The decollement hypothesis of Jura folding after 90 years

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The decollement hypothesis of Jura folding after 90 years[1)]

with 10 figures

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Zusammenfassung

Die erste Formulierung (1907) der Abscherhypothese der Jurafaltung basierte sowohl auf Geländebeobachtungen als auch auf Versuchen, bilanzierte Profile bis ins Grundgebirge zu konstruieren, namentlich im östlichen Jura. In der Folge wurde die Hypothese von verschiedenen Seiten angegriffen (namentlich von drei Seiten: den Fixisten, den Kennern des zentralen und westlichen Juras sowie von Tektonikern, die ein mechanisch akzeptables Modell der Jurafaltung suchten). Nach nunmehr 90 Jahren erweist sich das Abschermodell als stärker denn je: Der Fixismus ist der mobilistischen Plattentektonik gewichen, seismische Daten und Bohrungen im zentralen und südlichen Jura haben früher unvermutete grosse epidermale Überschiebungen zutage gefördert. Endlich haben neue Entwicklungen in der experimentellen wie theoretischen Gesteinsmechanik, im Verein mit neuen Einsichten in die Mechanik der epidermalen Deformation aufgrund von Theorie und Modellierung dargelegt: Nicht nur ist die Abscherung des Juras auf Triasevaporiten mechanisch möglich, sie ist sogar notwendig, um den minimalen kritischen Keilwinkel zu erklären. Damit ist das Abschermodell des Juras in seiner allgemeinen Form eines der durch Fakten am besten gestützten Modelle in den Erdwissenschaften überhaupt. Es lässt sich aber im einzelnen noch weiter ausgestalten, wobei zu bedenken ist, dass man dabei auf weitere Fakten und Annahmen angewiesen ist, die weniger sicher sind. So lässt sich das Abschermodell in die Alpen ausweiten, wo es ein kohärentes Bild der miozänen Deformationen zu zeichnen erlaubt. Argumente, die immer noch gegen das Modell ins Feld geführt werden, basieren auf speziellen Interpretationen von mehrdeutigen Daten, manchmal auf eindeutiger Über-Interpretation.

Abstract

The first formulation in 1907 of the décollement hypothesis of Jura folding was based on both surface observations and attempts at the construction of balanced sections, particularly in the eastern Jura. Subsequently, the hypothesis was attacked mainly from three sides (the fixist faction of tectonics, the geologists familiar with the central and western Jura, and those tectonicians looking for a mechanically acceptable model). After 90 years the décollement model stands stronger than ever. Fixism has given way to mobilist plate tectonics; seismic exploration and holes drilled in the western and southern Jura revealed important thin-skin thrust faults where formerly none had been suspected. These new data now make that part of the Jura an even stronger example of thin-skinned frontal décollement tectonics than the eastern Jura, where the hypothesis had been first developed. New experimental and theoretical developments in rock mechanics and thrust tectonics- confirmed and exemplified by analog and digital modeling- demonstrate that not only is décollement on Triassic evaporites in the Jura mechanically possible but that it is even necessary in order to explain the minimal wedge taper. However, although in its general features the décollement model of the Jura now is one of the best fact-supported models in the earth sciences, there is still scope for improvements in detail. The most important aspect of the model, however, consists in its ability to explain otherwise isolated observations, e.g. the main features of the Miocene deformations in the Alps.

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1. Introduction: 1907-1950

90 years ago, in the spring of 1907, Buxtorf, my pre-predecessor at the University of Basel, gave a paper, which he subsequently published (Buxtorf 1907), on the «Tectonics of the folded Jura». It was the birth of the décollement hypothesis, which postulated that the folds and thrusts of the Jura were thin-skinned, on top of a basal décollement in the Triassic evaporites. As a corollary, it implied that the décollement sheet had been pushed from the south, from the distant Alps («Fernschub»).
Buxtorf based his hypothesis on a series of cross-sections (Fig. 1) through the eastern Jura (Fig. 2), compiled from publications by a number of authors. In the foreground there was a clear observational fact: Nowhere in the folded Jura are strata older than Middle Triassic exposed, even in the deeply eroded core of folds. Moreover, in many places the base of the thrust front consists of intensely deformed Triassic evaporites. But in the center of his presentation there was a constructional argument: It is well-nigh impossible to involve deeper than Triassic strata in the folds when extrapolating the cross-sections down to basement. Nowadays one would say that this is an argument based on section balancing.
Taking for comparison newer standards of profile construction, including those published later by Buxtorf himself (particularly Buxtorf 1916), the cross-sections of 1907 were quite crude. But by their very crudeness they made an important point: The décollement hypothesis, in its general form, is a very robust model, small modifications and improvements will not alter it substantially.
There was resistance particularly on three sides:
(1) In the early 20th century geoscientists were split into mobilists (mainly nappists), who believed in the predominance of horizontal movements, and fixists, who favored essentially vertical movements. Buxtorf was a nappist, he called his thin-skinned Jura «a folded décollement nappe» and compared it with the nappe of the Préalpes Romandes with their exposed décollement on Triassic evaporites. The fixists would have none of that.
(2) People working in the central and western Jura, where exposures are less deep and instructive, found it difficult to reconcile their findings with the décollement hypothesis (Fig. 3; compare Aubert 1958).
(3) The third point of resistance was a theoretical one. Many people held that transmission of the stresses required for folding and thrusting in the Jura from the faraway Alps through the Molasse basin- considered to be mechanically weak material- was impossible (e.g. Cadisch 1934).

2. New data and insights: 1950-present

After the second world war, the geosciences made leaps forward in many sectors all over the world, as the foundations were laid for the currently favored plate tectonics model- a mobilist concept. Geophysics, rock mechanics, theories of thrusting- all had their impact on views of Jura tectonics. The three centers of resistance against the décollement tectonics began to crumble without, however, their occupants giving in completly:
(1) At present, in the sway of Plate Tectonics, the extreme fixist position has become quite unpopular, and a discussion of all the data marshaled against it in the last few decades would appear to be a wasted effort in the context of this article.
(2) As to the problem of the central Jura, the first generally accessible seismic sec-

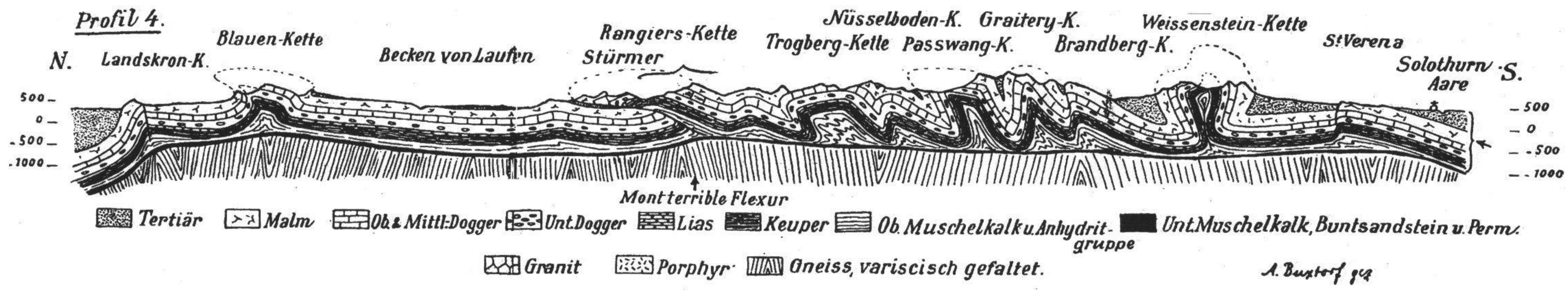

Fig. 1: Profile 4 from Buxtorf (1907).

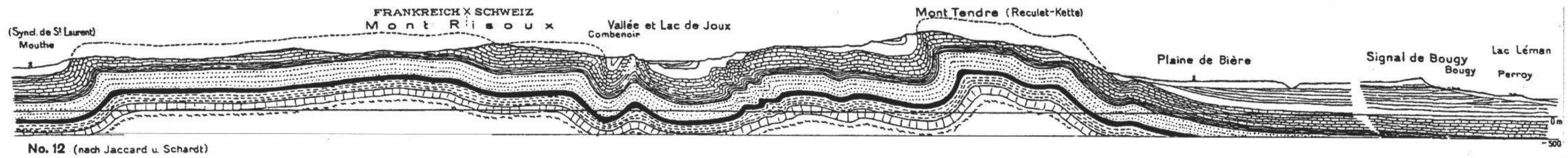

Fig. 3: Profile 12 through the central Jura, from Heim (1919).

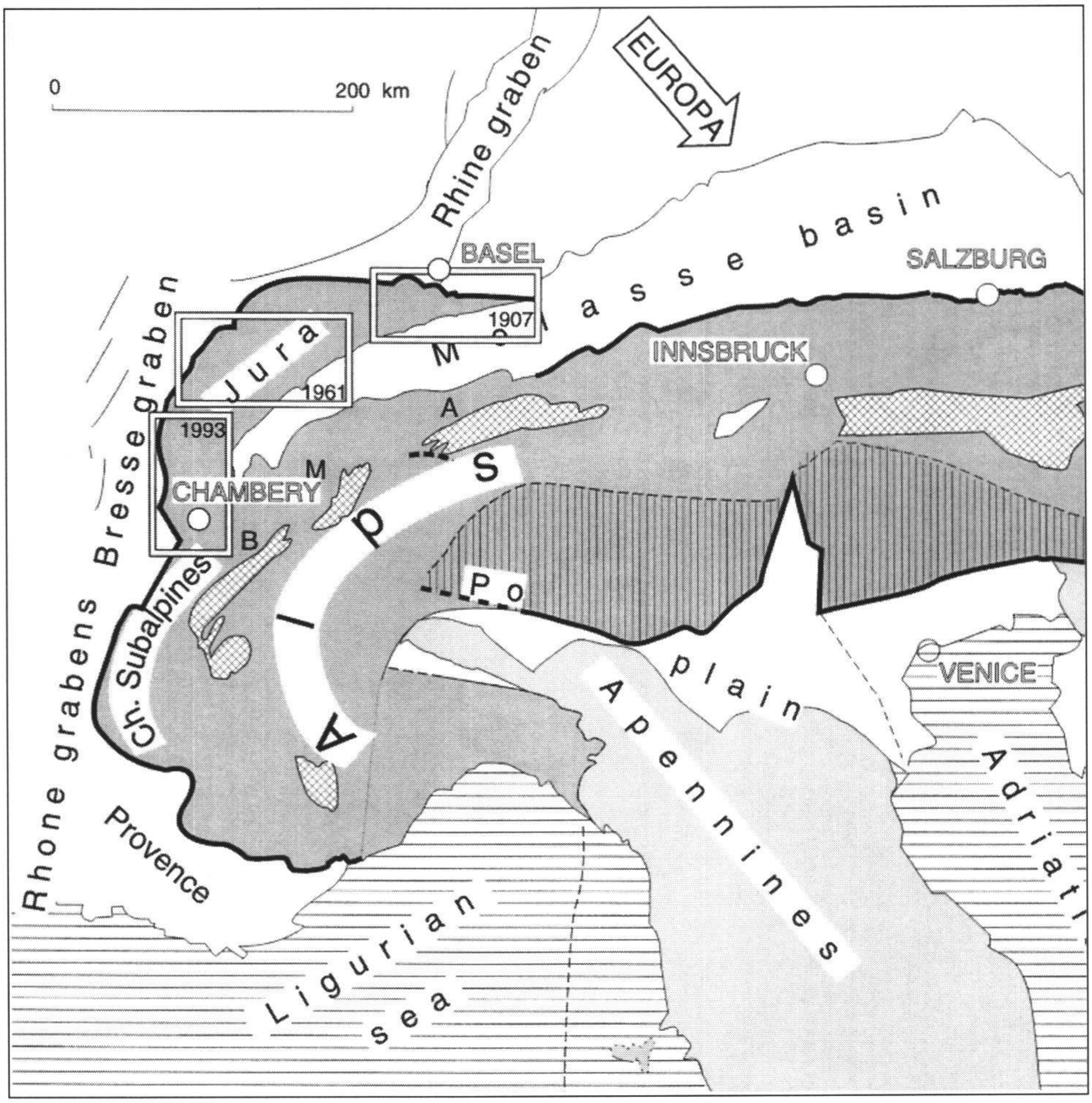

Fig. 2: The position of the Jura within the Alpine System (dark shading). The rectangles with the inset numbers define the approximate area and year where and when décollement was either proposed or verified. Vertical ruling: the Southern Alps where much of the deformation took place in the Jura phase. Heavy line: Latest front of the Jura phase; heavy dashed lines= some internal Alpine fault zones active in the late Tertiary. Cross-hatched: External Massifs with B= Belledonne-, M= Montblanc-, and A= Aar-Massif.

tion in combination with the well Risoux-1 (Winnock 1961) revealed the presence of hitherto unknown large overthrusts rather than the deep-rooted uplifts implied in the older sections as shown in Fig. 3. This was corroborated 30 years later by the deep-reflection ECORS line (Guellec et al. 1990, compare Philippe et al. 1997), in addition to the numerous more local seismic sections of the petroleum industry whose publication has lately been authorized (e.g. Sommaruga & Burkhard 1997; compare Diebold & Noack 1997). However, while they confirm the décollement model generally, there is still controversy in detail (e.g. Rigassi 1987)

But let me exemplify the progress made lately in the western and southern Jura by referring to the work done at the Institut Français du Pétrole by Yann Philippe (e.

g. Philippe 1994, 1995, Philippe et al. 1997). The results of his ambitious project have been the basis for his doctorate at the University of Savoy at Chambéry in 1995. Philippe not only did extensive field work, but he also had access to a number of seismic lines which he interpreted, and he constructed numerous balanced sections with the assistance of the French Loquace software (compare Fig. 4) (for the general problem of section balancing see, e.g. Woodward et al. 1989), and he spent considerable time producing analog models by means of a sand box monitored by x-ray tomography (compare Fig. 8). This permitted formerly inachievable insight into the interior of the deformed material in the process of deformation. Thus Philippe extended the fundamental analysis of Jura tectonics from the small portion in the eastern Jura worked on by Buxtorf into the hitherto neglected though even more important southern Jura, where it joins the Alps proper (Fig. 2). In addition, he contributed substantially to the solution of the mechanical problems.

In order to address the problem of resistance against the décollement model by people familiar with the central and southwestern Jura, compare the cross-sections Fig. 3 and Fig. 4. Although they do not cover the same area, they are valid examples of views held on the tectonics of the western half of the Jura. Times have changed indeed. It is hard to believe that this is the same mountain range.

Even more than Buxtorf's northeastern Jura, the southwestern Jura today stands revealed as a perfect example of the thin-skinned frontal fold and thrust belts, now known from all over the world, mostly thanks to petroleum exploration with its numerous seismic lines and drill holes. Nobody else would have had the resources and the incentive for the necessary huge investments.

However, even though one of numerous frontal thin-skin thrust belts, the Jura has a number of peculiarities, which make it special. The arguably most important one is the join Jura-Chaînes Subalpines at Chambéry (Figs. 2, 4, 5). In order to fully appreciate it, a brief discussion of the progress in rock mechanics and the theory of thrusting in the second half of this century would appear to be useful.

(3) Consider first the problem of stress transmission through the Molasse basin, which had been held impossible. The first misconception in this stance was that the Molasse basin is mechanically weak. In fact, numerous laboratory experiments particularly since the 1950s on the strength of rocks have shown, that under compression these easily disintegrating Molasse rocks (not to mention the Mesozoic limestones) are quite strong (e.g. Handin & Hager 1957, Hubbert 1951, Hubbert & Rubey 1959). Since then, progress in clarifying the problems of décollement tectonics has been made on many fronts (compare, e.g., the discussion in Hatcher 1995). For instance, the mechanical problems of evaporites have been studied extensively. Rock salt, it has been found (see for instance Urai 1983, Urai et al. 1986) is extremely weak, particularly in the presence of even minute quantities of water-which under natural conditions is virtually always the case. The sulfates are very weak too (e. g. Müller & Briegel 1980, Jordan et al. 1990, Jordan 1994, Laubscher 1984, who stressed the observational fact that water played an important role). Relatively small forces would have to be applied at the back of a thin skin above such evaporites to overcome basal resistance and make it move (compare Hafner 1951, Hubbert & Rubey 1959, Laubscher 1961). Indeed, the problem is not so much the strength of the skin but the amount of basal friction. It turns out that for evaporites, and particularly salt, transmission of the stresses necessary to make the skin move is no problem.

A further improvement in thin-skin mechanics was the introduction of the concept of the critical wedge taper (or critical wedge for short) (Dahlen et al. 1984, since

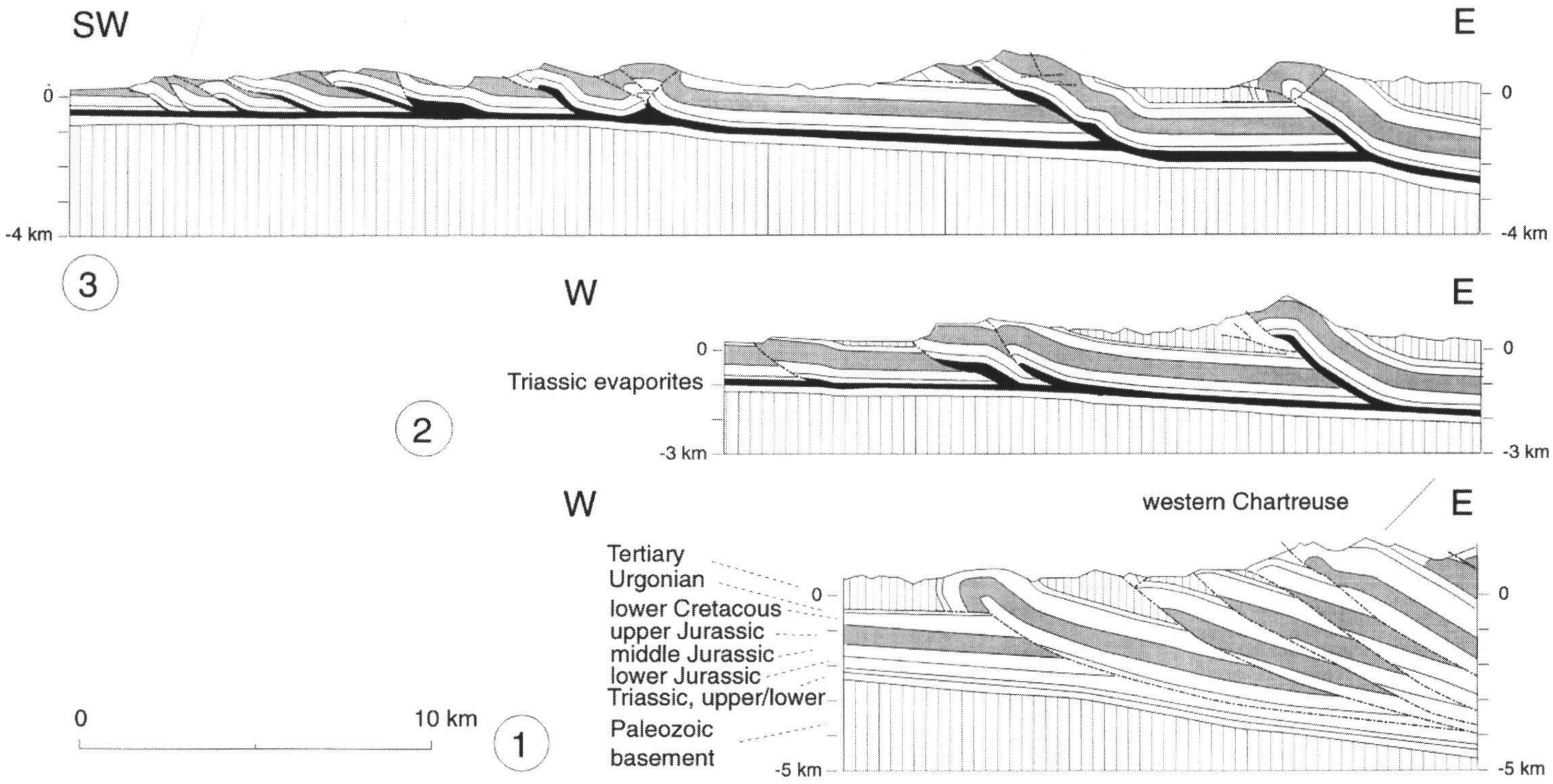

Fig. 4: Profiles 7, 12 and 14 through the southern Jura from Philippe (1994)

then in many textbooks on structural geology, e.g. Hatcher 1995) Although tectonicians specialized in foreland tectonics now are generally familiar with this important concept, it would appear that geologists at large often are not. It is, in essence, very simple. For a qualitative illustration, see Figs. 6-8, which are based on one of Yann Philippe's analog experiments. Experimental material are natural sands and artificial sands consisting of tiny glass beads. The evaporites are represented by silicone putty. Although scale models cannot represent all the rock mechanical characteristics, these materials appear to be acceptable in the light of the theory of scale models (e.g. Hubbert 1937, Ramberg 1981).
The gritty sands, in particular, exhibit considerable frictional resistance at the base of the sandbox (Fig. 6). Therefore, one has to push very hard from the rear, in order to move the sand at all. Basal décollement is minimal, just sufficient to permit the creation of a pile of imbrications. These now form a moving wedge with a very large tapering angle. Within this wedge, and particularly at its back wall, the section is thickened and average stress is reduced. Average strength, because of the increased weight, is increased. Although local basal friction is increased too this depends on the nature of friction. The taper marks the importance of section increase. Decrease of stress level and increase of strength are just sufficient to keep the wedge moving, but no propagation of décollement far into the foreland is achieved. Evi-

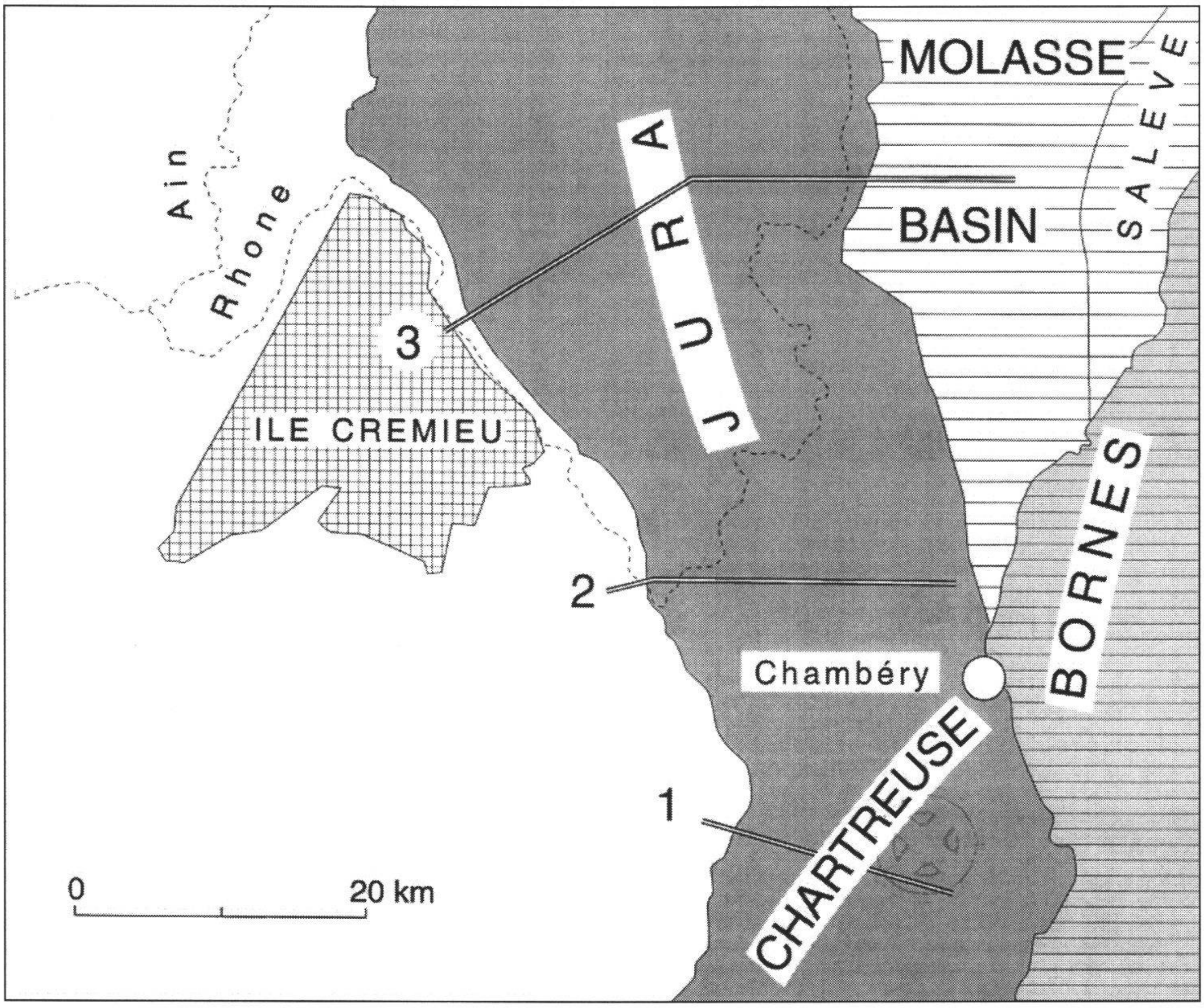

Fig. 5: Position of the profiles in Fig. 4.

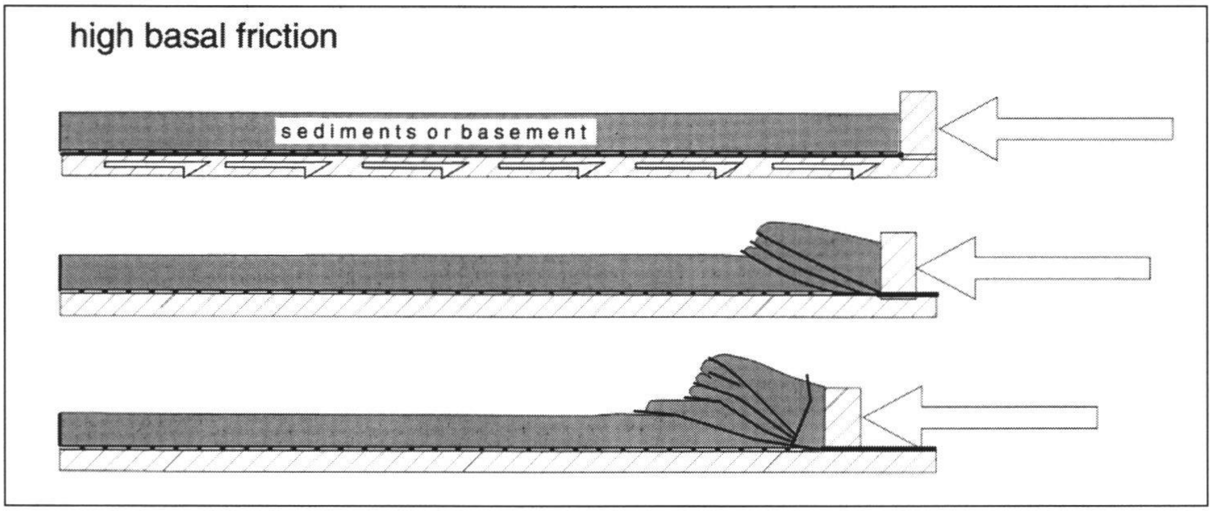

Fig. 6: Progressive décollement in a sandbox when basal friction is high (symbolized by the arrows in the basal plate).

dently, the stronger the basal resistance, the greater the necessary increase in section, the larger the angle of taper. This is the case for most shaly décollement layers (except for pockets of high pore pressure) and particularly for any postulated intra-basement detachment and shearing (e g. Umbgrove 1950, Ziegler et al. 1997): In the light of the current insight into thrust mechanics this cannot propagate far into the foreland.
At the opposite extreme is décollement on the silicone layer (Fig. 7). Basal resistance is much smaller, practically nil. Even a moderate push from the rear does not raise the stress level in the sand layer appreciably; its strength is not exceeded, it slides into the foreland, until some irregularity in the décollement layer (not shown in Fig. 7 but experimentally verified) impedes it temporarily and produces a local thrust wedge- a case important for the Jura (compare Laubscher 1986).
Whereas Figs. 6 and 7 show only partial aspects, Fig. 8 represents the total experiment. The layer below the evaporites (silicone putty) deforms into a pile of imbrications that stays in the rear, but where the thrust ramps arrive at the evaporites,

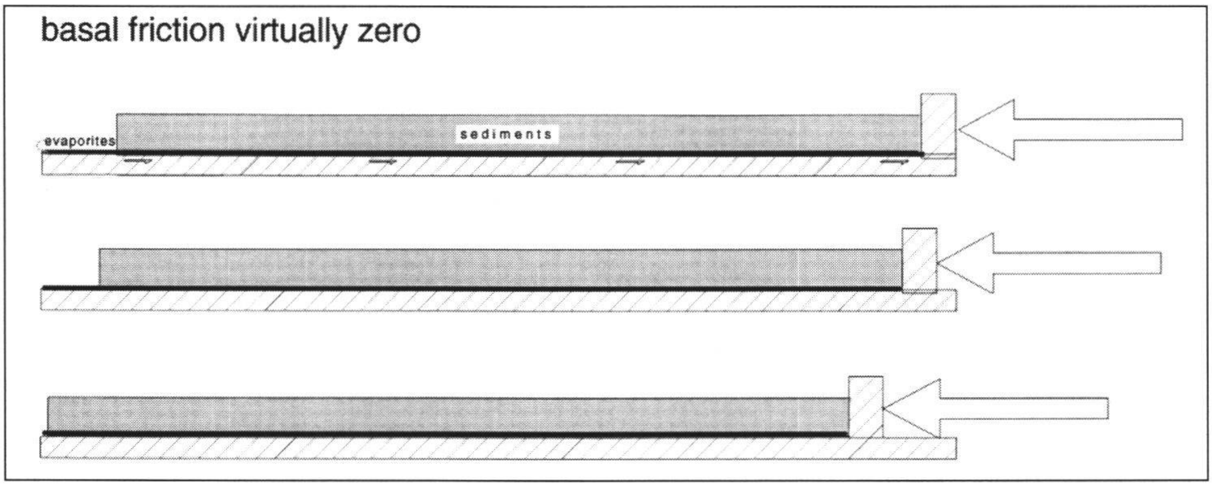

Fig. 7: Progressive décollement in a sandbox when basal friction is small.

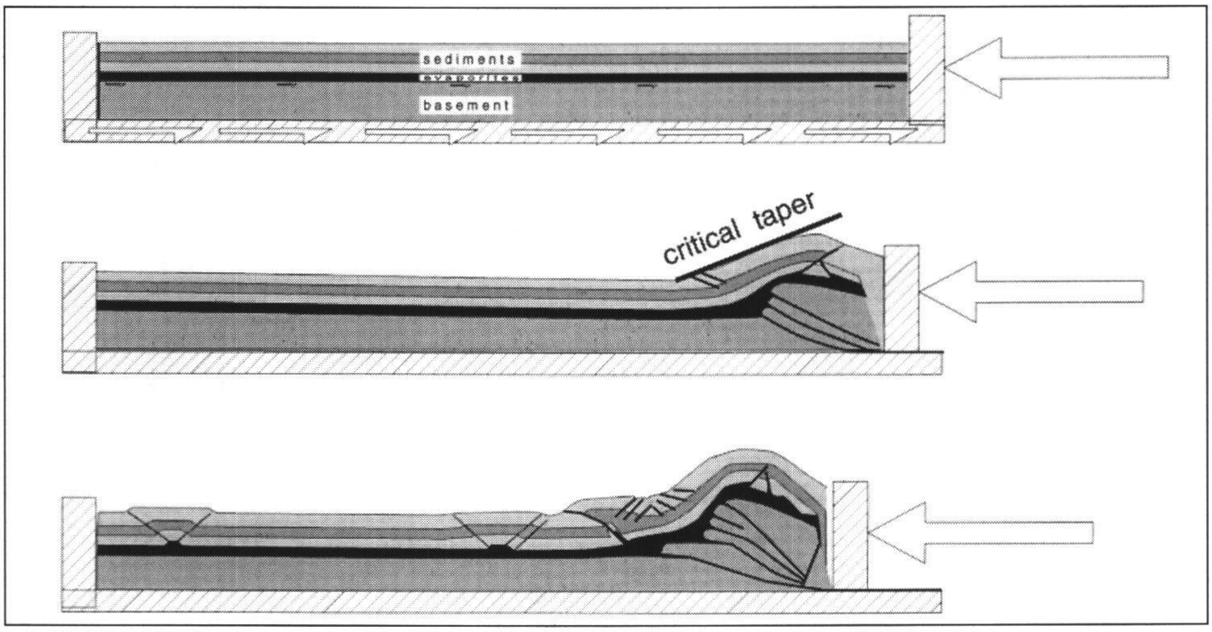

Fig. 8: The results of a sandbox experiment by Philippe (1995) with high basal friction and an intermediate low friction layer. Explanations in the text.

motion propagates far into the foreland. It is a simplified experiment, its boundaries are artificial, but the resemblance to the Jura system is obvious. But how do we define this Jura system?

For a first illustration see Fig. 4 after Philippe (1994). It shows the passage of the Jura into the Alps near Chambéry, which at long last becomes much clearer than it had been in the past. The role of the evaporites in this area could not be more drastic. Where they are missing, in the Chartreuse segment of the Chaînes Subalpines, décollement takes place in Liassic shales (compare Butler 1992). Friction in the shales is higher than in the evaporites, and a pile of imbrications is created that does not move far from the basement of the Belledonne Massif (Fig. 2). On the other hand, as soon as the presence of evaporites permits (profiles 2 and 3), the Jura separates itself from the Alps in the form of the the well-known arc, until, in eastern Switzerland, the Triassic evaporites disappear again, and so does the Jura (Fig. 2, 9). Thus the western Chartreuse may be considered either that part of the Jura that remained behind because of the lack of evaporites. Or, vice versa, the Jura may be thought of as that part of the Chaînes Subalpines underlain by an extensive evaporite basin that caused décollement into the far foreland until obstacles, particularly those due to the Rhine-Bressegraben system (Fig. 2, 9), stopped it.

Which are- in comparison with the western Chartreuse- the mechanically analogous elements of the Jura system farther east? Purely from their shape the imbrications of the Subalpine Molasse and those of the External Massifs (e.g. Masson et al. 1980) would qualify. But what about the timing?

In contrast to many Alpine geologists (e.g. Schmid et al. 1996, compare the discussion in Burkhard 1990) Laubscher (1996) submits that there is important evidence for a Jura phase of Alpine orogeny. In particular, the situation in the eastern Molasse basin is characterized by an erosional unconformity in the Early Miocene, cutting into the roof of the Helvetic nappes (Kittler & Neumayer 1983). This unconformity in turn is cut by younger thrusts such as those of the Subalpine Molasse

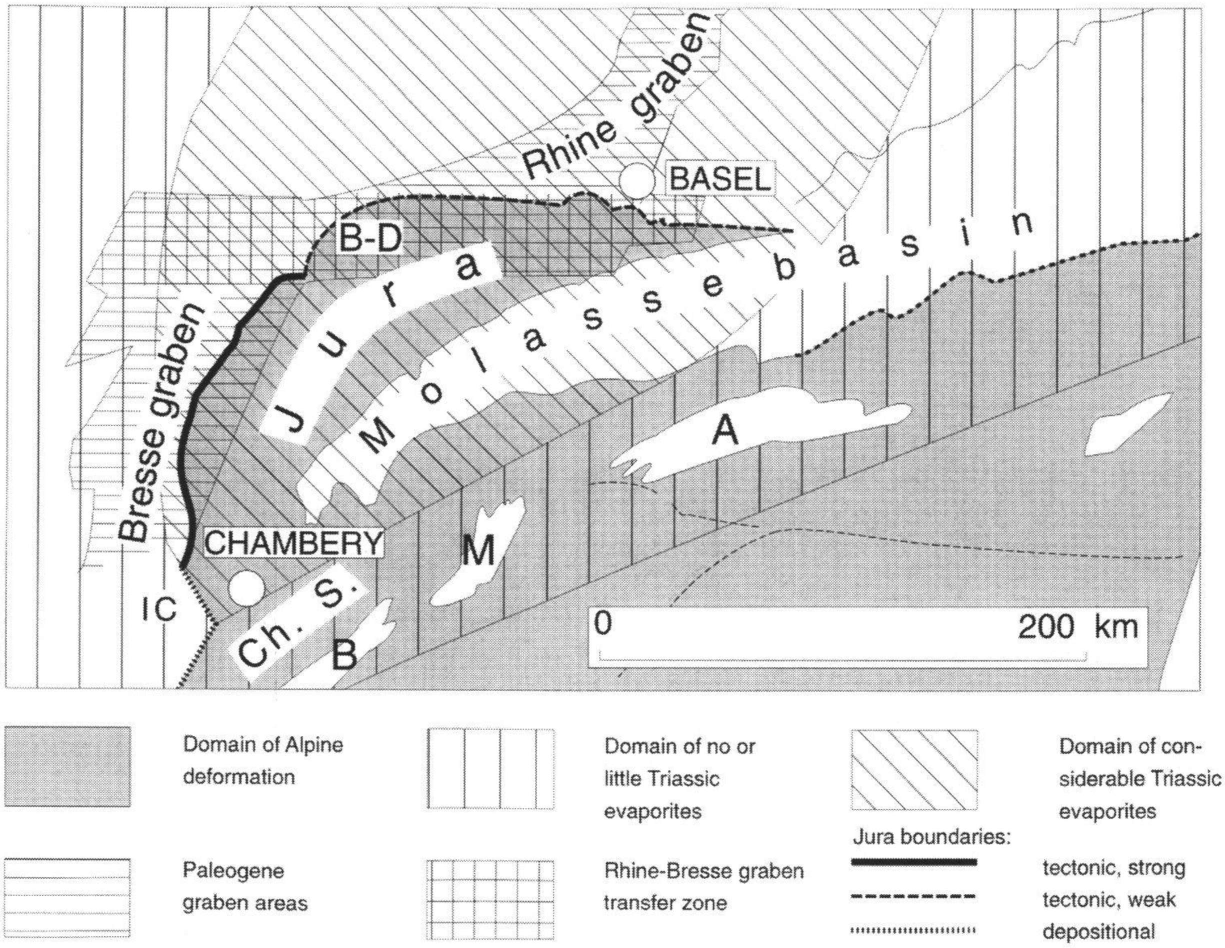

Fig. 9: The boundary conditions for Jura décollement. In the SW and NE décollement is bounded by the disappearance of appreciable evaporite (mainly halite) layers. In the west and north tectonic disturbances due to the Rhine-Bressegraben system impede propagation of décollement. IC= Ile Crémieu, Ch.S.= Chaînes Subalpines, B-D= Basel-Dijon transfer zone, B= Belledonne massif, M= Montblanc massif, A= Aar massif. Further explanations in the text.

(Kittler & Neumayer 1983, Bachmann & Koch 1983). This post-Early Miocene phase of motion Laubscher chose to call the «Jura phase» of Alpine orogeny.
The imbrications of the External Massifs too developed from the middle Miocene on, according to zircon fission track ages recently reported by Soom (1990) and Seward & Mancktelow (1994). These ages represent the tectonic movements lifting the basement imbrications up from depths of 7-10 km, depending on the geothermal gradient. Therefore, on the strength of these data, the External Massifs too qualify for the Jura phase and members of the Jura system. On this assumption, Laubscher (1996) proposed a quantitative, balanced though simplified and schematic forward model of Jura folding, involving all three crustal elements (Jura, Subalpine Molasse, External Massifs) (Fig. 10). It largely succeeds in explaining the quantitative relations between the elements and such prominent features as the nappe syncline between the Subalpine Molasse and the External Massifs and the antiformal shape of the Massifs. It also predicts qualitatively the late Miocene uplift and tilting of the Glarus thrust (Rahn et al. 1997). It does not take into account 3D aspects, which are discussed in Laubscher (1996) (compare Burkhard 1990) or the lithospheric load deformation.

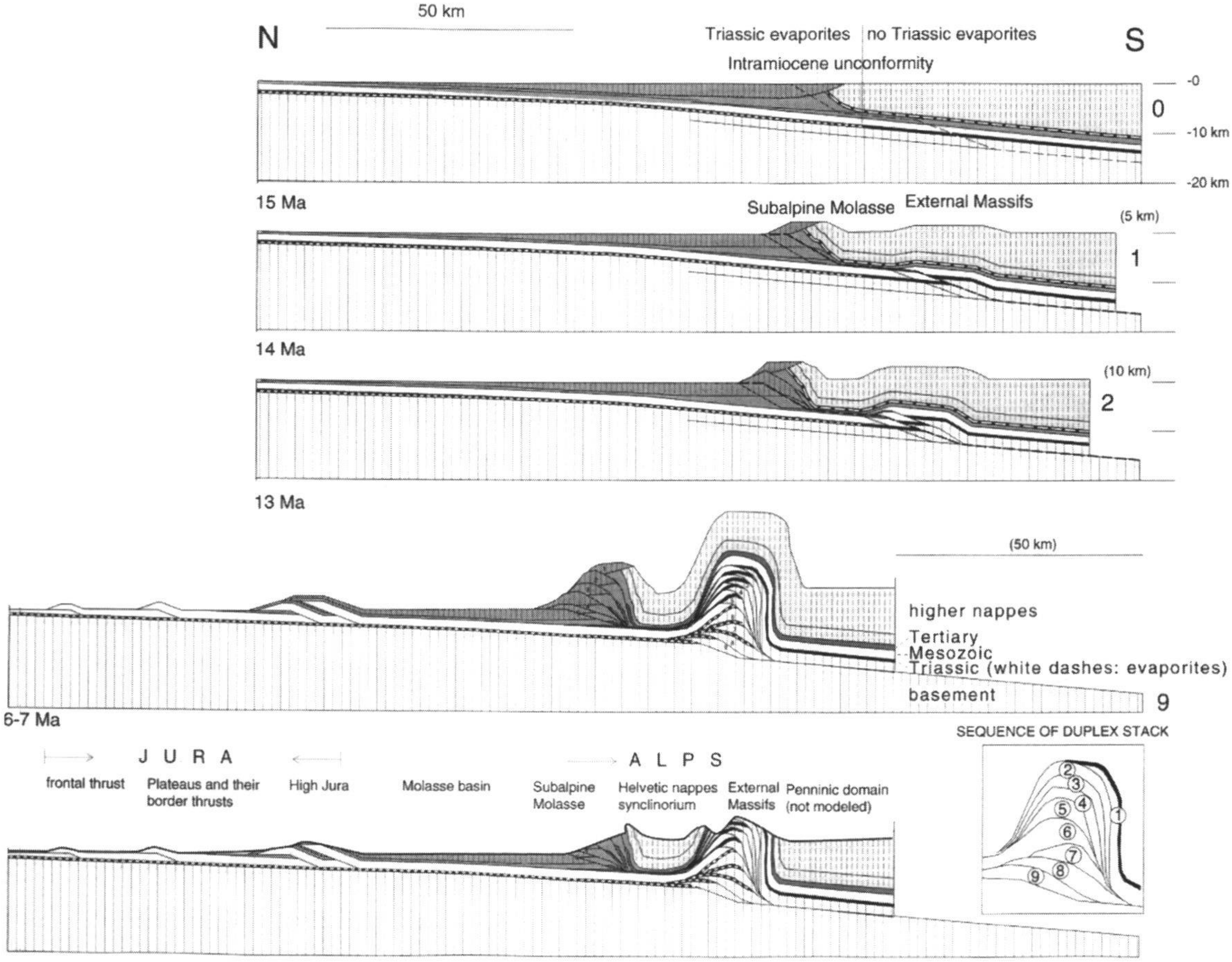

Fig. 10: A quantitative balanced kinematic forward model of the Jura phase in steps of 1 Ma, after Laubscher (1996), based on the thin basement slivers in the Aar Massif (Masson et al. 1980). Notice that the first steps raise the basement through the zircon fission track closure temperature (about 250° C, Soom 1990), and the later stages further raise the higher slivers through the apatite fission track closure temperature (about 110° C, Rahn et al. 1997). Further explanations in the text.

The Jura phase, as orogenic phases are wont to do, thus created a system that contains quantitatively related thin- and thick-skinned elements, whose shape is dictated by the boundary conditions and the rheology of the rocks involved, particularly by that of the basal décollement layer. In addition it contains an element of lithospheric deformation (not discussed in this article), also consonant with the expression of orogenic phases worldwide (compare Sinclair et al. 1991). Laubscher (1992) presented evidence from the forebulge of this element for two phases of lithospheric deformation, an earlier one in the early Miocene, attributable to the Helvetic phase, and a later one that developed from the middle Miocene on and that arguably represents the Jura phase.

Evidently, the lithospheric forebulge created basement deformations within the domain of the thin-skin décollement nappe (compare Laubscher 1986, compare

Laubscher & Noack 1997). One of the more vexing ones is that of Oyonnax in the French Jura (Philippe et al. 1997, Roure & Colletta 1997). The style of these basement structures, however, is entirely different from that of the thin-skin nappe, and their contribution to shortening is minimal. My considered opinion is that they are part of the lithospheric forebulge, which in the domain of the Paleozoic and Oligocene grabens created structures not foreseen in the simple models portraying the gravitational deformation of a homogeneous lithosphere. I am not aware of models that take into consideration the many factors operating in such a system: compression superimposed on gravitational loading, a lithosphere weakened by grabens, the presence and displacement of hot masses under such grabens. In view of the requirements of critical tapering for décollement, it would appear that for the basement deformations within the Jura the shallowest acceptable intra-crustal décollement would be at the brittle-ductile transition, at a depth of between 10 and 20 km.

Thus, the problem of décollement in the Jura itself has expanded into the problem of an entire orogenic phase and its tectonic system, involving not only décollement and thin-skin tectonics in the foreland but also thick-skin tectonics in the basement and lithospheric load deformation. After 90 years, the décollement theory fits into this system.

3. Outlook: The problem of models in a chaotic world

Models, of course, are never the truth. At best they portray approximately an island of rationality in the sea of chaos. However, they fulfill both a «psychological» and a practical need. Taking up only the latter, I refer to a recent publication in this Journal (Murris 1997) with reflections on the necessity and the risks of geological forecasts. No bidding for concessions, no decision on a drilling location would be possible without some model- formulated or not- in mind. Models consist of interpolations and extrapolations on accepted (sometimes erroneously) «facts». Model-building involves risks and the unavoidability of error- yet neither pragmatically nor scientifically is it avoidable.

Scientific model building turns- like the pragmatic one of the oil industry- around decision making for further action. In science, these decisions aim at an efficient application of resources- both the mental ones of the individual scientist and the financial ones. In the case of the décollement model of Jura folding, efficiency would appear to favor acceptance, if only pro tempore, of an overwhelmingly fact-supported model and to explore its logical conclusions, in order to make decisions on further fact-finding and model building.

It was stated above that in spite of the impressive data set supporting it there is still resistance against the décollement model in some quarters. This will remain so as nature never makes a full confession.

For instance, seismic lines through the Molasse basin show small irregularites in the Mesozoic section, and particularly in the Triassic. They have been interpreted as faults passing from basement through the evaporite layers into the overlying sediments, thereby proving that no décollement has taken place (Gorin et al. 1993). In my view and that of other geologists familiar with reflection seismology (e.g. Colletta and Philippe, personal communication 1993) those seismic sections shown in support of this opinion contain nothing beyond small disturbances of reflections that are more convincingly interpreted in different ways (about distortions of reflections by overlying irregularities, see e.g. Laubscher 1956). The balance between overinterpretation and underinterpretation of seismic lines, in my experience, is often a delicate one. This also applies to a recent publication by Pfiffner et al. (1997) who opine that small disturbances over Paleozoic troughs forbid large-scale décollement in the Triassic evaporites, without, however, coming up with a kinematically and dynamically viable alternative. In this case too there is ample scope for interpretations that do not contradict the dominating role of décollement on the Triassic evaporites demanded by the incontrovertible arguments listed above. Finally, Pfiffner et al. apparently find support for their view in a new cross-section of the Chasseral anticline which does not contain the thrusts possibly needed for section balancing if décollement took place on the Triassic evaporites. I know the Chasseral area only from excursions, but so far as I can see the quality and continuity of outcrops is not superior to that of other areas in the Jura with which I am thoroughly familiar. In many places a viable tectonic interpretation is possible only when the kinematic requirements inferred for neighboring areas are taken into consideration. After all, a comparison of Figs. 3 and 4 reveals some of the problems inherent in the use of limited surface information.

4. Conclusions

In conclusion, let me recapitulate briefly the modern arguments supporting the décollement model:

1. The observational argument of Buxtorf still stands. It has been strengthened in the intervening 90 years by subsurface data such as seismic sections an drill holes.
2. Computer assisted section balancing permits a better control on the sediments-basement relation. As sections are modified and refined, the décollement model more than ever appears to be the only viable one.
3. As to décollement mechanics, progress in rock mechanics proves that décollement on evaporites far into the foreland is mechanically possible.
4. Progress in the theory of thin-skin tectonics shows, that the vanishing angle of taper in the Jura, particularly in the flat-lying basins of the eastern Jura and the plateaus of the Franche Comté, *requires* décollement on the Triassic evaporites. Only their vanishing shearing strength permits a vanishing taper. Intracrystalline décollement somewhere in the shallow basement, propagating far into the foreland, as some have postulated, is out of the question. Intracrystalline décollement stays much in place and leads to a localized pile of imbrications such as the External Massifs.
5. This well founded theoretical requirement is convincingly illustrated by analog experiments.
6. It is also borne out by such natural examples as the transition of the Jura into the Chartreuse at Chambéry, where flat-lying tabular synclines, separated by thrust-ramp folds- typical for décollement on evaporites- give way to a pile of imbrications- typical for décollement on shales. Generally the statement is valid: The area of the Jura coincides with the area of Triassic evaporite deposition, modified by disturbances in the evaporite layer.
7. Finally, in the 90 years since the formulation of the décollement hypothesis, worldwide exploration for petroleum has revealed that thin-skin fold-and-thrust belts are commonplace the world over (see, e.g., Ziegler & Horvath 1997). The Jura is but one of them, albeit a particularly interesting one.

This formidable array of weighty arguments makes the décollement model of the Jura one of the best-supported models in the earth sciences. Still, the earth never reveals all its secrets. The data set for the Jura is far from complete. This and the fact that there are ambiguous data that lend themselves to a variety of interpretations keeps any model from being final.
In this context I would like to demolish an apparently widely held misunderstanding that equates supporters of the thin-skinned model of Jura folding, including myself, with a «Basel School», fighting loyally on the side of old Buxtorf. Nothing could be farther from the truth. Buxtorf's own students had abandoned the model as hopeless, and between Buxtorf and myself not much love was lost. My own support of the model was based on a new analysis of the problem, involving all its different aspects. Much as I would have liked to kill it, I had to accept it.

Acknowlegments

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