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Evidence for large-scale decoupling in the Triassic evaporites of Northern Switzerland: An overview

By PETER JORDAN [1])

Key words: "Fernschub", halite, anhydrite, flow mechanisms, basin geometry, Oligocene to Miocene normal faulting.

ABSTRACT

A number of field observations in the hinterland of the Eastern Jura Mountains support the concept of large-scale decoupling of the frontal-Alpine sedimentary wedge ("Fernschub"); these include the presence of regionally important shear zones in the basal Triassic evaporites. These shear zones tend to be localized in pure halite and anhydrite layers. Despite low paleotemperatures (ca. 75–150 °C) and high bulk strain rates (ca. $5 \cdot 10^{-14}$ to $2 \cdot 10^{-13}\,s^{-1}$), anhydrite has been deformed by crystal plasticity and grain boundary sliding processes. The low viscosity in the crystal plasticity field originates from an early onset of grain boundary migration at $T/Tm \leq 0.21$ which is probably triggered by pore fluids (fluid enhanced flow).

The geometry of the Jura–Molasse basin sole thrust is controlled by facies changes as well as Triassic and Tertiary extensional structures. It is suggested that some of the Middle Triassic halite deposits were located in tectonic depressions which were inverted during the formation of the Jura décollement. Oligocene to Early Miocene normal faults, which had cross-cut the evaporite horizons, are believed to have been overridden by the subsequent detachment of the Alpine foreland sedimentary prism.

ZUSAMMENFASSUNG

Die Mehrzahl der Feldbeobachtungen im Hinterland des Ostjura bestätigen die Fernschub-Hypothese, d.h. das Konzept einer grossräumigen Abscherung des alpinen Vorlandkeils auf den triassischen Evaporiten. In den Evaporiten, vor allem aber in den reinen Halit- und Anhydritlagen haben sich bedeutende Scherzonen entwickelt. Der Anhydrit wurde, trotz vergleichsweise tiefen Paläotemperaturen (75–150 °C) und hohen Scherraten ($5 \cdot 10^{-14}$ to $2 \cdot 10^{-13}\,s^{-1}$), durch kristallplastische (intrakristallines Gleiten, Verzwillingung, Korngrenzwandern) und interkristalline Gleitprozesse deformiert. Das unerwartet frühe Einsetzen von Korngrenzwandern bei $T/Tm \leq 0.21$, das nachhaltig für die niedrige Viskosität des Anhydrits im kristallplastischen Verformungsbereich verantwortlich ist, wird auf die Präsenz wässeriger Lösungen zurückgeführt ("fluid enhanced flow").

Die grossräumige Geometrie des basalen Abscherhorizonts wird von Faziegrenzen und triassischen, wie auch tertiären Bruchssystemen kontrolliert. Es wird postuliert, dass verschiedene der mitteltriassischen Salzlager in tektonischen Depressionen abgelagert waren, die während der Juraabscherung invertiert wurden. Die ursprünglich mehr oder weniger zusammenhängenden Evaporithorizonte wurden im Oligozän und frühen Miozän durch extensive und transtensive Brüche zergliedert. Es wird postuliert und anhand einfacher Modelle gezeigt, dass solche Verwerfungen nicht unbedingt ein Argument gegen das Fernschubkonzept sind. Vielmehr konnten diese Hindernisse aufgrund der tiefen Viskosität der Evaporitgesteine während der Abscherung überwunden werden.

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Introduction

The "Fernschub" concept proposes that basement shortening corresponding to the horizontal shortening of the epi-sole thrust sedimentary cover of the Late Miocene to Pliocene Jura fold-and-thrust belt is compensated somewhere in the Alps proper (e.g., Buxtorf 1907, Umgove 1948, Laubscher 1961, 1965). This proposal has been subject to many controversial discussions on the mechanical feasibility of large-scale décollements within the relatively thin Triassic evaporites (e.g., Pavoni 1961, Wegmann 1963, Müller & Hsü 1980, Laubscher 1980, Ziegler 1982, Burkhard 1990).

The objectives of this paper are to present micro- to mesostructural evidences for decoupling in the Triassic evaporites beneath the Molasse basin of Northern Switzerland and discuss the importance (or lack thereof) of the Oligocene to Miocene normal faulting on the formation of the large-scale Jura detachment.

The evaporites discussed here are the Middle Triassic Anhydritgruppe formation and the Late Triassic Gipskeuper formation (Fig. 1) – , which are separated by the 70 m thick carbonate "Hauptmuschelkalk" formation (Dronkert et al. 1990). These formations have been reached or penetrated by nine deep boreholes in the hinterland of Jura fold-and-thrust belt (Fig. 2). To date, investigations on the state of deformation in the evaporite layers have only been done (or released to the public) at the Schafisheim, Altishofen, Courtion and Entlebuch wells (Becker et al. 1987, Matter et al. 1988, Jordan

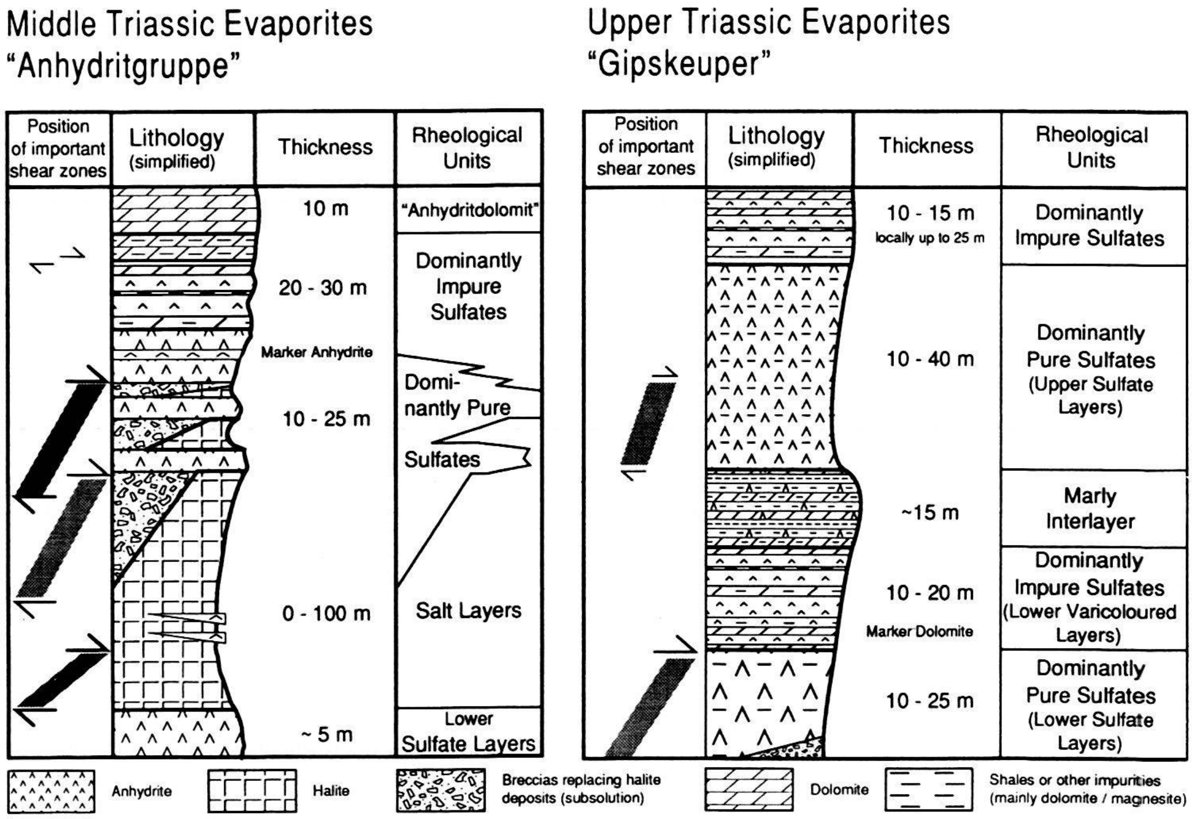


Fig. 1. Simplified stratigraphic columns of Middle Anhydritgruppe formation and Late Triassic Gipskeuper formation of the Eastern Jura and its hinterland showing the main rheological units and the location of the main decoupling horizons.

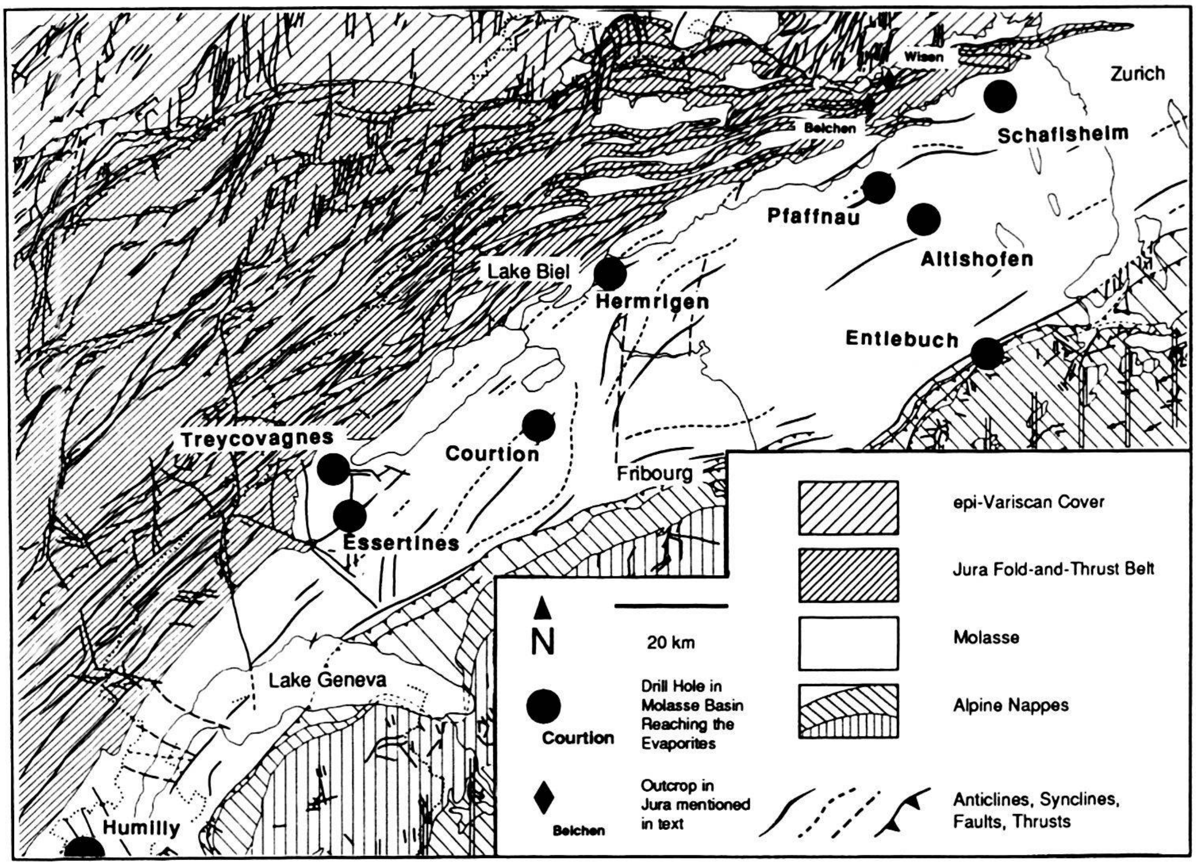
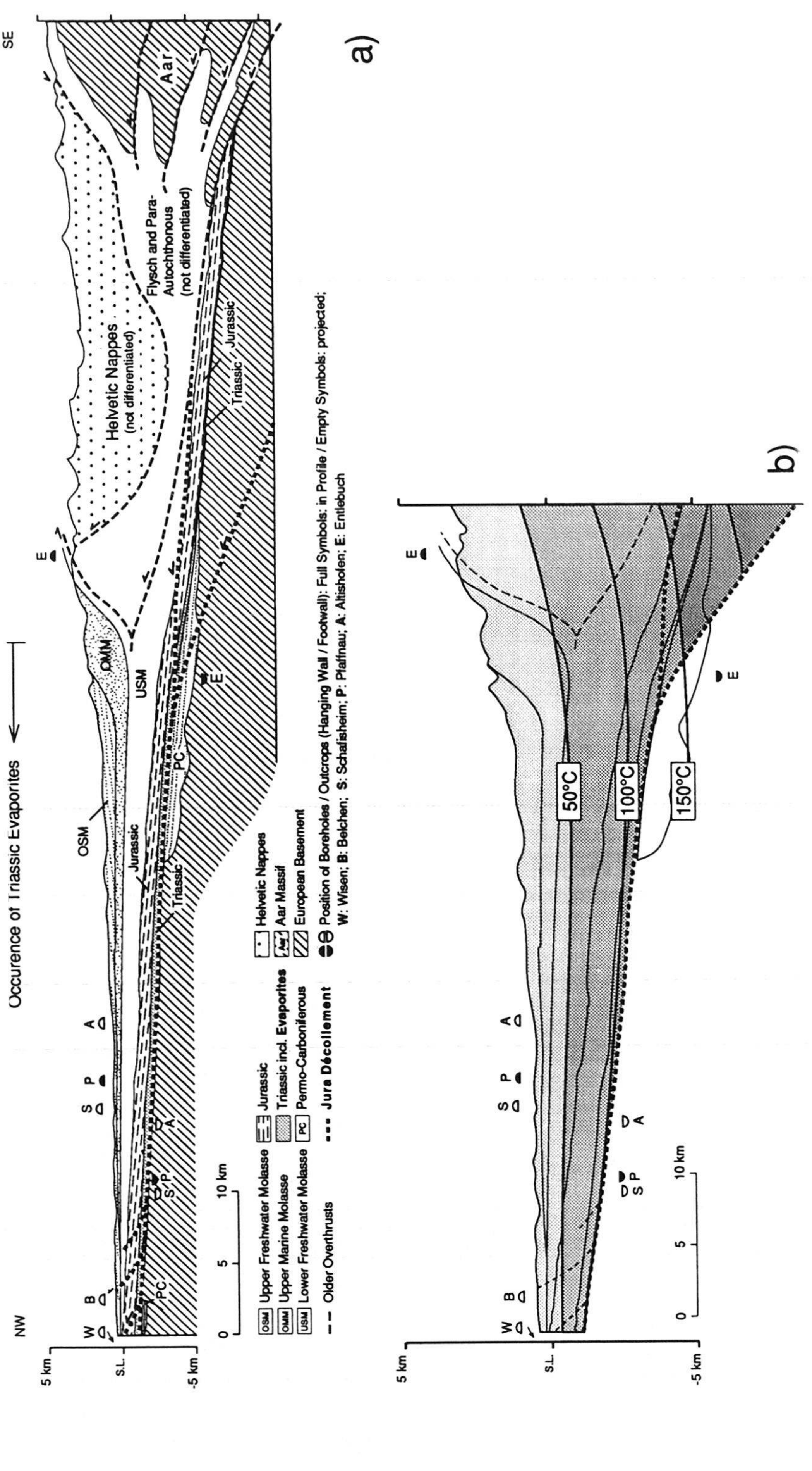


Fig. 2. Tectonic map of the Eastern Jura (from Nagra 1988) showing the drill holes in the Molasse basin reaching or penetrating the evaporite horizons and the two outcrops in the Jura (Wisen well and Belchen Motorway tunnel) mentioned in the text. The N-S-trending folds in the Fribourg-Lake Biel area are suggested to correlate with the change of the major sole thrust from the Anhydritgruppe in the NE to the Gipskeuper in the SW.

& Nüesch 1989, Fischer & Luterbacher 1963, Vollmayr & Wendt 1987). In the Jura proper, evaporite shear zones have been subject to structure and microfabric analysis at Belchen Tunnel, Wisen well (Fig. 2), and in the quarries of Riepel and Kienberg (Laubscher 1975, 1984, Jordan 1988, Jordan et al. 1990, Jordan & Noack 1992).

The composition of the Triassic evaporite formations (Fig. 1) is heterogeneous at nearly any scale. This resulted in variations of rheological behavior of the individual layers during Oligocene to Pliocene deformation, ranging from low strength viscous flow within the pure halite and anhydrite layers, to rigid behavior or high-strength cataclastic flow in pure shales, marls and carbonates (Jordan & Nüesch 1989). The differences in rheological response often allow the preservation of sedimentary structures; examples include enterolithic folds in impure anhydrite layers ($\geq$ 20% dolomite or clay) adjacent to highly strained pure anhydrite mylonites (the term "mylonite" is used here in the sense of Schmid & Handy 1991, i.e. as foliated rocks predominantly deformed by viscous processes).

The evaporites in the hinterland of the Eastern Jura have been deformed at depths of 1.5 to 6 km and at paleotemperatures of ca. 75 °C to 150 °C (Fig. 3). Provided that the whole shortening of up to 16 km documented in the Eastern Jura fold-and-thrust belt is concentrated within the 150 to 350 m thick Triassic evaporite layers, the bulk strain rates



Occurence of Triassic Evaporites
NW
SE
a)
5 km
S.L.
-5 km
W
B
S
P
A
E
S/P
PC
OSM
OMM
USM
Jurassic
Triassic
Helvetic Nappes
(not differentiated)
Flysch and Para-
Autochthonous
(not differentiated)
Aar
0
5
10 km
Upper Freshwater Molasse
Upper Marine Molasse
Lower Freshwater Molasse
Older Overthrusts
Jurassic
Triassic incl. Evaporites
Permo-Carboniferous
Jura Décollement
Helvetic Nappes
Aar Massif
European Basement
Position of Boreholes / Outcrops (Hanging Wall / Footwall): Full Symbols: in Profile / Empty Symbols: projected;
W: Wisen; B: Belchen; S: Schafisheim; P: Pfaffnau; A: Altishofen; E: Entlebuch
b)
50°C
100°C
150°C

vary between $5 \cdot 10^{-14}$ and $2 \cdot 10^{-13}$ s^{-1}), (due to variations in mineralogy and mechanical response, the local shear rates may vary between $< 1 \cdot 10^{-15}$ and $1 \cdot 10^{-12}$ s^{-1}) Jordan 1987a and in press).

Micro- and mesostructural deformation structures

Deformation of halite

The only information on halite deformation in the Jura hinterland is from the Schafisheim bore hole (Matter et al. 1988, Jordan & Nüesch 1989, Jordan, in press) (Fig. 2). At all other sites, halite layers have either not been reached or not been cored. At Schafisheim, the halite sequence at the base of the Anhydritgruppe can be subdivided from top to bottom into three deformation units. In the top unit (1400 to 1408 m below surface) and the bottom unit (1423 to 1434 m), halite mylonites have developed. The middle unit is nearly undeformed due to a higher anhydrite and shale content compared to the nearly homogeneous halite mylonites of the top and bottom units.

The halite mylonites are coarse-grained (ca. 2 mm) and show a distinct grain elongation (up to 10 : 1 : 1). Experimental work on halite with a similar grain size yields very low shear strengths, especially in the presence of pore fluids (e.g., Carter & Hansen 1983, Urai et al. 1986, Borns 1986, Spiers et al. 1988, 1990) (Fig. 4a). The rate controlling mechanism within the Jura décollement halites is suggested to have been either cross-slip or pressure solution (Fig. 4a); however, direct microfabric or textural analysis of halite has not been performed thus far.

Deformation of anhydrite

In the anhydrite shear zones of the Jura décollement, a large number of different microfabrics occur. These can be reduced to three typical patterns which we attribute to differences in paleotemperature and deformation mechanism (Fig. 5). It is suggested that these patterns may be related to three deformation regimes (Fig. 5): Regime 1 (twinning, low temperature), regime 2 (crystal plasticity, moderate temperature) and regime 3 (dif-

Fig. 3. Cross section through the hinterland of the Eastern Jura fold-and-thrust belt. a) Partly restored cross section through the wells Pfaffnau and Entlebuch. This cross section (based on a section by Vollmayr & Wendt 1987 and data by Naef et al. 1985) shows one possible configuration after the formation of the Subalpine Molasse triangle zone, and before the onset of Jura décollement (Middle to Late Miocene). The sole thrust of Jura décollement is suggested to follow the Triassic evaporites from the Jura to the Entlebuch area. Here it forks in an upper branch, which joins the Subalpine Molasse sole thrust, and a lower branch which ramps down into the basement. During Jura phase, thrusting on this latter branch causes a basement fold which deforms the Subalpine Molasse triangle zone and steepens its frontal limb. The major consequence of this model is that there is no major décollement in the Triassic strata South of Entlebuch where evaporites are rare or absent. b) Northern part of above cross section (vertical exaggeration = 2x) showing the possible geothermal configuration at the beginning of Jura décollement. This cross section is constructed on the assumption of an elevated geothermal gradient of 40 to 50 °C/km in the North (Diebold & Müller 1985, Mullis 1987), and a "normal" gradient of 20 to 30 °C/km in the Alpine domain.

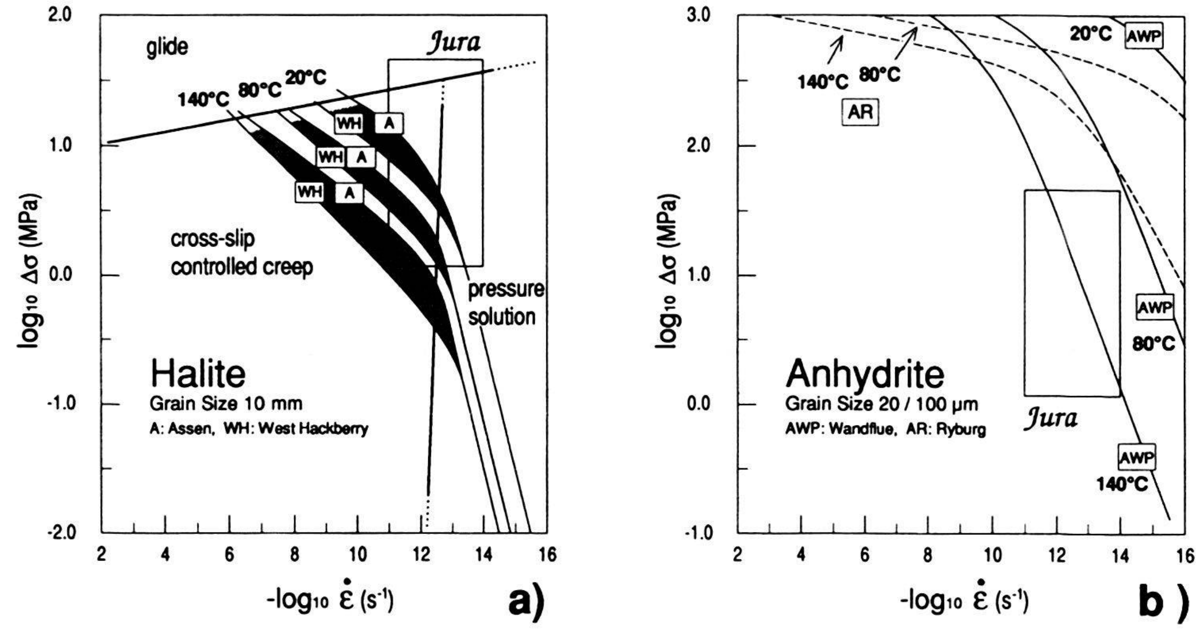


Fig. 4. Flow strength vs. shear ratio diagrams for halite and anhydrite as extrapolated from experimental data. The rectangle represents the ambient conditions relevant for Jura décollement. Flow strength is calculated for temperatures of 20, 80 and 140 °C. a) Flow strength and deformation mechanism map for coarse-grained (10 mm) halite after a compilation by Spiers et al. (1990); b) Flow strength of medium- (Ryburg) and fine-grained (Wandflue) anhydrite deforming by crystal plasticity processes (map constructed using the data of Müller et al. 1981).

fusional and grain boundary gliding processes, relative high temperature). Among them, regime 2 and 3 apply to the décollement level, while regime 1 is restricted to the near surface.

Regime 3 is suggested to dominate in the deeper part of the evaporite décollement level (i.e. south of well Altishofen) (Fig. 3). In the Gipskeuper of Altishofen well (subordinate décollement level, > 2.1 km deep during deformation) and the Anhydritgruppe of the Schafisheim well (major décollement level, > 1.7 km), laminated mylonites show a transition between regime 2 and 3. In these wells the microfabric is characterized by nearly isometric (ca. 2 : 1 : 1) and relatively small anhydrite grains (5 to 50 µm in the fine-grained laminae) (Fig. 6 b). This suggests that grain size dependent flow was active (c.f. Olgaard & Dell'Angelo 1991). On the other hand, textural evidence (Fig. 5) suggests that crystal plasticity processes (which dominate in regime 2) have still been operative.

Regime 2 (crystal plasticity) is found in the shallow parts of the décollement (Gipskeuper of Schafisheim, > 1.3 km deep, regime 2 b) as well as in the highly strained shear zones of the Jura frontal thrusts that emanate from the major décollement level (Jordan, in press) (Fig. 3). Here, crystall plasticity related to distinctly lower temperatures is

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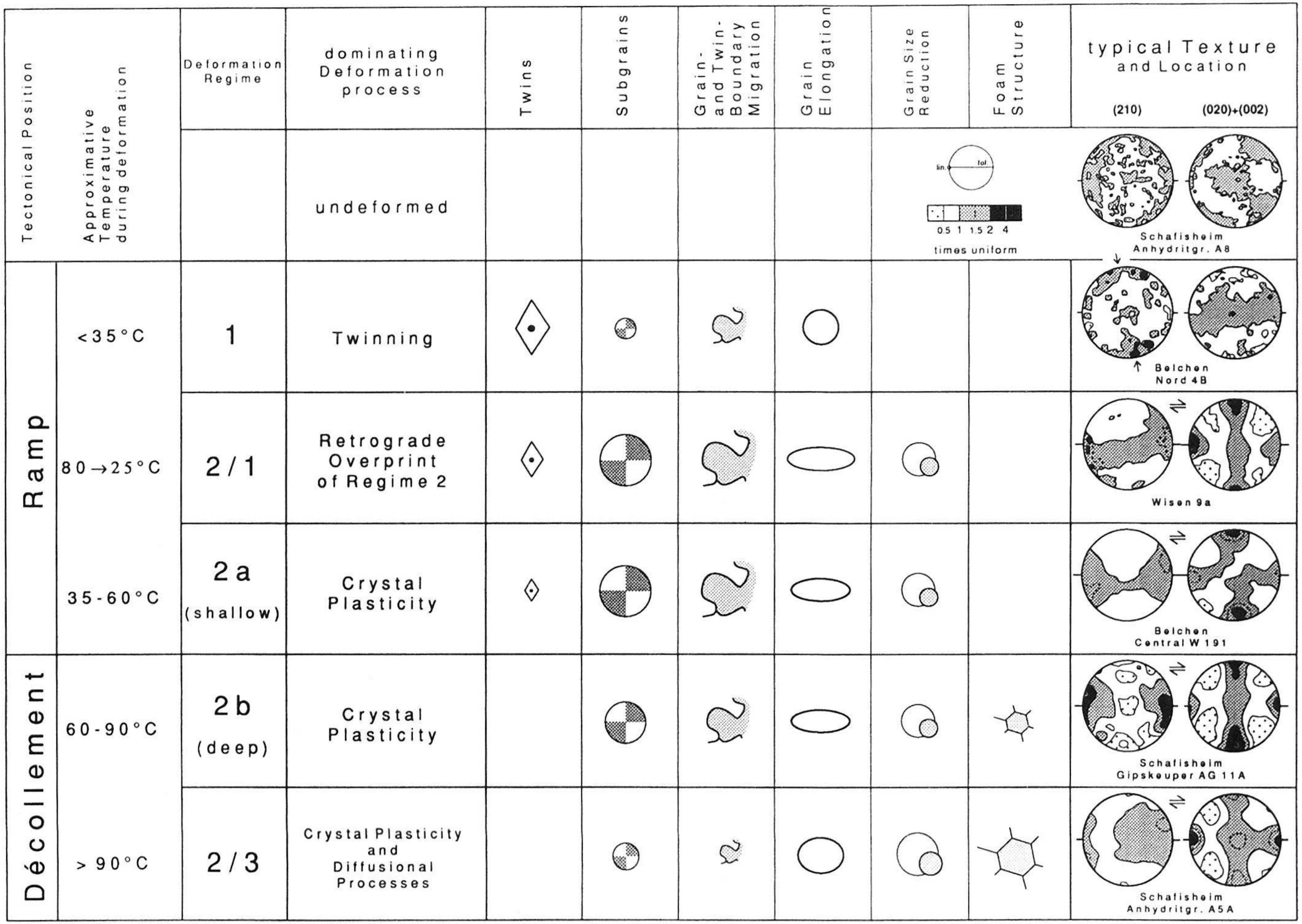
Fig. 5. Deformation regimes of anhydrite in the Eastern part of Jura décollement. With increasing temperature, the progression is: twinning (regime 1), crystall plasticity (mainly (001) [010]-glide) (regime 2) and finally diffusional or grain boundary sliding (regime 3). Microstructures and typical textures observed in each regime and subregime are shown. Symbol size is proportional to relative importance of the observed feature: texture analyzed with a texture goniometer. For location of samples see Fig. 2 and 3.


Tectonical Position
Approximative Temperature during deformation
Deformation Regime
dominating Deformation process
Twins
Subgrains
Grain- and Twin-Boundary Migration
Grain Elongation
Grain Size Reduction
Foam Structure
typical Texture and Location
(210)
(020)+(002)
undeformed
lin.
fol.
0.5 1 1.5 2 4
times uniform
Schafisheim Anhydritgr. A8
Ramp
<35°C
1
Twinning
Belchen Nord 4B
80→25°C
2/1
Retrograde Overprint of Regime 2
Wisen 9a
35-60°C
2a
(shallow)
Crystal Plasticity
Belchen Central W 191
Décollement
60-90°C
2b
(deep)
Crystal Plasticity
Schafisheim Gipskeuper AG 11A
> 90°C
2/3
Crystal Plasticity and Diffusional Processes
Schafisheim Anhydritgr. A5A

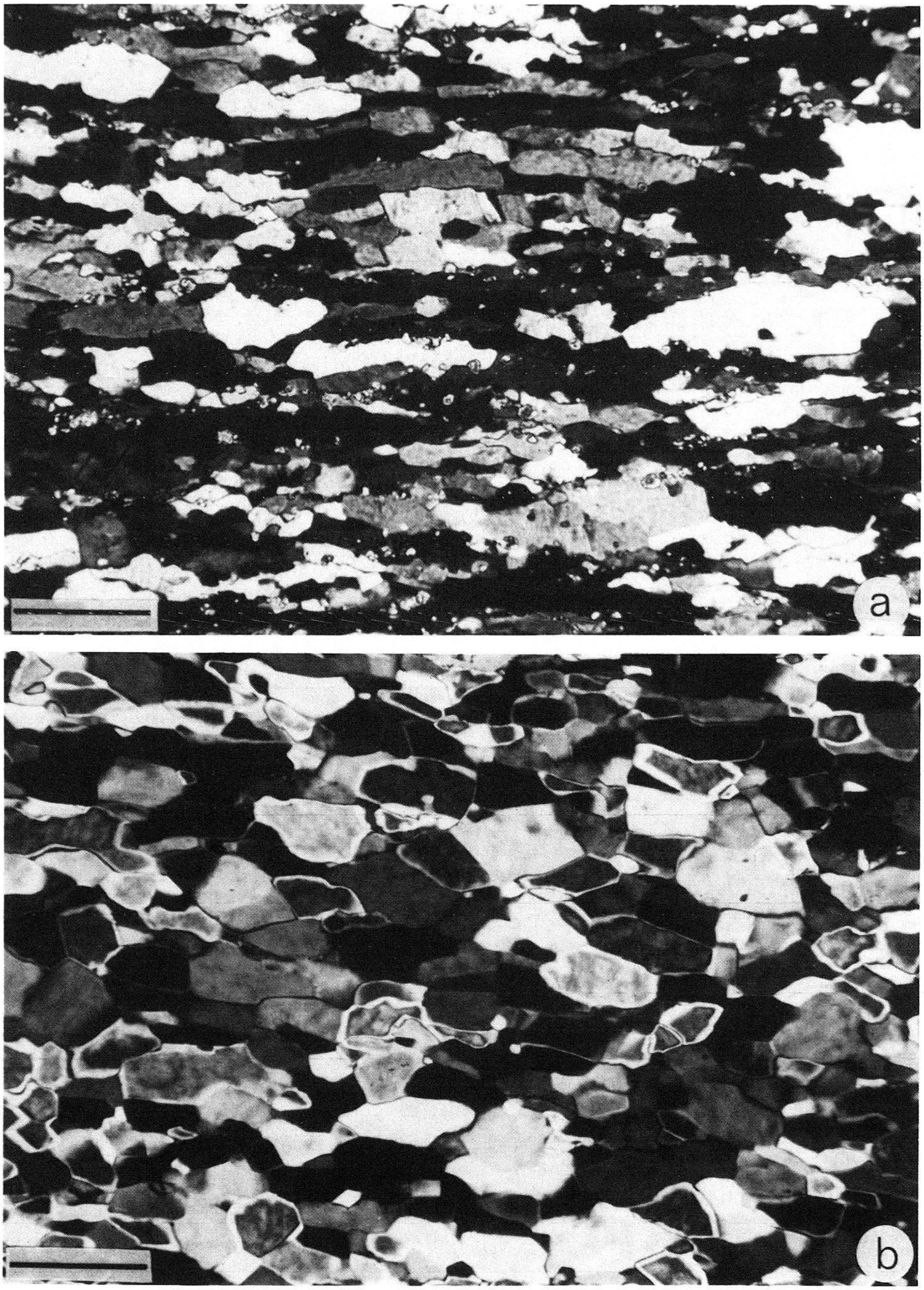


Fig. 6. Typical micrographs of two types of anhydrite mylonites (bar is 100 μm): a) from the Jura boundary thrust at Wisen, mainly deformed by crystal plasticity (regime 2); b) from the major sole thrust of Schafisheim, deformed by intracrystalline glide and diffusional or grain boundary sliding processes (regime 2/3).

observed (Belchen, Farisberg thrust, regime 2b, Fig. 5), as well as retrograde overprinting by the low temperature regime 1 (Wisen, regime 2/1, Fig. 5). Both outcrops show characteristic microfabrics (Fig. 6a) and textures (Fig. 5) that deviate from the décollement related regime 2b (Fig. 5). At décollement level, intracrystalline glide (mainly on (001)[010]), in combination with grain boundary migration, is the dominant deformation mechanism. In addition, anhydrite fibre growth parallel to (100) in pressure shadows of dolomites and shale pull-aparts is common as shown both by microfabric and textural evidence (strong (210) maxima subparallel to lineation, Fig. 5). The anhydrite grains are distinctly elongate and the grain size normal to the foliation varies from 5 to 100 μm. In the full array of regime 2 (subregimes 2b, 2a, 2/1) the anhydrite rocks are strongly foliated and may be called mylonites (in concordance with Schmid & Handy 1991).

Regime 2 coincides with the microstructural findings of Müller et al. (1981) in the samples experimentally deformed at temperatures between 400 and 450 °C and regime 3 has been recognized by Olgaard & Dell'Angelo (1991) in samples experimentally deformed at higher temperatures (up to 800 °C). Consequently, the mechanical data of Müller et al. (1981) (Fig. 4b) would apply for the low to moderate temperature field (regime 2). However, in naturally deformed anhydrite, the deformation regime (and therefore strength) is not only controlled by temperature and grain size alone, but also by the impurity content (e.g. Jordan & Nüesch 1989). Furthermore, evidence from the Jura boundary thrust domain (Jordan et al. 1990) suggests, that the strength of anhydrite deformed by crystal plasticity (regime 2) is even lower than that predicted by the extrapolation of the laboratory data of Müller et al. (1981). It is proposed here that fluids are responsible for the early onset of grain boundary migration (at $T \leq 100\,°C$, i.e. $T/T_{m\,Anhydrite} \leq 0.21$), and therefore for the weakening of the anhydrite (fluid enhanced flow, e.g. Urai 1983).

Finally, it has to be stressed that neither traces of syn- (or post-)kinematic hydration of anhydrite or gypsum fibre growth has been found at the décollement level. This observation is very important, as it shows that really anhydrite rather than gypsum was responsible for the low strength flow of the evaporite shear zones at this level. Both processes (synkinematic anhydrite hydration and gypsum fibre growth), which have a dramatic influence on the mechanical behavior of evaporite shear zones, are (at least in the Jura mountain area) restricted to the very shallow domain (≤ *ca.* 600 m, Jordan, in press).

Deformation within the anhydrite shear zones is not chaotic but rather well organized (e.g., Jordan et al. 1990, Jordan 1988, 1991b). Deformation structures in more or less pure anhydrite layers include secondary, narrow-spaced foliations, s- to s-c-fabrics, recumbent isoclinal folds (often with fold axis deflected into the transport direction) and (partly asymmetric) boudinage of more competent layers (impure anhydrites and non-sulfates) (Fischer & Luterbach 1963, Matter et al. 1988, Jordan & Nüesch 1989, Jordan et al. 1990, Jordan 1991).

The magnitude of deformation within the evaporite shear zones is difficult to estimate. However, the strongly developed foliation, the presence of pressure shadows (which document layer-parallel stretching of ≥ 10 : 1 at Schafisheim) and other microstructures suggest that it is not unreasonable to assume that the amount of deformation in these shear zones is in coincidence with the respective shortening in the sedimentary cover of the Jura proper (i.e. *ca.* 4 km in the Schafisheim cross section).

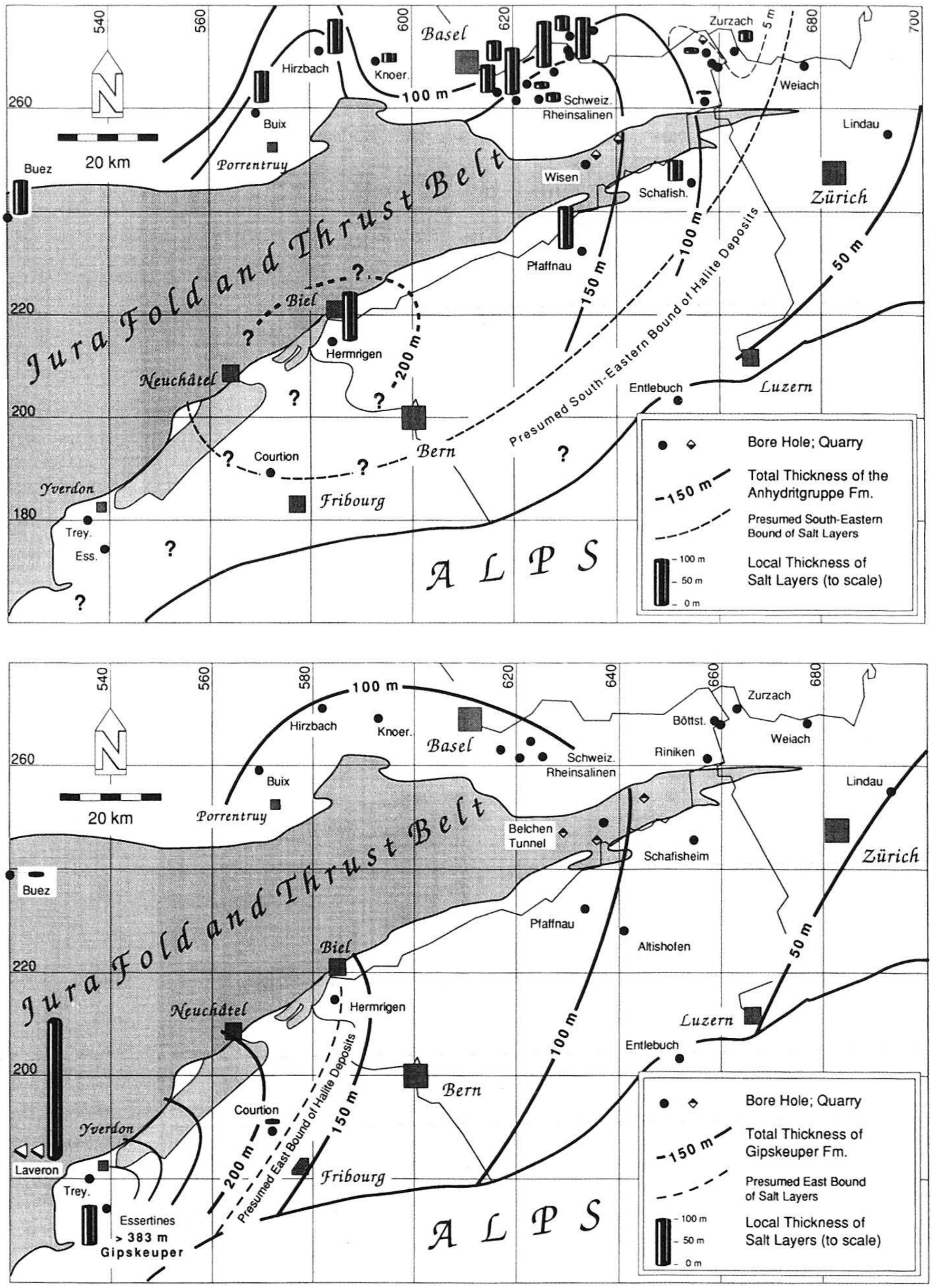


Fig. 7. Isopach maps of Triassic evaporites in Northern Switzerland: top) Middle Triassic Anhydritgruppe formation; bottom) Late Triassic Gipskeuper formation. The thickness of the halite deposits in individual bore holes is shown by columns.

Macro- to megascale deformation structures

Sedimentary basin geometry controlled structures

The depocenter of the Anhydritgruppe formation is located in the Lake Biel area (Fig. 7a). Thickness of up to 100 m of salt (Fig. 1) are documented from nearly all drill holes that reached the stratigraphic levels in question (Fig. 7a). However, the halite deposits ("salt layers") of the Anhydritgruppe formation are rather discontinuous across the basin and they appear to fill Early Triassic, ENE-trending grabens and depressions. This is supported by rapid local local changes in thickness and stratigraphy of the "salt layers" in the Basel area (Hauber 1980, Widmer 1991).

We propose that some of these halite graben and basin infills have been extruded and successively integrated into the major sole thrust during late Tertiary compression by basin inversion processes (Fig. 8). Although, no direct evidence has yet been found, field observations point to the existence of such inversion processes: 1) Convex salt cushions have been recorded by seismic profiling (P. Ziegler, pers. comm. 1991). 2) some out-of-sequence features in the Jura proper may be traced back to basin inversions (e.g. Mandach thrust, Sprüsel anticlines, c.f. Laubscher 1977, 1986). 3) The presence of severely deformed anhydrite layers underlain by less-viscous halite deposits (e.g. Schafisheim, Jordan & Nüesch 1989). The last observation can be explained if the salt layer was not originally part of the sole thrust at this locality, but was added later due superposition by thrusting.

Furthermore it is suggested that the halite deposits became a continuous layer (at least locally) by the expulsion of halite basin infills, as well as by the coalescence of isolated salt lenses due to focussing of main shear movements by the incompetent layers of the shear zone (c.f. Jordan 1987b).

The upper part of the Anhydritgruppe is characterized by the repetition of pure and impure anhydrite layers which can easily be correlated from outcrop to outcrop (Dronkert et al. 1990, Jordan, in press). This suggests that these layers formed a more or less continuous layer in the investigated area, by at least the end of the Triassic.

Towards the southeast, both halite and anhydrite facies of the Middle Triassic appear to wedge out. In the Entlebuch well, the Upper and Middle Triassic contains only small amounts of anhydrite which is (based on paleontological evidence) assigned to the Late Triassic (Vollmayr & Wendt 1987).The sequence of Entlebuch is undoubtedly severely deformed; unfortunately, no detailed investigations on the state and mechanisms of deformation have been done. Looking at the partly restored cross section in Fig. 3, it is suggested that the Triassic of Entlebuch is not part of the major décollement but rather part of a subordinate duplex zone between two important branches of the sole thrust. One branch, possibly the one that is responsible for the major part of the *ca.* 8 km shortening in the Jura Mountains, ramps down into the basement just north of the Entlebuch well. The other branch crosses the Mesozoic strata in the vicinity of Entlebuch well and joins the older blind ending sole thrust of the Subalpine Molasse (Fig. 3). Evidence for this latter crossing of the Mesozoic strata is given by a possible duplex zone in the Late Triassic/Early Jurassic sediments (lithological "melange" and repetition fossil records) of the Entlebuch well (Vollmayr & Wendt 1987).

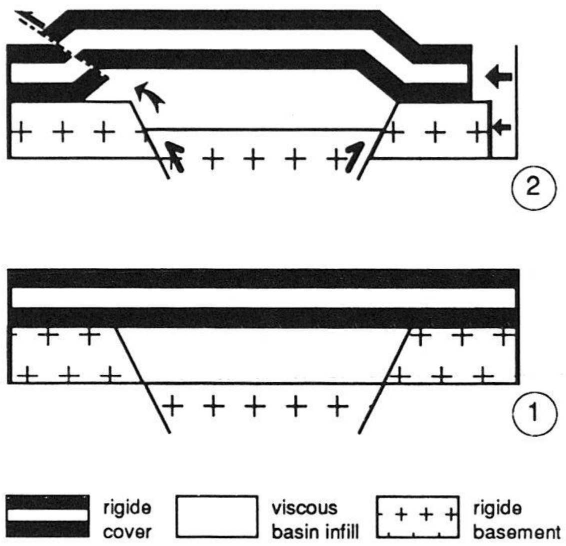


Fig. 8. Schematic sequence of the inversion of a halite basin in relation to the décollement of the rigid cover which results in an anticline and forward facing overthrust.

There are only poor data on the stratigraphic development of the Anhydritgruppe formation towards the Southwest. However, local observations in the Courtion bore hole (Fischer & Luterbacher 1963) and regional deformation patterns (see below) suggest that halite and anhydrite deposits may be replaced towards the Southwest by less viscous rocks, such as carbonates and shales.

The depocenter of the Gipskeuper formation was located further to the Southwest (W of Yverdon) compared to that of the Anhydritgruppe formation (Rigassi 1977) (Fig. 7a, b). Halite deposits (mainly in the middle part of Gipskeuper formation) are restricted to the depocenter area proper (up to 300 m in the Laveron hole, Bitterli 1972). They wedge out to the Northeast in the Fribourg-Lake Biel area which coincides with the (presumed) wedge out of the Anhydritgruppe evaporites (in the opposite direction). This geometry results in a change of the major sole thrust from the Anhydritgruppe in the Northeast to the Gipskeuper in the Southwest, which could be correlated with the N-S-trending folds in the Molasse basin (Fig. 2). In addition, the Anhydritgruppe and Gipskeuper evaporite facies wedge out toward the East (Fig. 7) wich probably determined the position of the Eastern end of the Jura fold-and-thrust belt (Fig. 2).

Tertiary normal faulting and the concept of a continuous sole thrust

As we have seen, the Triassic evaporite layers (except the halite deposits) probably formed a nearly ideal low-viscous link between the Middle Miocene (Late-Helvetic phase) orogenic front in the Subalpine Molasse and the Late Miocene (to Pliocene) Jura phase Alpine front in the Jura mountains (Fig. 3). However, during the Tertiary, this initially continuous horizon was affected by Oligocene NNE-trending extensional and ENE-trending transtensional structures (Rhine-Rhône-Graben rifting system), as well as by Early Miocene NE-trending normal faults (induced by the orogenic loading of the European foreland) (e.g Bachmann et al. 1982, Naef et al. 1985). The vertical throw on most of these normal or transtensive faults do not exceed a few meters; however, some

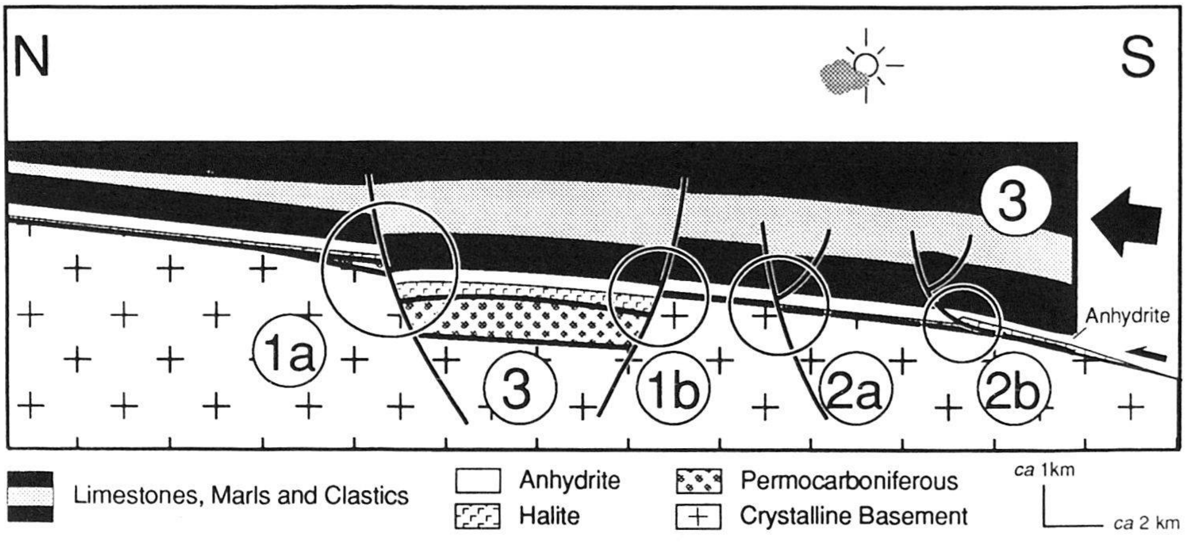


Fig. 9. Synoptic diagram of the various kinematic obstructions (observed or postulated) affecting the evaporite sole thrust: 1a and 1b) positive and negative throw on Late-Permian to Triassic normal faults reactivated during Tertiary extension; 2a and 2b) basement and décollement rooted normal faults originating from Oligocene to Early Miocene orogenic loading; 3) inversion of sedimentary basins due to Late Miocene to Pliocene compression in the Alpine foreland.

of the thrust faults are known have throws of 200 m or more (e.g. Sprecher & Müller 1985, Vollmayr & Wendt 1987, Nagra 1988, Diebold et al., in press).

Traditionally, those faults which have cross-cut both the evaporites and the crystalline basement have been regarded as important obstacles to the development of a continuous evaporite sole thrust (Fig. 9). These faults are thought to have "nailed" the sedimentary pile on its crystalline substratum and have been used to argue for the autochthonous position of the Molasse Basin and, consequently, against the "Fernschub" concept (e.g. Ziegler 1982, 1990). The most serious arguments against a large-scale decoupling in the Triassic evaporites is the supposed existence of normal faults that today appear to cross-cut both sedimentary cover and crystalline basement of the Jura hinterland in one straight plane (e.g. Vollmayr & Wendt 1987, Ziegler 1990). In the light of the already discussed evidence for an important décollement in the evaporites, we suggest that the latter configuration may also be interpreted by 1) superposition of initially independent structures due to thrusting, 2) synkinematic normal faulting in the sedimentary cover above a monocline which occurs over a basement normal fault, or 3) normal faulting in the sedimentary cover due to postkinematic reactivation of a basement normal fault.[2])

If we accept the initial dismemberment of the sedimentary pile by Tertiary normal faulting, we have to search for the processes that would allow the cover to override these obstacles. Two possible models for the formation of a continuous sole thrust of the Jura décollement are presented in Figure 9. In the first model (Fig. 10a), we assume that the evaporite horizons have not been interrupted by normal faulting, but rather have been

[2]) Due to the confidential nature of the seismic data on which the statements of Ziegler (1980, 1990) are based, neither the validity of the statement nor the relative merits of the alternate hypothesis can be tested.

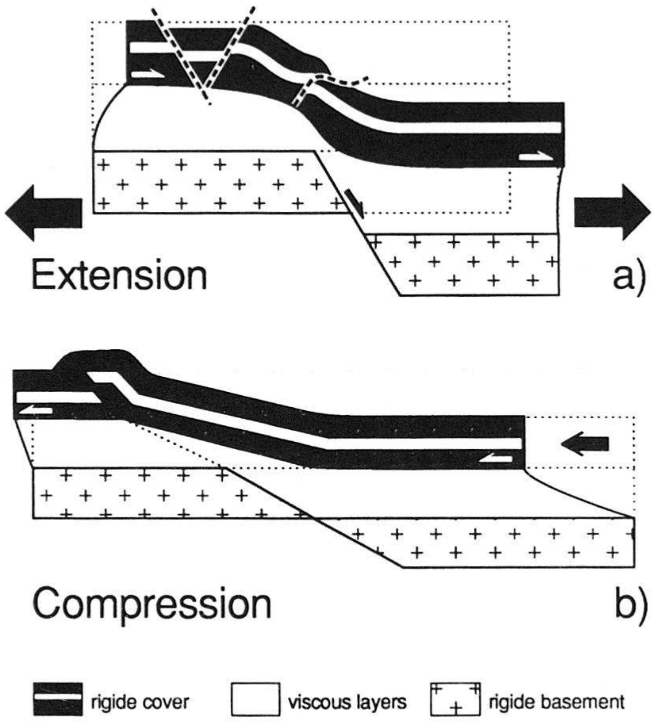


Fig. 10. a) Conservation of the continuity of a viscous evaporite layer during normal faulting (modified from Vendeville 1988); and b) re-establishment of a continuous evaporite layer during compression by a wedge-shaped accumulation of viscous material in front of the normal fault.

squeezed and stretched to form gentle monoclines (c.f. Laubscher 1982, 1986, Vendeville 1988, Bergerat et al. 1990). In model 2 (Fig. 10 b), the evaporite layer is interrupted or thinned by normal faulting, but is subsequently reconstituted to form a continuous layer during thrusting. Model 2 is inspired by field observations in the Jura proper, where we can observe that the highly viscous evaporites are accumulated in front of pre-existing ramps and squeezed out in the domain of the upper flat (Jordan & Noack 1992).

Conclusions

All cored and analyzed sections of the evaporite layers from the hinterland of the Eastern Jura reveal striking structural and micro-fabric evidence for the development of an important sole thrust within these layers. Due to significant differences in composition within the evaporites, the main shear movements are concentrated within distinct (often relatively thin) horizons of pure halite and anhydrite. The dominant deformation mechanism in these layers is fluid enhanced viscous flow (cross-slip controlled creep in halite, and crystal plasticity and grain boundary sliding in anhydrite). Cataclastic processes in impure anhydrite, shales, and dolomites are also observed but are of minor importance. Within the major shear zones, a distinct secondary, narrow-spaced foliation (plus shear folds) has developed. The total strain within these shear zones is sufficient to account for the respective shortening of the sedimentary cover of the Jura proper.

On a regional scale, the geometry of the Jura–Molasse basin sole thrust is controlled by facies changes as well as Triassic and Tertiary extensional structures. Facies changes mainly control the Eastern end of the décollement sheet and the change of the major sole thrust from the Middle Triassic Anhydritgruppe formation in the Northeast to the Late Triassic Gipskeuper in the Southwest. In the domain where the mechanically weak evaporites wedge out toward the Southeast (i.e. towards the Alps proper), the major sole thrust is probably not localized in the Triassic level but rather in the shales at the base of the Molasse, or at a much deeper level in the crystalline basement.

The Anhydritgruppe halite deposits ("salt layers") are believed to have been partly located in structural depressions that were expelled by thrusting related to inversion processes. It is suggested that the initially isolated halite deposits have coalesced due to focussing processes of the shear movements and now form (at least regionally) a more or less continuous sole thrust in the hinterland of the Eastern Jura.

Oligocene to Early Miocene normal faulting has undoubtedly affected the Triassic evaporites. However, it is proposed that these potential obstacles for the formation of a large-scale sole thrust have been eliminated by thickening and thinning processes during extension as well as during subsequent compression, and that a continuous evaporite sole thrust has developed.

In conclusion, a great number of field data support the "Fernschub" hypothesis. Nevertheless, future work which includes the extension of structural and microfabric analysis to a greater number of bore holes, kinematic analysis, and detailed studies on halite deformation mechanisms, as well as analysis of reflection seismic data, has to be done in order to achieve a better understanding of the mechanisms leading to the large-scale décollement of the Alpine foreland sedimentary wedge.

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