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Thrust structures in the eastern Dauphinois Zone (French Alps), north of the Pelvoux Massif

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Abstract—An examination of thrust structures in the eastern part of the Dauphinois Zone of the external French Alps (referred to in the literature as the Ultradauphinois Zone) shows that major basement thrusts climb up section to produce cover–basement synclines. These thrusts also climb laterally and are continuous with thrust in the cover rocks. The external basement massifs are recognized as thrust sheets with variably deformed and thrust cover sequences. The distinction made in the previous literature between the Dauphinois and Ultradauphinois Zones is no longer tenable. Cover thrusting proceeded by both smooth slip and rough slip, the latter producing a duplex of cover thrust slices. Restoration of this duplex indicates that a shortening of 70 km in the cover occured during its formation. Possible errors in this estimate include uncertainties in the original stratigraphic thickness and in the overall shape of the duplex. Another duplex is thought to have formed at a basement ramp created by the presence of an early basement normal fault. Partial footwall collapse of this basement ramp gave rise to a basement horse at the bottom of the duplex. The overall relation between cover and basement thrusting is indicated using a hanging wall sequence diagram. Recent geophysical studies suggest that the basement thrusts developed from a mid-crustal décollement which passes down dip to offset the Moho. Model studies of thin-skinned tectonics may not be appropriate to such thrust geometries.

INTRODUCTION

THE PRINCIPAL domains or units of the western Alps are summarised and reviewed by Ramsay (1963), Debelmas & Lemoine (1970) and Debelmas & Kerckhove (1980). Each major unit is seen as a structural entity bounded by thrust surfaces, the rocks in each constituting a different palaeogeographic realm. Thus the Dauphinois Zone is described as consisting of Mesozoic cover sequences resting on external crystalline basement. The internal zones of the sub-Briançonnais, the Briançonnais, the Schistes Lustrés and the Austro-Alpine nappes have all been thrust towards the west, and since the basal thrusts of each major nappe record large horizontal displacements, each zone is typified by a stratigraphy different from adjacent zones. The Ultradauphinois Zone has been defined (Ramsay 1963, Debelmas & Lemoine 1970) as the detached cover of the Dauphinois Zone below the sub-Briançonnais, etc. zones.

Figure 1 shows the Ultradauphinois Zone based on the definitions and maps of Barbier (1948). A strike length of 50 km is exposed and much of this is covered by recent 1:50,000 litho-stratigraphic maps (No. 798 La Grave, No. 774 St. Jean, B.R.G.M.). However, recent research in the French Alps recognises that many of the external basement massifs are thrust sheets (Ménard 1980, Thouvenot & Perrier in press, Perrier & Vialon 1980). Cover sequences resting on the basement were carried forward on these thrust basement masses. Thus it is suggested that the definition of the Ultra-dauphinois Zone as the para-autochthonous cover in the external Alps breaks down, and the use of this term should perhaps be discontinued. Further, examination of the basement–cover relations on the northern margin of the Pelvoux massif led Beach (in press) to conclude that basement thrusts climbed section sideways and were continuous with cover thrusts that previously constituted the Ultradauphinois Zone. This interpretation goes against that presented by Barbier (1963), Bartoli *et al.* (1974), Gidon (1979) and Bravard & Gidon (1979), but provides a consistent explanation of the geometry of thrusts in this area as originating in one main phase of post-Nummulitique deformation. Again, the distinction between the Dauphinois and Ultradauphinois Zones is lost when such an interpretation is made.

The interpretation here, presented principally as five cross-sections, is based on the approach that has been developed in the Rocky Mountain thrust belt, as summarised by Dahlstrom (1969, 1970), Bally *et al.* (1966), Elliott (1976a, 1976b) and Price (1973). Briefly, thrust surfaces arise at a décollement level and climb stratigraphic section in the direction of movement, generally dipping in the direction from which they moved, and also generally developing in a systematic sequence such that younger thrusts form in front of older zones, and carry these older thrusts forward in a 'piggy-back' fashion (Dahlstrom 1970).

Cross-sections can be drawn and interpreted by recognising the different décollement levels that were active, and, knowing the stratigraphic thicknesses, by rooting thrust faults back down to their original stratigraphic level (Dahlstrom 1969, Bally *et al.* 1966, Hossack 1979). In an area such as that described here, where all thrust faults have moderate to steep dips and where no down dip windows exist, the positions at which thrust faults are shown to root, in the cross-sections, are often arbitrary (cf. Bally *et al.* 1966, Hossack 1979).

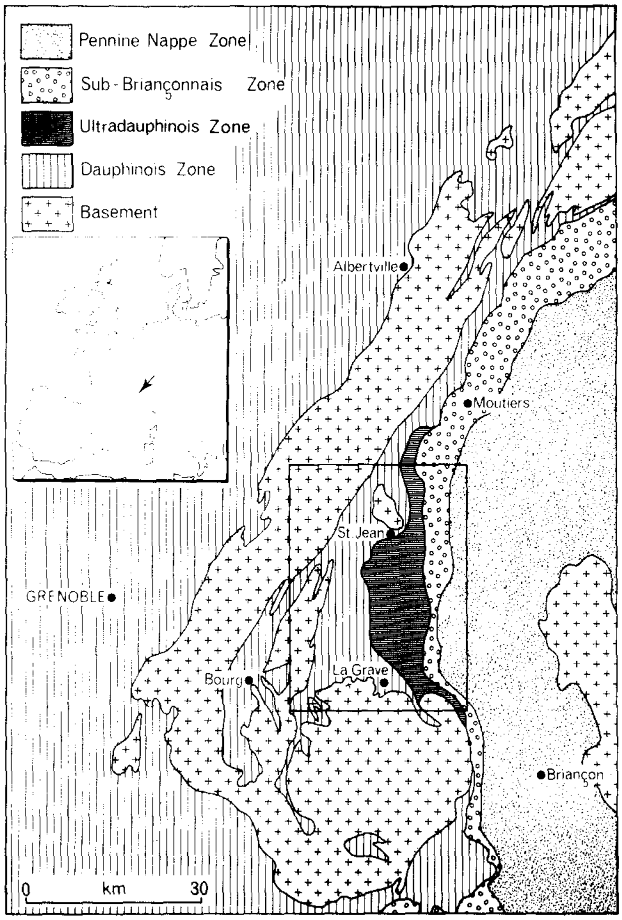

Fig. 1. Map showing the distribution of the principal zones in the French Alps (based on Barbier 1948 and Ramsay 1963). The area covered by Fig. 2 is indicated by the rectangle.

SUMMARY OF STRATIGRAPHY

The Mesozoic stratigraphy of the area consists of Trias, lower to middle Jurassic, with a little upper Jurassic, but no Cretaceous. A Tertiary sequence rests unconformably on the Mesozoic. Excellent summaries are presented by Ramsay (1963) and Barbier (1948), and the sequence is similar to that described by Gratier & Vialon (1980) for the Oisans area.

In the south, a thin Triassic sequence rests unconformably on Pelvoux basement and consists of a thin (1 m) arkose followed by up to 20 m of limestone and dolomite. There is a transition through dolomites and shales to lower Lias muddy limestone–shale alternations (20–80 m) followed by a sequence of lower to middle Jurassic shales. The Mesozoic succession is strongly imbricated NE of the Pelvoux massif and this tectonic telescoping of the stratigraphy exposes no great change in rock type or thickness until the topmost sheet is encountered. Here rocks with some affinities to the Briançonnais zone are found, i.e. shallow water and dolomitic rocks in the lower Lias, possibly laterally equivalent to stratigraphic breaks in the Briançonnais proper (cf. Ramsay 1963).

Northwards from the Pelvoux massif, and south of St. Jean (Figs. 1 and 2) the Mesozoic consists of up to 300 m of lower Jurassic muddy limestone–shale alternations followed by up to 500 m of lower to upper, Jurassic shales. Beneath this Jurassic sequence the Trias is much thicker. Gypsum is absent from the sequence at the southern end of the area around the Pelvoux massif, but appears to the north and attains a (deformed) thickness of about 200 m south of St. Jean. Basal Trias is not seen here, but immediately north of St. Jean (on the Grand Chatelard massif), it is similar to that around La Grave.

Rocks of middle Eocene age rest unconformably on all units of the Jurassic and Triassic, and cut down onto basement rocks SE of Lautaret and NE of St. Jean (Fig. 2). The basal deposits are conglomerates of very variable thickness (0–200 m), containing many basement pebbles and slumped limestone beds, and calcareous shales. These are followed by a present thickness of about 1500 m of flysch. The stratigraphy, and hence the internal structure of the flysch is largely unknown.

DÉCOLLEMENT LEVELS AND COVER-BASEMENT RELATIONS

One of the most effective ways of illustrating the development of a thrust belt is by constructing a hanging wall sequence diagram (Elliott & Johnson 1980). This diagram illustrates, through a sequence of longitudinal sections, how a thrust belt developed its structure as it passed forwards over successive footwalls during its displacement history. The diagram thus summarises not just the time sequence of thrust development, but also the levels at which décollement developed and the but also the levels at which décollement developed and the longitudinal changes in thickness in thrust sheets resulting from lateral climb of thrusts. In the present area, such a diagram is the most succinct way of describing the cover–basement relations. The diagram has been compiled from interpretation of the geological maps, and the cross-sections presented in Fig. 3, and is shown in Fig. 4.

Décollement levels are recognised in the basement and the cover. Basement thrusts emplaced the Combeynot, La Meije and Plateau components of the Pelvoux massif, separate the eastern and western parts of the Grandes Rousses massif, and underlie the basement horses of Grand Chatelard (cf. Gasquet 1979) and Sapey (see Figs. 2, 3 and 4) (see Perrier & Vialon 1980). The evidence for a pre-Nummulitique age for the basement thrusts is scant (Bravard & Gidon 1979). Rather than being truncated at the base of the Eocene succession, these thrusts are seen to climb to and pass into this horizon, which is marked by a shale sequence and acts as a local roof thrust. This is thus a cover décollement level, though thrusts are not seen, at the present level of erosion, to cut up through or to climb from this décollement. Décollement also occurred near the base of the Mesozoic succession, at the shales marking the transition from Trias to Lias, or if there is a Triassic gypsum layer present, at the base of this.

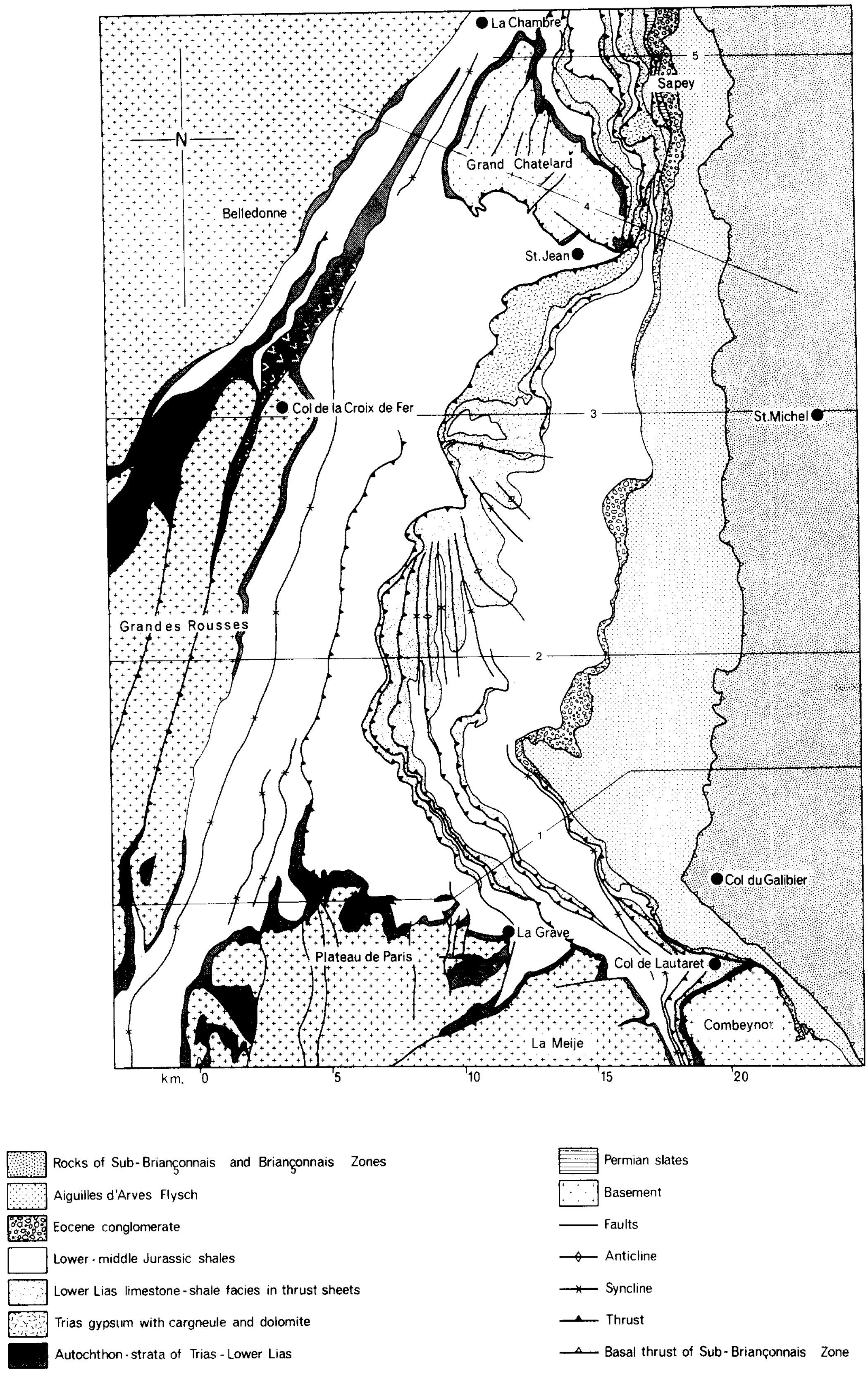

Fig. 2. Simplified geological map of area, located in Fig. 1, discussed in this paper. Principal rock types, and thrusts and folds are shown. The lines of cross-sections drawn in Fig. 3 are also shown. (Based in part on B.R.G.M. sheets 798-La Grave, 774-St. Jean de Maurienne).

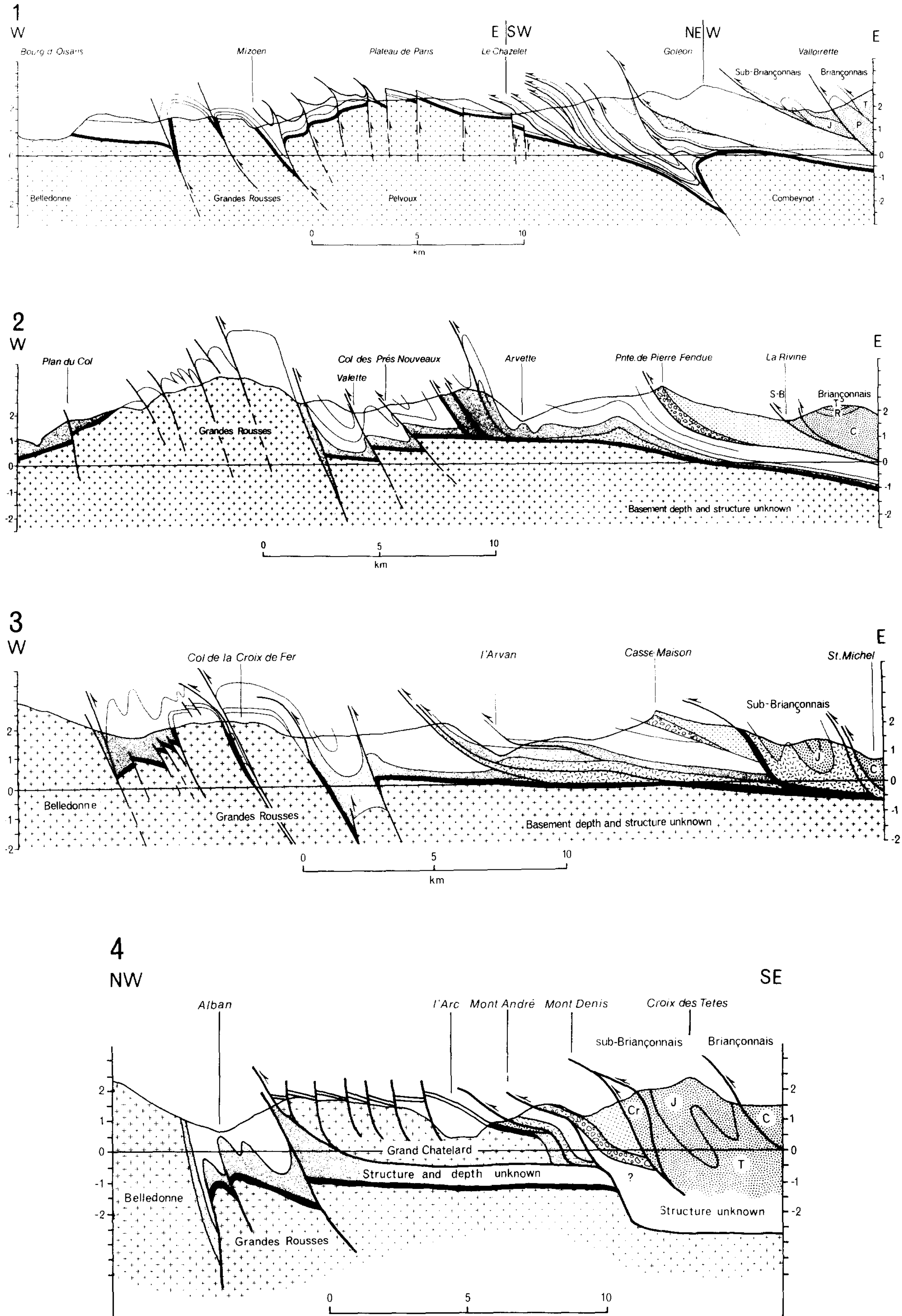

Fig. 3. Sections 1–4.

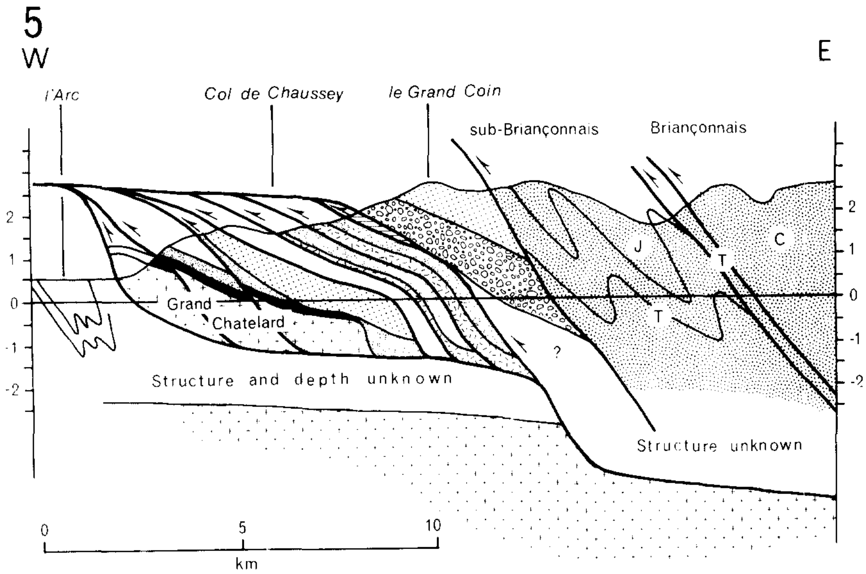

Fig. 3. Five cross-sections, located on Fig. 2, showing an interpretation of thrust geometry and of relations between basement and cover tectonics. The horizontal and vertical scales are equal for all the sections. The ornamentation used is the same as in Fig. 2. The letters C, R, T, J, Cr refer to rocks of Carboniferous, Permian, Triassic, Jurassic and Cretaceous age respectively in the Briançonnais and sub-Briançonnais zones. In many cases the depth to unexposed basement, and the structure within this basement are not known.

Section 1 : Principal basement thrusts emplacing segments of the Grandes Rousses and western Pelvoux massifs are shown. A central Grandes Rousses cover 'syncline', and a wider but similar structure at Mizoen, are produced. Hanging wall reverse faults across the Plateau de Paris are clearly seen. The imbricate sequence of cover thrust slices east of Le Chazelet and beneath the flysch can only be shown schematically at the scale of this section. The Combeynot massif and overthrust are projected onto this section from 7 km to the south of the actual line of section, where this structure is well exposed (Fig. 2). Since the Combeynot thrust shows lateral climb northwards, the exact nature of the basement structures beneath this part of the section are not known. Eocene conglomerates rest unconformably on the Combeynot basement.

Section 2: This section shows a more complex structure in the Grandes Rousses basement. To the east, cover structures are shown, but nothing is known concerning basement structure or the depth to and inclination of the pre-Triassic surface. Folding of cover rocks is seen to be more important than on section 1.

Section 3: This section passes through the northernmost part of the well-exposed Grandes Rousses basement. The nature of basement structures to the east of here is not known. In the cover both imbrication and folding have become much less important than in the previous two sections. Smooth slip on the glide horizon of Triassic gypsum has climbed section to produce one major thrust and two subsidiary thrusts in the area of the Arvan valley. The base of the Eocene conglomerates is little deformed and rests with a low angle discordence on upper Jurassic rocks.

Section 4: North of section 3, the Grandes Rousses basement plunges beneath Mesozoic cover, lateral climb of thrusts cutting out basement slices and reducing the width of this massif. The Grand Chatelard is shown thrust on a flat-lying surface (Gasquet 1979), the massif being affected by a number of small-displacement reverse faults. The position at which the Grand Chatelard massif was scooped from the basement is not known, and is shown schematically on the section to illustrate this interpretation of the rooting relationships. The structure beneath the Grand Chatelard thrust is not known.

Section 5: Similar relationships and comments as above for section 4. Section 5 shows the complete interpreted duplex of thrust slices of which the Grand Chatelard is the lowermost, and the thin slice of Permian (?) slate of Sapey is the uppermost. The geometry of this section is made more complex because rocks of Eocene age, found in one sheet in the duplex, rest with original unconformity on Jurassic, Triassic and basement at different points. It is not known what age rocks underlie the Eocene conglomerates of le Grand Coin at depth.

The climb up section of thrusts through the basement and emplacement of basement over cover produces the characteristic cover–basement syncline geometry. In his section from Grenoble to Pelvoux, Ramsay (1963) interpreted these structures as pinched in synclines produced by a competence contrast between cover and basement undergoing shortening. The recognition that such synclines are more commonly produced by overthrusting basement (Gratier & Vialon 1980, Thouvenot & Perrier 1979, Bravard & Gidon 1979, Ayrton 1980) was an important step forward in understanding Alpine tectonics. In the area under discussion, some of the faults have been shown to have a complex history, being initiated as normal faults during the early stages of the Alpine cycle where they controlled lower Jurassic sedimentation (Arnaud *et al.* 1978, Barféty *et al.* 1979, Graciansky *et al.* 1979, Vialon 1979, Gratier & Vialon 1980). Such faults are considered to have been reactivated as thrusts during the Alpine orogeny. However, there is a difference in the kinematic pattern between the interpretation of Vialon (1979) and Gratier & Vialon (1980), and that preferred here. The former show steep basement faults acting with a normal down dip displacement during the main Alpine deformation, the faults possibly steepening with depth and apparently without a décollement level to which they root. Following Perrier & Vialon (1980), it is now thought that the basement faults are listric in geometry. Gasquet (1979) has recorded the flattening with depth of the cover synclines in the basement (of the Belledonne massif). A greater resolution of deep crustal structure is clearly needed. In the sections presented here (Fig. 3, sections 1 and 3), basement faults are shown as thrusts climbing up through basement and then cover to put basement over a thin strip of cover. The structural development is analogous to the duplex of Elliott & Johnson (1980). The Combeynot structure (Fig. 3, section 1) is taken as the type example because the thrust forming the contact between the Combeynot massif in the hanging wall and the deformed unconformable cover to the La Meije massif in the footwall is clearly seen. It is inferred that the nature of the Mizoen fault (Fig. 3, section 1; cf. Gratier & Vialon 1980, fig. 14) is similar, but the basement of the hanging wall is not exposed at the present level of erosion. During the thrusting, the basement massifs were internally deformed and commonly an Alpine strain was superimposed on a pre-Alpine strain. Deformation may have been penetrative, localised in shear zones or as faults. The Combeynot massif has a penetrative fabric, part of which passes up through both the Triassic and Eocene unconformities. In the Plateau area and in the Grand Chatelard massif (Fig. 3, sections 1 and 4) numerous reverse faults are interpreted as hanging wall faults developed during emplacement of the basement over cover.

The hanging wall sequence diagram (Fig. 4) implies an orderly east to west development of thrusts through time according to the evolution of thrust belts proposed by Elliott & Johnson (1980). Such a sequence is recorded in the present area where the basement thrusts carrying the Combeynot, La Meije and Plateau parts of the Pelvoux massif successively cut up into the overlying cover. They each fold thrusts in this overlying cover. In addition, the slaty cleavage in the cover thrust sheet is deformed and crenulated by the deformation associated with the thrust cutting up from basement.

Figure 4 also illustrates how the basement thrusts undergo lateral climb into the cover so that movement can occur simultaneously in basement and cover in a longitudinal section of the thrust. The details of the relation of both the Combeynot and La Meije thrusts to the cover structures have been presented by Beach (in press). The northern margin of the Pelvoux basement massif as a structural high is thus considered to result from the northward lateral climb of thrusts into the cover. Basement is not involved in the thrust slices between La Grave and St. Jean (Fig. 2) at the present level of erosion. At the latter locality, the Grand Chatelard massif appears, as shown by Gasquet (1979) to be underlain by a gently dipping thrust, and interpreted to be a rootless 'ile flottante', or tectonic horse. The relation between basement and cover thrusts is not clear in this region. The interpretation presented here is that the Grand Chatelard horse evolved more or less synchronously with the major displacement thrusting the La Meije massif (Fig. 4). Structurally above the Grand Chatelard massif is a small slice of basement incorporated at the base of the Eocene succession—the Sapey horse (Fig. 4).

The origin of these horses is of interest. Elliott & Johnson (1980) describe the formation of a duplex through the accumulation of horses produced by progressive footwall collapse during thrusting. The duplex zone situated NE of St. Jean (Figs. 2 and 3, sections 4 and 5) consists of thrust slices of cover rocks except for the lowermost which is the Grand Chatelard massif itself. An explanation prompted by detailed mapping in the Col de la Croix de Fer (Fig. 2) region (V. Davies, pers. comm.) is proposed. Graciansky *et al.* (1979) have recognised normal faults in the French Alps that controlled sedimentation during the Jurassic. An example has been described by Barféty *et al.* (1979). During later thrusting, movement along a Trias-Lias décollement horizon will encounter these faults as pre-formed ramp structures (cf. Talbot 1979). In an attempt to climb such a ramp, the cover thrust sheets may undergo hanging-wall imbrication (cf. Dahlstrom 1970) possibly accompanied by partial footwall collapse producing a basement horse(s) at the bottom of the imbricate stack. Thin basaltic lava flows are developed locally in the Triassic sequence, and may record proximity to one of the major early normal faults described by Graciansky *et al.* (1979). Such a lava is present in the Triassic cover resting unconformably on the Grand Chatelard basement and this may be used in support of the hypothesis of basement imbrication at the site of an early normal fault. Also, the Triassic sequence contains a gypsum layer east of St. Jean but not to the west, suggesting a change in conditions of sedimentation in this area.

To summarise this section, it is suggested that (i) basement thrusts climbed section in the direction of movement to produce cover–basement synclines, (ii) these thrusts show lateral climb into cover and are post-Nummulitique in age, (iii) thrust develpment by progressive footwall collapse occured from east to west and (iv) some basement horses may have been generated where cover décollement encountered pre-existing normal faults stepping up the basement.

IMBRICATION OF THE COVER SEQUENCE

The cover rocks in the area under discussion vary from a single thrust sheet with a normal stratigraphy, in the central region, to an imbricated sheet further north and south (Figs. 2 and 4). The geometry and possible causes of the imbricates will now be examined.

In the area south of St. Jean, the thrust sheet is décollé on a thick basal gypsum, overthrust onto Jurassic shales, and from bottom to top the sheet is essentially a straightforward stratigraphic sequence of about 1 km of Mesozoic and a maximum present thickness of 1 km of Tertiary (Fig. 3, section 3). The basal gypsum is very strongly deformed and most of the thrust movement appears to have occurred at this level. The lower Jurassic records a low strain, but in the middle to upper Jurassic shales the strain dies out and the rocks are little deformed, as is the transition from Jurassic to Tertiary.

As this simple thrust sheet is traced southwards, the basal gypsum dies out (Fig. 2). The rocks are seen to have been folded, the large folds being mapped out most clearly by the lower Jurassic limestone–shale facies (Figs. 2 and 3, section 2). At the same time these folded rocks are

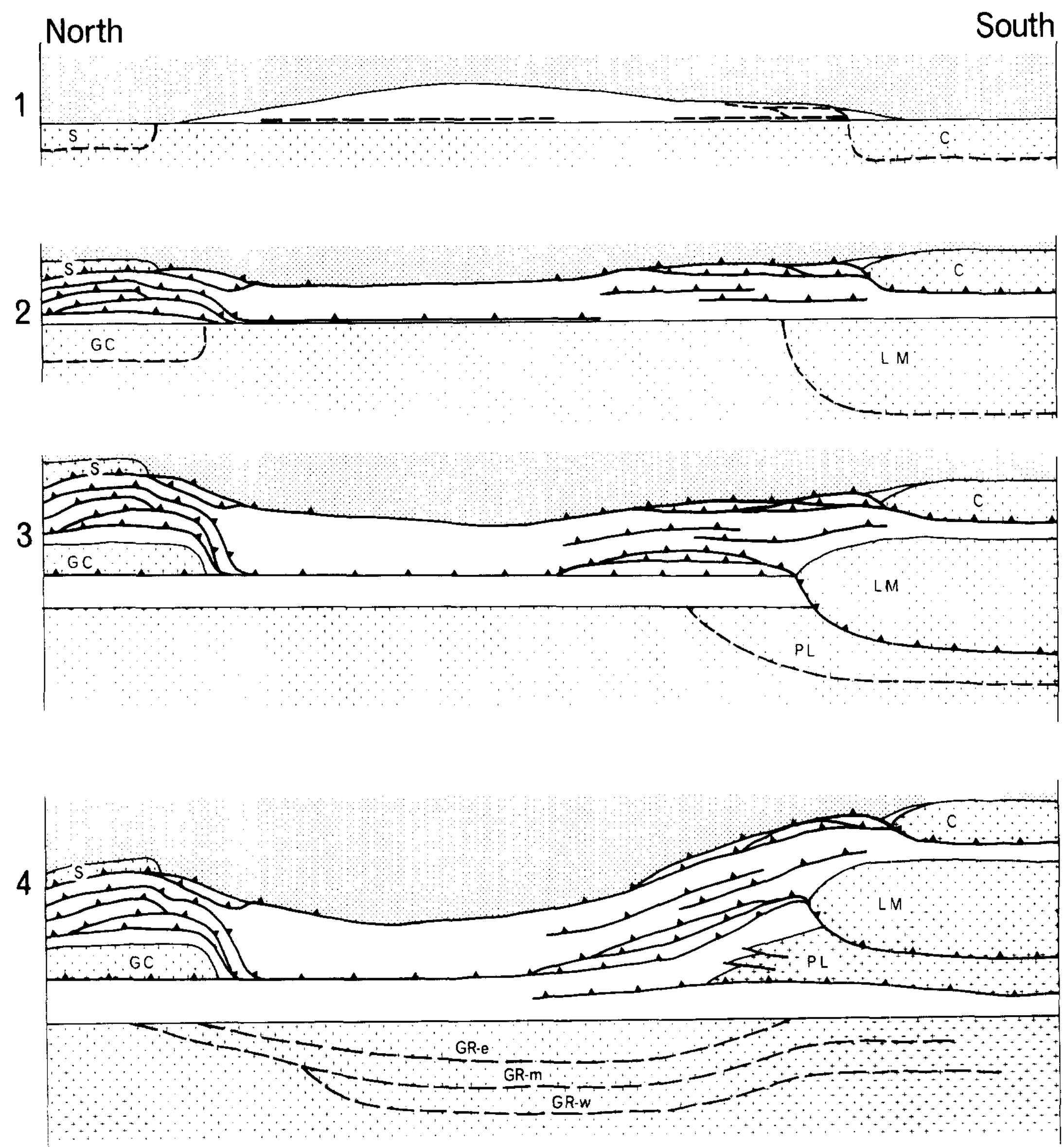

Fig. 4. Schematic hanging-wall sequence diagram from N to S in the area covered by Fig. 2, i.e. from the region of the Grand Chatelard massif in the north (left) to the northern margin of the Pelvoux massif in the south (right). This diagrammatic representation is the most succinct way of summarising the longitudinal correlation and development of thrusts in the area. No exact scale is intended. The Aiguilles d'Arves flysch and higher structural units are shown in stippled ornament, while the pre-Triassic basement rocks are shown in cross-ornament. The Mesozoic rocks lying between are not ornamented. Incipient thrusts are shown as dashed lines, stratigraphic contacts as ordinary lines, and thrusts and glide horizons as barbed lines. (1) The sequence starts after the emplacement of the Briançonnais and sub-Briançonnais units, the thrusts of which are therefore not shown. The Eocene Aiguilles d'Arves flysch and conglomerates rest unconformably across Mesozoic rocks, cutting down to basement in both the north and south at Sapey (S) and Combeynot (C) respectively. The thickest Mesozoic succession preserved lies in between these regions. The positions of incipient thrusts in the basement are shown. They show lateral climb and isolate the basement segments of Sapey (S) and Combeynot (C). Incipient glide on the gypsum near the base of the Mesozoic in the central region is also shown.

(2) The Sapey (S) and Combeynot (C) basement slices move west, the thrusts climb section and carry basement over a westerly increasing thickness of Mesozoic beneath the Eocene unconformity. Rough slip on the Trias beneath these overthrust basement slices produces the duplex zones of St. Jean (in the north) and La Grave (in the south). The thickest part of the Mesozoic sequence lying between these areas undergoes smooth slip on the Triassic gypsum glide horizon. The positions in the basement of the next incipient thrusts are shown. They show lateral climb to isolate the Grand Chatelard (GC) massif in the north and the La Meije (LM) massif in the south.

(3) The interpretation shows one major thrust moving west and climbing section. In the north this thrust carries the Grand Chatelard massif (GC) and in the south the La Meije massif (LM). In the central area, glide on the thick Triassic gypsum climbs section and places Triassic, etc. over M. to U. Jurassic rocks. The Grand Chatelard thrust climbs section to place basement over Jurassic. The La Meije thrust, carrying a much larger basement segment, is not seen to climb sufficiently at present erosion levels to put basement on cover. Further cover thrusts develop in association with the northward lateral climb of the La Meije thrust from basement into cover. All the principal thrusts of the St. Jean and La Grave duplexes have now formed. The position of the next incipient thrust in the basement is shown. This shows lateral climb to isolate the Plateau (PL) basement segment.

(4) The sequence shown ends with the westward climb of the Plateau thrust to place the Plateau massif (PL) over Mesozoic cover rocks. Minor hanging wall reverse faults develop in this massif. The precise point of northward termination in the cover of the Plateau thrust is not known. The Pelvoux massif in this region can now be seen to have been generated by successive overthrusting of basement segments to produce a structural high. The lateral climb of thrusts from basement to cover in a northward direction creates the northern margin to this structural high. The next thrust sequence to develop, which is not detailed in this diagram, involves the emplacement of the Grandes Rousses and Belledonne massifs. The incipient positions of the basement thrusts carrying the eastern, middle and western parts of the Grandes Rousses are shown (GR-e, GR-m, GR-w respectivley). The Grandes Rousses segments are separated from the Belledonne massif by a strip of Mesozoic rocks continuous with the Bourg d'Oisans syncline described by Gratier & Vialon (1980).

repeated by several thrusts décollé at the level of Triassic dolomitic rock. Movement on a single thrust in the gypsum to the north is thus interpreted to have been transferred to several thrust planes to the south with décollement located in the topmost Triassic beds.

There is a further change in tectonic style in passing south from the area of section 2 to that of section 1 (Fig. 3). The large-scale folds with a few thrusts are gradually replaced by an increasing number of thrust repetitions of lower Jurassic strata without significant folding. This change in geometry is considered to be related to the southerly disappearance of the gypsum layer in the Trias. When gypsum is present, it acts as a weak basal layer for thrust sheet movement, and smooth slip with little disturbance of the footwall occurred (cf. Elliott & Johnson 1980). Where movement started on a gypsum layer and this gypsum then disappeared in the general (westerly) movement direction, the increased resistance to movement gave rise to shortening by folding, whilst the same sheet to the north still moved on the gypsum. Eventually, thrusts cut up section from the décollement level at the position where the gypsum finally disappeared from the stratigraphic section (Fig. 3, section 2), and shortening by thrusting took place. To the south (Fig. 3, section 1), there is no gypsum present, except for one small and isolated mass contained in one of the uppermost thrust sheets. It is in this section that the most intense imbrication is found, and the thrust is said to have evolved by rough slip (Elliott & Johnson 1980).

ESTIMATE OF COVER SHORTENING BY IMBRICATION

Whilst the mechanism of thrust movement changed from north to south in the area as described, it is possible that overall shortening of the cover was more or less the same, or gradually decreased from north to south. The thrust slices of cover do show a N–S continuity of structure, and no significant strike slip structures (faults, shear zones) have been recorded.

Several methods exist to calculate shortening and displacement in thrust zones (see Elliott & Johnson 1980). In the present area, the most relevant method involves restoration of the duplex structure in the cover rocks (see Dahlstrom 1969, Hossack 1979, Elliott & Johnson 1980). Section 1 (Fig. 3) shows a duplex of cover thrust slices which are not seen to involve basement in a down dip direction at the present level of erosion. Restoration at constant cross-sectional area from the present duplex thickness to the original stratigraphic thickness provides an estimate of shortening. Section 1 (Fig. 3) suggests a minimum across strike length of the duplex of 10 km and a present thickness of 4 km between the floor thrust (Trias décollement) and roof thrust (base of Eocene flysch).

The Mesozoic rocks in the duplex are strongly deformed, and strictly speaking a strain integration (see Hossack 1978) should be carried out to ascertain the thickness of the duplex with undeformed rocks, prior to restoration at constant area. Strain measurements (largerly unpublished, but see Beach 1979) have provided mostly 2D results using deformed belemnites, and therefore an exact strain integration across the duplex is not possible. However, examination of pyrite pressure shadows suggests that strains accumulated irrotationally in the plane of bedding. Deformation was dominated by thrust sheet parallel simple shear in the lower part of the duplex. An increasing amount of layer parallel shortening upwards through the thrust sequence produced a subhorizontal finite extension with little bed thickening. To provide an order of magnitude estimate of shortening, the deformed stratigraphic thicknesses are thus assumed to be similar to the original thicknesses, that is, about 400 m at the bottom of the duplex and about 600 m at the top. Thus, a present across strike length of duplex of 10 km restored to an average thickness of 500 m indicates a shortening of 70 km. Such a result is an estimate only, but is broadly compatible with an estimate of 35 km displacement on the La Meije basement thrust (Beach in press) which is laterally equivalent to part of the cover duplex zone. The principal error has a predictable effect on the result—if the original stratigraphic thickness was as high as 1 km, the estimated shortening would reduce to 30 km. The shape and total across-strike length of the duplex are more difficult to determine with the present sheet dip and erosion. Finally, there is no evidence to suggest the presence of any major normal basement faults controlling sedimentation in the area originally covered by the duplex, following the model of Graciansky *et al.* (1979). For example, no basement horses derived from normal fault generated ramps are recorded in the duplex. Further, the only Triassic basaltic lava, which may have formed in proximity to an early normal fault, is found in the topmost thrust slice of the duplex towards the Col du Lautaret (Fig. 2). The stratigraphy now incorporated in the duplex may have therefore been bounded to the east by an early normal fault.

INTERPRETATION

Within the area described in this paper, a number of different thrust styles affect the cover rocks. A central, essentially unduplicated and little deformed sequence, moved by smooth slip on a basal gypsum layer. This zone passes to north and south into areas where displacement by rough slip is recorded in the strongly deformed and thrust-repeated imbricate successions. The change southwards from smooth to rough slip is attributed to the disappearance of the basal gypsum as a glide horizon. In contrast, the gypsum does not disappear northwards, and the change from smooth to rough slip in this direction is attributed to the presence of an early Mesozoic normal fault in the basement, creating a pre-formed ramp to the Triassic décollement horizon. Imbrication of the cover followed by partial collapse of this ramp in the footwall created a duplex with a basement horse as the lowermost thrust slice.

The thrusts in the Mesozoic developed after overthrusting of the sub-Briançonnais and structurally higher units, and were preceded by smooth slip on the base of the Eocene flysch succession. The shortening on the La Grave cover duplex is taken into the basement by two major thrusts which pass down lateral ramps beneath the Combeynot and La Meije components of the Pelvoux massif. Perrier & Vailon's (1980) crustal profile interprets the basement thrusts as rooting down to a mid-crustal décollement level, linked down dip to an overthrust in the Moho beneath the Ivrea body. The question arises as to how appropriate the analysis of thin-skinned thrust tectonics (Elliott 1976a, b, Chapple 1978) is to this geometry.

Chapple's (1978) model is expressly aimed at thin-skinned fold and thrust belts where only those rocks above some stratigraphic horizon are involved in the deformation. If as suggested (Perrier & Vialon 1980) the thrusts in the external Alps pass down dip through the basement to the Moho, then this area may not be a good choice for testing Chapple's model. Further, the published discussions of Chapple's paper (Elliott 1980, Rod 1978) draw attention to ambiguities and contradictions in the formulation of this model. However, Elliott's earlier paper on the motion of thrust sheet (1976b) does simplify the stress equations for the example he discusses (Canadian Rockies) further than would be justified for the Alps. In order that longitudinal deviatoric stresses may be considered negligible compared with shear stresses, the maximum principal stress must make an angle of greater than 32° with the horizontal (Elliott 1976b, p. 951). Thrust belts thus form with a strong component of simple shear deformation, for which there is commonly good field evidence. Further, a small angle of basal back slope and surface slope allow Elliott to simplify the equation for the basal shear stress. In his later discussion (Elliott 1980) he analyses this further, showing that when the sum of surface and basal slope are as high as 15°, then longitudinal stresses and shear stresses are of the same magnitude for principal stress inclinations as low as 14°. Elliott considers this situation to be most applicable to the deforming toe region of a thrust belt. However, referring again to Perrier & Vialon's (1980) profile, the average dip of the mid-crustal décollement is indicated to be about 15° in the present configuration, steepening rapidly to the surface. Adding to this the surface slope that existed during thrusting, it is quite likely that both longitudinal deviatoric stresses and shear stresses played a role in the evolution of the external Alps during thrusting on a crustal scale. To move entirely by gravity, a thrust sheet must lower its centre of gravity and Elliott (1976b, p. 957) shows that this is promoted by increasing the surface slope, thinning the sheet by strain or erosion, or by decreasing the basal slope. The existence of a basal slope equal to or greater than a reasonable estimate of surface slope again implies that longitudinal deviatoric stresses played a significant role in the thrust tectonic evolution of the external Alps.

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