Pergamon

Journal of Structural Geology, Vol. 18, No. 5, pp. 533 to 548, 1996

0191–8141/96 $15.00+0.00

0191–8141(95)00130–1

Transition from basement to cover: a geometric model

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(*Received* 29 *November* 1994; *accepted in revised form* 4 *September* 1995)

Abstract—A new simple geometric model is proposed that explains the possible relationships between superficial thrust sheets and deeper fold nappes. It demonstrates that the simultaneous formation of these two types of structures at different levels of the crust is kinematically and geometrically possible. The model is based on the difference of rheological behaviour between a lower tectonic unit that will suffer mainly a ductile deformation along a shallow dipping shear zone and an upper and rigid tectonic unit that will deform mostly by bedding parallel slip at constant bed length. The difference in rheologic behaviour implies that the horizontal shortening that can be produced within the two units is unequal and therefore leads to a relative movement between them. This movement takes place within a detachment level of variable thickness. The most efficient layers to enable detachment will consist of ductile sediments like evaporites, shales or flysch-type sediments.

Recent geophysical data have confirmed the view that compressional mountain belts are mainly the result of continental lithosphere subduction. The deformation is essentially localized in the upper part of the down-going continental crust. This fundamental basally-driven mechanism constrains the geometry and kinematics of the proposed model. Examples from the Alps show that it can be applied to many cases where cover thrust sheets are directly related to basement fold nappes. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

For many years, two main nappe types have been recognized in the Alps and in other orogenic belts. Termier in 1906 had already distinguished between what he called 'nappe du 1er genre' or 'fold nappe' and 'nappe du 2ème genre' or 'thrust sheet'.

Fold nappes are big recumbent folds with an amplitude of at least 10 km and often much more, that are probably mainly formed by heterogeneous ductile simple shear. Their core is mostly made of metamorphic basement surrounded by a sedimentary cover. This cover is generally incomplete, the upper part being often detached and translated to a more external part of the belt. Fold nappes are frequently found in the more internal part of an orogen where the metamorphic conditions allowed ductile deformation. The Antigorio, Siviez-Mischabel, Pontis and Morcles–Mont-Blanc nappes are several among many typical examples from the Alps (Steck 1984, 1987, Escher *et al.* 1988, 1993).

Thrust sheets are characterized by the absence of a clear and prominent overturned limb and therefore are limited at their base by a thrust. The internal structure of the nappe can nevertheless be complex and may contain several folds. Thrust sheets are characteristic of the upper tectonic levels, involving mainly a weakly or unmetamorphic sedimentary cover. The Jura Mountains and the Prealps are examples of this nappe type.

Two centuries of geology in the Alps demonstrate that these two nappe types spatially and chronologically coexist. In other words, huge recumbent folds are created at depth while thrust sheets are produced in the upper part of the crust. Several new attempts to model Alpine structures do not take into account this double behaviour. They wrongly extrapolate to depth known models of thin-skinned tectonics, valid only for the upper part of the crust (Boyer & Elliott 1982, Butler 1983, 1985, Butler *et al.* 1986).

The aim of this paper is to propose a new simple geometric model that can explain the possible relationships between thrust sheets and fold nappes. It will demonstrate that the simultaneous formation of these two types of structure at different levels of the crust is kinematically and geometrically possible, but it does not pretend to predict all the detailed geometry within each individual nappe. Finally we will point out how this simple model can be applied to some examples from the Alps in order to explain important points of nappe geometry and kinematics.

THE MODEL

The model develops one initially proposed by Ramsay (1980, fig. 22) to explain the evolution of a shear zone from a ductile to a brittle part of the crust. It is based on the difference of rheological behaviour between a lower tectonic unit that will suffer mainly a ductile deformation and an upper and brittle tectonic unit that will deform mostly by bedding-parallel slip at constant bed length. This difference in rheological behaviour implies that the horizontal shortening that can be produced within the two units is unequal and therefore leads to a relative movement between the two units. This movement takes place within a detachment level of variable thickness. The special case where the thickness of the detachment unit is zero corresponds to a movement on a discrete surface or thrust plane.

New reflection seismic data across the Swiss–Italian Alps provide important information on the geometry of

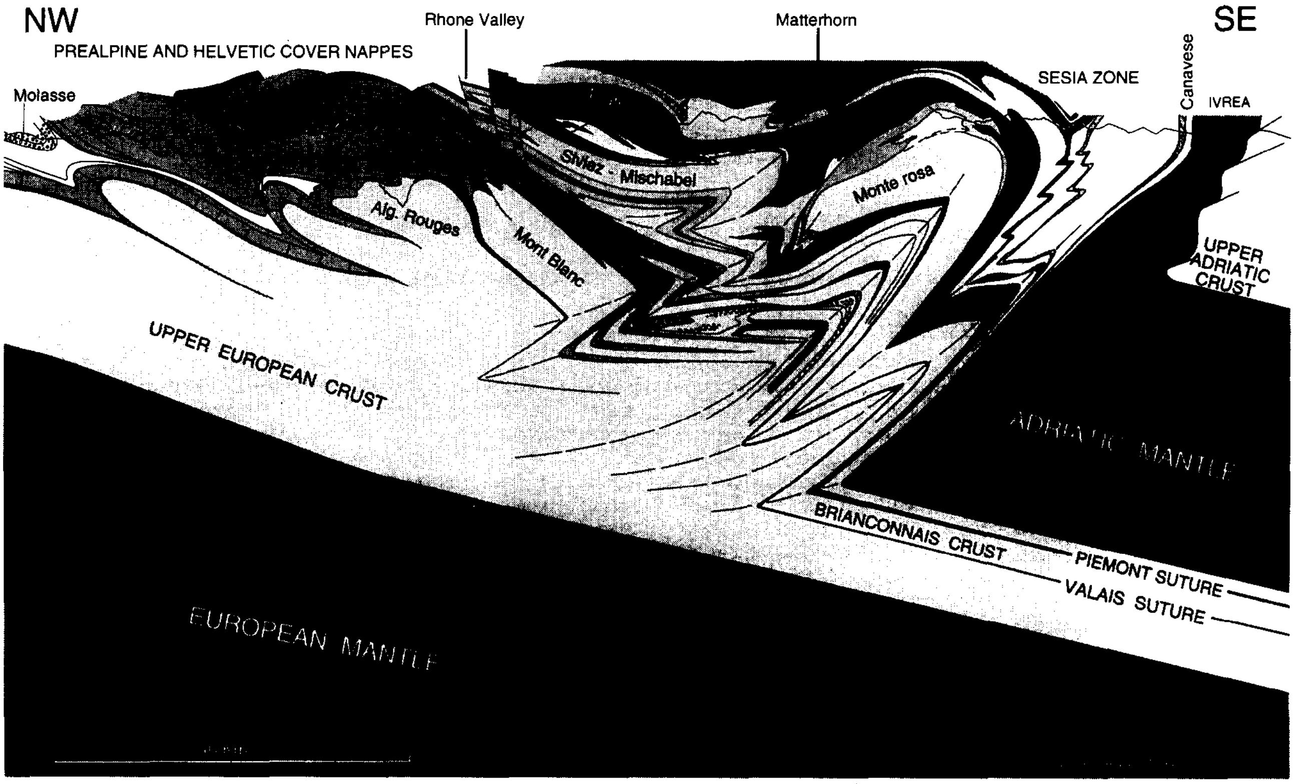


Fig. 1. Schematic geological profile through the central part of the Western Swiss–Italian Alps, based partly on the results of the recent reflection seismic data. The overall structure, if rightly interpreted, clearly demonstrates that the main response to compressional stress was the subduction of the European lithosphere. It also shows that the deformation and stacking of nappes took place within the down-going upper part of the continental crust, while its lower part subducted in a passive way together with the underlying lithospheric mantle.

the Alps at crustal scale (Marchant 1993, Marchant *et al.* 1993, Escher *et al.* in press), and confirm the view that the formation of a mountain chain such as the Alps has to be considered more as the final result of a lithospheric subduction of the European plate than an 'overthrusting' of the Adriatic plate (Fig. 1). This basally-driven mechanism was proposed as the main one responsible for the formation of continent–continent collisional orogens by Willett *et al.* (1993) and Beaumont *et al.* (1994). It constrains in a fundamental way the geometry and the kinematics of the proposed model.

The basic geometric setting is described in Fig. 2. It consists (Fig. 2a) of a homogeneous lower tectonic unit and a bedded sedimentary cover (upper tectonic unit), separated by a detachment unit. A fixed reference point is placed on the right side of the model. During deformation, the volume is maintained constant for each unit.

The *lower tectonic unit* is characterized by the development of a ductile shear zone, modelled in a simplified way as a shallow dipping zone of homogeneous simple shear. Keeping the reference point in the right part of the model fixed, the progressive development of the shear zone will produce a subduction of the left part of the model. Material points in the left part of the lower tectonic unit undergo a horizontal translation (D), pass through a flexure and then are subducted parallel to the shear zone (Fig. 2c). Simple shear causes a change in length of the upper limit of the lower tectonic level (horizon T, Fig. 2) within the shear zone (i.e. segment L_2 is shorter than L_1). By simplification, these length changes are supposed to occur only within the shear zone. One important point is that the continuity of horizon T is never disrupted. In other words this horizon T is folded and not faulted. Translation D of the left end of the lower level can also be considered as horizontal shortening of the model, mainly compensated by movement inside the shear zone, and to a much smaller degree, by the formation of a synform.

Two prominent properties distinguish the *upper tectonic unit* from the lower level: (a) it is not homogeneous but consists of a stratified sequence; (b) it maintains not only constant volume but also constant bed-length. Bedding-parallel slip has therefore to be admitted as the principal strain mechanism in this level. The maximum horizontal shortening does not exceed the shortening caused by the synform. This shortening is significantly smaller than that applied simultaneously to the lower tectonic level. This difference in horizontal shortening leads to a relative movement (d) of one unit with respect to the other (d is always smaller than D). The difference between D and d represents the horizontal shortening, consumed in the synform, in the upper tectonic unit. The value 'd' can also be considered as 'efficiency' of the detachment mechanism of the proposed model.

If no relative movement is allowed between the two units (if a pin line is placed at the left end of the model) or, in other words, if the horizontal shortening in both units is forced to be equal, this will lead to the formation

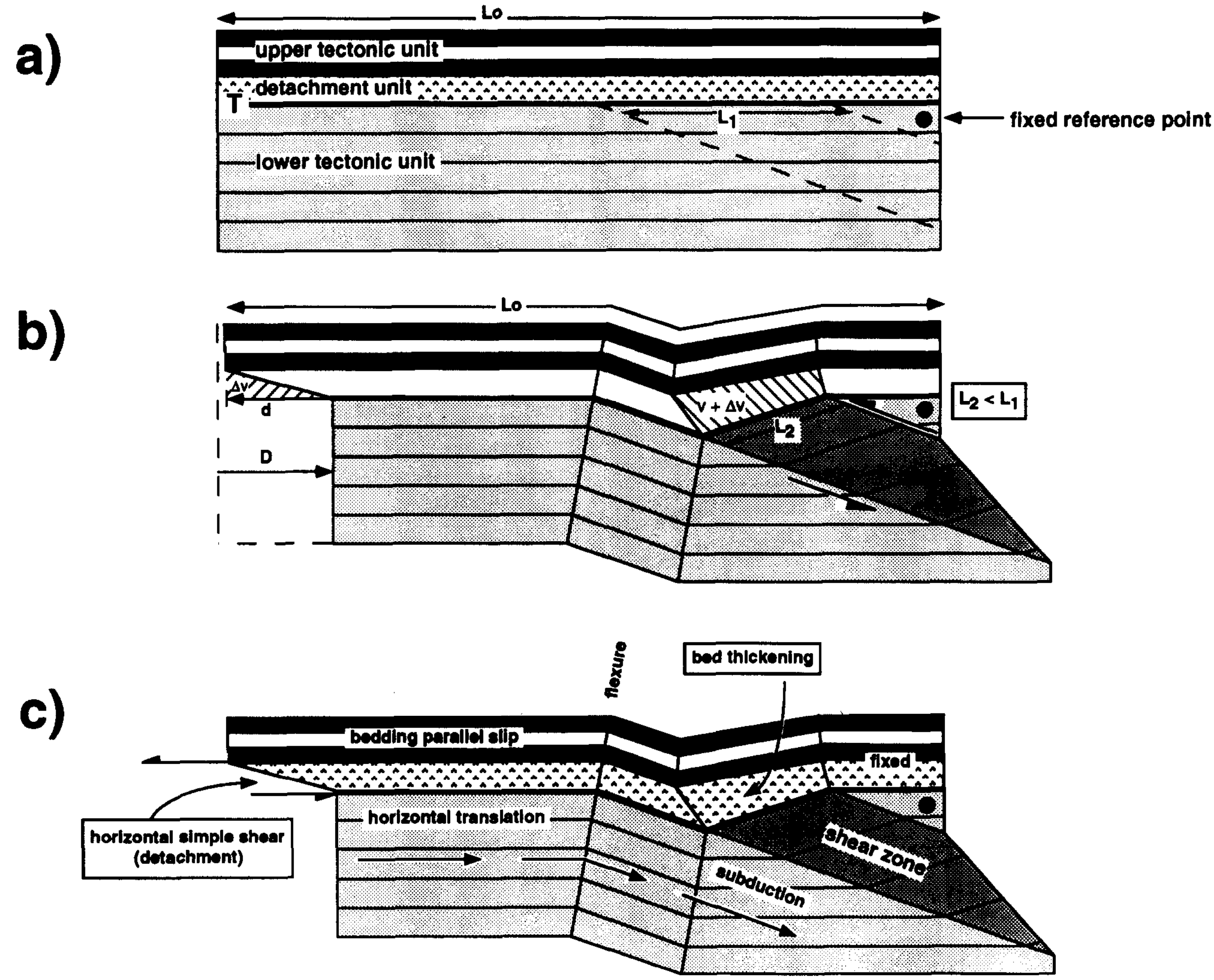


Fig. 2. Principle of the model. (a) Initial setting. L_0 = bed length in the upper unit; T = upper limit of the lower tectonic unit; dashed lines in the lower tectonic unit = position of the future shear zone; L_1 = initial length of a horizontal marker in the shear zone. (b) Geometry after a translation D of the lower tectonic unit. The lengths of the beds in the upper tectonic unit are unchanged. L_2 = length of an originally horizontal marker in the shear zone; d = relative movements between the upper and the lower tectonic units. The lost volume ΔV produced by shearing in the left part of the detachment unit is balanced by an increase of volume ($V + \Delta V$) located in one limb of the synform. (c) Strain mechanisms and relative movements implied by the model.

of decollement folds in the upper tectonic unit in order to compensate for the forced horizontal shortening.

The relative movement between the two units occurs along the *detachment level* (or *unit*) parallel to the limits of the upper and lower tectonic units. It is expressed as a homogeneous simple shear. The balance of volume within this detachment level implies that it has to be thickened locally, in order to compensate volume (ΔV) 'lost' by shearing at the left end of the model. The thickening is assumed to be restricted to the limb of the synform that suffers major shortening in the lower tectonic level too.

In order to simplify the model, *isostatic compensation*, *surface erosion* and *sedimentation* are not taken into account. These simplifications allow concentration on the essential geometric part of the model. The influence of isostatic adjustment will be discussed shortly in a separate section. It appears to modify only slightly the geometry of the proposed model (see Fig. 12c).

KINEMATICS

The evolutionary model during increasing subduction of the lower tectonic unit is illustrated by Fig. 3. The values of the parameters used here probably correspond best to those observed in similar structures in the Alps. Volume balance in the overall model, together with bed-length balance of the upper tectonic level, make it possible to draw the geometry for each step of increasing subduction of the lower tectonic level. The relative displacement d can be evaluated by basic trigonometric equations. It is therefore possible to plot a graph of d vs D (Fig. 4). During its evolution, the model passes through the following steps.

(1) In the first steps, the top surface T of the lower tectonic unit will undergo a shortening, restricted to the segment localized within the shear zone (T_s). This shortening will be maximum when T_s is perpendicular to the shear zone (D=7.5 in Fig. 3c and point A in Fig. 4). A

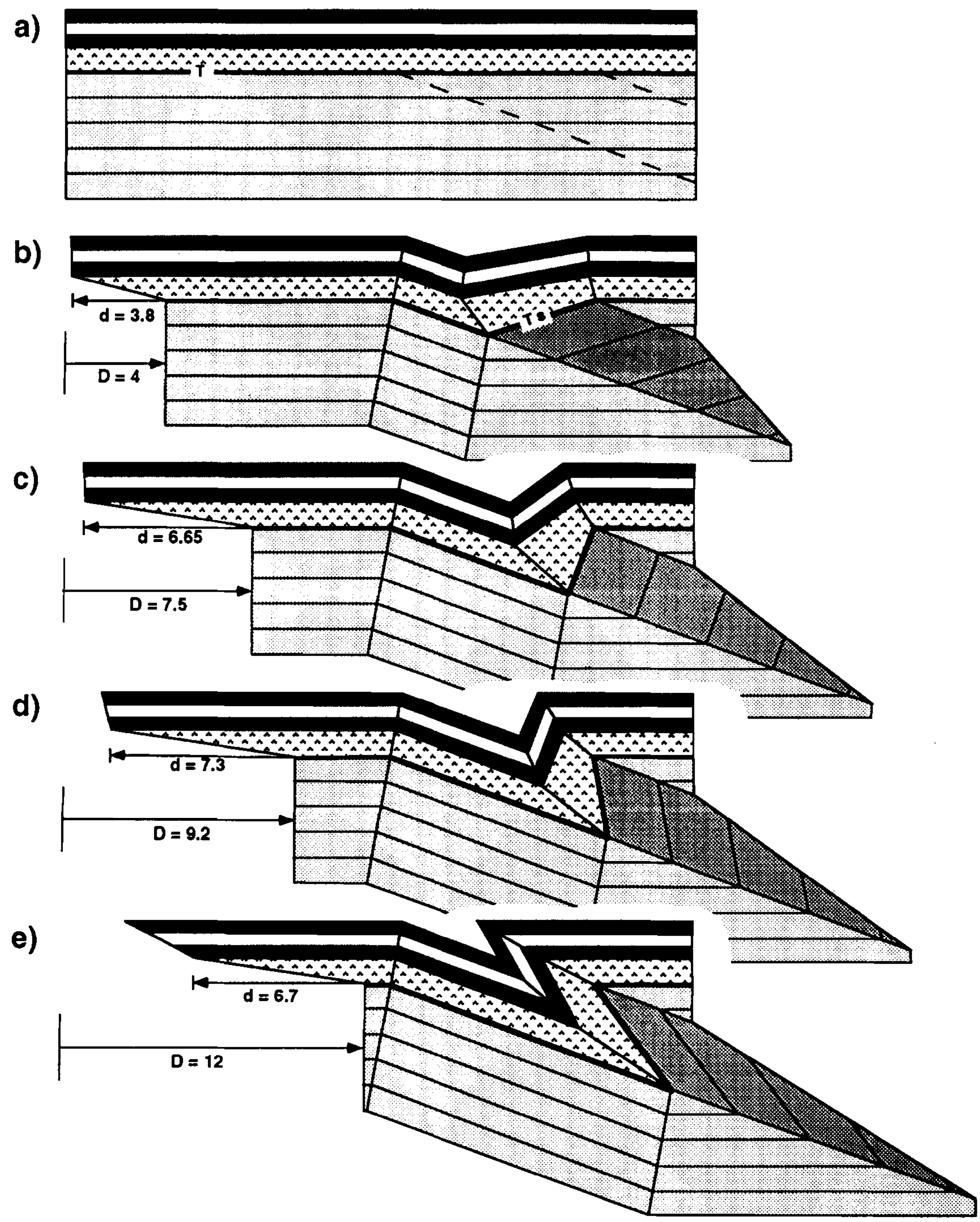


Fig. 3. Model evolution at different amounts of translation D of the lower tectonic unit. Shear zone dip = 20°; thickness t of the detachment level = 1; width w of the shear zone = 2.75. Step a = initial situation (D = 0); steps b, c, d and e = geometries for increasing values of D.

rapid and almost linear increase of d with respect to D characterizes this part of the model evolution.

(2) With increasing values of D, the segment T_s continues to rotate. From step c in Fig. 3 onward, it suffers incremental extension, and is in an overturned position with respect to the shear zone. The beds in the upper tectonic unit are also progressively rotated to a position perpendicular to the shear zone (step d, Fig. 3). The difference between step c and step d is that T_s is overturned whereas the corresponding beds of the upper tectonic level are steeply dipping but still in a normal position. This important property of the model is possible due to the local thickening of the detachment unit. It shows how it is geometrically and kinematically possible to make a fold with an overturned limb in a lower tectonic unit, while keeping the stratified sequence of the cover in a normal position. The importance of this 'disharmonic effect' is related to the thickness of the detachment level. It will increase with a thicker detachment zone. During steps a to d, d is still increasing (Figs. 3 and 4).

(3) From step d in Fig. 3 onward, the beds of the

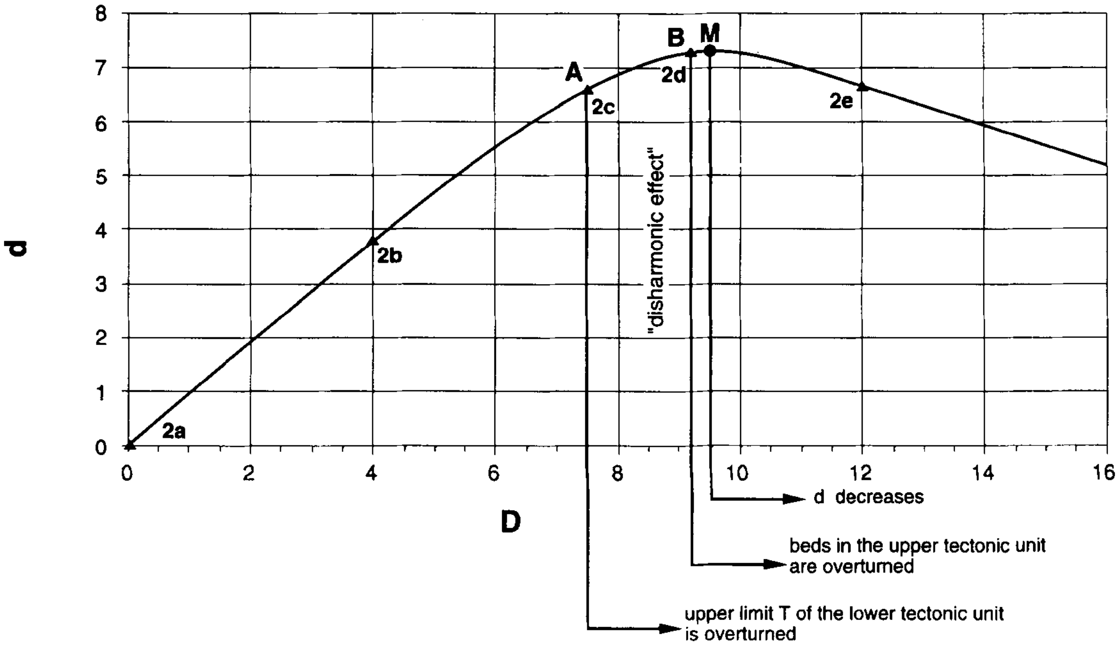


Fig. 4. Graph of d vs D related to steps 2a, 2b, etc. of Fig. 2. A = d value when T_s is perpendicular to the shear zone (Fig. 3c); B = d value when the beds of the upper tectonic unit are rotated perpendicularly to the shear zone (Fig. 3d); M = maximum value of d.

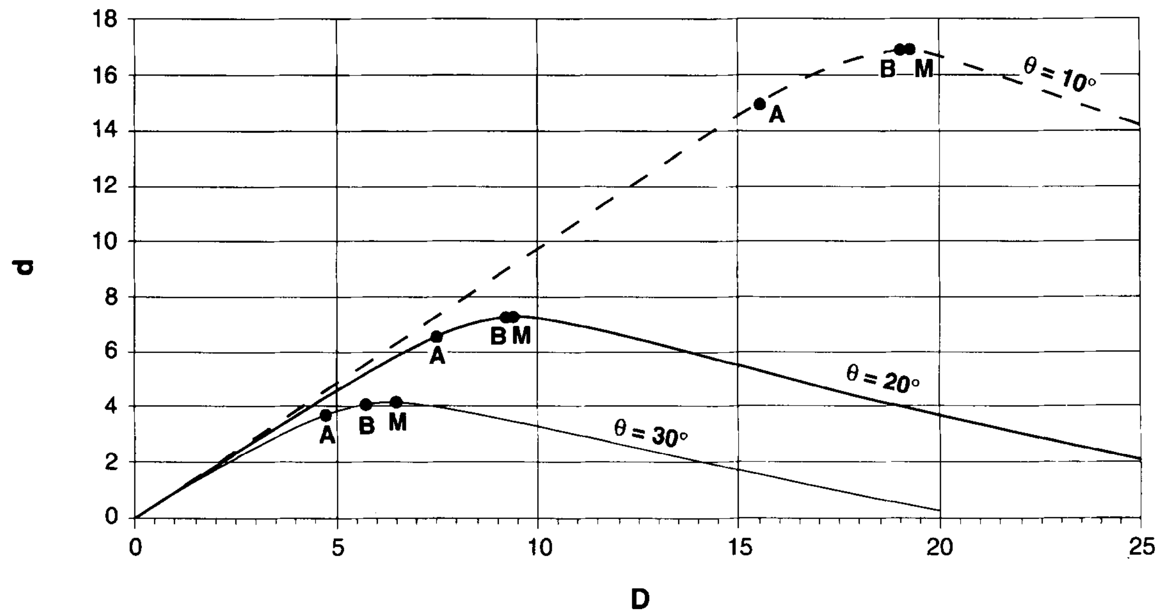


Fig. 5. Graph of d vs D for different shear zone dips θ. Thickness of the detachment unit = 1. Width of the shear zone = 2.75. A, B and M as in Fig. 4.

upper tectonic level are locally overturned and progressively dragged down by the lower unit shear zone (step e, $D = 12$, Figs. 3 and 4). The graph in Fig. 4 clearly shows that, after an almost linear increase, the d value reaches a maximum (M) and then decreases. This decrease in d value is caused by the fact that the 'disharmonic effect' is not strong enough to prevent finally the upper level being equally dragged to depth along the shear zone.

It is interesting to note that during all the progressive steps described above, the hinge lines in the upper unit migrate considerably. This is necessary in order to keep the thickness constant.

INFLUENCE OF GEOMETRIC PARAMETERS

The geometric parameters that have to be assumed in the initial setting influence the amount of relative displacement, d. These relations are examined with the help of specific examples.

Dip θ of the shear zone in the lower tectonic unit

Figure 5 shows a graph of d vs D, for different values of shear-zone dip, the other parameters remaining constant (namely the width of the shear zone and the

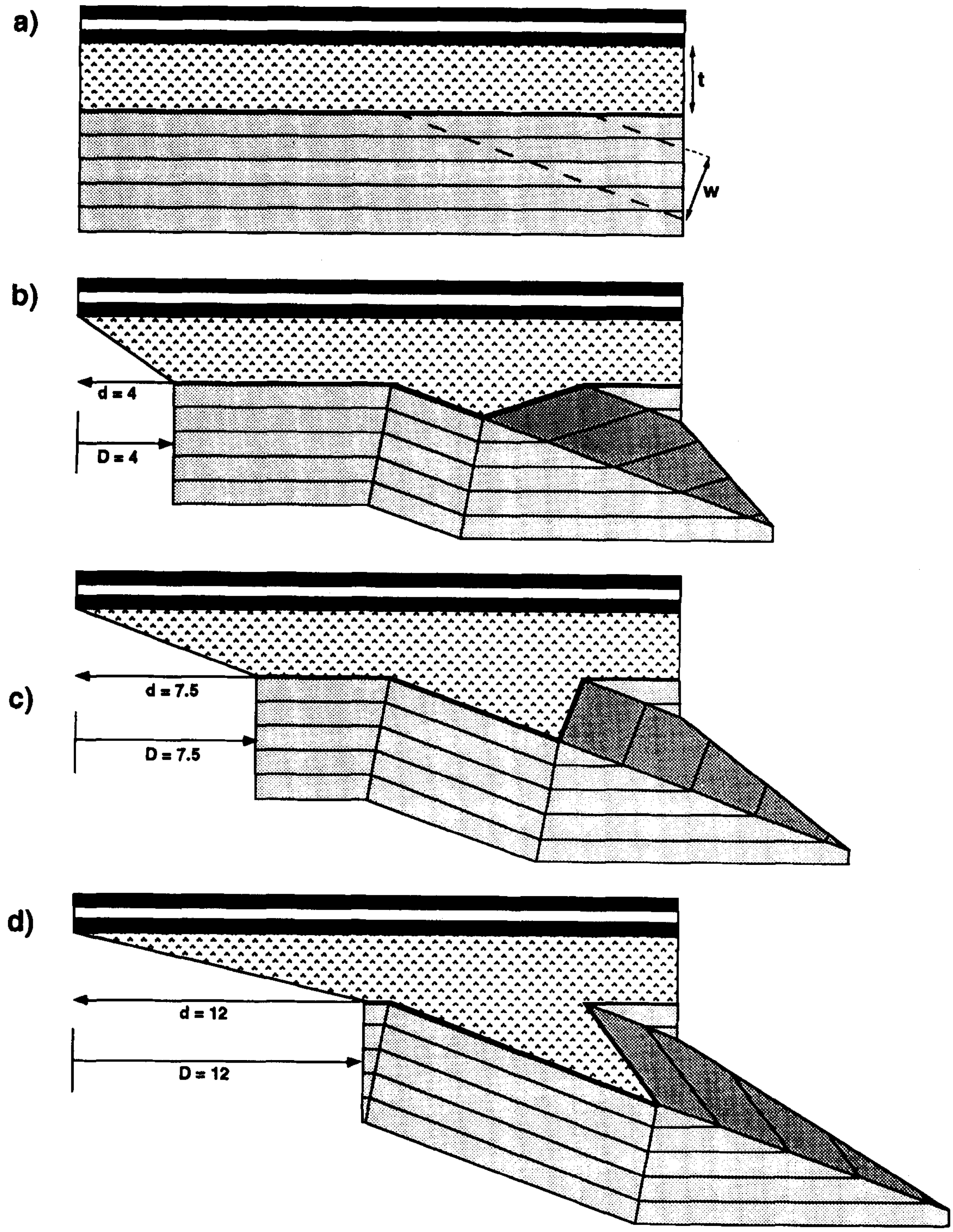


Fig. 6. Model evolution if the thickness of the detachment unit is equal to the width of the shear zone ($t = w$). In this case D remains equal to d during the progressive deformation.

thickness of the detachment level). From this graph we can conclude that:

(a) the shallower the dip θ, the larger is d;

(b) the maximum values of d (points M on the different curves) increase when the dip θ decreases. This increase is not linear; the differences between the curves are greater towards the small angles. For instance, a reduction of θ by 10° will increase the M value of approximately 3 units between 30° and 20°, and of 10 units between 20° and 10°.

The efficiency of the detachment mechanism is thus greatly improved by reducing the dip angle of the shear zone.

The influence of thickness t *of the detachment level and width* w *of the shear zone*

The special case where $t = w$ is considered first. This very particular initial setting is illustrated in Fig. 6. In this case, no synform is formed at the upper tectonic unit. The amount of shear produced in the lower tectonic unit is completely transferred to the shear within

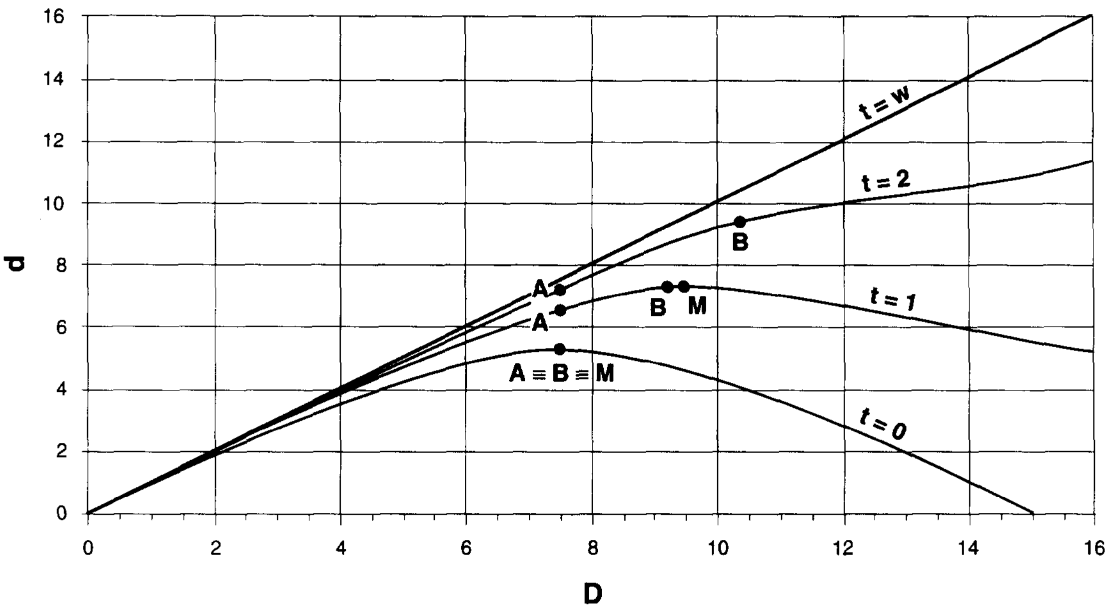


Fig. 7. Graph of d vs D for different thicknesses t of the detachment unit. Shear zone dip = 20°; shear zone width = 2.75.

the detachment level. The d value is equal to D for every value of D (Fig. 7).

When the thickness t of the detachment level is greater than the width of the shear zone, an antiform will be created in the upper tectonic level. The following discussion will be limited to the cases where $t < w$, a condition which appears to be most realistic in the European Alps.

The effect of the variation of t is illustrated in Fig. 7. The special case where $t = 0$ corresponds to a detachment on a discrete surface. It is characterized by the absence of a 'disharmonic effect'. Figure 8 represents the kinematic evolution of such a setting.

If the detachment level is thick enough (i.e. $t = 2$, Fig. 7), the curve of d vs D does not go through a maximum, but presents a decrease in slope beyond which d keeps growing but with a smaller increase. This intermediate setting between those of Figs. 3 and 6 is illustrated in Fig. 9.

Variations of the shear zone width w have two effects on the curves of d vs D (Fig. 10): (a) d and M (maximum value of the curves) increase if w increases; (b) if w decreases, a change in the shape of the curves appears. These do not present a maximum point anymore, but a decrease in positive slope (i.e. $w = 1.25$, Fig. 10), approaching the situation $t = w$.

In conclusion our model is mainly defined by two geometric parameters: (a) the dip θ of the shear zone; and (b) the ratio (t/w) of the thickness of the detachment level with respect to the width of the shear zone.

GEOMETRY OF THE FOLDS AND SIMPLE SHEAR ZONES

The former illustrations are based on a very simple geometry involving kink-style hinges and homogeneous simple shear. This simplification affects the value of d vs D. It does not affect however the basic principle of the model stating that a difference in horizontal shortening can take place simultaneously in two different superposed tectonic units. Similar models that satisfy this hypothesis can be built assuming rounded hinges and heterogeneous simple shear along a curved shear zone (Fig. 11). As in the kink-style model, each tectonic unit has to be area balanced, and the upper tectonic unit has to be, in addition, bed-length balanced. It is evident that rounded fold shapes adapt themselves easier to the hinge-line migrations taking place in the upper unit during progressive deformation (Figs. 3 and 11). Moreover, the heterogeneous shear in the detachment level, with higher shear values toward the upper tectonic unit, increases the amount of ΔV. This, together with the rounded fold hinges, makes it possible to attain higher D and d values before the right-hand synclinal fold limb in the upper unit becomes overturned (compare Figs. 3 and 11).

In Figs. 12(a) & (b) an attempt is made to integrate the model in a subducting continental crust. The basement fold nappe is shown here as a simple structure with only one active shear zone. In reality it is quite possible to imagine a complex nappe structure limited by several frontal folds generated by parallel shear zones. The superficial thrust sheet is characterized by the formation of a fault-bend fold (Suppe 1983). Any other type of thin-skinned tectonic structure could be formed here.

ISOSTATIC COMPENSATION

Any vertical variations in rock volume must be isostatically compensated. Therefore, the relatively important volume of basement rocks added downwards to the crust during the formation of the basement fold nappe of Fig. 12(b) must be followed by an isostatic adjustment (Fig. 12c). This will be an uplift corresponding approximately

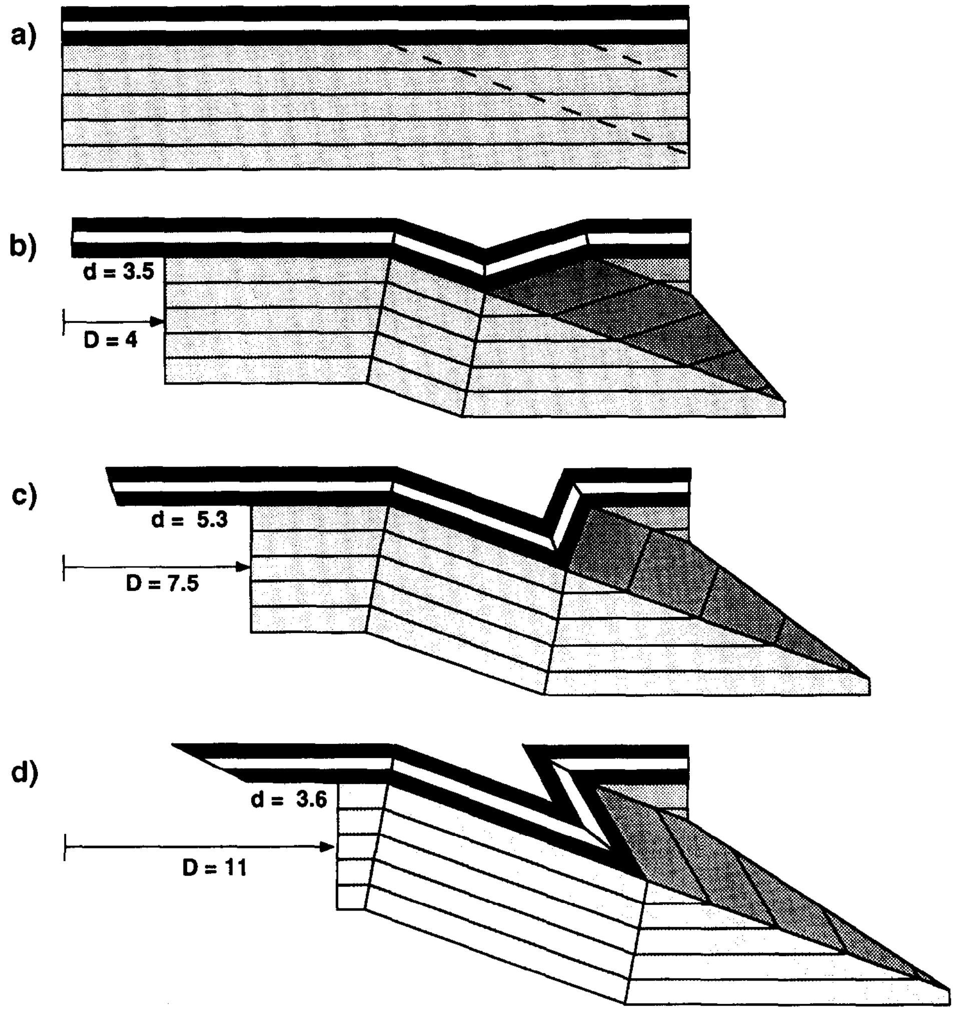


Fig. 8. Model evolution if the thickness t of the detachment unit is equal to zero. Shear zone dip = 20°; shear zone width = 2.75.

to only 1/5 the amount of subsidence (calculated for a density of the gneiss basement of 2.6). For similar reasons the upward addition of cover rocks in the thrust sheet will cause a subsidence in the external part of the model of approximately three-quarters the original uplift. The total approximate isostatic compensation causes a slight rotation of the entire structure without important internal modifications (Fig. 12c). At the topographic surface, the initially existing flysch basin is displaced to the left, while a new depositional basin could be formed in a more internal position, directly above the cover syncline (Figs. 12a & c). The final picture remains incomplete, lacking the effects of erosion and sedimentation.

PURE SHEAR COMPONENT

It is very likely that in reality the simple shear deformation in the lower structural unit often has a pure shear component superimposed on it. This could be a homogeneous flattening affecting the internal part of the lower unit or, more likely, it could be a heterogeneous wedge-shaped pure shear as proposed by Dietrich & Casey (1989) for some of the Helvetic nappes in the Swiss Alps. In this case the pure shear components decrease towards the external and upper parts of the nappes. Anyway the result would be an even more important difference in horizontal shortening between the upper and lower units, and hence an increase in d. Wedge-shaped pure shear oriented in the same direction as the simple shear zone in the lower level, would moreover increase considerably the amplitude of the fold structure at this level (Ramsay & Huber 1987, p. 620).

GEOLOGICAL CONDITIONS

In order to apply the proposed model geologically, the following essential conditions must be met.

(1) The pressure–temperature conditions existing in the lower tectonic level must allow the creation of wide ductile shear zones. These conditions could be induced by a pile of superficial nappes forming a 'traîneau écraseur' or tectonic lid, as was probably the case in the Alps (Termier 1903, Laubscher 1988, Schmid *et al.* 1990). During the progressive subduction of continental crust beneath the tectonic lid, a ductility front made the formation of successive ductile shear zones possible

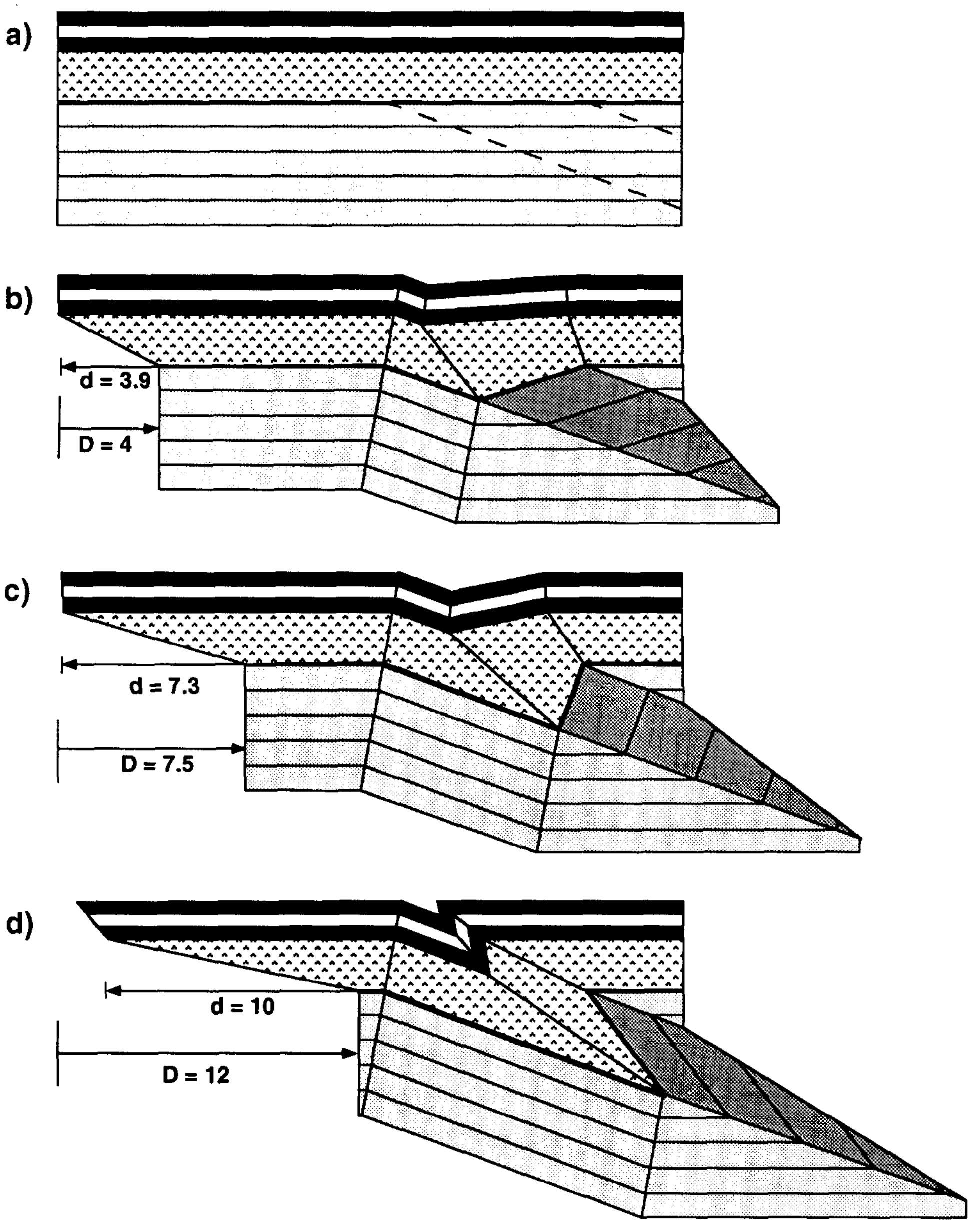


Fig. 9. Model evolution for a thickness t of the detachment unit = 2. Shear zone dip = 20°; shear zone width = 2.75.

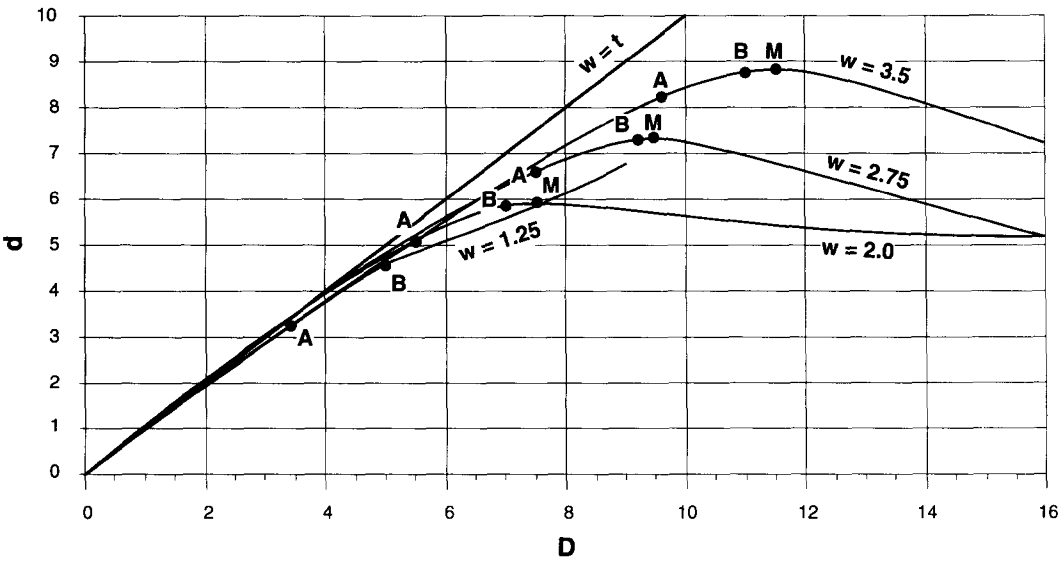


Fig. 10. Graph of d vs D for different widths w of the shear zone. Shear zone dip = 20°; thickness t of detachment unit = 1.

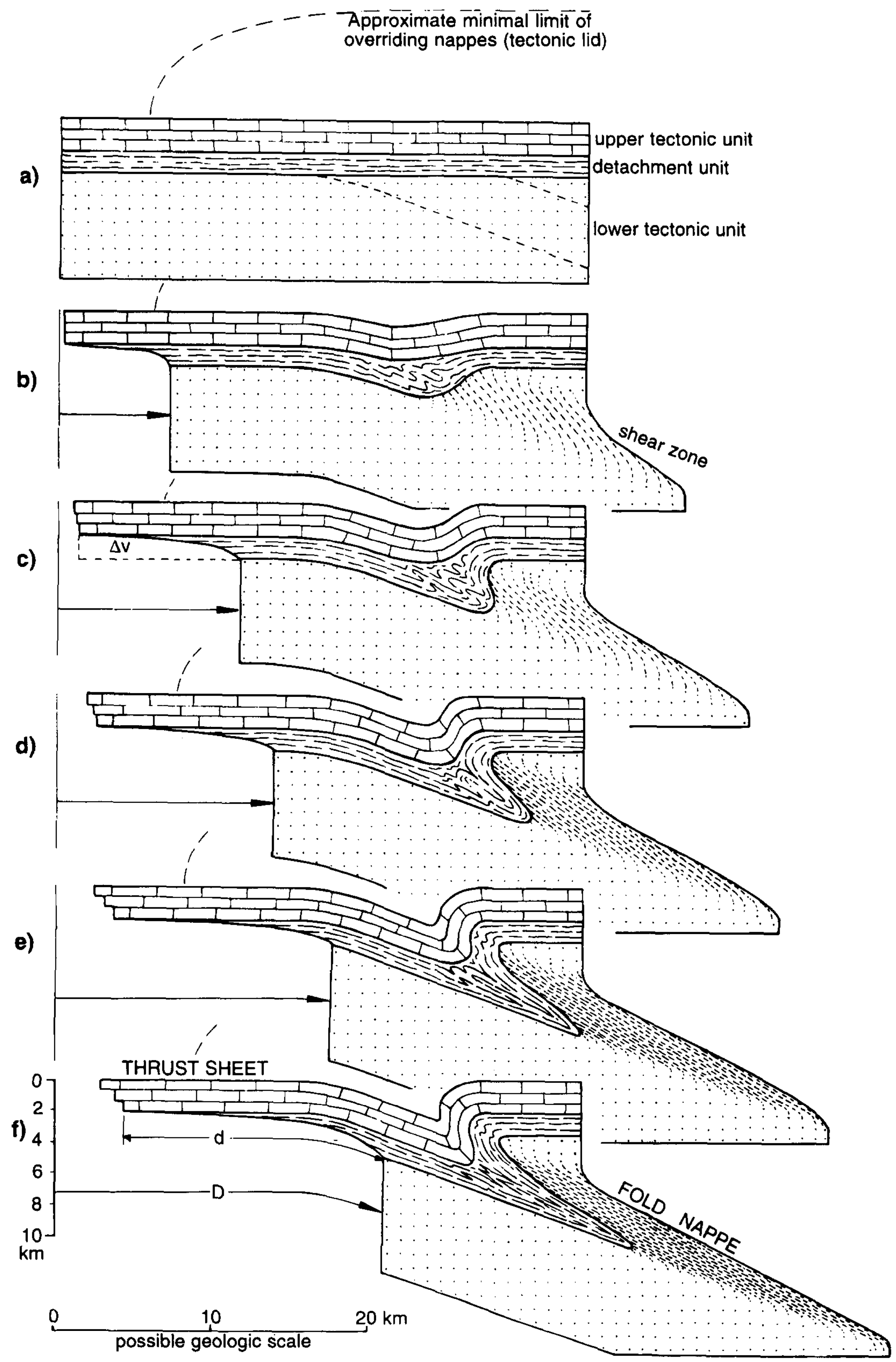


Fig. 11. Model resembling existing structures, with rounded hinges and heterogeneous simple shear, volume balanced for every unit and bed-length balanced for the upper unit. The orientation and intensity of the schistosity during progressive simple shear in the lower unit has been indicated approximately. It is assumed that during the last steps (e and f) the fold hinge of the upper unit becomes partially deformed by ductile shear, as it gets more and more dragged inside the lower shear zone.

(Steck 1987, Escher *et al.* in press.). It is probable that at an early stage of crustal subduction this ductility front was situated at great depth and that Monte Rosa-type basement fold nappes were formed here.

(2) The detachment unit must consist of ductile sediments. The most efficient units to enable detachment will be made of evaporites, shales, schists or flysch-type sediments. Fluid-rich remnants of accretionary prisms

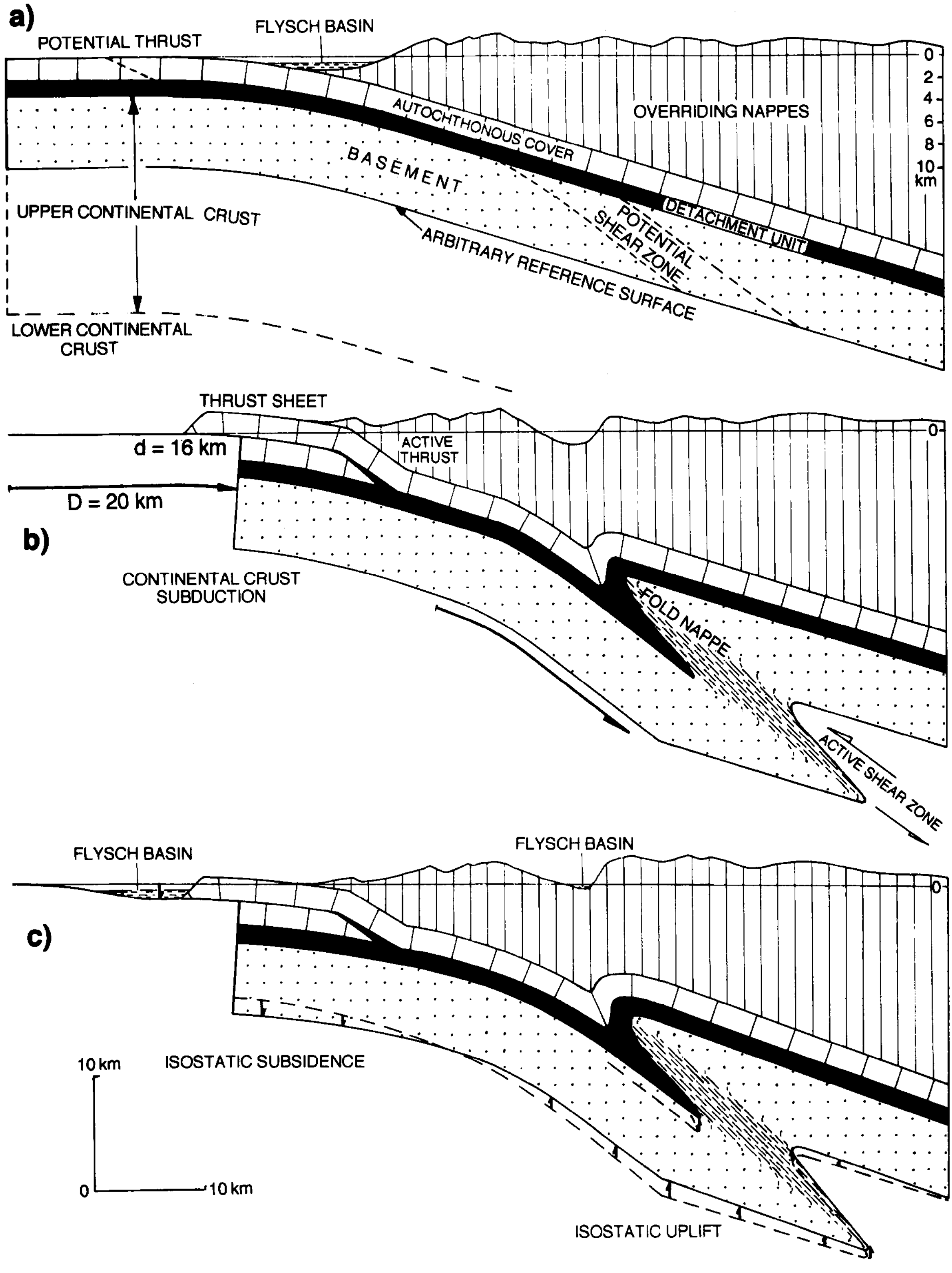


Fig. 12. Model similar to that of Fig. 11 (initial and final steps) adapted to a subducting continental crust and isostatically compensated. The superficial thrust sheet is here characterized by the formation of a fault-bend fold (Suppe 1983). The approximate isostatic compensation causes a slight rotation of the entire structure without important internal modifications (c). At the topographic surface, the initially existing flysch basin (a) is displaced to the left, while a new depositional basin could be formed in a more internal position, directly above the cover syncline (c).

probably were important detachment units during the early stages of basement nappe formation inside a subducting continental plate.

(3) The upper structural level should ideally consist of a stratified sequence in which bedding-parallel slip is possible. This could be a simple autochthonous sedimentary cover-sequence, or it could be a stack of various nappes separated by ductile layers. In both cases it is

necessary that the rock material can escape horizontally, generating one or more thrust sheets. These conditions exist generally at the frontal part of fold and thrust belts.

APPLICATION OF THE MODEL TO ALPINE STRUCTURES

The model is illustrated in the following pages by three examples from the Swiss Alps. It does not pretend to explain every detail of the generally very complex nappe geometry and kinematics. It is mainly, but not exclusively, designed to describe the first essential steps of nappe formation. The geological descriptions and figures are very short and simplified. For more extensive descriptions the reader is referred to the related publications.

Jura thrust sheet and the Infra-Rouges basement anticlines

The Jura mountain belt corresponds to the most external thrust sheet of the Alpine chain, formed during the Late Miocene and the Pliocene. It consists of Mesozoic and Cenozoic rocks, detached from their Palaeozoic basement. The Triassic evaporites form the detachment layer (Buxtorf 1907, Laubscher 1980, Jordan 1994). The structures in the Jura are typically those of 'thin-skinned tectonics' (Laubscher 1961). The Jura is separated from the main part of the Alpine chain by the Molasse Basin.

From published cross-sections the horizontal shortening accommodated by detachment folds and other structures can be estimated to be a minimum of 20 km. Ten kilometres have to be added as the minimal movement along the frontal thrust on the Bresse Graben. The total displacement of the Jura belt thus reaches at least 30 km. The Palaeozoic basement beneath the Jura or the Molasse Basin does not indicate any structures that could account for this amount of horizontal shortening. The origin of the Jura translation has therefore to be found south of the Molasse Basin. This is the 'Fernschubhypothese' proposed by Buxtorf (1907) and Laubscher (1961). Movements south of the Aiguilles-Rouges external crystalline massif cannot be at the origin of the Jura displacement for two reasons: (a) the Triassic evaporites are absent in the thin and only slightly displaced sedimentary cover of the Aiguilles-Rouges massif; (b) the main movements in the Helvetic units are older than the formation of the Jura. This leads to the conclusion that the origin of the Jura displacement has to be placed south of the Molasse Basin but north of the Helvetic domain.

New seismic data reveal the presence of three important seismic reflector-bundles in front of and below the Aiguilles-Rouges massif. They are interpreted as wedges of cover sediments separated by basement units (Escher *et al.* in press). These structures are probably geometrically similar to those of the Chamonix zone and are therefore represented as synclines in Fig. 13(a). If this interpretation is correct, the three synclines and their overlying basement fold-nappes could well have been generated by a mechanism similar to the one proposed in our model (compare with Figs. 11 and 12). The Jura cover displacement may then be the direct consequence of the formation of these three structures, cumulatively, or it could be the result of only the most external basement fold nappe.

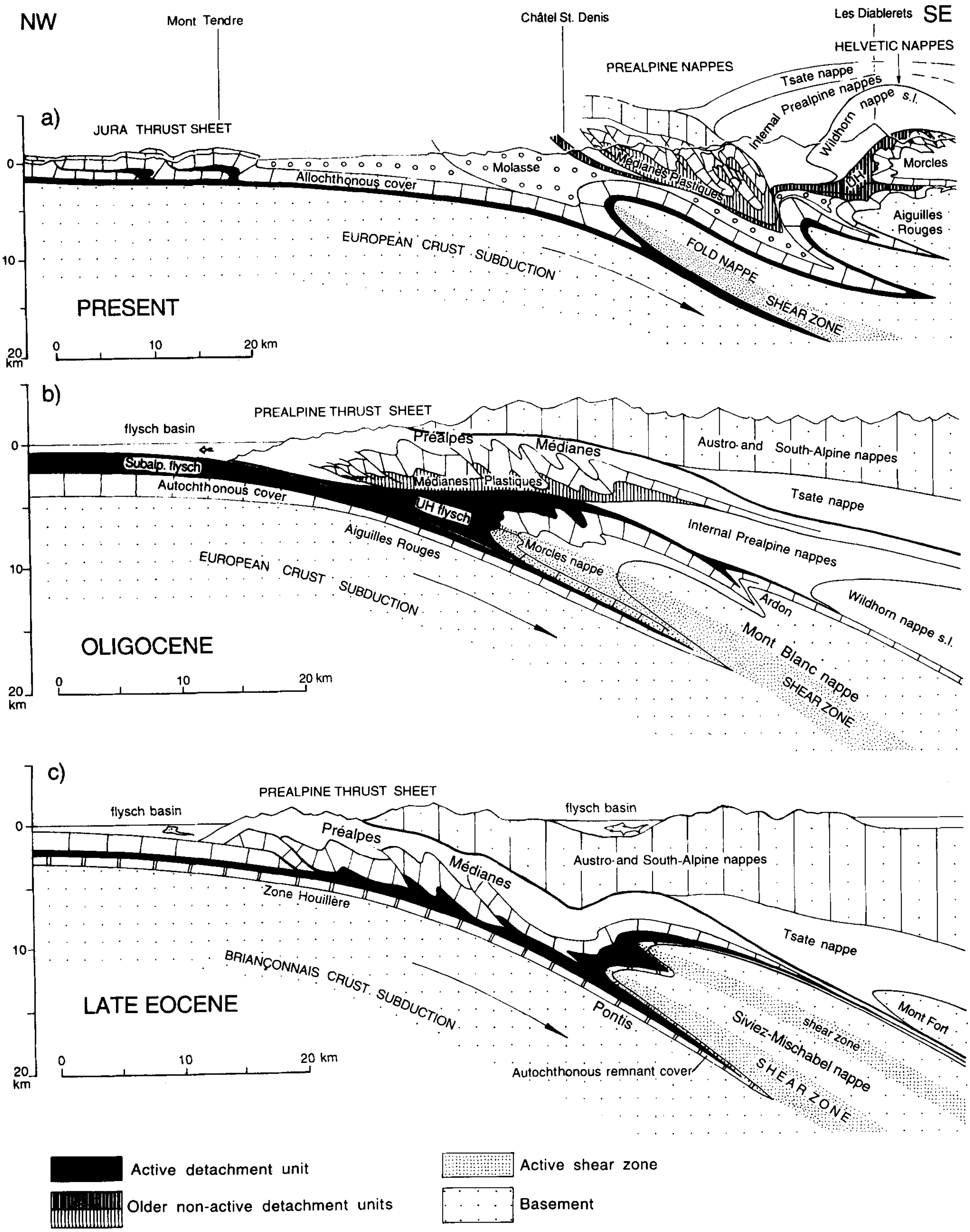
The Prealpine thrust sheet and the Morcles–Mont Blanc fold nappe

The Prealpine nappe complex forms a huge thrust sheet at the front of the main Alpine belt, overriding the southeast part of the Molasse deposits. It is composed of a stack of at least 12 different cover nappes of Penninic and southern Alpine origin. The entire complex rests presently on a basal detachment unit made of Morcles–Ultrahelvetic and Subalpine flysch deposits ('UH' on Fig. 13a). These flysch sediments constitute a tectonic link between the Prealpine thrust sheet and the underlying Morcles–Mont Blanc fold nappe to the southeast.

The Morcles nappe consists of a thick pile of Triassic to Lower Oligocene sediments. It forms a large overturned isoclinal anticline, with a NW vergence and with a basement gneiss core corresponding to the external Mont Blanc massif (Lugeon 1914, Badoux 1972, Ayrton 1980, Masson *et al.* 1980, Epard 1986, 1990). The inverted limb is clearly much more tectonically thinned than the normal flank (Ramsay 1981, Dietrich 1989). An important sediment-filled syncline, the Chamonix zone, separates to the northwest the Mont Blanc massif from the Aiguilles Rouges basement.

It is likely that at the end of the Early Oligocene the external part of the Prealps (mainly the Médianes Plas-

Fig. 13. Simplified and schematic examples from the Swiss Alps which can be explained in part by the proposed geometric model. The figures show three stages (from c to a) during which the active Alpine front moved in relative motion toward the northwest. Basement fold nappes were formed successively from the southeast to the northwest during continuous crustal subduction, while at the same time a frontal stack of Prealpine thrust sheets was built up. (a) Present cross-section through the external part of the Western Swiss Alps. The lower unit is composed of European crustal basement including a cover of Permo-Carboniferous and Lower to Middle Triassic sediments. The detachment level is made of Triassic evaporites and dolomitic breccias. The upper unit is essentially represented by the Jura and Molasse thrust sheet. This European crustal subduction took place probably during the Late Miocene and the Pliocene. (b) Cross-section showing the relationship which probably existed at the end of the Early Oligocene between the Prealpine thrust sheet and an embryonic Morcles–Mont Blanc fold nappe. The active detachment horizon was made of Ultrahelvetic and Subalpine flysch deposits. The Aiguilles Rouges basement was subducted along a ductile shear zone which created simultaneously the inverted limb of the Morcles–Mont Blanc nappe and caused the further 'advancement' to the northwest of the Prealpine thrust sheet. (c) Cross-section representing the relationship which may have existed during the Late Eocene between the Préalpes Médianes thrust sheet and the Siviez–Mischabel fold nappe. The active detachment unit was made of Triassic evaporites. The Pontis basement started probably to subduct along a ductile shear zone which generated simultaneously the inverted limb of the Siviez–Mischabel nappe and the Préalpes Médianes thrust sheet.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Mont Tendre
Châtel St. Denis
Les Diablerets
SE
HELVETIC NAPPES
PREALPINE NAPPES
Tsate nappe
Internal Prealpine nappes
Wildhorn nappe s.l.
a)
JURA THRUST SHEET
Molasse
Allochthonous cover
Médianes Plastiques
UH
Morcles
Aiguilles Rouges
EUROPEAN CRUST SUBDUCTION
FOLD NAPPE
SHEAR ZONE
PRESENT
0
10
20 km
b)
PREALPINE THRUST SHEET
flysch basin
Préalpes
Médianes
Austro- and South-Alpine nappes
Subalp. flysch
Autochthonous cover
Médianes Plastiques
Tsate nappe
UH flysch
Internal Prealpine nappes
Aiguilles Rouges
Morcles nappe
EUROPEAN CRUST SUBDUCTION
Ardon
Wildhorn nappe s.l.
Mont Blanc nappe
SHEAR ZONE
OLIGOCENE
c)
PREALPINE THRUST SHEET
flysch basin
Préalpes
Médianes
Austro-and South-Alpine nappes
Zone Houillère
Tsate nappe
BRIANÇONNAIS CRUST. SUBDUCTION
LATE EOCENE
Pontis
Mont Fort
shear zone
Siviez-Mischabel nappe
SHEAR ZONE
Autochthonous remnant cover
km
Active detachment unit
Older non-active detachment units
Active shear zone
Basement

Fig. 13.

tiques), was situated somewhere above an embryonic Morcles nappe (Escher *et al.* in press). Both units were separated by a thick horizon of Ultrahelvetic flysch. This ductile material acted probably as a detachment horizon during the progressive subduction of the Aiguilles Rouges basement and cover to the southeast, following more or less the rules of the proposed model. In this way the Morcles–Mont Blanc fold nappe could have been formed simultaneously with the advancement of the Prealpine thrust sheet toward the northwest (Fig. 13b). The width of the shear zone in the lower tectonic unit (Morcles–Mont Blanc) was approximately equal to the thickness of the Ultrahelvetic detachment unit (compare with Fig. 6). For this reason the Prealps, representing in our model the upper tectonic unit, have not been involved in the syncline separating the two basement units. The actual shape and internal structure of the Morcles nappe shows clearly that important pure shear deformation was superimposed on the simple shear (Dietrich & Casey 1989). This means that if the proposed model (Fig. 13b) can explain the main initial structures and displacements, later pure shear (flattening) deformation had to follow.

The Préalpes Médianes thrust sheet and the Siviez–Mischabel fold nappe

The Préalpes Médianes (Plastiques and Rigides) unit occurs in the external part of the Prealps where it was extensively studied by Badoux (1962, 1965) and Baud (1972). It forms the major body of the Prealps and has a stratigraphic sequence which ranges from Triassic to Eocene. This sequence is stratigraphically continuous in the northwest where shales and marls are common (Médianes Plastiques), but passes southwards to a much thinner sequence where stratigraphic gaps replace most of the ductile layers (Médianes Rigides). These sequences are mostly normal and display locally a thin-skinned structural style characteristic of thrust sheets (Plancherel 1979, Mosar 1991). The basal detachment zone is made of Middle to Upper Triassic evaporites.

According to Baud & Masson (1975), Baud & Septfontaine (1980) and Sartori (1987, 1990), the largest part of the Préalpes Médianes thrust sheet originated from the huge synclinal structure which links the Siviez–Mischabel fold nappe to the underlying Pontis basement (Fig. 13c). Stratigraphic sequences which complement the basal Médianes Plastiques are found in the Pontis normal limb, and for the Médianes Rigides in the overturned Siviez–Mischabel flank.

The Siviez–Mischabel nappe forms the central unit of the Grand Saint-Bernard super-nappe (Escher 1988). It has the geometry of a very large recumbent fold with an amplitude of more than 35 km. Surrounding the gneiss core, a Carboniferous to Triassic metasedimentary cover can be followed from the normal flank throughout the front of the nappe to its inverted limb. Most rocks of the Siviez–Mischabel nappe display an early Alpine penetrative axial-surface schistosity. The inverted limb is more intensely deformed than the rest of the nappe. A large syncline links this unit to the underlying Pontis nappe (Escher *et al.* 1993).

It seems possible that at some time during the Late Eocene the Pontis basement started to be subducted towards the southeast, creating thus an embryonic Siviez–Mischabel nappe (Fig. 13c). Simultaneously, following the rules of the proposed model, the cover sediments were detached along a basal Triassic evaporite horizon. In this way the Préalpes Médianes thrust sheet may have started to form and to move in a relative way to the northwest, together with its overlying tectonic units. As in the case of the Morcles–Mont Blanc nappe, this first important stage of deformation must have been followed and accompanied by penetrative flattening throughout most of the Siviez–Mischabel rocks. It is evident that this additional deformation must have caused an even more important translation to the northwest of the Prealpine thrust sheet.

DISCUSSION AND CONCLUSIONS

The proposed two-dimensional geometric model explains the possible relationships between superficial thrust sheets and deeper fold nappes. It demonstrates that the simultaneous formation of these two types of structure at different levels of the crust is possible. The geometry and the kinematics of the model are constrained by the subduction mechanism of continental crust: a mainly downward movement with respect to a fixed horizontal surface. Recent geophysical data (Fig. 1) have confirmed that compressional mountain belts are essentially the result of lithospheric subduction in which deformation and stacking of nappes took place within the upper part of the continental crust, while its lower part subducted in a passive way together with the underlying lithospheric mantle (Marchant 1993, Marchant *et al.* 1993, Willett *et al.* 1993, Beaumont *et al.* 1994, Escher *et al.* in press). The thickening of the upper crust during subduction must however be accompanied by an almost synchronous isostatic uplift. The amount of this uplift is a relatively small fraction of the downward movement and modifies only slightly the model (Fig. 12c). Its main result is the creation of an internal topographic high and a frontal depositional (flysch or molasse) basin. It is evident that the topographic relief of a compressional belt is only of minor geologic importance compared to the 40–60 km deep root zone.

In a schematic way, the model as summarized in Fig. 12 can be interpreted as a sequence of the following 'fashionable' structures: from an external discrete thrust-flat and ramp to a ductile and wider flat (detachment zone), to an internal and even wider ductile ramp (shear zone). It is logical to assume that even more internally and in depth, the ductile ramp must pass into an equally ductile and wide flat. This shallower dipping shear zone could be situated in the highly ductile lower portion of the upper crust, just above the Conrad discontinuity.

Examples from the Alps show that the proposed model can be applied to many cases where cover thrust sheets are directly related to basement fold nappes. Basement fold nappes were formed successively from the internal to the external part of the Alps, during continuous crustal subduction, while at the same time a frontal stack of Prealpine thrust sheets was built up (Figs. 12 and 13). This frontal Prealpine stack probably extended the tectonic lid to the northwest, making it possible to create ductile shear zones in the frontal basement areas.

It is evident that the proposed model only tries to explain the initial formation of ductile basement nappes. It is very likely that in reality the simple shear deformation in the lower structural unit is often superimposed by a pure shear component. This could be a homogeneous flattening affecting the internal part of the lower unit or, more likely, it could be a heterogeneous wedge-shaped pure shear as proposed by Dietrich & Casey (1989) for some of the Helvetic nappes in the Swiss Alps. Anyway, the result would be an even more important difference in horizontal shortening between the upper and lower units, and hence an increase in d value. It would moreover increase considerably the amplitude of the basement fold nappe structure (Ramsay & Huber 1987, p. 620), and cause an oblique upward 'extrusion' of lower level rocks. This mechanism may well be responsible for bringing near the surface high-pressure eclogitic rocks at an early stage of continental crust subduction.

Whatever the importance of the pure shear (flattening) component, it is likely that the proposed model, with its simple shear mechanism, accounts for most of the crustal shortening in the upper crust.

It is clear that the proposed model only deals with the formation of ductile basement fold nappes and their related superficial thrust sheets. In no way does it exclude the possibility of generating basement thrust slices in higher and more external parts of the basement, where temperature and pressure conditions do not allow ductile strain to take place. In such a case the model could still be valid, only it would be considerably simplified, the shear zone width w going towards 0. The amount of D would always be equal to d, independent of the thickness of a possible detachment unit. But then, of course, no inverted limb would be formed in the basement.

Finally, if the model proves to be acceptable, it should be completed in three dimensions, taking into consideration non-cylindrical lateral extensions and oblique transtensional movements.

Acknowledgements—John Ramsay is particularly thanked for his help and encouragement and for constructive critical reading of the manuscript. We also thank very much Chris Beaumont, Martin Burkhard, Rick Groshong, Michel Jaboyedoff, Robin Marchant, Henri Masson, Gérard Stampfli and Albrecht Steck, for their help during the preparation of this paper. Dorothée Dietrich, Peter Hudleston and an anonymous reviewer greatly improved the manuscript. Financial support by the Swiss National Science Foundation (grants 21.31082.91 and 20-37470.93) is gratefully acknowledged.

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