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Jura kinematics and the Molasse Basin

By H. LAUBSCHER[1]

ABSTRACT

The Jura kinematic system consists of several units – the thin skin frontal fold and thrust belt with décollement in the Triassic evaporites, the thin skin thrust belt of the Subalpine Molasse with décollement in Late Eocene to Middle Oligocene shales, the anticlinal stack of basement duplexes in the External Massifs with décollement in the brittle-ductile transition zone, and the subduction zone traced for the lower crust and the Moho by NFP 20. Between the subduction one and the other elements, which all have been obducted, there is a divergence where partly exotic material (lower crust and mantle) has been wedged in. In addition, the forebulge or outer flexural rise of the lithosphere belongs to the same system, being a part of the equilibrium figure of the subducted Jura lithosphere. Where the bulge was superimposed on the West-European rift system, conspicuous domal uplifts resulted such as the Rhine and Loire domes. The timing for all of these events is post-Early Miocene and probably pre-Pliocene.

ZUSAMMENFASSUNG

Das Jura-System umfasst eine Anzahl von kinematischen Einheiten: Die frontale Falten- und Überschiebungseinheit mit Abscherung in den Trias-Evaporiten, die Schuppen der Subalpinen Molasse mit Abscherung im oberen Eozän bis mittleren Oligozän, der antiforme Duplex-Stapel von Grundgebirgslappen, die in der spröd-duktilen Übergangszone abgeschert wurden und die Externen Massive aufbauen, und die Subduktionszone von Unterkruste-Obermantel, die von den Reflexionen des NFP 20 dokumentiert wird. Die Subduktionszone und die andern, obduzierten Elemente divergieren, und in die Divergenzzone wurden z. T. exotische Unterkruste- und Obermantelmassen gekeilt. Ebenfalls zum Jurasystem gezählt werden sollte der Vorlandwall („external flexural rise", „forebulge"), da er zur lithosphärischen Gleichgewichtsfigur der Jurasubduktion gehört. Wo er dem Westeuropäischen Grabensystem aufgesetzt wurde, entwickelten sich ansehnliche, domartige Hebungen (Rhein- und Loire-Dom). Alle diese Vorgänge spielten sich nach dem frühen Miozän und wohl vor dem Pliozän ab.

Introduction

In this article I wish to tie up a number of loose ends left over after more than 30 years of struggle with the wider implications of Jura tectonics. Although ever conscious of the interdependence of all the elements of what may be called the "Jura system", I have, for practical reasons, always concentrated on quite limited subsystems. Because of this summing-up now of almost a lifetime's work, my own contribution to the bibliography of this article is rather extensive and may even appear excessive, in which case I beg for forbearance.

Jura kinematics is an important aspect of the Swiss Molasse Basin. The thin-skin nature of the Jura fold and thrust belt implies that a large part of the Swiss Molasse

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Basin is allochthonous, displaced by as much as 30 km on top of the Triassic décollement layers (Laubscher 1965, Guellec et al. 1990). The vertical component of this displacement may exceed 2 km and has decisively changed the hydrological system, terminating Molasse sedimentation (Laubscher 1974). Superimposed on this thin-skin tectonics are basement motions, and the relation between the two is somewhat puzzling and has led to a number of hypotheses that, on closer look, are not well compatible with the available data set (compare Laubscher 1980).

In this article, the cross-sectional aspects of the Jura kinematic system are examined, using those recently published papers that appear to offer significant new data. This kinematic system is a part of the Africa-Europa plate boundary and comprises the entire lithosphere, from forebulge to subduction zone. 3D aspects are exceedingly complex and will be touched upon only in passing.

In these more and more computer-dominated times an asessment of the nature of the information system on which any model of Jura kinematics has to be erected cannot be completely left aside. Everybody supposedly is aware that at the beginning of any scientific enterprise there is the stage of data acquisition, followed by data processing and finally by interpretation in terms of models. The set of the acquired data is the data base. In the case of the Jura system, this set, accumulated for many years by many people, has an uneven spatial distribution, and its members have different attributes such as physical parameters and quality. The densest concentration of data is in the eastern Jura, and early thin-skin models such as those by Buxtorf (1907, 1916) were based entirely on this subset, whereas Laubscher (1965) was in a position to profit from new drilling and seismic data in the central Jura. Within this large subset of data the thin- skin models proved extremely robust as new geophysical data and techniques of cross-section construction became available (Laubscher 1980, 1986, Noack 1989, Diebold 1990). That large part of the Jura system south of the Jura, comprising the Molasse basin, until recently was comparatively devoid of published data, particularly from the subsurface, and its structure and kinematics had to be postulated on the strength of the Jura subset. This seems to be about to change as the petroleum industry begins to release more and more information. All of what has been published or shown in public meetings so far underscores the thin-skin models.

A certain measure of confusion arose from the seismic data in the area of the well Entlebuch-1 (Vollmayr & Wendt 1987). An early interpretation showed considerable normal faults of presumably Oligocene-Early Miocene age dislocating the Mesozoic and consequently the postulated décollement zone, and this was taken as proof for the non-existence of Triassic décollement under the Molasse basin (compare Ziegler 1988, Fig. 63). However, according to Vollmayr & Wendt, this interpretation was later considered questionable and replaced by an embryonic thrust system that can be harmonically integrated into Jura kinematics without violating the bulk of the data (see p. 662). On the other hand, small normal faults are still shown by Vollmayr & Wendt and other authors as cutting the postulated Triassic décollement zone, and in the light of the Jura data there would appear three possible explanations for them: Either the faults are younger than the décollement, or they are present in the hanging wall only and have been extended downward because of seismic distortions (compare Laubscher 1956), or they are misinterpretations of line-ups of reflection irregularities. Geophysical data, indispensible as they are, always require interpretation in geological terms which often are not unambiguous.

From discussions I have the impression that normal faults in the Swiss Molasse Basin are often postulated because they are so important in its eastern continuation in Germany and Austria. However, such cylindrical extrapolations are to be used with caution: they often fail in the Alps. On those seismic lines I have seen there is no clear-cut normal faulting comparable to the one in the German-Austrian Molasse basin. An alternative scenario envisaging the fault belt to swerve into the Helvetic domain of the Swiss and French Alps, which at that time was foreland (compare Günzler-Seiffert 1952, Pairis & Pairis 1975, Charollais et al. 1977, Herb et al. 1978), together with Late Eocene-Early Oligocene isofacies lines, is perhaps better compatible with the data. The beginning of normal faulting here is dated as Eocene, and at least in some instances faulting ceased before the early Miocene Helvetic phase (Herb et al. 1978). My preferred interpretation of these normal faults is that they began with the late Eocene collapse of the Pyrenees-Provence and other vast domains in the western Mediterranean and the Alps (Laubscher 1983c), and that they are not inevitably linked with the Molasse basin.

Because of the virtual non-accessibility of industry data from the Molasse Basin efforts to continue the Jura kinematic system into the Alps have been half-hearted. Laubscher (1973, 1983b) argued for a role played by the Doldenhorn nappe or, more generally, by the southern portions of Aar massif, at least qualitatively. The Doldenhorn nappe is seen to have shoved away the originally thick cover (mainly Tertiary and Helvetic nappes) of the Gastern Massif, which requires large thrusts surfacing in front of the Helvetic nappes. Only the thrusts of the Subalpine Molasse and the Jura would appear to be compatible. With regard to the Subalpine Molasse, similar conclusions seem to have been reached by other authors, e.g. by Boyer & Elliott (1982, Fig. 32) and Vollmayr & Wendt (1987).

A new challenge arises from the data set recently acquired by NFP 20 and Ecors-Crop (e.g. ETH Working Group on Deep Seismic Profiling 1991, Bois & ECORS Scientific Party 1991) about the deep structure of the Alps. It calls for an integrated interpretation of the latest deformation recorded north of the Alps, from the thin-skin front to the subduction zone (compare (Guellec et al. 1990). This article is an effort aiming at this goal for the central Alps.

Typical cover kinematics in the eastern Jura

The most detailed data about the cover kinematics in the Jura have been acquired in the eastern Jura. Not only are the surface geological data clearer than elsewhere, but a number of railroad and highway tunnels have been perforated and a series of modern seismic lines have been published (Sprecher & Müller 1986). The gist of the results is shown in Figs. 1–3. I want to stress here two particular aspects. One is the "Muschelkalk-Schuppenzone", which is typical for the main thrust zone of the eastern Jura. It consists of the imbricate repetition of the middle Triassic limestone interval with some associated dolomites (see, e.g. Thornburg 1925). In modern terminology it would be called a "stack of hinterland-dipping duplexes" (Boyer & Elliott 1982). It indicates repeated ramping from the basal Jure décollement in the middle Triassic Anhydritgruppe

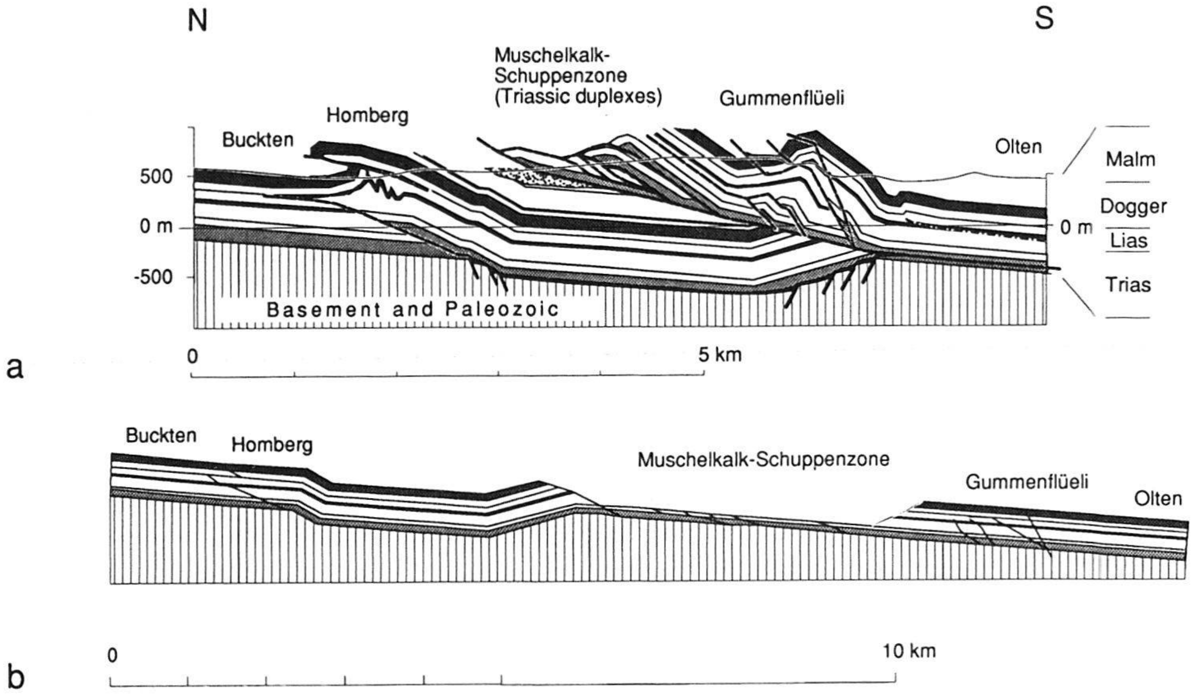

Fig. 1. Profile "Unterer Hauenstein", from Noack (1989). (a) balanced profile, (b) restored pre-thrusting profile. Figs. 2 and 3 are located farther E.

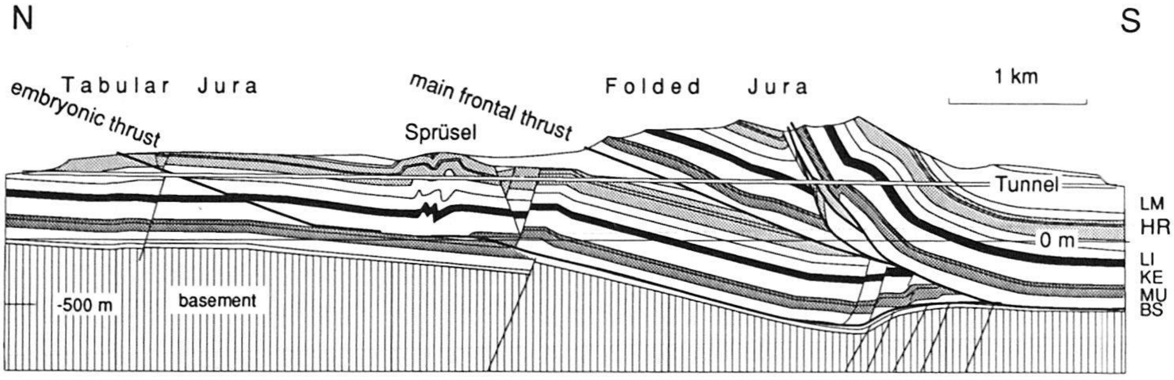

Fig. 2. Profile of the Hauenstein-Basistunnel, after Buxtorf (1916) and Laubscher (1977). BS = Buntsandstein, MU = Muschelkalk, KE = Keuper, LI = Lias, HR = Hauptrogenstein, LM = lower Malm. Note that normal faults (small grabens) of the Tabular Jura are cut by the younger thrusts.

(below the carbonates) to a higher décollement layer in the middle to upper Triassic Keuper evaporites (above the carbonates; see Fig. 4). Although the individual horses of the duplex system are often folded, the general characterization as a stack of duplexes holds throughout.

Ramp-flat thrust tectonics is typical of the Jura although it has been camouflaged in places (particularly that part SW of Basel) by large-scale folds which have given rise to expressions like "folded Jura" for the whole thin-skin belt, and "Jura folding" for the process responsible for its formation (Laubscher 1983a). The folds, however, have been recognized as frequently thrust-related (e.g. Suter 1981). Smaller folds are developed above blind thrusts, particularly where ramps flatten into décollement segments (e.g. Laubscher 1977). These folds require, for reasons of material balance, support by accumulation of material in their core. Small-scale duplexing is suggested by the seismic

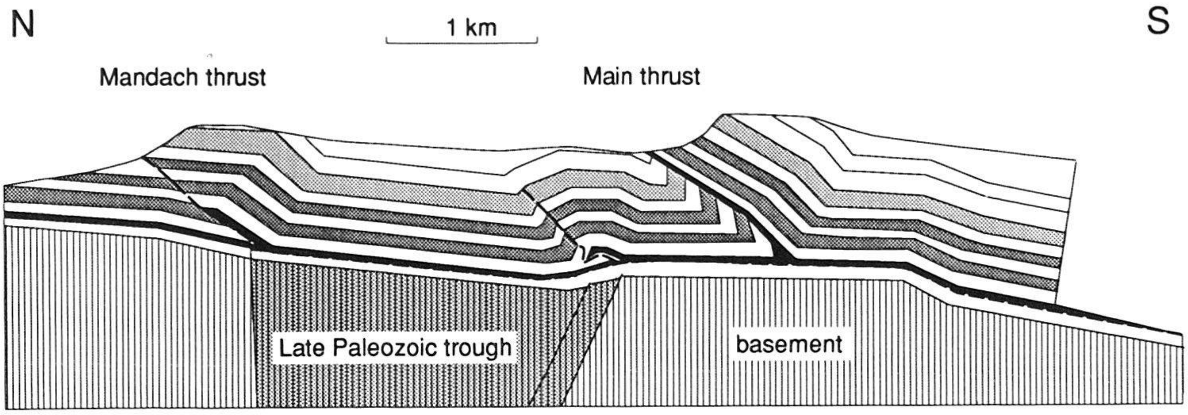

Fig. 3. Generalized profile through the easternmost Jura, W of the Aare-Rhine confluence, after Diebold (1990); it is based on the extensive network of modern reflection lines of Nagra. Distance between Fig. 1 and Fig. 3 is about 25 km.

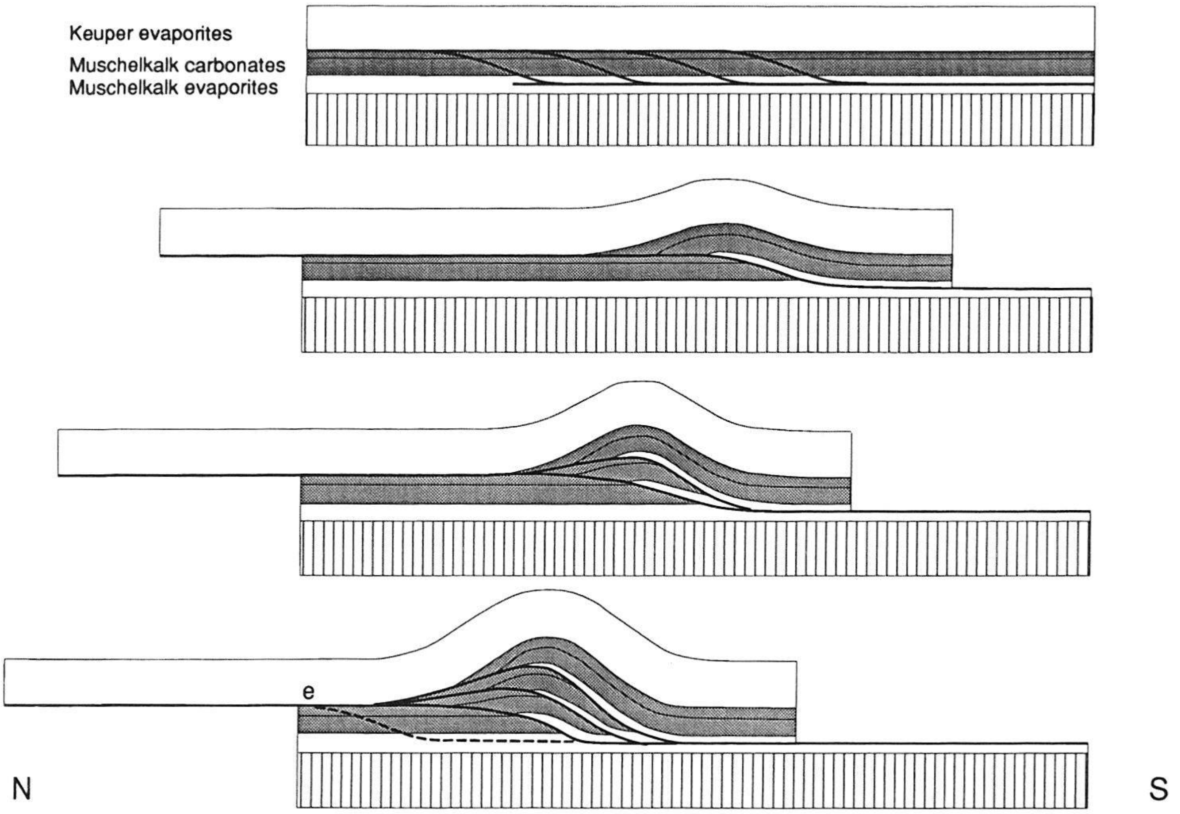

Fig. 4. The development of antiformal stacks of Muschelkalk duplexes which are conjectured to support large Jura folds, e.g. the Grenchenberg anticline. Note that the thrusts may be completely hidden in the subsurface, but that knowledge of the thickness of the duplexes can be used to estimate the amount of shortening.

evidence (Laubscher 1986). I have recently mapped systems of such small-scale duplexes in the upper Jurassic south of Basel (unpublished originals). Larger-scale folds such as the famous Grenchenberg fold (Buxtorf 1916) require support by the accumulation of lower Jurassic to Triassic in their core. Buxtorf (1916) suggested disharmonic upright folds, but the surface evidence in the Muschelkalk-Schuppenzone rather points to anticlinally stacked duplexes (Fig. 4). Such a solution looks very reasonable in Fig. 1 for the Gummenflühli fold immediately behind the Muschelkalk duplexes exposed at the surface (Noack 1989). Imbricate stacking of material, associated with small-scale folding, is also responsible for the development of triangle structures with passive-roof backthrusting at the very front of the thrust system at an initial stage of fold formation (Fig. 3). Bitterli (1990) advocated late large-scale backthrusting in the south-limbs of the internal Jura folds as an alternative to stuffing by imbrication. However, these large thrusts are nowhere exposed, and they would have to cut through complexly deformed units irrespective of bedding anisotropy, which from present evidence is crucial for the formation of Jura folds. This raises the question of admissibility (Boyer & Elliott 1982). I consequently prefer the disharmonic solution offered by Buxtorf, modified to accommodate in their core antiformal stacks of duplexes in addition to folds.

Insistence on the important role of duplexes and antiformal stacks of duplexes in the thin-skin kinematics of the Jura is deliberate and serves a purpose. I want to stress this aspect for the following discussion of ramp folding where the thrust ramps down from décollement in the middle Triassic into basement.

The link of the Jura system with the Alps

What do we expect at the place where this ramp into basement occurs? Material balance requires a large basement fold that could not possibly have escaped early detection (compare Laubscheer 1961). One place in another part of the Alps where such a basement ramp-fold is directly observable is the Orobic fold in the southern Alps (Laubscher 1985, Schönborn 1992). Here a ramp-flat system in many ways comparable to the Jura system is marvelously exposed (Fig. 5). The sedimentary thin-skin part exhibits a regional décollement at the base of the middle Triassic, as observed in the Grigne mountains east of Lake Como. The Orobic basement thrust into which it ramps down is exposed in a series of localities in the Orobic Alps farther north. There seems to be a décollement in the basement about 4 km below the top, and its position at the time when thrusting was initiated had been at a depth exceeding 10 km, apparently at about the brittle-ductile transition zone. The Orobic anticline seems to consist of an antiformal stack of at least two major basement slices, augmented by a series of smaller-scale imbrications (Keller 1986, Schönborn 1986, Schumacher 1986, Keller et al. 1987, Schönborn & Laubscher 1987, Schönborn 1992).

What does this model suggest for the basement ramp deformation in the Jura system? The maximum amount of shortening in the thin-skin part in the Jura has been estimated at about 30 km (Laubscher 1965, Guellec et al. 1990). Shortening by this amount a basement slab 4 km thick results in a cross-sectional mass (area) excess of 120 km^2. Moreover, taking the thin-skin ramp-flat geometry and the situation in the Southern Alps as a cue and modeling the Jura basement ramp as an antiformal stack of duplexes, this implies an approximately triangular basement structure 30 km wide and 8 km high.

This is the order of magnitude represented by the External Massifs. Moreover, if – as in the southern Alps – décollement in the basement was located at the brittle-ductile transition at a depth of 10 to 15 km with a temperature on the order of 300 °C two further characteristics of the External Massifs are met; the beginning of greenschist metamorphism and the transition to ductile deformation (Voll 1976, 1980, Frey et al.

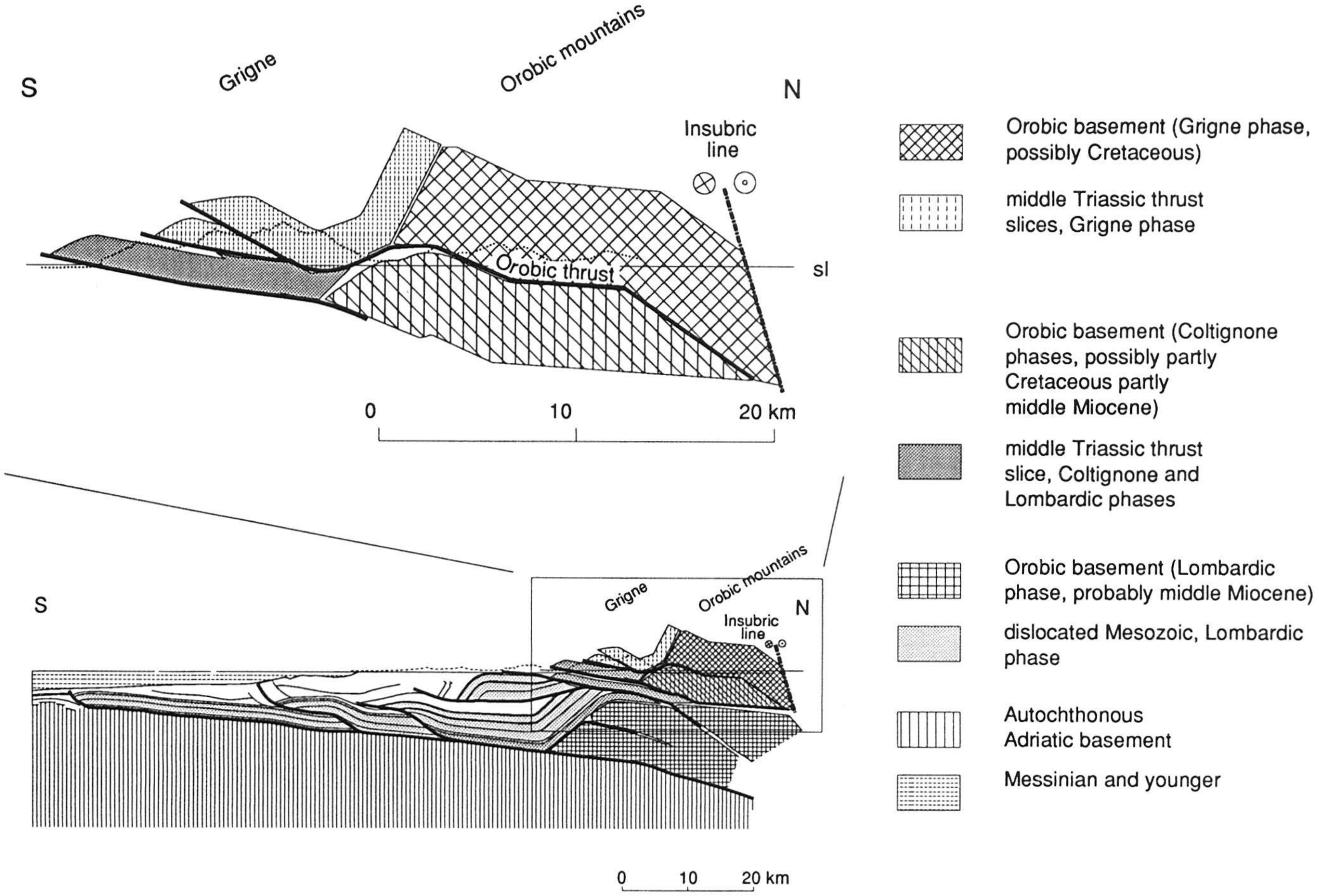

Fig. 5. Balanced profile through the Southern Alps and their foreland, from Schönborn (1992, compare Laubscher 1985, 1990 b).

1980). In the field this is evident on the megascale as stacked basement lobes (Rohr 1926, Scabell 1926, Collet & Parejaz 1931, Masson et al. 1980, Laubschner 1983b), and on the microscale as plastic deformation of quartz and pressure solution transfer ("hydraulic pumping" of Urai et al. 1986) of silicate minerals, particularly feldspars, which crumble into cataclastic fragments with the cracks healed by mostly chlorite-sericite-epidote (Voll 1980). As to timing, the external massifs deform the Helvetic nappes and therefore are definitely younger than the Insubric-Helvetic phase (post-Early Miocene). Soom (1990) has worked out a number of zircon fission track ages which are believed to data cooling to about 220 °C. Reliable ages for the Aar massif cluster about Middle Miocene times (8–12 Ma for the southwestern Aar massif), although interpretation in terms of tectonic events is not easy: Local uplift by stacking of crustal duplexes is counteracted by lithospheric downbulging due to loading by thrust masses, pulling by the negative buoyancy of the mantle part of the subduction zone and other boundary loads; this lithospheric subsidence is of a more regional nature and is eventually superseded by isostatic uplift because of erosion and the breaking off of the lithospheric root. The apparent ages reflect the sum of all these motions and therefore give only an imprecise figure for the actual thrusting event. All that can be said at present is that the middle Miocene ages are compatible with both Jura thin-skin deformation and Subalpine Molasse imbrication (compare, e.g., the frontal triangle zone or underthrust of the Subalpine Molasse under middle Miocene, Habicht 1945). Indeed, the two deformational events may well be grouped into the same post-Helvetic phase – the Jura phase – that affected the European foreland of the western and central Alps (Fig. 6). Its lateral continuation in the eastern Alps is still enigmatic (compare Laubscher 1988, 1990b). If the thin-skin deformation of the Subalpine Molasse also has its basement ramp in the External Massifs, the additional shortening of maybe up to 20 km would add another 80 km^2 to their antiformal stack. This would then be about 40 km wide and 10 km high – very close to that depicted in Fig. 7.

Indeed, no other model seems to be able to account for the shape, size, internal structure and timing of the External Massifs. It is still customary to speak of the "uplift of the autochthonous External Massifs", and this emphasis on the vertical component and "autochthony" tends to obscure the much more important horizontal shortening of which the uplift of the massifs themselves is a mere consequence. As explained above, this latter should not be confused with the current, much more regional, geodetically determined uplift of the Alps (Gubler et al. 1981), the dynamic interpretation of which is still debated (Neugebauer et al. 1980), although its regionality suggests isostatic adjustment due to unloading of the lithospheric downbulge by erosion at the top and possibly detachment of parts of the subduction zone at the bottom.

The main problem in the External Massifs is the distribution of shortening, and particularly what share is due to the imbricated thrusts and lobes (or recumbent folds) and how much to a possible basal thrust (e.g. Mugnier et al. 1990). Laubscher (1973), while attributing the Doldenhorn nappe and its basement equivalent farther east, the Jungfrau lobe (Masson et al. 1980) to Jura décollement, interpreted the Gastern massif as the frontal fold of the youngest, blindly ending basement décollement thrust. This interpretation comes fairly close to that proposed in this article but seems to be contradicted by recent reflection surveys whose results indicate thrusting (or lobes, which

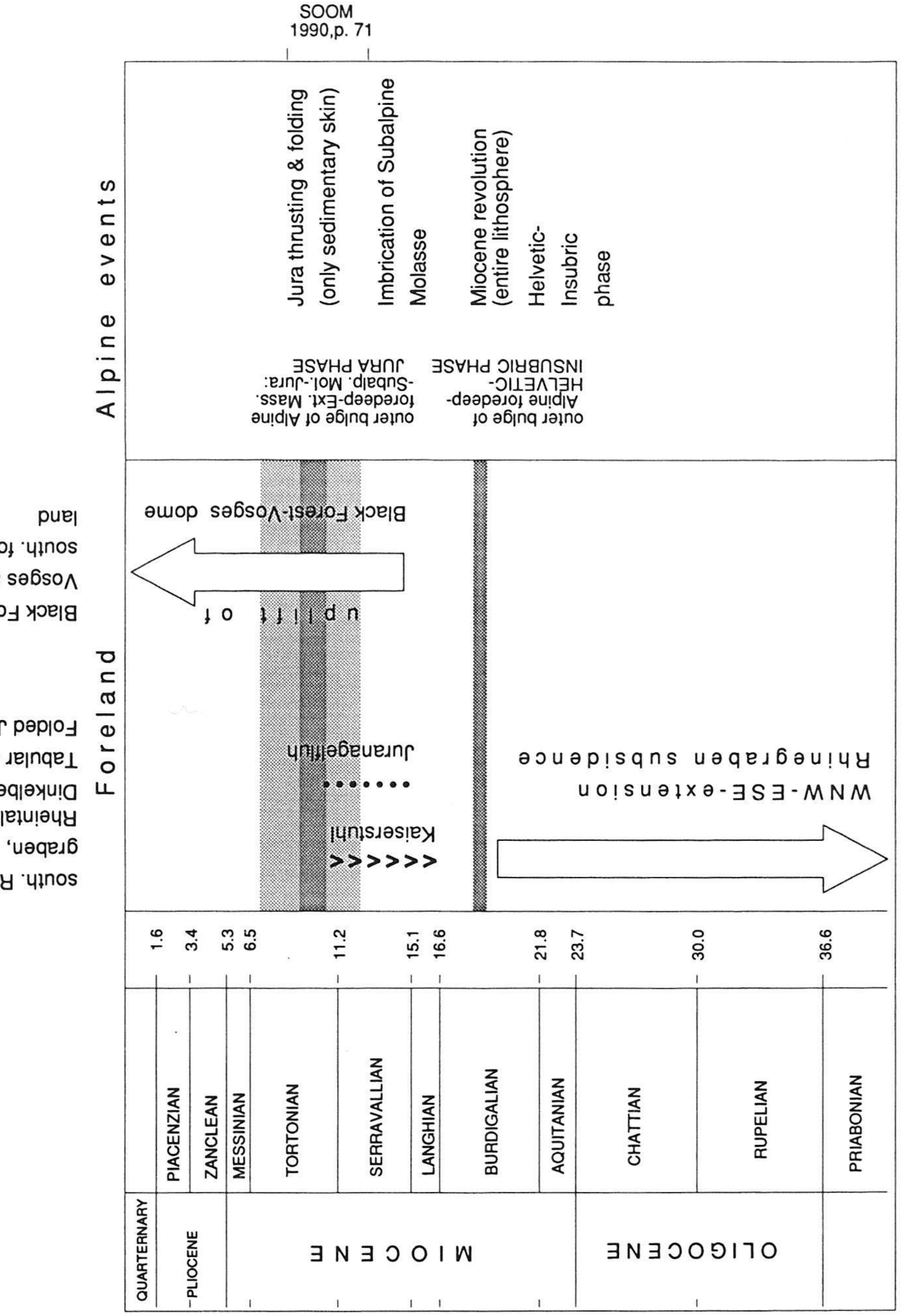

Fig. 6. Timing of events in the northern Central Alps and their foreland, after Laubscher (1987).

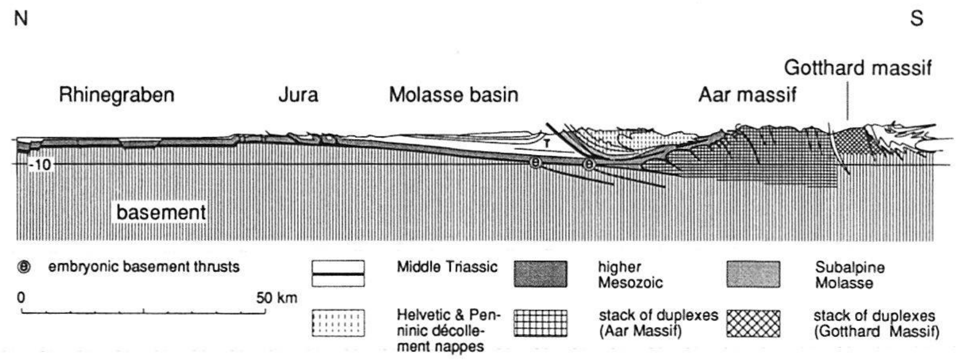

Fig. 7. Profile through the northern Central Alps and their foreland, after widely accepted representations (compare Trümpy 1980). On top of the Aar massif – here interpreted as an antiformal stack of ductile duplexes (lobes) – the base of the older Helvetic décollement nappes is deformed in the manner of the model Fig. 4. Where the Triassic evaporites are locally absent, shear distributed throughout the Mesozoic is assumed to take its place (compare Rohr 1926), eventually passing into Tertiary shale layers such as the Rupelian shales at the base of the slices of Subalpine Molasse. A step-down into the Triassic evaporites where these reappear is conjectured, after the fashion envisaged by Laubscher (1983b). The Gotthard massif, in this section, may be interpreted tentatively as the antiformal stack of basement duplexes for the Helvetic décollement nappes; the connection would be similar to that between the Aar massif and the Jura, except that the Helvetic nappes were covered by older and higher nappes.

would be hard to distinguish seismically) down to the very base of the massifs and, embryonically, even as far in the foreland as the Subalpine Molasse (Vollmayr & Wendt 1987). Similar conclusions – in essence if not in detail – were reached by Guellec et al. (1990) and Mugnier et al. (1990) for the ECORS profile in the western Alps.

In the central Alps, at least, both the Jura and Subalpine Molasse décollements appear to ramp down into basement by means of an antiformal stack of basement duplexes similar to that shown in Fig. 4 for the Triassic in the Jura: the "autochthonous" Aar(-Gastern) Massif. If thrusting proceeded strictly in sequence, then the higher, southern duplexes of the stack are to be connected with the Subalpine Molasse, but a quantitative, balanced kinematic model of these connections has yet to be worked out.

One problem that remains to be discussed is the link between basement lobes and thin-skin décollement where well defined décollement horizons are lacking. There, distributed simple shear such as that manifest in the "autochthonous" Jurassic may substitute for the more discrete simple shear commonly assumed for décollement, as suggested by Laubscher (1983b). Again, quantitative modeling is still to be done.

The subduction part of the Jura system

The further fate of the Jura system in the deeper parts of the crust and the mantle is elucidated by the results of NFP 20 (e.g. ETH Working Group on Deep Seismic Profiling 1991). Fig. 8 shows a selection of reflections pertinent to this issue (compare Laubscher 1990a). That part of the south-dipping subduction zone clearly imaged is quite short and corresponds to a shortening, or Adria-Europa plate convergence, of 50 km at the utmost. This, however, is the shortening of the Jura system, including the Subalpine Molasse, which is the expression of the latest phase of Europa-Adria convergence. The many hundreds of kilometers of earlier convergence are either not

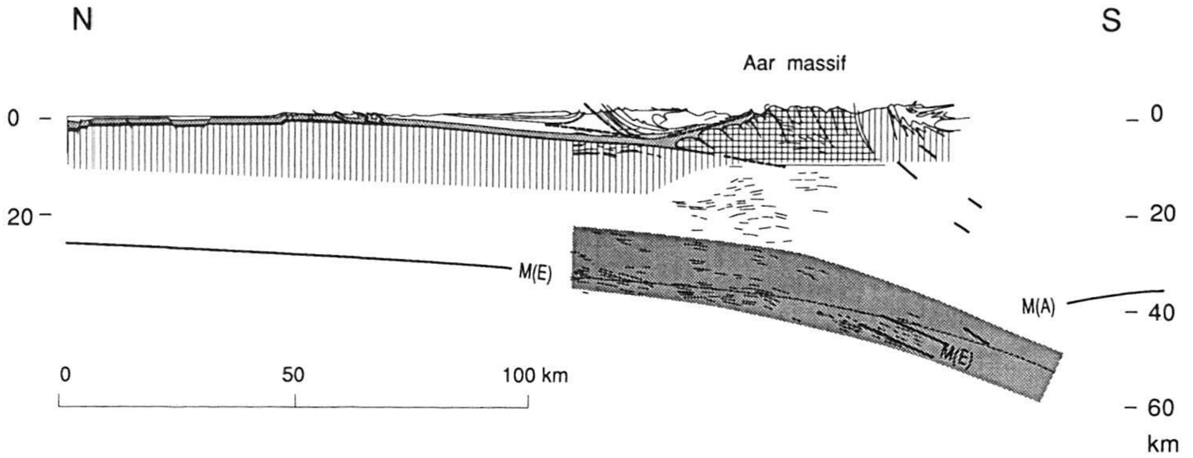

Fig. 8. The Jura-Subalpine Molasse-Aar Massif system and the Europa subduction zone as revealed by NFP 20 (selected reflections, migrated where heavy lines, projected from the Eastern Traverse, from Laubscher 1990, compare ETH Working Group on Deep Seismic Profiling 1991 and Ye & Ansorge 1990). Dark shading: subducting lower crust; M(E): European Moho; M(A) Adriatic Moho. Other signatures as in Fig. 5.

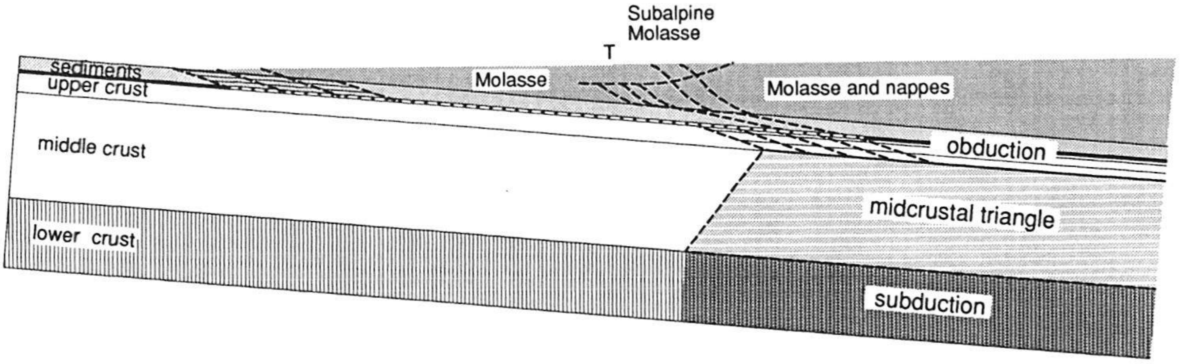

Fig. 9. The shear system of the Jura-Subalpine Molasse-Aar Massif phase (or simply "Jura phase"). Simple shear is supplemented by pure shear, particularly in the ductile domain.

imaged or, more probably, have been disengaged from the lithosphere (Laubscher 1988, 1990b, 1991). It may be concluded that it is inadmissible to judge from the present geophysical picture, which reflects only the comparatively small latest stage of Alpine deformation, the overall nature of Africa-Europa plate convergence. Only regional historical geology can do that.

Between the south-dipping subduction zone, delineated by the reflections of the lower crust and the Moho, and the uppermost crust, that was subject to obduction and piling up in the antiformal stack of the External Massifs, there is a wedge-shaped space of ill-defined structure. Laubscher (1970 and later publications, e.g. 1988) early on insisted on the fact of this divergence for which in the meantime several names have been proposed. Impressed by the "bird's head" shape of the Ivrea body (Giese 1968, Berckheimer et al. 1968) he argued for the insertion of lower crust-upper mantle wedges into this zone of divergence. Such a mechanism seems to be supported by results of several recent seismic surveys (e.g. ETH Working Group on Deep Seismis Profiling 1991, Ye and Ansorge 1990, Bois & ECORS Scientific Party 1991). In the case of the Jura-phase intracrustal divergence under the External Massifs the situation is not clear. There are layered reflections, but they may represent accumulated middle crust.

In summary, the ramping down of the Jura thrust system into the subducting lower crust-upper mantle is not a straightforward ramp-flat scheme (Boyer & Elliott 1982). Rather, there is a profound structural disharmony in the highly ductile middle crust which somewhow, possibly with the aid of lower crust-upper mantle slices, fills in the space of divergence between the obducted higher and the subducted lower parts of the zone of plate convergence. The summary character of the complete shear zone is represented in Fig. 9.

The migration of the northern Alpine forebulge

Subducting lithospheric plates are characterized by the subduction zone at one end and, in the foreland, by the foreland bulge or forebulge ("outer flexural high" of Royden 1988, corresponding to the "outer rise" of oceanic subduction), which ordinarily has a structural relief of no more than a few hundred meters (compare Le Pichon

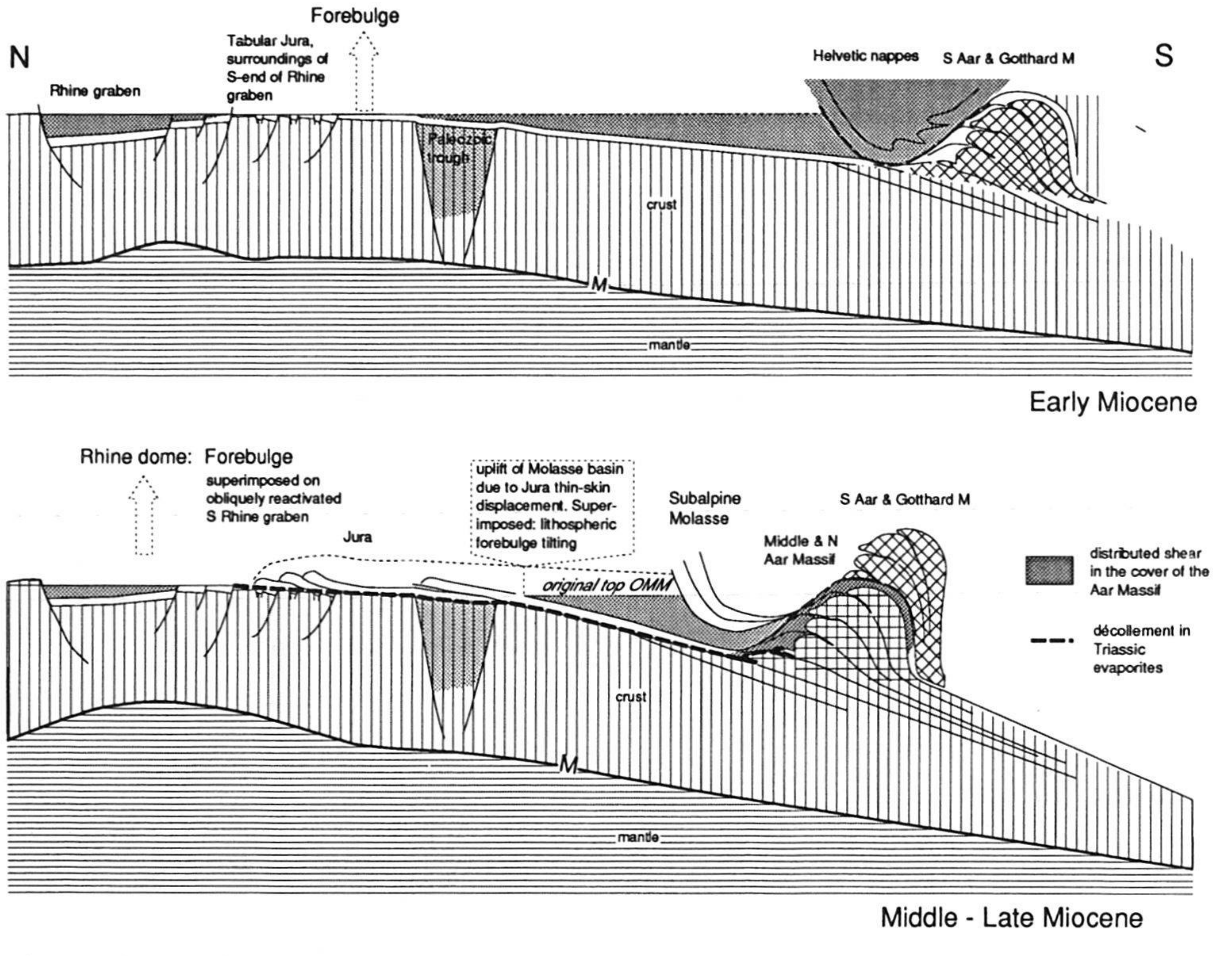

Fig. 10. The migration of the lithospheric foreland bulge due to the Jura phase, qualitative model. Where it is superimposed on the southern Rhinegraben, the Rhine Dome develops, apparently through activation of asthenospheric flow (Werner & Kahle 1980).

et al. 1973, Suppe 1985, Royden 1988, Sinclair et al. 1991). This bulge should be expected to mark the external flank of the Molasse basin. There, two important Neogene erosional events have been known for a long time (compare Fig. 6) and may be considered candidates for an approximate location of the bulges corresponding to the two Neoalpine phases. The younger, Jura phase forebulge should be expected about 50 km farther in the foreland than that of the Late Oligocene-Early Miocene Helvetic phase, as an additional amount of about 50 km of lithosphere was subducted in the Jura phase (compare the schematic Fig. 10).

The Helvetic phase forebulge

For the Late Oligocene-Early Miocene (Helvetic) phase the existence of an external hinge of the Molasse basin, with beginning erosion, had been recognized early on (e.g. von Braun 1953) and has recently been defined more precisely by the results of the exploration efforts of Nagra (Naef & Diebold 1990, Naef et al. 1985). This hinge is superimposed on the Late Paleozoic trough of Northern Switzerland (or of Constance-Frick), which has been slightly reactivated in the process (Fig. 3). The existence of this old, largely consolidated lithospheric heterogeneity obviously influenced the shape of the bulge somewhat, but not dramatically, Laubscher (1986, 1987) argued that the Oligocene-Early Miocene flexures and small faults resulting from the reactivation of the Paleozoic trough might constitute a link between the contemporaneous belts of normal faults in the northern slope of the German-Austrian Molasse basin and the late stages of rifting in the Rhine graben. The main part of that fault belt, however, may have swerved into the Helvetic domain of the Swiss and French Alps as suggested above.

Within the folded Jura, there are further indications of the Helvetic phase forebulge. In the syncline of Tavannes, in the continuation of the Rhine graben (Rauracian depression), there is a relic of OMM considered to be Burdigalian (Rothpletz 1933). It is covered unconformably by Middle Miocene (Langhian?) marine conglomerates. In the central and western Jura the bulge is not documented in as much detail, but the Miocene unconformity on tilted older beds in various synclines are reminiscent of the situation at the eastern end of the Jura (Laubscher 1986), and the mere fact of the pre-middle Miocene erosion points towards the existence of an Oligocene-Early Miocene bulge there (Guellec et al. 1990). This unconformity has often been considered as indicative of an early phase of Jura folding (Buxtorf & Schlaich 1928, Aubert 1958), although its basement-rooted structures in no way resemble thin-skin Jura folds and thrusts (Laubscher 1986).

In a recent article, Sinclair et al. (1991) have attempted some quantitative dynamic modeling of the relation between sedimentation, erosion and lithosphere deformation in the transect discussed here. As an input they use the intra-marine Miocene unconformity as given by Naef et al. 1985 and Naef & Diebold 1990 for location and quantification of the forebulge. This coincides with the Helvetic phase forebulge of this article. However, they also assume a continuity of deformation from the Eocene on. This assumption is in agreement with Pfiffner (1986); it is, however, not supported by the data summarized in Fig. 5; these demand two distinct events separated by an interval of peneplanation and shallow marine transgression.

The Jura phase forebulge

The peneplanation and shallow marine transgression (Late Burdigalian to Langhian) is particularly well documented in the Tabular Jura of Basel (Buxtorf 1901). It dates what Laubscher (1987) termed the "Miocene revolution" in the northern foreland of the Alps (Fig. 5). Apparently, at that time the stress system in the Rhine graben domain underwent a radical change (Figs. 11, 12). The maximum compressional stress σ_1, which had been vertical in the Oligocene, now became horizontal and was rotated into a NW-SE direction; σ_3 remained horizontal but was rotated into a NE-SW direction, whereas σ_2 became vertical (Illies 1978, Illies et al. 1981). This stress system precluded a continuation of general rifting in the Rhine-Bresse graben system (for developments in the Bresse graben see Bergerat et al. 1990). It called for strike-slip tectonics, which, because the Rhine graben constituted a profound lithospheric in-

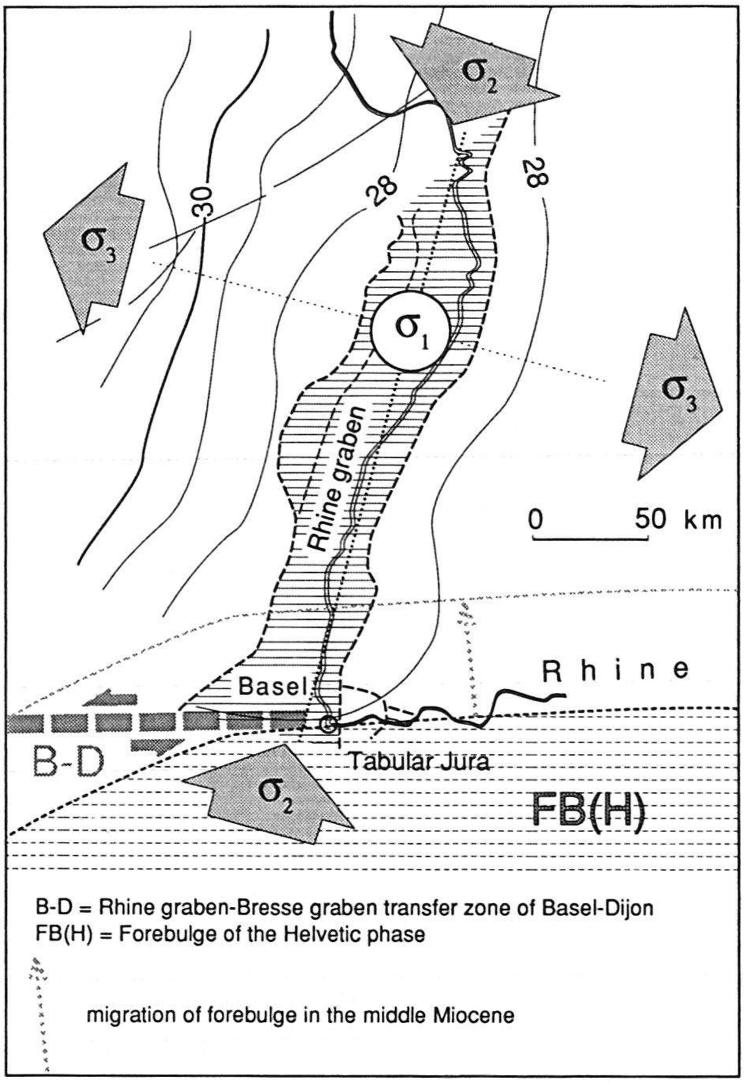

Fig. 11. Forebulge and Rhine graben in the early Miocene. The best documented unconformity that approximately positions the forebulge for the Helvetic-Insubric phase (FBH) is between the early Burdigalian and the Langhian. Rhine graben activity continued through the Chattian-Aquitanian probably into the Burdigalian, when an entirely different tectonic development was initiated (compare Fig. 6 and Fig. 12).

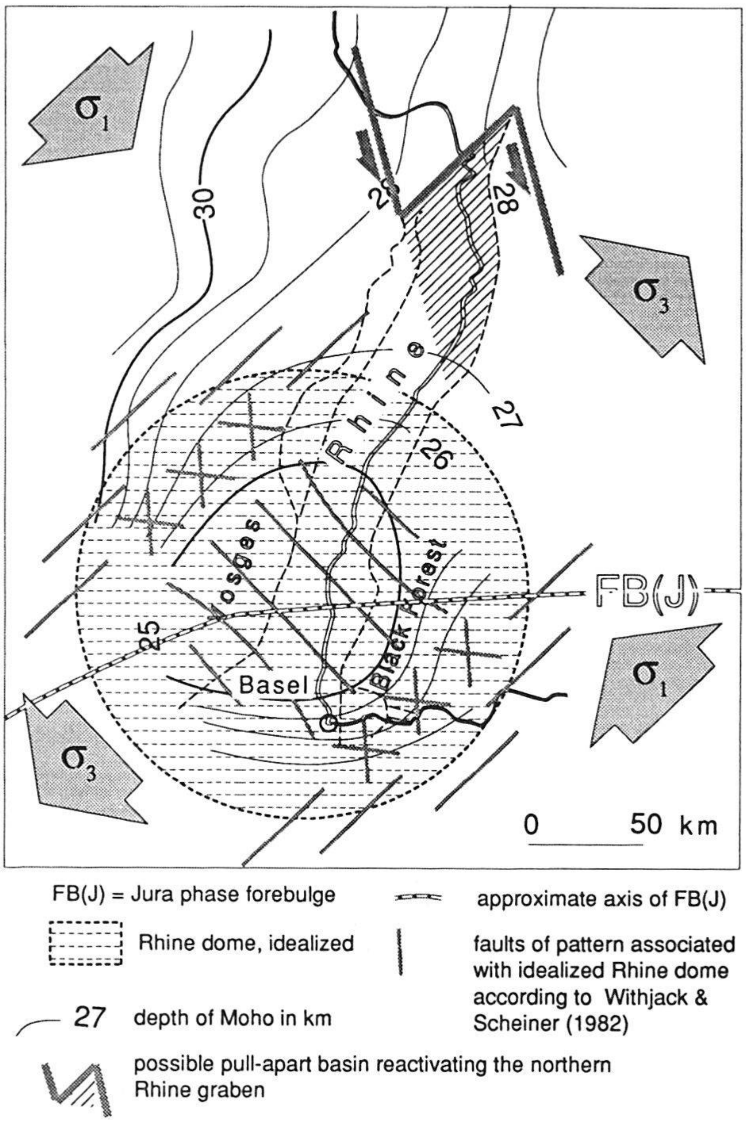

Fig. 12. After the pre-Langhian unconformity, uplift of the Rhine dome in the southern part of the Rhine graben set in, coupled with a rotation and change of indices in the regional stress field. In this stress field Rhine graben activity was unable to continue as before. The graben now is an inherited inhomogeneity, an oblique zone of weakness where strike-slip and limited pull-apart normal faulting occurred. The dome is supported by hot asthenospheric masses supplanting part of the lithosphere and somehow provoking crustal thinning.

homogeneity, manifested itself in both transpressive and transtensive structures. In this context, the well-known continued subsidence of the northern part of the Rhinegraben would have to be attributed to local transtension. The southern part of the Rhinegraben, on the other hand, now became the locus of what may be termed neutrally as "constructive interference" with the Alpine forebulge (Figs. 10, 12, 13).

The nature of this interference may be gathered from a number of geological data. Still in the middle Miocene, the Langhian shallow marine deposits were tilted and uplifted, and the reasons and regional tectonic implications of this deformation have been a subject of controversy for some time. Lemcke (1973) combined the part east of the Jura with that south of the Jura into one system of basement uplift. Laubscher (1974), on the other hand, argued for a separation of the two parts. He showed that

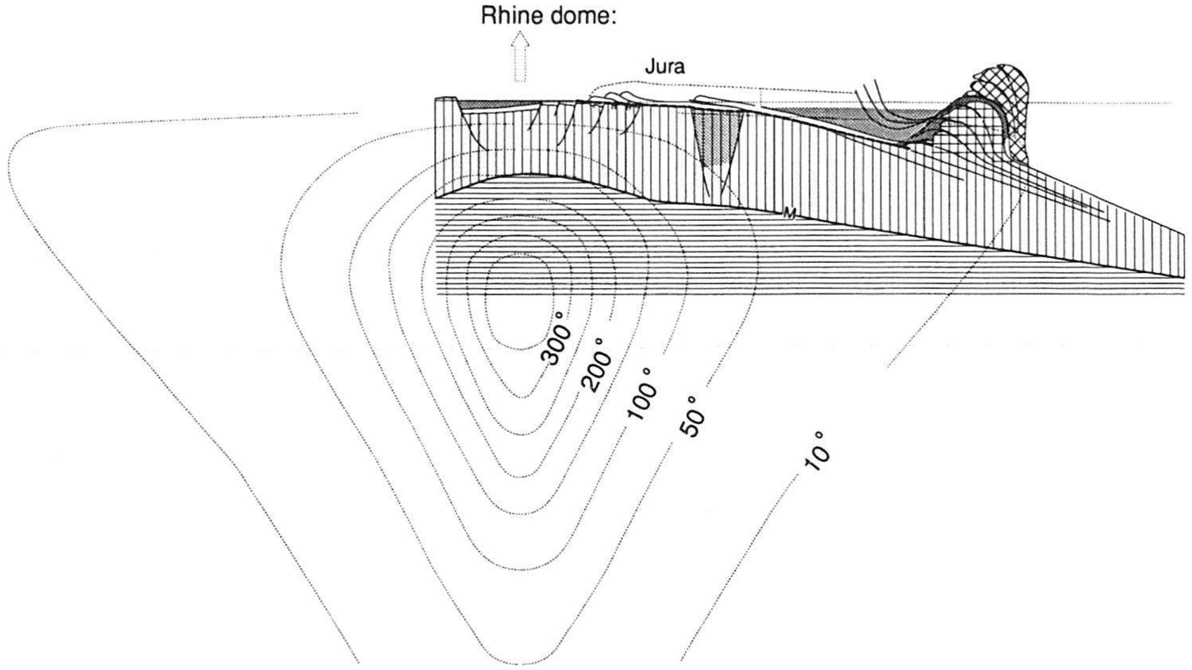

Fig. 13. The thermal anomaly (isoanomalies in degrees Celsius) which according to Werner & Kahle (1980) supports the Rhine dome and its gravity anomaly, superimposed on Fig. 10b. Although the Figure is only roughly to scale, it is evident that the thermal anomaly is of the dimension of the Alpine plate suture, and that deformation of the lithosphere in the northern foreland of the Alps will be strongly conditioned by it.

the uplift of the OMM behind the Jura, increasing almost linearly from the eastern end of the Jura to more than 2000 m behind the central Jura could be more easily explained by the vertical component of Jura décollement which had to ramp up through the northern slope of the Molasse basin (compare Fig. 10). That left a post-Langhian basement tilt which in the east uplifted the northern limit of the OMM by several hundred meters, increasing westward to 900 m in the Randen area and, by extrapolation, to more than 1500 m in the Black Forest. The beginning of this uplift is dated by the onset of the sedimentation of the Juranagelfluh conglomerates in the Serravallian about 14 Ma ago (Fig. 6; compare Diebold 1990, Laubscher 1987). It lasted to at least 11 Ma, the youngest OSM beds dated so far (Matter & Weidmann, this volume). It is approximately coeval with the Jura-Subalpine Molasse décollement. Moreover, its axis seems to be about 50 km outside the Late Oligocene-Early Miocene (Helvetic phase) forebulge; it is a little more, if the center of the Black Forest-Vosges uplift (Kaiserstuhl volcano) is assumed to be on the axis (Fig. 11).

Thus both space and time of these events coincide with those of the Jura phase forebulge. But what about the excessive uplift in the domain of "constructive interference" with the Rhine graben in the Black Forest-Vosges region? Two considerations would appear to have a bearing on this problem. The first is that ordinary foreland bulges are those developed in a homogeneous lithospheric slab, and the second is that calculations are usually based on the theory of homogeneous elastic beams or thin elastic plates loaded at the subduction end (compare Turcotte & Schubert 1982, Royden 1988). But what happens if the outer bulge coincides with a major inhomogeneity such as the lithospheric Rhine-Rhone fault system that has stopped its ac-

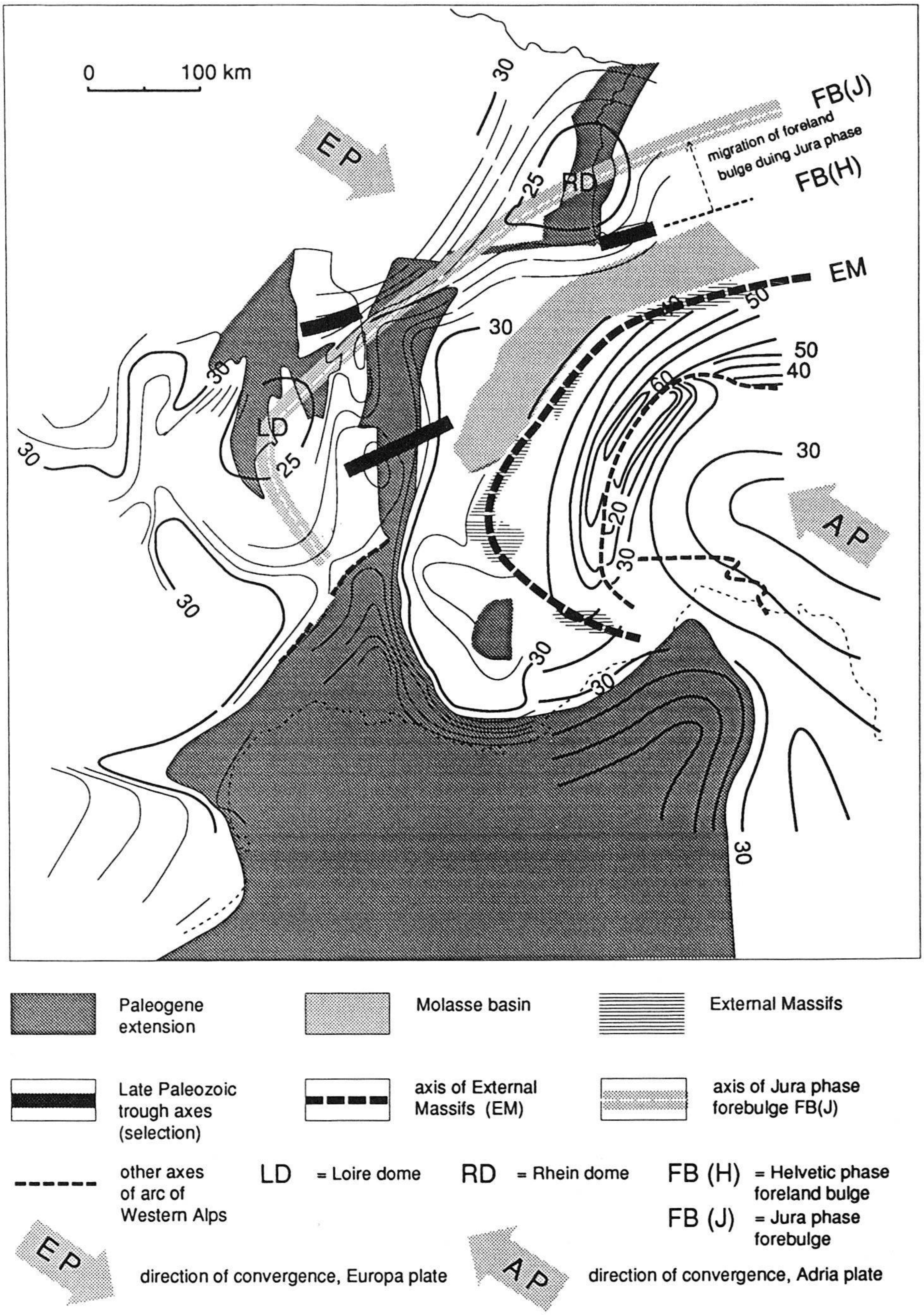

Fig. 14. The estimated positions of the foreland bulges attributable to the Helvetic-Insubric phase (FBH) and the Jura phase (FBJ), superimposed on the isobaths of the Moho (after Hirn 1980, Giese). Very dark bands: examples of known late Paleozoic troughs. Dark shading: Paleogene to Early Miocene extensional structures.

tivity a mere 5 Ma before and is still hot, offering a rheological weakness of lithospheric dimensions? Kahle & Werner (1980) and Werner & Kahle (1980; compare Villemin et al. 1986) have modeled the Rhine dome gravimetrically and thermally and concluded that it must be supported by a considerable mass of hot mantle material advected from below (Fig. 13). Such asthenospheric motions are linked with every subduction process as the subducted lithosphere displaces asthenospheric masses. If channelled into a zone of weakness in the foreland such as the west-European rift system, they would impose another set of boundary forces on the elastic plate, presumably leading to a greater deflection at the forebulge. This conjecture is hardly provable at this time, yet suspicion that all the diverse events documented in the Rhine dome domain are causally linked rather than mere coincidence is hard to avoid. Fig. 13 demonstrates that the thermal anomaly under the Rhine dome and the lithospheric deflection in the northern Alpine foreland are of similar dimensions and largely superimposed on each other.

The conjecture is further supported by the regional Moho contours (Fig. 14). There is an arcuate Moho ridge nearly parallel to the arc of the External Massifs. It closely coincides with the location of the Jura phase forebulge as expected both from its location north of the German Molasse basin and its distance from the Helvetic phase forebulge W of Lake Constance. From the Rhine dome to the W it approximately follows the Paleogene Rhine-Bresse transfer zone (Laubscher 1970a), after which it arrives at a new prominent Moho dome, here called the "Loire dome", that developed approximately where the putative bulge interferes with the Paleogene Limagne graben. Again, it would appear that such a regional coincidence of lithospheric anomalies with the expected position of the foreland bulge ought to be causally related. Conversely, the position of the Moho ridge and the superimposed Moho domes calls for an explanation. I am not aware of any alternatives offered so far.

There is, of course, no exact age relation between the activity in such a lithospheric foreland bulge and the thin skin compressive features in the foreland such as the Jura. The motions of asthenospheric hot material modeled by Werner & Kahle (1980) developed a dynamics of their own, and even though Jura thrusting seems to have stopped before the Pliocene (Matter & Weidmann 1991), resumption of subsidence in the Bressegraben in the Plio-Pleistocene (Guellec et al. 1990) is documented. However, in view of the complex dynamic situation it is doubtful that this locates the youngest Alpine foredeep as assumed by Guellec et al. (1990).

A brief outlook on 3D problems

The individual constituents of the Jura system – thin-skin Jura fold and thrust belt, the Subalpine Molasse, the External Massifs – all are laterally discontinuous. On the other hand, the system as a whole is the result of the Middle to Late Miocene oblique convergence between Adria and Europa and must be laterally continuous. This poses difficult, as yet unsolved problems in 3D material balance on several scales. Most of these problems have been addressed if not solved in various publications, see, for instance, Laubscher (1961, 1965) for the eastern margin of the Jura décollement sheet in the Molasse basin, and Laubscher (1988) for the eastern end of the External massifs and the axial depression between them. The general conclusion is that in an easterly direction the Jura system withdraws to the South, joining the Insubric Line at the Brenner transverse zone and reactivating dextral transpression in the Klagenfurt basin and the Karawanks.

This withdrawal to the south requires several dextral transverse zones, which are not obvious, else they would have been recognized long ago. On a smaller scale, such diffuse transverse zones abound in the Jura (e.g. Laubscher 1965, 1981); the associated strike-slip faults are mostly small and not mappable. This is also true for the eastern margin of the Jura décollement sheet in the Molasse Basin and for the lateral discontinuities in the External Massifs. As far as the Subalpine Molasse and the front of the overlying nappes are concerned, they are characterized by numerous axial irregularites and comparatively small dextral faults that are shown on a number of regional maps. However, I know of no attempt to link these obviously very young transfer features with the large-scale Late Miocene kinematics.

A particular problem is posed by the relation of the Middle to Late Miocene Jura phase with the equally Middle to Late Miocene Lombardic phase at the internal (southern) margin of the Alps. A connection is postulated by Laubscher (1988) in the Brenner area where the two might join and cross. Another connection is suggested by the Middle Miocene cooling ages on the eastern flank of the Simplon-Rhone line (e.g. Soom 1990; compare Laubscher & Bernoulli 1982). However, no quantitative kinematics of these links have been worked out so far.

Discontinuities in the very deep structure at approximately the expected position appear on geophysical maps. The gravity map (Miller et al. 1985) shows as discontinuity in the axial low E of Chur, and the map of the base of the lithosphere by Babuška et al. (1988) contains a considerable dextral offset between the deep lithospheric roots of the Alps in that location.

Conclusions

Thin-skin Jura kinematics is of the ramp-flat type characteristic of foreland fold and thrust belts. Duplex formation of the Muschelkalk carbonates between the evaporitic décollement horizons below and above is the rule where the Triassic is exposed in the eastern Jura. It is conjectured that the large folds in the southern part are supported by anticlinal stacks of Muschelkalk duplexes. Similarly, anticlinally stacked basement duplexes occur, where Jura décollement ramps down into basement, and form the External Massifs. They developed in the brittle-ductile transition zone as recumbent folds and faulted lobes rather than simple brittle thrusts. Early décollement under the Molasse basin was locally cut by the youngest, embryonic basement thrusts as far out as the Subalpine Molasse. The décollement tectonics of the Subalpine Molasse is conjectured to be an early stage of post-Early Miocene Adria-Europa plate convergence at the northern margin of the central and western Alps, which was kinematically linked to the External Massifs and ended with Jura décollement.

These elements form the obducted part of what may be called the Jura system. The subducted part, lower crust and upper mantle, is imaged by the results of recent deep seismic sounding and suggests lithospheric shortening of no more than 50 km, compatible with estimates for thin-skin shortening in the obducted part. Obducted and subducted parts diverge, leaving space for the insertion of wedges, in some cases consisting of lower crust and upper mantle material.

The Jura system is completed by the lithospheric forebulge, corresponding to the ordinarily small external deflection of the damped lithospheric sine wave in whose center is the subduction zone. Where it was superimposed on the West-European (Rhine-Bresse-Limagne-Rhone) rift system, "constructive interference" took place, and unusual processes were initiated. A new stress system developed, and rifting ceased except as limited transtension. Asthenospheric convection set in and created mantle domes of hot masses resulting in such puzzling features as the Rhine dome (Black Forst-Vosges) and the Loire dome.

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REFERENCES

AUBERT, D. 1958: Sur l'existence d'une ride de plissement oligocène dans le Jura Vaudois. Bull. Soc. neuchât. Sci. nat. 81, 47–53.

BABUŠKA, V., PLOMEROV'A, J. & PAJDUSAK, P. 1988: Lithosphere-asthenosphere in central Europe: Models derived from P residuals. In: Fourth EGT Workshop: The Upper Mantle (Ed. by NOLET, G. & DOST, B.). European Science Foundation, Strasbourg, 37–48.

BERGERAT, F., MUGNIER, J.-L., GUELLEC, S., TRUFFERT, C., CAZES, M., DAMOTTE, B. & ROURE, F. 1990: Extensional tectonics and subsidence of the Bresse basin: an interpretation from Ecors data. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.), Mém. Soc. géol. Suisse 1, 145–156.

BITTERLI, T. 1990: The kinematical evolution of a typical Jura fold: a reinterpretation based on 3-dimensional balancing techniques (Weissenstein Anticline, Jura Mountains, Switzerland). Eclogae geol. Helv. 83, 493–511.

BOIS, C. & ECORS SCIENTIFIC PARTY 1991: Late- and post-orogenic evolution of the crust studied from ECORS deep seismic profiles. In: Continental Lithosphere: Deep Seismic Reflections (Ed. by MEISSNER, R., BROWN, L., DÜRBAUM, H.-J., FRANKE, W., FUCHS, K. & SEIFERT, F.), Geodynamics Series 22, Amer. geophys. Union, Washington D.C., 59–68.

BOYER, S. & ELLIOTT, D. 1982: The geometry of thrust systems. Amer. Assoc. Petrol. Geol. Bull. 66, 1196–1230.

BUXTORF, A. 1901: Geologie der Umgebung von Gelterkinden. Beitr. geol. Karte Schweiz (NF) 11.

– 1907: Zur Tektonik des Kettenjura. Ber. Versamml. oberrh. geol. Ver., 30. 40. Versamml. 1906/7, 29–38.

– 1916: Prognosen und Befunde beim Hauensteinbasis- und Grenchenbergtunnel und die Bedeutung der letzteren für die Geologie des Juragebirges. Verh. natf. Ges. Basel 7, 184–254.

BUXTORF, A. & SCHLAICH, E. 1928: Gliederung und Verbreitung des Miocaens in der Mulde von Court (Berner Jura). Eclogae geol. Helv. 21, 342–349.

CHAROLLAIS, J., PAIRIS, J.-L. & ROSSET, J. 1977: Compte rendu de l'excursion de la Société Géologique Suisse en Haute-Savoie (France) du 10 au 12 octobre 1976. Eclogae geol. Helv. 70, 253–285.

COLLET, L.W. & PAREJAZ, E. 1931: Géologie de la chaîne de la Jungfrau. Beitr. geol. Karte Schweiz N.F. 63.

DIEBOLD, P. 1990: Die tektonische Entwicklung der Nordschweiz. Nagra informiert 2/90, 47–54.

ETH Working Group on Deep Seismic Profiling (Ansorge & 12 Collaborators) 1991: Integrated analysis of seismic normal incidence and wide-angle reflection measurements across the eastern Swiss Alps. In: Continental Lithosphere: Deep Seismic Reflections (Ed. by MEISSNER, R., BROWN, L., DÜRBAUM, H.-J., FRANKE, W., FUCHS, K. & SEIFERT, F.), Geodynamics Series 22, Amer. geophys. Union, Washington D.C., 195–205.

FREY, M., BUCHER, K., FRANK, E. & MULLIS, J. 1980: Alpine metamorphism along the geotraverse Basel-Chiasso – a review. Eclogae geol. Helv. 73, 527–546.

GIESE, P. 1968: Die Struktur der Erdkruste im Bereich der Ivrea-Zone. Schweiz. min. petr. Mitt. 48, 261–284.

GUBLER, E., KAHLE, H.-G., KLINGÉLÉ, E., MÜLLER, ST. & OLIVIER, R. 1981: Recent crustal movements in Switzerland and their geophysical interpretation. Tectonophysics 71, 125–152.

GUELLEC, S., MUGNIER, J.-L., TARDY, M. & ROURE, F. 1990: Neogene evolution of the western Alpine foreland in the light of Ecors-data and balanced cross-section. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.), Mém. Soc. géol. Suisse 1, 165–184.

GÜNZLER-SEIFFERT, H. 1952: Alte Brüche im Kreide/Tertiär-Anteil der Wildhorndecke zwischen Rhone und Rhein. Geol. Rundschau 40, 211–239.

HABICHT, K. 1945: Geologische Untersuchungen im südlichen sanktgallisch-appenzellischen Molassegebiet. Beitr. geol. Karte Schweiz N.F. 83.

HERB, R., BREITSCHMID, A., MATTER, A., MOJON, A. & NABHOLZ, W. 1978: Bericht über die Exkursion der Schweizerischen Geologischen Gesellschaft ins Helvetikum des Berner Oberlandes vom 9. und 10. Oktober 1977. Eclogae geol. Helv. 71, 233–254.

HIRN, A. 1980: Le cadre structural profond d'après les profils sismiques. In: Evolution géologique de la France (Ed. by AUTRAN, A. & DERCOURT, J.), 26. Congrès Géol. Int., Coll. C7. Mém. BRGM 107, Orléans, 34–39.

ILLIES, J.H. 1978: Two stages Rhinegraben rifting. In: Tectonics and geophysics of continental rifts (Ed. by RAMBERG, I.B. & NEUMANN, E.-R.), Reidel, Dortrecht, Holland, 63–71.

ILLIES, J.H., BAUMANN, H. & HOFFERS, B. 1981: Stress pattern and strain release in the alpine foreland. Tectonophysics 71, 157–172.

KAHLE, H.-G. & WERNER, D. 1980: A geophysical study of the Rhinegraben – II. Gravity anomalies and geothermal implications. Geophysical Journal of the R. Astron. Soc. 62, 631–648.

KELLER, P. 1986: Die Geologie des Passo San Simone (N-Italien). Unveröff. Diplomarbeit, Univ. Basel.

KELLER, P., SCHÖNBORN, G., SCHUMACHER, M. & LAUBSCHER, H. 1987: The Suborobic imbrications in the Bergamasc Alps. Terra Cognita 7, 60.

LAUBSCHER, H. 1956: Structural and seismic deformations along normal faults in the eastern Venezuelan basin. Geophysics 21, 368–387.

– 1961: Die Fernschubhypothese der Jurafaltung. Eclogae geol. Helv. 54, 221–282.

– 1965: Ein kinematisches Modell der Jurafaltung. Eclogae geol. Helv. 58, 231–318.

– 1970a: Grundsätzliches zur Tektonik des Rheingrabens. In: Graben Problems (Ed. by ILLIES, J.H. & MÜLLER, ST.), Schweizerbart, Stuttgart, 79–86.

– 1970b: Bewegung und Wärme in der alpinen Orogenese. Schweiz. mineral. petrogr. Mitt. 50, 565–596.

– 1973a: Faltenjura und Rheingraben: zwei Grossstrukturen stossen zusammen. Jber. Mitt. oberrh. geol. Ver. N.F. 55, 145–158.

– 1973b: Jura Mountains. In: Gravity and Tectonics (Ed. by DE JONG, K.A. & SCHOLTEN, R.), J. Wiley & Sons, Inc. New York, 217–227.

– 1974: Basement uplift and décollement in the Molasse basin. Eclogae geol. Helv., 67/3, 531–537.

– 1977: Fold development in the Jura. Tectonophysics 37, 337–362.

– 1980: Die Entwicklung des Faltenjuras – Daten und Vorstellungen. N. Jb. Geol. Paläont. Abh. 160, 289–320.

– 1981: The 3-D propagation of décollement in the Jura. In: Thrust and Nappe Tectonics (Ed. by MCCLAY, K.), Geol. Soc. (London) Spec. Publ., 311–318.

– 1983a: Überschiebungen im Jura. Jber. Mitt. oberrh. geol. Ver. 65, 181–189.

– 1983b: Detachment, shear, and compression in the central Alps. Geol. Soc. Amer. Mem. 158, 191–211.

– 1983c: The late Alpine (periadriatic) intrusions and the Insubric Line. Mem. Soc. Geol. It. 26, 21–30.

– 1985: Large scale, thin skinned thrusting in the southern Alps. Kinematic models. Geol. Soc. Amer. Bull. 96, 710–718.

– 1986: The eastern Jura: Relations between thin-skinned and basement tectonics, local and regional. Geol. Rdsch. 73, 535–553.

– 1987: Die tektonische Entwicklung der Nordschweiz. Eclogae geol. Helv. 80, 287–303.

– 1988: Material balance in Alpine orogeny. Geol. Soc. Amer. Bull. 100, 1313–1328.

– 1990a: Seismic data and the deep structure of the central Alps. In: Proc. sixth Workshop Europ. Geotraverse Proj. (Ed. by FREEMAN, R. & MUELLER, ST.), Europ. Sci. Found., Strasbourg, 149–156.

– 1990b: Deep seismic data from the Central Alps: Mass distributions and their kinematics. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.), Mém. Soc. géol. Suisse 1, 335–344.

– 1991: The deep structure of the central Alps inferred from both geophysical and geological data. Terra Nova 2, 645–652.

LAUBSCHER, H. & BERNOULLI, D. 1982: History and deformation of the Alps. In: Mountain Building Processes (Ed. by HSÜ, K.J.), Academic Press, London, 169–180.

LE PICHON, X, FRANCHETEAU, J. & BONNIN, J. 1973: Plate tectonics. Developments in Geotectonics 6, Elsevier Scientific Publishing Co., Amsterdam.

LEMCKE, K. 1973: Zur nachpermischen Geschichte des nördlichen Alpenvorlandes. Geol. Bavarica 69, 5–48.

MASSON, H., HERB, R. & STECK, A. 1980: Excursion No. I. Helvetic Alps of Western Switzerland. In: Geology of Switzerland, a guide-book, Part B, Excursions (Ed. by Schweiz. Geol. Komm.), Wepf & Co. Publ., Basel/New York, 109–153.

MATTER, A. & WEIDMANN, M. 1992: Tertiary sedimentation in the Swiss Molasse basin: an overview. Eclogae geol. Helv. 85, 776–777.

MEIER, L. & EISBACHER, G. 1991: Crustal kinematics and deep structure of the northern Rhine graben, Germany. Tectonics 10, 621–630.

MEISSNER, R. & THE DEKORP RESEARCH GROUP 1991: The DEKORP surveys: Major results in tectonic and reflection styles. In: Continental Lithosphere: Deep Seismic Reflections (Ed. by MEISSNER, R., BROWN, L., DÜRBAUM, H.-J., FRANKE, W., FUCHS, K. & SEIFERT, F.), Geodynamics Series 22, American Geophysical Union, Washington D.C., 69–76.

MILLER, H., MUELLER, ST. & PERRIER, G. 1985: Structure and dynamics of the Alps – a geophysical inventory. In: Alpine-Mediterranean Geodynamics (Ed. by BERCKHEIMER, H. & HSÜ, K.), Geodynamics Series 7, American Geophysical Union, Washington D.C., 175–203.

MUGNIER, J.-L. & MARTHELOT, J.-M. 1991: Crustal reflections beneath the Alps and the Alpine foreland: Geodynamic implications. In: Continental Lithosphere: Deep Seismic Reflections (Ed. by MEISSNER, R., BROWN, L., DÜRBAUM, H.-J., FRANKE, W., FUCHS, K. & SEIFFERT, F.), Geodynamics Series 22, American Geophysical Union, Washington D.C., 177–183.

MUGNIER, J.-L., GUELLEC, S., MÉNARD, G., ROURE, F., TARDY, M. & VIALON, P. 1990: Crustal balanced cross-sections through the external Alps deduced from the Ecors profile. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.), Mém. Soc. géol. Suisse 1, 203–216.

NAEF, H. & DIEBOLD, P. 1990: Tektonik des östlichen Tafeljuras und der angrenzenden Molasse. Nagra informiert 2/90, 37–46.

NAEF, H., DIEBOLD, P. & SCHLANKE, S. 1985: Sedimentation und Tektonik im Tertiär der Nordschweiz. Nagra Tech. Ber. (NTB) 85–14.

NEUGEBAUER, H.J., BRÖTZ, R. & RYBYACH, L. 1980: Recent uplift and the present stress field of the Alps along the Swiss geotraverse Basel-Chiasso. Eclogae geol. Helv. 73, 489–500.

NOACK, T. 1989: Computergestützte Modellierung geologischer Strukturen im östlichen Jura; Konstruktion balancierter Profile, Gravimetrie, Refraktionsseismik. Diss. Univ. Basel.

PAIRIS, B. & PAIRIS, J.-L. 1975: Précisions nouvelles sur le Tertiaire du massif de Platé (Haute-Savoie). Géol. Alpine 51, 83–128.

PFIFFNER, O.A. 1986: Evolution of the north Alpine foreland basin in the Central Alps. Spec. Publs. int. Ass. Sediment. 8, 219–228.

ROHR, K. 1926: Stratigraphische und tektonische Untersuchungen der Zwischenbildungen am Nordrande des Aarmassivs (zwischen Wendenjoch und Wetterhorn). Beitr. geol. Karte Schweiz N.F. 57/1.

ROTHPLETZ, W. 1933: Geologische Beschreibung der Umgebung von Tavannes im Berner Jura. Verh. naturf. Ges. Basel 43, 12–150.

ROYDEN, L. 1988: Flexural behavior of the continental lithosphere in Italy: Constraints imposed by gravity and deflection data. J. Geophys. Res. 93, B7, 7747–7766.

SCABELL, W. 1926: Beiträge zur Geologie der Wetterhorn-Schreckhorn-Gruppe (Berner Oberland). Beitr. geol. Karte Schweiz N.F. 57/3.

SCHÖNBORN, G. 1986: Geologie und Geometrie der Schuppen von Taceno (Provinz Como, Südalpen). Unveröff. Diplomarbeit Univ. Basel.

– 1992: Alpine tectonics and kinematic models of the central Southern Alps. Ph. D. thesis Basel and Memorie di Scienze Geologiche, Padova, in print.

SCHUMACHER, M.E. 1986: Zur Tektonik des Passo San Marco (Bergamasker Alpen). Unveröff. Diplomarbeit Univ. Basel.

SOOM, M.A. 1990: Abkühlungs- und Hebungsgeschichte der Externmassive und der penninischen Decken beidseits der Simplon-Rhone-Linie seit dem Oligozän: Spaltspurdatierungen und Apatit-Zirkon und K-Ar-Datierungen an Biotit/Muskowit (Westliche Zentralalpen). Unpublished Ph. D. thesis, University of Bern.

SINCLAIR, H.D., COAKLEY, B.J., ALLEN, P.A. & WATTS, A.B. 1991: Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion: an example from the Central Alps, Switzerland. Tectonics 10, 599–620.

SPRECHER, C. & MÜLLER, W.H. 1986: Geophysikalisches Untersuchungsprogramm Nordschweiz: Reflexionsseismische Messungen 82. Nagra Tech. Ber. (NTB) 84–15.

SUPPE, J. 1985: Principles of structural geology. Prentice-Hall, Inc., Englewood Cliffs, NJ.

SUTER, M. 1981: Strukturelles Querprofil durch den nordwestlichen Faltenjura, Mt.-Terri-Randüberschiebung-Freiberge. Eclogae geol. Helv. 74, 255–275.

THORNBURG, D.H. 1925: Über die geologischen Verhältnisse des alten Hauensteintunnels und des Gsieggrabens bei Läufelfingen (Basler Jura). Verh. natf. Ges. Basel 36, 224–233.

TRUFFERT, C., BURG, J.-P., CAZES, M., BAYER, R., DAMOTTE, B. & REY, D. 1990: Structures crustales sous le Jura et la Bresse: contraintes sismiques et gravimétriques le long des profils Ecors Bresse-Jura et Alpes II. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.), Mém. Soc. géol. Suisse 1, 157–164.

TRÜMPY, R. 1980: An Outline of the Geology of Switzerland. In: Geology of Switzerland, a guide-book, Part A. (Ed. by Schweiz. Geol. Komm.), Wepf & Co. Publ., Basel/New York, 109–153.

URAI, J.L., MEANS, W.D. & LISTER, G.S. 1986: Dynamic recrystallization of minerals. In: Mineral and rock deformation: laboratory studies (Ed. by HOBBS, B.E. & HEARD, H.C.), Geophysical monograph 36, the Paterson volume. Amer. Geophys. Union, Washington D.C.

VILLEMIN, T., ALVAREZ, F. & ANGELIER, J. 1986: The Rhinegraben: extension, subsidence and shoulder uplift. Tectonophysics 128, 47–59.

VOLL, G. 1976: Recrystallisation of quartz, biotite and feldspar from Erstfeld to Leventina nappe, Swiss Alps, and its geological significance. Schweiz. min. petr. Mitt. 56, 641–647.

– 1980: Ein Querprofil durch die Schweizer Alpen vom Vierwaldstättersee zur Wurzelzone. N. Jb. Geol. Paläont. [Abh.] 160, 321–335.

VOLLMAYR, T. & WENDT, A. 1987: Die Erdgasbohrung Entlebuch 1, ein Tiefenaufschluss am Alpennordrand. Bull. schweiz. Petroleum-Geol. u. -Ing. 53, 125, 67–79.

VON BRAUN, E. 1953: Geologische und sedimentpetrographische Untersuchungen im Hochrheingebiet zwischen Zurzach und Eglisau. Eclogae geol. Helv. 46, 143–170.

WERNER, D. & KAHLE, H.-G. 1980: A geophysical study of the Rhinegraben – I. Kinematics and geothermics. Geophys. J. R. Astr. Soc. 62, 617–629.

WITHJACK, M.O. & SCHEINER, C. 1982: Fault patterns associated with domes – an experimental and analytical study. Bull. Amer. Assoc. Petroleum Geol. 66, 302–316.

YE, S. & ANSORGE, J. 1990: A crustal section through the Alps derived from the EGT seismic refraction data. In: Integrative Studies, Results from the 5th earth science study center in Rauischholzhausen, 26.3.–7.4.1990 (Ed. by FREEMAN, R., GIESE, P. & MUELLER, ST.), European Science Foundation, Strasbourg, 221–236.

ZIEGLER, P.A. 1988: Evolution of the Arctic-North Atlantic and the western Tethys. Amer. Assoc. Petroleum Geologists Mem. 43.