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Artikel: Geology of the central Jura and the molasse basin : new insight into an evaporite-based foreland fold and thrust belt = Géologie du Jura central et du bassin molassique : nouveaux aspects d'une chaîne d'avant-pays plissée et décollée sur des couches d'évaporites

Autor: Sommaruga, Anna

Kapitel: 5: Synthesis and discussion

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5. SYNTHESIS AND DISCUSSION

The synthesis and discussion emphasize the following important points:

- the boundary conditions such as the geometry of the basement top, the distribution of the very weak décollement zone
- the geometry of structures in the Jura and the Molasse Basin
- correlation between inherited structures in the basement and in the cover
- the Molasse Basin, example of a foredeep basin
- the link from the Jura to the Alps.

Structure of the basement top

The depth conversion of all seismic lines has allowed a mapping of the depth to top basement in the central Jura and the Molasse Basin (Fig. 5.1). In the Jura area, a simple velocity model, attributing a constant velocity to each major interval (Tertiary, Cretaceous, Jurassic and Triassic), has been used. In the Molasse Basin, however, more complex depth-dependent conversion functions from NAGRA (NAEF & DIEBOLD, 1990) were used in order to account for increased velocities due to the considerable thickening and facies changes of Tertiary sediments (see Appendices 3 for seismic velocities). The contour map highlights a smooth basement that dips uniformly at 1° to 3° to the SSE. Some broad irregularities in Figure 5.1, e.g. Treycovagnes, are better illustrated in the three-dimensional view of the top basement map (Fig. 5.2). An apparently flat area (with a high at Treycovagnes) at the SW edge of Lake Neuchâtel is visible. The Treycovagnes area has been analyzed carefully (see Chapter 4) and no major basement high appears on the interpreted seismic lines. Depths from well data (e.g. Treycovagnes, Laveron, Essavilly, Valempoulières) fit to +/-200 m the depths obtained from depth converted seismic time lines. Discrepancies may be due to the use of inappropriate seismic velocities, especially in the weathering layer (SCHNEGG & SOMMARUGA, 1995). However, seismic velocities used in this work are compatible with the overall well information, but do not satisfy precisely individual drill hole data. It seems that the velocity model used here lies on the fast side (i.e. seismically obtained depths are slightly deeper than those obtained from drill holes).

The trend of the basement is E-W in the Neuchâtel Jura and NE-SW or ENE-WSW in the other regions (Risoux, external Jura and Molasse Basin, Fig. 5.1). The E-W trend of the Neuchâtel Jura differs by an angle of 30° from the orientation of structures in the Jura fold and thrust belt. The contour map presented here is coherent with the crude map from BÜCHI & ETHZ (1981). Even if the values of the contour map are not absolute, Figures 5.1 and 5.2 clearly demonstrate the morphology and orientation of the basement structures, which are important in understanding the formation of the Jura foreland fold and thrust belt.

It has to be emphasized, that the major tear faults (e.g. Pontarlier, La Sarraz) presented in Chapter 3 do not show any significant offset of the basement top. Along these faults, data are reasonably well constrained in the Molasse Basin and no major bend is visible (Fig. 5.1). The tear faults are therefore limited to the sedimentary cover of the Jura. In addition, evaporite-related folds and thrust-related folds are floored by subhorizontal layers at their base. No evidence has been found (see description in Chapter 3) for construction of thrust faults downward into the pre-Triassic basement. Nowhere in the study area has this basal décollement layer been disrupted by later thrusts.

Any irregularities which exist in the top of the basement are small compared to the thickness of Triassic Unit 2 (see Figure 3.6), which ranges from 100 m to more than 1000 m. On the south-eastern edge of the map (Fig. 5.1), near the front of the Subalpine Molasse, the basement dips toward the North showing an important uplift. The latter, highlighted by only one seismic line (Section 43), has been already discussed in Chapter 4 (§4.5). This map shows a basement high resulting either from an inversion of a Permo-Carboniferous graben or else a basement slice. No reflector appears beneath the supposed basement top and therefore it is difficult

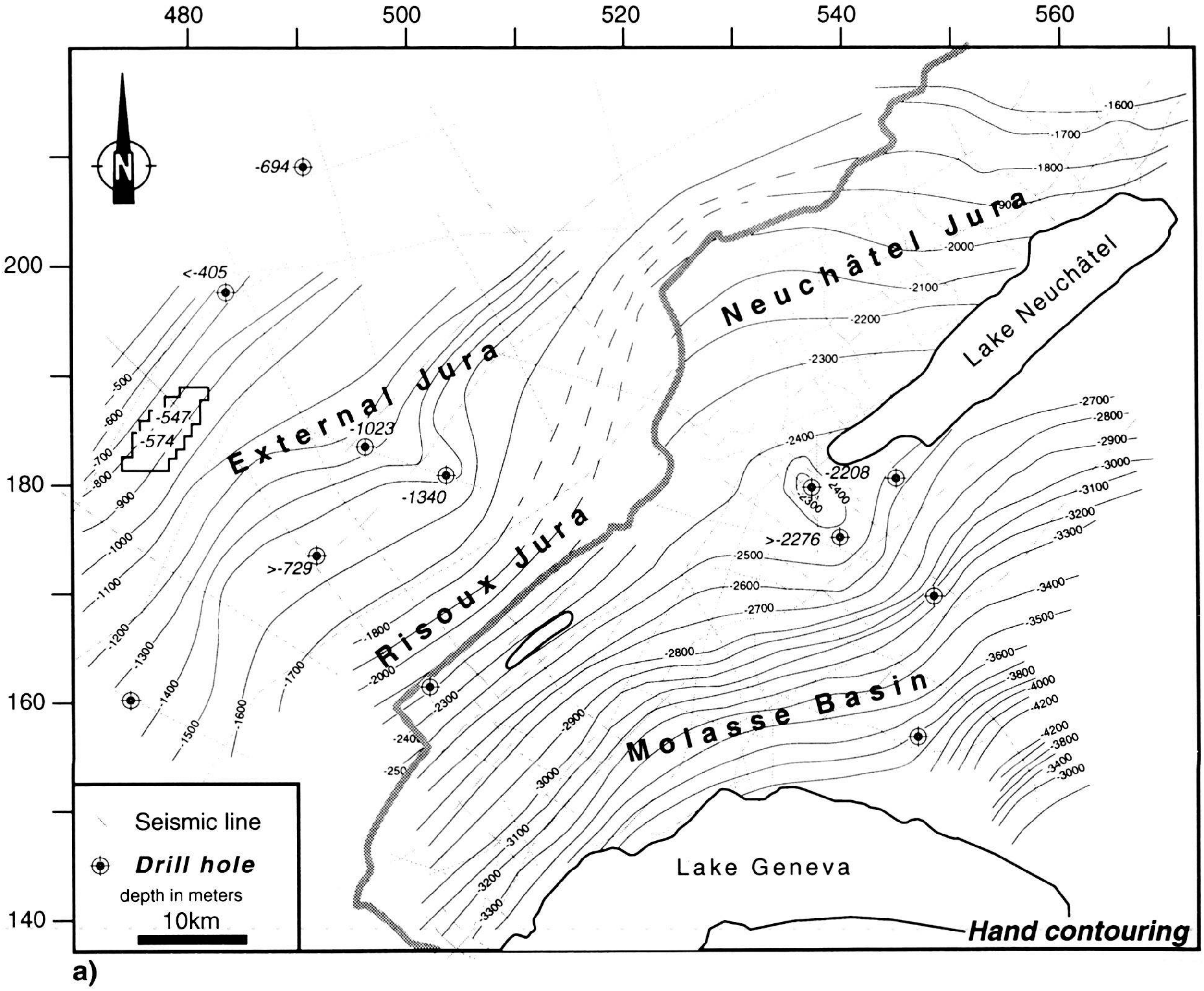

Figure 5.1 (pages 142, 143): Map of the depth to top basement in the central Jura and western Molasse Basin. Depths are in meters with reference to the sea level. Depths next to drill holes correspond to top basement depth from drill hole data. Minimal depths (>...) are from drill holes which ended within the Triassic layers. No depth indication is given for drill holes which did not reach the Triassic. Coordinates (in km) are according to the Swiss national geographical coordinate system.

a) Contours made by hand. Gray thin lines represent the seismic grid. Modified from SOMMARUGA (1995).

b) Contours made automatically by computer. Compare with Figure 5.1a. Black dots correspond to location of depth control at shot points along seismic lines.

Carte du toit du socle du Jura central et du Bassin molassique occidental. Les profondeurs sont exprimées en mètres par rapport au niveau de la mer. Les chiffres à côté des forages indiquent la profondeur du toit du socle dans le forage. Les profondeurs minimales (>...) sont indiquées pour les forages se terminant dans les couches du Trias. Aucune indication n'a été donnée pour les sondages n'atteignant pas les séries du Trias. Les coordonnées (en km) correspondent à la grille de référence géographique de la Suisse.

a) Contourage interpolé à la main. Les fines lignes grises fines représentent la grille sismique. Modifié de SOMMARUGA (1995).

b) Contourage automatique assisté par l'ordinateur. Comparer avec la Figure 5.1a. Les points noirs représentent la position géographique des points de tir, utilisée pour le contrôle des profondeurs de la carte de contours.

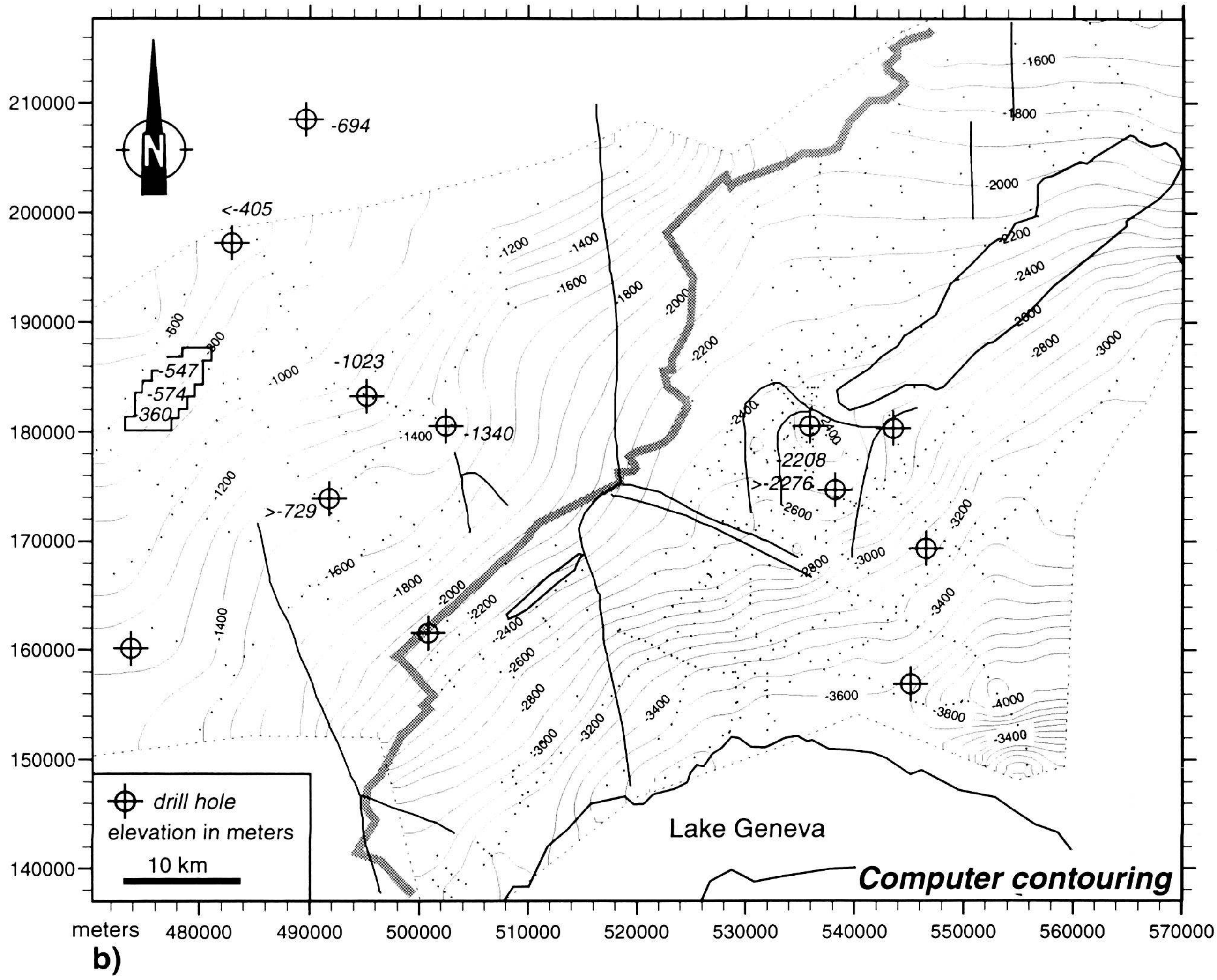

Figure 5.1b: For legend see page 142.
Pour la légende, voir page 142.

to interpret the nature of this high. It has also to be recalled, that Section 43 is a non migrated line running at a low angle to the direction of local structures and caution is required in interpretation. There is a problem related to seismic interpretation of fact or artifact.

It should be noted that the presence, beneath the Jura fold and thrust belt, of a continuous basement dipping 1° to 3° toward the South and underlying a weak décollement level was previously proposed by BUXTORF (1907) almost ninety years ago, from subcrop observations along the Grenchenberg railway tunnel (see Figure 1.5, cross-section 2).

Extension of the Triassic evaporites

In the central Jura and the Molasse Basin, the presence of the very weak (Fig. 2.30) Triassic Unit 2, at the base of the sedimentary cover has been confirmed by well data (see Figs. 2.11 to 2.13), by sample analyses (JORDAN, 1994) and also by interpretation of seismic lines. This very weak zone consists of salt, gypsum, anhydrite and clay, of which salt is by far the weakest lithology. In the Jura, thicknesses of pure salt range between 20 m and 300 m (Laveron drill hole). The Triassic Unit 2 zone is bound by two décollement horizons (roof and basal décollements). The style of deformation within this zone is very different from the overlying weak Triassic Unit 1 layer and the strong Jurassic layers, as well as from the underlying crystalline (or sedimentary) basement.

In the Molasse Basin, the isopach map of Triassic Unit 2 (Fig. 3.6) clearly shows changes in thickness along a NE-SW trend. These changes in thickness contrast significantly with the smooth and planar top basement (Fig. 5.1), suggesting "ductile" defor-

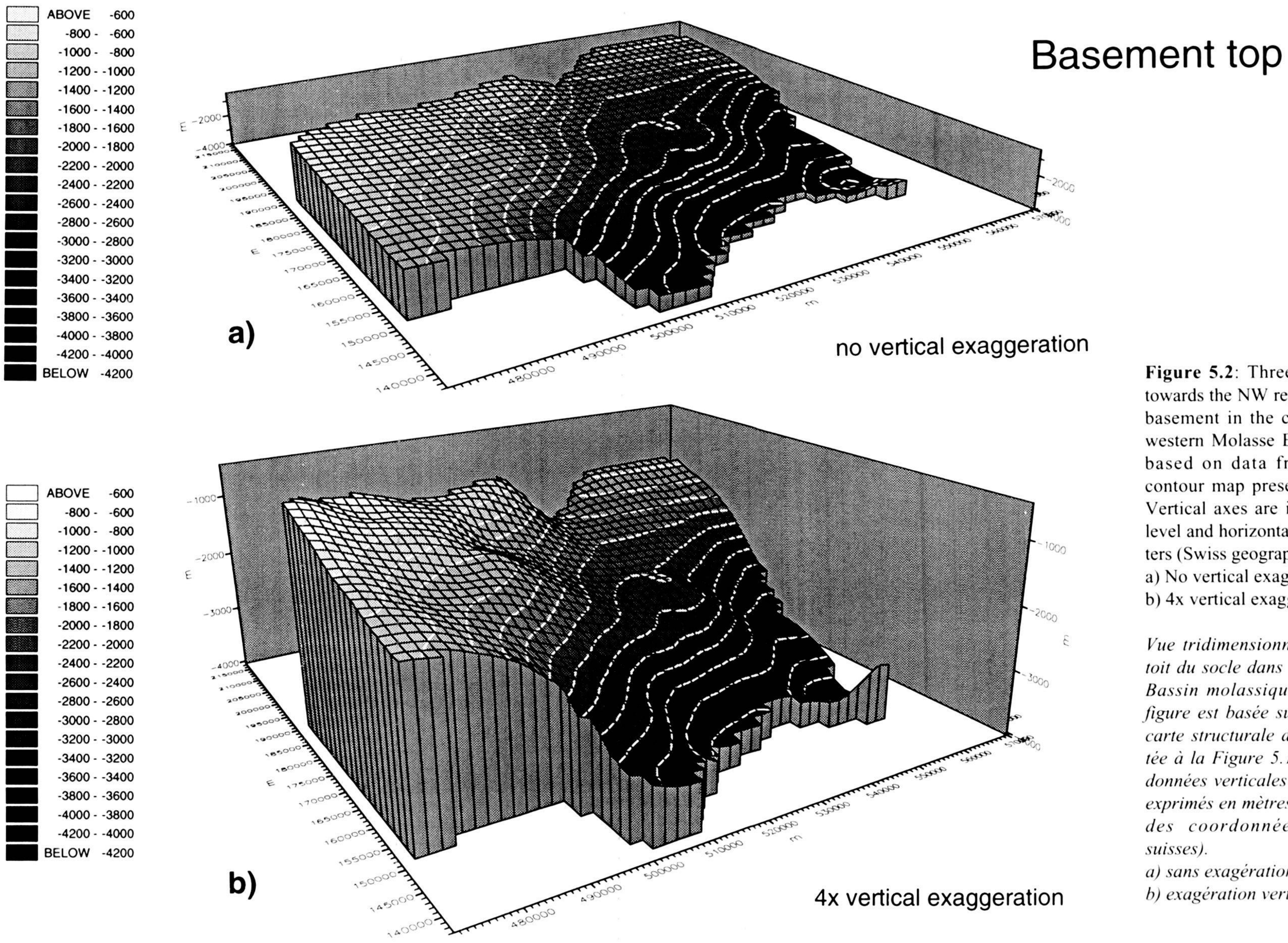

Figure 5.2: Three-dimensional view towards the NW representing the top of basement in the central Jura and the western Molasse Basin. This figure is based on data from the structural contour map presented in Figure 5.1. Vertical axes are in meters below sea level and horizontal axes are in kilometers (Swiss geographic coordinate grid).
a) No vertical exaggeration;
b) 4x vertical exaggeration.

Vue tridimensionnelle vers le NW du toit du socle dans le Jura central et le Bassin molassique occidental. Cette figure est basée sur les données de la carte structurale des contours présentée à la Figure 5.1. Les axes de coordonnées verticales et horizontales sont exprimés en mètres (grille de référence des coordonnées géographiques suisses).
a) sans exagération verticale;
b) exagération verticale de 4 x.

mation within Triassic Unit 2. In the eastern Jura, both, Triassic Unit 1 and Unit 2 layers seem to host décollement horizons. An isopach map of both Triassic Units in the Jura and its vicinity has been compiled in order to examine possible correlation between the distribution of Triassic strata and the extent of the deformed Jura cover (Fig. 2.5). A rather good correlation between both may be inferred from Figure 2.5. The thickest regions correspond to the central Haute Chaîne Jura and to the southern part of the external Jura. Towards the East (e.g. German Molasse Basin), even where Triassic sequences are preserved, they do not contain evaporites (BACHMANN *et al.*, 1987). Towards the Southwest, several drill holes have also demonstrated the absence of evaporitic layers (PHILIPPE, 1994). It therefore appears likely that the existence, as well as the arcuate shape of the Jura fold and thrust belt, is intimately linked to the presence of Triassic evaporites. Within the whole Molasse Basin, the change in structural style along strike, from a transported basin (western Molasse Basin) to an autochtonous basin (eastern Molasse Basin), is therefore due to the thinning and then absence of evaporite horizons. The presence of a thick and very weak basal layer beneath the Jura and the western Molasse Basin is thus important for the understanding of the formation of this foreland fold and thrust belt.

Characteristics of fold and thrust belts developed over a very weak basal décollement

A common feature of foreland fold and thrust belts is the presence of a basal décollement surface or zone, which dips towards the hinterland and below which relatively little deformation occurs (CHAPPLE, 1978; DAVIS & ENGELDER, 1985). The basal layer bounding the thin-skinned belt is generally composed of particularly weak rocks, e.g. salt, evaporite or shale. The undeformed sediments below this layer often do not differ much in rheology from those above the basal décollement and which have participated in the deformation. According to CHAPPLE (1978), it is not the mechanical contrast between basement and cover but rather the presence of a weak layer that seems to determine the thin-skinned nature of such folded belts.

Many fold and thrust belts around the world (e.g. Melville Island Fig. 3.13, Appalachian Plateau Fig. 3.14, Alberta and British Columbia Rocky Mountains,...) have developed above a weak basal layer (salt and/or evaporites and/or shales). A comparison of these belts has allowed some authors e.g. BALLY *et al.* (1966), DAVIS & ENGELDER (1985, 1987) to characterize these compressional terranes as broad belts with a low-angle cross-sectional taper, laterally continuous symmetric folds, broad synclines, anticlinal salt flow and forward as well as backward verging folds and thrusts.

The critical taper is the cross-sectional wedge profile maintained when an entire thrust belt is on the verge of horizontal compressive failure. The magnitude of the angle between surface topography and the décollement surface of the critical taper of belt or accretionary prism is governed by the relative magnitudes of the frictional resistance along the base and the compressive strength of the wedge material (DAHLEN, 1990). Therefore, the contrast in competence between the basal décollement zone and the overlying cover series is responsible for the minimum (and maximum) permissible critical taper angle. The critical angle is therefore the sum of the angles of the décollement dip, which is towards the hinterland, and the topographic slope towards the foreland (CHAPPLE, 1978; DAVIS & ENGELDER, 1985; DAHLEN, 1990). The lowermost permissible critical taper angle determines the locus of the thrust front in any transport parallel cross section. Propagation of this front toward the foreland is achieved by thickening at the back of the thrust wedge which results in an increase of the topographic slope.

Foreland fold and thrust belts riding above salt décollements typically have extremely low critical taper angles of less than 1° (DAHLEN *et al.*, 1984; DAVIS & ENGELDER, 1985, 1987) and in these cases topographic slopes may be virtually absent. In such a low angle taper, internal deformation of the wedge may take place by symmetric foreland- or hinterland-vergent thrusts. This is in contrast to higher angle tapers (commonly in excess of 8°), where a predominance of shallow foreland vergent thrusts is both predicted and observed (DAVIS & ENGELDER, 1985; DAHLEN, 1990). Recently PHILIPPE (1995) calculated a critical taper angle of 3,4° for the Jura fold and thrust belt, based on an angle of 1,6° for the topography and 1,8° for the basement. This is in good agreement with results herein, since an angle of 1° to 2° for the basal décollement is observed on the top of basement map (Fig. 5.1). However, the topographic slope, when considered from the toe of the Jura to the crest of the Alps, does show a conspicuous hinterland-dipping portion located at the transition from the Jura to the Molasse Basin. This hinterland-dipping slope can be explained by the important glacial erosion that occurred during

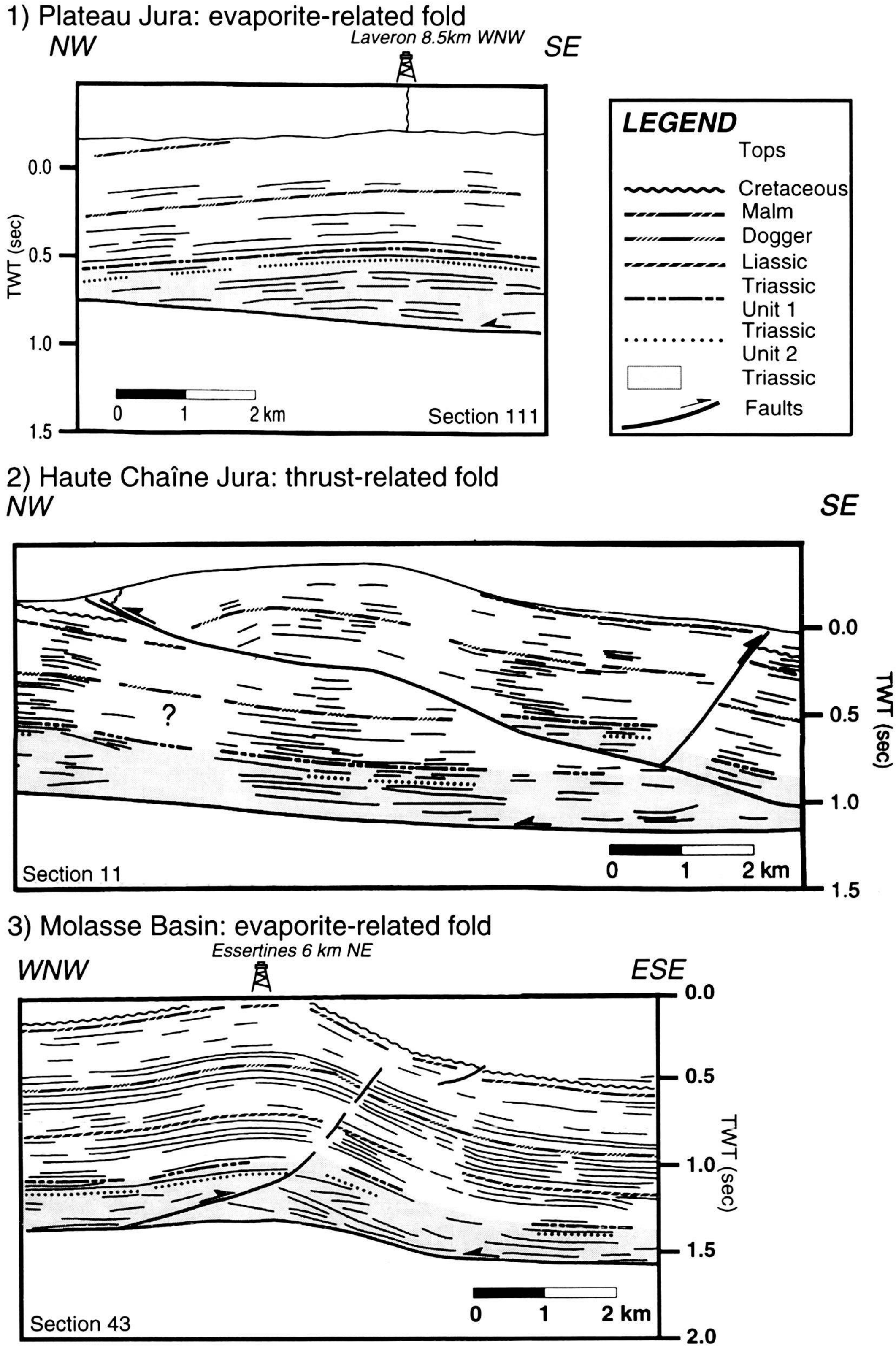

Figure 5.3: Line drawings of examples of typical fold structures in the Jura and the Molasse Basin (example numbers refer to Figure 3.1). Horizontal scale is in meters, whereas vertical scale is in seconds (two way travel time). Triassic Unit 2 is highlighted in gray. Examples 1 and 3 show low amplitude evaporite-related folds, whereas example 2 presents a high amplitude thrust-related fold. Modified from SOMMARUGA (1995).

Exemples de plis dans le Jura central et le Bassin molassique (numéros d'exemples réfèrent à la Figure 3.1). L'échelle horizontale est en mètres, par contre l'échelle verticale est en secondes (temps double). L'Unité 2 du Trias est soulignée en grisé. Les exemples 1 et 3 montrent des plis de faible amplitude en relation avec des évaporites, par contre l'exemple 2 présente un pli en relation avec un chevauchement. Modifié de SOMMARUGA (1995).

Pleistocene time in the Molasse Basin. Deformation behind this line is considerably less than in the Jura itself, apparently in contradiction with a simple foreland fold thrust belt wedge model which would predict increasing deformation intensity from the foreland to the hinterland. Perhaps the most outstanding feature of the Jura arc is its position at the outward rather than the inward side of the foreland basin, which is directly related to the Triassic evaporite distribution.

Thrust-related folds in the Haute Chaîne Jura are either foreland- or hinterland-vergent (see Panels and descriptions in Chapter 3). Most evaporite-related folds in the Molasse Basin are symmetrical, but some folds show either a forward or backward vergent asymmetry. In the Plateau Jura, most of the broad folds end against tear or thrust faults and therefore do present an aborted geometry; though some examples show entire symmetric folds (Panel 10). Anticlines and synclines have a lateral continuity over 30 km in the Risoux Jura, whereas in the Neuchâtel Jura the lateral continuity is limited to 10 km. In the Haute Chaîne Jura, synclines are mainly broad e.g. Val de Ruz, Vallée de la Sagne, but some exceptions exist (e.g. Areuse syncline in the Neuchâtel Jura).

In conclusion, the Jura presents most of the characteristics of fold and thrust belts developed above a weak basal layer.

Evolution of the central Jura and Molasse Basin folds

The surface geology and especially the seismic subsurface data of the central Jura and the Molasse Basin display two different types of folds: thrust-related folds and evaporite-related folds (Fig. 5.3). The first type is located in the Haute Chaîne Jura, whereas the second type has been observed not only in the Plateau Jura at the very front to the NE of the Haute Chaîne Jura folds, but also beneath the Molasse Basin. According to BALLY *et al.* (1966) and critical taper models (DAHLEN *et al,*. 1984) fold and thrust belts evolve by progressive deformation from the hinterland to the foreland. If we admit this consideration as a rule, the southernmost structures of the Jura fold and thrust belt should have formed first, to then have evolved into the present day structures. The northern folds should therefore represent a later stage of deformation, with less evolved geometries. This corresponds to what we have observed and inferred from the surface and especially subsurface data.

The Plateau Jura evaporite-related folds (Panel 10) may also represent an early stage of the Jura folds. The folds would have been initiated as low amplitude, apparently symmetric, buckle folds in response to layer-parallel compression. The very weak rocks of the Triassic Unit 2 infilled the space generated at the base of the sedimentary cover by flow mechanism. The core of the folds present a thickening within the very weak basal zone, whereas the strong layers buckle without any change of thickness (concentric folding). With progressive deformation, a fault ramp nucleates in the hinge area at the base of the strong layers in order to accommodate further the strain. Fault ramps will then propagate upward within the stiff layers or bend their trajectory within overlying weak or incompetent layers. With further transport the cover may be doubled, as has been observed in the present day Haute Chaîne Jura folds (e.g. Mt-Risoux or Nouvelle Censière anticlines). The spacing between adjacent early stage buckle folds should be large, since in the Haute Chaîne Jura the formation of subsequent folds does not alter the geometry of the adjacent fold.

In the northern part of the area, seismic data are poor and structures are only revealed with difficulty. Even if from geological maps no major anticlines can be inferred, it is possible that embryonic folds as described by HARRISON (1995), i.e. early stage buckle folds may exist. Moreover, the Plateau Jura buckle folds are located at the front of the high amplitude Jura folds. The Laveron well drilled into one of the Plateau Jura low amplitude folds penetrated 1400 m of Triassic strata (300 m of rock salt). This seems rather thick for an early stage Jura buckle fold compared to the Molasse Basin folds. From the location of the Plateau Jura folds, it appears that part of the thickening may be due to salt flow resulting from the load beneath the thrust-related anticlines of the Haute Chaîne (e.g. Risoux).

Folds beneath the Molasse Basin are located in a more internal position of the Alpine foreland belt than the Jura. The folds observed on the seismic lines represent typically early stage buckle folds and their cores seem to be filled with reasonably well organized evaporite duplexes, whereas those of the Plateau Jura suggest salt flow features. The question remains as to why the Molasse Basin folds did not further evolve into thrust-related folds as did the Haute Chaîne folds? The most obvious reason seems to be the load of Tertiary sediments. The Tertiary Molasse Basin has a wedge shape, with strong thickening of the sediments from North to South. Furthermore, the amplitude of folds within the Molasse Basin increases toward the Northeast, i.e. toward the Jura belt (e.g. Section 43 and Section 45). There may be two explanations for this: on the one hand, the thickness of Tertiary sediments decreases towards the North and on the other hand the thickness of Triassic sediments decreases slightly towards the South in the Molasse Basin (see Figure 2.22). With progressive erosion and deformation of the Tertiary wedge, it can be supposed that the Molasse Basin anticlines may evolve into Jura folds supported by antiformal duplexes, such as is seen in examples from the eastern Jura (NOACK, 1989; LAUBSCHER, 1992).

Inherited structures and their consequences

The décollement at the base of a fold and thrust belt follows frequently the contact between the crystalline basement and sedimentary cover (BUXTORF, 1907; BALLY *et al.*, 1966; RODGERS, 1990). Pre-existing structures along this contact may form an important boundary condition and play a role in the location of thrust faults during the deformation of the sedimentary cover. Local irregularities in the basal décollement may act as stress concentrators to determine instabilities in the sedimentary cover and therefore act as a nucleation point for a thrust fault (LAUBSCHER, 1977). In the eastern Jura fold and thrust belt, many authors have seen a relation between thrust nucleation and inherited structures e.g. Paleozoic graben system or Oligocene N-S oriented normal faults related to the Rhine-Bresse graben system (LAUBSCHER, 1985; 1986; NAEF & DIEBOLD, 1990; NOACK, 1995). In the western Molasse Basin, especially the Geneva area, recent work based on seismic data (GORIN *et al.*, 1993; SIGNER & GORIN, 1995) highlights the presence of NE-SW and NW-SE trending Permo-Carboniferous lineaments which would have been reactivated several times until the present day. Further East in the Molasse Basin (Bern area), the Hermrigen anticline (for location see Figs. 1.3 and 1.4) is interpreted by some authors as a result of inversion tectonics, reactivating a Permo-Carboniferous graben (PFIFFNER, 1994; PFIFFNER *et al.*, 1997a). This latter interpretation, based on one dip seismic line only, is however not well constrained and an alternate interpretation of an evaporite pillow in the Triassic beds, has been suggested by Erard (oral communication).

In this study area, thickening in the Triassic Unit 2 and duplication of the Mesozoic cover represent the only clear tectonic features visible beneath the anticlines. Reflections attributed to Permo-Carboniferous sediments have been recognized beneath the Molasse Basin. In the Neuchâtel Jura, many reflectors, visible beneath the top of the basement, may represent either Permo-Carboniferous strata or multiples. Seismic data interpreted in this work do not present any positive evidence for inversion of Permo-Carboniferous grabens or for thrust fault nucleation related to inhomogeneities in the basement.

Clear evidence for normal faults on seismic data has been observed within the Bavarian Molasse Basin (BACHMANN *et al.*, 1982; BACHMANN *et al.*, 1987), whereas in the Swiss Molasse Basin no distinct evidence is visible. Early interpretations by VOLLMAYR & WENDT (1987) in the central Swiss Molasse Basin showed many normal faults of presumably Oligocene-Early Miocene age offsetting the whole Mesozoic cover. These authors later reconsidered their interpretation and replaced the normal faults by an embryonic thrust system, as illustrated and discussed by LAUBSCHER (1992). However, normal faults, confined below the Middle Muschelkalk Triassic layers, have been identified by HAUBER (1993) from drill hole data in the Rhine valley of northern Switzerland. These faults have offsets of 50 m or less (Fig. 5.4) that which would corresponds to 0.01s or 0.02s TWT on the seismic lines (more or less one reflector). Unfortunately, the resolution of the seismic lines is too low to observe such faults.

N-S oriented tear faults in the North Alpine foreland are interpreted by many authors as inherited features related to the Oligocene opening of the Rhine-Bresse Graben system (LAUBSCHER, 1973a; ELMOHANDES, 1981; ILLIES, 1981; BERGERAT, 1987; LAUBSCHER, 1992). AUBERT (1972) was indeed able to identify N-S oriented karst crevasses with Oligocene Molasse infill in the Pontarlier region. Accordingly, AUBERT (1972) postulated an Oligocene age for these N-S trending structures, without being specific about their tectonic significance. During Miocene folding and thrusting of the Jura, preexisting faults and joints represented major anisotropies within the Mesozoic cover. They were reactivated during and after folding and played an important role in localizing bends and discontinuities in folds during shortening deformation. The N-S orientation of preexisting faults and joints thereby induced a reactivation with sinistral transcurrent deformation, compatible with the overall N to NW directed Alpine push (LAUBSCHER, 1972). However,

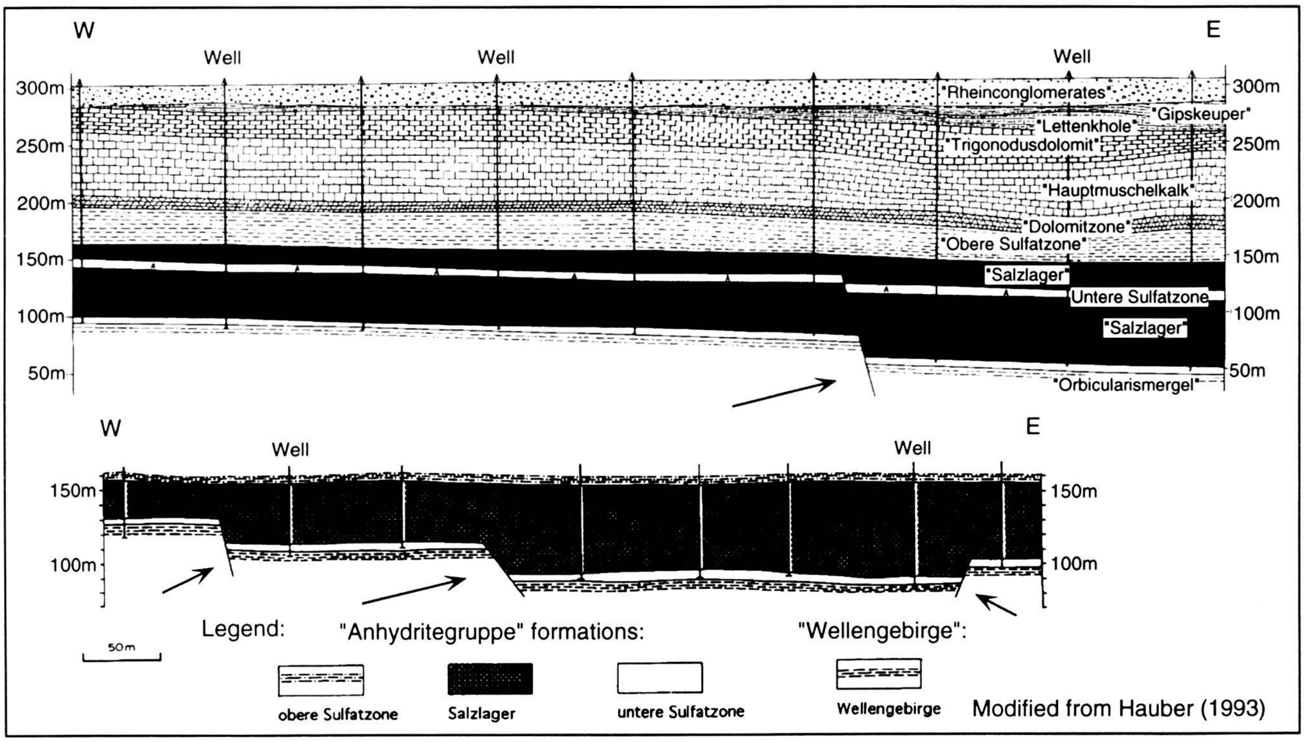

Figure 5.4: Geological cross-sections exhibiting normal faults within the Triassic layers calibrated from drill holes (Rhine Valley of northern Switzerland). Modified from HAUBER (1993).

Coupes géologiques montrant des failles normales au sein des couches du Trias, calibrées à partir de forages (Vallée du Rhin, Nord de la Suisse). Modifié de HAUBER (1993).

seismic lines in the central Jura do not present, in general, arguments in favor or against inherited faults. In the Treycovagnes area, minor thickness changes within the Liassic and Dogger beds are visible from one side of the fault to the other one (MURALT *et al.*, 1997). These thickness changes may be due to Liassic synsedimentary normal faults, which may have been reactivated during the Miocene deformation.

The Molasse Basin: a foredeep basin

The wedge shaped Molasse Basin is presently considered to be a foreland basin. Foredeep or foreland basins are defined as sedimentary basins, located between the front of a mountain chain (orogen) and the adjacent craton and developed in the context of a A-type subduction (BALLY & SNELSON, 1980). PRICE (1973) and BEAUMONT (1981) suggested that foredeep basins result from lithospheric flexuring in response to overthrust loading in the mountain chain. Foreland basins are characterized by a downwarp flexure, the foredeep basin, and an upwarp flexure or forebulge located in the foreland. Models predict an outward-migrating peripheral bulge, which is often responsible for a characteristic basal foredeep unconformity. Because the thrust load is inherently mobile, the foreland basin itself becomes eventualy involved in deformation.

DICKINSON (1974) was the first to define the North Alpine Tertiary Molasse Basin as a peripheral foreland basin located against the outer arc of the orogen. The Alpine Molasse Basin system extends from the Jura to the Prealps and even to the Helvetic nappes. Therefore the Jura and especially Plateau Molasse subsurface data interpreted in this work, represent only the distal parts of the North Alpine foreland basin system. According to BALLY (1989, idealized foredeep Figure 4), foredeep basins present many common features and units. These are recognized on seismic lines crossing the Plateau Molasse: (1) a basement: a crystalline basement has been confirmed by drill holes in the Jura and has been inferred from seismic interpretation beneath the Molasse Basin Mesozoic strata; (2) a rifting

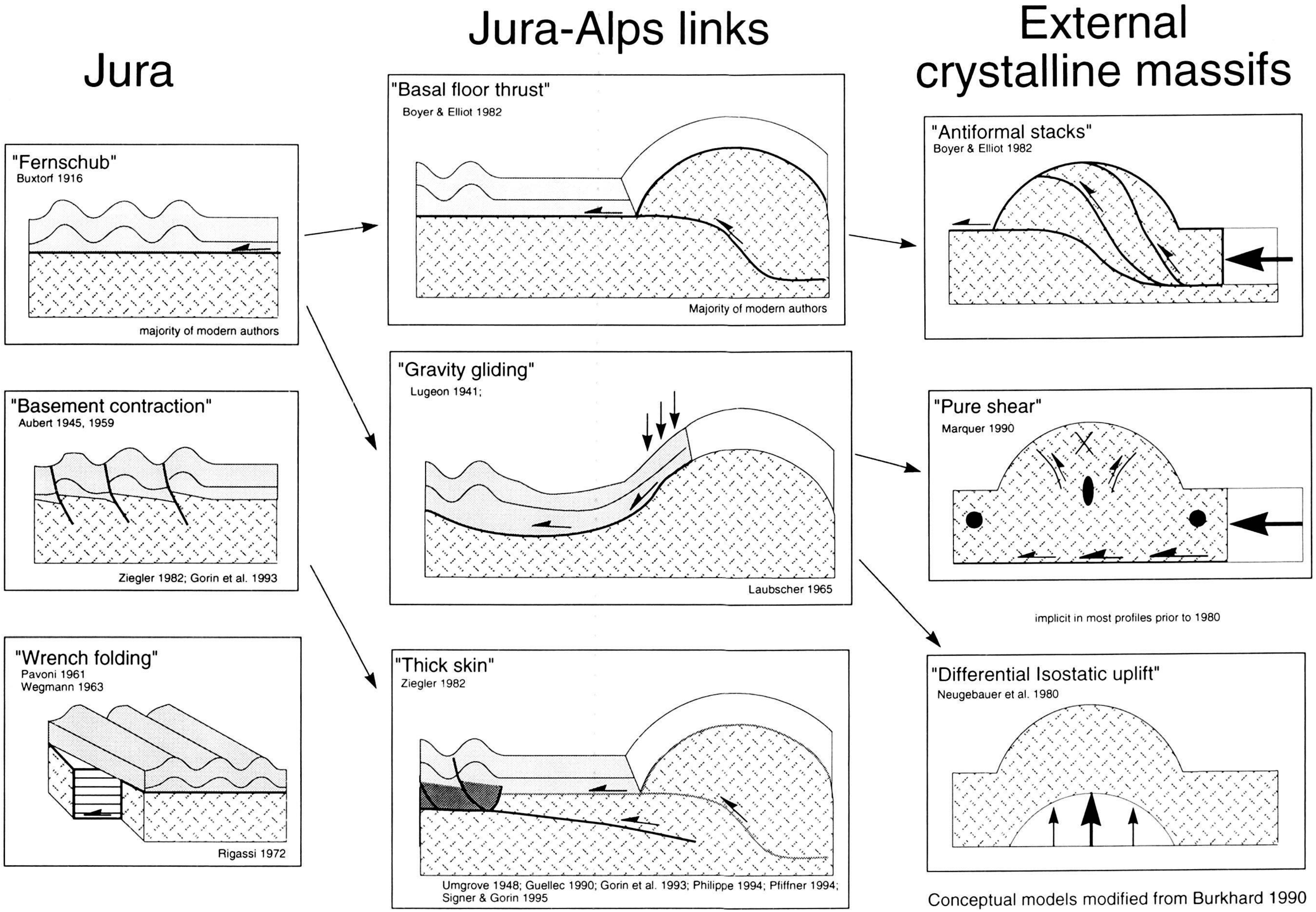

Figure 5.5: Conceptual models on the formation of the Jura fold and thrust belt and its links to the Alps (external crystalline massifs). Modified from BURKHARD (1990).

Modèles conceptuels sur la formation de la chaîne plissée du Jura et son lien avec les Alpes (massifs cristallins externes). Modifié de BURKHARD (1990).

sequence: no real rift sequence has been identified on the seismic lines, although Permo-Carboniferous grabens present characteristics of extension tectonics; (3) a passive margin or platform sequence: during the Triassic an epicontinental shallow water environment developed and then during the Jurassic and Cretaceous interlayered marl and limestone beds were deposited in a platform or lagoonal environment. These strata, 1 to 3 km thick, overly the basement; (4) a deep water phase representing the inception of the foredeep: this early sequence consists of deposits located in the hinterland parts of the Molasse Basin. In Switzerland, the oldest deposits of the foreland basin are Flysch series, which are involved in the Helvetic nappes. Moreover the Molasse underlies the Prealpine klippen. This unit is not visible on the Plateau Molasse seismic lines; (5) a prograding sequence: the sequence of Tertiary shallow water Molasse sediments has been observed on the seismic lines.

These five units are separated by basically different unconformity types (see also BALLY, 1989): (a) The pre-rift unconformity at the base of the Permo-Carboniferous grabens. (b) The breakup unconformity at the base of the Mesozoic strata. Unconformities (a) and (b) are inherited and are not related directly to the formation of the foredeep. (c) The basal foredeep unconformity which marks the beginning of the flexural response to the Alpine loading of the European plate. Subhorizontal Tertiary sediments onlap the Cretaceous (Mesozoic) strata dipping a few degrees (the same dip as the basement) toward the South. This unconformity is the most obvious on all Molasse Basin seismic lines. Unfortunately reflections are poor within this sequence and do not give the possibility to recognize minor unconformities due to sea level changes. The possibility of interpreting the Tertiary sediment onlaps in relation to salt flow deformation has been discussed in Chapter 3. However it appears most reasonable to attribute them to the basal foredeep unconformity.

Evidence that the Molasse Basin represents a flexural basin has already been provided, based on stratigraphy, sedimentology, subsidence profiles and gravity anomaly studies (LEMCKE, 1974; KARNER & WATTS, 1983; NAEF *et al.*, 1985; HOMEWOOD *et al.*, 1986). LAUBSCHER (1992) suggested that the forebulge developed during two different phases: the Helvetic phase (Late Oligocene-Early Miocene) and the Jura phase (Middle to Late Miocene). Recently CRAMPTON & ALLEN (1995), using modeling work and surface outcrop data, proposed the existence of the forebulge flexure throughout the early evolution of the Alpine foreland basin, although its topographic expression has changed over time. It is beyond the scope of this work to join this discussion. Further arguments of the evolution of the Molasse Basin and its structural relations with the Jura and the Alps are developed by BURKHARD & SOMMARUGA (in press). The present work, nevertheless, shows what was previously inferred, that the basement is homoclinal and can be followed with reasonable continuity from the foreland to the Alps beneath the foreland basins. The foreland basement (the Jura basement) is the shared link with the Alpine belt.

Jura - Alps links

The two fundamental questions, i.e. the cover-basement relationships within the Jura and the Molasse Basin and the compensation of the Jura cover shortening, were discussed in a short review in Chapter 1. The review shows that answers to both questions remain open and various authors still argue the possibility of shortening the basement beneath the Jura and the Molasse Basin, based on debatable seismic evidences (ZIEGLER, 1982; GUELLEC *et al.*, 1990; GORIN *et al.*, 1993; PFIFFNER, 1994; SIGNER & GORIN, 1995; PFIFFNER *et al.*, 1997a).

However, the interpretation of more than 1500 km of seismic reflection lines across all the Jura tectonic units (external Jura: Plateau and Faisceau; internal Jura: Haute Chaîne) and also the Molasse Basin tectonic units (Plateau- and Subalpine-Molasse) has not revealed any obvious examples where cover structures can be related to observable, reliable deformation in the underlying basement. No deformation features are observed in the basement, instead the overlying Triassic Unit 2 layers are deformed, showing mainly evaporite swells. Any irregularities which might exist in the top of the basement (Fig. 5.1) are small compared to the thickness of Triassic Unit 2. This leads to the key conclusion that the Jura and Molasse Basin cover has been deformed over a main décollement zone located in Triassic Unit 2. This conclusion corresponds to the "Fernschub theory" formulated at the beginning of the century by BUXTORF (1916). Nevertheless the link between the Jura fold and thrust belt and the Alps chain remains an item for discussion. Many authors have proposed various hypotheses (Fig. 5.5) based on field work, fission track data, balancing concepts and recently refraction or reflection seismic data (see also review by BURKHARD, 1990; LAUBSCHER, 1992). One hypothesis connects the Jura basal thrust to the basal Helvetic thrust and implies that uplift of the external crystalline massifs would post-date the Jura-thrusting (LAUBSCHER, 1973b). The internal deformation within the external crystalline massifs would be explained by vertical pure shear (MARQUER, 1990) or by differential isostatic uplift (NEUGEBAUER *et al.*, 1980). Another hypothesis, first expressed by BOYER & ELLIOT (1982), states that the Jura basal thrust continues beneath the Molasse Basin and then roots in the frontal part of the external crystalline massifs. This hypothesis is the most widely accepted today, even if some authors see contrary seismic evidence. This work provides a map of the basement top showing a basement dipping gently towards the South underneath the Jura and the Molasse Basin but does not provide new critical information beneath the external crystalline massifs. Therefore it is beyond the scope of this work to embark in a detailed discussion of the large scale relationship of the Jura - Alps system. The relationship of the Jura system to the deeper parts of the crust and the mantle has been elucidated by the results of the NFP20 research projects (PFIFFNER *et al.*, 1997b) and has been discussed recently by LAUBSCHER (1992).