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Aspects of the large-scale Miocene deformation in the most external part of the Swiss Alps (Subalpine Molasse to Jura fold belt)

By MARTIN BURKHARD[1])

ABSTRACT

Four cross-sections through the frontal part of the NW Swiss Alps are compiled, interpreted and restored. Strictly speaking, balancing of these sections is impossible because too much information is lacking. After filling gaps with geologically reasonable hypotheses regarding thrust geometry and kinematics, a minimum of 25 to 30 km shortening between the NW mountain front and the crest line of the Aarmassif is obtained. This shortening is constant across the major cross-strike structural discontinuity which is represented by the disappearance of the Jura fold and thrust belt in the east. The decreasing importance of Jura shortening toward the east is supposed to be compensated by an eastward increase in shortening within the Subalpine Molasse belt. The two most external alpine deformation zones: Jura and Subalpine Molasse, are proposed to be formed in an "en échelon" array in front of a large indenter, represented by the main body of the Alps and the external crystalline massifs in particular. Thereby, the seemingly undeformed Plateau Molasse of central Switzerland had to undergo either a 7° clockwise rigid body rotation (LAUBSCHER's model 1961) or, alternatively, a corresponding dextral shearing deformation. Different possible indenter models to explain the Jura arc are discussed and compared with the observed type of deformation within the Jura and its hinterland, the Molasse basin. The Jura arc itself is best explained with a deformable indenter (the Plateau Molasse) with a more or less constant overall transport direction to the NNW or NW. Some divergence of transport directions in the western Jura could be compensated by late alpine NE-SW extension in the western Molasse basin and the external parts of the Alps in the Rawil area.

ZUSAMMENFASSUNG

Vier Querprofile durch die frontalen Schweizer Alpen werden zusammengestellt, interpretiert und abgewickelt. Strenggenommen fehlt dabei zuviel Information um die Profile wirklich zu «balancieren». Nachdem Lücken mit geologisch plausiblen Hypothesen betreffend die Geometrie und Kinematik der Überschiebungen gefüllt wurden, erhält man Mindestwerte von 25 bis 30 km horizontaler Einengung zwischen der Deformationsfront im NW und der Kulmination des Aarmassivs. Diese Einengung bleibt im Streichen konstant, obwohl der Jura von West nach Ost stark an Bedeutung verliert und dann ganz verschwindet. Die ostwärtige Abnahme des Verkürzungsbetrages im Jura scheint durch ostwärts grösser werdende Verkürzungsbeträge in der Subalpinen Molasse kompensiert zu sein. Es wird vorgeschlagen, dass sich die beiden externsten alpinen Deformationszonen (Jura und Subalpine Molasse) gleichzeitig in einer «en échelon» Anordnung bildeten. Die Hauptmasse der Alpen, insbesondere die externen Kristallinmassive, wirkten dabei als eine mehr oder weniger rigide Schubmasse. In diesem Modell wird die scheinbar undeformierte Plateau-Molasse der Zentralschweiz entweder «en bloc» um 7° im Uhrzeigersinn rotiert (LAUBSCHER 1961), oder entsprechend dextral geschert. Verschiedene «Indenter» Modelle zur Erklärung des Jura-Faltenbogens und deren Auswirkung auf den Jura selbst sowie dessen Hinterland, das Molassebecken, werden diskutiert. Der Jurabogen wird am einfachsten mit einem deformierbaren «Indenter» mit NNW bis NW gerichteter Transportrichtung erklärt. Divergierende Transportrichtungen im westlichen Jura könnten durch spätalpine NE-SW Streckung im westlichen Molassebecken sowie im Rawilgebiet kompensiert sein.

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RÉSUMÉ

Quatre coupes géologiques à travers la partie frontale des Alpes suisses sont compilées, interprétées et restaurées. Trop de lacunes d'information interdisent une équilibration dans un sens stricte de ces coupes. Après avoir remplacé ces lacunes par des hypothèses raisonnables concernant la géométrie des chevauchements ainsi que la cinématique, un minimum de 25 à 30 km de raccourcissement est obtenu entre le front de la déformation au NW et la linge de crête du massif de l'Aar. Ce raccourcissement reste constant à travers la discontinuité latérale que représente la disparition du Jura à l'est. La diminution du taux de raccourcissement dans le Jura en direction est, est apparemment compensé par une augmentation de la déformation dans la Molasse Subalpine en allant de l'ouest vers l'est. On propose de considérer ces deux zones externes de déformation tardive dans les Alpes, le Jura et la Molasse Subalpine, comme étant formées en échelon au front des Alpes centrales et surtout des massifs cristallins externes, faisant office de poinçon plus ou moins rigide. La Molasse du Plateau de la Suisse centrale doit par conséquent soit avoir subi une rotation de 7° dans le sens horaire (Laubscher 1961) soit être cisaillé dans le sens dextre. Afin d'expliquer la formation de l'arc jurassien, différents modèles de poinçon possibles sont discutés et comparés avec les déformations observés dans le Jura et son arrière pays, le Plateau. L'arc du Jura s'explique le plus facilement par un poinçon, lui-même déformé, avec une direction de transport plus ou moins constant vers le NNW voire le NW. Une certaine divergence des directions de transport dans le Jura occidental pourrait être compensé par une extension NE-SW tardi-alpine dans le bassin molassique, les Préalpes ainsi que la région du Rawil.

1. Introduction

The Jura fold and thrust belt represents the most external part of the Alpine chain in its northwestern sector (Fig. 1). Horizontal shortening in the Jura takes place above a basal decollement horizon within Triassic evaporites and the corresponding basement shortening is believed to be compensated somewhere in the Alps proper ("Fernschub-hypothese" Laubscher 1961). With this model any NW-SE cross-section through the frontal part of the Alps can be made "balanced" and "consistent" with surface geology (Boyer & Elliott 1982; Mugnier & Ménard 1986), mainly because large rockvolumes in an unexposed zone beneath the Helvetic chain in front of the external crystalline massifs allow for considerable freedom in interpretation regarding thrust geometry at depth. This thrust geometry is crucial for the understanding of the NW alpine front and represents still a matter of controversy in alpine tectonics. Apart from this geometric uncertainty in Alp-Jura cross-sections, there is also a problem with the lateral continuity of thrusts. In particular the arcuate form of the Jura foldbelt and its eastern termination in the Lägern anticline still awaits a satisfactory kinematic explanation (Laubscher 1961, 1965, 1973, 1980). East of Zürich, where no Jura fold belt exists anymore, the alpine deformation front steps back to within the Molasse basin (Fig. 1). The northern border of "deformation" is not sharply defined and is associated with a blind thrust ending somewhere beneath the Plateau Molasse. Shortening above an assumed basal decollement at the base of the Tertiary leads to intense thrusting of the most internal Subalpine Molasse and a prominent triangle zone (recently identified as such by seismic and drill hole data (Bachmann et al. 1982; Müller et al. 1988) marking the transition between Plateau and Subalpine Molasse. This triangle zone can be followed westward into the Entlebuch where it seems to disappear.

Two tectonic problems associated with the large-scale deformation of the Jura fold and thrust belt are approached: 1) Where is the Jura cover shortening compensated in the basement? 2) What are the geometric consequences of the Jura arc for the hinterland (Molasse basin and Alps) in terms of deformation both in cross-sections and in map view. The viability of current tectonic models for the formation of the Jura arc will

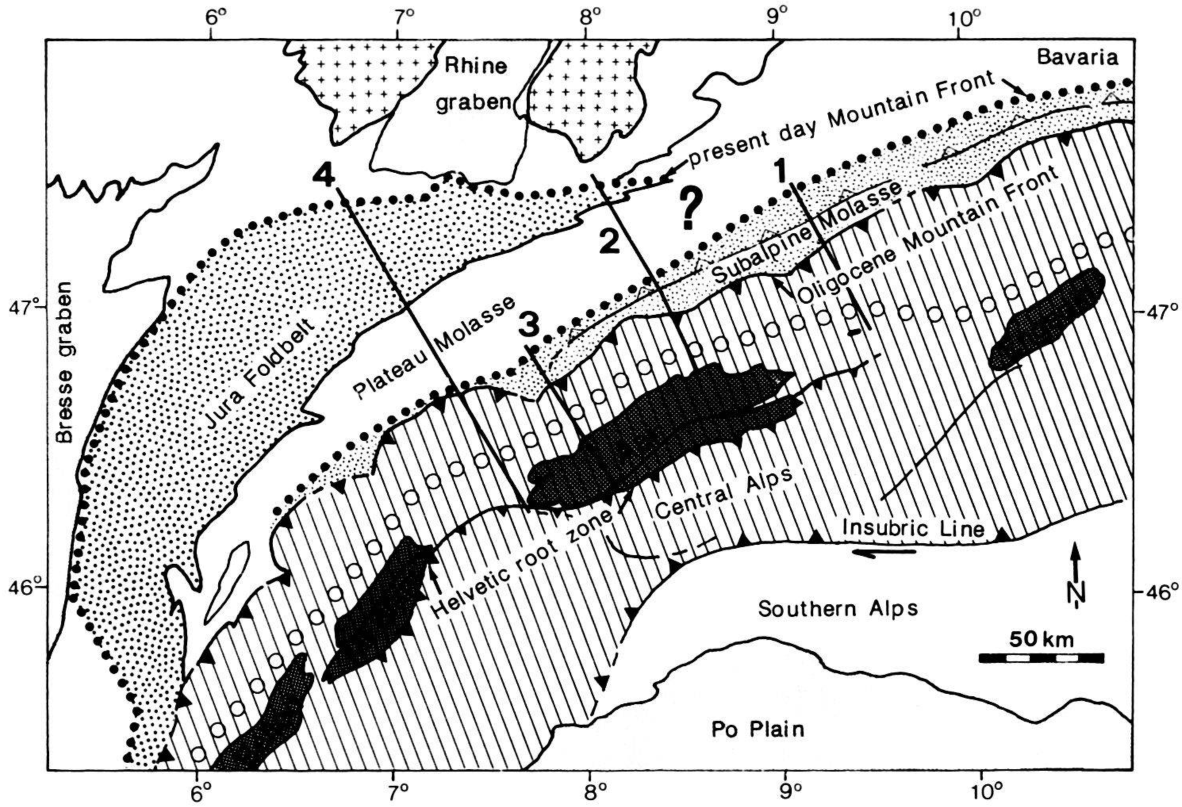


Fig. 1. General tectonic situation of the Jura fold and thrust belt in the most external part of the NW Swiss Alps. Major tectonic units referred to in the text are labelled. Bold NW-SE lines mark the position with corresponding number of sections shown in Fig. 3. The question mark (at Zürich) indicates the position where the present day deformation front (dotted line) steps from the Jura back to the Subalpine Molasse without leaving any obvious trace. Within the Subalpine Molasse, only the late Miocene backthrust (triangle zone) is distinguished. Open circles mark the approximate position where the latest alpine sole thrust is thought to cut downward into the crystalline basement.

be discussed: can the predicted deformations be identified in the Molasse basin?, in the Alps?

Ideas presented in this paper are based on the well established balanced cross-sections for different parts of the Jura (LAUBSCHER 1961, 1965; MUGNIER & VIALON 1986; GUELLEC et al. 1990) and new "balanced" sections across the Molasse basin that will be discussed in more detail. By combining the two areas (Jura and Subalpine Molasse), deformations of the most external parts of the Alps back to the crest line of the Aar massif can be restored. Surprisingly, only few attempts to restore this last and shallowest deformation of the Alps have been published (MUGNIER & VIALON 1986; PFIFFNER 1986; GUELLEC et al. 1989, 1990). A better understanding of the most external alpine deformations has implications for the tectonic interpretations in the hinterland, i.e. the Plateau Molasse, the external crystalline massifs and possibly the arc of the western Alps in general.

2. General aspects of section balancing in frontal parts of the Alps

There will never be enough surface geology, drillhole and seismic data to completely unravel the entire frontal alpine thrust system. Therefore, in order to balance cross-sections, more or less important gaps have to be filled with hypotheses. The most significant uncertainties are the following: the precise thrust geometry at depth, the thickness of Molasse strata, the tectonic style, the depth and geometry of basement and the internal deformation. Major assumptions regarding thrust geometry have to be made for any cross-section through the alpine front (Fig. 2). For instance, the "Fernschub" of the Jura folding, i.e. the assumption of a basal decollement reaching backwards into the Alps, although widely accepted, still has its opponents (PAVONI 1961; ZIEGLER 1982, Fig. 26; for a detailed discussion see LAUBSCHER 1961, 1980). Recently, GEHRIG et al. (in press) presented new paleomagnetic evidence in favour of the "Fernschub-model" and against an "in situ" Jura folding above strike-slip faults in the base-

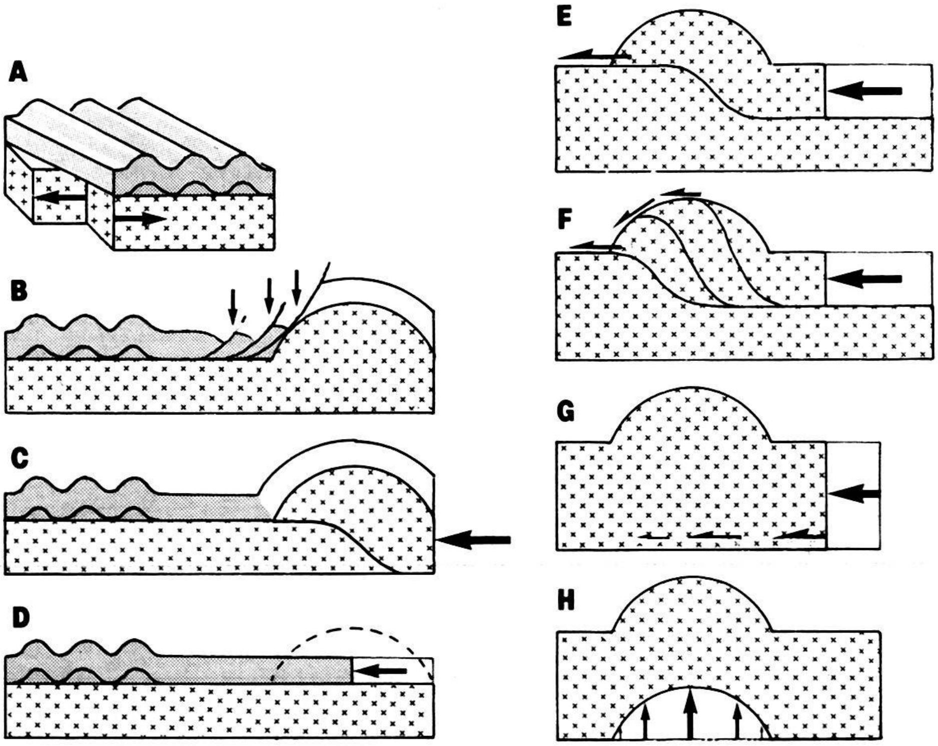


Fig. 2. Conceptual models of Jura- and/or Molasse-shortening and possible relationships with the external crystalline Aarmassif. A first series of sketches illustrates the four fundamentally different possibilities to explain shortening in the Jura (or Subalpine Molasse):

A) "In situ" formation without "Fernschub" – i.e. as wrench folds above strike-slip faults in the underlying crystalline basement (PAVONI 1961; compare also PLANCHEREL 1979 for the Pennine Prealps).

B) Shortening in the foreland is compensated by extension above the pre-existing or rising Aarmassif (LAUBSCHER 1965).

C) External thrusts root in a basal sole thrust; shortening in the external zones is contemporaneous and directly linked with thrusting and uplift of the Aarmassif (e.g. BOYER & ELLIOTT 1982).

D) External thrusts root in the Helvetic thrust system, behind the Aarmassif. The latter raises after thrusting of the Jura (LAUBSCHER 1973).

A second series of sketches illustrates different tectonic interpretations of the external crystalline Aarmassif:

E) "Mega Fold bend fold" above a sole thrust and frontal ramp

F) Antiformal stack of several thrust imbricates (BOYER & ELLIOTT 1982).

G) Localized ductile deformation with horizontal shortening and subvertical stretching (as seen today within the massif) (MARQUER 1990).

H) Differential vertical uplift ("isostatic") with no horizontal shortening (NEUGEBAUER et al. 1980).

ment as proposed by Pavoni (1961; sketched in Fig. 2A). If one accepts the "Fernschub" there are still various possibilities to compensate the Jura shortening within the Alps (Fig. 2B, C, D). The same situation exists for the Subalpine Molasse. These thrusts may be splays off a postulated alpine sole thrust (Boyer & Elliott 1982), they may "root" in thrusts within the still buried frontal part of the external crystalline Aar massif, they may be connected with the Helvetic thrust system "rooting" behind this massif or, alternatively, be due to gravity gliding phenomena, compensated by stretching above the antiform of the external crystalline massifs. Thus, any restoration of the frontal part of the Alps inevitably has to deal with the tectonic interpretation of the external crystalline massifs and their geometry at depth (Fig. 2E-H).

2.1 External crystalline massifs

In the reconstructions presented here, all of the frontal thrusts (basal Jura decollement and Subalpine Molasse schuppen) are rooted either beneath the Aar massif or within its northern flanc. This seems the only viable solution for balancing and timing reasons as will be discussed below. According to Müller & Briegel (1980), this is also the most plausible model for mechanical reasons. A different interpretation is given by Laubscher (1973, Fig. 6): the external thrusts are connected with basal Helvetic thrusts and consequently the uplift of the massif would have to post-date the Jura-thrusting. In the interpretations presented here, uplift in the massifs is directly related with thrusting of the massifs either by several thrust slices forming an "antiformal stack" (Fig. 2F) and/or by thrusting over a ramp within the basal thrust (Fig. 2E: the Aar massif being a "mega fold bend fold"). Internal deformation with subvertical schistosities and lineations in the central Aar massif could be explained by essentially vertical differential shear (Fig. 2G) (Marquer 1990, Fig. 14). The schistosity as seen today in these parts of the massif, however, could have been (back-)rotated into its steep position. Whatever the significance of the steep schistosities in the massif is (original position vs. reoriented), there is no equivalent found in cover units immediately above the Aar massif and if any vertical stretching of the basement occured, this seems to be transferred into NW-ward thrusting at the basement/cover contact and could thus add to the NW displacement along more external thrusts.

Internally consistent NW-SE cross-sections can be drawn with the hypothesis of a direct connection between a basal Aarmassif-thrust and external (Jura, Molasse) thrusts. 3-D difficulties, however, arise at both lateral extremities of the Aar massif (compare Fig. 1): The Aar massif culmination disappears east of the Vättis inlayer but shortening in the Molasse continues to exist far to the east in Bavaria. The western Aar massif has no direct connection with the Mt. Blanc-Aig. Rouges culmination whereas Jura- and/or Molasse-thrusts in front of the Rawil depression do not reflect this lateral discontinuity (for a different opinion see: Chenevart & Riesen 1985). This problem could be overcome by the assumption of a more complex geometry in the basal sole thrust (lateral ramps, changes in dip of the frontal ramp, as proposed by Burkhard 1988b, Fig. 6) for the Rawil depression. Similar lateral "relais" could be postulated between the Aarmassif, Engadin- and Tauern-windows. The dextral "en échelon" pattern of these culminations, caused by a Miocene "transpression" according to Laubscher (1988, p. 1317ff.), requires such transverse zones unless the culminations were explained by differential vertical uplift (Fig. 2H) – in which case the culminations were not compressional. The Rawil depression is the only place to date where map- and outcrop-scale deformations in cover units have been directly related to such a transverse zone in the basement (HUGGENBERGER & AEBLI 1989).

2.2 Shortening in the Jura fold and thrust belt

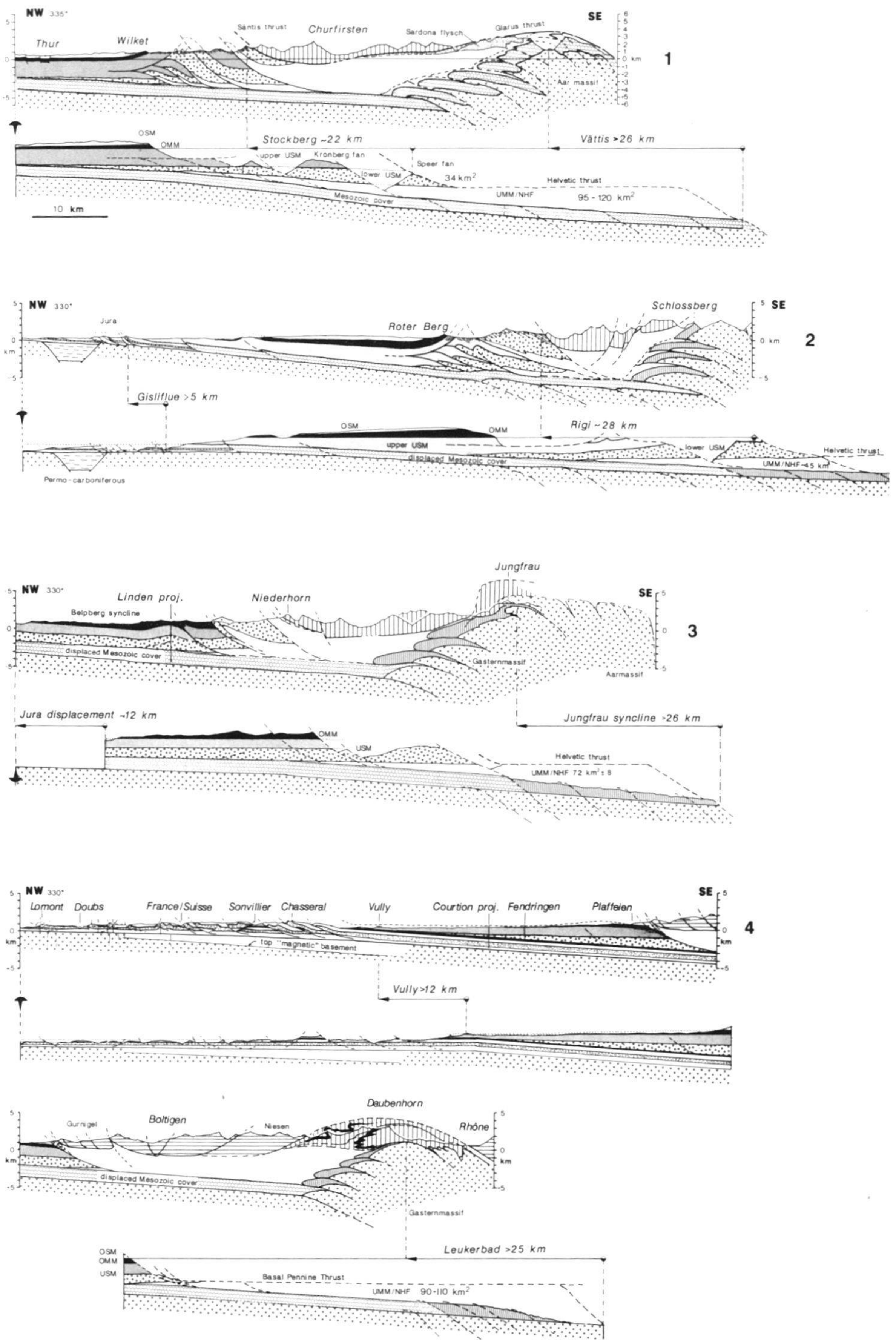
Shortening in NW-SE to N-S cross-sections of the Jura fold and thrust belt has been determined by LAUBSCHER (1965) in a pioneer article on cross-section balancing. All fundamental questions regarding cross-section balancing in the Jura are discussed in this article and will not be repeated here. Wherever new data became available, LAUBSCHER'S shortening estimates were confirmed or increased (MÜLLER et al. 1984, Beil. 2; MUGNIER & VIALON 1986; LAUBSCHER 1986; BITTERLI 1988, 1990; GUELLEC et al. 1990). Since accessible seismic and drill hole data are still scarce in large parts of the Jura, section balancing relies on the assumption of a more or less flat basal decollement horizon. Together with the well-known geometry of the top Malm, total shortening of the Jura can be determined without knowing any details of the internal structure (LAUBSCHER 1965; MUGNIER & VIALON 1986). Based on this assumption, cross-sections through the Neuchâtel Jura require between 8 and 12 km of bulk shortening. Further west, MUGNIER & VIALON (1986), GUELLEC et al. (1990) determine 25 to 30 km net shortening, a number comparable to the 25 km obtained by LAUBSCHER (1965) for the Risoux section (see also BITTERLI 1972).

In summary and for all further discussions, shortening in the Jura is considered as increasing from nil east of the Lägern anticline to more than 25 km in central and western parts of the Jura. Estimated uncertainties of around 25% (MUGNIER & VIALON 1986) for shortening determined in any cross-section through the Jura will not significantly alter this general picture.

2.3 Shortening in the Molasse basin

The Swiss Molasse basin is classically subdivided into three areas: the flatlying Plateau Molasse, the folded and the thrusted Subalpine Molasse. Balancing of Molasse cross-sections is not as straightforward as in the Jura foldbelt. Unlike the well bedded, fairly constant and extremely well-known Mesozoic strata of the Jura, the Molasse basin is filled with wedge shaped (in cross-section) layers of clastics with only few marker horizons and laterally irregular sediment bodies (MATTER et al. 1980; HOMEWOOD 1986). The total thickness of sediments varies from several hundred metres in the north to 4 km and more in the south. Some drill hole data are available for the Plateau Molasse (e.g. MATTER et al. 1980) whereas in the tectonically more complex Subalpine Molasse both sedimentary thicknesses and geometry of thrust sheets have to be extrapolated over several km at depth as will be discussed below for four sections.

Fig. 3. Four cross-sections (1, 2, 3, 4) through the NW alpine front in Switzerland, see Fig. 1 for positions and tectonic context. Sections are approximately area-balanced and restored. In the restored sections only preserved units are shaded, eroded lithostratigraphic limits are dotted; dashed lines indicate thrusts. Compare lithostratigraphic Molasse units with Fig. 4 for legend and approximate age.


1
NW 335°
SE
Thur
Wilket
Säntis thrust
Churfirsten
Sardona flysch
Glarus thrust
Aar massif
0 km
OSM
OMM
Stockberg ~22 km
Vättis >26 km
upper USM
Kronberg fan
Speer fan
lower USM
34 km²
Helvetic thrust
UMM/NHF
95 - 120 km²
Mesozoic cover
10 km
2
NW 330°
SE
Jura
Roter Berg
Schlossberg
0 km
Gisliflue >5 km
OSM
OMM
Rigi ~28 km
upper USM
lower USM
Helvetic thrust
displaced Mesozoic cover
UMM/NHF ~45 km
Permo-carboniferous
3
NW 330°
SE
Jungfrau
Linden proj.
Niederhorn
Belpberg syncline
displaced Mesozoic cover
Gasternmassif
Aarmassif
Jura displacement ~12 km
Jungfrau syncline >26 km
OMM
USM
Helvetic thrust
UMM/NHF 72 km² ± 8
4
NW 330°
SE
Lomont
Doubs
France/Suisse
Sonvillier
Chasseral
Vully
Courtion proj.
Fendringen
Plaffeien
top "magnetic" basement
Vully >12 km
Daubenhorn
Gurnigel
Boltigen
Niesen
Rhône
displaced Mesozoic cover
Gasternmassif
Leukerbad >25 km
OSM
OMM
USM
Basal Pennine Thrust
UMM/NHF 90-110 km²

Despite the presence of minor gentle anticlines (1 to 5° dips) and synclines within the Plateau Molasse (SCHUPPLI 1950, 1952; ALTHAUS & RICKENBACH 1947; SPICHER 1980), this part of the cross-sections will be regarded as undeformed – the scale of the cross-sections presented in Fig. 3 does not allow to show these undulations. However, internal deformations in the Plateau Molasse does occur and an overall 20% "ductile" horizontal shortening has been determined by BREDDIN (1958, 1964; compare also SCHRADER 1988). This deformation seems to be incompatible with the gentle dip changes (20% shortening in the underlying stiff Malm layer should have lead to the formation of thrusts and folds), but if confirmed, it could add as much as 5 to 7 km to all the shortening estimates presented below and therefore increase the space problems associated with the homeland for the Jura and Subalpine Molasse.

2.4 "Balanced" cross-sections through the NW alpine front

2.4.1 Profile 1: Thurtal-Stockberg-Calanda (Fig. 3)

Profile 1 shows a cross-section through the frontal part of the Alps in eastern Switzerland. Emphasis is placed on the internal structure of the Subalpine Molasse whereas the older internal structures of the overriding Helvetic nappes are omitted. This section clearly illustrates the fact that a large cross-sectional area between the basal Helvetic thrust and the top of the crystalline basement is virtually unknown as far as its tectonic significance and internal structure is concerned. Any reconstruction of the northern border of the Alps is confronted with this problem and different solutions have been proposed (see TRÜMPY 1980; Fig. 8 and profiles; compare also: PFIFFNER 1985, Fig. 10 with PFIFFNER 1986, Fig. 4).

The section 1 in Fig. 3 passes far enough east of the Lägern anticline, to be "undisturbed" by the eastern end of the Jura fold belt. Within the Subalpine Molasse this section crosscuts two important gravel fans: the Late Oligocene Speer-fan and the Early Miocene Kronberg-fan, both belonging to the lower fresh water Molasse (USM) (HABICHT 1945). Recent investigations (BERLI 1985) in the Sommersberg fan revealed that even upper fresh water Molasse (OSM) may be present within the Subalpine Molasse schuppen south of the triangle zone. This finding has important consequences for both the restoration and the timing of tectonic events within the Subalpine Molasse. The known surface geology of this cross-section (LUDWIG 1930; HABICHT 1945; BÜCHI 1950; HOFMANN 1973, 1988) leaves much freedom in the extrapolation of the structures at depth and therefore, balancing cannot be done without far-reaching hypotheses. Some constraints concerning depth of the "top Mesozoic" are extrapolated from nearby drill hole data (BÜCHI et al. 1965a, b) and from recent seismic reflection profiling of the NFP-20 (PFIFFNER et al. 1988; STÄUBLE et al. in prep.).

The main characteristics of the interpretation given in profile 1 are the following: 1) The monoclinal structure at the southern margin of the flat-lying Plateau Molasse is interpreted as a triangle structure according to MÜLLER et al. (1988). 2) The Subalpine Molasse thrust sheets are approximately area-balanced using a hypothetical thickness of lower USM of about 2 km in the Stockberg slice. Note that the assumed geometry of these schuppen has only little effect on the shortening estimate. 3) The remaining 95 to 120 km^2 (depending on the assumed geometry of the top Mesozoic in front of the Aar massif) of lower marine Molasse (UMM) and north Helvetic Flysch (NHF) are redistributed into an original sedimentary wedge 2 to 4.5 km thick. Since these are maximum thicknesses, the resulting shortening distances: 22 km for Stockberg and 26 km for Vättis are considered minimum estimates. Even so, this solution requires a considerable (>26 km) shortening within (or beneath) the external crystalline Aarmassif which is schematically subdivided into four major crystalline thrust sheets, each having more than 6 km of displacement, despite the fact that no positive evidence for such large imbrications could be found with seismic reflection profiling (STÄUBLE et al. in prep.). Alternatively, this shortening could be derived from one single basal thrust beneath the Aarmassif (PFIFFNER 1985, Fig. 10), with crystalline basement overriding Mesozoic, or, less probably (for timing reasons; see below), from displacements along the Glarus thrust, which roots south of the Aarmassif.

2.4.2 Profile 2: Gisliflue-Rigi-Schlossberg (Fig. 3)

Section 2 through central Switzerland shows some folding and thrusting in the Jura (MÜLLER et al. 1984) and in a considerable portion of Subalpine Molasse. This section, according to BUXTORF et al. (1916) and SCHMID in FUNK et al. (1983, plate) is constrained at depth only by the approximate top of the crystalline basement beneath the triangle zone as projected over about 30 km along-strike from the Entlebuch well (VOLLMAYR & WENDT 1987). The Roter Berg monocline is interpreted as the continuation of the triangle zone drawn in Profile 1 and similarly, is stuffed with two hypothetical schuppen of USM. The proximal thickness of lower USM has to be more than 2 km as exposed in the Rigi slice. With only these data, the cross-section is poorly constrained and just one possible solution is proposed. Compared to the previous section, the unknown volume of UMM and NHF beneath the Helvetic thrust is considerably reduced, due to a shorter distance between the Subalpine Molasse front and the Aarmassif.

In order to restore some 5 km of Jura shortening, three basal thrusts are postulated to root beneath the frontal Aarmassif. Note that these thrusts do not step up through the Mesozoic cover but in the Jura mountains. Consequently, such thrusts may be extremely difficult to identify even in a detailed seismic survey (VOLLMAYR & WENDT 1987). Molasse thrusts are tentatively rooted in the frontal part of the Aarmassif – a solution which leaves just barely enough space on top of this massif to restore the entire cover shortening beneath the basal Helvetic thrust. The extremely steep frontal part of the Aarmassif is drawn as a stack of crystalline imbricates according to VOLLMAYR & WENDT (1987).

Spectacular normal faults seen within the Helvetic nappes could qualitatively be interpreted in terms of an "extensional collapse" model for the Jura formation (Fig. 2B) – restoring these normal faults, however, is by no means sufficient to explain the 5 km or more of Jura shortening.

2.4.3 Profile 3: Linden-Jungfrau (Fig. 3)

This profile cuts the Aarmassif where it is most elevated today. The Jura part has been omitted – the missing Jura shortening is estimated to be about 12 km (LAUB-

SCHER 1961, 1965). The top of the basement beneath the Plateau Molasse can be estimated from drill holes (Ruppoldsried and Linden 1, CHENEVART & RIESEN (1985) and RIGASSI in MATTER et al. (1980). The Subalpine Molasse is drawn according to BECK & RUTSCH (1958), completed at depth with a hypothetical south-looking fault propagation fold in order to explain the "Belpberg syncline" and the anticline north of Linden. The Helvetic nappes and (par-)autochthonous cover of the Gasternmassif are well exposed in deep valleys (e.g. ARBENZ 1934) and leave little freedom to the assumed position of the basal Helvetic thrust. The unknown volume of UMM and NHF can thus be estimated at 72 ± 8 km^2, depending on the assumed dip of the frontal Gasternmassif and the depth of the trough in front of this massif. Despite the enormous structural relief in front of the Aarmassif, there are no major late normal faults developed; however, ancient ones (Sundlauenen) may have been reactivated (JEANNIN 1990) and there could be some undetected late alpine NW-SE stretching in the lake Thun area.

2.4.4 Profile 4: Lomont-Chasseral-Plaffeien-Daubenhorn (Fig. 3)

Profile 4 crosses a large portion of Jura, a relatively narrow tabular Molasse basin and very little Subalpine Molasse dipping beneath the Pennine Prealps klippe. The french Jura section is constructed from the french geologic maps (BRGM 1:50,000; sheets Montbéliard, Maîche, Damprichard). This part of the Jura is characterized by steep N-S running, so called rhenish faults which predate the folding and thrusting of the Jura. Folds in this part of the Jura might also be older than the main thrusting and could be related to strike-slip deformation connecting the Rhine- with the Bressegraben. Depth of basement is extrapolated from the known stratigraphic thickness (Buez drill hole; BITTERLI 1972). Assuming a flat basement beneath the French Jura, area balancing indicates some 3 to 5 km of shortening between the Lomont anticline and the french/swiss border. The swiss part of the Jura is drawn according to sections by BOURQUIN & SUTER (1946), SCHÄR (1971). The swiss section is approximately balanced assuming a flat basal decollement horizon in the Triassic and no doubling of sedimentary series beneath Sonvillier, nor beneath Vully, which results in 5 to 7 km of shortening. The top of the "magnetic basement" as determined by KLINGELE & MÜLLER (1987) is considerably deeper than the top basement as predicted for a single Mesozoic sedimentary pile. This discrepancy could be due either to the presence of Permo-Carboniferous sediments, a deep seated magnetic anomaly or, alternatively to a doubled series of Mesozoic sediments. The latter possibility would have important consequences for the Jura shortening which could be virtually doubled. The tabular Molasse section is constrained by drill hole data (CHENEVART & RIESEN 1985, Fig. 1): Fendringen and Courtion, projected over 3 and 10 km respectively; compare also with RIGASSI in MATTER et al. (1980, Fig. 5). The southern part of the section is compiled from SCHMID (1970), DE KAENEL et al. (1989), MOSAR (1989) and BURKHARD (1988a). A large unknown rockvolume is hidden beneath the basal Prealpine thrust, in front of the external crystalline Gastern massif. This massif is cut here in an atypical position, on its western border, where it plunges laterally 10 to 20° (out of the cross-section) into the Rawil depression. The estimation of 110 km^2 of UMM and NHF (and USM?) is dependent on the precise geometry of the basal Pennine thrust and the northern flanc of the Gastern massif, the depth of the autochthonous basement and cover beneath the

Prealps and the presence or absence of imbrications within this Mesozoic cover units. Still, these 110 km^2 of unknown tectonic units may hide a substantial amount of shortening that would have to be added to the estimated 20 or so km of NW-ward displacement of the Gasternmassif top.

As a preliminary conclusion of this section, it appears that balancing in the Subalpine Molasse zone and a hidden area beneath the Helvetic and/or Pennine Prealpine nappes leaves considerable freedom to interpretations and restoration of cross-sections. Despite all these uncertainties, the amount of shortening associated with thrusts affecting the Subalpine Molasse, mainly USM, seems to be increasing from west to east. This trend is opposed to the eastward decreasing importance of the more external Jura fold and thrust belt. The two deformation belts together (Jura and Subalpine Molasse) seem to result in a more or less constant shortening of around 25 km between the most external deformations and the crest line of the Aarmassif.

3. Timing of Deformation:
Folding in Jura and Molasse basin vs. uplift of the external crystalline massifs (Fig. 4)

3.1 Jura folding

The timing of Jura deformation has recently been reviewed by NAEF et al. (1985) and LAUBSCHER (1987). Although direct arguments are sparse, there is a general consensus about the onset of main Jura deformation which started in the Late Miocene (Serravallian/Tortonian). Latest Middle Miocene sediments, recently confirmed at NM8 und NM9 by WEIDMANN (pers. comm.; BERGER 1990) are seen to be folded in synclines (Le Locle, Bois de Raube) and are found beneath external thrusts in the Bresse graben. On the other hand, AUBERT (1958) and LINIGER (1967) found indications of Oligocene tectonic activity in the form of angular discordancies interpreted as early Jura folds. Alternatively, these geometric relationships could also be interpreted as wrench faults (folds?) connecting the Rhine- and Bresse-graben or as tilted blocks in an extensional environment (LAUBSCHER 1961; NAEF et al. 1985). Both would be more compatible with the general tectonic setting of the Jura during this period (BERGERAT 1987; HOMEWOOD et al. 1989). The end of Jura deformation is still a matter of debate too: LAUBSCHER (1987, p. 301) uses large-scale considerations and data from the southern Alps to infer a probable end of Jura tectonic activity in the Tortonian, whereas NAEF et al. (1985) conclude that Jura folding and thrusting, at a moderate pace, could still be going on today.

3.2 Subalpine Molasse

The precise time of thrusting and folding within the Subalpine Molasse is even more difficult to determine than in the Jura. The problem is easily understood when examining any of the restored sections presented in Fig. 3. The youngest folded sediments within the Molasse basin are latest Middle Miocene (OSM) (HOFMANN 1973, 1988; SCHMID 1970; BERLI 1985). There is no sedimentary record between this latest Middle Miocene and the Pleistocene glacial and interglacial deposits. The most external Molasse structures, in particular a pronounced triangle structure in Bavaria,

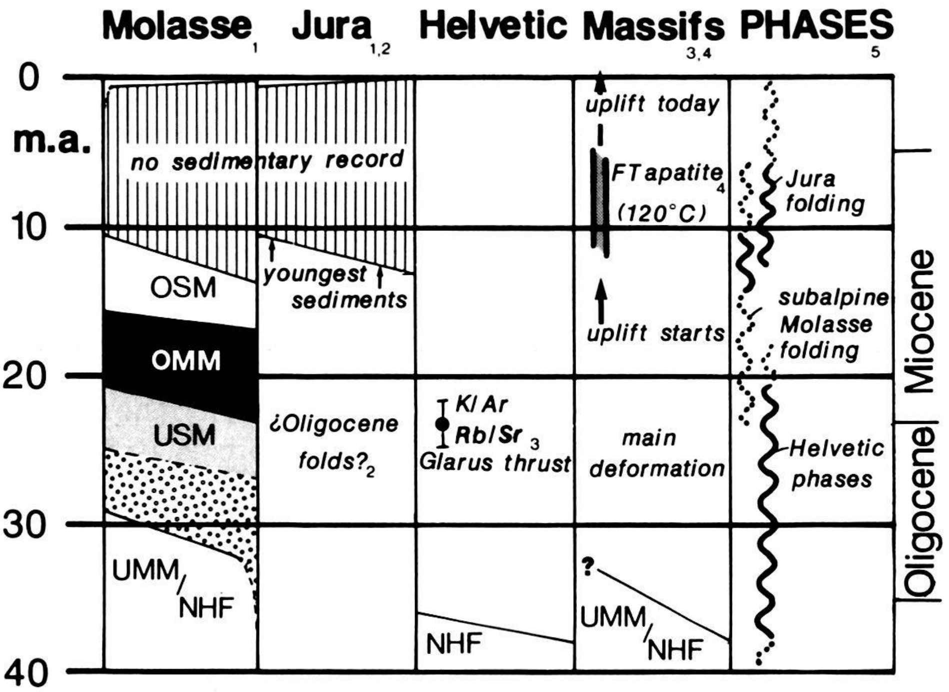


Fig. 4. Time constraints on the tectonic evolution of the NW alpine front are shown in a synoptic diagram for the main tectonic units involved. The obliquity of limits between lithostratigraphic units of the Molasse basin corresponds to the uncertainty in their age on an absolute time scale. Small numbers are references: 1) Berger (1990), 2) Aubert (1958), Liniger (1967), 3) Hunziker et al. (1986), 4) Schaer et al. (1975), 5) Milnes & Pfiffner (1980), Burkhard (1988a), Laubscher (1987), Naef et al. (1985).

eastern and central Switzerland are certainly younger than Serravallian and thus appear to be formed simultaneously with the Jura folding. On the other hand, the more internal thrust slices of the Subalpine Molasse are truncated at their top by either Subalpine Molasse-, Helvetic- or Pennine-thrusts. The youngest sediments preserved within the Subalpine Molasse thrust sheets are Late Oligocene to Early Miocene (USM) but most of the internal zone only reaches Middle to Late Oligocene (lower USM). Ages of these clastic series are often based on lithostratigraphic arguments and Berli (1985) could show, that part of the St. Gallen Subalpine Molasse, formerly considered as USM contains OMM and reaches even upper OSM. Still, thrusting could have started in internal zones as early as Middle Oligocene. This situation is usually interpreted as a northward propagation of the thrusting activity which started in Late Eocene in the southern Helvetic realm to reach the Molasse basin by Middle Oligocene and ending in the Late Miocene (Pfiffner 1986; Burkhard 1988a). The question remains open, if this northward propagation corresponds to a progressively advancing "Oligocene Mountain front" using the basal Helvetic thrust alone or, alternatively, if deeper thrusts within the Molasse itself are activated, carrying the "Oligocene front" in a piggy-back manner further northward. Direct evidence for the detailed timing of events north of the Aarmassif is scarce. The preserved sediments within the Plateau Molasse yield little evidence for synsedimentary tectonic thrusting activity (see review by Homewood et al. 1989). The widespread occurrence of resedimented Molasse pebbles on the other hand could be used as an argument for a continuous N- and down-ward propagation of thrusting activity, where older internal

Molasse sediments are already thrusted and eroded while younger ones are still deposited.

In tectonic reconstructions, arguments depend critically on the assumed thrust geometry at depth and continuity of events. In fact, as in the discussion of Jura tectonics (compare NAEF et al. 1985, p. 98ff.), there are two alternatives: 1) short pulses of tectonic activity are separated by relatively longer, calm intervals or 2) continuous tectonic activity since the Middle Oligocene. Estimations of the overall horizontal shortening yield quite small values around 2.5 mm/a for the case of a continuous history (PFIFFNER 1986, Fig. 4; BURKHARD 1988a, Fig. 16). Since tectonically active areas might easily be displaced at the rate of a few cm/y, the magnitude of deformation in the external part of the Alps is not an obstacle to the assumption of an intermittant tectonic evolution. Radiometric age determinations, can be used as a positive argument for a continuous and ongoing evolution as discussed below.

3.3 Uplift of the Aarmassif

Most important among the radiometric age data from the Helvetic region are Fission track (FT) determinations of the cooling/uplift rates of the Aarmassif and surrounding areas (SCHAER et al. 1975; HURFORD 1986). Original data, projected onto a N-S profile, are shown in Fig. 5 together with an interpolated interpretation in terms of paleo-isotherms for 15, 10, 5 m.a. and the present day situation. This Figure clearly illustrates, that the uplift of the Central Alps must have started in the Early Miocene at a time, when the Molasse basin was still subsiding. By Late Miocene (around 10 m.a.) the top Aarmassif, which has been metamorphosed to at least 300 °C during Oligocene (HUNZIKER et al. 1986 and references therein), has already cooled to less than 120 °C. The lack of a discontinuity in the paleo-isotherm pattern across the steep Helvetic "root zone" indicates that steepening (backfolding) of this area is older than 15 m.a. This means that during the thrusting of the Jura, there exists already an Aarmassif culmination that has about half its present amplitude. This has important tectonic consequences: 1) There is hardly enough structural relief in the hinterland to allow the Jura (or Subalpine Molasse) to be derived from extension above the Aarmassif high (Fig. 2B). 2) The basal Jura and Subalpine Molasse thrusts cannot be rooted within the Helvetic thrust system (Fig. 2D) because it is already backfolded by Middle Miocene times. Radiometric ages therefore provide a strong argument for the basal Jura thrust to be rooted within the front or beneath the Aarmassif (Fig. 2C, D). This conclusion is further substantiated by radiometric dating of the Helvetic Glarus thrust (HUNZIKER et al. 1986, Tab. 5) determined as 23.2 ± 1.2 (Rb/Sr) and 23.2 ± 1.3 m.a. (K/Ar) for a limestone mylonite sample from the Lochseiten type locality. One might object that this age does not necessarily reflect the latest thrusting activity.

Another interesting feature of the cross-section in Fig. 5 is the altitude dependance of the FT data. The vertical spacing of the paleo isotherms can be approximately correlated with "uplift rate" independant of an assumed geothermal gradient. The 10 and 5 m.a. paleo-isotherms are well documented datum lines in the Aar and Gotthard massif (SCHAER et al. 1975); they are less constrained in the Ticino area (HURFORD 1986). The depth of the present day (0 m.a.) 120 °C isotherm beneath the Central Alps, is not too well constrained either. However, the geothermal gradient in this region is

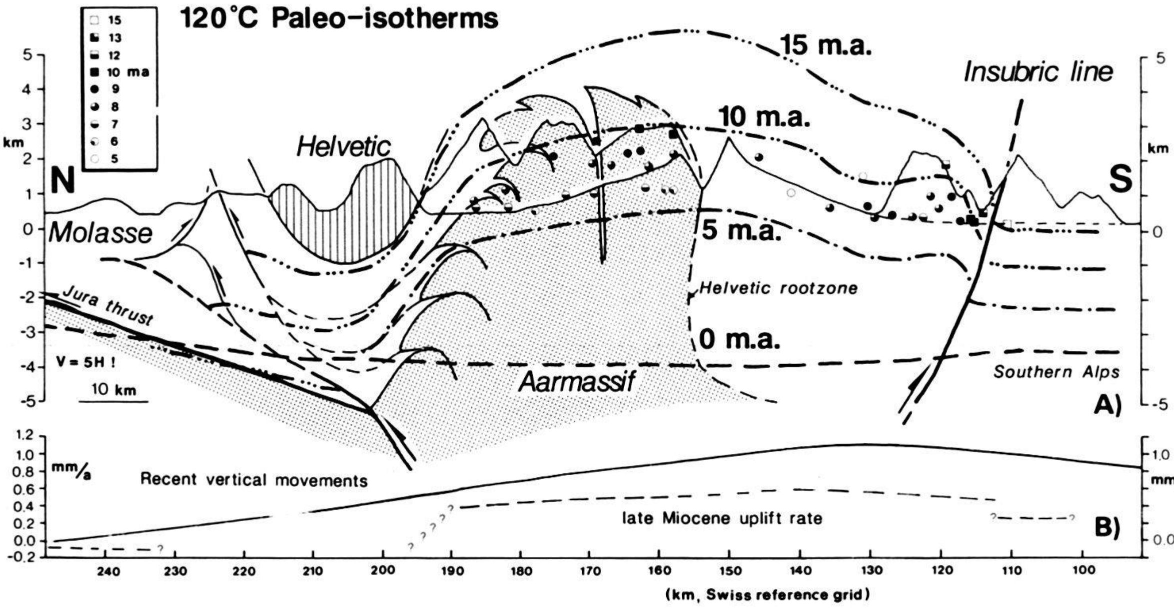


Fig. 5. Miocene and recent uplift rates of the central Alps in a N-S cross-section across the Gotthard pass (coordinate line 690) as recorded by various methods:

A) Apatite (and zirkon) fission track ages (Schaer et al. 1975; Hurford 1986), considered to represent cooling ages below 120 °C (and 240 °C for zirkons), are used to extrapolate the position of the "120 °C isotherm" in space and time. Original apatite FT ages are projected horizontally onto the profile. The present-day 120 °C isotherm is extrapolated from Rybach et al. (1987) for the Molasse basin and assumes a geothermal gradient of about 20 °C/km beneath the central Alps. The approximate position of paleo 120 °C isotherms is estimated within the thrusted Molasse below the Helvetic nappes (see text for discussion).

B) Present-day vertical uplift rates as interpolated from Gubler et al. (1984 and unpublished data 1990) with an arbitrary zero point at Aarburg in N-Switzerland are compared with Miocene uplift rates as determined by Schaer et al. (1975) from apatite FT ages and by Hurford (1986) who combined apatite and zirkon FT ages. During Middle Miocene, Molasse sedimentation continued in northern Switzerland, this is schematically indicated with a negative uplift rate (Naef et al. 1985).

thought to be around 20 °C/km or less (Rybach, pers. comm. 1990; Schulz 1990, Fig. 1). This means that the vertical 2.5 km spacing between the 10 and 5 m.a. paleo-120 °C-isotherm is considerably less than the 4.5 to 5 km interval between the 5 m.a. and the present day 120° isotherm. In other words, the apparent uplift rate would have increased from ca. 0.5 mm/a (late Miocene) to almost 1 mm/a during the last 5 Million years (Fig. 5B). Note that a present day uplift rate of ca. 0.8 mm/a is indeed measured in the Central Alps (with respect to a reference point in northern Switzerland; Gubler et al. 1984).

The present day vertical movements have been interpreted as a differential vertical uplift (Fig. 2H) which started in the Pliocene, mainly as a response to the gravimetric anomaly of the Alps (Neugebauer et al. 1980; Milnes & Pfiffner 1980). On the other hand, in analogy with the Miocene uplift caused by horizontal shortening and thrusting, the present day uplift pattern could just as well be interpreted in terms of ongoing thrusting deformation (Mugnier & Menard 1986; Burkhard 1988a). The apparent increase in uplift rate could qualitatively be interpreted as due to an increase in tectonic shortening activity and/or as due to the passage of the Aarmassif over a ramp in the assumed sole thrust (Fig. 2E). Hopefully, the answer to this controversy (isostasy vs. thrusting) will be found within the next ten years from satellite base length measurements across the Alps.

4. Map scale models of Jura arc formation and implications for the Alps

4.1 A deformation grid

In this section large-scale relationships of the Jura arc with its hinterland and the Alps are examined in map view. Miocene deformation is visualized through an initially rectangular grid of N-S and E-W coordinate lines which is shown in its present day deformed state (Fig. 6). In this representation, deformation is idealized as homogeneous on a large-scale (30 by 30 km). Any type of deformation, observed or inferred, is visualized through the shape and area change of the former squares:

a) square with no area change = no deformation
b) lozenge with no area change = plane strain (strike-slip) deformation
c) lozenge with area decrease = shortening (folding, thrusting)
d) lozenge with area increase = extension (normal faults)
(note that lozenges can be rectangles).

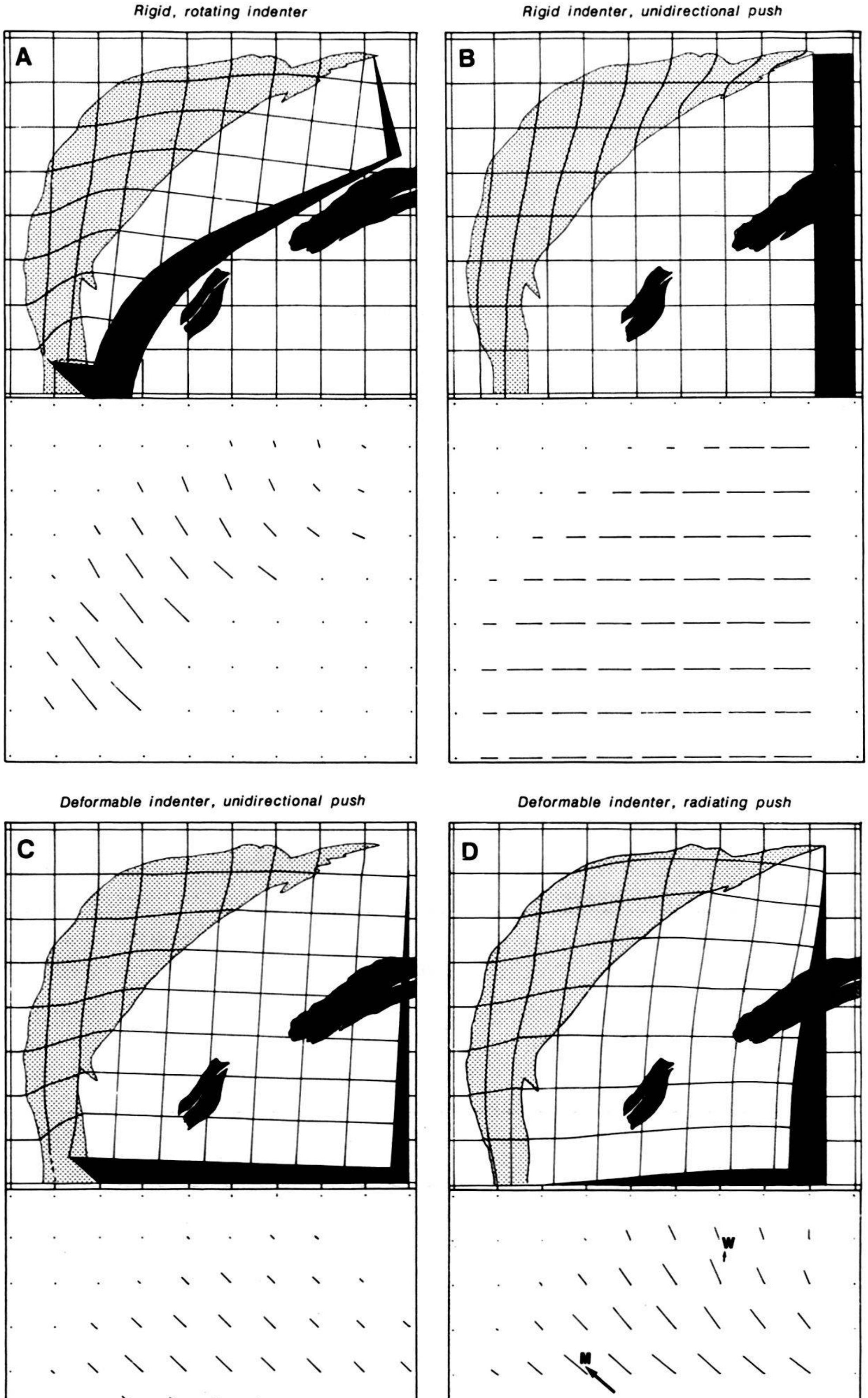
The aim of this exercise is to force one to think of the Jura as a 3-dimensional tectonic entity rather than argue only on 2-D cross-sections. The map scale viability of any tectonic model for the Jura fold belt can be tested because this representation indicates geometric consequences for the Jura itself and its hinterland in particular.

4.2 Stable Europa vs. Alpine Chain

The northern European foreland of the Alps and Jura is considered as a stable reference frame which did not suffer any deformation nor rotation during Miocene and Pliocene. This assumption is not entirely valid: the Rhine-Bresse-graben system and many faults in all of Europe up to the North Sea testify the presence of deformations within this "stable foreland" (ILLIES 1974, Figs. 9, 10; ZIEGLER 1987; BERGERAT 1987). The main extensional deformation in the Rhine and Bresse graben, however, is older (Oligocene) than the main Jura folding. Deformations within the adjacent "stable foreland" are an order of magnitude smaller than deformations discussed here. Considering the uncertainties in quantification of deformations within the Jura, Molasse basin and Alps, the assumption of an undeformed foreland seems justified.

Unlike the Helvetic thrust system, with its well defined emergent basal thrust, there is no such clear cut line between the stable foreland and the Jura (or the Subalpine Molasse). The latest alpine deformation often terminates in the NW above a blind thrust. This is an important boundary condition for the models presented below: coordinate lines of the Miocene grid pass smoothly from the undeformed foreland into the deformed Jura.

Within the immediate hinterland of the Jura, the Plateau Molasse can be considered as essentially undeformed and only very gentle warping occurs. Strike-slip faults are postulated (MATTER et al. 1980, Fig. 4; CHENEVART & RIESEN 1985), but rarely identified, let alone quantified in the field. The type and orientation of weak deformations within the Plateau- and Subalpine Molasse have nevertheless been deter-


Rigid, rotating indenter
Rigid indenter, unidirectional push
A
B
Deformable indenter, unidirectional push
Deformable indenter, radiating push
C
D
W
M
B
Z
A

mined from microstructural observations (SCHRADER 1988). The dominant type of deformation is found to be compressional, and locally (Napf area) compressional strike-slip with a regionally constant NNW to N directed shortening direction.

The Subalpine Molasse belt underwent shortening deformations during the Miocene as discussed above. In the Pennine Prealps, PLANCHEREL (1979) interprets N-S sinistral strike-slip fault zones and even folds as Late Mio-Pliocene, a point of view, however, which is not generally accepted (e.g. MOSAR 1989).

Within the main body of the Alps, Miocene deformations are not easily distinguished from older deformations but there is no direct evidence for active Mio-Pliocene NW-SE shortening deformation in the Central Alps. Note, that this does not exclude a NW translation along deeper thrusts, causing vertical uplift associated with minor accomodating deformations. Clear evidence for Miocene SW-NE extension is found in the Simplon area (MANCKTELOW 1985), the Rhone valley and the Rawil depression (BURKHARD 1988a, b) and other parts of the Alps (RATSCHBACHER et al. 1989).

4.3 Jura arc models

If one accepts the "Fernschub" hypothesis of the Jura formation, one automatically assumes that the entire hinterland of the Jura has been displaced by at least the amount of shortening determined in the Jura. In other words, the Plateau Molasse is part of the indenter that transmits the alpine push. It may then be interesting to know more about the geometry, internal deformation and transport direction of this indenter. Can this information be obtained from the large-scale finite strain pattern observed in the Jura today? This question is discussed on the basis of four different indenter models (Fig. 6) that could explain the general increase of Jura shortening from 0 to 25 or 30 km from east to west. These models were drawn by hand, trying only to coincide roughly with the actually determined shortening distances in the various parts of the Jura. The arcuate Jura shape thereby is taken as a boundary condition where the external curvature is given by the foreland, acting as a buttress; the internal arc represents the front of the indenter. The Molasse basin and Alps are either undeformed (rigid indenters) or weakly deformed. For each model, both a large-scale *finite strain* pattern (grid) and the corresponding *displacement vector field* are represented in Fig. 6 (compare RAMSAY & HUBER 1983, session 4).

Fig. 6. Models for the Jura formation in map view. In the upper row, an initially rectangular N-S and E-W coordinate grid with 30 km spacing is shown in its deformed state. The shaded area outlines the Jura arc; the external crystalline massifs are shown in dark grey. The lower row represents resulting displacement vector fields. Different types of indenters are illustrated. Given boundary conditions are 1) no deformation within the european foreland, 2) the arcuate shape of the Jura, 3) increasing total shortening from E to W, 4a) no deformation within rigid indenters, 4b) "as little as possible" deformation within deformable indenters.

A) Rotation model (LAUBSCHER 1961). A rigid indenter is rotated by 7° clockwise about the eastern tip of the Jura in order to obtain an increasing shortening from E to W

B) Rigid indenter with unidirectional push to the W

C) Deformable indenter with unidirectional push to the NW

D) Deformable indenter with radiating push. Points A and B indicate 15% N-S extension. Points M (Morges) and W (Wiedlisbach) are reference points discussed in the text. At point Z, horizontal stylolithes point toward the SW (PLESSMANN 1972). For discussion see text.

a) Rigid, rotating indenter (Fig. 6A): This model, proposed by LAUBSCHER (1961) is characterized by a rigid, rotated hinterland. Deformation zones (black gaps=extensional deformation) are necessary to limit the rotating block in space to the SW, S and E. The southern limit is drawn according to the initial proposition by LAUBSCHER (1961, Fig. 14) as a gap north of the external crystalline massifs. Unlike LAUBSCHER'S (e.g. 1973) hypothesis, however, in Fig. 6A, the "Alps" are undeformed and do not participate in the NW transport; the Jura is sketched as a gravity sliding phenomenon (Fig. 2B).

b) Rigid indenter, unidirectional push (Fig. 6B): If a rigid indenter is to be responsible for the map scale finite strain pattern observed in the Jura, the only possible pushing direction compatible with the eastern disappearance of shortening deformations is east-west. A major dextral strike-slip zone is therefore required at the eastern end of the Jura with 25 to 30 km offset in order to account for the same amount of E-W shortening in the western Jura. Folds within the eastern and central Jura would have to be considered as wrench folds, formed obliquely with respect to the overall transport direction. LAUBSCHER (1972) proposed a rigid NW pushing indenter in order to account for the observed "paleo-stress directions" in the Jura (see also BECKER 1989; TSCHANZ 1990). This indenter, however, does not allow for a variable global shortening along-strike, it would also need major strike-slip zones on either side of the indenter and is therefore incompatible with the finite strain pattern of the Jura.

In summary, it seems obvious that rigid indenters are poor approximations to explain the finite strain pattern seen in the Jura and surrounding areas. Geometric consequences at the borders of any rigid indenter are such, that they would have to show up in the Alps and the Molasse basin even in areas where Quaternary cover leaves some freedom in interpretation of geologic maps. The indenting hinterland certainly was deformed to some extent simultaneously with folding and thrusting in the Jura.

c) Deformable indenter, unidirectional push (Fig. 6C): If the Jura indenter is allowed to be deforming itself, an infinity of possible models can be found to be more or less compatible with the bulk shortening estimates in the Jura. Two extreme cases are discussed here. "Unidirectional" means, that the overvall transport direction is identical in all parts of the Jura. Independant of the transport direction (anything between S-N and E-W), this type of indenter has to be dextrally sheared in order to account for the increasing shortening from east to west. This dextral shearing (of the indenter, not the Jura!) is a geologically plausible alternative to the rigid body rotation of model a). Note that this plane strain simple-shear deformation of $\gamma=0.122$ (for a NW 315° directed push), corresponding to a clockwise 7° rotation of the Jura, is difficult to see in Fig. 6C (and may not be noticeable in nature): the Jura hinterland consists of lozenges not squares and is characterized by a very weak NE-SW stretching of less than 1% ($1/\cos 7° = 0.0075$). Folds within the Jura would have formed perpendicular to the transport direction in the central part, but as slightly dextral and sinistral wrench folds with some fold-axis parallel extension at the eastern and western extremity respectively.

d) Deformable indenter, radiating push (Fig. 6D): If the Jura was pushed at all places perpendicular to the regional fold axis trend, deformations within the indenter would have to compensate the space problems arising from this radiation. Again, an infinity of possible solutions exist for the hinterland to accommodate this radiation. It is clear, however, that the divergent movements in the Jura have to be accommodated by some divergence within the indenter as well. As a consequence, this model needs considerable NE-SW extension to occur within the indenter. This is particularly pronounced behind the strongest curvature of the SW Jura. For instance the solution shown in Fig. 6D needs about 15% N-S extension between points A and B. Within the Jura itself, this extension rapidly decreases with decreasing displacement toward the outer border.

Even if model Fig. 6D seems extreme, the problem is not entirely fictitious. PLESSMANN (1972, Fig. 6) e.g. describes SW oriented horizontal stylolithes in the southernmost Jura (location Z in Fig. 6D). If interpreted as transport direction, perpendicular to the local fold-axis trend, (e.g. PLATT et al. 1989, Fig. 1), far more than the 15% extension calculated above are required in the hinterland. As another example, let us consider the two points Morges (M) and Wiedlisbach (W) in Fig. 6D. According to MUGNIER & VIALON (1986) Morges has to be restored to a point 25 km to the SE (132°); Wiedlisbach, according to BITTERLI (1990), restores to a point maybe 8 km (the northernmost Jora folds are not included in BITTERLI's 6 km estimate) to the S (195°). From this it follows, that the present day distance of 120 km between M and W measured initially only 114 km. Accordingly, the Plateau Molasse behind the central Jura also has to display an average of 5% NE-SW extension. The two balanced cross-sections may be internally consistent each; to be mutually compatible within the Jura arc as a whole, the NE-SW extension of the hinterland has also to be documented. Alternatively, if the 5% SW-NE extension can be ruled out, one or both assumed transport directions will have to be modified.

The question of the overall transport direction in the different parts of the Jura is far from being solved. The curvature of the Jura is often intuitively taken as evidence for divergent movement directions (LAUBSCHER 1980; BECKER 1989; PLATT et al. 1989). A comparison of the models (Fig. 6C, D) shows that the answer to this question (divergent vs. constant movement directions) may not be found within the Jura itself but rather in its hinterland. The resulting finite strain pattern for the Jura arc may indeed not be sufficiently different from one model to the other to allow a distinction. Both cases display some fold axis parallel extension within the Jura. It is questionable whether map scale simple-shear deformation with area loss (Fig. 6C) resulting in "wrench folds" at the Jura SW and NE extremities could be unambiguously distinguished from pure shear deformation with area loss (Fig. 6D) resulting in "cylindrical folds" in all parts of the Jura. The consequences for the hinterland, on the other hand, are such that a distinction should be possible: only weak plane strain simple-shear results from model C whereas model D needs important NE-SW stretching within the Plateau Molasse behind the Jura.

As a conclusion of these simple models it follows that quantification of the strike-parallel extension in the Jura hinterland, would provide an important constraint to the degree of divergence in the Jura arc formation.

4.4 A modified indenter model for the Miocene alpine Front in Switzerland

Based on "balanced" cross-sections from the Jura and Molasse basin as well as the more theoretical map view considerations discussed above, a new modified indenter model for the entire NW alpine front is proposed in Fig. 7.

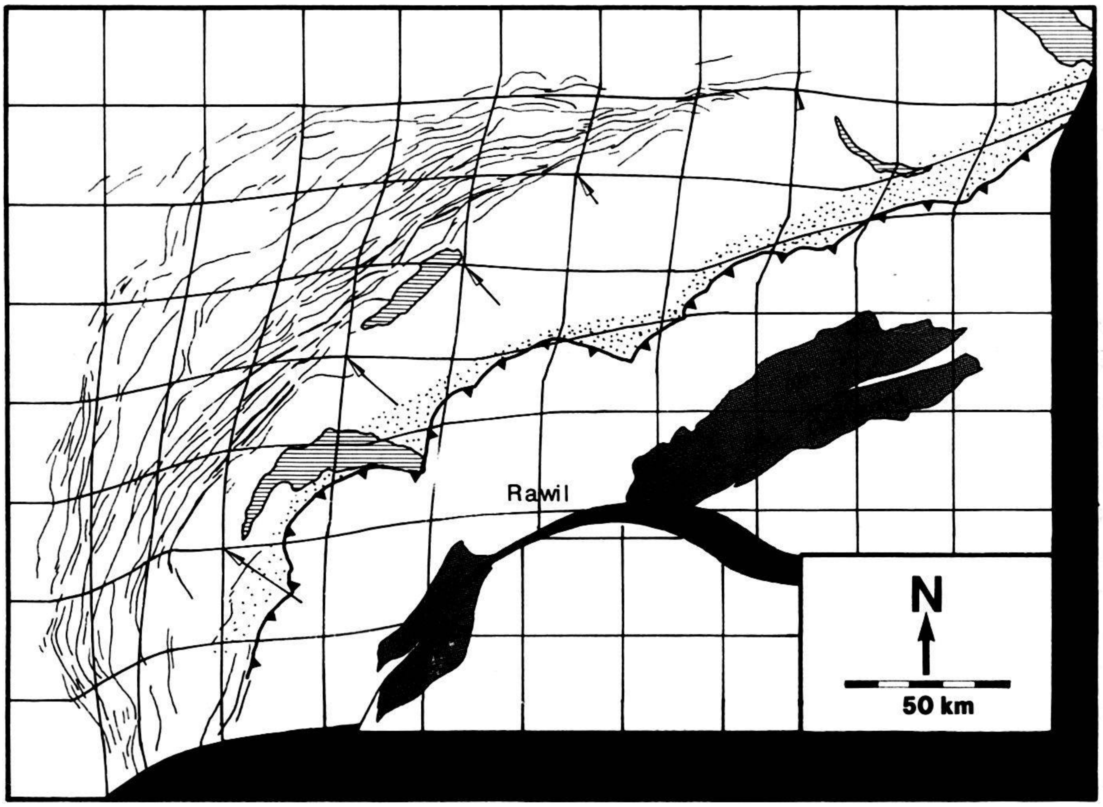


Fig. 7. New model for the large-scale Miocene deformation of the northwestern mountain front of the Swiss Alps. Deformation is visualized through the present day, deformed state of an initially rectangular Miocene coordinate grid with 30 km spacing. Fold trends (anticlines) in the Jura fold and thrust belt are copied from HEIM (1921; Table XX).

In this model, the Central Alps are considered as an essentially rigid indenter, pushed about 30 km to the NNW during Late Miocene. This push is responsible for both the Jura fold and thrust belt and the Subalpine Molasse thrusts. The two deformation zones formed in an "en echelon" array where eastward decreasing shortening in the Jura is compensated by eastward increasing shortening in the Subalpine Molasse belt. The Plateau Molasse of central Switzerland thereby still has to undergo a 7° rotation either "en bloc" or more realistically as a dextral simple-shear deformation. This could be present in form of hidden strike-slip zones within the Molasse basin (HSÜ & KELTS 1984, plate) or be more evenly distributed as "homogeneous" deformation (SCHRADER 1988, Figs. 1, 6a). In order to allow a divergent movement of the Jura, which seems to be pushed in a more northwesterly direction in its western parts, both the western Molasse basin and the western Swiss Alps have to accommodate this divergence by some NE-SW extension. Strike-slip faults and fault zones are indeed described to cross-cut the entire western Molasse basin (RIGASSI in MATTER et al. 1980, Fig. 4) and the Prealps (PLANCHEREL 1979). Late alpine NE-SW extension is also known from the Rawil area west of the Aarmassif (BURKHARD 1988a, b; HUGGENBERGER & AEBLI 1989; DIETRICH 1989). In Fig. 7, extension in the Simplon Rhone area (MANCKTELOW 1985; STECK et al. 1989) is sketched more rigidly (with the Simplon fault as a "pull apart basin"). If the assumed westward continuation of the Simplon and

Rhone line is correct, this fault zone is located too far south to have any influence on the Jura arc, however, it offers the opportunity to limit the Jura indenter quite naturally toward the south.

So far, at least qualitatively, the new model seems not completely inconsistent with geologic evidence. In particular, required deformations within the Plateau Molasse are weak enough to go unnoticed. Furthermore, the model does not need a major lateral ramp at the eastern Jura extremity (compare VANN et al. 1986, Fig. 3) and Miocene deformations within the Alps are restricted to areas where late alpine extension is well documented.

Models are built to be tested and modified, and new data will show if Fig. 7 is a viable proposition. The most critical point is the assumed synchronous shortening deformation in both the Jura and Subalpine Molasse. Further unknowns are the Miocene deformations within the Alps. Large-scale rotations, strike-slip deformation and/or extensional structures may play a more important role than recognized at present. All of these could help explain the arcuate shape of the Jura in particular and the divergent movement picture of the western Alps in general (PLATT et al. 1989). In the previous sections, I argued that rigid indenters create as many geometric problems as they solve; they are geologically unlikely: every indenter needs to be limited in space. Thus the proposed still too rigid indenter model may explain some features within a limited sector of the NW Alps but it certainly has to be modified in order to fit into the western Alps as a whole. More quantitative data, especially about the strike-parallel extensions, are needed for the Molasse basin and the latest deformations within the Alps. Paradoxically, such data might be more important to solve the large-scale Jura arc problem then analyses within the Jura itself.

5. Conclusions

Cross-sections through the frontal part of the Swiss Alps show invariably 25 km or more of bulk shortening between the most external thrusts and the crest line of the external crystalline Aar massif. Thrusts responsible for this shortening have to be rooted within the frontal (hidden) part and beneath this massif for balancing and timing reasons because:

a) There is no potential homeland to restore the Jura and Subalpine Molasse shortening behind the Aarmassif.

b) At the time of main deformation of the Jura, the Aarmassif is already in existence and the Helvetic rootzone backfolded into its partly vertical position behind this massif. The basal Jura thrust therefore cannot be rooted within the basal Helvetic thrust system.

c) There are not enough extensional features in front of the Aar massif high, to explain the Jura (even partly) as being the result of gravity gliding off the Aarmassiv culmination.

The eastward decrease of Jura shortening could be compensated by an increase in shortening within the more internal Subalpine Molasse zone. The present day alpine deformation front is poorly defined between the eastern tip of the Jura and a Subalpine Molasse triangle zone. This situation is interpreted as due to a simultaneous formation of both structures in an "en echelon" array. As a direct consequence, the seemingly undeformed Plateau Molasse (the Jura indenter) has to be dextrally sheared between Zürich and Bern. In this model the Swiss Alps (Aarmassif) are considered as a more or less rigid indenter that was pushed at least 30 km to the NNW or NW during the last (Paleocene) stages of alpine shortening.

According to map scale balancing considerations, the extent of strike-parallel extension in the frontal parts of the Swiss Alps, including the Plateau Molasse can be used as an argument to constrain the degree of divergence in transport directions in the Jura arc. Fold-axis parallel extension in the Helvetic zone west of the Aarmassif and strike-slip deformation within the Prealps and the western Molasse basin could allow for some divergence in the movement picture of the western Jura arc.

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