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

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Abstract—The structure of the northwest external French Alps, around the internal Belledonne and Mont Blanc massifs in the Beaufortain area, can be explained by foreland (WNW) propagating thrust tectonics. The internal Belledonne massif is interpreted as having developed by imbrication of an originally thin 'skin' of basement with a Mesozoic cover. Above this massif all thrusts tend to climb lateral sections to the south to converge with the frontal Pennine thrust; the southern termination of the Mont Blanc massif is merely a spectacular example of such a lateral ramp.

I THANK Platt (1984) for his interest in the Beaufortain area and for raising a number of important points regarding the structural evolution of this critical region in the northwest Alps. Here I will try to briefly answer his questions in turn: a more detailed account of the thrust structures will appear in a forthcoming issue (Butler in press).

MONT BLANC–PENAZ COMPLEX

Platt confirms my interpretation that the Mont Blanc massif has been carried by a major (the Mont Blanc) thrust but considers that this fault post-dates the development of a stack of (Penaz) imbricates in Mesozoic rocks. These imbricates he considers to completely envelop the Mont Blanc basement on the southwest margin of the massif. While it is clear that cover imbricates do wrap, and effectively terminate, the Mont Blanc basement to the southwest (as recognized by Butler 1983) it is equally obvious that along strike to the north, the Mont Blanc thrust is marked by a broad mylonite zone which carries a thick stack of basement rocks. The mylonites are subparallel to bedding in the Mesozoic rocks which lie in the footwall to the Mont Blanc thrust; these sediments now constitute the Penaz imbricates. The variable dips in the Mesozoic rocks can be readily attributed to the development of the Penaz imbricates which have locally steepened higher structures, including the Mont Blanc thrust and its mylonites. The Penaz imbricates change their geometry gradually along strike, on the Col du Bonhomme the steep dips suggest that their trailing branch lines are closely bunched and the imbricates have an antiformal stack geometry (Boyer & Elliott 1982). The generally consistent outcrop trace of the Mont Blanc thrust is retained since the Penaz imbricates show no drastic local changes in lateral profile. It seems reasonable on these simple grounds that the Mont Blanc basement sheet was emplaced onto the Mesozoic rocks before the development of the Penaz imbricates and that Platt's 'out-of-sequence' model is unlikely.

Additional evidence can be obtained from the Penaz imbricates themselves, which contain thin slices of basement and Triasic rocks. I (Butler 1983) interpreted these basement slices as 'roof pendants' derived from the Mont Blanc sheet during imbrication while Platt (1984) suggests that these slices were derived from beneath the Mesozoic rocks of the Penaz complex. I can confirm

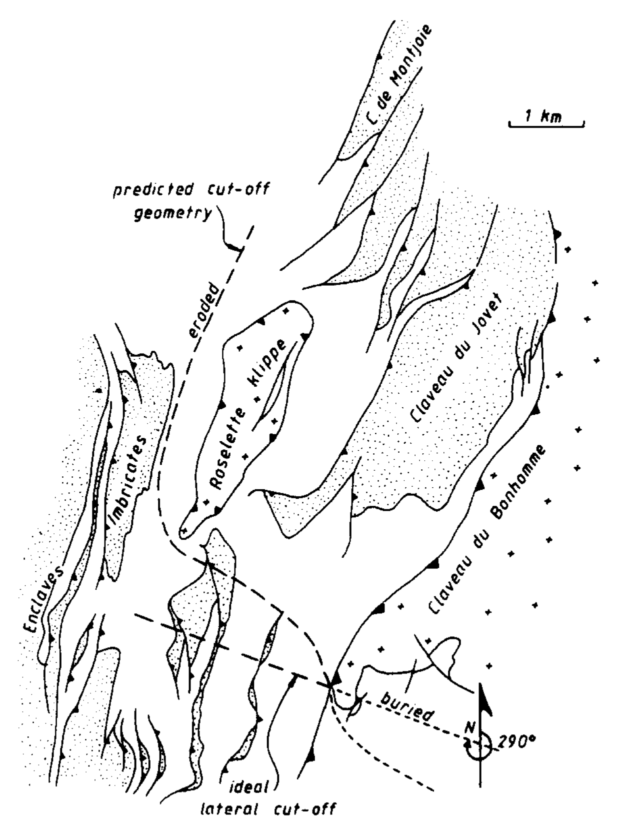

Fig. 1. A cut-off map of basement in the hangingwall of the Mont Blanc thrust (large barbs) illustrating that the southern continuation of basement slices (stipple) within the Penaz complex beyond the ideal lateral cut-off line precludes my breached-roof model. The map also shows my interpretation of the Roselette klippe as an outlier of the Mont Blanc thrust sheet (crosses). For clarity only those thrusts which carry basement sheets at outcrop are illustrated, the termination of these thrusts on the map does not imply the presence of thrust tips since the faults form a branching network.

Platt's interpretation since basement slices can be traced south of the southwest termination of the Mont Blanc massif. The hangingwall cut-off line of basement against the Mont Blanc thrust terminates the massif 1 km south of Bonhomme as illustrated on Fig. 1. If the slices were part of the hangingwall the thrust would show a complex undulating profile composed of extensional and compressional (thrust) segments relative to stratigraphy. I do not favour such a profile although Platt's (1984) proposal of 'plucking' would allow such profiles to develop. The basement slices are not folded around the domal structure of the southwest termination of the Mont Blanc massif as would be expected by Platt's 'out-of-sequence' interpretation of the Mont Blanc thrust. Rather, the basement slices and imbricate thrusts continue southwards and are unaffected by the overlying Mont Blanc thrust system. Therefore I retain my interpretation of the Mont Blanc thrust pre-dating the Penaz imbricates and the proposal that it climbs laterally from basement in the north into cover in the south so that the massif is terminated by a lateral hangingwall ramp. To the north of Bonhomme the Penaz imbricates pass laterally into a thick stack of basement slices which lie in the footwall to, and bulge up, the overlying Mont Blanc thrust. This geometry is confirmed by sub-surface studies by Bordet (in Mennessier *et al.* 1977) of a hydroelectric tunnel, showing that the Penaz cover imbricates are underlain by repetitions of basement and Triasic rocks.

While it seems likely that the majority of basement slices are derived from the footwall to the Mont Blanc thrust, the possibility remains that one, the 'Roselette klippe', lies in the hangingwall (Fig. 1). Both Landry (1978) and I (Butler 1983) have wrongly suggested that this sheet is continuous with other slices in the Penaz complex whereas it is entirely underlain by Mesozoic rocks (see also Bordet in Mennessier *et al.* 1977). The trailing edge of this klippe is abruptly terminated by imbricates of Malm limestone and Callovo-Oxfordian shales which suggests two possible geometries. Firstly, the basement sheet might be part of a large imbricate slice within the Penaz complex although no such sheet is recognizable at outcrop. This objection might be overcome by suggesting that the trailing-edge contact is a normal fault which has brought down the Mesozoic imbricates and isolated the Roselette klippe from its basement 'root'. This root would then lie buried beneath the Penaz complex. The second model, which follows my previous interpretation, is that the klippe is an outlier of the Mont Blanc sheet and that the trailing edge is cut by an imbricate thrust. This geometry is illustrated on Fig. 1 and implies that the Mont Blanc thrust sheet lay over the entire Penaz complex so that the basement hangingwall cut-off lies 4 km west of the main outcrop trace of the thrust. The first model slightly reduces displacement estimates across the area but I have not recognized any other normal faults in the required orientation in the area while there are abundant thrusts capable of breaching the Mont Blanc thrust (option 2).

'PLUCKING'

Platt suggests that the slices of basement within the Penaz imbricates might have been 'plucked' from the footwall of the imbricates' floor. The mechanism requires the propagation of synthetic (R_1) fractures into basement rocks and an additional fracture to propagate along and then up a ramp to rejoin the original level of the floor thrust (Platt's fig. 3). However, I have not recognized any conclusive examples of these fractures in Mesozoic limestones and shales. It would indeed be curious if such a mechanism propagated fractures into basement rocks alone. Perhaps more crucially, there is no evidence for low-angle extensional fault profiles cutting down into basement rocks, as displacements were transferred onto the Riedel fracture system, as suggested by Platt.

The 'plucking' hypothesis is unlikely not only because of the complete lack of corroborative evidence in Beaufortain but also on general grounds. Recent work in thrust systems (e.g. Fischer & Coward 1982, Suppe 1983, Knipe in press) suggests that thrust sheets must strain as they climb up a simple staircase trajectory of flats and frontal ramps. The plucking mechanism would produce a new family of ramps introducing more corrugations into an already irregular thrust surface and so increasing the cumulative strain in the hangingwall. While a fracture might propagate into the footwall in the manner envisaged by Platt, I can see no 'sound mechanical reasons' for displacements to be transferred onto the synthetic systems to any degree. I have certainly not recognized the extensional strains required in the hangingwall as a geometric consequence of his suggested pluck profiles in the Penaz complex. Note also that Tchalenko's (1970) experiments cited by Platt (1984) do not show the propagation of synthetic fractures into up-cutting fault segments nor any indication that the displacements on the dominant shear zone might be transferred onto the synthetic system.

Geometrically, the development of a particular fracture is not likely to be laterally continuous yet the basement slices in the Penaz complex have outcrop lengths of up to 2 km. This suggests a rather more widespread process, such as the propagation of a flat into the footwall at a basement ramp, that is, Elliott & Johnson's (1980) 'footwall collapse' mechanism. Platt suggests that the presence of small-scale fragments of material from beneath the 'normal décollement level' (flats) might be the result of plucking. This is not necessary since an individual flat only forms part of a staircase and the accretion of rocks from levels beneath flats along particular stratigraphic contacts can be accomplished by footwall collapse.

However, as Platt notes, there are examples of extensional geometries not only within the Alps (Vanoise) but also in other orogenic belts, even if such geometries are not found in Beaufortain. For the reasons discussed above, I do not consider plucking to be responsible; there are other interpretations. Firstly, extensional 'avalanche structures' (e.g. Coward 1982) have been described from the Moine thrust belt of N.W. Scotland and elsewhere, these being the presumed products of locally accelerated gravity tectonics. Alternatively, portions of fault profiles which cut down at low angles into stratigraphy might result from a pre-existing dip in the footwall rocks towards the hinterland (e.g. Butler in press a) so that datum-parallel flats extend stratigraphy. Finally, the apparent extension can result from the misinterpretation of thrust transport direction so that a lateral ramp to a N-directed thrust might appear to be part of an extensional, W-directed fault. There is no, as yet, conclusive evidence for the transport direction of the Piemontaise sheets in the French Alps, the example cited by Platt.

ENCLAVES IMBRICATES

The internal Belledonne massif in Beaufortain is composed of a thick stack of basement rocks which are divided into fault-bounded slices (the 'claveaux' of Mennessier *et al.* 1977) by thin, persistent strips of Triassic quartzites, dolomites and cargneules. I interpreted these Enclaves imbricates (Butler 1983) as being the result of stacking a relatively thin 'skin' of basement rocks while Platt (1984) suggests that the faults developed at a high angle to the sub-Triassic unconformity, by reactivation of the pre-existing basement foliation from splays above a moderately dipping thrust. Some of these basement faults pass along strike to join the Median thrust which separates the internal from the external Belledonne massif. Therefore it seems likely that the Median thrust is the floor to the Enclaves imbricates and this indeed has a moderate to steep ESE dip (Bordet 1961). However, bedding and schistosity within the Liassic cover rocks in the footwall to the Median thrust are subparallel to the fault and the schistosity in basement in its hangingwall. This strongly suggests that the Median thrust 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 underlying external Belledonne massif. The leading basement faults in the Enclaves imbricate thrusts do not show markedly different dips to the Median thrust suggesting that they did not develop at a high angle.

As Platt suggests, at some localities the angular discordance between the sub-Triassic unconformity and the underlying basement foliation is high. These discordant relationships are common in the highest structural levels within the Enclaves imbricates where thrusts climb from basement to cover and the Triassic slices show laterally variable thrust geometries. Generally, the highest levels in imbricate stacks are characterized by the highest stratigraphic units, which in the Enclaves system are Triassic dolomites and cargneules. These units are readily weathered and are commonly poorly exposed so the thrust structures are best displayed on the valley sides where imbricates contain both basement and cover.

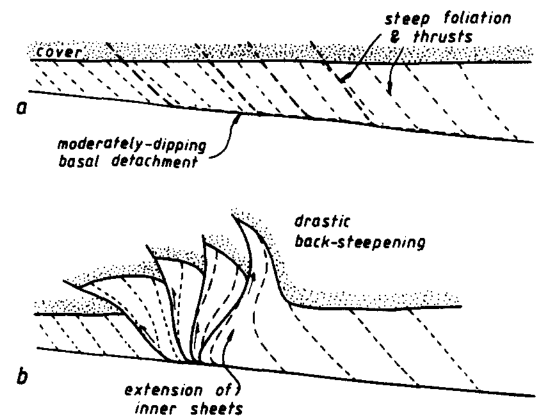

Fig. 2. Schematic illustration showing the sequential (a–b) development of the Enclaves imbricates by Platt's (1984) proposed reactivation of steep basement foliation above a moderately dipping basal detachment. The displacements on the imbricate thrusts are greater than envisaged by Platt but are consistent with the exposed geology (see text). The juxtaposition of trailing branch lines at depth results in a back-steepening and extension of higher sheets.

Triassic cargneules and well-bedded dolomites marking Mennessier *et al.*'s (1977) 'synclinal de Sallestet' can be traced for 1100 m up from the Doron valley bottom (1200 m altitude) to the hills on the north side (generally at 2300 m). This geometry is as obvious from the Beaufortain–Roselend road as when mapped out: foliation in both the overlying and underlying basement sheets is sub-parallel to the Trias rocks (*c.* 56° E) and the basement thrust can be traced across the valley. Here the Triassic and Liassic cover rocks have been repeated eight times by imbricates developed in the footwall to this basement thrust. Each imbricate slice has a dip-length of at least 250 m, an unknown excess length has been eroded. There is no evidence for plunge variations which would give 'apparent' dip-lengths for the cover slices. A minimum restoration of these imbricates is 2 km which is the minimum displacement on the basement fault. Four such faults can be easily recognized on the northern termination of the internal Belledonne massif when viewed from the Col du Joly.

The recognition of thrusts with displacements of several kilometres rules out Platt's proposal of reactivation of originally steep basement foliation. The consequences of such steep faults coupled with the relatively large displacements suggested by the above observations are illustrated on Fig. 2. The basal detachment is located at approximately the same relative level as the Median thrust to the Enclaves imbricates. To retain cohesion between basement sheets at depth, each splay must rotate so that earlier structures are progressively reoriented. Thus on a traverse across these splays, pre-existing basement foliation should show extensive back-steepening, and may become inverted towards the back of the internal Belledonne massif. The problem is more pronounced if the dip on the Median thrust is increased to the 'moderate' dips suggested by Platt. The Doron valley section does not show this drastic back-steepening, rather, pre-existing foliation in basement retains a constant, easterly dip of 50–60°. This consistency, together with the large thrust displacements implies that the imbricate slices were originally thin, with a pre-Alpine foliation subparallel to the floor thrust and to the sub-Triassic unconformity. Note that the parallelism between bedding in Mesozoic cover rocks and foliation in the underlying basement is implicit in many Alpine cross-sections (e.g. the section through the innermost part of the Aiguilles Rouges by Ramsay *et al.* [1983]; the inner margin of the internal Belledonne massif by Barbier [1948]).

STRATIGRAPHY

Platt (1984) rightly questions the prudence of using stratigraphic thicknesses of cargneule to perform an area balance on the shortened Triassic rocks within the Enclaves imbricates. However, for large parts of the area, the Triassic succession is dominated by well-bedded dolomites. Faults within single formations can be recognized by identifying tectonic bedding-cut-offs and this was done in culminations of Triassic rocks. Short sections were then balanced by line-length methods (Hossack 1979) independent of stratigraphy and thus I was able to resolve the original stratigraphic thicknesses. Note that this method is insensitive to ductile shortening (e.g. Cooper *et al.* 1983) so will overestimate original thicknesses and underestimate shortening. However, there is little evidence for large ductile strains within these Triassic rocks. Additional corroboration for stratigraphic thicknesses was obtained by measuring sections where both the basal unconformity and overlying Liassic or Callovo-Oxfordian shales were exposed. Such sections occur rarely within much of the area but are relatively common along the northern margin of the internal Belledonne massif. All these sites give consistent results of 10–12 m.

Continuing the stratigraphic theme, Platt also correctly notes that the Mesozoic cover shows complex variations both in thickness and facies elsewhere in the western Alps. However, where these variations have been described (e.g. Trumpy 1960, Badoux *et al.* 1972, Ramsay *et al.* 1983) they are systematic. It is important to realize that the distribution of cover rocks on basement in Beaufortain is generally unknown and can only be resolved by restoring sections. Such reconstructions are products of particular structural interpretations and are not necessarily unique. Thus the two interpretations of the basement slices within the Penaz complex, either as 'roof pendants' as I originally suggested or as rooting beneath cover imbricates as is now preferred, have different implications for local Mesozoic stratigraphy. A layer-cake stratigraphy of the maximum observed stratigraphic thickness was used in my original interpretation in order to minimize displacements within the Penaz complex. This simplification is in part supported by the general consistency in thickness of the Malm limestones, yet must be rejected because of the new interpretation of basement slices. It seems likely that, as Platt suggests, the Penaz Mesozoic cover shows rapid stratigraphic variation, at least below the Malm limestone. Note that these variations are not systematic and so are not analogous to those described elsewhere in the external western Alps (see discussion in Butler in press).

DISPLACEMENTS

Finally, Platt suggests that I have overestimated displacements across Beaufortain by combining equivalent shortening values. Despite my new interpretations it is pertinent to discuss some aspects of these assertions in general, particularly the problem of breached roof duplexes (Butler 1983). The ideal breaching model implies that displacements on imbricate thrusts are not transferred onto the roof since the individual fault junctions are not branch lines (Boyer & Elliott 1982) but fault–fault cut-offs. Thus the higher, breached sheet must have been emplaced across the entire width of the footwall before subsequent imbrication. Numerous authors (e.g. Boyer & Elliott 1982) have shown that each imbricate thrust within a duplex propagates and moves sequentially: note that this can readily be demonstrated throughout the Beaufortain region (Butler 1983). Any breaching of a duplex roof will occur as part of this sequence and so will not reflect the 'last few kilometres of displacement' as envisaged by Platt. When restoring any cross-section it is imperative to sequentially remove displacements on thrusts in the reverse order to their development: this method can be applied to the schematic example of Fig. 3. Each imbricate thrust must be restored (B–C, D–E, etc.) to reconstruct the breached thrust sheet to a state where it overlies an undeformed footwall. Similarly, partially breached roof thrusts can be restored in this manner but in the ideal model illustrated here the roof thrust must have a displacement at least as great as the restored length of its footwall. The total restoration here is: (A–B) + (C–D) + (E–F) + (G–H) + (J–K) + (the restored length of the marker which overlies the duplex). This is approximately twice the restored width of the footwall imbricates. The important general implication is that the simple duplex structure (e.g. Boyer & Elliott 1982), where all fault intersections are branch lines, represents a markedly lower displacement compared to structures with breached roof thrusts or with faults which propagate 'out-of-sequence' so that intersections are locally fault–fault cut-offs.

DISCUSSION

In summary, the structure of the internal Belledonne massif can be explained in terms of imbrication of an originally thin 'skin' of basement with a Mesozoic cover, broadly as described by Butler (1983). The Penaz imbricates are composed of an imbricated sequence of Mesozoic cover (Butler 1983) but which also locally incorporates basement rocks (as suggested by Platt). Note that in many respects the distinction between the Enclaves and Penaz imbricates now becomes rather

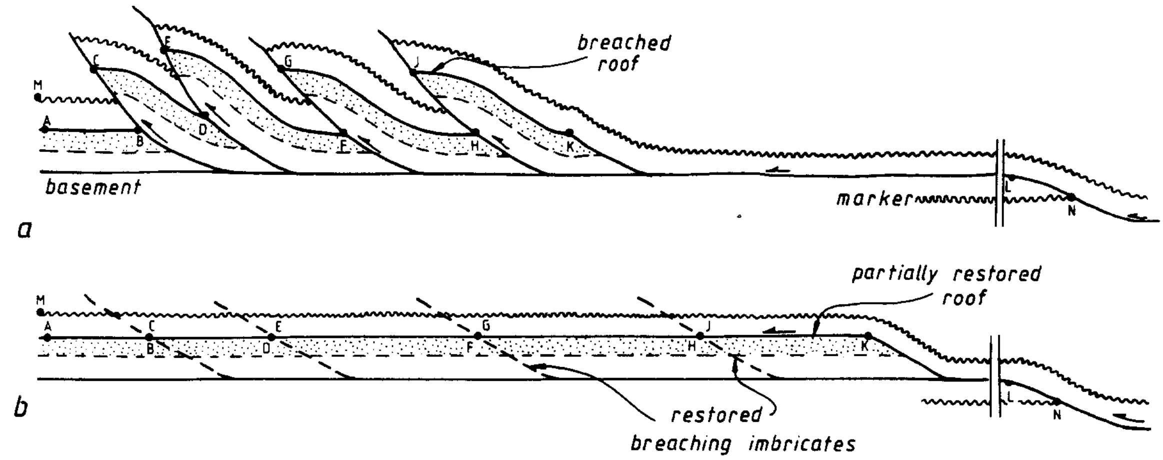

Fig. 3. Schematic representation of the method of balancing breached roof duplexes. (a) Final deformed state and assuming no displacements are transferred from the imbricate thrusts onto the roof. To gain a displacement estimate across the structure, each imbricate thrust must be restored (B–C, D–E, F–G, H–J). (b) Result of the above restoration illustrating that the roof sheet now lies on the entire width of the footwall which in the deformed state constitutes the duplex. A total restoration must also include the undeformed marker length (K–M) which must restore to lie to the right of point N. Therefore the total restored width of the structure is: (A–B) + (C–D) + (E–F) + (G–H) + (J–K) + (the restored width of the marker which overlies the duplex).

arbitrary. There is a tendency for higher thrusts to be folded or back-steepened above lower structures testifying to an overall piggy-back thrust sequence (as suggested by Butler 1983). The stratigraphy of cover rocks in the Penaz complex prior to Malm deposition appears complex as suggested by Platt.

Above the internal Belledonne massif all thrusts tend to climb section laterally from basement in the north to cover in the south. My interpretation of the southward termination of the Mont Blanc massif remains unchanged (Butler 1983) as being merely a spectacular example of this lateral variation in fault profile. The reinterpretation of the Penaz area does not require this thrust to be breached by all the Penaz imbricates (as suggested by Butler 1983 and refuted by Platt) although such a geometry might be required to explain the trailing edge of one slice, the Roselette klippe.

A new estimate of shortening across Beaufortain which incorporates the above geometric relationships is outside the scope of this discussion and will be reported later. It is important to realize that any displacements in Beaufortain must be added to those obtained on structures beneath the Median thrust (e.g. the basal Belledonne thrust) which Boyer & Elliott (1982) and Doudoux *et al.* (1982) suggest or imply exceed 30 km. Furthermore, no account has been taken of shortening above the Mont Blanc massif which includes the Ultrahelvetic and frontal Pennine thrusts. These structures are found as klippen 39 km west-northwest of their main outcrop traces on the southeast of Mont Blanc. This suggests that an additional 70 km of restored section length must be added to any figure derived from Beaufortain. It would appear that large displacements are unavoidable (see Butler *et al.* in press b) so that my conclusions about the deep Alpine structure remain valid.

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