New constraints for indentation mechanisms in arcuate belts from the Jura Mountains, France

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ABSTRACT

The mechanism of indentation in arcuate belts is discussed using the Jura Mountains as an example. Using fault-inversion analysis from numerous sites, the Miocene-Pliocene stress pattern is reconstructed. Two superimposed compressional stress fields have been recognized. Considering the theoretical distribution of compression in front of a rigid indenter, we interpret the complex stress pattern in the Jura Mountains as a result of a major change in the mechanism of indentation of the Jura by its hinterland. Initially, the indenter was narrower and limited in the southwest by the Vuache transfer fault. With time, it expanded to the southwest and included the entire Molasse basin. This evolution highlights the importance of decoupling along faults, which here controlled the indenter shape.

INTRODUCTION

Previous studies demonstrated that various factors may play a major role in the generation of arcuate orogenic belts: indentation of the deformable belt by a rigid back-domain, gravity sliding induced by body forces within the wedge, and/or obstacles in the foreland (e.g., Platt et al., 1989; Marshak et al., 1992). Although indentation has been recognized as a major driving mechanism for many orogenic belts such as the Himalayas (Peltzer and Tapponnier, 1988), the Superior-Churchill collision zone (Canada; Gibb, 1983), the Cantabrian zone (northwestern Spain; Julivert and Arboleya, 1986), and the Taiwan belt (Huchon et al., 1986), the detailed mechanism of indentation has rarely been discussed. This lack of information has led previous researchers to describe the indenter as a rigid domain of constant shape that moves uniformly. This assumption seems oversimplified. We believe that the indentation should instead be considered as a nonuniform process in time, involving possible changes in the kinematics and shape of the indenter.

The aim of this paper is to define a more realistic model of indentation. We examine the tectonic features in a fold and thrust belt where indentation is thought to be the major driving mechanism (i.e., the Jura Mountains, France). The results of an extensive mechanical analysis of fault-slip data conducted in the entire belt led us to revise the mechanism of the Jura indentation. This Jura case example of an evolving indentation process offers new research lines for the understanding of tectonic features in other areas where indentation has occurred.

WHAT IS THE JURA INDENTER ?

The Jura Mountains are a thin-skinned fold and thrust belt that underwent about 30 km of total shortening in Miocene-Pliocene time (Guellec et al., 1990) during the Alpine orogeny. The frontal thrust of the Jura cover over the Bresse-Rhine graben is the outermost thrust of the western Alpine orogenic belt (Fig. 1A). Palinspastic reconstructions before the Neogene movements show that the situation in the Jura was not favorable for gravity sliding (Laubscher, 1973). At that time, the Jura was a wedge, the northwest part being the sharp edge. The wedge was later pushed northwestwards, that is, against gravity. The base of the wedge is a decollement level within the Upper Triassic evaporites; the decollement is rooted, as inferred from seismic profiles (Guellec et al., 1990), below the external crystalline massifs (Fig. 1B). Thus, gravity cannot be invoked at a regional scale for the Jura emplacement, which is related to the push of the hinterland.

The lack of major gravity effects in the Jura led workers to explain the fan-shaped distribution of compression trends within the belt (Plessmann, 1972) in terms of indentation by the hinterland. Laubscher (1972) located the front of the indenter at the northern Alps front (i.e., the southern Molasse boundary; Fig. 1A). However, due to the greater thickness of its cover compared to that of the Jura Mountains, the Molasse basin should be considered as part of the indenter, as suggested by Vialon et al. (1984) and Burkhard (1990). This rigid behavior is supported by the absence of large deformation in the basin (Burkhard, 1990), except locally in the Bavaria molasse (eastern Molasse basin). The movement of the indenter was first described as a clockwise rotation of about 7°. Later, a translation of the indenter, westward or northwestward, was suggested (Burkhard, 1990). The far-field Miocene-Pliocene compression characterized in the Jura foreland trends northwest-southeast on average (Bergerat, 1987; Lacombe and Angelier, 1993). This direction resembles that of the Africa-Eurasia relative motion during this period (Le Pichon et al., 1988). It is thus likely that the Jura indenter moved in a northwest direction relative to western Europe.

In the light of the geologic data presented here, we consider that the Jura indenter includes the Molasse basin which moved northwestward. However, tectonic data suggest that the Jura Alpine deformation is more complex than expected. First, two directions of displacement of the cover, making an angle of 45°, were identified within Triassic layers in the northern Jura (Jordan et al., 1990). Second, two compressions, both related to the Alpine phase, were inferred from microtectonic data (Sopena and Soulas, 1973). Because this superimposition of compression during the Miocene-Pliocene deformation has been recognized at various localities within the Jura belt, it does not reflect local effects. Instead, it corresponds to actual polyphase deformation of the Jura, which deserves attention.

TECTONIC EVIDENCE FOR A TWO-STAGE ALPINE COMPRESSION IN THE JURA MOUNTAINS

To decipher the Alpine tectonic evolution of the Jura, we performed an extensive mechanical analysis of brittle tectonic features (striated faults, tension gashes, and stylolites) collected in the entire belt. Three main phases of deformation were identified. The first two are not discussed herein, as they are thought to relate to earlier events that affected the Jura belt, namely, the Pyrenean orogeny (Eocene) and the Oligocene rifting of the European platform. This paper focuses on the Miocene-Pliocene Alpine events. The detailed stress pattern, reconstructed from the analysis of ~10 000 brittle structures at 200 sites, is illustrated in Figure 1C. We used the inversion method of Angelier (1990), which determines the directions of the three principal stresses, σ_1, σ_2, and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$, compression positive). Because horizontal block rotations are <8° in the Jura Mountains, as shown by paleomagnetic studies (e.g., Gehring et al., 1991), the stress tensors reconstructed from fault data reliably reflect the initial orientations of the principal stresses. Most of the data were collected away from major fault zones, that is, out of large deformation zones, so that strain can be viewed as small and coaxial, with stress to a first approximation. Attribution of each stress state to the Alpine phase (Fig. 1C) was based not only on the stratigraphic-structural determinations of Miocene-Pliocene age for folding and displacement of the Jura cover, but also on local relative chronologies between brittle structures (e.g., crosscutting relationships, and superimpositions of striations on fault surfaces) and criteria establishing the age of structures relative to folding (Fig. 2). For a full description of the method (e.g., attribution of each stress state to a given tectonic event, and quality estimators), see Homberg et al. (1994).

As shown in Figure 1C, the Alpine stress field is relatively simple in the central and northern Jura, and a fan-shaped compressional stress pattern can be reconstructed. From north to south, the average direction of compression

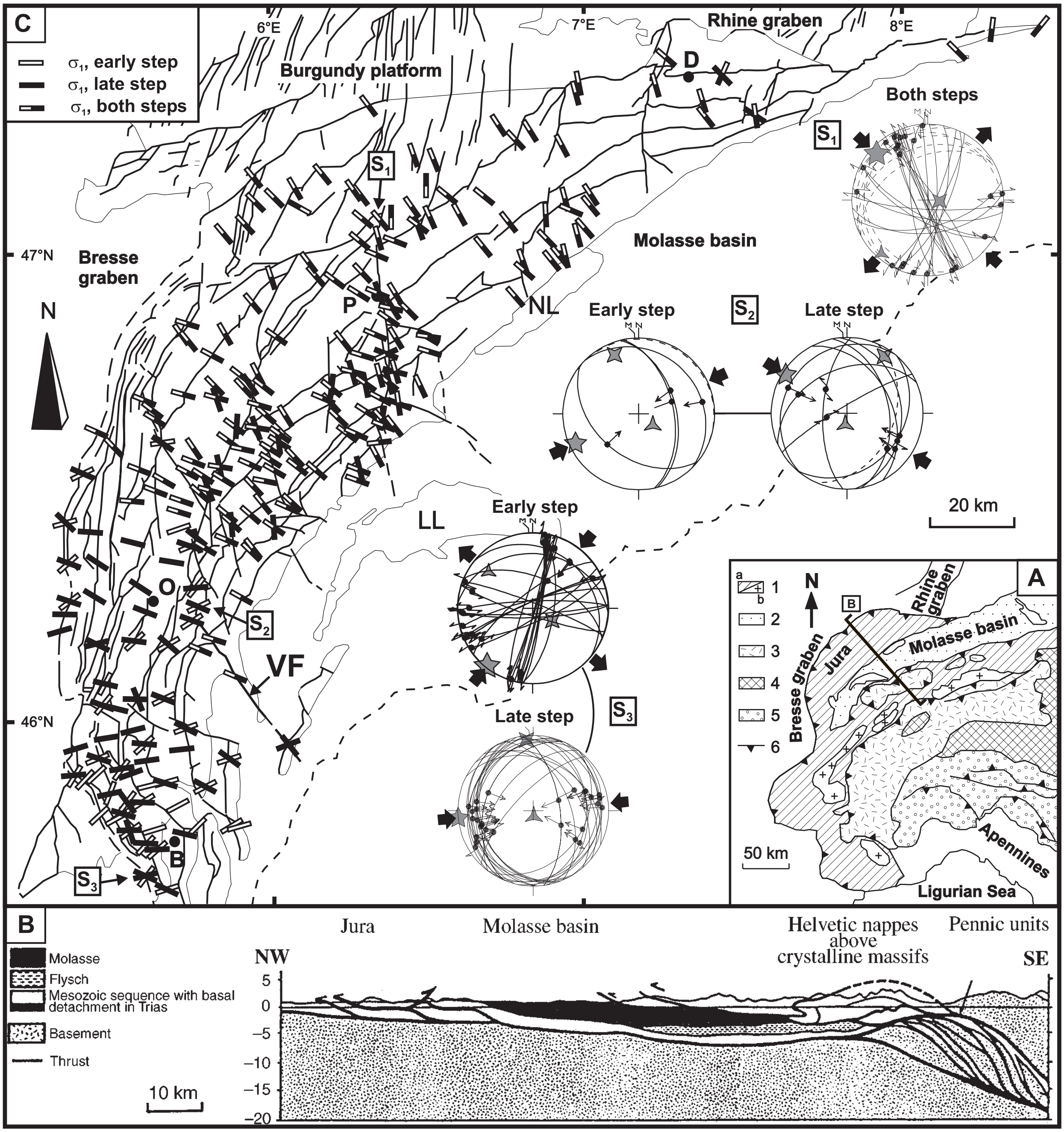

Figure 1. A: Simplified map of Alps and location of Jura belt. 1: External zones; a, cover (Jura and Helvetic nappes) and b, basement. 2 and 3: Penninic units and Austro-Alpine domain (internal zones). 4: Miocene molasse. 5: Pliocene-Quaternary infill of Pô plain. 6: Major thrusts. B: Cross section from Jura Mountains to external Alps. Modified from Vann et al. (1986). See A for location. C: Miocene-Pliocene stress field. Open and black bars show calculated directions of compression (σ_1) for early and late deformation steps, respectively. Fault-slip data (lower hemisphere, equal-area projection) are shown for three sites (S_1, S_2, and S_3). Continuous lines are fault planes; dots with double and inward-directed arrows are slickenside lineations for strike-slip and reverse motion, respectively. Dashed lines are bedding planes. Gray stars with 5, 4, 3 arms: σ_1, σ_2, and σ_3, respectively. Convergent and divergent large black arrows show directions of σ_1 and σ_3, respectively. Cities: Délémont (D), Pontarlier (P), Oyonnax (O), and Belley (B). VF: Vuache fault. NL and LL: Neuchâtel and Léman lakes.

varies from N160° to N120°. In contrast, in most sites of the southern Jura, the Alpine phase included two successive compressions (Fig. 1C). Chronologies between structures indicate that the compression direction rotated clockwise about 45° during the Miocene-Pliocene. For each of these two events, the compressional trajectories are fan shaped. In the southern Jura, the first compression trends N060° in the north to N045° in the south, whereas the second compression trends N120° in the north to N090° in the south (Fig. 1C).

The age of fracture development and related stress regime with respect to folding can be obtained following the Andersonian model, with one vertical principal stress. If this criterion is fulfilled for the stresses calculated with backtilted faults (rotation around the local bed strike of the amount of tilting), faults have moved before folding. If it is fulfilled with the present attitude of faults, fault slips postdated folding. Chronological data indicate that the late compression in the southern Jura always postdated folding (Fig. 2). Most of the brittle structures associated with the earlier compression predated folding, but some of them occurred after folding. The first and second compressions in the southern Jura are therefore associated with prefolding and postfolding steps of deformation, respectively. Because the Miocene-Pliocene compression identified in the central and northern Jura is the same for both steps, it is representative of the entire major deformation. Considering the entire Jura, both of the distributions of compressions associated with these two steps are fan shaped (Fig. 1C), but the angles of the fans differ, reaching 115° (compressions trending N160°–N045°, from north to south) for the prefolding step, and only 70° (compressions trending N160°–N090°, from north to south) for the postfolding step (Fig. 1C).

DISCUSSION: DID MULTIPHASE INDENTATION OCCUR IN THE JURA ?

As shown in Figure 3A, the compression pattern in front of a rigid indenter, as inferred from analog modeling experiments (e.g., Peltzer and Tapponnier, 1988), is fan shaped. Processes other than indentation that could generate such a stress field at a regional scale (e.g., gravity) are not indicated for the Jura case. For this reason, we believe that the two deformation steps in the Jura (Fig. 1C) reflect a major change in the mechanism of indentation. The theoretical stress field has the following characteristics (Fig 3A). First, on a line parallel to the indenter front, the directions of com-

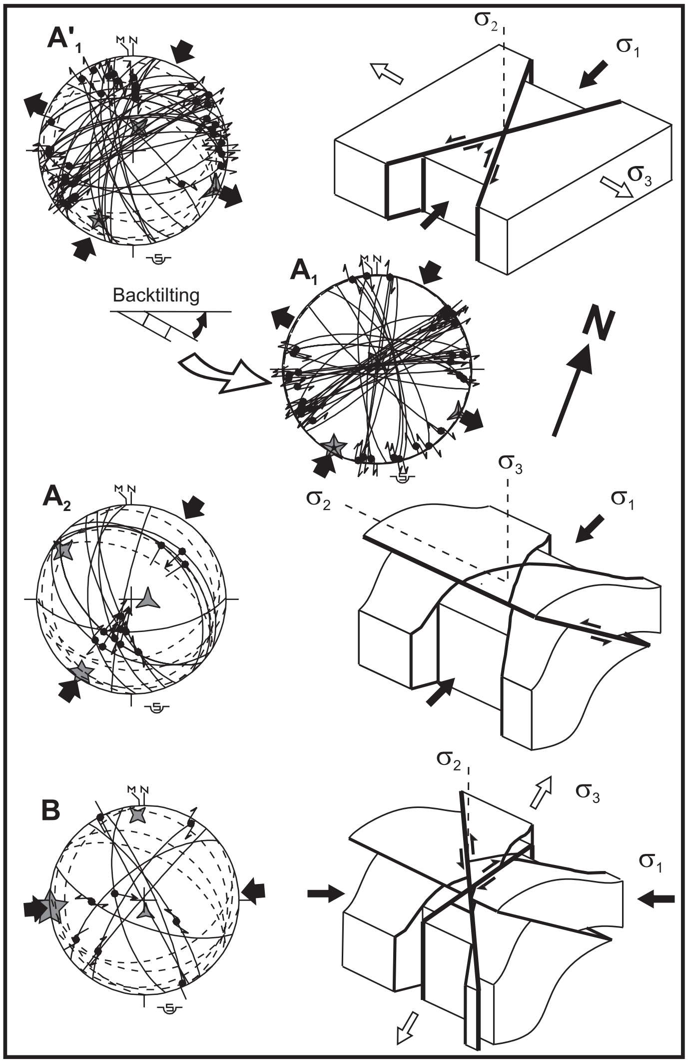

Figure 2. Two inferred Alpine compressions in southernmost Jura. Fault data collected at one site indicate three stress states (A_1, A_2, B). A_1 (strike-slip regime) and A_2 (reverse regime) both show N045° direction of compression (first step of deformation). Strike-slip regime took place before folding (see explanation in text). Faults and corresponding stress state are shown before (A'_1) and after (A_1) backtilting. Note that σ_2 is close to vertical after backtilting (cf. A'_1 and A_1). Misfit estimators of inversion process (not discussed here) are also largely improved after backtilting. Direction of compression in state B is N090°; it is associated with second, postfolding deformation step. Block diagrams illustrate successive deformations and stress states.

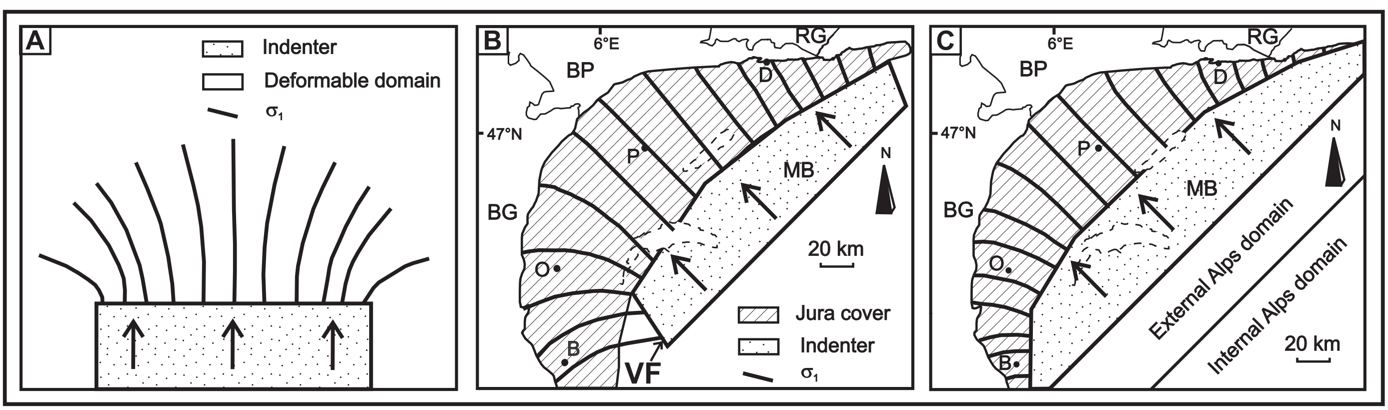

Figure 3. Mechanism of indentation of Jura belt. A: Theoretical distribution of compressions in front of rigid indenter. B and C: Two steps of indentation, before and after folding, with proposed distribution of compressions. Arrows indicate indenter movement. BG, Bresse graben; RG, Rhine graben; BP, Burgundy platform; MB, Molasse basin; VF, Vuache fault. Neuchâtel and Léman lakes are shown by dotted lines. Same symbols for cities as in Figure 1. See explanation in text.

pression exhibit increasing deviation as the distance from the middle of the indenter front increases. This deviation occurs clockwise on the right side and counterclockwise on the left side, with respect to the central direction. Second, the central direction of compression, occurring in front of the indenter center, is nearly parallel to the movement of the indenter and approximately corresponds to the undeviated far-field stress.

Our interpretation for the superimposition of the two inferred Miocene-Pliocene stress fields in the Jura belt (Fig. 1C) is illustrated in Figure 3 (B and C). The stress fields for each indentation step are inferred from modeling results (Fig. 3A). In light of the numerical results on different indenter shapes of Huchon et al. (1986), we believe that changing the shape of the indenter from Figure 3A (perfect rectangle) to Figure 3, B and C (irregular domain) does not drastically change the stress distribution. Concerning the prefolding episode, the distribution of compressions, exhibiting a larger deviation of the compressional trends in the southern Jura than in the northern Jura (Fig. 1C), is in agreement with an indenter of restricted extension to the southwest (Fig. 3B). The better candidate for the southwest boundary of the indenter is the major Vuache fault. This fault cuts through both the cover and the basement and is thought to have formed during the Oligocene rifting or the Variscan orogeny (Wildi et al., 1991). After folding, the indenter extended to the entire Molasse basin (Fig. 3C). The behavior of the entire basin as a single block at this stage is probably related to a decrease of the decoupling on the Vuache fault. This final shape of the indenter accounts well for the late pattern of stress trajectories in the Jura, characterized by a fan-shaped distribution nearly symmetrical relative to the central undeviated northwest-southeast direction of compression (Fig. 1C).

CONCLUSIONS

A detailed tectonic study conducted in the fold and thrust arcuate Jura belt led us to recognize two superimposed stress fields, both related to the Alpine phase of deformation. This confirms, as suggested by Homberg et al. (1997), that several stress states at a single locality can be related to a single tectonic phase. This superimposition has been related to a change with time of the indenter width.

The Jura case demonstrates that indenters should not be considered as simple moving rigid blocks. It is likely that in most cases, the indentation process is nonuniform in time. One of the factors controlling the mechanism illustrated here is the presence of deep discontinuities controlling the size of the indenter. These discontinuities act as decoupling surfaces with easy sliding, which may behave as transfer faults if appropriately oriented. Because the dynamics of sliding change with time, such transfer faults of indenters may or may not be active, so that the shape of the indenters also changes, leading to major modifications in the deformation pattern within the deformable facing domain. This major role of the decoupling on large faults should be generalized to most regional block displacements.

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