Journal of Structural Geology, Vol. 6, No. 5, pp. 603 to 606, 1984
Printed in Great Britain

0191-8141/84 $3.00 + 0.00
Pergamon Press Ltd.

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

J. P. PLATT

Department of Geology and Mineralogy, University of Oxford,
Parks Road, Oxford OX1 3PR, U.K.

(*Received* 21 *October* 1983)

Abstract—Field evidence around the southwestern termination of the Mont Blanc basement massif casts doubt on Butler's interpretation of the massif as a relatively thin thrust-sheet extending over the imbricated Dauphiné cover. A thick-skinned model of basement faulting, analogous to Laramide faulting in the western U.S.A., seems more appropriate for the area.

BUTLER (1983) is to be congratulated on his imaginative reconstruction of the tectonic history of the Mont Blanc massif: his provocative conclusions will undoubtedly stimulate Alpine geologists to review both their assumptions and their methods. The principal value of the method of balanced cross-sections is that it determines minimum necessary displacements, however; and I feel that for several reasons Butler's estimates are substantially greater than the minima required in his study area. This may therefore cast doubt on his interpretations about the deep structure of the Alps.

There are four main points that I wish to discuss: Butler's interpretation of the Mont Blanc basement massif as a thrust-sheet; the nature of basement faulting in the internal Belledonne massif; the stratigraphic assumptions underlying the construction of Butler's cross-sections, and some errors in calculation that exaggerate his estimates of displacement.

Butler's interpretation of the Mont Blanc massif depends critically on the field relations around its southwestern termination. Discussion must therefore involve some consideration of the local field data, which I hope will not prove too tedious. Butler interprets the termination of the massif as a lateral branch line, where a major thrust beneath the massif meets a décollement thrust along or just above its upper surface. The branch line would be oriented roughly parallel to the transport direction, terminating the basement to the south, but allowing it to have continued to the west above the present erosion level. This leads him to conclude that the massif overlies his Enclaves and Penaz imbricates, so that its displacement includes the total amount of shortening within these imbricates (note that Butler has made some computational errors in estimating this displacement, see point 4 below).

Butler's interpretation is in marked contrast to that of previous workers in the area, as shown, for example, by the 1:80,000 Albertville sheet (BRGM 1966), the 1:50,000 St.-Gervais-les-Bains sheet (BRGM 1976), and Landry (1978). These workers believed that the Mesozoic rocks constituting Butler's Penaz imbricates tectonically overlie the Mont Blanc basement, and that the basement termination is a S-plunging antiform around which the previously deformed cover, with its basal décollement surface, has been folded. In this interpretation, the Mont Blanc massif is unaffected by the shortening in the cover, and its minimum displacement is correspondingly reduced. The differences in interpretation seemed to me to be sufficiently important to warrant a visit to examine the field evidence. The field relationships in the critical area between the Col du Bonhomme (9400 0910 Lambert on the St-Gervais-les-Bains topographic sheet) and Tête des Fours (9415 0906) are fortunately excellently exposed and can be reached by a pleasant 2-hour walk along the Crête des Gittes from the road at Cormet de Roselend. I present the field data in the form of a panorama (Fig. 1) of the region viewed looking north, as this makes the three-dimensional relationships clearer. The panorama covers the eastern 5 cm of the section line shown on Butler's map (his fig. 2). Note firstly that the Mesozoic rocks west of the basement culmination dip east, towards and beneath the massif. This, no doubt, led Butler to his conclusion that the massif was allochthonous, and he is clearly correct in suggesting that the basement is bounded to the west by a major fault. It is also clear, however, that the imbricated Triassic cover above the massif wraps right around the basement to the south, and also over the top, so that on the west side, the Trias dips steeply west (Fig. 1). The Triassic cover effectively terminates the basement to the west, which would seem to preclude Butler's suggestion that the massif formed a thrust-sheet extending westwards above the Penaz imbricates. The simplest way to explain the field relationships seems to me to be that the basement has been faulted up along a high-angle reverse fault into the previously imbricated cover sequences. This fault need only have a displacement of about 3 km, though it is probably only one of several such faults that bring up the massif as a whole [significant thrusting is probable along the line of the Chamonix syncline, for example (Ayrton 1972)]. This model is illustrated in Fig. 2(a), and compared with Butler's in Fig. 2(b). Landry's interpretation in terms of folding is shown in Fig. 2(c). The latter interpretation depends on

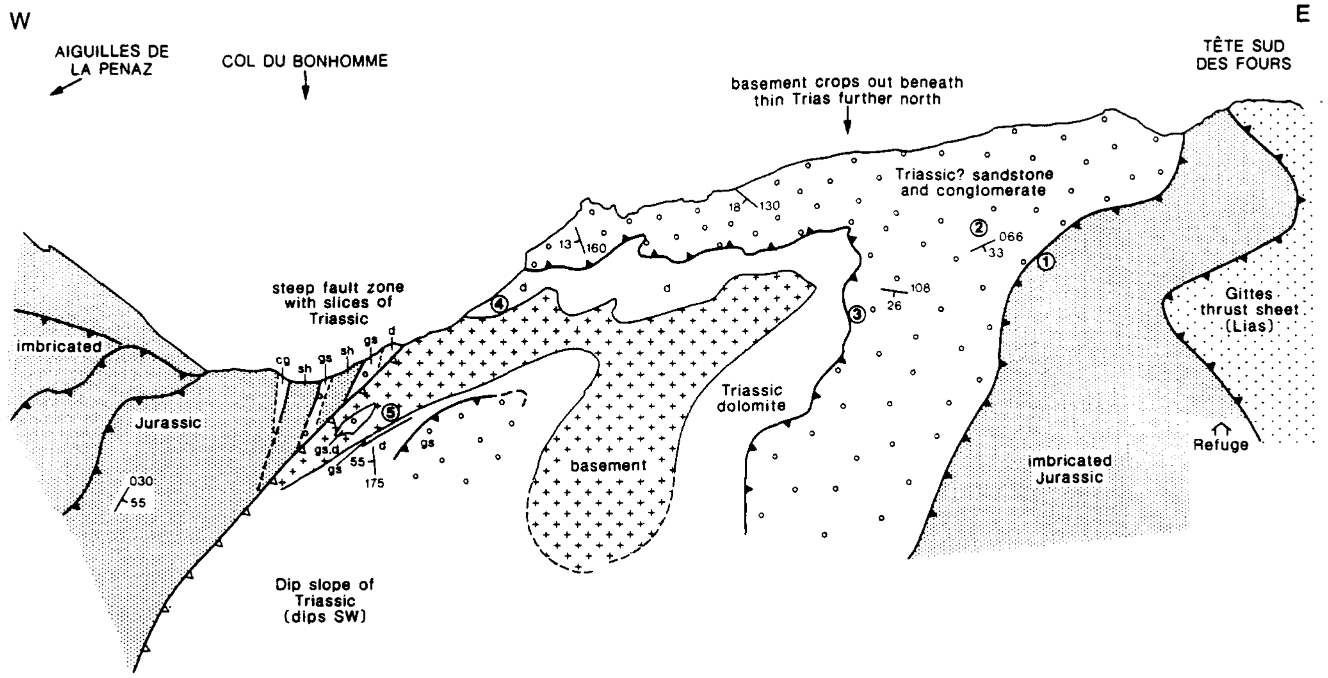

Fig. 1. Field sketch of the southern termination of the Mont Blanc massif looking north from the Crête des Gittes. cg, cargneule; d, Triassic dolomite; gs, 'gres singuliers'—sandstone and conglomerate attributed by Landry (1978) to the Lias, but probably early Triassic in age; sh, black calcareous shale (Mesozoic). (1), décollement surface beneath folded and imbricated Jurassic. The Triassic dolomite is missing along this fault; (2), cross-bedded sandstone, right way up; (3) décollement thrust places sandstone over brecciated and foliated dolomite. Thrust strikes 060°, dips 24° SE, but turns horizontal up the hill; (4), iron-enriched dolomitic breccia rests directly on the basement. Contact dips gently W; (5), 1 m thick sandstone overlain by Triassic dolomite rests non-conformably on basement. The contact dips steeply W.

the identification of inverted stratigraphic sequences, but it remains a possibility: note that Butler advances no evidence to refute it. Both my suggestion and Landry's have several advantages over Butler's model. (a) They are compatible with the westward termination of the basement by the folded Triassic unconformity at Col du Bonhomme. (b) They explain the slices of Trias, belonging to the Mont Blanc cover sequence, in the frontal fault zone. These were probably derived from the hangingwall. (c) They explain why the Mesozoic rocks east and above the basement massif are identical to the Penaz imbricates. In Butler's interpretation, these were separated by several tens of kilometres, leading him to postulate a 'hitherto unsuspected Dauphinois stratigraphic consistency'!

We are left with one loose end, however. Butler has a delightful interpretation of the isolated basement slices in the Penaz imbricates as 'roof pendants' of his Mont Blanc thrust-sheet, formed where imbricate thrusts 'leaked' upwards through the roof of the Penaz duplex. Some of these slices, such as the one forming the Aiguille de Roselette–Tête de la Gicle ridge, lack any Triassic cover. This favours Butler's model, as he would interpret the lower surface of the basement slice as the original Mont Blanc thrust, and the upper surface as the leaking imbricate fault. Landry (1978), however, reported a transgressive middle Jurassic sequence with a basal conglomerate on one of these slices, indicating its original top surface. Butler's interpretation is therefore unnecessary, and possibly invalid, on these grounds alone. Landry suggested that the basement slices are olistoliths, as they are commonly associated with Eocene flysch—a possibility that Butler does not discuss. I think the simplest interpretation is that they are fragments of basement 'plucked' from beneath the basal décollement surface. This process of plucking or peeling of material from the footwall of a thrust implies that the thrust locally cuts down section in the transport direction, which contravenes the current dogma of thrust tectonics. There are, however, sound mechanical reasons for believing that this can happen. A thrust fault, like any zone of brittle or semi-brittle deformation, consists of anastomosing sets of fractures, including a dominant set of synthetic (R_1) fractures inclined at about 15° to the zone (Fig. 3). In the case of a horizontal décollement fault, these will dip in the direction of transport. Propagation of these fractures out of the fault zone downward into the footwall for a short distance is likely, and if the main slip surface follows this fracture, the thrust will cut down section. It may then cut back up again along a ramp, removing a slice of footwall rock (Fig. 3). Note that this is similar to the mechanism proposed by Gay (1970) for the formation of small-scale pluck marks on fault surfaces. Examination of any detailed geological map of the Alps shows that many thrusts are decorated by small fragments of material from below the normal décollement level. These can most easily be explained by plucking. The same explanation was implied by Elliott & Johnson (1980) to explain the Lewisian basement slices involved in the Moine thrust zone in Scotland. The most spectacular example of large-scale plucking that I know of is the wholesale removal of the

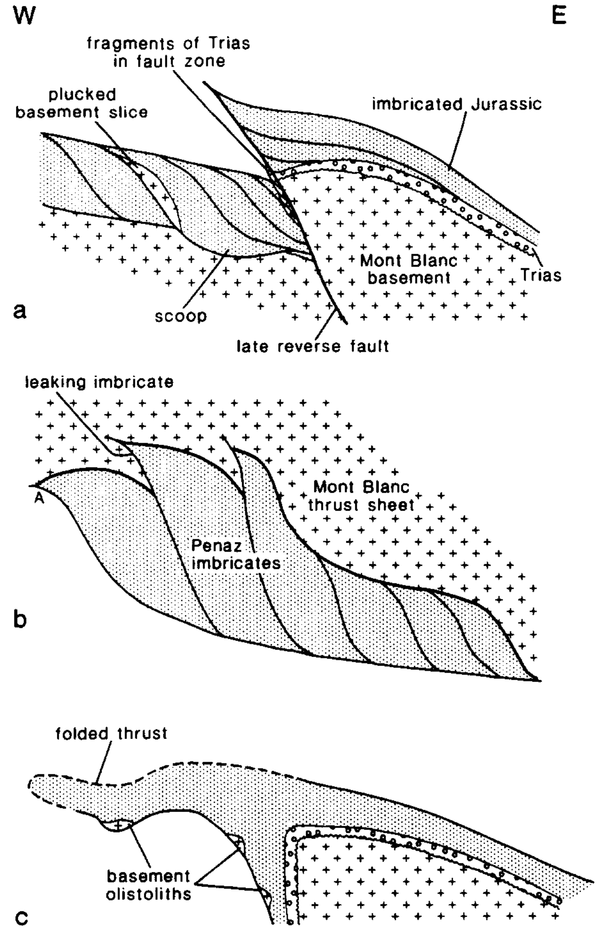

Fig. 2. Schematic sections across the southern end of the Mont Blanc massif, to illustrate different models for its formation. Not to scale. (a) Late reverse fault punches basement up into previously imbricated cover. Isolated basement slices are produced by 'plucking' (see text). (b) Basement forms a thrust sheet which is then imbricated into the underlying cover (Butler 1982). (c) Major overturned fold in basement and previously imbricated cover. Basement slices are olistoliths in Eocene flysch (Landry 1978). Col du Bonhomme is at centre of each section, compare with Fig. 1.

Briançonnais-facies cover from the Bernhard–Briançon zone of the internal Alps [see, for example, the 1:250,000 Annecy sheet (BRGM 1980)]. The overlying Piemont nappe clearly cuts down section locally, as it rests on a stack of cover nappes in the eastern Vanoise, for example, but cuts down to rest almost directly on basement further west (Grand Sassière, Mont Jovet).

My second point of discussion concerns the Enclaves imbricates in the internal Belledonne massif. Butler's suggestion that the basement has undergone a sort of décollement thrusting for tens of kilometres along a surface only 100 m below the Triassic unconformity struck me as so remarkable (and mechanically implausible) as to need checking. His hypothesis depends on his assertion that the thrusts, the Hercynian foliation in the basement, and bedding in the Trias, are all parallel and dip steeply east. I found the Enclaves imbricates to be disappointingly poorly exposed, and the Triassic rocks there consist largely of cargneule. This is at least partly a tectonic breccia, and commonly lacks bedding. I identified bedding, however, at four separate localities around lac Noir (9354 0918), adjacent to one of the basement faults. This is just northwest of the word 'Enclaves' on Butler's (1983) fig. 2. Dips in the Trias vary from 8 to 15° W. The basement faults are steep, and the Hercynian foliation dips 65–85° E. I think the field evidence favours high-angle reverse faults in this area, involving small displacements. These very steep faults may be splays, controlled by the pre-existing basement foliation, rising from a more moderately dipping thrust at depth.

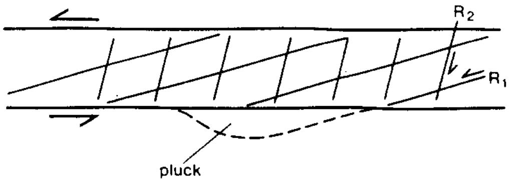

Fig. 3. Pattern of fractures in a brittle shear zone (Tchalenko 1970). R_1, R_2: conjugate Riedel fractures. A possible propagation path of an R_1 fracture which would pluck material out of the shear-zone wall is shown.

My third point of discussion concerns Butler's rather simplistic treatment of the stratigraphy of the area. He suggests that it is reasonable to assume a layer-cake stratigraphy for distances of over 100 km (his estimate) across an old continental margin. Is this really reasonable? The stratigraphic complexity of the Mesozoic cover on the nearby Aiguilles Rouges massif is superbly illustrated by the geological map of the Dent de Morcles area (Badoux *et al.* 1972). Butler also states that the Triassic rocks have a 'remarkably constant thickness of 10–12 m'. Much of this sequence, as Butler notes, consists of cargneule, an unbedded breccia produced by a variety of tectonic and solution processes. Some of the cargneule in the Rocher des Enclaves area is a true tectonic breccia incorporating clasts of basement rock-types. How did Butler determine a stratigraphic thickness in such a material, bearing in mind that the next stratigraphic unit up is rarely seen in the area? I am concerned that Butler's displacement estimates, based on area balancing, may be significantly exaggerated by these rather unrealistic assumptions about the stratigraphy.

My last point concerns Butler's method for computing the displacement on his Mont Blanc thrust. If we assume that his tectonic model is correct in all respects, then the basement slices in the Penaz imbricates show that the leading edge of his Mont Blanc basement thrust-sheet reached at least as far as the present leading edge of the Penaz imbricates (point A in Fig. 2b). This requires, as Butler (1983) points out, that the Mont Blanc thrust has a minimum displacement equal to the restored line-length of the Penaz imbricates, which he estimates at 12.5 km (his fig. 5) or 44.6 km (his fig. 6). This displacement, however, could have been largely achieved by the imbrication of the underlying Penaz. For a minimum displacement, there is therefore no reason to add the shortening within the Penaz imbricates to the estimate derived above. Butler justifies doing this by his suggestion that Penaz imbricate faults cut the Mont Blanc thrust sheet, but this effect could have been produced during the last few kilometres of displacement.

Butler also appears to equate the shortening of the imbricates to their restored line-lengths. The true shortening is of course the difference between the restored and deformed line-lengths. Butler (1983) does not give us the present (deformed) line-lengths, but his fig. 6 suggests that the Enclaves imbricates are now about 8 km long. He restores them to 25.5 km (his fig. 5) or 50 km (his fig. 6), giving a shortening of 17.5 or 42 km. This can be added to the previous estimate, as the Enclaves imbricates lie west of point A. The minimum displacement of the Mont Blanc sheet, according to his two models, is therefore 30 or 86.6 km, not 50.5 or 139.2 km.

CONCLUSIONS

Field evidence around the southwestern termination of the Mont Blanc basement massif casts doubt on Butler's (1983) interpretation of the massif as a relatively thin thrust-sheet extending over the imbricated Dauphiné cover. The simplest interpretation is that the massif is bounded to the west by a relatively steep reverse fault that has brought the basement up through its previously imbricated cover sequences. Basement faults in the internal Belledonne massif are also at a high angle to the cover unconformity. A 'thick-skinned' model of basement faulting, analogous to Laramide faulting in the western U.S.A. (Brewer *et al.* 1982), seems more appropriate for the area than Butler's 'thin-skinned' interpretation.

Butler's assumption of constant stratigraphic thickness, and errors in his calculations, further exaggerate his estimates of shortening. Allowing for all these factors, a realistic minimum estimate of the shortening across his study area is probably about 40 km.

Acknowledgements—I thank Marcus Parish, Frank Peel and Graham Williams for discussion.

REFERENCES

Ayrton, S. 1980. La géologie de la zone Martigny-Chamonix (versant Suisse) et l'origine de la nappe de Morcles (un exemple de subduction continentale). *Eclog. geol. Helv.* **73**, 137–172.

Badoux, H., Burri, M., Gabus, J. H., Krummenacher, D., Loup, G. & Sublet, P. 1971. Atlas Géologique de la Suisse, 1:25,000, feuille 1035: Dent de Morcles. Commission Geologique Suisse.

Brewer, J. A., Allmendinger, R. W., Brown, L. D., Oliver, J. E. & Kaufman, S. 1982. COCORP profiling across the Rocky Mountain Front in southern Wyoming, Part I: Laramide structure. *Bull. geol. Soc. Am.* **93**, 1242–1252.

Butler, R. W. H. 1983. Balanced cross-sections and their implications for deep structure of the northwest Alps. *J. Struct. Geol.* **5**, 125–138.

BRGM 1966. *Carte Géologique de la France à* 1:80,000, *feuille Albertville.* Bureau des Recherches Géologiques et Miniéres, Orleans.

BRGM 1976. *Carte Géologique de la France à* 1:50,000, *feuille St-Gervais-les-Bains.* Bureau des Recherches Géologiques et Miniéres, Orleans.

BRGM 1980. *Carte Géologique de la France à* 1:250,000, *feuille Annecy.* Bureau des Recherches Géologiques et Miniéres, Orleans.

Elliott, D. & Johnson, M. R. W. 1980. Structural evolution in the northern part of the Moine Thrust Belt. *Trans. R. Soc. Edinb., Earth Sci.* **71**, 69–96.

Gay, N. C. 1970. The formation of step-structures on slickensided shear surfaces. *J. Geol.* **78**, 523–532.

Landry, P. 1978. Données nouvelles sur la couverture sédimentaire des massifs externes au sud du Mont-Blanc. *Géol. Alpine* **54**, 83–112.

Tchalenko, J. S. 1970. Similarities between shear zones of different magnitudes. *Bull. geol. Soc. Am.* **81**, 1625–1640.