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An intriguing example of a folded thrust in the Jura

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ABSTRACT

Folded thrusts are commonplace in the Jura, although the details of the deformation of the original thrust plane generally elude observation. In a first approximation folded thrusts may be constructed by assuming simple (bed-slip) shear in the fold limbs considered as a system of kink bands in the locking position. That this cannot be strictly correct is obvious as layering has been interrupted by the thrust. In the north limb of the Raimeux anticline 40 km SW of Basel a series of fault contacts have been mapped which may be explained best as an initial thrust deformed first by interpenetration of the hanging wall and the footwall where the faulted ends of competent and incompetent beds had been brought into thrust contact; second by approximately simple shear in the footwall which was rotated into a vertical position; and third by adjustive shear of the hanging wall on the thrust plane during rotation of the footwall.

ZUSAMMENFASSUNG

Gefaltete Überschiebungen sind häufig im Jura, doch können die Details dieser Verfaltung nur selten beobachtet werden. In erster Näherung kann man verfaltete Überschiebungen auf Profilen konstruieren, indem man einfache Scherung in den Faltenschenkeln postuliert und diese als eine Serie von Knickbändern «in locking position» darstellt. Es ist jedoch klar, dass diese Konstruktion nicht ganz richtig sein kann, weil ja durch die Überschiebung die ursprüngliche Schichtung, die wesentlich ist für die schichtparallele Scherung in den Schenkeln, gestört ist. Im Nordschenkel der Raimeux-Antiklinale südlich Undervelier ist nun eine Reihe von Störungen aufgeschlossen, die am einfachsten als eine durch verschiedene Komplikationen geprägte Verfaltung einer Überschiebung gedeutet werden können. Durch eine kleine Überschiebung wurden die abgescherten Enden von kompetenten und inkompetenten (vor allem Natica-) Schichten in Kontakt gebracht; unter andauernder Kompression und beginnender Schenkelrotation wurden die kompetenten Obermalm-Keile des Liegenden in die inkompetenten Natica-Schichten des Hangenden eingespiesst; bei der weiteren Rotation des Liegenden in den vertikalen Schenkel wurde dieser, mitsamt der begrenzenden Überschiebungsfläche, einer bedeutenden einfachen schichtparallelen Scherung unterworfen. Diese konnte sich nicht in das eine andere Anfangsstruktur aufweisende Hangende fortsetzen, so dass es gegen die Synklinale zu ausweichen musste.

Thrusting commonly preceded folding in the Jura (BUXTORF 1916, LAUBSCHER 1977). Folded thrusts have been reported from the Grenchenberg tunnel, from the river gorges of Balsthal-Mümliswil, and from numerous other localities where they are less well exposed. In many instances steep faults can safely be reinterpreted as folded thrusts. Many enigmatic elements of faults have turned out, on closer inspection, to be segments of folded thrusts. Though these folded thrusts are obvious, exposures do not generally permit detailed insight. It is not easy to predict what

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happens to a thrust when it is folded, but this problem is important for profile construction in the Jura. As a first approximation and a standard, against which the natural examples may be tested, I propose to consider Jura fold limbs to consist of a series of kink bands in a locking position (LAUBSCHER 1976, 1977). In that case, the internal deformation of the fold limb consists of simple shear $\gamma = 2 \tan \delta/2$ where δ is the dip of the rotated beds. If a fault of original dip α with respect to bedding is rotated into a locking position, α changes to α' and α'', resp. (Fig. 1, the formulas apply to single kink bands; for multiple kink bands see caption Fig. 2).

If the thrust strikes obliquely to the kink band, the difference in strike between the two structures being θ, it is the angle $\alpha''' = \text{arc tan} (\tan \alpha \cos \theta)$ in a section perpendicular to the kink band that is to be used, as shearing deformation is in the direction of that section.

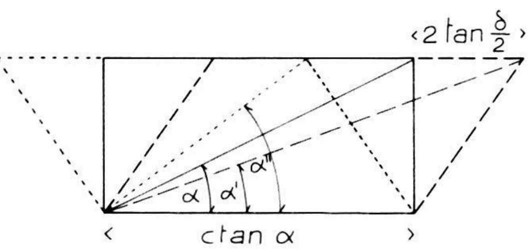

Fig. 1. Deformation of a thrust plane by a single kink band in locking position (simple shear). α = original dip of thrust, α' (α'') = angle with respect to bedding after positive (negative) shear, $2 \tan \delta/2$ ($-2 \tan \delta/2$), where δ = dip of the kinked beds (originally horizontal).

A simple construction using the formulas of Figure 1 results in kinked thrusts of the type of Figure 2. Though such a rigorous if simplistic construction offers the satisfaction of knowing exactly what one is doing, there are, of course, several objections. The most severe is that simple shear is possible only in a homogeneously thin-bedded (orthotropic) medium, and that at the thrust contact the even originally imperfect layering is interrupted. The objection is particularly relevant where prominent competent beds are in thrust contact with pronouncedly incompetent ones. In such cases important deviations from simple shear deformation must be expected. It is this case that probably lies at the bottom of a series of otherwise incoherent if not enigmatic disturbances in the north limb of the Raimeux anticline near Undervelier, 40 km southwest of Basel (compare BIRKHÄUSER 1925).

The case which has kept puzzling me for a long time presents itself as follows.

In the Sorne river gorge south of Undervelier a series of peculiar fault contacts can be mapped (Fig. 3, 4). As exposures are imperfect they may be combined and interpreted in different ways. The more conservative and, at first sight, possibly more acceptable version is given in Figure 3 where the faults visible on the east side of the gorge are considered to belong to a series of northeast striking cross faults that have been identified farther west. In essence they would then constitute a narrow graben which because of the rotation of the beds into a near-vertical position now appears as a somewhat deformed cross-section on the map; the southeast striking segment in the southern part of the gorge, which is not directly exposed, may be considered the original dip of the fault, whereas the northeast

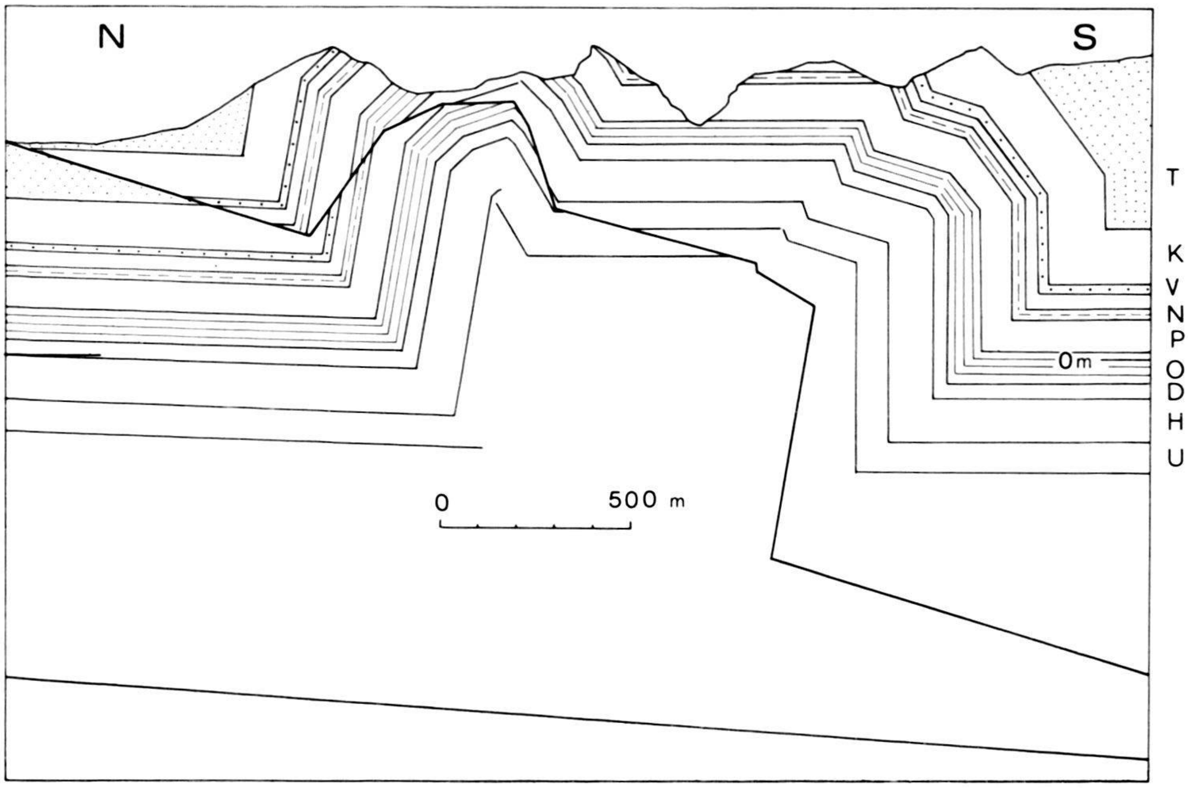

Fig. 2. Model of a kinked thrust, Raimeux anticline in the area of Figure 3, simplified; compare Figure 5.

The thrust in the Tertiary syncline of Undervelier, shown in Figure 3, is assumed to be larger and deeper than the structure dealt with in Figures 3–6 which has been neglected on this section. The angle of the kinked fault has been computed according to Figure 1 although it applies strictly only for single kinks. For limbs built up of multiple kink bands the pertinent relations are (dip of bed in kink band $j=\delta_j$, $\Sigma\delta_{i+1}-\delta_i=\Sigma\Delta\delta_i$, $\Delta\delta_i$ being the angle between beds of adjoining kink bands):

$$\gamma_j = \text{shear in kink band } j = \Sigma\, 2\tan\Delta\delta_i/2 < 2\tan\delta_j/2.$$

A further question, not discussed, is the special mode by which transfer of shear from one kink band through the hinge into an adjoining band may be accomplished; circular hinges seem indispensable. γ_j would actually have to be introduced instead of $2\tan\delta/2$ in Figure 1 and the formulas for α' and α'' derived from it. For simplicity this has not been done in the construction of Figure 2. If the number of kink bands is large, and angular differences between beds of adjoining bands are small, a circular hinge is approximated with $\gamma_c = \mathrm{rad}\,\delta < 2\Sigma\tan\Delta\delta_i/2 < 2\tan\delta/2$.

There are other problems in the construction of such sections to be dealt with in a future article; particularly, the conservation of constant length for all beds in the anticline, and the crowding of material in the core of anticlines where sections are thickened by initial thrusting.

T = Tertiary, K = Kimmeridgian limestones, V = Verena Oolite, N = Natica beds, P = Oxfordian Pichoux and coral limestones, O = Oxfordian clays and marls, D = Upper Dogger, H = Hauptrogenstein, Middle Dogger, U = Lower Dogger.

striking segments had been reactivated and deformed during folding. As the two border faults converge on top of the Oxfordian coral limestones (St. Ursanne Formation) it does not displace the base of these limestones by a significant amount.

This simple solution, however, is not quite satisfactory for several reasons. In the first place, it leaves unexplained a number of associated tectonic elements. The eastern fault which would be the continuous, main feature in this interpretation is comparatively small; on the other hand there is a northwest trending thrust element east of the gorge which is a more pronounced feature that, on morphological grounds, continues into the Sorne valley where it connects with the western cross-fault; in the simple solution, this is an isolated feature without any rational connection with the other structures. There are, furthermore, other apparently disconnected thrust elements to the southeast.

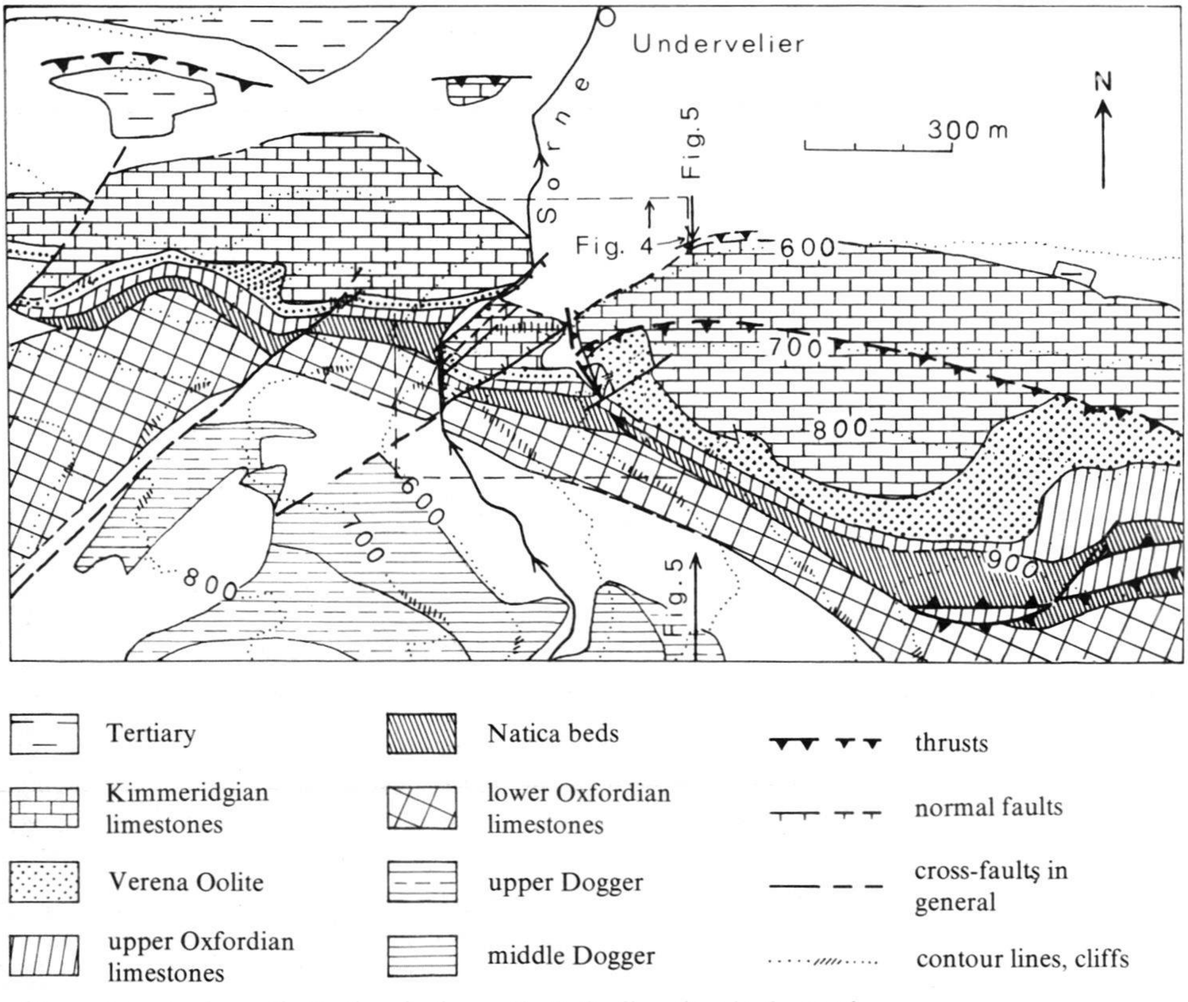

Fig. 3. Fault contacts in the north limb of the Raimeux anticline south of Undervelier, 40 km SW of Basel, simplified map. Interpretation of fault contacts on the east side of the Sorne river gorge as a graben (compare Fig. 4).

In order to take these thrust elements out of their isolation and connect them with the "graben" in the river gorge, a second, more imaginative solution is proposed, as sketched in Figures 4–6. It has an interesting bearing on the question raised initially: what really happens when a thrust is folded?

We first note that the anomalous (fault) contacts on the east side of the gorge and farther southeast have something in common: they all are associated with a divergence of strata above ("Upper Malm") and below the argillaceous Natica beds which in this area are an important incompetent interval. It looks as if the beds had been forced apart by the intrusion of a wedge of foreign material. This suggests that the "graben" in the gorge may actually be combined with the disharmonic thrust of the Upper Malm to form the window of a deformed thrust. Possibly the elements of thrusting mappable farther north in the Tertiary syncline of Undervelier (Fig. 3) are further pieces of the same thrust though for regional reasons I suspect they belong to the lower of at least two separate thrusts. The windows in the Natica beds of Mont Dedos (southeast corner of Fig. 3) are the eastern continuation of the window in the Sorne river gorge, which requires an average 14 degree westward axial plunge of the crest of the deformed thrust. This is in keeping with the Sorne river gorge window itself which has an average axial westerly plunge of 25 degrees, with a steep to overturned western border that probably is due to the revival of small cross-faults during deformation of the thrust. Indeed, reactivated cross-faults seem to play a significant role in the 3-dimensional kinematics of the folded thrust, and for the present geometry of the windows.

On a cross-section, this solution essentially looks as shown in Figure 5. The hanging wall of the thrust is split along the Natica beds, and into this split the

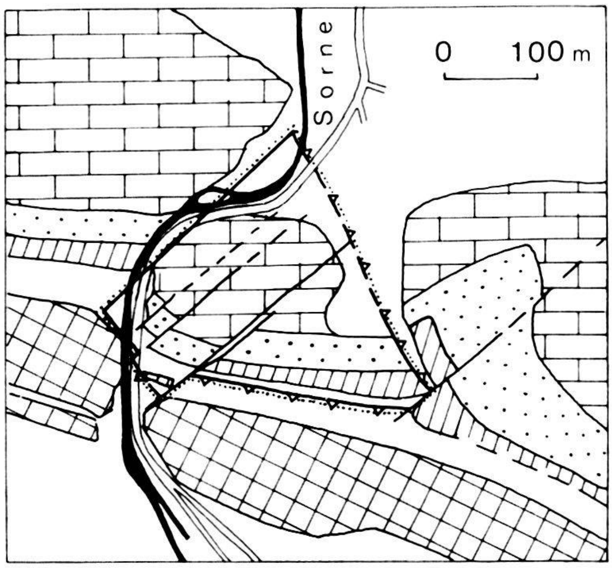

Fig. 4. Interpretation of the same fault contacts (compare Fig. 3) as a window of a deformed thrust delineated by fine dots. For other symbols, see Figure 3.

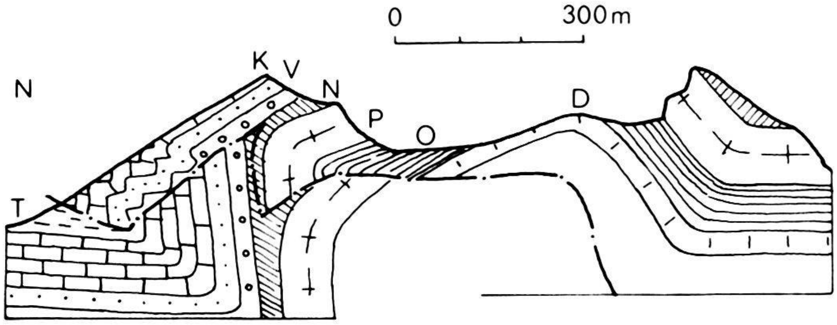

Fig. 5. Cross-section through the northern part of the Raimeux anticline, showing the deformed thrust – a free-hand sketch (index-letters see Figure 2).

Upper Malm of the footwall has been squeezed. It may be conjectured that conversely the Oxfordian reef limestones of the hanging wall have been squeezed into a split in the Natica beds of the footwall, but this is not exposed, and the situation is slightly different.

Thus it may be demonstrated that in this interpretation the various elements are geometrically compatible with one deformed thrust with an axial plunge, accentuated by cross-faults, to the west. However, this structure is so novel in the Jura that it calls for a plausible genetical interpretation, as proposed in Figure 6.

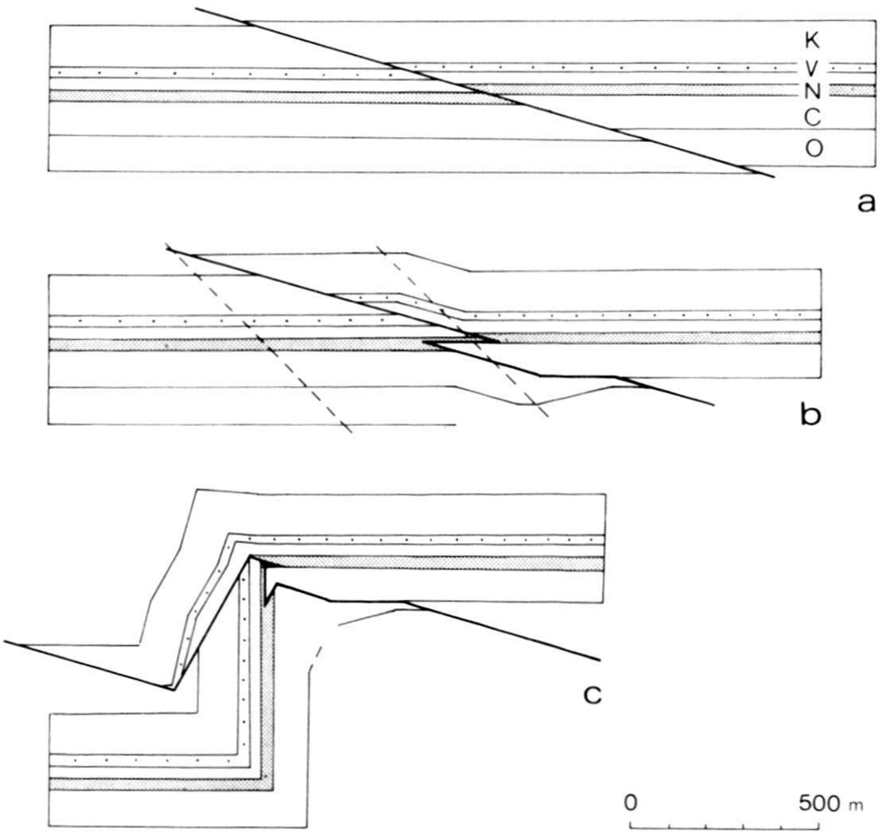

Fig. 6. Model construction for the superposition of thrusting, penetration, and kinking in the north limb of the Raimeux anticline.

a) Small thrust (15° dip). The base of the competent Upper Malm of the footwall is in contact with the incompetent Natica beds in the hanging wall. *K* = Kimmeridgian limestones, *V* = Verena Oolite, *N* = Natica beds, *C* = Coral limestones (St. Ursanne Formation), *O* = Oxfordian clays.

b) Initiation of kinking (hinge lines dashed) under continued horizontal compression facilitates penetration of the competent fault wedges into the incompetent Natica beds because of interlayer dilation. Volume of displaced Natica beds neglected. Adjustive slight kinking above and below the interpenetration.

c) Kink band in locking position. The thrust is deformed by simple shear in the footwall. The hanging wall glides parallel to the thrust during deformation; however, as further thrusting is impeded at the hinge of the deformed thrust, wrinkles as actually observed in the field would be expected to develop (compare Fig. 7). Further minor adjustments (not specified) are necessary in the hinge of the footwall as the simple kink band would accommodate only strictly parallel beds. Deviations from simple shear due to inhomogeneous layering causes uneven deformation of the thrust and consequently adjustments in the masses sheared along the thrust.

Figure 6 shows an initial thrust in the Upper Jurassic (Malm) with a typical dip of 15° (LAUBSCHER 1977). The displacement (a mere 80 m) is such that the tip of the competent Upper Malm of the footwall is in contact with the Natica beds of the hanging wall, and the tip of the competent Oxfordian coral limestones of the hanging wall is in contact with the Natica beds of the footwall. Now superpose an initial rotation (kink). At this stage the beds, and particularly along incompetent layers such as the Natica beds, tend to separate ("interlayer dilation", LAUBSCHER 1976), under continued horizontal compression. These circumstances, coupled with stress concentrations on the tips of faulted competent beds ("wedge effect") facilitate interpenetration of the Upper Jurassic as the easiest way to yield to compression (Fig. 6b). The Middle Jurassic below the incompetent Oxfordian clays and marls is not considered for a further extrapolation as they are known regionally to act as secondary decollement for disharmonic folding.

If rotation is completed into a locking position at 90°, interlayer shear according to Figure 1 demands an increase of thrust dip (with respect to bedding) from 15° to 30°. This, on the other hand, requires an equal rotation of the hanging wall of the thrust by another 15°, adjustments taking place along the thrust plane and in the Natica beds which continue to split apart (Fig. 6c). The geometry now is strikingly similar to that of Figure 5. A similar process in the Oxfordian coral limestones down-section (farther to the south) is not exposed and purely conjectural.

As to the axial dip, it may be the consequence of a divergence in the strike of the original thrust and the superposed kink band - a phenomenon that is frequent in the Jura (LAUBSCHER 1977). Furthermore, original irregularities in the thrust contact along strike would facilitate interpenetration at some places more than at others, and lateral adjustments are necessary, e.g. through revival of cross-faults.

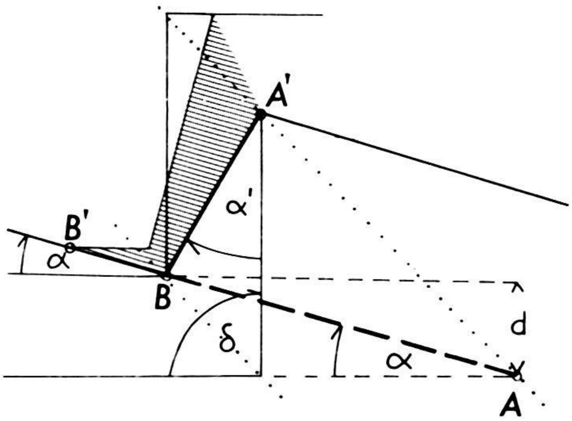

Fig. 7. The amount of the shear between hanging wall and footwall of the thrust in the kink band; layering in the hanging wall assumed parallel to the thrust. Dashed situation before kinking.

d = stratigraphic thickness of kinked interval affected by the thrust. $d/\sin\alpha$ is the original length of the thrust segment before kinking; $d/\sin\alpha'$ after kinking. Upon kinking, A moves to A', whereas B in the hanging wall moves to B' because simple shear in the footwall is assumed not to cross the thrust: there is a concentrated shearing displacement of the hanging wall (ruled) with respect to the footwall amounting to $d/\sin\alpha - d/\sin\alpha'$. This would normally lead to disharmonic wrinkling rather than simply enhanced thrusting in the hanging wall, as the deformed thrust does not lend itself readily to continued thrusting. If layering in the hanging wall is not parallel to the thrust, the amount of secondary displacement is smaller.

In re-assessing the map Figures 3 and 4 in the light of the model Figure 6 several observations acquire new relevance. The southern frame of the window is essentially parallel to bedding and is not readily recognizable. The main amount of thrusting is due to adjustive shear during rotation of the fold limb along the originally small thrust as illustrated in Figure 6c. That is why it appears so suddently and apparently without relation to the other elements above the "graben" of Figure 3, without readily betraying its significance as eastern frame element of the window. Finally, the situation is exacerbated by the fact that the western frame element along the river is steep and, according to local measurements, even overturned to the east, apparently along a series of originally small cross-faults that served for adjustive movements in the third dimension. It limits to the west the thrust elements that may be followed eastward for some distance. It abruptly exposes the eastern part of the deformed thrust which, hidden in the subsurface, probably also continues to the west for some distance.

Conclusions

Details during folding of a thrust in the Jura apparently depend on the nature of the original fault contacts. Where competent and incompetent beds have been brought together, simple shear during rotation is impeded at the thrust and initial interpenetration of the beds is facilitated instead. Further rotation of the beds then may proceed with simple shear (at least in a rough approximation) in the footwall, and differential rotation, with adjustments on the fault plane, in the hanging wall. Such mechanisms are expected to work in limited segments of an anticline that are often bounded by cross-faults.

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