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The restoration of thrust systems and displacement continuity around the Mont Blanc massif, NW external Alpine thrust belt

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Abstract—Foreland-propagating external thrust belts may be considered as essentially plane strain phenomena so that displacements can be correlated throughout their linked, three-dimensional fault geometry. This approach has been applied to part of the northwest external French–Swiss Alps, around the Mont Blanc basement massif. Imbricates of basement and cover sequences on the SW margin of this massif restore to a width in excess of 77 km with an implicit shortening of at least 67 km. These displacements can be correlated with those in the neighbouring Helvetic nappes by transferring movements, via lateral branch lines, onto the Mont Blanc thrust. By reappraising thrust geometries, the Helvetic/Ultrahelvetic nappe complex has been restored to a width of 114 km to the ESE of the Aiguilles Rouges basement massif. Displacements on the internal (SE) margin of the Mont Blanc massif, estimated by balanced sections and a restoration of the Ultrahelvetic klippen in the sub-alps, exceed 59 km. Thrust continuity, incorporating the restorations of nappes and imbricate geometries around the Mont Blanc massif, is illustrated on a crude, restored branch-line map which also serves as a preliminary palaeogeographic reconstruction. External thrust systems, to the east of the external Belledonne/Aiguilles Rouges massif, restore to a width of at least 140 km in the footwall to the Frontal Pennine thrust.

INTRODUCTION

THE USE of thrust tectonic models in the interpretation of the external portions of orogenic belts is now well-established (e.g. Bally *et al.* 1966, Elliott & Johnson 1980, Beach 1981, Boyer & Elliott 1982). The cornerstone to this work has been the construction of balanced cross-sections, sections which when drawn parallel to the direction of orogenic contraction are capable of restoration to geologically realistic, undeformed states. Elliott (1983) noted that such sections are rarely unique and generally only serve to test the internal consistency of a particular structural model erected to solve a particular geological problem. While hydrocarbon explorationists, for example, may construct balanced cross-sections to constrain sub-surface structure, in recent years the main use of section restoration has been to gain estimates of orogenic contraction (Hossack 1979, Elliott & Johnson 1980). Such values are simply obtained by subtracting the deformed from restored section lengths, assuming plane strain and constant-volume deformation. Eroded or deeply buried parts of sections can be constructed to minimize the restored section length and so minimize the required orogenic contraction. Therefore, when shortening estimates between adjacent cross-sections are compared they may vary simply because the comparison is made between minimum rather than actual values.

Most recent structural investigations in thrust belts at the margins of orogens stress that faults generally form linked networks which propagated sequentially, piggy-back fashion, from the tectonic hinterland to foreland (e.g. Boyer & Elliott 1982). Away from lateral tips, thrust displacements must be broadly conserved along the strike of a thrust belt or higher sheets would be cut by cross faults or shear zones parallel to the transport direction, which collectively reflect differential movement. This essentially paraphrases Dahlstrom (1969, p. 751) who stated that: "... in adjacent cross-sections the amount of 'shortening' at a specific horizon between comparable reference lines must be nearly the same unless there is a tear fault between them."

The importance of this concept can be gauged from a hypothetical example (Fig. 1) which consists of a map and three serial sections which are drawn parallel to the thrust transport direction. The central section (B–B′, Fig. 1b) has been constructed to minimize displacements by siting the unseen hangingwall cut-offs just above the present erosion surface. An adjacent section (A–A′, Fig. 1) also minimizes displacements but was initially constructed (Fig. 1c) independently of B–B′. The solution requires the rather odd juxtaposition of a hangingwall ramp on a different footwall ramp but it balances and so would be admissible in the absence of additional information (Elliott 1983). However, the shortening in A–A′ is not equal to that in the adjacent section (B–B′) and thus it has been reconstructed (Fig. 1d). Not only does this revised section balance but it is also compatible with the adjacent section line B–B′. Similarly C–C′ (Fig. 1e) has been constructed to restore with the same amount of shortening. Thus all these sections are mutually compatible and restore to the same width. This is obviously an over simplification since some, probably minor, differential movement might be expected in natural examples, particularly near lateral tips (Coward & Potts 1983). It is also obvious from this hypothetical example that great care must be exercised when constructing cross-sections which require offsets. On the hypothetical map (Fig. 1a) the 'K' thrust has a hanging-

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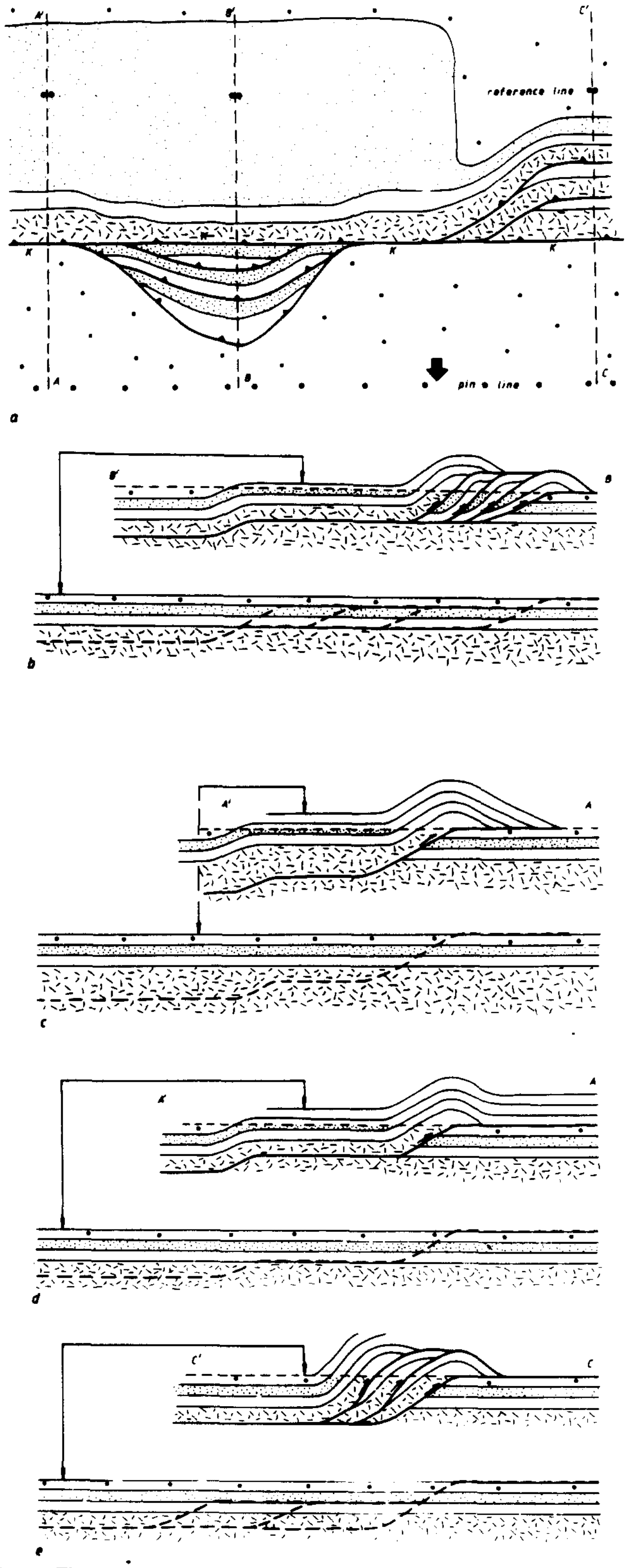


Fig. 1. The importance of lateral continuity of thrust displacements. (a) Schematic map of thrust structures: section lines (A–A', B–B', C–C') and reference and pin lines are indicated. The thrust transport direction is represented by the large arrow. (b) Section (B–B'), constructed to minimize displacements by locating hangingwall cut-offs just above the erosion surface. Displacement is indicated on this and other sections in Fig. 1 by the offset of the reference point between balanced and restored sections. (c) Section (A–A'), constructed to minimize displacements. Note that, although this section restores, it implies a reduced displacement from that of (B–B') so that the two parallel sections are not compatible. (d) Section (A–A'), reconstructed to be compatible with the adjacent section (B–B'). (e) Section (C–C'), constructed to be compatible with parallel sections (A–A') and (B–B').

wall in basement rocks. The imbricates in section B–B' (Fig. 1b) lie in the footwall to this 'K' thrust, but in section C–C' (Fig. 1e) imbricates which represent the equivalent shortening lie in the hangingwall of the 'K' thrust. An unfortunate choice of offset might incorporate both sets of imbricates on the same section line and so over estimate thrust displacements. It is crucial to establish the 'interconnectiveness' or 'logic' of the fault network (Boyer & Elliott 1982) so that displacements can be correlated between sections.

Just as lateral variations in orogenic contraction require higher sheets to be cut by tear faults or shears, laterally variable transport directions require thrust sheets to deform as they are emplaced. In arcuate orogenic belts such as the Alps it has been noted that radial, outwardly diverging transport vectors require major, along-arc extension (Goguel 1963, Ricou & Siddans in press). Although examples of tear faults, block rotations and non-plane strains are documented from many orogenic belts, it is important to realize that the magnitude of these strains and displacements must balance with those required by variable displacement vectors. Where thrust sheets are not significantly deformed after their individual emplacements a reasonable initial working hypothesis might be to assume lateral consistency of displacement vectors during particular periods of orogenesis. Such an approach has been used here to resolve the structural evolution of part of the external western Alps, around the Aiguilles Rouges, Mont Blanc and Belledonne basement massifs (Fig. 2). A possible three-dimensional fault network is proposed which links the Helvetic nappes in Switzerland with a thick stack of intersliced basement and cover rocks on the southwestern margin of the Mont Blanc massif, together with the Ultrahelvetic sheets which lie in the immediate footwall to the Frontal Pennine thrust. Larger-scale fault connections in the external western Alps are proposed by Butler *et al.* (in press). The plan here is to describe a balanced cross-section through the Belledonne and Mont Blanc massifs before tracing these displacements northward into the Helvetics and Ultrahelvetics.

BEAUFORTAIN

Figure 3 is a map of the distribution of basement and cover rocks in the Beaufortain area, between the external Belledonne massif and the Frontal Pennine thrust. Aspects of thrust geometry in this region are described by Butler (1983, 1984) and stratigraphy by Landry (1978) and Eltchaninoff-Lancelot *et al.* (1982). A balanced cross-section has been constructed through part of this region (Fig. 4) which restores the geometry of basement slices and fault profiles within basement. It is appropriate to discuss the geometric solutions adopted on this section.

The internal and external portions of the Belledonne massif are separated by a thin belt of cover rocks (the 'synclinal median'). Work by Bordet (1961) and later by

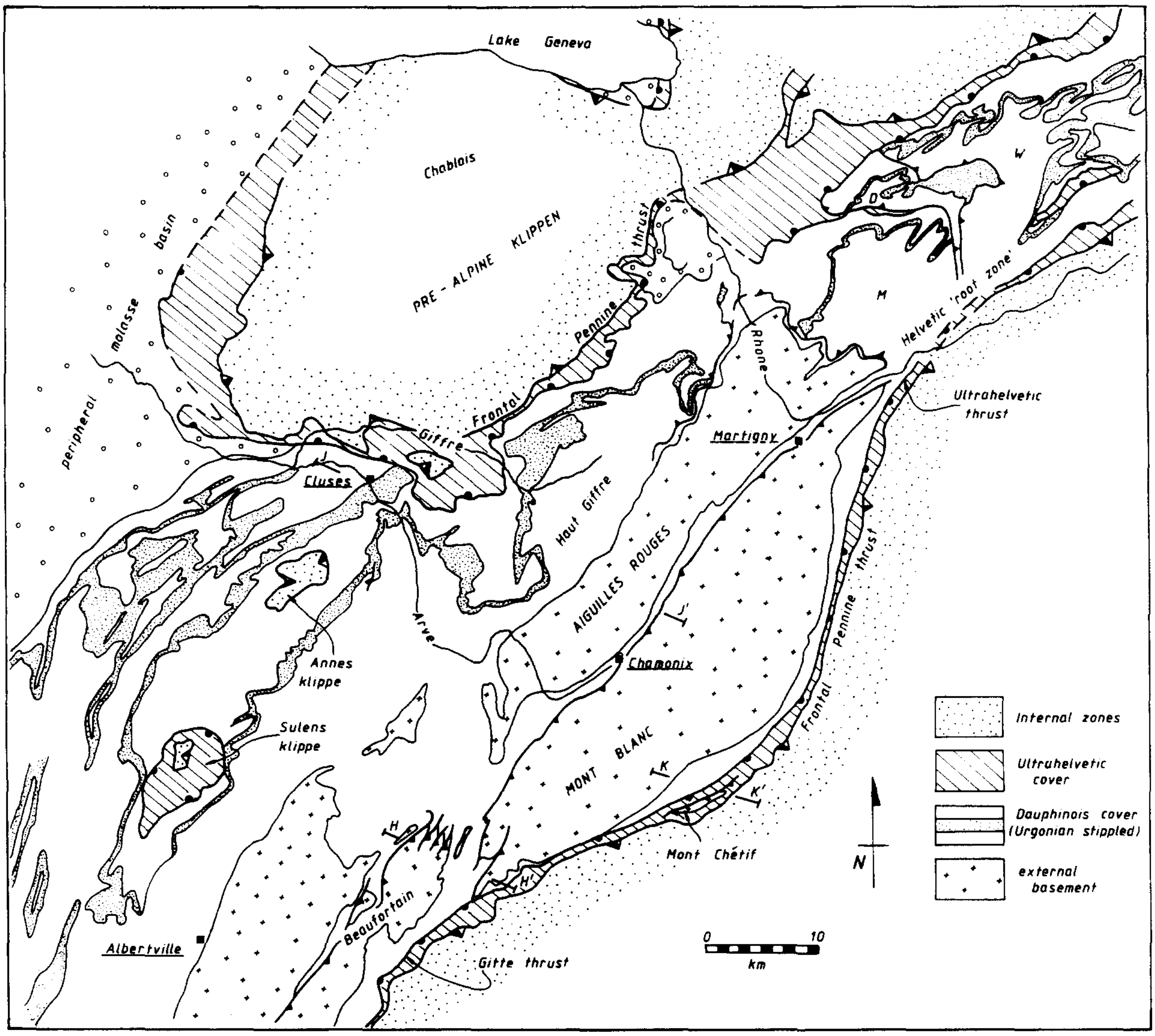


Fig. 2. Map of the northwest external Alps. Section lines on Figs. 4, 9 and 10 are depicted as H–H', J–J' and K–K', respectively. W, Wildhorn nappe; D, Diablerets nappe; M, Morcles nappe.

Ménard (1979) suggested that the internal Belledonne massif was faulted against the cover of the 'synclinal median' and that this fault is apparently subparallel to the unconformity between these cover rocks and the underlying external Belledonne massif. This view is supported by published maps (e.g. 1 : 50 000 St Gervais les Bains, BRGM 1977b) and by work by the author. Schistosity surfaces within both the Liassic cover rocks and the immediately overlying basement are subparallel to each other and to bedding in the cover. The schistosity generally contains a well-developed ESE-plunging mineral lineation which together with the older-over-younger stratigraphic separation on the fault, implies a thrust-sense movement towards the WNW. This Median thrust could have originated as a gently dipping structure but has subsequently been steepened, together with the cover rocks in its footwall, presumably by the domal uplift of the external Belledonne massif. Around Beaufort (Fig. 3) the Liassic cover contains a slab of basement rocks (the Beaufort 'horse') which I consider to have been emplaced on a similar flat-lying thrust which has since been steepened.

Above the Median thrust the internal Belledonne massif is composed of a thick stack of basement sheets (Mennessier *et al.* 1977, the Enclaves imbricates of Butler 1983) (see Fig. 3). On Fig. 4 the length of basement sheets are constrained by the restoration of imbricated cover rocks which now lie sandwiched, in the footwall to basement thrusts [e.g. slice 23 on Fig. 4, see discussion in Butler (1984)] or by thinner slices of basement which must lie on other sheets to achieve a balance (e.g. slices 18–20). Thus, although the maximum thickness of basement sheets on the section line of Fig. 4 is illustrated as about 500 m, thinner slices are common (e.g. the 'ecaille du Col de la Gitte' of Mennessier *et al.* 1977, see slice 18 on Fig. 4). Note that these thinner slices cannot be the noses of very thick wedge-shaped slices since this would reduce the dip of more internal imbricates (i.e. slices 7–12). The upper 1500 m of the basement slices illustrated on Fig. 4 are exposed in the deeply in-cut Doron Valley (Fig. 3) and shows no great variation in the dip of pre-Alpine basement foliation. The basement thrusts are presumed to be parallel to this pre-existing foliation since there are very

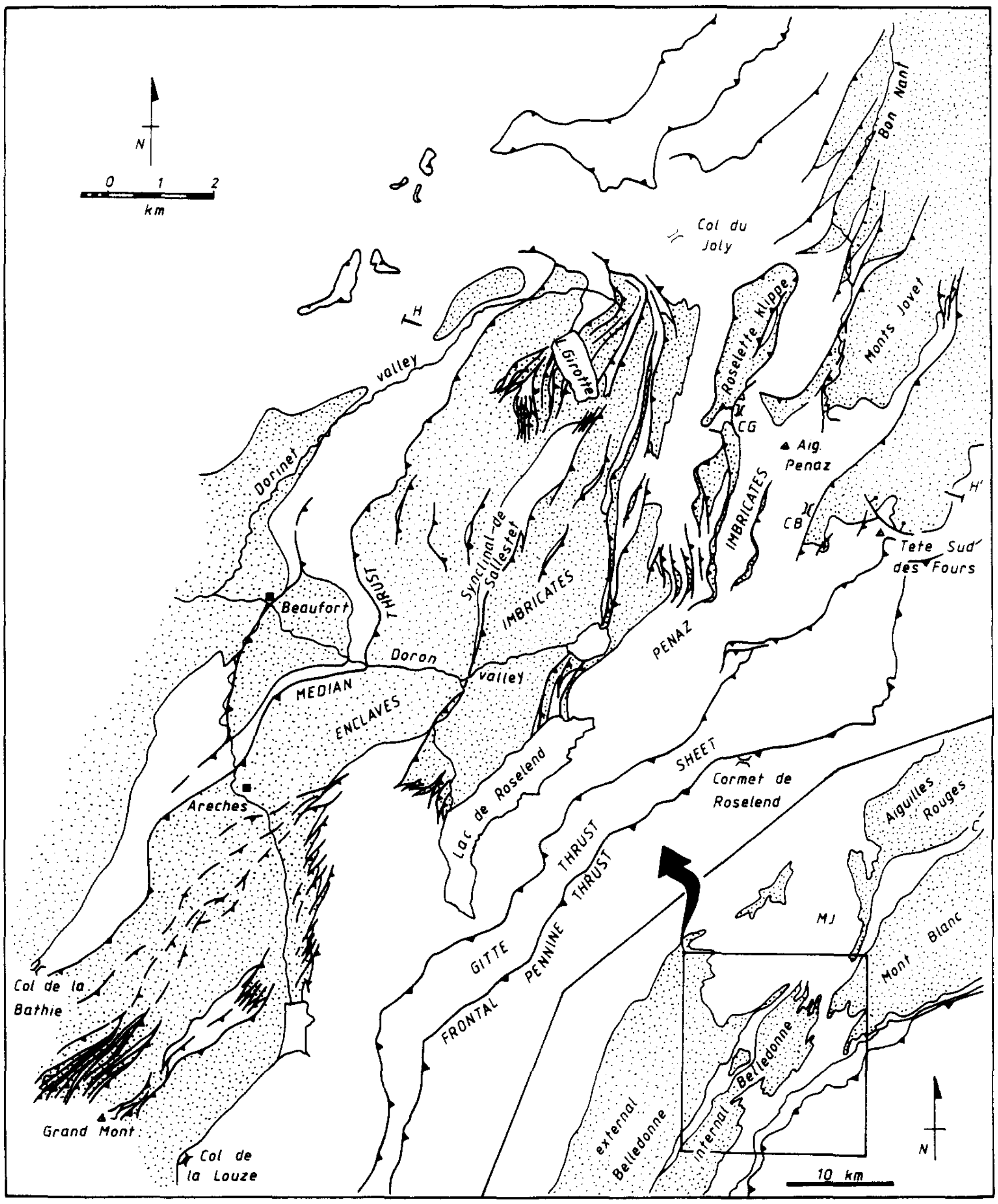


Fig. 3. Simplified map showing the distribution of basement (stippled) and Mesozoic cover (blank), together with important thrusts, in Beaufortain. CB, Col du Bonhomme; CG, Col. de la Gicle; H–H', section line on Fig. 4. Inset: location map. MJ, Mont Joly; C, Chamonix.

few cut-offs exposed (see Butler 1984 for discussion).

A stack of imbricated Carboniferous basement, the 'Claveau de la Grande Pierriere' of Mennessier *et al.* (1977), crops out in the northeastern part of the internal Belledonne massif (see Fig. 3, slices 13–17 on Fig. 4). Towards the southern end of this 'claveau' Triassic rocks become incorporated in the footwall of the imbricate thrusts and the whole sheet has the geometry of an antiformal stack (Boyer & Elliott 1982). Useful information from an EDF hydroelectric gallery 200 m beneath the present erosion surface shows that bedding within the Carboniferous basement increases in dip and becomes inverted on the eastern side of the 'claveau'. This suggests that the trailing branch lines of the imbricate thrusts have converged, a feature which is diagnostic of antiformal stacks. The structure is interpreted as having been back-steepened by the accretion of lower basement sheets (slices 21–33, Fig. 4). Note that a restoration of the thin Carboniferous sheets in the 'claveau' constrains the length of the underlying basement slices onto which they restore (slice 17, see Fig. 4).

The length of the inner, eastern basement slices shown on Fig. 4 (slices 4–9) can be locally estimated by restoring Mesozoic cover rocks near the Aiguilles de la Penaz (the Penaz imbricates of Butler 1983, see Fig. 3). Thrust geometry in this region is illustrated here on a map (Fig. 5) and cross-section (Fig. 6). Imbricates of Malm limestone at the head of Bon Nant (Figs. 3 and 5) restore onto the back of slice 7 (Fig. 4) for at least 3 km. Thus basement slices within the cover rocks in the Penaz area presumably must restore to be thin sheets, carried on thrusts which developed broadly parallel to the sub-

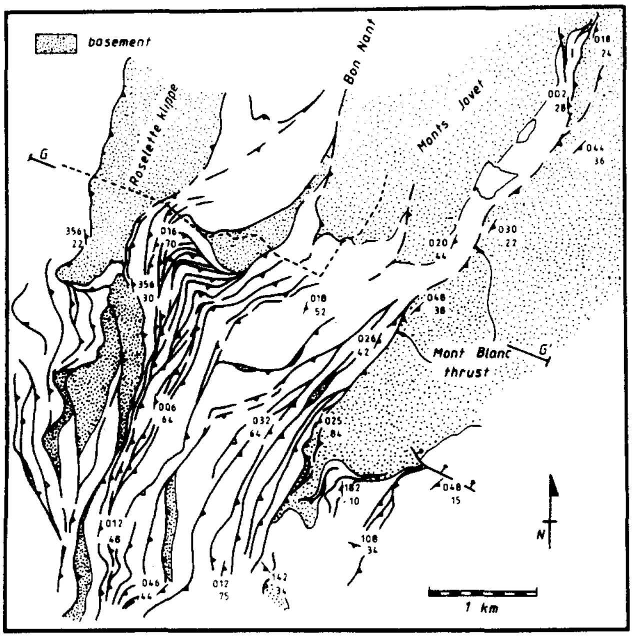


Fig. 5. Simplified map of the southern margin of the Mont Blanc massif; Mesozoic rocks are unornamented, basement is stippled. The orientation of bedding in the cover, and of mylonitic foliation within basement in the hangingwall of the Mont Blanc thrust, is illustrated. The termination of a thrust trace does not imply a thrust tip. The course of the EDF hydroelectric gallery is depicted with a pecked line. Section line G–G' on Fig. 6.

Mesozoic unconformity (see Fig. 4b). Note that although the lengths of basement slices 4–6 cannot be directly constrained by restoring cover rocks, which have been eroded, on Fig. 4a they cannot be less than that illustrated without reducing the observed dip of the Mont Blanc thrust. Butler's (1984, fig. 1) interpretation of the Mont Blanc thrust acting as a roof to the cover imbricates near Penaz, but breached by one imbricate thrust at the trailing edge of the 'Roselette klippe' (Figs. 3 and 5) is retained here. Note that the amount of basement within the Mont Blanc sheet increases laterally to the north, away from the postulated lateral hangingwall cut-off near Bonhomme (Butler 1983, fig. 3).

Thrust transport direction

The balanced section through the internal Belledonne massif shown in Fig. 4 has been constructed in a vertical WNW–ESE plane, parallel to the direction of thrust transport. It is necessary then to justify this direction, first, by using traditional displacement indicators, namely mineral lineations. Figure 7 is a stereoplot of mineral and stretching lineation orientations from the Beaufortain area, the lineations being measured on Alpine mylonitic foliation planes in basement and from thrusts in cover rocks. There is a crude cluster around an ESE plunge, however, the spread in data suggests that the fault network and even some individual thrusts developed with variable directions of transport. Sequential forward propagation of thrusting can be demonstrated in Beaufortain (Butler 1983) because lower structures either fold or breach through higher ones. Thus high-level sheets would have been carried passively, piggy-back fashion, by lower sheets. Variable movement directions require higher sheets to be deformed after movement has ceased on their internal thrusts, yet no such major post-emplacement strain deforms thrust geometries in Beaufortain. Therefore the thrust network is required to have retained a broadly constant displacement vector along its length.

Transport direction in thrust belts can be estimated using the distribution of ramps, or stratigraphic cut-offs, and branch line trends (Elliott & Johnson 1980, Butler *et al.* in press). Assuming that in the direction of transport thrusts can only cut up-section, up-cutting fault profiles can limit movement to a 180° arc. It is well established that in the western Alps the external thrusts developed and moved towards the foreland, namely generally westwards. Therefore, cut-off and branch line geometries constrain movements to be either from the north or the south of a particular direction. These extreme limits can be plotted on a histogram, the orientations of trailing branch lines and footwall cut-offs lying along the abscissa. Note that this is essentially the same concept as

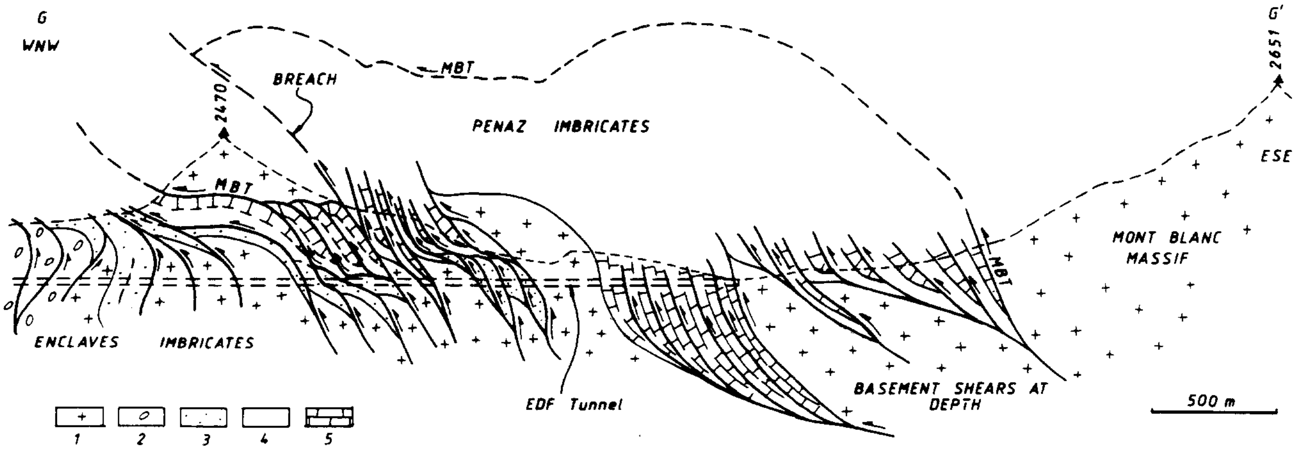
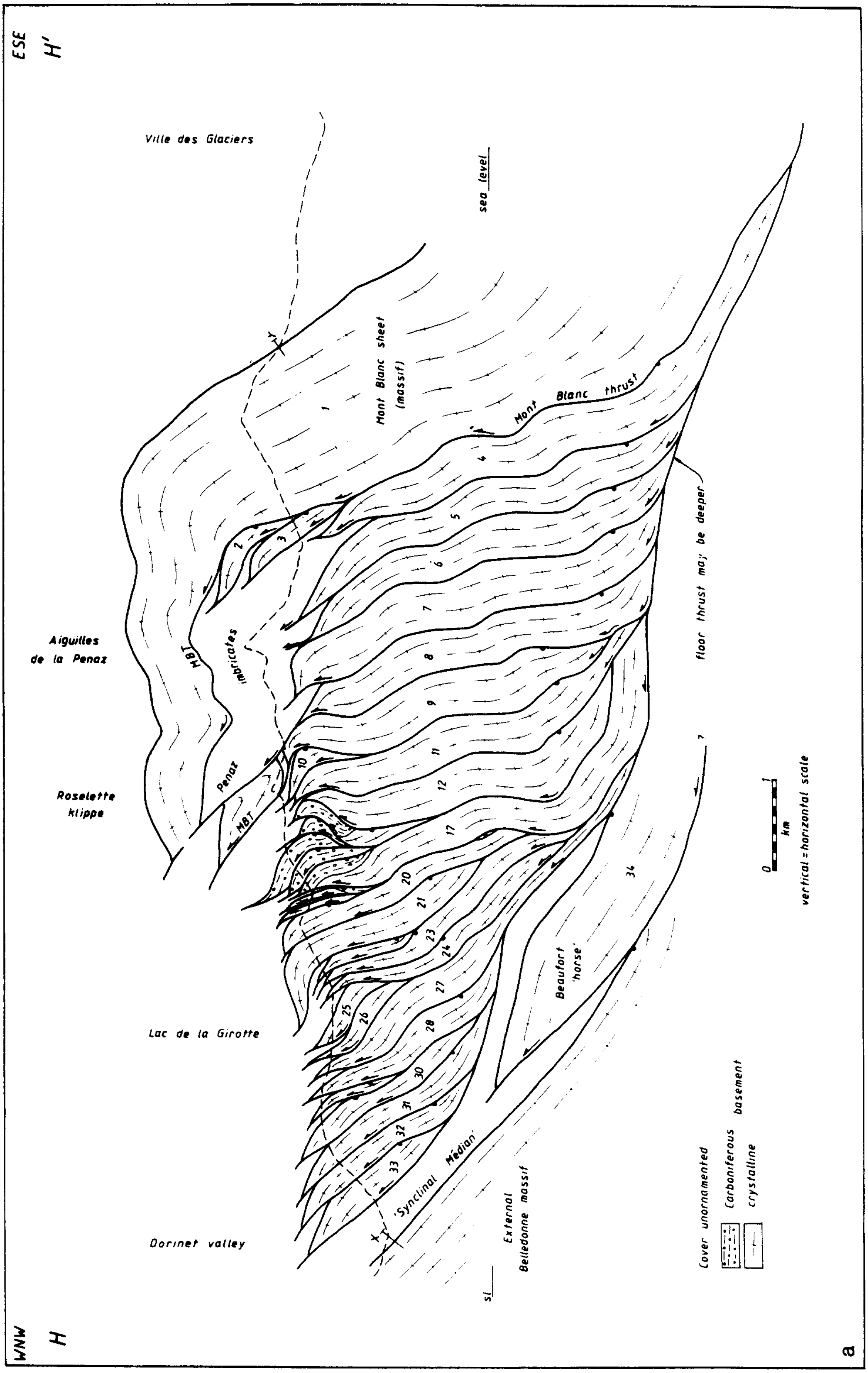


Fig. 6. Cross-section through the southern margin of the Mont Blanc massif, illustrating critical relationships resolved from surface and gallery data; location of section (G–G') shown on Fig. 5. Key: 1, crystalline basement; 2, Carboniferous basement; 3, Triassic (mostly cargneules); 4, Callovo-Oxfordian shales; 5, Malm limestones. Vertical and horizontal scales equal.


WNW
H
ESE
H'
Ville des Glaciers
Aiguilles de la Penaz
Roselette klippe
Lac de la Girotte
Dorinet valley
Mont Blanc sheet (massif)
Mont Blanc thrust
MBT
imbricates
Penaz
MBT
floor thrust may be deeper
?
Beaufort 'horse'
'Synclinal Médian'
External Belledonne massif
sea level
sl
1
2
3
4
5
6
7
8
9
10
11
12
17
20
21
23
24
25
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Cover unornamented
Carboniferous
basement
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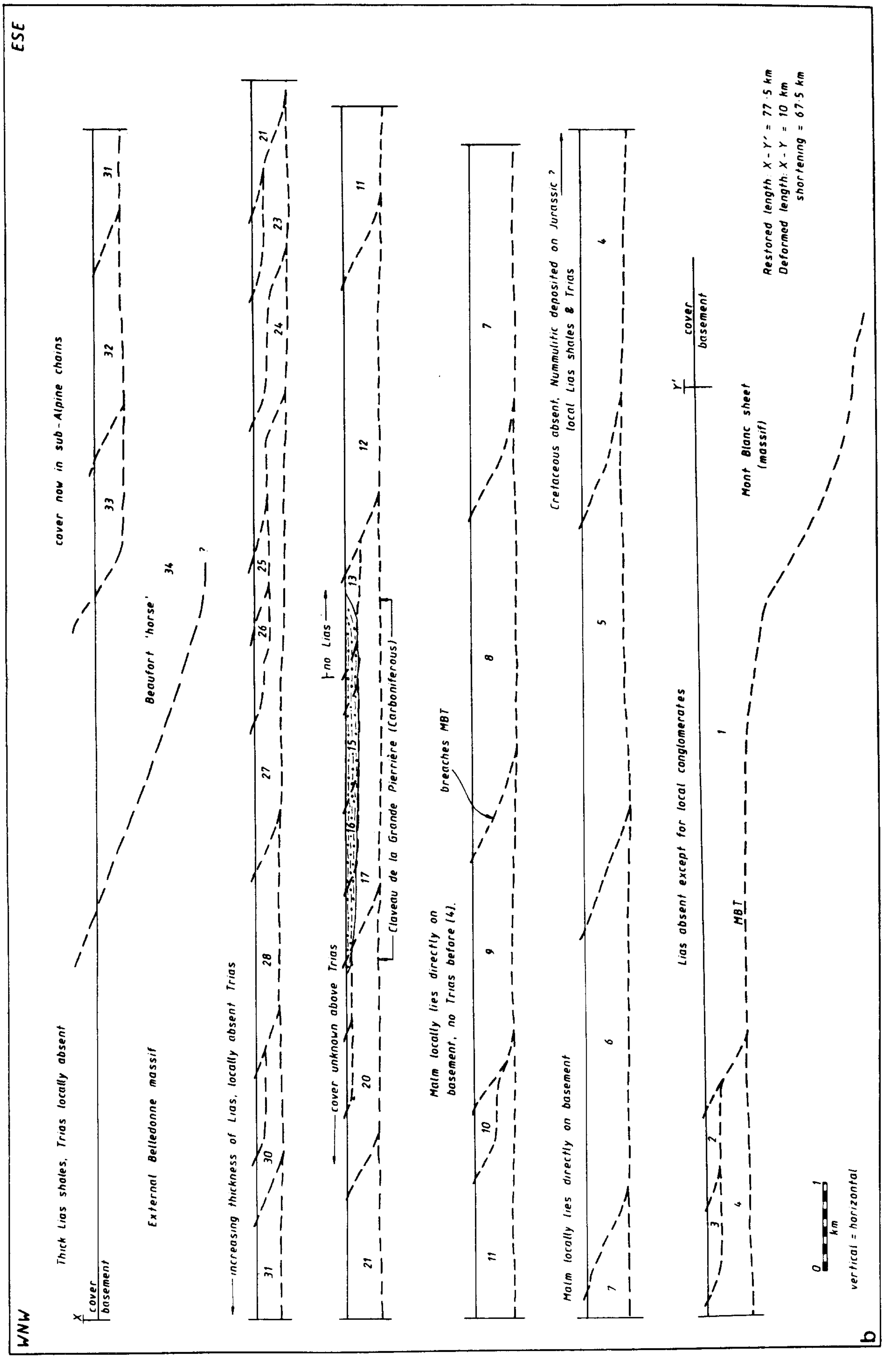

Fig. 4. (a) Balanced and (b) restored cross-section through Beaufortain, along section line H-H' on Fig. 3.

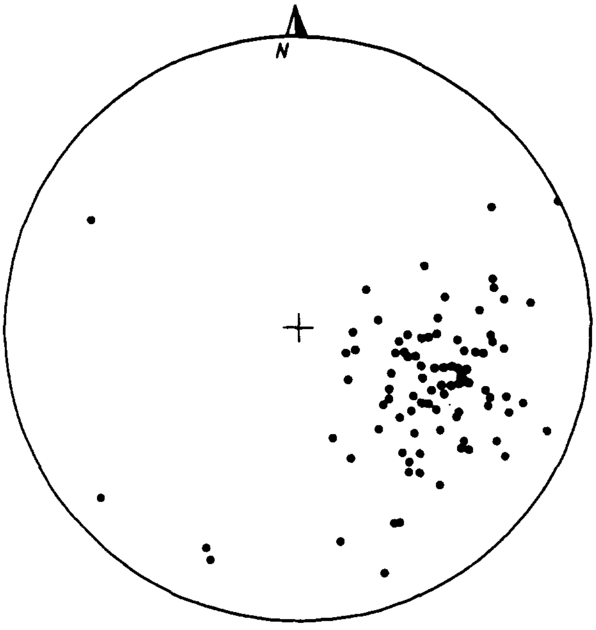

Fig. 7. Equal-angle, lower-hemisphere, stereoplot of stretching and mineral lineations in cover rocks and along basement thrusts in Beaufortain.

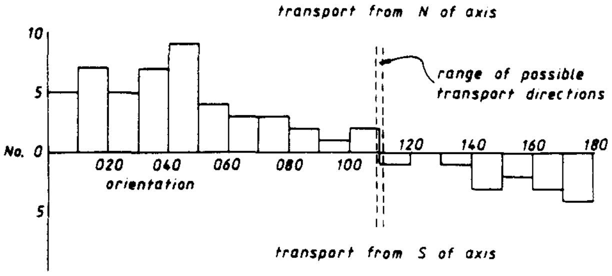

Fig. 8. Histogram showing the orientation of limits of transport direction defined by trailing branch lines (Butler 1982) and footwall cut-offs in the Beaufortain area.

Elliott's (1976) 'bow-and-arrow rule' but, by plotting limit axes, allows a more immediate appreciation of the transport direction. Figure 8 is such a histogram, containing data from throughout Beaufortain. The actual numbers of particular axes are unimportant; far more crucial is that there is no overlap which might be the product of extensional faulting (relative to the stratigraphic datum), 'out-of-sequence' thrusting or variable transport directions. The distribution of trailing branch lines and cut-offs constrains the transport direction to be from about 110° (i.e. towards 290°) which is subparallel to that obtained from the lineation data (Fig. 7). Particularly crucial to this plot are the data which lie close to the transport direction since these are interpreted as being ideal lateral structures. The lateral ramp which defines the northern limit of the internal Belledonne massif (Fig. 3) (see Butler 1983) requires a transport direction from the south of 108°. The culmination wall (Butler 1982) above the lateral hangingwall cut-off of basement against the Mont Blanc thrust (see Butler 1984, fig. 1) and other basement-cover thrusts in this system define the transport direction as being from the north of 116–142°. These important basement-cover thrusts have been interpreted as branching onto the Mont Blanc thrust along strike to the north (Butler 1983, Butler *et al.* in press) and therefore, to form part of the same linked system.

Thrust displacements and restored geometry

The restored length of the cross-section of Fig. 4, for the present 10 km distance between the cover of the external Belledonne and Mont Blanc massifs is 77.5 km. Therefore, for the geometry illustrated on Fig. 4, these thrust structures require a displacement in excess of 67 km, compared with previous estimates for the area of 50–139 km (Butler 1983) and 'about 40 km' (Platt 1984). Note that the figure suggested here is greater than that required by simply restoring basement-cover off-sets since there is an additional requirement to restore the cover unconformity to be regionally horizontal. Furthermore, the consistency of pre-Alpine foliation orientation in the Doron Valley (Fig. 3) section suggests a flat against flat thrust wall–rock relationship. At outcrop, Butler (1983, 1984, but see Platt 1984) noted that the pre-Alpine foliation in basement commonly, but not exclusively, made a small angle with the overlying cover unconformity. The exceptions commonly occur within the thicker basement sheets at outcrop. As a result of restoring the imbricated cover sequences, basement-cover offsets and the cover to the horizontal, while still requiring thrusts to have not developed markedly downcutting profiles in their transport direction, the pre-Alpine foliation is restored to a regionally flat-lying attitude prior to Alpine tectonics. Perhaps the inferred flat-lying attitude of the foliations provides a mechanical explanation for the development of thin basement thrust sheets to form the internal Belledonne massif, while other basement massifs, where pre-Alpine foliation makes a large angle with the cover unconformity, have been little deformed.

To the north of Beaufortain the Mont Blanc and Aiguilles Rouges (external Belledonne) massifs are only separated by a thin strip of cover rocks (Fig. 2) which constitute the Chamonix–Martigny zone (Ayrton 1980). The external (NW) margin of the Mont Blanc massif is marked by a major shear zone which continues southward into a belt of shears and basement slices on the east of Bon Nant (Fig. 3). Thus it is reasonable to follow Butler's (1983) suggestion that the Beaufortain displacements are transferred onto the Mont Blanc thrust near Chamonix (Fig. 2). I cannot envisage displacements being transferred onto the back of the Mont Blanc massif since it is composed largely of undeformed late Hercynian granite; there are no deformation zones at outcrop which link the internal and external margins of the outcrop. Furthermore, the Mont Blanc thrust developed 'in sequence' since it is folded and probably cut by imbricates generated in its footwall, contrary to the model of Mennessier *et al.* (1977) and Eltchaninoff-Lancelot *et al.* (1982).

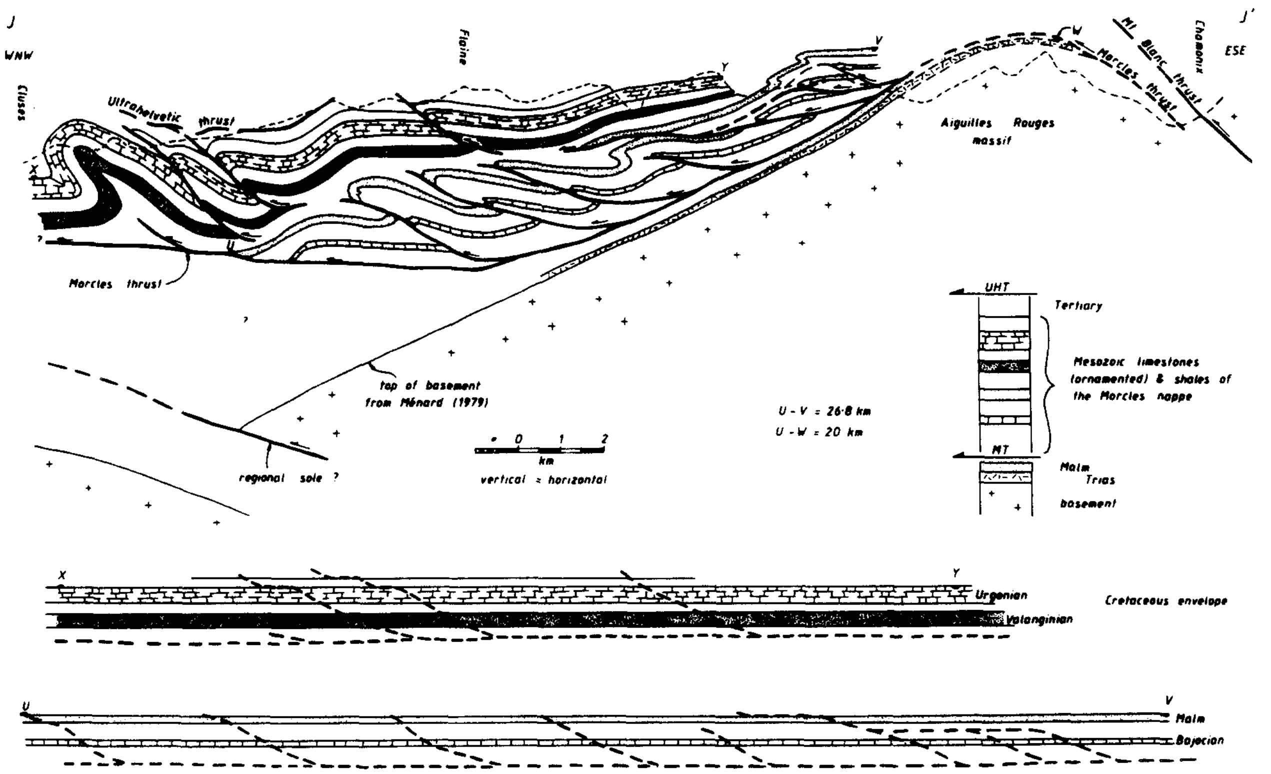

Fig. 9. Balanced and restored cross-section through the Haut Giffre sub-Alpine cover massif. The section line (J–J') is located on Fig. 2.

THRUST CONTINUITY BETWEEN BEAUFORTAIN AND THE HELVETIC NAPPES

When a major thrust does not develop imbricates in its footwall, or if these imbricates are subsequently eroded, it is often difficult to establish displacements. This is the situation for the Mont Blanc thrust near Chamonix (Fig. 2) since it is separated from the Aiguilles Rouges (external Belledonne) massif by apparently unrepeated Liassic shales. Its displacement can only be gauged by projecting estimates from Beaufortain along a longitudinal section (Butler *et al.* in press), the imbricates to the south joining the Mont Blanc thrust by lateral branch lines. However, structurally above and to the west-northwest of the Aiguilles Rouges lie a variably folded and thrust sequence of Mesozoic rocks which form the sub-Alpine Haut Giffre massif. If these rocks restore to lie in the footwall to the Mont Blanc thrust they can provide a useful estimate of shortening which is partially equivalent to that in Beaufortain.

The geology of Haut Giffre is superbly illustrated in a memoir by Collet (1943), which together with the 1:80 000 Vallorcine Mt. Blanc map (BRGM 1966) and reconnaissance by the author, has been used to construct a balanced cross-section across the southern part of the region (Fig. 9). The domal shape of the Aiguilles Rouges basement has been constructed from geophysical data by Ménard (1979).

Collet (1943, see also Charollais *et al.* 1977, Pairis & Pairis 1978) recognized that, in the eastern part of the section, the Jurassic limestones and shales were repeated by folds and shear zones beneath an envelope of Cretaceous rocks. The envelope becomes imbricated towards its leading edge, at Cluses (Fig. 9) but otherwise remains largely intact above the shortened Jurassic sequences. The geometry implies a major detachment horizon within the lower Cretaceous (Berriasian) shales which transfers displacements upwards and forwards from Jurassic rocks in the east to the Cretaceous envelope in the west. Note that displacements are unlikely to have been transferred towards the hinterland as has been suggested for the Rocky Mountain front in Canada (Jones 1982), since there are no documented reversals in shear sense at the base of the envelope. The geometry suggested here is similar to Fallot's (1949) 'ecailles intercutanees' in the Provencal Alps (see also Graham 1981).

The restored length of the stratigraphy within the Haut Giffre can be estimated from the Jurassic rocks. A line-length measurement of the Cretaceous rocks as presently exposed will underestimate the restored length since shortening has been transferred out of section to the west-northwest. The restored line-length of the Malm limestone is 26.8 km (U–V on Fig. 9), the present (deformed) length is just 8 km so the shortening is 18.8 km. Collet (1943) recognized that the Jurassic imbricates had been emplaced on the top of upper Jurassic (Malm) limestones which now lie in the footwall to their floor thrust. To the north this thrust marks the base of the lowest Helvetic (Morcles) nappe and so is considered to be the Morcles thrust (e.g. Collet 1943). The Malm limestones in its footwall are the only representatives of an otherwise absent Jurassic succession and rest directly on Triassic rocks. They crop out as a solitary outlier on the Aiguilles Rouges, projected from 2 km northeast of the line of section from the Aiguille de Belvedère. The displacement on the Morcles thrust can be estimated as the arc length between hangingwall and footwall cut-offs of Malm limestones (U–W) on Fig. 9, namely *c*. 20 km. Thus all the Mesozoic cover rocks above the Morcles thrust restore to lie 20 + 26.8 = 46.8 km southeast of the hangingwall cut-off of Malm limestones (U). The Mont Blanc thrust crops out just 2 km down-dip from the footwall cut-off (W) so the displacement on this fault must exceed 46.8 − 2 = 44.8 km. Any length of Malm limestones now eroded from the hangingwall of the Morcles thrust should be added to this minimum estimate. The present construction could infer that the footwall cut-off of Malm limestones against the Mont Blanc thrust lies just E of V on Fig. 9.

A restoration of the Helvetic nappes

The Haut Giffre massif passes laterally to the north into the Morcles nappe, the lowest of three Helvetic sheets exposed in Switzerland. A major difference in the internal geometry of this sheet between the cross-section in Fig. 9 and that described by Ramsay (1981) in Switzerland is that the Morcles nappe develops into a recumbent fold with inverted Cretaceous rocks lying continuously against the hangingwall of its basal thrust. Ramsay *et al.* (1983, fig. 1) provide the most recent published cross-section across the Helvetics which they restore to a width of *c*. 60 km to the southeast of the Aiguilles Rouges massif. It is tempting to correlate the displacements on the Helvetics with those obtained from Beaufortain. However, many reconstructions of the Swiss structures place the Mont Blanc massif in the core of the Morcles nappe (e.g. Ramsay 1981, Ramsay *et al.* 1983) so that the Beaufortain displacements can only pass onto the Morcles thrust. The majority of the Helvetics' displacements would then have to be added to those from Beaufortain. An alternative hypothesis is that the Helvetics restore to lie in the footwall of the Mont Blanc thrust. Mapping by the author of the critical area in the Valais Rhone around Martigny (Fig. 2) did not resolve this problem as a complete absence of outcrop did not permit testing of the rival hypotheses. Therefore, I suggest that the Helvetic nappes restore to lie in the footwall of the Mont Blanc thrust (see also Eltchaninoff-Lancelot *et al.* 1982, Butler *et al.* in press) since this geometry leads to a lower shortening estimate across the external zones. The thrusts at the base of the upper two, Wildhorn and Diablerets, Helvetic nappes might then branch onto the Mont Blanc thrust near Martigny. There is no evidence that these higher sheets overlay the Morcles nappe in Haut Giffre.

Ramsay (1981) and Ramsay *et al.* (1983) illustrate the Helvetic nappes enveloped by a further series of sheets, the Ultrahelvetic nappes, which lie in the immediate footwall to the Frontal Pennine thrust in the Valais Rhone (Fig. 2). The present outcrop width of the Ultrahelvetic nappes is 26 km, from the Valais Rhone to the frontal pre-Alpine klippen, but Ramsay (1981) notes that these high-level sheets have been rethrust by the Wildhorn and Diablerets thrusts, by 9.8 km and 18.5 km, respectively. A total minimum displacement on the Ultrahelvetic thrust is simply the combination of these three figures, namely 26 + 9.8 + 18.5 = 54 km. This figure may be combined with the restored width of the underlying Helvetic sheets (60 km) to give a minimum bulk restoration of the footwall to the Frontal Pennine thrust of 60 + 54 = 114 km.

THRUST DISPLACEMENTS ABOVE THE MONT BLANC MASSIF

In the preceding discussion of shortening in Beaufortain (see also Butler 1983) no balanced sections completely traversed the external zones to the Frontal Pennine thrust. Rather Fig. 4 stopped abruptly in the cover of the Mont Blanc massif, which is separated from the Pennine front by the Gitte thrust sheet (Butler 1983) (Fig. 3), the along-strike equivalent to the Ultrahelvetic nappes (Antoine *et al.* 1975). It was noted earlier here that all the displacements calculated in the footwall to the Mont Blanc thrust must pass to the northwest of the massif. Likewise all displacements along the internal (SE) side of the massif must either be transferred onto the Gitte thrust sheet, its basal thrust or the Frontal Pennine thrust. Unfortunately the Gitte thrust sheet in Beaufortain is composed almost entirely of Liassic slates which inhibits the recognition of thrust repetitions. This is not the case elsewhere on the internal margin of the Mont Blanc massif; any estimates of shortening derived from these more internal parts of the belt may be directly added to those already obtained for the footwall to the Mont Blanc thrust. The result will be a total restoration of the footwall of the Frontal Pennine thrust, namely the French external zones, excluding thrusting beneath the external Belledonne massif (Ménard 1979, Butler *et al.* in press). The area chosen to estimate this additional shortening lies 18 km northeast along the back of the Mont Blanc massif, in the vicinity of a thin slice of external basement rocks, the Mont Chétif massif (Fig. 2).

A balanced cross-section through the Mont Chétif area

Figure 10 is a balanced and restored cross-section drawn through the Mont Chétif area, based on the 1:50000 Mont Blanc map (BRGM 1977a), detailed but spatially limited stratigraphic work by Antoine *et al.* (1975) and reconnaissance mapping by the author. It has been constructed parallel to the WNW thrust-transport direction derived from Beaufortain (Butler 1983).

The most striking feature of the balanced cross-section is that the cover rocks directly southeast of the Mont Blanc massif, together with the basement contact, are inverted and dip to the NW. The underlying basement is locally mylonitized which led previous workers (e.g. Antoine *et al.* 1975) to suggest that the Mont Blanc

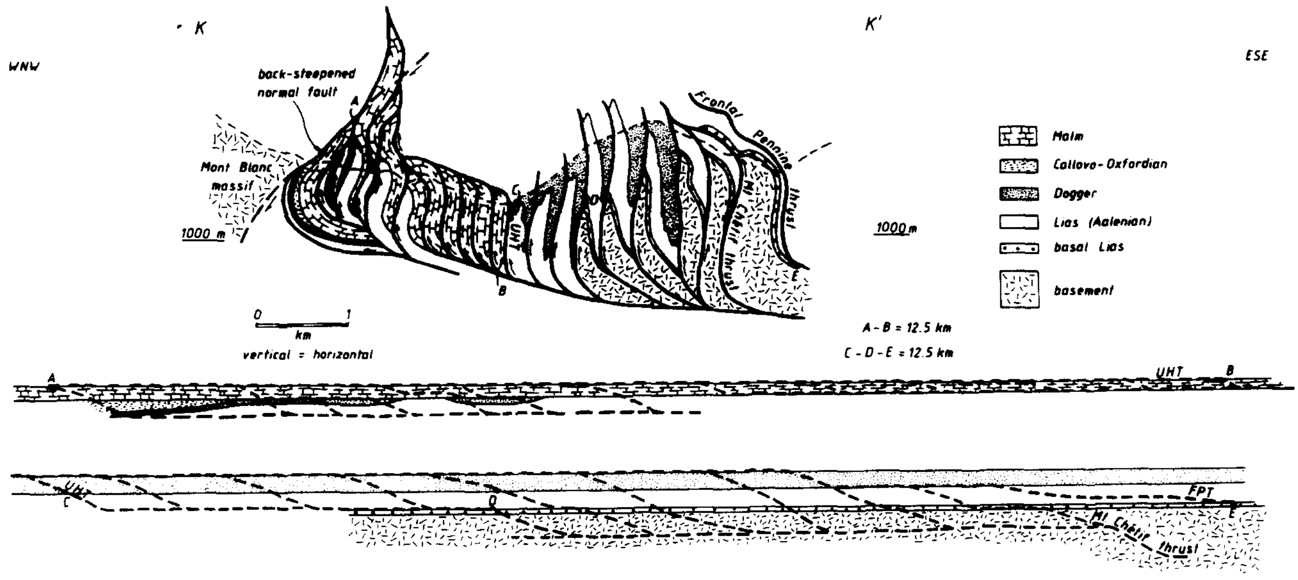

Fig. 10. Balanced and restored cross-section through the Mont Chétif area. The section line (K–K') is located on Fig. 2.

massif had been back-thrust. However, elsewhere on the internal margin of the massif, cover rocks are unconformable on basement and there is no mappable back-thrust surface. Indeed, 4 km along strike from the section line inverted upper Cretaceous sandstones are unconformable on basement. I suggest that the internal margin of the massif has been back-steepened so that imbricates which were originally developed without stratigraphic inversions have been inverted subsequently. The mylonitized basement contact has an extensional geometry, downthrowing to the SE, when the back-steepening has been removed, and this fault can be interpreted as a hangingwall drop fault accommodating extension on the dorsal culmination wall (Butler 1982).

Following normal practice, the balanced cross-section was constructed to minimize shortening while still incorporating all available surface data, hence the floor thrust to the imbricates might lie at a greater depth than shown here. However, the imbricates in the footwall to the Ultrahelvetic thrust restore to a minimum width of 12.5 km. The restored section shows important stratigraphic variations so that Dogger and Callovo-Oxfordian formations are limited to the northwest. Elsewhere, Malm limestones rest directly on Liassic shales. The imbricates presumably overlie the cover to the Mont Blanc massif at depth (probably upper Cretaceous sandstones) which at outcrop have been truncated by the drop fault.

A major variation in formation thickness occurs across what is now the Ultrahelvetic thrust, implying a significant displacement on this fault. The Dogger shales which are only locally present in the footwall have a thickness of *c*. 200 m and together with the Liassic shales are typical of so-called Ultrahelvetic stratigraphies (e.g. Debelmas & Kerckhove 1980). These imbricates of Ultrahelvetic rocks contain basement slices which crop out towards their internal margin. The largest of these basement slices is called the Mont Chétif massif (see Figs. 2 and 10). Their geometry suggests that prior to back-steepening the imbricates had an antiformal-stack structure. A restoration of the Ultrahelvetic imbricates provides a minimum width of 12.5 km. The combined restored width of cover rocks and basement slices to the southeast of the Mont Blanc massif is therefore 25 km, plus an, as yet, unestimated displacement on the Ultrahelvetic thrust.

Displacement on the Ultrahelvetic thrust

Besides its main outcrop trace behind Mont Blanc, Fig. 2 shows that the Ultrahelvetic thrust sheet lies in a number of important structural outliers, rimming the pre-Alpine klippen of internal zone rocks at Chablais and Sulens. Following conventional interpretations (e.g. Debelmas & Kerckhove 1980) these klippen are considered to be the last remnants of a now largely eroded Ultrahelvetic sheet which originally overlay all the intervening ground to restore to the southeast of the Mont Blanc massif. The Sulens klippe is largely composed of Eocene 'wildflysch'.

The present separation of the leading edge of the Sulens klippe and the outcrop trace of the Ultrahelvetic thrust to the southeast is 39 km (Fig. 2). Assuming no imbrication within this sheet, other than that already described, this value may be directly added to those from the Mont Chétif area to give a bulk restoration of 25 + 39 = 64 km for the cover rocks in the footwall to the Frontal Pennine thrust above Mont Blanc. The present outcrop width is just 5 km so the bulk shortening is 59 km, a figure which would be greatly increased if the Ultrahelvetic sheets imbricated. Following the same reasoning as given earlier this value can be added to those obtained in Beaufortain to gain a total minimum restored width of basement and cover between the external Belledonne massif and the Frontal Pennine thrust of 77.5 + 64 = 141.5 km. The shortening is 67.5 + 59 = 126.5 km.

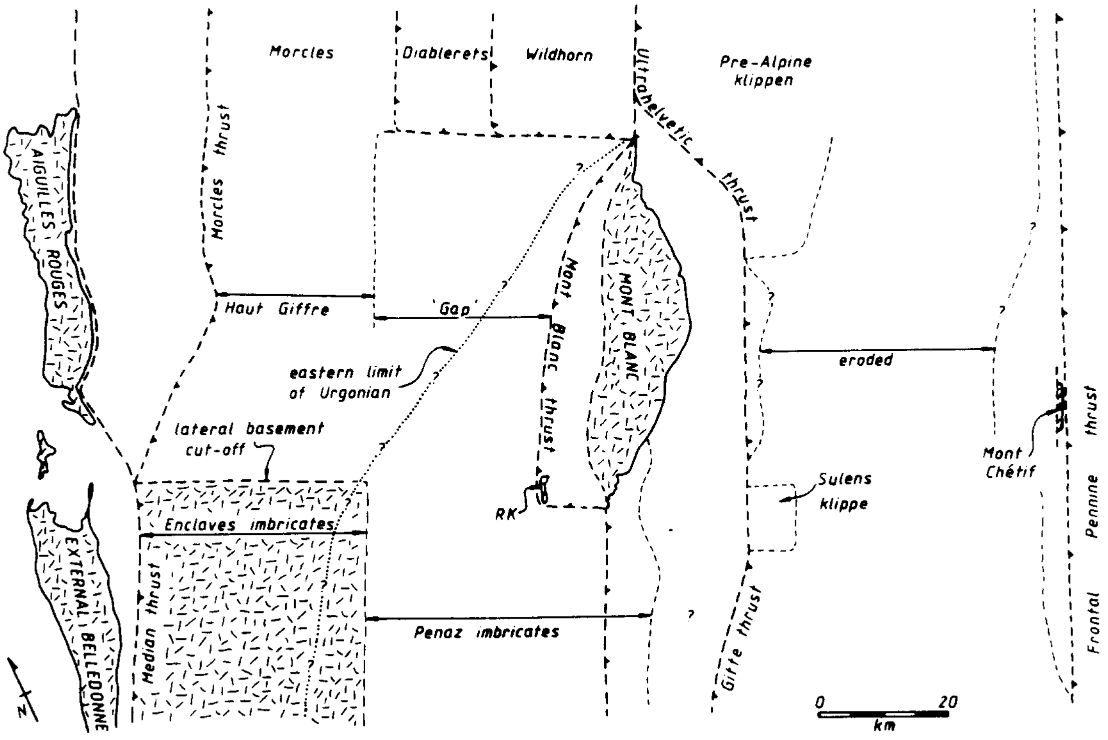

Fig. 11. Preliminary and highly schematic restored branch line map for the NW external Alpine thrust belt in the Mont Blanc area. It illustrates the presumed pre-thrust positions of the external basement massifs (random-dash ornament) as well as some important thrust sheets and imbricate systems. Most thrusts within the internal Belledonne massif (Enclaves imbricates of Butler 1983) and its cover (Penaz imbricates of Butler 1983) branch onto the Mont Blanc thrust to the north of the Roselette klippe (RK); see text for discussion.

A RESTORED BRANCH LINE MAP

From balancing sections around Mont Blanc it would appear that the external zones restore to at least 140 km to the east-southeast of the Aiguilles Rouges–external Belledonne massif. In constructing these sections and establishing thrust continuity around the region it was found necessary to dismantle some of the palaeogeographic reconstructions suggested by Alpine stratigraphers. Such reconstructions have previously been used to constrain tectonic interpretations, notably in the Helvetics (e.g. Ramsay 1981, Ramsay *et al.* 1983) and to a lesser extent in Beaufortain (e.g. Eltchaninoff-Lancelot *et al.* 1982). However, Trumpy (1960, p. 896) noted: "Palaeogeographic evidence has been widely used for nappe correlation but the two methods should be kept apart as we cannot *a priori* assume the parallelism of structural and palaeogeographic units." The following discussion attempts to illustrate how to go about rebuilding palaeogeographies from a foundation in balanced cross-section techniques.

Figure 11 is a preliminary and speculative reconstruction of thrust sheets and basement areas around Mont Blanc based on the balanced cross-sections presented earlier. Such a diagram might be called a 'restored branch line map' since it illustrates the relative positions of thrust-bounded sheets prior to thrusting in plan view. The ultimate expression of this technique would be to present a series of maps showing the positions of ramps cutting a succession of datum surfaces. The present diagram oversimplifies the situation by considering all ramps to cut directly across the stratigraphy in a single step; it nevertheless provides a useful starting point for discussion.

The laterally variable restored widths of footwalls to major thrusts are immediately obvious as gaps on the diagram. These, like those on poorly constructed cross-sections, illustrate non-viable solutions. However, in the case of the footwall to the Mont Blanc thrust in Haut Giffre, the 'hole' can be filled by additional, but now eroded, imbricates at the trailing edge of the Morcles nappe as currently exposed. Alternatively, the missing rocks can be assigned to the hangingwall of the Mont Blanc thrust, thereby placing its footwall ramp further to the west-northwest than illustrated here. Another solution might be to increase the displacement on the Morcles thrust by imbrication in its footwall, a possibility recognized by Collet (1943) but not considered here. A more complete analysis of the Helvetics and sub-Alpine chains using balanced sections will, I hope, shed light on this problem.

Once a restored branch line map, based on as many balanced sections as is feasible, has been constructed the various regional variations in stratigraphy can be plotted to produce a palaeogeographic map. The supposed eastern limit of the Urgonian (mid-upper Cretaceous) limestone has been plotted on Fig. 11 since this boundary has been used to define the transition between the 'Dauphino-Helvetic' and 'Ultrahelvetic' realms (see discussion in Eltchaninoff-Lancelot *et al.* 1982). It is unfortunate that these workers and others have used the term 'Ultrahelvetic' to describe not only a palaeogeographic realm but also a thrust sheet. The cover rocks in the footwall to the Mont Blanc thrust in Beaufortain do not include Urgonian limestone, rather, Eocene (Nummulitic) limestones lie directly on Jurassic rocks. In this sense the cover sequences are 'Ultrahelvetic' yet structurally do not lie within the Ultrahelvetic nappe (the Gitte thrust sheet of Butler 1983). Potential confusion and miscorrelation might be avoided if future Alpine geologists keep the names of palaeogeographic realms distinct from those of particular thrust surfaces and the sheets they carry. It should be noted here that the restored branch line map, like most balanced cross-sections (Elliott 1983) is not a unique solution and therefore the palaeogeographic boundaries on Fig. 11 should not be treated as a final statement.

DISCUSSION

While this analysis of thrust displacements may provide a satisfactory restoration of thrust sheets around the Mont Blanc massif, it is difficult at present to envisage such a simple approach being valid on a larger scale in the western Alps. The assumption of plane strain within this segment of the Alps seems reasonable and is underpinned by the undeformed state of the Mont Blanc massif together with the apparently consistent transport direction in Beaufortain. This WNW-directed thrust system, with its implications for large-scale (i.e. in excess of 100 km) displacements seems incompatible with the traditional view (e.g. Argand 1916, Milnes 1978, Ricou & Siddans in press) that the Alps developed by primary north–south plate convergence. At the outset it was suggested that, for piggy-back thrust sequences, non-parallel transport directions require the disruption of higher sheets. In the Alps such disruption of nappe systems has few advocates, indeed a traditional approach of large-scale correlation of palaeogeographies and tectonic events seems untenable without constant movement directions. Variations are still theoretically possible provided that each direction is confined to a particular period of orogenesis (e.g. Butler *et al.* in press). Unfortunately, the tectonic transport direction in most parts of the Alps is poorly known. The only fundamental constraint on any large-scale structural investigation, whether in the Alps or elsewhere, is the ability of the suggested tectonic model to be restored to a geologically realistic undeformed state. Therefore it is hoped that other tectonic geologists will attempt to restore their own suggestions of thrust and nappe geometry thereby identifying potential areas of conflict. I hope mutually compatible solutions can then be developed to explain and predict the three-dimensional geometry of thrust belts.

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