rooting model implies a major virgation between the Bornes and Platé massifs that remains to be explained either by paleostratigraphic or by tectonic effects (or both). The palinspastic map of figure 5a is very close to the paleogeographic reconstructions from Epard (1990) and Butler (1985). Epard (1990) defines a 'Morcles nappe basin' (op. cit., Fig. 53) which is similar to our palinspastic reconstruction of the Subalpine Chains sedimentary cover. Butler (1985) restores the Morcles nappe and Haut-Giffre massif between the Aiguilles-Rouges and the Mont-Blanc massifs, in a way similar to figure 5a. However, these authors did not integrate the Jura and Molasse thrust systems in their paleogeographic reconstructions. It could be argued that the shortening observed within the Molasse could be accommodated by displacement on the Subalpine Chains floor thrust, whereas Jura deformations could be taken up by potential basement thrusts in the External Basement Massifs. The result of our map-view restoration would then be different because we assume that shortening in the Jura-Molasse system was entirely accommodated by one of two blind thrusts, but not both. From a geometric and geochronological point of view, this latter scenario would be possible. However, even if the 10 km displacement observed along the Molasse thrust in Pla-MBl section is accommodated by the Subalpine Chains floor thrust rather than along basement thrusts, the restored front of the Subalpine Chains would still be offset by some 20 km instead of 30 km between Bor-Bel and Pla-MBl sections on figure 5b. For this reason even if the Molasse thrusts are not linked to basement thrusts, a sharp virgation still remains between these two cross-sections in the case of a kinematic link between the Jura and hypothetical thrusts in the External Basement massifs.

Testing the strain compatibility of the two models using a map-view restoration based on regional restored cross-sections allowed us to evaluate the strength and weakness of the two models. From this point of view, the SAC-rooting model restoration leads to a smooth continuous restored line for the basement line reference whereas the EBM-rooting model leads to a sharp virgation of the same restored line. Strain compatibility tests do not necessarily discard this last model. The sharp virgation is found in an area that is well known for its complexity (Pfiffner 1993), being for example the southern end of the liassic tilted blocks of the Aiguilles Rouges massif and possibly the place of transform zone. An alternative explanation would be the uncertainty on the displacements deduced from restoration. The displacements obtained from the Jura restoration are rather accurate because they were determined using a map restoring technique consisting in unfolding and best-fitting folded and faulted surfaces. The displacement on the Pla-MBl section is well constrained by the use of the stratigraphic heterogeneity of the basin. The Bor-Bel section is a synthesis of our present knowledge and new studies are needed to bring new data. In the present state, this lateral compatibility problem remains a weakness of the EBM-rooting model of the Jura that must be taken into account when promoting this model.

As explained in the description of the SAC-rooting model, a kinematic link between the Jura-Thrust Molasse and the Subalpine Chains implies that the formation of the Jura and Subalpine Chains arcs was coeval. Since the southern Jura bend results from an important displacement gradient (Affolter & Gratier 2004), this displacement gradient can also be responsible for the formation of the Subalpine Chains arc. This accords well with the model of Ferrill & Groshong (1993) who have shown that the formation of the Subalpine Chains arc was associated with a differential shear parallel to a transport direction evaluated to N315. The model proposed by Ferrill & Groshong (1993) shows a first stage of deformation with the formation of cylindrical folds and a second deformation phase with a simple shear perpendicular to fold axes.

A kinematic link between the Jura and Subalpine Chains implies an uplift of the External Basement Massifs along a blind thrust zone (Fig. 4) with internal deformation of the basement. The analysis of shear zone patterns in the Belledonne massif by Marquer et al. (2006) for example reveals a bulk NW-SE compression, associated with vertical stretching. Although localized horizontal stretching is seen near the median fault zone associated with strike slip, the sediments pinched in this major thrust zone still imply a large vertical extension. The interpretation of the authors is that the main progressive deformation corresponds to NW-SE shortening and vertical stretching during the overthrusting of the External Basement massifs, with localized NE-SW dextral retro-shear zones. This internal deformation of the basement, which is schematically drawn on Fig. 4, is compatible with SAC-rooting model.

The contribution of geochronological data was already discussed in the introduction of the paper. We acknowledge that the SAC-rooting model relies on minimum values of both ages (9–12 Ma) and thickness (10–12 km) variables whereas the EBM-rooting model use data of both age (20–22 Ma) and thickness (18–20 km) that are near the maximum of the uncertainty range. As far as geophysical data are concerned, the deep seismic lines shot in the frame of the ECORS and NRP20 national research programs in France and Switzerland have shown evidence of Mezosoic "rooting" into the basement, below the External Basement massifs. However, basement thrusts are required for both SAC-rooting and EBM-rooting models but with very different displacements. Large displacement of basement thrusts over sedimentary cover (more than 20km), if demonstrated, would be in favor of the EBM-rooting model.

5. Conclusions

Map-view restoration of the frontal part of the Swiss-French Alps was done in order to test the hypotheses of a 'rooting' of the Jura basal detachment along the basal thrust of the Subalpine Chains or along basement thrusts beneath the External Basement Massifs.

- Subalpine Chains "rooting" (SAC-rooting model) implies three steps: (i) Deformation of the Subalpine Chains with cylindrical folds before 15 Ma (ii) Jura-Molasse deformation from 15 to about 9 Ma linked to passively transported Subalpine Chains, with the Jura-Molasse basal detachment being connected to the Subalpine Chains basal thrust and synchronous development of their coaxial arcs (iii) Development of the External Basement massifs by pure shear over a mid-crustal reverse shear zone from 9–12 Ma to the present.
- External Basement massifs rooting (EBM-rooting model) implies two steps: (i) Thrusting of the Subalpine Chains with an initial arcuate shape before 15 Ma, (ii) Jura-Molasse deformation from 20 Ma to the present, with independent development of the Jura arc, linked to the thrusting of the External Basement massifs over the foreland cover.

Because of their uncertainty range, geochronological data on the exhumation of the External Basement Massifs are not decisive to discriminate between SAC-rooting and EBM-rooting models. SAC-rooting model requires the use of minimum values within uncertainty ranges for both ages (9–12 Ma) and thickness (10–12 km) variables whereas EBM-rooting model need the use of data of both age (22 Ma) and thickness (20 km) that are near the maximum of the uncertainty ranges.

Interpretation of geophysical data shows evidence of Mesozoic rooting below the External Basement massifs. However, as basement thrust is required for both models, but with different displacement values, only an estimate of such displacement would be discriminatory.

Finally, testing the strain compatibility by map-view restoration of cross-sections reveals a weakness of the EBM-rooting model. Whereas, smooth continuous lines are restored with the SAC-rooting model, they are restored with a sharp virgation with the EBM-rooting model. As such a virgation is found in a region that is well known for its complexity, this is probably not a critical point to discard the EBM-rooting model but this aspect must be taken into account in the future when using this model.

As a general conclusion, this work does not rule out of the two main models of deformation in the External Alps. It shows however that the model that links the Jura-Molasse with the Subalpine Chains (SAC-rooting model) that is clearly the less popular at the present time must not be discarded. On the contrary, and at least from the strain compatibility point of view this model is more consistent that the alternative model, which link the Jura Molasse with the External Basement Massifs (EBM-rooting model).

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