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Balanced cross-sections and their implications for the deep structure of the northwest Alps

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Abstract—The Mont Blanc massif is one of a chain of basement culminations which crop out along the external French Alps. Its southwestern margin is interpreted as being a major thrust belt which propagated in a piggy-back sequence towards the foreland. These imbricates have developed in the footwall of the high-level Valais thrust. The depth to the floor thrust and shortening within imbricates above this thrust are estimated by a series of partially balanced cross-sections drawn between the 'synclinal median' and the Valais thrust. These sections restore to a pre-thrust length of at least 50 km, probably exceeding 100 km, above a floor thrust never deeper than 1 km below the sub-Triassic unconformity. All this thrust displacement is transferred via a series of lateral branch lines onto the Mont Blanc thrust in the Chamonix area. A corollary of this is that the Aiguilles Rouges and the main part of the Mont Blanc massif were separated by probably as much as 100 km prior to Alpine thrusting. Such large shortening estimates imply a hitherto unsuspected Dauphinois stratigraphic consistency in both thickness and lithology.

To achieve a balance a restored crustal cross-section must show an equal length of both lower and upper crust. Thus a high-level basal detachment which floors large thrust displacements must overlie a long, undeformed lower crustal wedge. A restored section 100 km long requires such a lower crustal wedge to exist beneath the entire Alpine internal zones. Perrier & Vialon's crustal velocity profile through the western Alps is reinterpreted in these terms. The Ivrea body is considered to be a portion of an external lower crustal wedge which has been uplifted by thrusts after most of the displacement on the external thrust belt.

INTRODUCTION

THE WESTERN Alps is classical ground for structural geology where major thrusts have long been recognized (e.g. Heim 1921). However, the dominance of this thrust tectonic style, particularly in the external zones, is a recent realization. The external French Alps contain a number of crystalline basement massifs which form a chain from the Mont Blanc and Aiguilles Rouges in the north to the Argentera in the south. Models of thin-skinned thrusting, largely derived from the foothills of the Canadian Rocky Mountains (e.g. Bally *et al.* 1966) have been applied to the northern margin of the Pelvoux massif (see Fig. 1) by Beach (1981 a,b) who was able to explain some otherwise problematic basement-cover relationships. This led to a greater understanding of the geometry of external thrusts and allowed Beach to draw a series of balanced cross-sections through the region.

A further thin-skinned interpretation of Alpine structure by Boyer & Elliott (1982) provides a balanced and restored section through the western Helvetics. These workers consider the Helvetic nappes to constitute a duplex which developed in the footwall of the frontal Pennine thrust.

This paper is concerned with an area of the external Alps which lies between those studied by Boyer & Elliott (1982) and Beach (1981 a,b), and is centred on the southwestern margin of the Mont Blanc basement massif (Fig. 1). It aims to discuss briefly the geometry of the thrust structures and their propagation sequence in order to construct and restore a balanced cross-section through this part of the external Alps. General methods of section balancing are now well established and have been discussed by several authors (e.g. Dahlstrom 1969, Hossack 1979, Elliott & Johnson 1980). Particular attention will be given to the depth to décollement, or floor thrust, of imbricate stacks together with the amount of shortening above these décollement levels.

The resultant restored section will be shown to have an important bearing on the deep structure of the western Alps. A published seismic velocity profile through part of the French Alps (Perrier & Vialon 1980) is reinterpreted in the light of these new interpretations of external structure.

As stated above, the models of thrusting which have been applied to the western Alps do not owe their derivation to this area and so some of the inherent terminology used here may be unfamiliar to Alpine geologists. This terminology has been reported by several workers (e.g. Elliott & Johnson 1980, Boyer & Elliott 1982) and reviewed by Butler (1982); whose nomenclature is followed here.

THE SOUTHWESTERN MARGIN OF THE MONT BLANC MASSIF

The external zones around the Mont Blanc massif have been interpreted in terms of a foothills style thrust belt by Butler (in press). Here the basic field observations used in that interpretation are discussed to build up a balanced cross-section through this part of the zone. First the stratigraphy is appraised to constrain some of the restored sections which are presented later.

Stratigraphy

The stratigraphy of basement and Dauphinois cover rocks in the northwestern external zones is well estab-

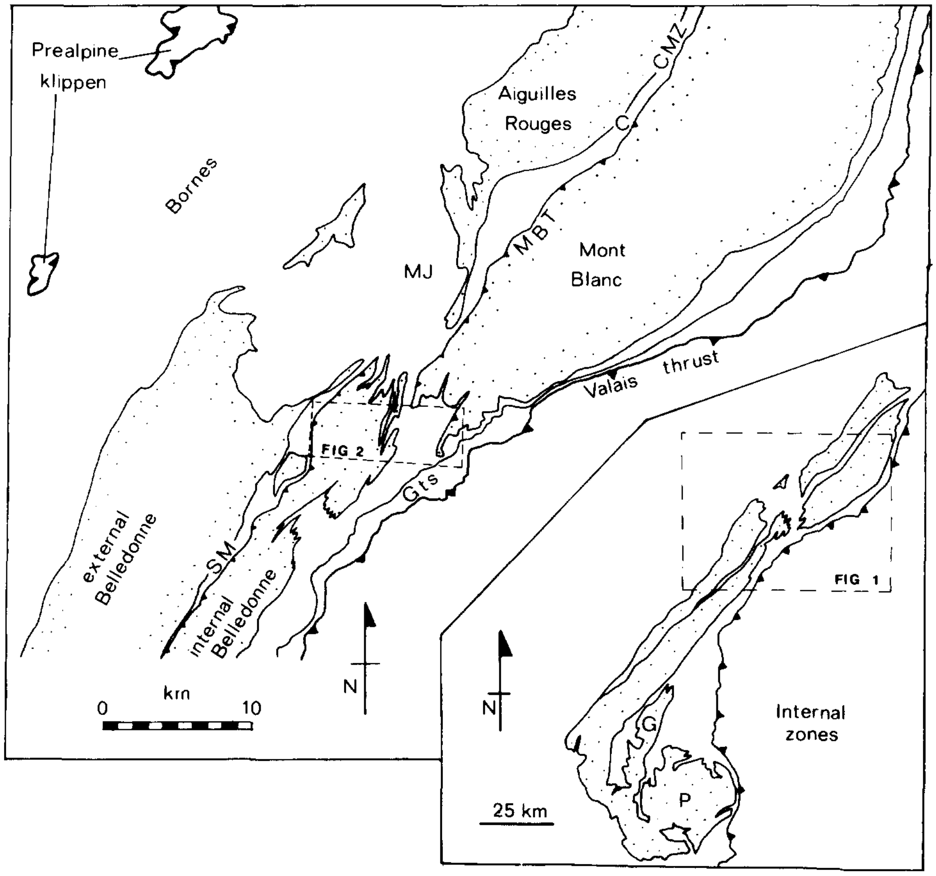

Fig. 1. Distribution of basement (stippled) and cover rocks in the region of the Mont Blanc and Belledonne massifs. C, Chamonix; CMZ, Chamonix Martigny zone; Gts, Gitte thrust sheet; MJ, Mont Joly; SM, 'synclinal median'. Inset: external basement massifs of the northwestern Alps; G, Grandes Rousses; P, Pelvoux.

lished and has been the subject of several review papers (e.g. Ramsay 1963, Debelmas & Lemoine 1970, Debelmas & Kerckhove 1980). This paper follows the broad outlines of the stratigraphy reported by these workers but the new structural interpretations presented here may cast doubt on the detailed stratigraphic work in the Mont Blanc area by Landry (1978).

The pre-Triassic basement rocks include pre-Carboniferous migmatites, schists and gneisses which together with Carboniferous sandstones and conglomerates were deformed in the Hercynian. Late Hercynian granitic bodies such as the Mont Blanc granite make up the remainder of the basement suite.

Triassic rocks unconformably overlie basement but are not typical of the Dauphinois stratigraphy reported from elsewhere in the French Alps. Triassic conglomerates and quartzites are restricted to the margin of the Mont Blanc massif, below the Tête Sud des Fours (Fig. 2). Elsewhere bubbly dolomites, termed 'cornieules' (cf. Warrak 1974), directly overlie basement of the internal Belledonne massif. These cargnueles have a remarkably constant thickness of 10–12 m wherever they are found in imbricate slices which include basement, though obviously this thickness can be increased by imbrication of the Triassic sequence alone.

The cover succession of the external Belledonne massif as exposed in the 'synclinal median' (Fig. 1) includes a thick Liassic formation of thinly interbedded limestones and shales which are commonly slaty. In the region of Mont Joly (Fig. 1) this Liassic sequence has an imbricated thickness of over 2 km. However, Liassic rocks are rarely found in the cover succession of the internal Belledonne and Mont Blanc massifs and here Oxfordian black shales generally rest directly on Triassic cargnueles. This omission has long been recognized (e.g. Ayrton 1972) and considered to be of stratigraphic origin. An alternative model has been suggested by Butler (in press) who postulates tectonic removal of cover rocks before the local onset of thrusting. From the viewpoint of establishing a template for a restored section, the mechanism for Liassic omission from the local Dauphinois stratigraphy is irrelevant and need not be considered here.

The Oxfordian black shales are between 20 and 25 m thick and pass up into a 30–40 m thickness of Malm limestones. No younger Mesozoic rocks are found as part of the cover succession in the Mont Blanc area.

Throughout the cover sequence of this part of the internal Belledonne and Mont Blanc massifs there is no significant variation in stratigraphic thickness and lithology of the Jurassic rocks. It seems reasonable to assume a layer-cake Dauphinois stratigraphy for restored templates of sections drawn through the external zones to the east of the 'synclinal median'.

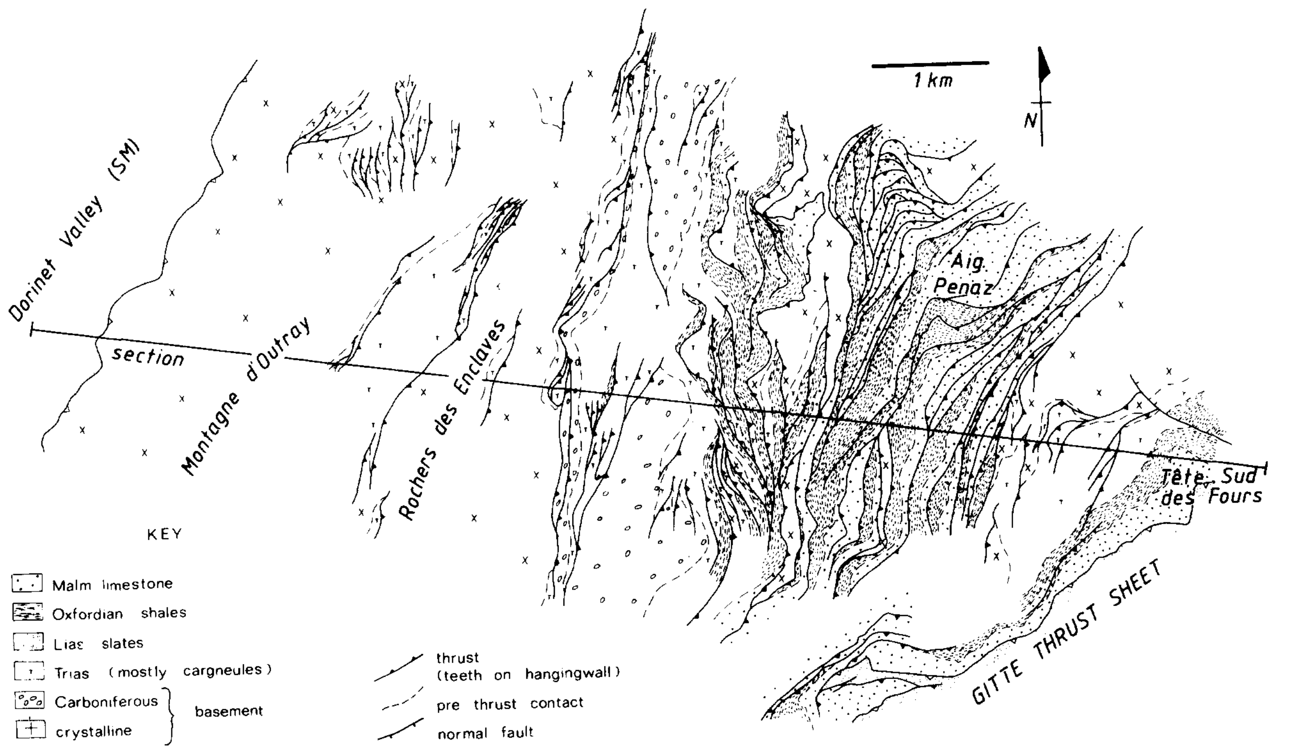

Fig. 2. Detailed geological map of the southwest margin of the Mont Blanc massif.

Tectonic units

Figure 2 is a detailed map of part of the external zones to the east of the 'synclinal median' around the Mont Blanc area and shows a number of tectonic units. These will be briefly described from east to west. Additional details are given by Butler (in press) and are summarized in Fig. 3. Lateral variations in thrust geometry are reserved for later discussion except where they provide useful evidence for thrust sequences.

The Valais zone lies directly beneath the internal zones of the French Alps and is bounded by the Valais thrust. This thrust appears to join along strike the frontal Pennine thrust of Boyer & Elliott (1982). A simple map interpretation (Figs. 1 and 8) shows this to be warped by the culmination of the Mont Blanc massif and so displacement on the Valais thrust predates the development of the massif.

The footwall of the Valais thrust is another distinct unit, termed the Gitte thrust sheet (Butler in press) which is composed of highly deformed Liassic rocks and locally incorporated basement slices. This sheet has been correlated with the Ultrahelvetic nappes further north (Antoine *et al.* 1975). The Gitte thrust has a footwall in Malm limestones which form part of the cover sequence of the Mont Blanc massif. Minor imbricates developed in the footwall of the Gitte thrust have cut through into its hangingwall, emplacing Malm limestones onto Liassic slates. Thus the Gitte thrust sheet was emplaced onto Malm limestones before subsequent lower-level imbrication disrupted the sheet.

Basement rocks of the Mont Blanc massif, which are in excess of 10 km thick in the Chamonix area (Fig. 1), have been emplaced onto the cover rocks of the Chamonix–Martigny zone and the internal Belledonne massif by the Mont Blanc thrust. Imbrication in the hangingwall of this thrust towards the southwest of Mont Blanc has duplicated basement and local slices of Triassic cover which accentuates the culmination of this basement massif. Commonly the belt of mylonites and imbricate slices is in excess of 1500 m thick with each slice less than 50 m across. Local variations in imbrication within the hangingwall of the Mont Blanc thrust has caused what is interpreted as a hangingwall drop fault (Butler in press) to develop on the Tête Sud des Fours (Figs. 2 and 4) caused by differential uplift of the thrust sheet.

The footwall of the Mont Blanc thrust is everywhere in Malm limestones within the detailed study area shown in Fig. 2. These limestones and the underlying Oxfordian

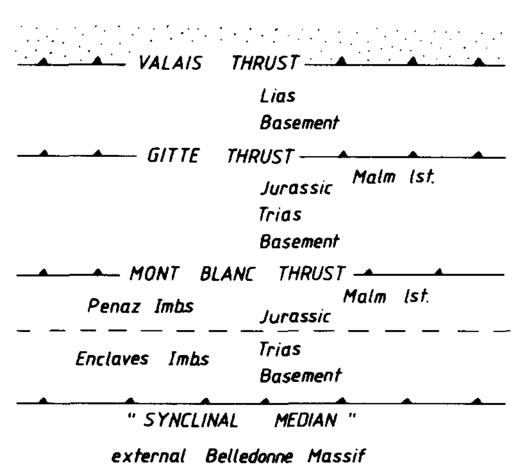

Fig. 3. Schematic diagram showing distribution of major tectonic units.

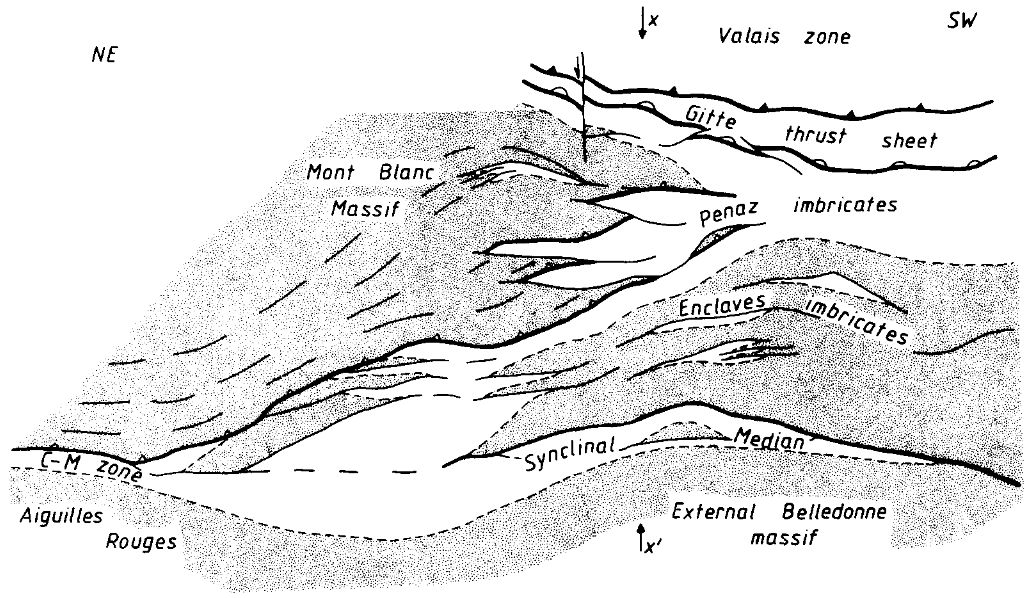

Fig. 4. Schematic longitudinal section showing basement (stippled)/cover relationships. Thick lines are thrusts, pecked lines are stratigraphic contacts. X–X′, line of the cross sections in Figs. 5 and 6. Note that the thrust transport direction is out of the page.

black shales have been imbricated on many scales to produce a complex stack of thrust sheets centred on the Aiguilles de la Penaz (Fig. 2). This stack is termed the Penaz imbricates (Butler in press). These imbricates have cut through into the Mont Blanc thrust sheet and the remnants of this higher sheet crop out locally in the Penaz area as 'roof pendants'. The oldest rocks within the imbricates are Oxfordian black shales implying that the floor thrust runs at the base of this formation. However, towards their trailing edge Triassic rocks are found within imbricate slices implying that the floor thrust has cut down to lie within these rocks further to the east.

Between the floor thrust of the Penaz imbricates and the 'synclinal median' is a considerable thickness of basement and Triassic thrust slices which are centred on the Rochers des Enclaves (Fig. 2). These constitute the Enclaves imbricates (Butler in press) and show rapid lateral variation in structure. Figure 4 is a schematic longitudinal section through the thrust belt and shows the relationship between thrust sheets and imbricates which is discussed in more detail later. Of more immediate interest is the amount of lateral variation within the Enclaves imbricates, which can best be considered to form a stack of small culminations caused by thrusts migrating in and out of basement with a great deal of lateral branching. These culminations have warped the structurally higher Penaz imbricates and so the Enclaves imbricates probably constitute a duplex with a roof along the floor thrust of the Penaz imbricates.

Thrusts which emplace basement onto Triassic rocks commonly cut down along-strike to merely repeat basement slices. Detailed mapping shows these basement repetitions to be separated by mylonite zones which are sub-parallel to the dominant Hercynian schistosity and never exceed a 100 m separation on the ground. This separation is about 80 m for thrusts within Carboniferous rocks. Hercynian and Alpine fabrics, together with bedding in Carboniferous rocks, are commonly sub-parallel to bedding in the Triassic rocks which generally dips steeply to the east. This implies that imbrication only repeats the upper 100 m of basement. The outcrop of the Enclaves imbricates is dissected by deep valleys which expose over 1500 m of basement rocks which have steep, easterly dipping schistosity planes with no evidence of discordant Alpine thrusts. Thus the Enclaves imbricate thrusts must be parallel to the Hercynian schistosity to some considerable depth. The implications of this hypothesis are discussed later. The floor thrust to the Enclaves imbricates emplaces basement of the internal Belledonne massif over the cover rocks of the external Belledonne massif in the 'synclinal median' (Fig. 2). The footwall lithology is Liassic slates.

Propagation and direction of thrusting

Throughout the area described above imbricates branch off other thrusts. The entire thrust belt is considered to be a large imbricate splay and the sequence of thrust propagation is now considered. In all cases, higher thrusts are either cut or folded by those developed beneath (Fig. 4). This implies that thrust propagation was foreland-directed and has resulted in a piggy-back sequence (Elliott & Johnson 1980). However, ideal duplex structures are rarely identified since these require imbricate thrusts to anastamose to form a single roof thrust. Rather than roof into a single fault, imbricates tend to cut up into higher thrust sheets, the resultant structure being termed a 'leaky duplex'. Imbricates behaving in this way appear 'out of sequence' and to have propagated back into the thrust belt. Such faults can often be shown to spawn from the footwall of the higher thrust which they cut and so have indeed developed in a piggy-back sequence.

The resolution of a thrust transport-direction is more problematical. Stretching lineations are traditional transport direction indicators but in the cover rocks they may owe their origin to the earlier episode of extensional tectonics briefly suggested above. The 'bow and arrow' rule of Elliott & Johnson (1980) is not directly applicable to the Mont Blanc area since it is reliant on a symmetrical distribution of lateral ramps throughout a particular study area. This symmetry is not evident since several large-scale culminations (see Fig. 4) have lateral terminations in the area. However, superb local exposure allows the complete resolution of individual thrust topographies. Ideal lateral ramps can be identified: (a) in small-scale imbricates within the Triassic cover of the Mont Blanc massif just west of the Tête Sud des Fours (Fig. 2); (b) both southeast and northwest of the Aiguilles de la Penaz (Fig. 2); (c) to the east of the Rochers des Enclaves (Fig. 2) and at several other localities outside the area covered by the detailed map. Regardless of their structural positions these ramps always strike WNW–ESE, facing either north or south. Frontal footwall ramps dip to the east so the thrust transport direction was consistently towards the west-northwest.

A BALANCED CROSS-SECTION

A line of section has been chosen which is parallel to the thrust transport direction and runs from the Tête Sud des Fours on the southwestern margin of the Mont Blanc massif to the 'synclinal median' (Fig. 2). Two cross-sections, which rely on different amounts of projected data, were constructed along this line. They will be used to gain minimum estimates of shortening in the footwall of the Valais thrust.

The first section to be discussed is shown in Fig. 5 and is a partial one from the Montagne d'Outray (see Fig. 2) to the Mont Blanc thrust. It concentrates on structures in the footwall of this thrust, namely the Penaz and Enclaves imbricates. In view of the large amounts of lateral variation in the structure of the Enclaves imbricates discussed above (see Fig. 4), no data has been projected from further than 200 m distant from the section line.

The restored section presented in Fig. 5 is of a minimum length due to two factors. Firstly, the depth to the floor thrust to the east of X is an arbitrary minimum. The basement horses are bounded by ramps separated by long flats (see the restored section). Any increase in the depth to the floor thrust on the balanced cross-section will be accommodated by an increased flat length rather than in the height of the ramps. Since the depth to the floor thrust on a restored section is controlled by the height of ramps this depth will remain constant. The increased area of rock involved in the balanced section is accommodated by an increase in the length of the restored section which in turn implies more shortening on the section line. The cross-section of Fig. 5 has been restored by an area balance and the thrusts located by a line length measurement on the sub-Triassic unconformity. Since the Triassic and basement rocks are commonly imbricated independently, resulting in single-lithology culminations, the unconformity must show considerable slip. Consequently a direct correlation of thrusts within Triassic rocks with those in basement is

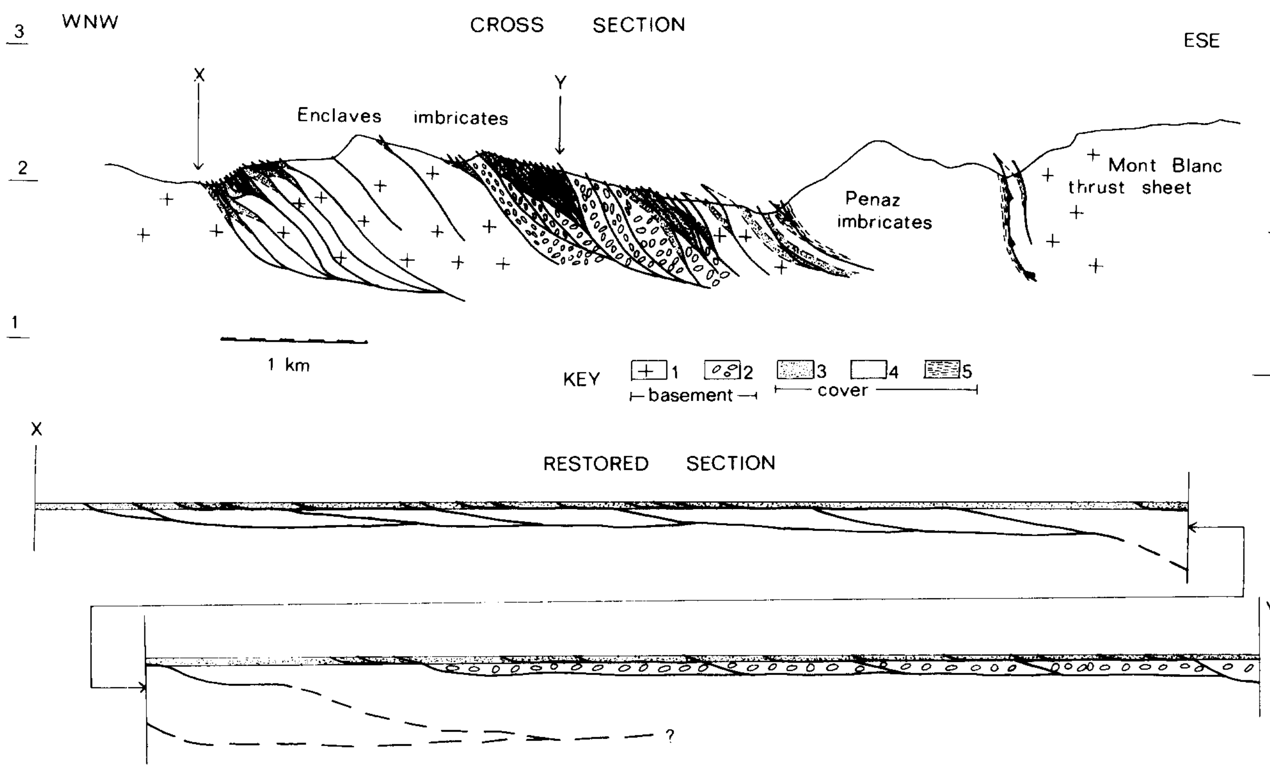

Fig. 5. Balanced cross-section through part of the thrust belt, see text for explanation. 1, Crystalline rocks; 2, Carboniferous; 3, Trias; 4, Oxfordian; 5, Malm. Vertical and horizontal scales are equal.

imprudent. However, if there is any increase in basement length in the restored section there must be a corresponding amount of Triassic sequence added to the section to achieve a balance. This Triassic sequence has now been lost through erosion and this loss is the second factor in the underestimate of shortening for the Enclaves imbricates. The section in Fig. 5 has been restored for the Triassic sequence remaining in outcrop. Even so, the imbricates between X and Y, now just 2.5 km wide, restore to an undeformed length of 15.5 km.

To the east of Y the Enclaves imbricates continue to and probably beneath the Penaz imbricates. Several cross-sections (not presented here) drawn through these imbricates have been restored to lengths in excess of 10 km. Thus restored section lengths for the entire Enclaves imbricates to the east of Y are at least 25.5 km. Since the thickness of basement rocks within individual thrust slices never exceeds 100 m this is the depth to the floor thrust on the restored section.

The Penaz imbricates have also been balanced. The cross-section (Fig. 5) does not show the internal geometry of thrust slices but no basement 'roof pendants' occur to the east of the frontal edge of the imbricates. The area of the Penaz imbricates illustrated in Fig. 5 is approximately 0.825 km^2. A simple area balance can be performed using the maximum undeformed stratigraphic thickness of the only two Jurassic sequences within the imbricates, namely 65 m. A simple division gives a restored section length of 12.5 km with a floor thrust at the base of the Oxfordian black shales. Because the Penaz imbricates must be underlain by Triassic and basement rocks this length can be added to the restored section for the Enclaves imbricates calculated above. The total section must be at least 38 km long, a figure which is considerably increased if the Triassic sequence beneath the Penaz imbricates is shortened.

The calculation of shortening within the Penaz imbricates allows an estimate of the displacement on the Mont Blanc thrust. The footwall to this thrust everywhere lies in Malm limestones on this line of section which, after being overthrust by basement, have imbricated. Because these Penaz imbricates cut across the Mont Blanc thrust they do not transfer displacement onto it. Thus the Mont Blanc thrust shows at least 12.5 km displacement, a value which does not include movement on flats in any stratigraphic level below the Malm limestones and is therefore a gross underestimate. However, it is an estimate that can be added directly to those obtained above for the imbricates in its footwall. Thus the thrust belt shows more than 50.5 km shortening.

The value given above does not account for any imbrication within the hangingwall of the Mont Blanc thrust which so far has proved impossible to calculate. However, it seems likely that, on the southwestern margin of the massif, these imbricates are at least as important as those in its footwall. Another addition to the minimum estimate above is likely to be from thrusts to the west of X as depicted on Fig. 5. These include part of the Enclaves imbricates directly east of the 'synclinal median'. These imbricates incorporate Triassic rocks to the north of the Montagne d'Outray (Fig. 2), and are lost in a wide belt of anastamosing basement shear zones between this hill and the Dorinet Valley. Thrusting to the west of the 'synclinal median' will be considered after a discussion of the alternative cross-section drawn along the same line as that shown in Fig. 5.

The alternative cross-section shown in Fig. 6 relies on more projection of structural data into the line of section than does that of Fig. 5. The most important difference is in the predicted geometry of the floor thrust of the Enclaves imbricates on which they are carried over the Liassic cover of the external Belledonne massif. This thrust is considered to flatten out beneath the Rochers des Enclaves, but at a much greater depth than the arbitrary minimum level of the previous section (Fig. 5). Basement rocks crop out to a depth of 1000 m (1500 m beneath the Rochers des Enclaves) just 3 km to the south of the section line. Schistosity planes and presumably the imbricate thrusts to which they are sub-parallel are still steeply dipping to the east. An additional 1200 m of basement thickness is predicted to allow the imbricates to curve into the Enclaves floor thrust. Large-scale open folds (see Fig. 4) within the Enclaves imbricates appear to be due to culminations within the imbricates rather than upwarping of the entire stack by imbrication beneath. Thus the regular form of the floor thrust seems reasonable. If this geometry is correct then the floor thrust passes beneath the Tête Sud des Fours at a depth of 3.6 km.

The floor thrust to the Penaz imbricates is also considered to flatten but not as quickly as shown in Fig. 5. Again structure exposed in deep valleys is projected into the line of section, this time from just 1 km to the south. Jurassic rocks within the thrust slices are dipping at 45° at 1500 m (750 m) below the outcrop on the section line) with no evidence of a shallow, floor thrust. The absence of open folds in the section line implies an unfolded floor. The geometry of the now-eroded upper portion of the stack is based on the distribution of 'roof pendants' to the north of the Aiguilles de la Penaz (Fig. 2). The Penaz imbricates are considered to continue beneath the Tête Sud des Fours and the trailing edge shown in Fig. 6 is arbitrary.

Figure 6, although somewhat speculative, does allow a further series of shortening estimates for the Penaz and Enclaves imbricates. Based on this section geometry, the Enclaves imbricates have a cross-sectional area of 19.92 km^2 plus an unknown area lost through erosion. The amount of shortening this represents depends on the thickness of each imbricate slice which at outcrop is 100 m. If this figure is correct for the entire stack the restored section length would be just under 200 km. This length seems excessive in view of the amount of eroded cover rocks required to balance this cross-sectional area of basement which could be more than 40 km^2. Rather than being simple 100-m thick sheets the imbricate slices could be wedges which thicken considerably at depth. An average thickness of 400 m with slices

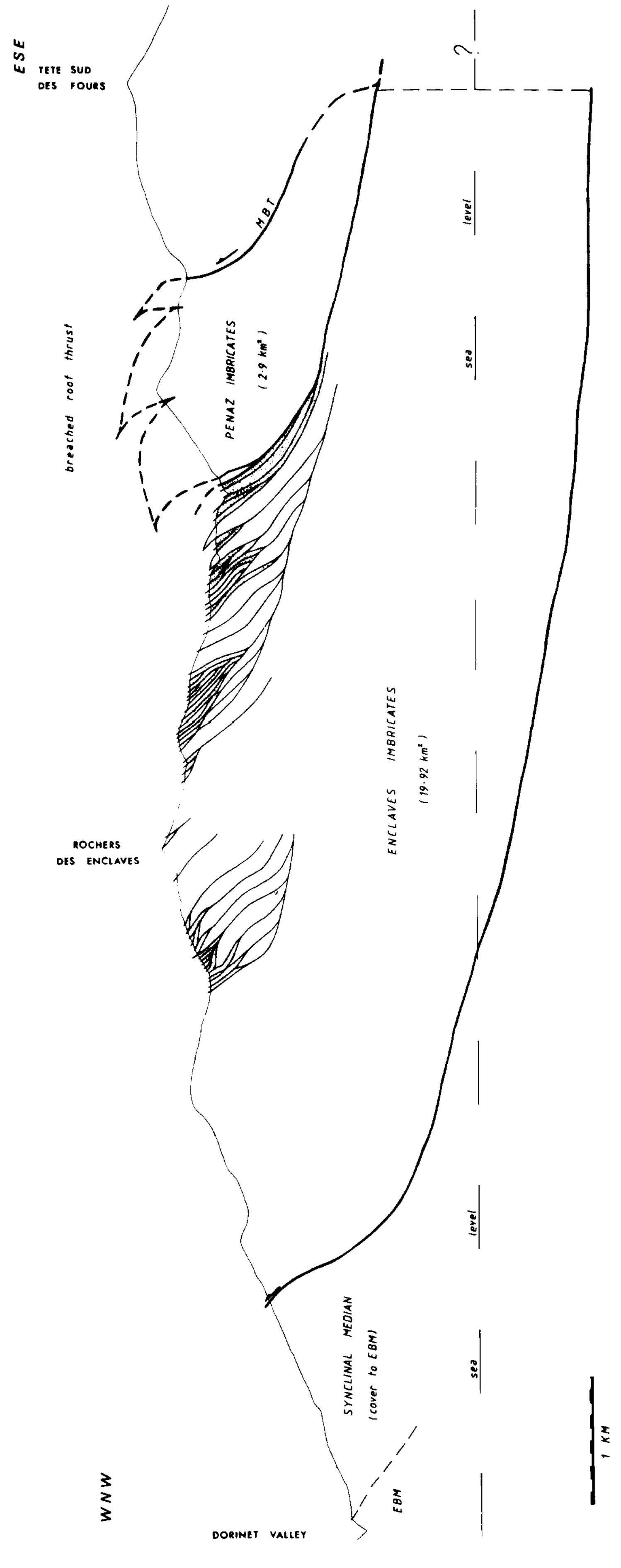

Fig. 6. Alternative cross-section from the external Belledonne massif (EBM) to the Mont Blanc thrust (MBT).

broadening to about 1 km towards the floor thrust gives a restored section length of 50 km which may be more reasonable.

The Penaz imbricates have a cross-sectional area of 2.9 km^2. The maximum thickness of each imbricate slice is 65 m, the stratigraphic thickness of the incorporated Jurassic rocks. This gives a restored section length of 44.6 km and is well constrained by the known stratigraphic content of the imbricates.

Using the same logic as in the discussion of Fig. 5, the Mont Blanc thrust shows a minimum 44.6 km displacement over the Malm limestones. The total restored section length is the sum of all the estimates above which, depending on that for the Enclaves imbricates, could exceed 139.2 km above a floor thrust never deeper than 1 km below the sub-Triassic unconformity.

Lateral branch lines and thrust displacements

The intersection of two thrust surfaces is termed a branch line (Boyer & Elliott 1982) and where this is parallel to the thrust transport direction the intersection is termed a lateral branch line. Where there is no differential movement of thrust sheets there is an equal amount of displacement on either side of the lateral branch line although the number of thrusts will vary.

The longitudinal section drawn through the thrust belt between the Valais thrust and the 'synclinal median' (Fig. 4) shows some important features. The line of section described above (X–X′) crosses a number of imbricate faults which represent a great deal of displacement. The Gitte thrust sheet forms a continuous unit across the top of the Mont Blanc massif, and the Aiguilles Rouges and external Belledonne massifs are probably a continuous basement sheet. Because there is no evidence for differential movement of thrust sheets above the Mont Blanc massif all displacement shown on cross-sections (Figs. 5 and 6) is transferred onto the Mont Blanc thrust and the shear zone in its hangingwall. In the Chamonix area this fault zone must represent at least 50 km thrust displacement and probably as much as 150 km, if Fig. 6 is accurate.

The Chamonix–Martigny zone has long been recognized as a major zone of overthrusting. Ayrton (1980) termed it a 'zone de subduction continentale' and considered the Mont Blanc thrust sheet to have more Penninic rather than Helvetic structural affinities. He estimated a 20–30 km displacement on the Mont Blanc thrust on the basis of stratigraphic evidence. This is considerably less than the displacement estimates obtained using the balanced section approach adopted here. However, any displacement on the Mont Blanc thrust on a flat along the sub-Triassic unconformity would go undetected using stratigraphic arguments. Even if this is the case, it is difficult to resolve displacements in the order of 100 km on the Mont Blanc thrust with the published accounts of Helvetic tectonics (see Ramsay 1981). Possible solutions would be to transfer movement onto the base of the Helvetics, below the inverted limb of the Morcles nappe (e.g. Ramsay 1981) or onto the frontal Pennine thrust (Boyer & Elliott 1982) behind the Helvetic nappes. It is a problem that will no doubt promote further debate.

To the south of the cross-section line the problem of thrust displacements is less difficult. Lateral branch lines can transfer movement from the Penaz imbricates and Mont Blanc thrust onto the Gitte thrust and ultimately the Valais or frontal Pennine thrust. Shortening in the Enclaves imbricates can be transferred onto the mid-Belledonne thrust, the along-strike equivalent of the Enclaves floor thrust.

Thrusts to the west of the 'synclinal median'

The 'synclinal median' is by no means the western limit of Alpine thrusting. Ménard (1979) demonstrated that the external Belledonne massif has been emplaced onto cover rocks in the Grenoble area (Fig. 7), and thrusts are recognized within the cover rocks of this massif further north (Pijolat 1978). To the west, in the Bornes and Bauges areas, many thrusts and folds which represent significant shortening have been described (e.g. Gratier *et al.* 1973). One such description (Charollais *et al.* 1977, fig. 2) includes a near-balanced section through the frontal parts of these imbricates where they become emergent into the Tertiary molasse basins. This section shows 7.5 km shortening on the Triassic–Dogger boundary with imbricate thrusts apparently flooring along the sub-Triassic unconformity.

Some of this thrusting may be equivalent to displacements described previously from further east, particularly where it is at higher stratigraphic levels. This means that these displacements cannot be simply added to those calculated for the Mont Blanc area. It remains to be seen how much of this further external displacement can be incorporated into a total external section balance.

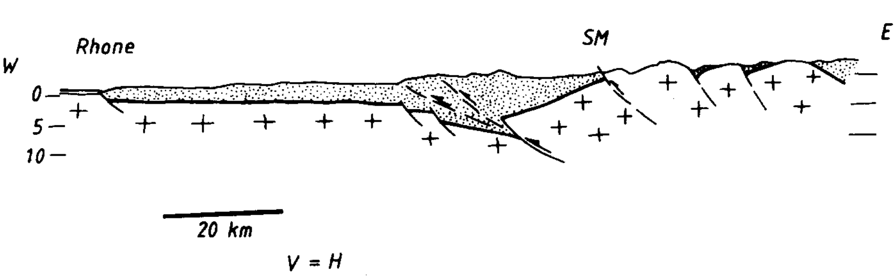

Fig. 7. Cross-section through the external French Alps after Ménard (1979, fig. 24) along (t–t′) in Fig. 8. SM, 'synclinal median'.

DISCUSSION: IMPLICATIONS FOR THE DEEP STRUCTURE OF THE WESTERN ALPS

Having gained a variety of minimum estimates of shortening and depth to the floor thrust for a cross-section through part of the northwestern external Alps some further implications are now considered. As mentioned above, this shortening has occurred in the footwall of the frontal Pennine thrust and therefore has a profound bearing on its subsurface geometry. But first it is necessary to discuss the basic structural elements of the northwestern Alps (Fig. 8).

The internal zones, which lie in the hangingwall of the frontal Pennine thrust, consist of an interleaved and metamorphosed complex of basement and cover rocks. Towards their eastern, more internal, margin they incorporate deep-water sediments, mélanges and ophiolitic units. The entire zone has variously been interpreted as a telescoped continental–oceanic margin (e.g. Debelmas & Kerckhove 1980). Lower crust and mantle rocks are absent in outcrop. A simple map interpretation shows that a maximum thickness of crystalline basement involved in the zone to be 10 km, this being the greatest continuous thickness of basement rocks below any outcrop of the sub-Triassic unconformity. This implies that the hangingwall to the frontal Pennine thrust lies in the middle crust although it is by no means certain what happens when possible oceanic crust becomes involved.

However, there is a zone within the western Alps where lower crust and mantle rocks have been incorporated and these lie on the eastern, internal margin. This Ivrea zone has been described by many authors (e.g. Gansser 1968) as being separated from the remaining internal zones, the two being bound by a belt of faults collectively known as the Insubric line. Unfortunately much of the outcrop of the Ivrea zone around the type area, together with its critical eastern margin are masked by late Tertiary molasse in the Po Valley. Models of deep geophysical data (e.g. Perrier & Vialon 1980) have all considered the zone to have a deep structural root, termed the Ivrea body. This simple geophysical model forms the basis of the following discussion on the relationship between the internal, external and Ivrea zones.

The valuable geophysical studies of Ménard (1979) include a map of the depth to the *Moho* in southeast France, part of which is repeated here (Fig. 9). The map was drawn from a series of seismic-velocity profiles and a gravimetric survey. A gravimetric map (Perrier & Vialon 1980, fig. 1) shows an ambient negative Bouguer anomaly over much of the Alps which increases to a maximum of −160 mGals under the western internal zones. However, to the east, a large positive anomaly (+40 mGals) is centred on Turin and the outcrop of the Ivrea zone. This allowed Ménard (1979, fig. 58) and Perrier & Vialon (1980, fig. 2) to construct maps of the depth to the *Moho* under the western Alps (Fig. 9). They interpreted the increasing negative Bouguer anomaly over much of the Alps as reflecting a gradual increase in crustal thickness which reaches 45 km beneath the internal zones. Superimposed on this is a higher level 'second *Moho*' at 35 km which rapidly shallows to the east to lie less than 10 km beneath the Po Valley. These uplifted dense mantle rocks relatively near the surface account for the positive Bouguer anomaly and constitute the Ivrea body.

This and other elements of crustal structure are shown on a seismic-velocity profile (Fig. 10, after Perrier & Vialon 1980, fig. 5). This section is along line (t–t′) on Fig. 8. Perrier & Vialon (1980) identified the uplifted

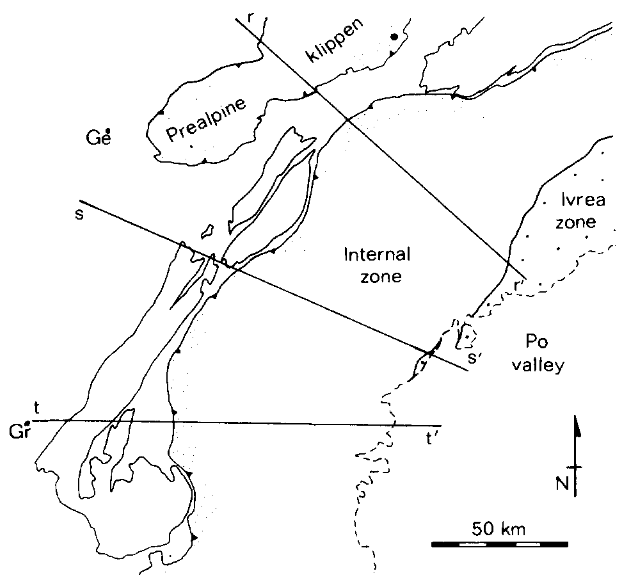

Fig. 8. Major structural elements of the western Alps. Ge, Geneva; Gr, Grenoble. (s–s′), line of the cross-sections in Figs. 5 and 6, (r–r′) and (t–t′), other published sections. See text for discussion.

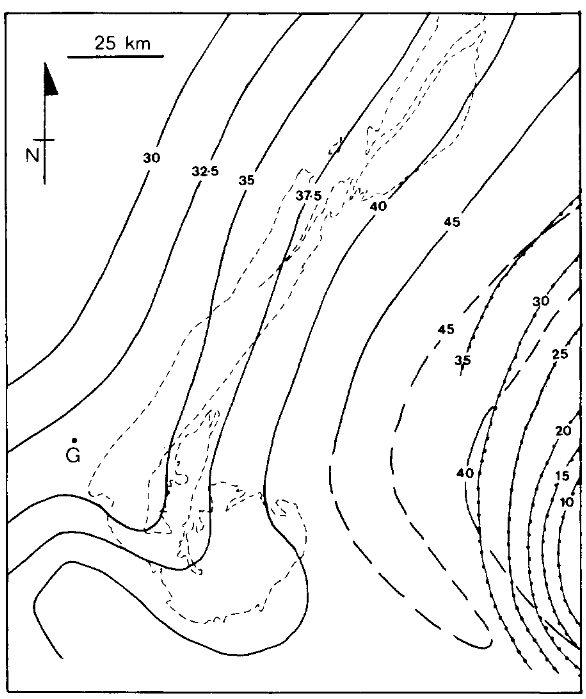

Fig. 9. Map of the depth to *Moho* (contoured in km) beneath the northwest Alps (after Ménard 1979, fig. 58). Dotted contours are to the uplifted Ivrea body. G, Grenoble. The external basement massifs are shown by pecked lines.

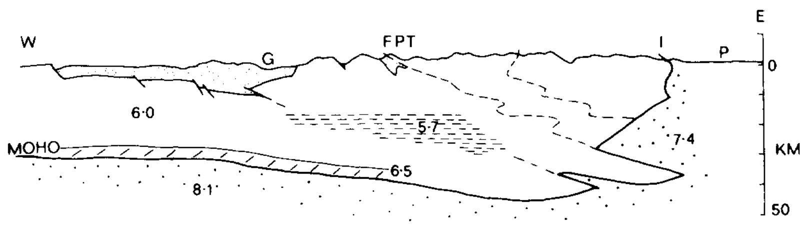

Fig. 10. Perrier & Vialon's (1980, fig. 5) true-scale seismic velocity profile through the western Alps. Velocities are in km s^{-1}. I, Insubric line; FPT, frontal Pennine thrust; G, Grenoble; P, Po Valley. The profile lies on (t–t') in Fig. 8.

Ivrea body with its characteristically high velocities (7.4 km s^{-1}) compared to the average crustal velocity of 6.2 km s^{-1}. They considered that the body was uplifted on thrusts which they ran into a low velocity zone (5.7 km s^{-1}) 10–15 km beneath the external basement massifs. The implication of this is that the thrusts in the external basement massifs all branch off this main mantle thrust which may become the frontal Pennine thrust up dip. This relationship was followed by Beach (1981c) who performed a whole crustal balance based on Perrier & Vialon's (1980) velocity profile.

A further seismic velocity profile has been constructed and is repeated here (Fig. 11, after Saliot *et al.* 1980, fig. 5). It runs through the internal zones to the southeast of Mont Blanc. The *Moho* appears to lie between 40 and 50 km and is at its greatest depth beneath the central internal zones. However, unlike the profile of Perrier & Vialon (1980) there is no offset in this *Moho*. A high velocity zone (7.0 km s^{-1}), presumably the Ivrea body, underlies the Ivrea zone at outcrop but does not continue beneath a depth of 20 km. Rather, this Ivrea body is cut off against rocks with upper crustal velocities (6.2 km s^{-1}) and this relatively low-velocity zone continues beneath the internal zones to the Mont Blanc massif. The implication is that the Ivrea body has been emplaced onto upper-middle crustal rocks which are continuous with those of the external Alps.

These geophysical studies and interpretations imply a simple relationship between the three basic structural elements of the western Alps discussed above. The Ivrea zone appears to be the deep structural 'root' of the internal zones which have been emplaced together onto the external basement and cover rocks of the French craton. A rather different relationship is apparent when the consequences of external thrusting are considered and this is now discussed.

The estimates of shortening and depth to décollement for the external thrust belt around Mont Blanc presented above are important in constraining the footwall of the frontal Pennine thrust. The floor thrust to the imbricates in this section line (s–s' on Fig. 8) is never deeper than 1 km and may be even shallower. Laterally this floor thrust may drop down to 8–10 km in the Chamonix area to incorporate the thick basement horse of the Mont Blanc massif. These two levels are presumably linked by a lateral ramp (see also Butler, in press). These general depths seem to be the range for all external thrusts (e.g. Beach 1981 a,b). Returning to the particular section line (s–s'), the imbricates between the Mont Blanc thrust and the 'synclinal median' restore to a minimum length of 50.5 km and a more realistic estimate may exceed 100 km. To this value must be added much of the displacement on the Mont Blanc thrust together with that on its hangingwall imbricates and the high level Gitte thrust. Further shortening on the more external thrusts to the west of the 'synclinal median' will also increase the restored section length which may well exceed 200 km measured from the 'synclinal median'. This figure bears comparison with that of another balanced section through the northwestern external Alps by Boyer & Elliott (1982) which relies heavily on published accounts of structure. This section line is shown on Fig. 8 (r–r') and these workers estimate 120 km shortening with a restored section length of 278 km from a pin-line at Besançon to the frontal Pennine thrust. Again the floor thrust (also the Alpine sole thrust) is considered to lie no deeper than the upper crust.

For these and other sections to balance an equivalent section length of middle and lower crust must exist in the footwall of the Alpine sole thrust. Beach (1981 c) who also balanced and restored a crustal cross section (t–t' on Fig. 8), suggested that this lower crustal wedge need not be necessary if the crust was attenuated during Mesozoic deposition. This crustal attenuation is not obvious in the region of the internal Belledonne and Mont Blanc massifs. Syn-sedimentary growth faults within the local upper Jurassic succession are not apparent. However, a post-deposition, pre-thrusting ductile extension within these

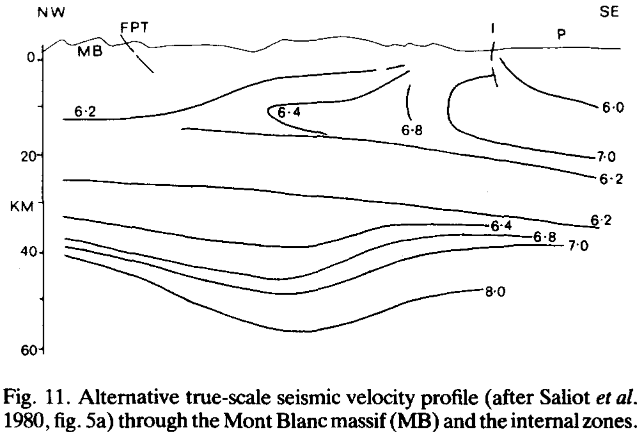

Fig. 11. Alternative true-scale seismic velocity profile (after Saliot *et al.* 1980, fig. 5a) through the Mont Blanc massif (MB) and the internal zones. Contours are in km s^{-1}. I, Insubric line; FPT, frontal Pennine thrust; P, Po Valley.

rocks seems significant. Such extension lies above a low-angle detachment along the top of the Triassic cargnueles because the sub-Triassic unconformity is not affected. Such a site for an extensional detachment accounts for the omission of the Liassic rocks but cannot account for any postulated basement extension directly beneath. Basement extension may be possible to the east of the restored internal Belledonne massif with an extensional detachment cutting across Triassic rocks and into basement. This cut off may occur below the Penaz imbricates, which mask any Triassic succession and basement of the Enclaves imbricates beneath. Such a site for an extensional detachment is extremely fortuitous. Furthermore, the overlying Mont Blanc basement is largely composed of undeformed, Hercynian granite showing no extension. An additional low-angle detachment is required above the Triassic sequence to remove the Liassic rocks from the cover succession of the Mont Blanc massif.

While extension of the cover rocks within the study area is evident it seems unlikely that this overlies an extended basement. The detachment along the top of the Triassic sequence may cut into basement rocks to the east of the restored positions of the external basement massifs. Such a geometry would not affect the requirement for a lower–middle crustal wedge directly beneath the restored external floor thrust. The tectonic removal of Liassic rocks by this mechanism requires the extensional detachment to have a restored length along the top of the Triassic sequence for probably over 100 km. The mechanics of low-angle extensional fault is by no means understood but displacements in excess of 100 km along a flat may be considered unlikely. At present, gravity sliding (e.g. Butler in press) seems a more plausible mechanism for removal of the Liassic succession.

The stratigraphic consistency of upper Jurassic rocks within the Mont Blanc area implies a broadly layer-cake crustal profile beneath. Since this crust is between 25 and 30 km thick away from the orogen (Fig. 9) this thickness is adopted for a pre-Alpine crustal template. Therefore a wedge of lower crustal rocks must exist beneath the internal zones as partially indicated by the seismic-velocity profiles discussed above (Figs. 10 and 11).

Figure 12 is a highly schematic cross-section through the western Alps which nonetheless illustrates some important relationships. The footwall of the frontal Pennine thrust (stippled in Fig. 12) has shortened to give the external thrust belt above a floor thrust at level T.

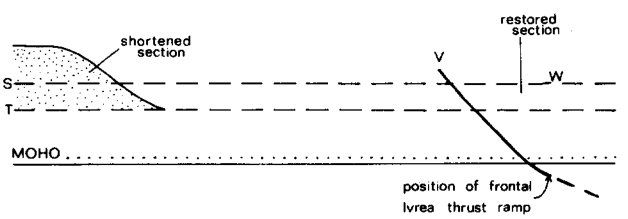

Fig. 12. Schematic restored section through the western Alps and its relationship to the sub-Ivrea thrust. See text for discussion.

The restored stratigraphic thickness is represented by S–T. The external section must restore to lie on 15 km of lower crustal rocks. Two situations can be considered. (1) The trailing edge of the restored section lies in front of that indicated by V, the position of the footwall ramp of the sub-Ivrea thrust across the lower crust. (2) The trailing edge of the restored section lies at a point beyond that indicated by V (e.g. W).

Should the first situation be applicable, the Ivrea zone can be considered as part of the hangingwall to the frontal Pennine thrust because the required length of lower crust is satisfied. This model is favoured by the geophysical models described above. However, if the second situation is true then there is a deficiency in the length of lower crust and so the Ivrea body cannot be regarded as part of the frontal Pennine thrust sheet. Rather the sub-Ivrea thrust must be a late structure which cuts through the lower crustal footwall of the frontal Pennine thrust. To test which situation is applicable it is essential to determine not only the restored section length but also the distance back to the footwall ramp across the lower crust of the sub-Ivrea thrust.

The position of this footwall ramp cannot be directly observed and so its detection is reliant on geophysical data. Perrier & Vialon's (1980) profile shown in Fig. 10 indicates that the frontal sub-Ivrea thrust cuts the *Moho* approximately 80 km down dip from the outcrop of the frontal Pennine thrust. This is not on the line of the section considered here but the subcrop of the Ivrea body can be projected to the north using the depth to *Moho* map (Fig. 9). This shows that the sub-Ivrea thrust lies 10 km above the *Moho* just 55 km east-southeast of the 'synclinal median' on the section line (s–s'). Since the external restored section exceeds this distance, possibly by as much as 150 km, the second alternative model for the position of the sub-Ivrea thrust seems appropriate. Therefore, the Ivrea body represents an uplifted portion of the lower crust and mantle rocks from the footwall of the thrust belt which now crops out as the French external zones. A model for the development of these structures is shown in Fig. 13.

It has been tentatively suggested that the internal zones have shortened in the footwall of the Austro-Alpine nappe (Boyer & Elliott 1982). These two major units have then been emplaced onto the external cover rocks by the frontal Pennine thrust whose footwall has shortened to give the external thrust belt. Subsequent to much of this displacement, thrusts developed in the mantle have climbed through the lower crust to roof into the frontal Pennine and external floor thrusts and so uplifted the Ivrea body. The resultant culmination may have caused some faulting on its margin and the reactivation of structures along the Insubric line.

The models of Fig. 13 are somewhat naïve in that they do not allow for any isostatic loading of the crust due to the thick stack of thrust sheets (see Coward 1983). A more realistic crustal cross-section is presented in Fig. 14 which is based on Perrier & Vialon's (1980) profile. It shows a variety of levels for the external floor thrust (X, Y) which have branched off the frontal Pennine

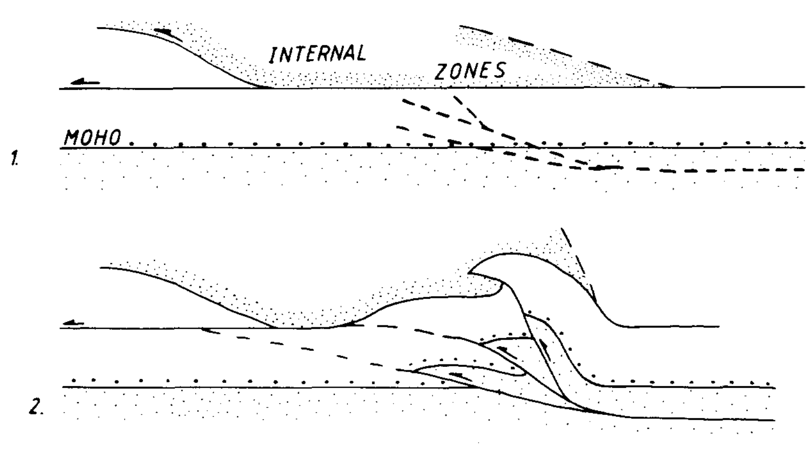

Fig. 13. Sequential development (1,2) of the deep structure of the western Alps. See text for discussion.

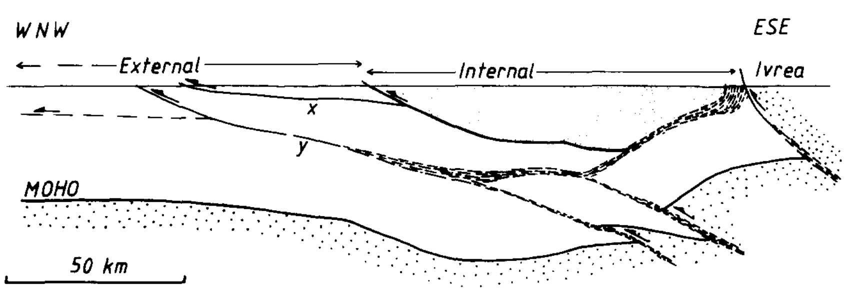

Fig. 14. Interpretation of the seismic section given in Fig. 10. See text for discussion.

thrust at the base of the internal zones. A predicted lower crustal–upper mantle duplex is illustrated where the sub-Ivrea thrusts have joined one or other of the higher thrusts.

CONCLUSIONS

(1) The external zones of the western Alps around Mont Blanc constitute a 'foothills'-style thrust belt which developed in a piggy-back sequence of thrust propagation in the footwall of the Valais thrust. The thrust transport direction was to the west-northwest.

(2) Balanced cross-sections drawn through this belt from the 'synclinal median' to the Gitte thrust above the Mont Blanc massif restore to lengths greatly in excess of 50 km and probably more than 100 km above a floor thrust no deeper than 1 km within basement. Laterally this thrust drops to a depth of 8–10 km to incorporate larger basement slices in the thrust belt.

(3) Lateral branch lines have transferred much of the displacement shown by a wide belt of imbricates onto the Mont Blanc thrust in the Chamonix area. This implies that the Mont Blanc and Aiguilles Rouges massifs were separated by at least 50 km and probably 100 km prior to Alpine thrusting. Published accounts of the structure of the western Helvetics preclude running the Mont Blanc thrust through the Helvetic nappes. A better solution might be to branch the Mont Blanc thrust onto the basal Morcles thrust (at the base of the Helvetics). This satisfies both the accounts of Helvetic structure and the thrust belt described here.

(4) The length of the restored template for the external zones demonstrates the large-scale Dauphinois stratigraphic consistency in a WNW–ESE axis. Thus most of the important stratigraphic variations in external cover rocks occur obliquely to the Alpine crustal shortening direction.

(5) In the absence of any direct evidence for major crustal extension before the onset of thrusting, it is suggested that large displacements above relatively high-level floor thrusts in the external zones require the internal zones to be underlain by a middle–lower crustal wedge. To achieve a crustal balance the length of this wedge must be equal to or greater than the length of the restored section above the floor thrust. Because this restored section is probably longer than 100 km, the entire Alpine belt must be underlain by lower crust continuous with that below the external zones. When this geometry is applied to Perrier & Vialon's (1980) model for the deep structure of the Alps, the Ivrea body is part of this lower crustal wedge. These lower crust and mantle rocks may have been uplifted on a series of imbricate thrusts. Thus the Ivrea body can be interpreted as a culmination of a lower crustal duplex, which may underlie much of the western Alps.

Finally this paper may open more questions than it solves regarding the deep structure of the western Alps.

The configuration presented here is dependent on the deep geophysical model of Perrier & Vialon (1980). Such models are not unique solutions; alternatives may be compatible both with the more traditional location of the Ivrea body in the hangingwall of the frontal Pennine thrust, and the balanced sections presented here. Particularly useful in testing these models would be some high-resolution reflection seismology. It remains to be seen how much further these 'thin-skinned' models for Alpine tectonics can be applied.

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