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Displacements along thrust faults

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ABSTRACT

A new diagram is presented which displays displacement variations on faults and helps in the construction and interpretation of cross sections. Displacement in this diagram are finite slips. Gradual displacement variations are due to penetrative distortions in the rocks adjacent to the fault and reflect differences of finite stretches parallel to the fault and to the slip direction. Merging or branching splay faults give rise to abrupt variations and even simple linked-fault systems have complex displacement patterns. As illustrated with examples from the Alps, the diagram allows predictions concerning fault terminations or fault tips to be made. For the Glarus thrust it follows that this fault must have broken surface rapidly and that it reaches rearward deep into the crust forming a stack of basement wedges.

ZUSAMMENFASSUNG

In dieser Arbeit wird ein neues Diagramm vorgestellt, welches es erlaubt, Verschiebungsbeträge an Brüchen darzustellen. Das Diagramm ist ein nützliches Hilfsmittel zur Konstruktion und Interpretation von geologischen Schnitten. Verschiebungsbeträge in diesem Diagramm sind finit, und Änderungen dieser Beträge können kontinuierlich oder sprunghaft sein. Kontinuierliche Änderungen ergeben sich aus der inneren Deformation der Gesteine im Liegenden und Hangenden des Bruches und widerspiegeln unterschiedliche Streckungsbeträge parallel zum Bruch und zur Bewegungsrichtung. Sprunghafte Verschiebungsänderungen ergeben sich bei der Aufgabelung oder Vereinigung von Brüchen, und selbst für einfache gekoppelte Bruchsysteme sind Verschiebungsbetragsänderungen komplex. Anhand eines solchen Diagrammes können sehr einfach ursprünglich einander benachbarte Gesteinspakete bestimmt werden, was bei Abwicklungsfragen von Bedeutung ist. Die praktische Anwendung dieses Diagramms auf einige Beispiele aus den Zentralalpen zeigt, dass z. B. Prognosen für die Existenz von Überschiebungen in der Tiefe oder für die Begrenzung von Überschiebungen gemacht werden können. Für die Glarner Hauptüberschiebung ergibt sich, dass diese in Richtung des Vorlandes rasch die Erdoberfläche erreicht haben musste und die Front der Helvetischen Decken sich über den Boden des sich deformierenden Molassebekkens bewegte. Im internen Teil spaltet sich die Hauptüberschiebung in die Frisal-, Disentiser und Garvera-«Mulden» auf. Diese «Mulden» müssen tiefe Trennungen darstellen, die durchaus bis an die MOHO reichen können.

RÉSUMÉ

Dans cet article, un nouveau diagramme est présenté qui permet d'étudier les rejets de failles, ainsi que les variations de ces rejets. Ce diagramme est utile dans la construction et dans l'interprétation de coupes géologiques. Les rejets de failles, apparents dans ce diagramme, sont des rejets finis et leur variations peuvent être graduelles ou abruptes. Les variations graduelles sont provoquées par des déformations pénétratives des roches adjacentes à la faille et ces variations reflètent les différences d'étirements parallèles à la faille et à la direction du mouvement. Des failles en biseau, s'écartant de ou rejoignant la faille principale, donnent naissance à des variations de rejets abruptes. Même un simple système de failles couplées montre des variations de rejets déjà complexes. Grâce à ce diagramme il est possible de déterminer facilement les paquets de roches au mur et au toit de la faille qui étaient

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primitivement juxtaposés. Une opération d'importance pour les réconstitutions palinspastiques. L'application de ce type de diagramme sur quelques coupes des Alpes centrales montre qui'il est possible de faire des pronostics sur l'existence de chevauchements en profondeur ou sur leurs terminaisons. Pour le maître-chevauchement de Glaris, il faut admettre que celui-ci aurait rejoint la surface de la terre rapidement, entraînant le front des nappes helvétiques sur le fond du bassin molassique. Dans sa partie interne, ce maître-chevauchement se divise en chevauchements en biseau (Frisal, Disentis et Garvera) qui pourraient bien s'étendre jusqu'à la MOHO.

Introduction

Cross sections are one of the important tools to display and interpret geological structures such as faults and folds. The construction of cross sections usually involves various projection techniques, the interpretation of map patterns and the use of borehole, stratigraphic and geophysical data. If coupled with the correct local structural style, the resulting cross section is called "admissible" (ELLIOTT 1983). An admissible cross section can be further refined by the use of balancing techniques, rendering it "restorable" or "viable". DAHLSTROM (1969) discusses the concept of bed-length consistency to render cross sections geometrically valid. This balancing technique, implicitly probably used by many geologists, requires volume and bed-length conservation and plane strain, and its application is thus restricted. HOSSACK (1979) describes the more general situation where these assumptions are not made.

This paper uses a slightly different approach in that emphasis is put on the consistency of fault displacements. If displacement on a fault in a cross section varies, there must be an explanation for this variation. To analyze displacement variation, an new diagram relating marker points in the fault's footwall to their originally contiguous points in the hangingwall is presented. Then follows a discussion of the most important theoretical situations leading to displacement variations. The use of the diagram is demonstrated for some natural examples.

The aim of this paper is to present a method for the analysis of displacement along faults, to show the importance of displacement variations with regard to the construction of (balanced) cross sections and to demonstrate the consequences of thin-skinned tectonics at depth.

Displacement

Net slip of a fault is the displacement vector connecting originally contiguous points in the hangingwall and footwall. On a fault plane, the offset of planar features measured down dip of the fault is the dip separation. Thus when analyzing a fault on the basis of a cross section, the observed offset is in general an apparent dip separation. Only if cross sections are drawn exactly parallel to the slip direction is the observed apparent dip separation identical to the net slip.

The determination of the slip direction of faults is in general problematic due to the lack of reliable markers. In the examples presented, indicators for transport directions include reoriented fold axes and stretching lineations, as well as the alignment of equivalent structures in the hangingwall and footwall (see PFIFFNER 1981, FUNK et al. 1983, Fig. 3). Because net slip is only obtained in cross sections drawn exactly parallel to the transport direction, a situation probably rarely realized, the less strictly defined term "displacement" for the offsets is used here.

It has been known for some time that faults die out and that the associated deformation may be accommodated by various types of foldes (GALLUP 1951, FOX 1959, DAHLSTROM 1969, CHAPMAN & WILLIAMS 1984) or splay faults (CHINNERY 1966, PFIFFNER 1981), or some other, more homogeneous type of deformation (ELLIOTT 1976, PFIFFNER 1981, SIMPSON 1981, COWARD & POTTS 1983). Recently displacements along faults have been discussed using distance-displacement diagrams (MURAOKA & KAMATA 1983, WILLIAMS & CHAPMAN 1983, CHAPMAN & WILLIAMS 1984). Although using the same axes, displacement is with reference to an unslipped state in MURAOKA & KAMATA (1983), and WILLIAMS & CHAPMAN (1983) define distance strictly with reference to the hangingwall.

This paper presents a different type of diagram, where reference is made to both hangingwall and footwall. As will be shown, the advantages are that, a) original readings appear directly, without any processing on the diagram, b) slopes of curves in the diagram reflect strain differences in the rocks adjacent to the fault, and c) once the diagram is constructed, the position of originally contiguous segments of hangingwall and footwall rocks can be read off easily. The construction of the diagram (Fig. 1) involves the following steps:

1. Draw a cross section as parallel as possible to net slip.
2. Choose an arbitrary origin on the fault trace.
3. Measure the distance of the cutoff points of marker beds from this origin along the fault's trace in the hangingwall.
4. Measure the distances of the equivalent points in the footwall.
5. For each marker, plot the two distances using the footwall (FW) as abscissa and the hangingwall (HW) as ordinate.
6. Points with zero net slip corresponding to tip lines have identical distances on hangingwall and footwall and thus plot on a line inclined at 45° to the axes.

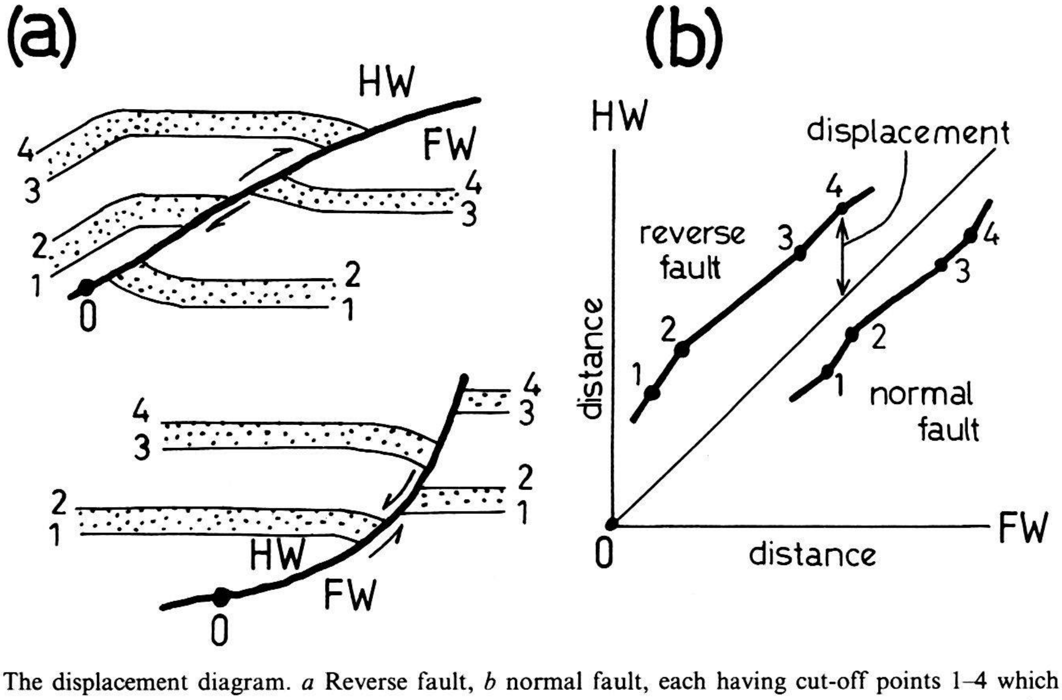


Fig. 1. The displacement diagram. *a* Reverse fault, *b* normal fault, each having cut-off points 1–4 which were originally contiguous. *c* Displacement diagram where the distances of equivalent cut-off points (1–4) from the origin O are plotted. HW: hangingwall, FW: footwall.

On such a diagram, the vertical distance above the line inclined at 45° of any point of the curve represents the relative displacement of the two originally contiguous points. With this choice of axes, reverse or thrust faults plot in the field above the line inclined at 45°, and normal faults in the field below it. For vertical, particularly transcurrent or strike-slip faults the same diagram applies but the axes need to be renamed.

Any fault, if totally preserved and not breaking surface, plots as a curve which on both ends eventually rejoins the line inclined at 45°. These two points correspond to the fault's tip line(s). Under certain circumstances the curve may change over from the reverse to the normal field (see Fig. 2). The general shape of the curves are linked to displacement variations and will be discussed in the next chapter.

Displacement variation

Variation in displacement can be gradual, provoked by penetrative distortions in the rocks adjacent to the fault, or abrupt, caused by splay faults. These two cases are treated separately, although in nature they are likely to occur together. In addition, growth faults may give rise to gradual or abrupt variations because of thickness changes or complete absence of individual layers.

1. Gradual changes

The translation of any point say in the hangingwall of a fault can be caused by slip along the fault and by stretching (or shortening) the hangingwall rocks parallel to the slip direction. The situation is illustrated in Figure 2, where a segment of a fault is considered. In all three cases, an original length l_o parallel to the slip direction, made up of 10 units characterizes the penetrative strains parallel to this slip direction. In addition the amount

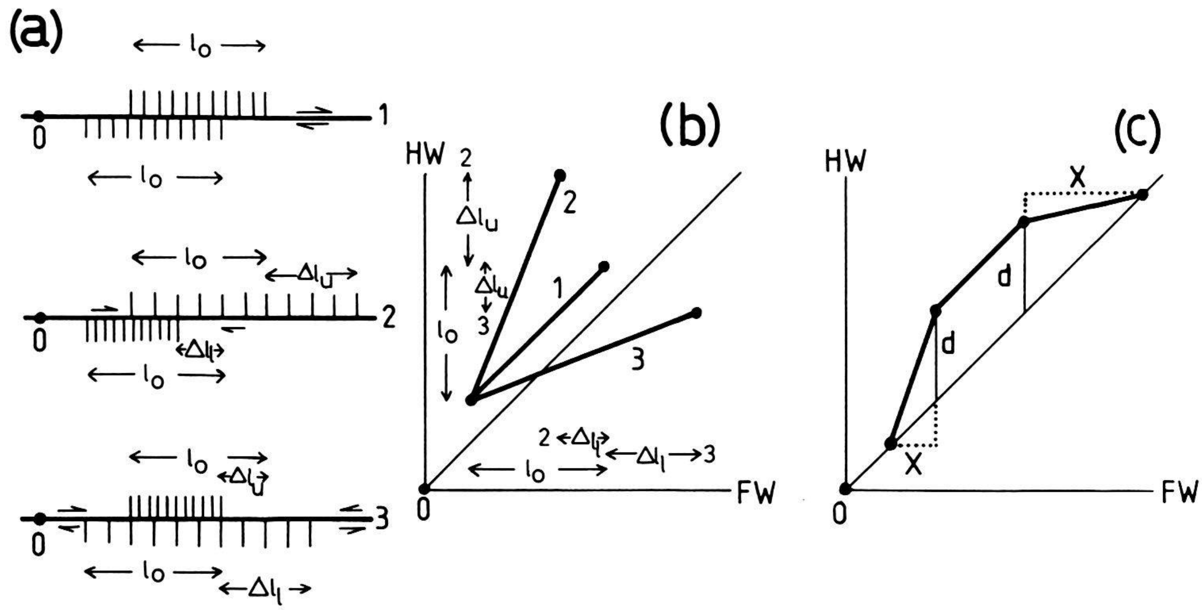


Fig. 2. Displacement variation due to penetrative distortion of the rocks adjacent to the fault. l_o: original length, Δl_u: length change in upper plate, Δl_l: length change in lower plate. *a* Three fault profiles with grid showing various relative distortions. *b* Displacement diagrams for these three faults. *c* Diagram for the derivation of equation 2; x is distance measured in the footwall over which displacement, d, vanishes.

of displacement of the left end of the segment l_o is arbitrarily chosen and equal in all three cases.

Case 1 involves only slip, without any penetrative stretch, as is indicated by the constant length l_o in the upper and lower plate. Hence the amount of slip remains constant over the segment considered and the curve labelled 1 in Figure 2b is a straight line parallel to the line through the center inclined at 45° (vertical distances between these two lines remain constant).

In *case 2* the upper plate suffered a positive extension, Δl_u, and the lower plate a negative extension Δl_l. As a result the displacement increases continuously to the right and the curve in Figure 2b becomes a straight line with a slope greater than 1. It is evident from Figure 2b that the slope $m = (l_o + \Delta l_u)/l_o - \Delta l_l)$. Remembering that the stretch s is defined as $s = (l_o + \Delta l)/l_o$, the slope of this line is found to be $m = s_u/s_l$, where s_u and s_l are, respectively the stretches parallel to the slip direction in the upper an lower plate.

In *case 3* the upper plate suffered a negative extension, the lower plate a positive one. The effect is to decrease the displacement from left to right, in the example to a degree that the displacement becomes zero (within the 4th element from the left) and reverses its sense. As a consequence curve 3 in Figure 2b changes over from the reverse to the normal field, and the slope of the curve is less than 1 and equals again s_u/s_l. The same is true for case 1 where $s_u = s_l$. Thus, in summary one finds that the slope m of displacement curves is given by the quotient of stretches parallel to the slip direction between hangingwall (upper plate) and footwall (lower plate)

$$m = s_u/s_l \ . \qquad (1)$$

From equation 1 it also follows that negative slopes are not possible.

For a particular material point adjacent to the fault, the following sequence of deformations can be envisaged:

1. The region around this point is or is not subjected to some homogeneous or inhomogeneous distortions prior to fault formation.
2. During the propagation of the fault, the ductile bead at the fault's tip sweeps through this point.
3. Various accommodating strains may affect the region around the material point considered, and
4. the region around the point and the fault itself may be subjected to strains post-dating movement on the fault.

It follows that the actual shape of the displacement curves will reflect the finite state of the stretches in the rocks adjacent to the fault and the displacement itself is a finite displacement. Moreover a non-plane state of strain will influence displacement in various ways not discussed here in any detail.

Equation 1 is particularly useful when faults without obvious termination that end "somewhere" are analyzed (e.g. blind and bedding plane thrusts). To calculate how far beyond a certain point a fault extends, given the displacement, d, at that point and the slope, m, of the displacement curve, one easily derives the following equation from Figure 2c:

$$x = \pm d/(m - 1), \qquad (2)$$

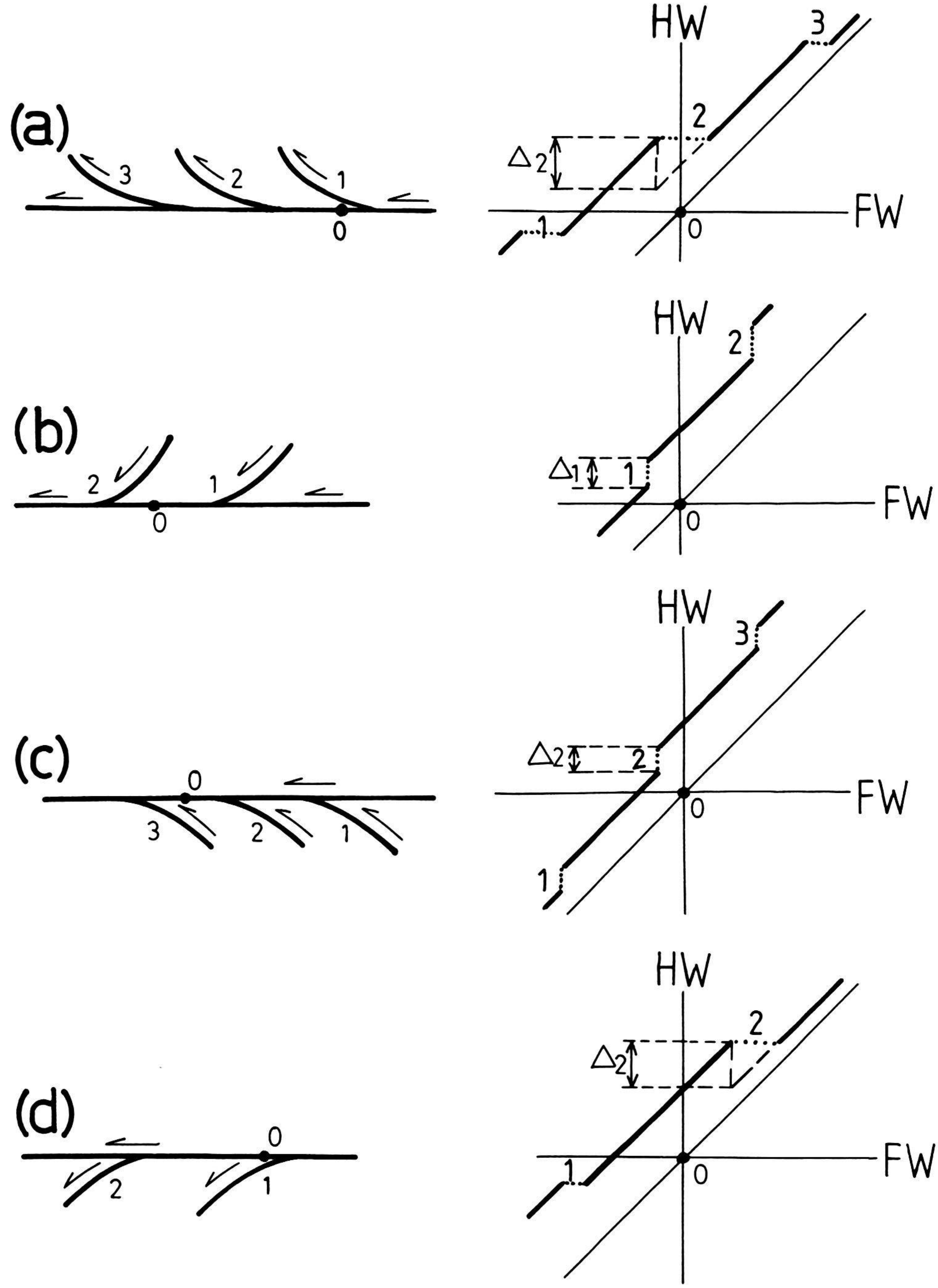


Fig. 3. Various possibilities of linked-fault systems leading to abrupt displacement variations. On the left are possible cross sections, on the right their displacement diagrams. Δ_i: displacement consumed by splay i. *a* Branching splays forming hangingwall imbricates. *b* Merging splays (e.g. extensional linked-fault system). *c* Merging splays forming footwall imbricates. *d* Branching splays in footwall.

where x is the distance along the fault trace in the footwall. The plus sign is for $m > 1$, the minus sign for $m < 1$. Equation 2 is only valid if the stretch differences in hangingwall and footwall are linked to movement on the fault, i.e. they must not be due to inhomogeneous deformation which pre- or postdates the fault.

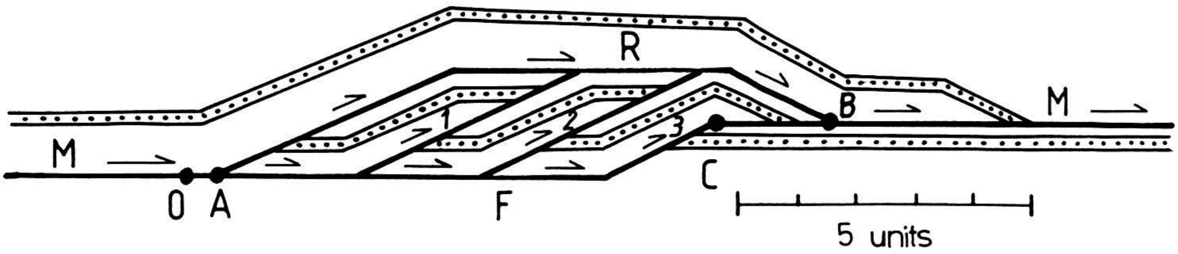
2. *Abrupt changes*

It is common for faults to have branching or merging splays. Various possibilities of such linked-fault systems are shown in Figures 3a through 3d. For the displacement curves in Figure 3, distances are measured positive in the direction indicated by the arrows. Branching splay faults have the tendency to move material away from the master fault, while merging splays move material from the hangingwall or footwall towards the master fault. Therefore if the diagram is constructed for the master thrust, some of originally contiguous material points are no longer situated along the same (master) fault surface. These points are represented by the dotted segments of the displacement curves. As an example consider two points in the hangingwall on the schematic cross section in Figure 3a, situated immediately to the right and left of the branch line of splay 2. The point on the left will then belong to imbricate 3, the one on the right to imbricate 2. Because the points are neighbors in the hangingwall, they plot at the same vertical distance above the horizontal (FW) axis. Their originally contiguous points in the footwall, however, are not neighbors. Rather they are separated by the amount of (arbitrarily chosen) slip Δ_2 that occurred on splay 2 between their equivalents in the hangingwall. The amount of slip Δ_2 is equal to the length of the horizontal dotted segment. The same argument explains the other vertical or horizontal segments in Figure 3.

In Figure 3a the splays are reverse faults that "consume" displacement of the master thrust and hence, going from the branch points of splays 1 to 3 the displacement on the master thrust decreases. Accordingly the envelope of the displacement curve has a slope less than 1. This simply reflects that, viewed on a larger scale the splays represent a shortening of the hangingwall and $s_u < s_l$ in equation 1. In contrast, the splays in Figure 3b are normal faults and hence $s_u > s_l$ and the envelope has a slope greater than 1. Similar arguments, finally, explain the slopes of the envelopes in Figures 3c and d, where splays occur in the footwall.

In the case of thrust systems, displacement variations become more complex. In Figure 4, inspired by Figure 19 of Boyer & Elliott (1982), a master thrust (M) breaks up into a floor (F) and roof (R) thrust at A to form a duplex consisting of three successively formed imbricates 1 to 3. At B floor and roof thrust rejoin and continue as master thrust. For the upper displacement curve, the roof thrust was chosen as reference. The amount of slip along the master thrust is given by the offset of the marker bed. At A slip is lost due to the branching off floor thrust, causing the dotted horizontal segment marked F. This slip is regained stepwise at the points where the splays 1 to 3 rejoin the roof thrust. Beyond point B slip on the master thrust is slightly larger than before point A due to the shortening represented by the folding within the imbricates.

For the lower curve, the floor thrust was chosen as reference. It has a dotted horizontal segment provoked by the branching off roof thrust (R) and two horizontal segments caused by splays 1 and 2. The dotted vertical segment sets in at point C already. This is so



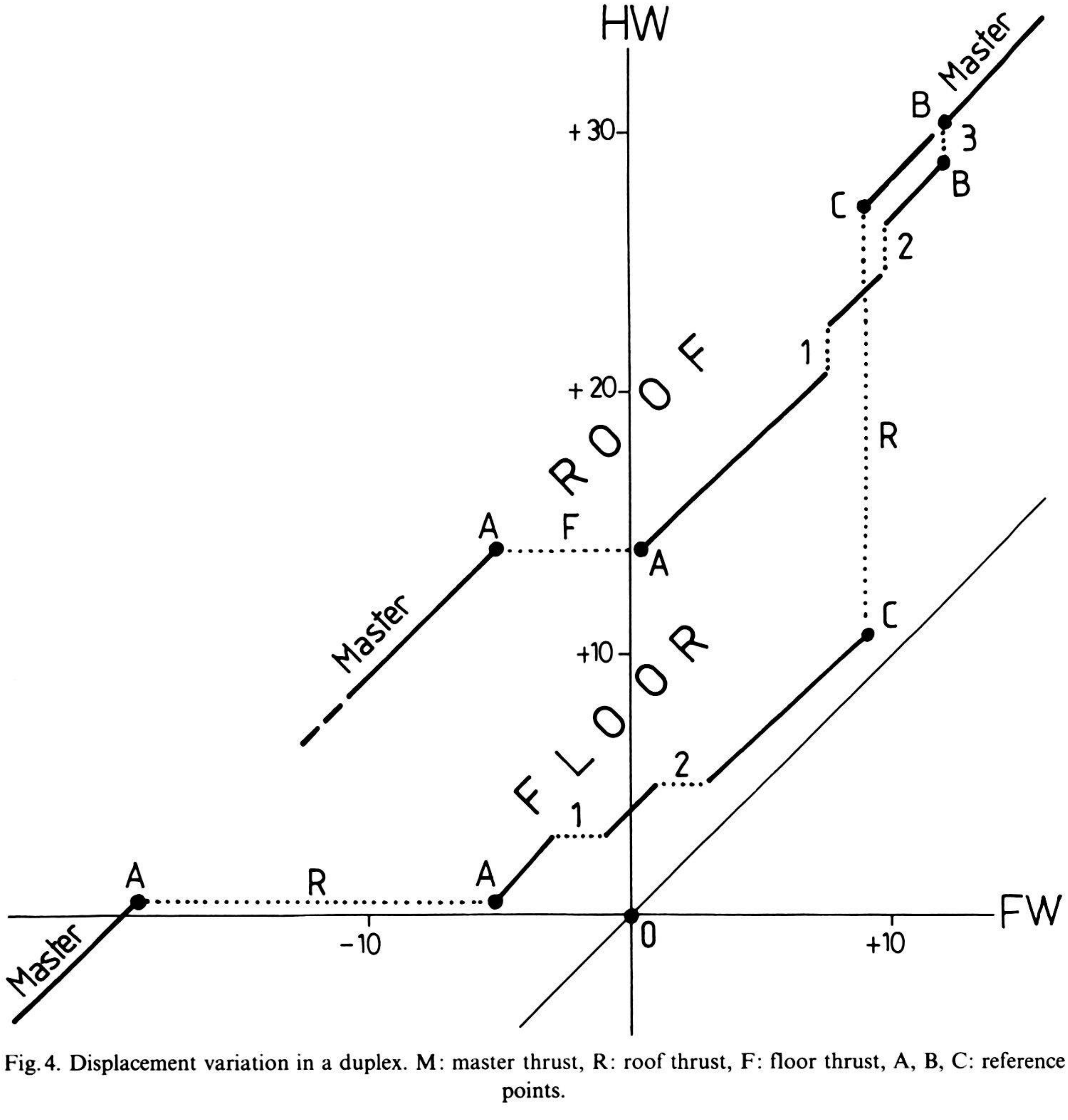


Fig. 4. Displacement variation in a duplex. M: master thrust, R: roof thrust, F: floor thrust, A, B, C: reference points.

because the fault segment CB was already active as part of the master thrust prior to the formation of imbricate 3. It will be noted that at the left of point A, upper and lower displacement curve show the same amount of displacement. The same is true beyond point B. But otherwise the two curves cannot be brought into coincidence. This stems from the fact that the length of the floor and roof thrusts are not identical and from the choice of the origin O.

3. Growth faults

A particular type of abrupt of nearly abrupt displacement variation can be provoked by the reactivation of originally normal or growth faults as reverse faults. Figure 5a, inspired by Figure 14 of MANDL & CRANS (1981), shows the initial state, a listric growth fault terminating at T. The steep segment of the displacement curve a in Figure 5c is caused by the thickness variations of the bed underlying T. If an entire marker bed was missing on the horst side of the fault, a vertical segment would result (see Fig. 8 as example). In Figure 5b the fault is shown to have propagated beyond T as reverse fault. Because only slight distortions were allowed for in the model, the effect of this thrusting is to shift the displacement curve of the growth fault vertically and almost parallel to itself. Thus the steep segment is preserved in curve b of Figure 5c. It is important to note that these displacement curves always indicate the finite displacement.

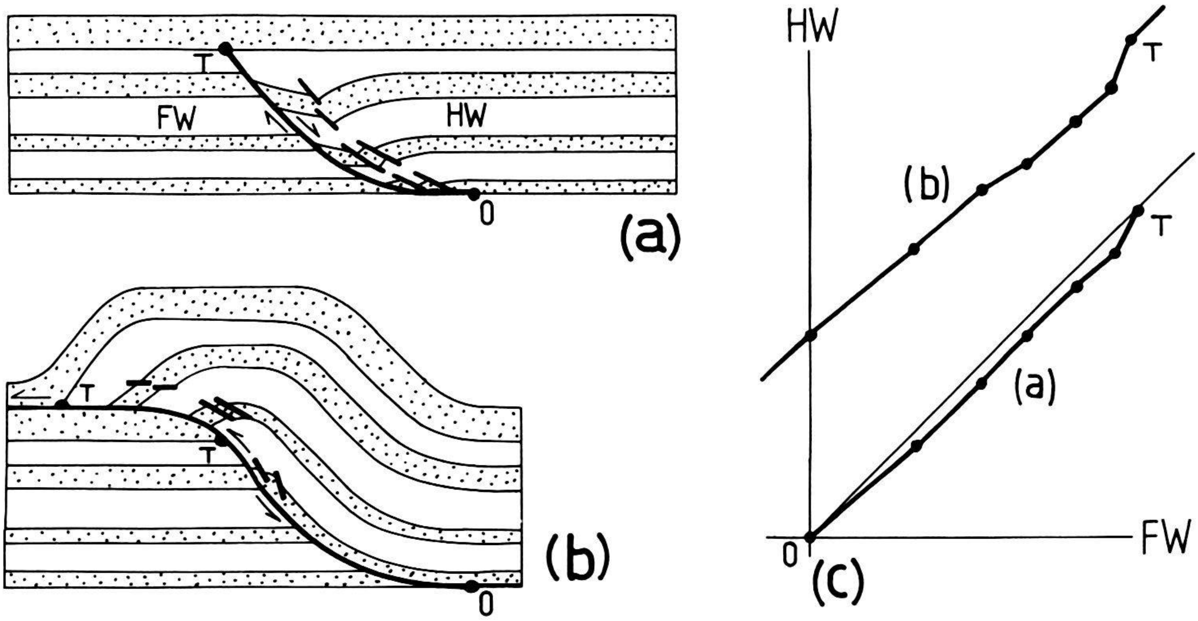


Fig. 5. Reactivated normal fault. *a* Original state with listric normal fault terminating at T and O. *b* Fault propagated beyond T and O with reverse sense of slip. *c* Displacement diagram for *a* and *b*.

Decollement tectonics

Decollement tectonics are characterized by thrusts following detachment horizons over long distances (e.g. long flats), usually important amounts of displacement and independent internal deformation in the hangingwall and footwall. Large displacements of the order of 50–200 km may result in this process hand the question arises where this displacement disappears. In many fold-and-thrust belts listric splays occur at the leading edge of the basal decollement (see DAVIS et al. 1983), but only rarely is the trailing edge considered (e.g. COWARD 1983).

Figure 6 is a very simple model to illustrate the situation. The basal decollement around the (arbitrarily chosen) origin O forms splays 1 to 5 in the frontal part. Each of those splays terminates upwards as indicated by the wavy line representing folds. Splay 5 is the reference fault used in the displacement diagram and it terminates at B. It is

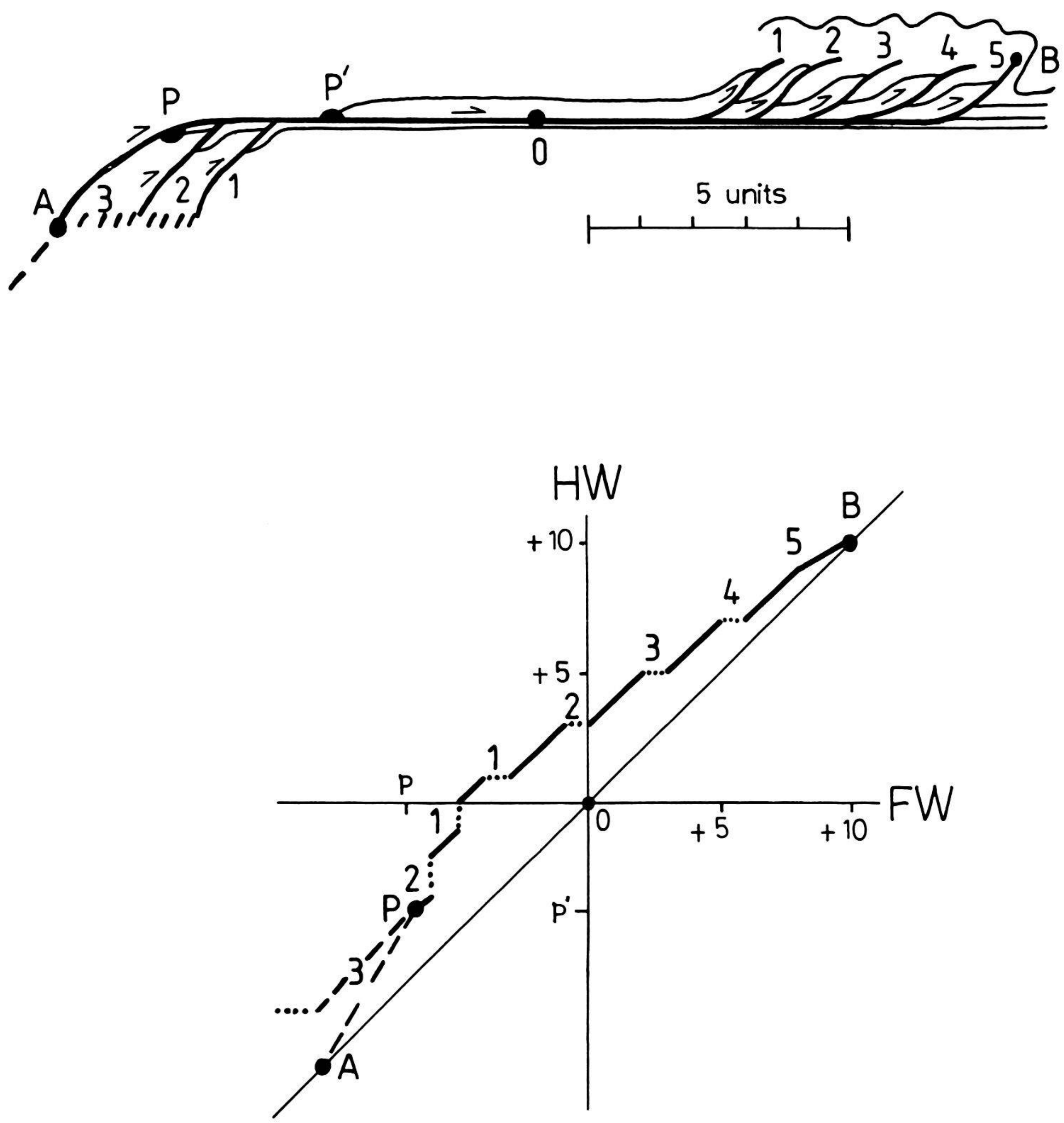


Fig. 6. Decollement tectonics and displacement variation. The reference fault extends from P over O to B. The rear end of the detached cover slipped from P to P'. The frontal branching splays 1–4 give rise to horizontal segments in the displacement curve, which diminish displacement on the reference fault. The internal merging splays 1–2 cause vertical segments and abruptly increase displacement on the reference fault.

assumed that the numbers represent the order of formation of the splays. Such a migration is plausible in the case of the Rocky Mountains (ORIEL & ARMSTRONG 1966) and the Subalpine Molasse in the Alps (MILNES & PFIFFNER 1980). The model in Figure 6 displays a stack of basement imbricates at the rear end of the basal decollement. The numbering reflects one possible sequence for the migration of splaying; this point will be discussed in more detail for one particular example below (Fig. 9). Displacement on these splays could be thought of as vanishing downwards, the reference fault terminating at point A. This could be accomplished by letting the faults become steeper downwards and being linked by some decoupling at depth as described by COWARD (1983, Fig. 5). Alternatively the splays could be thought of as rejoining a common floor thurst, displacement being transferred further back and down.

The fault segment showing the greatest amount of displacement is represented by the solid displacement curve segment between the two dotted segments labelled. 1. The exact location of this fault segment on the cross section is discussed to illustrate the use of the displacement diagram. The segment has a length of 1 unit (length of its projection onto the HW- or FW-axis). On the HW-axis, the segment extends from O to +1, that is in the cross section the fault segment is situated at the right of O in the hangingwall and has a length of 1 unit. On the FW-axis, the segment extends from −5 to −4, i.e. on the cross section the segment is situated 4 to 5 units on the left of O in the footwall (from about the place where splay 1 merges with the basal decollement to the right).

Examples from the Alps

1. The terminations of the Kistenpass thrust

The Kistenpass thrust shown in Figure 7 is one in a series of thrust faults slicing up the cover of the Aar-massif basement (Infrahelvetic complex of the Helvetic zone, eastern

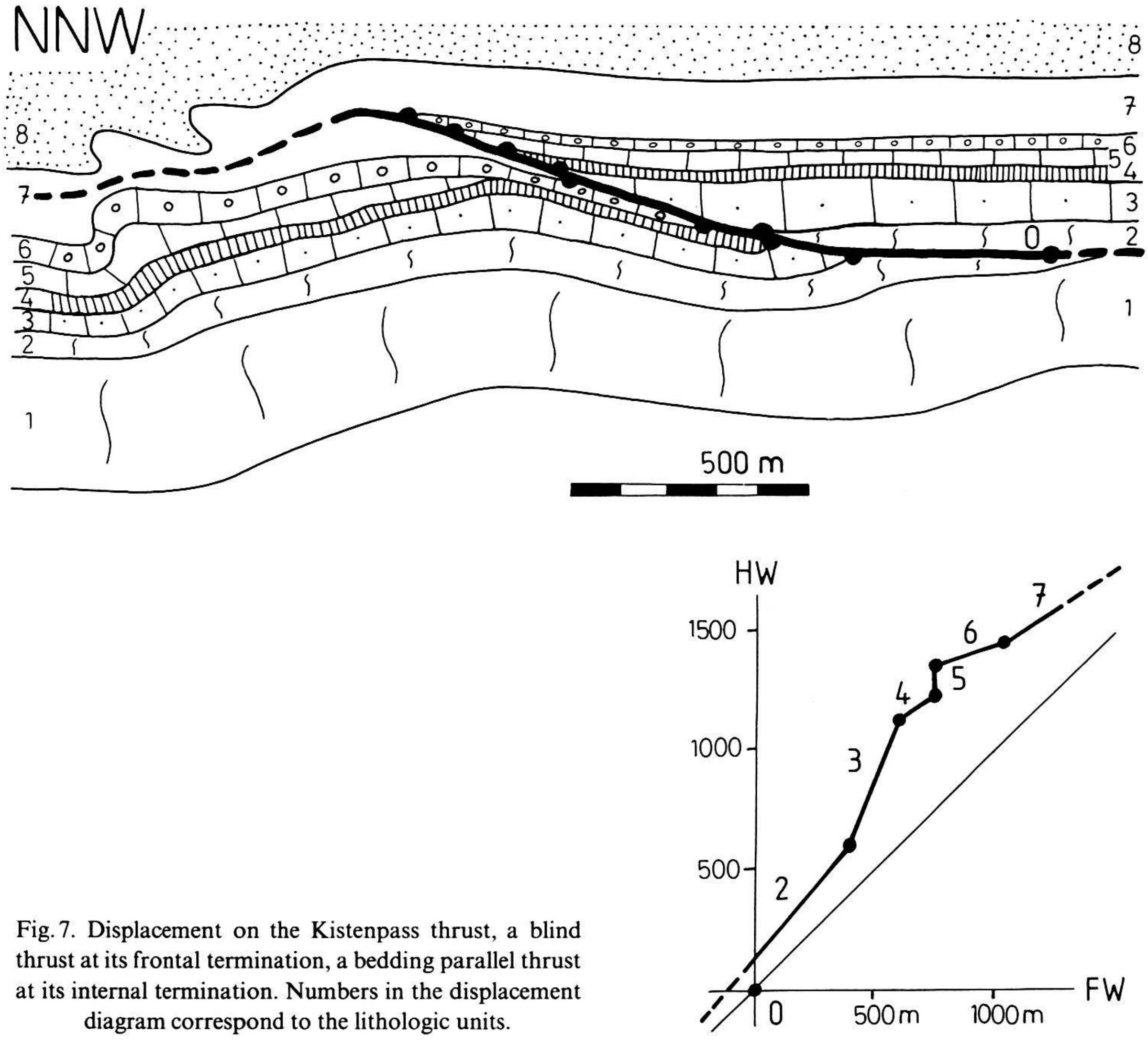


Fig. 7. Displacement on the Kistenpass thrust, a blind thrust at its frontal termination, a bedding parallel thrust at its internal termination. Numbers in the displacement diagram correspond to the lithologic units.

Switzerland). The fault forms a ramp through Cretaceous (layers 3–5) and Eocene (layer 6) limestones. Upward it then follows a marly detachment horizon (layer 7) and the overlying sandstones (layer 8) are thrown into folds, making the fault a "blind fault". Downwards the Kistenpass thrust levels off and becomes a bedding parallel thrust in the Upper Jurassic limestones (layers 1–2). The base of layer 6 is an unconformity. Layer 5 is probably eroded in the footwall of the fault, which could indicate that the thrust fault originally was a normal fault. The cross section shown is admissible, i.e. it contains structures observed in a cliff, but it is difficult to make it a restorable or viable cross section due to e.g. substantial strains in the rocks adjacent to the fault changing cut-off angles. This is a common problem in highly deformed parts of the Alps, where in addition strain states must a priori be assumed inhomogeneous and non-plane (PFIFFNER 1980) and where strain magnitudes are generally known for isolated sites only.

In the displacement diagram the vertical segment 5 is caused by the absence of layer 5 in the fault's footwall. The rearward termination is somewhere within layer 1. The location of this can be estimated as follows. If it is assumed that the hangingwall rocks suffered say 10% more stretch parallel to the slip direction than the footwall rocks (e.g. 1.65 vs 1.5), then the slope of the curve m = 1.1 and, from equation 2 the fault would extend 1.4 km beyond O to the SSE. For stretches of 1.8 and 1.5 this distance would reduce to 700 m. Such differences in strain states are realistic but likely to go unnoticed by the field geologist and one arrives at the conclusion that bedding plane thrusts that end "somewhere" may do so rapidly.

The upward termination as blind thrust seems straightforward with the folds in the hangingwall absorbing displacement by excessive shortening compared to the footwall. However, folds are not very efficient in providing important shortening and if only folding is responsible for the necessery strains in this example, the thrust fault would extend beyond the cross section to the NNW. It may well be that additional penetrative strains affected the rocks, similarly to what was described above, but no data are available on that subject.

2. The Calanda–Kaminspitz thrust system

Figure 8 shows the sliced up cover of the Aar massif below the Glarus thrust, displaying all the complexities of Alpine geology. The section line is along km 755 of the Swiss coordinate net. The cross section is thus parallel to the probable transport direction along the Glarus thrust, but deviates by about 20° from the likely NNW transport direction on the Calanda and Kaminspitz thrusts. The choice of a N–S oriented section line minimizes projection distances to less than 3 km (mostly less than 1 km). The cross section is admissible and an attempt was made to make it somewhat restorable. The main feature due to "balancing" is the slab of Trias extending deeply into basement (see below). The Glarus thrust is shown to truncate underlying structures at low angle. The southernmost is the Tschep thrust and transforms downwards into folds. The Calanda and Kaminspitz thrusts are interpreted to merge rearwards as they reach basement; upward they bracket a folded thrust fault. When unfolded this thrust fault has a hangingwall consisting of an already inverted sequence, witnessing extensive folding at a still earlier stage (Cavistrau phase of PFIFFNER 1977, 1978, and MILNES & PFIFFNER 1977).

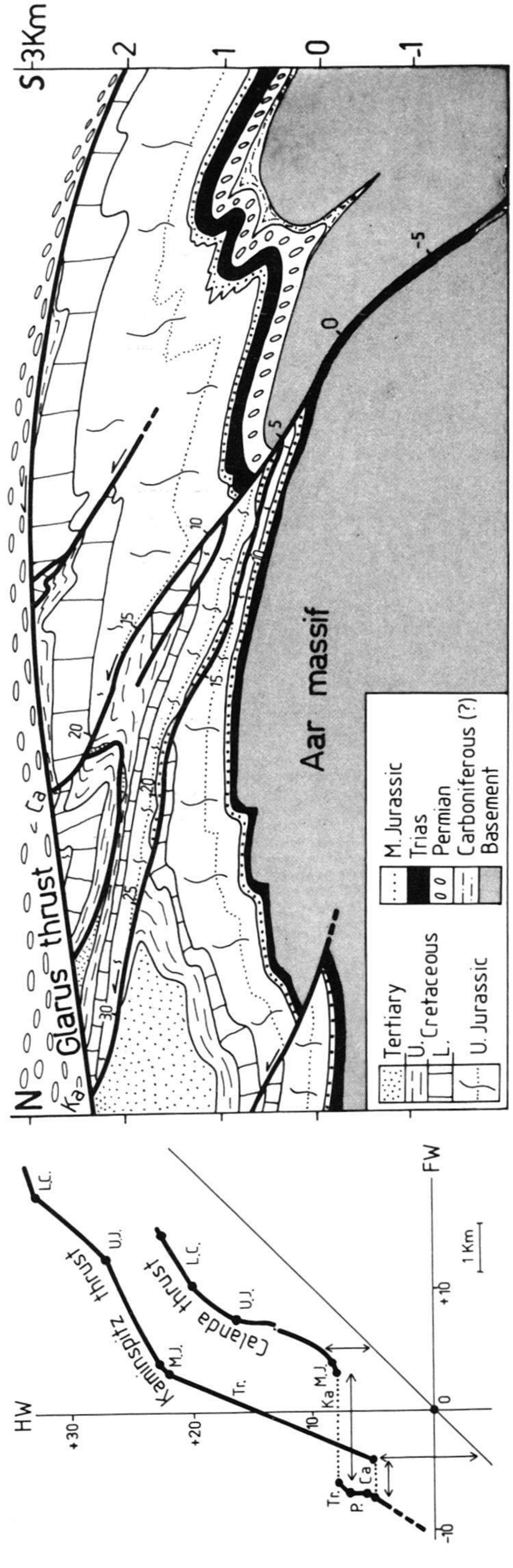


Fig. 8. Displacement on the Calanda–Kaminspitz thrust system. The Calanda (Ca) and Kaminspitz (Ka) thrusts are shown to merge rearward.

By choosing the origin O on the common branch of the two thrusts, both thrusts can easily be represented on the same displacement diagram. The Calanda thrust shows a vertical segment caused by the absence of Paleozoic rocks in its footwall. These Paleozoic rocks do outcrop in the folds in the hangingwall, but are absent 1 km north of the fault in the footwall. The location of their disappearance is in subsurface. A termination as a normal fault bordering a graben is plausible from the regional geology and in the cross section it is interpreted that this normal fault was later used as thrust fault. The displacement curve has a horizontal, dotted segment (Ka) at the base of the Middle Jurassic, caused by the branching off Kaminspitz thrust. The length of this segment equals the displacement on the Kaminspitz thrust where it breaks away (long double arrows). The steep portion of the displacement curve is provoked by the thinned Upper Jurassic in the footwall, which amounts to a shortening parallel to the slip direction, as the fault forms a footwall ramp here. The displacement curve cannot rejoin the line of zero slip upwards because it is truncated by the Glarus thrust.

The displacement curve of the Kaminspitz thrust shows a dotted horizontal segment (Ca) where the Calanda thrust breaks away. Its length equals the displacement on the Calanda thrust at that location (short double arrows). The following steep segment reflects the extensive stretching of the hangingwall, evident from the boundinage of the Middle Jurassic. As for the Upper Jurassic, both hangingwall and footwall suffered observable, substantial penetrative strains; their relative magnitudes vary and thus cause the break in slope near the center of the segment.

For both thrusts the Trias–Middle Jurassic boundary shows the greatest displacement. This stems from the slab of Trias reaching deeply into basement, introduced for balancing the long flat at the base of the Middle Jurassic, a structure which can be mapped.

3. Decollement tectonics in the Helvetic zone

The Helvetic zone of the Alps is a classic example of decollement tectonics, where the sedimentary cover has been separated from its crystalline substratum and pushed northwards on to the foreland. Figure 9 is a cross section through the root zone showing the complexities that may arise in such a process and to what extent basement is involved. The Limmern sub-massif and its overlying sedimentary cover are both affected by harmonic folding (Calanda phase structures of MILNES & PFIFFNER 1977, PFIFFNER 1977, 1978), whereas Punteglias and Trun sub-massifs have only remnants of this cover in the form of boudins of mainly Triassic dolostones. The bulk of the cover was sheared off along a nearly bedding parallel fault and replaced by a sedimentary sequence, the Cavistrau nappe, already overturned when emplaced (Cavistrau phase structures, op.cit). This is evident on Figure 9 if the basal thrust of this sequence, the Cavistrau thrust, is thought unfolded. The Cavistrau-nappe sediments represent the overturned limb of a W-facing Cavistrau-phase fold of the embryonic Lower Glarus nappe complex now overlying the Axen–Glarus thrust in Figure 9. The tight folding leading to the deep synform betwen Punteglias and Trun sub-massifs is a later, Calanda-phase structure and was controlled by the presence of a rigid Variscan granitoid. The Tavetsch massif's cover, apart from some remnants of Paleozoic sediments, was sheared off completely, and the Gotthard massif is lacking cover sediments of age younger than Lower Jurassic. These sediments now form the Helvetic nappes overlying the Axen and Glarus thrust.

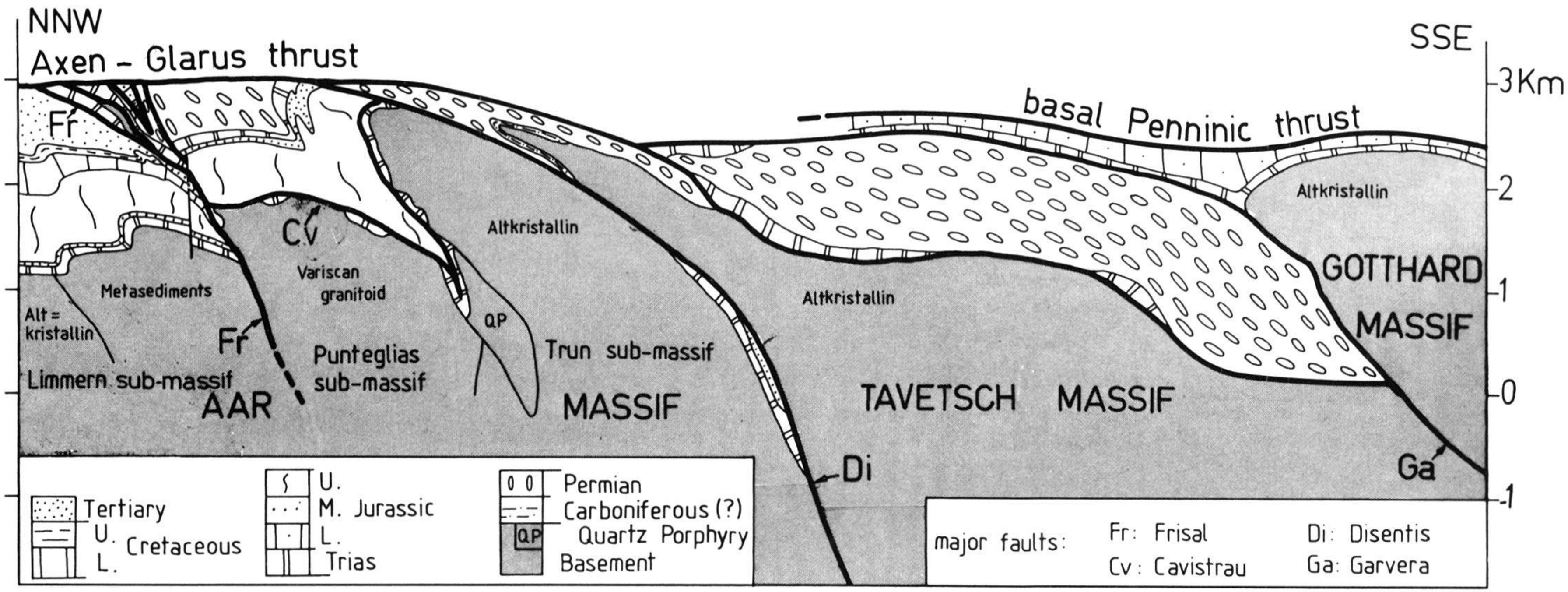


Fig. 9. The root zone of the Helvetic nappes. The cover of the Punteglias and Trun sub-massifs was detached and sheared off along the Cavistrau thrust (Cv) and replaced by an inverted sequence.

Another feature that Figure 9 displays is the telescoping of basement wedges: the envelope of the upper limit of basement is a nearly horizontal curve, demonstrating that basement stayed back in the root zone.

The cross section in Figure 9 yields an argument for the sequence of the formation of basement wedges. Since only the cover of the Punteglias and Trun sub-massifs were sheared off, these sub-massifs must have moved up relatively to the Limmern sub-massif along the Frisal thrust before decollement on the Cavistrau thrust occurred (see also TRÜMPY 1969 and KÄCH 1972). The amount of this early displacement on the Frisal thrust is difficult to assess, for it could be argued (PFIFFNER 1977, Fig. 4) that the Cavistrau thrust stepped up from the decollement horizon to from a ramp through the cover of the Limmern sub-massif (rather than being an even surface as envisaged by KÄCH 1972 in his Fig. 14). The southern continuation of the detachment between basement and cover of the Punteglias and Trun sub-massifs along the Cavistrau thrust must have been the Disentis thrust, a thrust now separating Tavetsch from Aar massif. Any other solution would imply a thrust cutting down section in the movement direction. The Disentis thrust is possibly a reactivated normal fault bordering the graben of Paleozoic sediments above the Tavetsch massif. At some stage the Disentis thrust broke away from the Cavistrau thrust allowing the Cavistrau nappe to be wrapped in. In any case the Frisal thrust must have formed prior to the Disentis thrust, and hence the migration of splaying was towards the rear (cf. Fig. 6). In a next step detachment occurred between basement and cover of the Tavetsch massif along the Garvera thrust. Due to increased burial, the rocks in the footwall reacted more and more ductily and thus lead to the (Calanda phase) folding of the early Cavistrau thrust. It could be envisaged, although due to erosion no arguments can be put forward, that in a last stage decollement occurred in the most internal part, within the cover of the Gotthard massif.

Figure 10 is an attempt to understand the displacements on the Glarus thrust at the scale of the Alps. The section line is parallel to the probable transport direction on the Glarus thrust and is on km 755 of the Swiss coordinate net. Consequently it is slightly oblique to the likely NNW transport direction on the thrusts in its footwall (the Infrahelvetic complex) and slightly oblique to the X and Z principal strain axes within much of the rocks in its hanging wall (the Helvetic nappes). Moreover the ramps e.g. through the Triassic dolostones and the Lower Cretaceous limestones form a complex pattern oblique to the transport direction (PFIFFNER 1981, Fig. 4). These facts represent an unfortunate but inevitable situation rendering true balancing virtually impossible. The Glarus thrust is shown to splay at the rear into the Disentis, Garvera and an unnamed thrust in the cover of the Gotthard massif. The Cavistrau thrust cannot be postulated in this cross section. Towards the front, the Säntis splay branches off the Glarus thrust, but rejoins it again. The horse between the two thrusts is the Lower Glarus nappe complex (PFIFFNER 1981) and consists of Triassic–Jurassic sediments separated from the overlying Cretaceous sediments of the Upper Glarus nappe complex by a detachment horizon on which about 10 km of slip occurred (dotted vertical segment in Fig. 11).

On Figure 10 the Aar massif is shown to be allochthonous. The hypothetical slab of Mesozoic sediments is a consequence of balancing the duplex consisting of Tertiary sediments, the frontal ones being observable (Subalpine Molasse), the rear ones hypothetical. The actual bed length of these thrust sheets is difficult to assess for two reasons: 1. the actual thickness of the duplex down to the top of the Mesozoic overlying basement is poorly known, and 2. the nature of the sedimentary sequence renders estimates of stratigraphic thicknesses vague. An alternative solution would be to keep the floor thrust of this duplex within the Tertiary sediments and let it merge with the Glarus thrust somewhere north of point T. This solution is sketched in Figure 1 in FUNK et al. (1983) and in Figure 2 in GROSHONG et al. (1984). For the voluminous duplex sketched in Figure 10 this alternative solution seems unlikely. It would imply that the southernmost Subalpine Molasse imbricates were originally deposited on the Aar massif and removed from there by the emplacement of the relatively thin, exotic strip sheets (Blattengrat, Sardona and Ragaz units) without leaving any trace. The solution in Figure 10 is highly speculative and intends to show the possible consequences of balancing the section.

The internal structure of the Penninic nappes is highly simplified and emphasis is solely put on the existence of thin slabs of Mesozoic sediments (Deckenscheider) representing deep sutures. The depth of the MOHO and seismic velocities are taken from MÜLLER et al. (1980). The uppermost low-velocity zone (5.8) in the central part is interpreted as "granitic crust" of the Gotthard massif, giving the latter a crustal structure comparable to the one in the northern foreland and the one south of the Tonale (Insubric) fault.

The displacement diagram in Figure 11 gives a maximum displacement of about 50 km for the Jurassic–Cretaceous boundary as marker (C–C′–C″). The frontal portion of the Glarus thrust is characterized by a horizontal curve in the displacement diagram. This slope results from the fact that T′, the cut-off point of the base of the Tertiary in the hangingwall, is very close to the toe region and originally contiguous points do not exist much north of T and T′. The only explanation is that the thrust had cut up to the earth's surface just north of T and that the toe of the Helvetic nappes was creeping on the floor of the shallow waters of the Molasse bassin.

For the internal portion, two solutions are presented. Both allow for some slip to be accommodated on the Disentis thrust. The upper curve is the solution whereby all of the cover sediments making up the Helvetic nappes are derived from the Tavetsch massif, a solution advocated e.g. by TRÜMPY (1973). This requires a basement surface reaching back as far as point A in Figure 10. Point A was originally contiguous with the rear of the Helvetic nappes (A′) as well as with the front of the Gotthard massif (A″) and thus a displacement of some 30 km (A′–A″) remains. To accommodate that much displacement one would be forced to extend the thrust some 30 km to south of A (allowing generously $s_u/s_l = 2$ in equation 2), which would bring it to either the MOHO or the Tonale fault! An extension as far as the Tonale fault cannot be ruled out in fact, particularly when thinking that the intrusions (Novate: 26 my, Bergell: 30 my) and some deformations (Cressim phase, see MILNES & PFIFFNER 1980) just north of the Tonale fault are at least partly contemporaneous with movements on the Glarus thrust and the deformations are also kinematically compatible with horizontal crustal shortening. The shape of the Garvera thrust (dashed in Figure 10) is arbitrarily drawn to imitate the known shape of the Misox zone between Adula and Tambo. It could equally well be much steeper at its rear and reach towards the MOHO.

The second solution, the lower curve in Figure 11, proposes the cover sediments to be derived from as far back as point B and from both the Tavetsch and Gotthard massif (situation sketched in Figure 10) with the Garvera thrust taking up some 15 km of slip. This is in agreement with the comparison of the facies of the Lower Jurassic sediments,

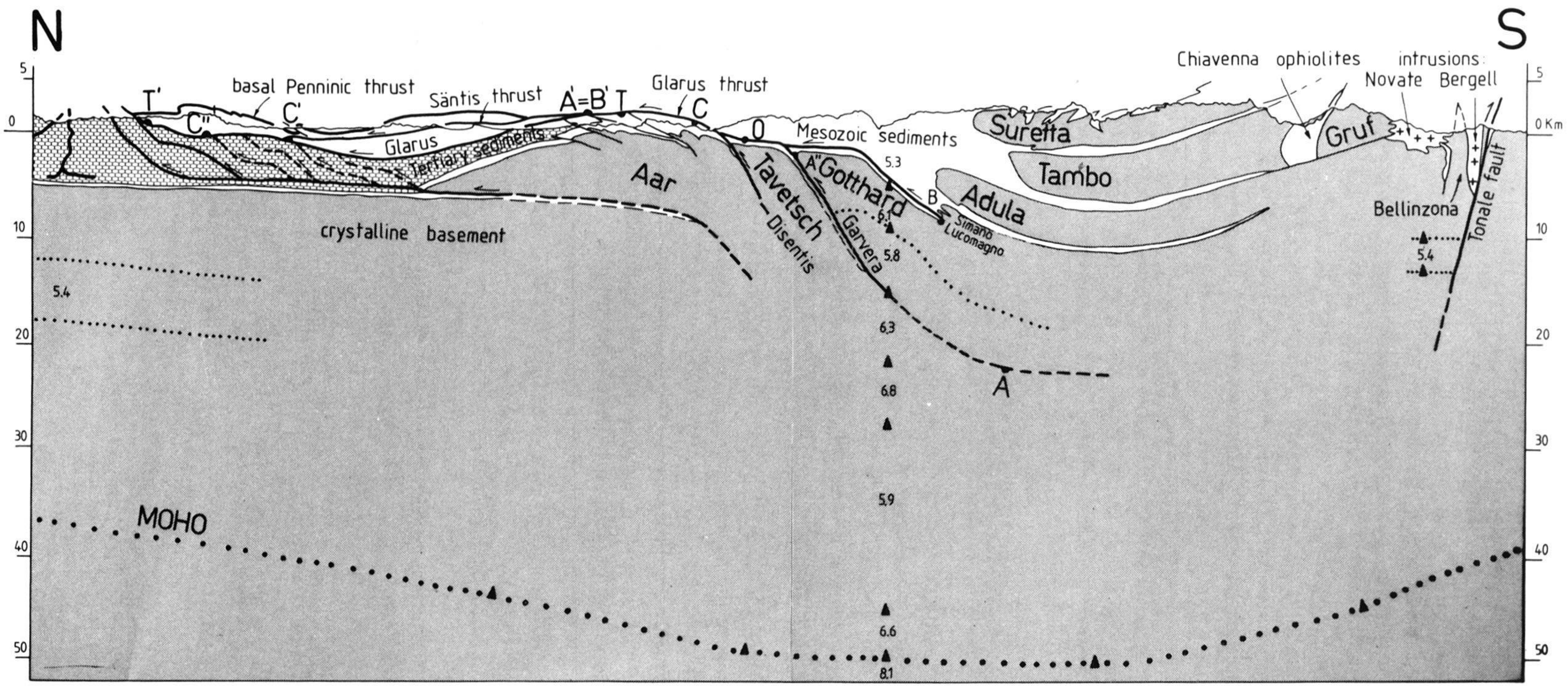


Fig. 10. Interpretative cross section through the Alps showing basement–cover relations for the Glarus thrust.

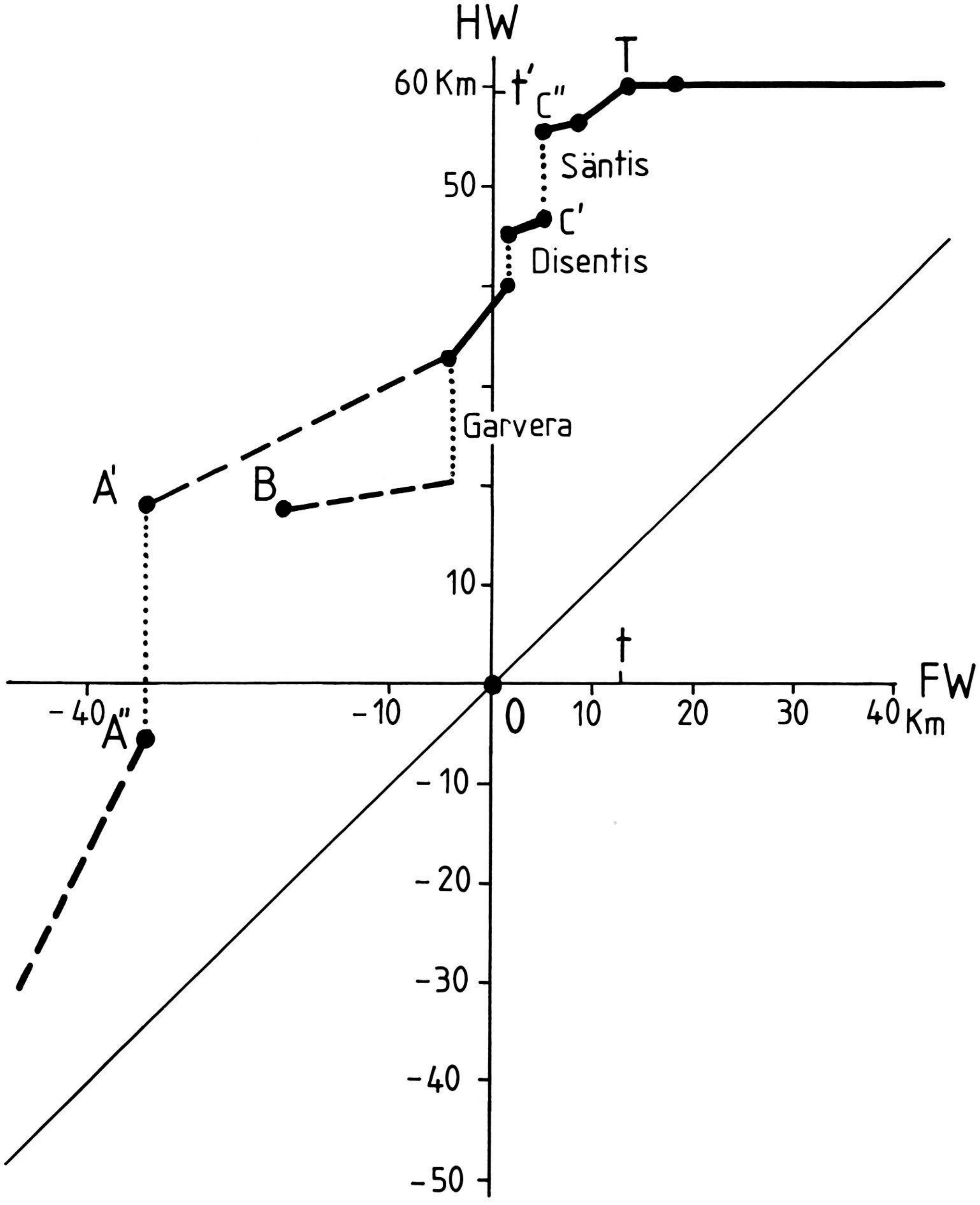


Fig. 11. Displacement diagram of the Glarus thrust. For the upper curve (through A′ and A″) all of the Helvetic nappes are detached from the Tavetsch massif, for the lower one (through B) from both, Tavetsch and Gotthard massif.

where TRÜMPY (1949) found correspondance between the sediments of the front of the Gotthard massif (Val Nalps; A″) and the southernmost ones within the Helvetic nappes (A′). The second solution too, requires that the Garvera thrust be a deep suture that may still extend far beyond point A. The continuation of the displacement curve beyond B depends on the interpretation of the still controversial regional structure. No preference is given at the moment for either of the two solutions.

Conclusions

The displacement diagram presented in this paper is a useful additional tool for the analysis of faults and the construction and interpretation of (balanced) cross sections. Displacement curves in these diagrams give the finite displacement and the slope of these curves or their envelopes reflect finite strain differences in the rocks adjacent to the fault.

Bedding plane thrusts may terminate over relatively short distances, slip being accommodated by penetrative distortions in hangingwall and footwall rocks. Splay faults give rise to abrupt changes in displacement and even simple linked-fault systems prove to have complex displacement patterns.

In the case of the Glarus thrust in the Helvetic zone of the Alps (eastern Switzerland), the highest displacements turn out to be related to an important decollement horizon, the Säntis thrust. The Glarus thrust must have broken surface quickly. In the thick-skinned portion, the Glarus thrust shows merging splay thrusts separating basement wedges, called massifs. The order of formation of these wedges seems at least partly to have progressed rearwards, i.e. towards the internal parts of the chain. Some of these splays represent deep sutures and may extend, possibly as broadening ductile shear zones, as far down into the crust as the MOHO.

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