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Thrust zone kinematics in a basement–cover imbricate stack: Eastern Pelvoux massif, French Alps

ROBERT W. H. BUTLER

Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, U.K.

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Abstract—Thrust imbrication is now widely accepted as a major process in controlling basement–cover relationships in the external parts of the Western Alps. Complications in the simple geometries expected from thrusting alone arise from Alpine deformation affecting pre-existing extensional faults inherited from the old Mesozoic basins. This contribution describes the structural geology of part of the Eastern Pelvoux massif, centred on the Rocher de L'Yret, where Alpine deformation has masked any pre-existing structures. A series of major thrusts carry basement onto cover. These lie west of, and in the footwall to, the Pennine Front, a major zone of thrusting which carries the Internal Alps onto the external zones. Stretching lineations in calc-mylonites derived from Eocene limestones deposited on the basement, indicate a tectonic transport axis of WNW–ESE (plunging *ca* N100°E). This direction is supported by the orientation of striae and corrugations on faults which cut basement rocks. Shear criteria in the calc-mylonites imply top-to-the-WNW shearing. Despite this simple kinematic picture, basement–cover relationships cannot be explained by thrusting alone. A series of faults cut down through the thrust stack towards the WNW and show net extensional offsets with respect to the tectonic pile. These faults and associated shears in the calc-mylonites cannot be traced to depth, rather they appear to branch onto earlier thrust surfaces. This geometry is interpreted as due to distributed shearing in the hanging-wall to the local floor thrust, perhaps reflecting late reactivation of the Pennine Front.

INTRODUCTION

BASEMENT involvement in the structures of the external Alpine thrust belt can take many different forms. Classic studies from the Swiss Alps (e.g. Collet 1923) have tended to emphasize the rôle of distributed strain leading to the generation of 'pinched-in' synclines of cover into basement. This style has been explained as reflecting the competence contrast between basement and cover. The model has been widely applied away from its type area along the front of the Aar massif in Switzerland to explain the presence of thin cover slices within other basement massifs in the Western Alps (e.g. Ramsay 1963, Gratier & Vialon 1980). Beach (1981), Boyer & Elliott (1982) and Butler (1983) proposed an alternative model whereby thrusts carried basement in their hanging-walls. It is now recognized that both styles of basement involvement (1, distributed, apparently pure-shear dominant, straining and folding of the basement–cover contact and 2, discrete thrust imbrication of basement into overlying cover sediments) exist in the Alps, both equally well-constrained by field observations. Pfiffner (1985) proposed that both styles may exist on the same cross-section, with discrete thrust segments linking volumes of basement which deformed through more distributed means.

The simple thrust imbrication model predicts that basement sheets should continue downwards with their imbricate thrusts splaying from a common floor (Boyer & Elliott 1982) (Fig. 1a). However, other studies show that this model requires modification if it is to explain some basement–cover relationships in the Alps. Beach (1981) described isolated basement sheets that appear to 'float' in cover sediments. Butler (1983) proposed that these geometries could result from a 'breaching' geometry whereby a deep level thrust climbed up and across a higher level basement sheet (Fig. 1b). Platt (1984) suggests that the isolated basement slices could be explained by local down-cutting thrust segments which 'plucked' basement sheets from beneath a décollement surface (Fig. 1c). This mechanism required the décollement to be a distributed shear zone within which Riedel shears could cut down in the direction of overthrust shear. Transfer of displacement onto the Riedels, relaying back through conjugate compressional faults, could isolate basement slices and carry them up into cover. Alternatively, Gillcrist *et al.* (1987) proposed that an isolated basement slice could result from a thrust encountering a hinterland-dipping normal fault (Fig. 1d). Rather than being reactivated, a new fault surface could cut into the footwall of the normal fault, creating a thrust surface with smoother shape. It is now thought that this 'short-cut' model provides the correct explanation for Beach's (1981) isolated basement slice. Indeed a whole suite of old normal faults have been found in selected parts of Alpine basement massifs which have been modified in the way proposed by Gillcrist *et al.* (1987).

Within the external Western Alps the range of thrust geometries, resulting from simple imbrication, breaching of basement thrust sheets or short-cutting normal fault blocks has been demonstrated to be appropriate for local thrust geometries. However, there has yet to be a clear demonstration of Platt's (1984) plucking model. There are few places where there is suitable stratigraphical control to investigate the nature of the pre-thrusting template, together with adequate exposure of a substantial part of the structure. This contribution examines a

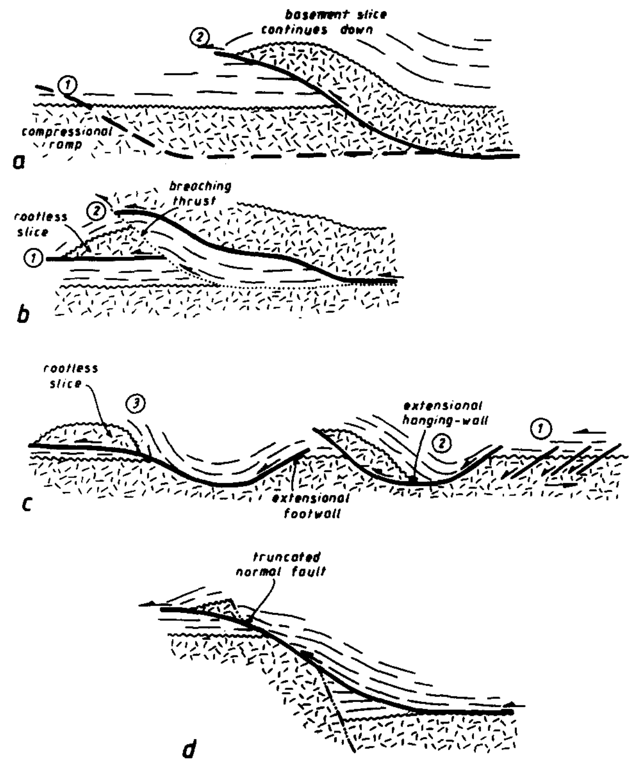


Fig. 1. Possible basement–cover relationships. (a) Simple thrust imbrication (Boyer & Elliott 1982) developed by thrusts progressively developed towards the foreland. (b) Breaching (Butler 1987) of a previously emplaced basement sheet (1) by a thrust climbing from its footwall (2). (c) The 'plucking' model of Platt (1984), whereby distributed shearing aligned parallel to a basement–cover contact decomposes into a suite of principal Riedel shears (1). Transfer of displacement onto these Riedels, and the development of compression conjugate faults can isolate fault blocks (2) to be emplaced into the cover as rootless slices (3). (d) The isolation of a basement slice by the truncation of a pre-existing normal fault by a thrust, as proposed by Gillcrist *et al.* (1987).

well-exposed and deeply excised part of a basement–cover thrust stack, in the eastern part of the Pelvoux massif (Fig. 2) in the French Alps. Outcrops lie on a high Alpine ridge permitting clear observations and access can be gained to the highest, apparently critical, parts of the thrust stack on the Rocher de L'Yret (Fig. 2).

The L'Yret region is pivotal for studies of Alpine tectonics. It lies immediately beneath the Pennine Front, a major tectonic break in the Alps which traditionally has been used to separate the external parts of the orogen from the more complexly deformed inner (or Pennine) zones. Tectonic transport to the north of the L'Yret area is now widely believed to have been on a WNW–ESE axis (e.g. Butler *et al.* 1986, Platt *et al.* 1989). However, to the south there is far greater uncertainty about thrusting directions. Numerous authors have assumed, and latterly demonstrated, that there is an important SW-directed component of thrust transport here (e.g. Fry 1989). Merle & Brun (1984) proposed a dual movement history, partially towards WNW and partially SW. Gillcrist *et al.* (1987) showed a range of stretching lineation trends between WNW and NE–SW in the Pelvoux massif which they interpreted as representing a region of transition between two segments of the orogen with divergent thrust transport. Ricou & Siddans (1986) interpreted the Pennine Front in terms of N–S sinistral transcurrent shear. So collectively there is considerable controversy relating to Alpine orogenic transport and shortening directions. This contribution first addresses the kinematics in order to define movement directions at the Rocher de L'Yret and then examines the basement–cover relationships and their evolution in terms of these new data.

GEOLOGICAL SETTING

Before examining the structures at L'Yret it is prudent to introduce the regional setting. Additional information of a stratigraphic nature is provided by Debelmas & Kerckhove (1980) and Lemoine *et al.* (1986) amongst many others. Rocks to the northwest of the Pennine Front constitute the external or 'Dauphinois zone', a restacked series of half-graben bounded by E-dipping extensional faults which operated in Jurassic times. The most famous and well-preserved of these old faults is the 'faille du Col d'Ornon' (Grand 1988). It is marked by olistoliths of pre-rift Triassic formations and Liassic carbonates deposited amidst background sedimentation of Liassic marls and shales. The half graben is capped by a poorly preserved 'post-rift' limestone of Tithonian age. To the east other half-graben structures have been proposed, controlling the present-day basement–cover relationships (e.g. Lemoine *et al.* 1986, Gillcrist *et al.* 1987). However, the Alpine compressional deformation is much stronger in these eastern areas and hence the geometry of the pre-compressional basins is far less certain. The critical relationships lie around a composite stack of basement units, collectively referred to as the Pelvoux massif.

Within the Pelvoux massif lies a major regional unconformity surface which steps across Jurassic onto basement rocks. Above lies a suite of Eo-Oligocene rocks, collectively known as the 'Nummulitique'. Its base is marked by a thin (locally absent) encrusting limestone with abundant nummulite (foraminifera) assemblages. It is overlain by a dark shale sequence which is free of sandbodies for the lower 10–50 m but which becomes progressively more clastic at higher stratigraphic levels. The alternating sandstone and shale units are interpreted as turbidite deposits, variously known as the 'Gres du Champsaur' or the 'flysch des Aiguilles d'Arves'. Modern accounts generally consider this triptych (limestone, shale, sandstones/shale) to be the earliest foredeep deposits, marking the onset of the major episode of Alpine compression. The age of deformation within the Pelvoux massif relative to the deposition of the foredeep sediments which overlie it has been the subject of intense debate.

Stratigraphic studies by Gidon & Pairis (1981) have shown that thrusts which stack basement and Jurassic rocks in southern Pelvoux (the 'Soliel Beouf' district, Fig. 2) are truncated by the sub-Nummulitic unconformity so that thrust stacking within the massif is presumed to predate the foredeep. This interpretation can be

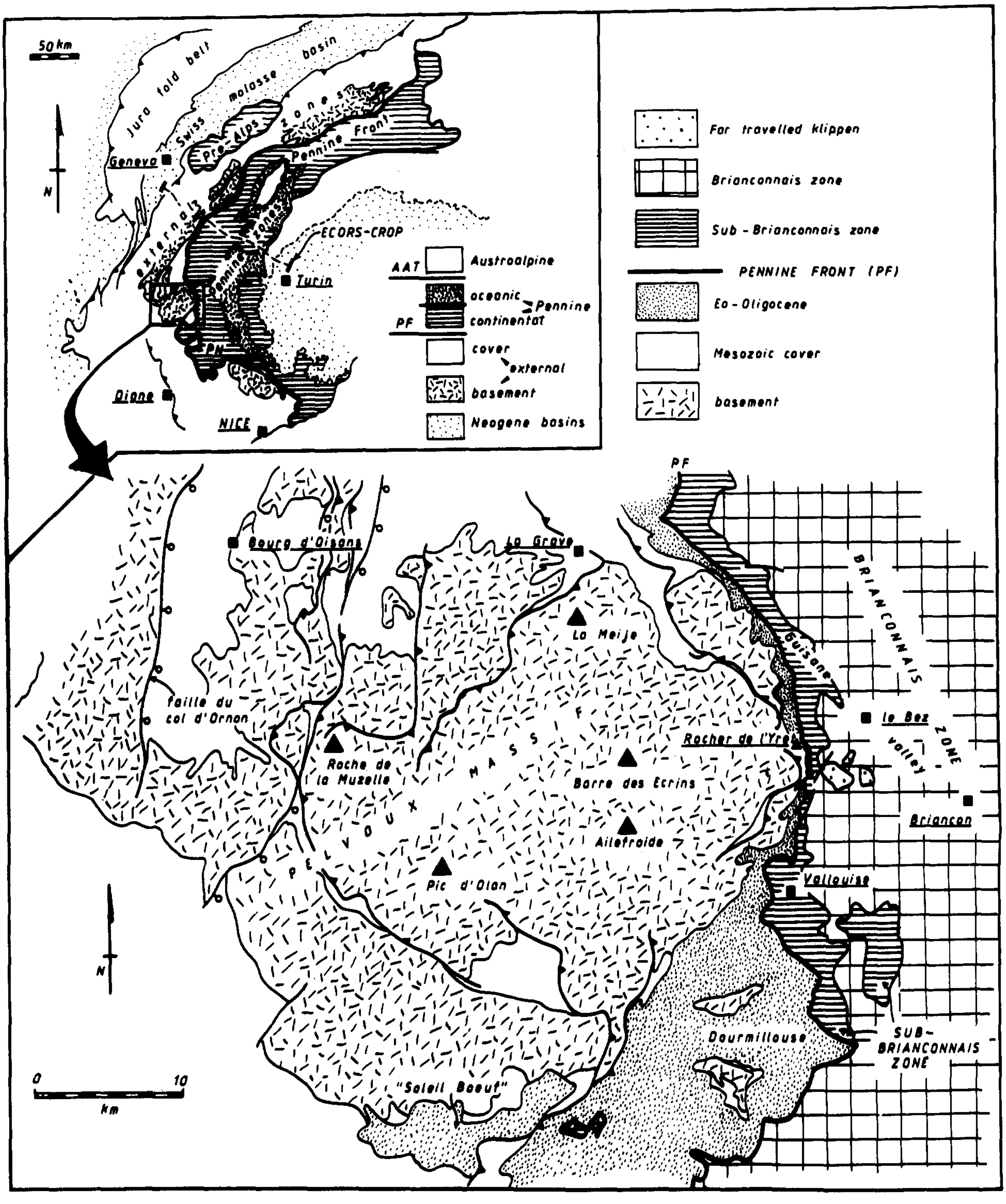


Fig. 2. Simplified map of the Pelvoux district of the Western Alps showing the location of the Pennine Front and Rocher de L'Yret. Inset: Location map for the Western Alps, showing the location of the ECORS-CROP deep seismic reflection profile. PN—Parpaillon nappes.

contrasted with that of Beach (1981) who suggests that major basement thrusts ran into the base of the Nummulitic strata so that the unconformity surface was activated as a thrust zone. However, these studies were sited to the north of Pelvoux, well away from those reported by Gidon & Pairis (1981).

To the east of the Pennine Front the Mesozoic units are far better preserved than to the west. A series of Jurassic platform carbonates pass up into a sequence of Cretaceous carbonates and marls (described by Debelmas 1955). The transition is widely believed to represent the foundering of a Jurassic platform, perhaps by a thermal subsidence mechanism (Gillcrist *et al.* 1987). However, the oldest stratigraphic unit preserved at the base of the frontal Pennine units in the Pelvoux sector is a thick sequence of Triassic evaporites. These rocks acted as a major detachment horizon during Alpine thrusting, hence the original basement–cover contacts

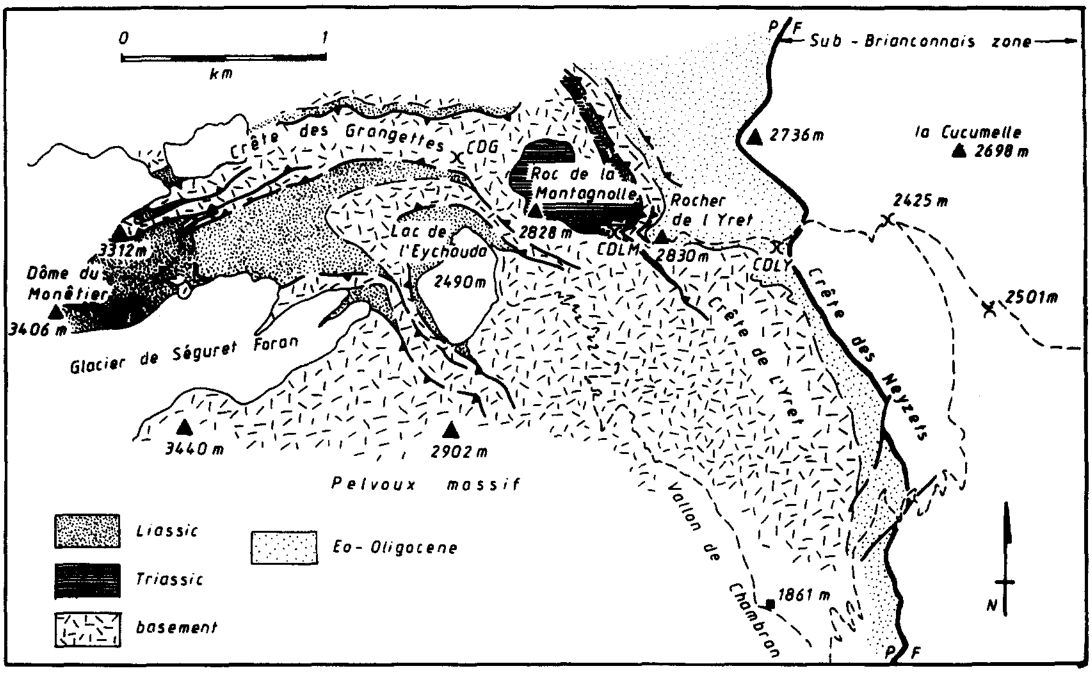


Fig. 3. Geological sketch map of the ground around the Rocher de L'Yret, showing the main approach path in the Chambran Valley and from Le Bez, via the Col de la Cucumelle (2502 m). CDG—Col des Grangettes, CDLM—Col de la Montagnolle, CDLY—Col de L'Yret.

have yet to be recognized. Furthermore the evaporites are extensively weathered and recrystallized so that kinematic indicators are not preserved.

STRUCTURAL GEOMETRY ON THE ROCHER DE L'YRET

Much of the structure of the Pelvoux massif is dominated by a few large thrust sheets dominantly composed of crystalline basement (Goguel 1948, Gillcrist *et al.* 1987). However, towards the eastern margin of the massif the spacing between thrusts it greatly reduced, as illustrated in Fig. 3. A series of thin basement sheets are exposed on the north face of the Crête des Grangettes, separated by thin screens of Liassic slates. The geometry of these sheets is easier to appreciate, however, to the south of the ridge where the retreat of the glacier du Séguret Foran (Fig. 3) has exposed an accessible valley transect. An array of thrusts imbricate *ca* 100 m of basement into cover sediments exposed around the headwall of the Chambran valley. Overlooking this region is the Rocher de L'Yret (Fig. 3), the structural geology of which forms the main focus of this paper.

A structural section is presented through the Rocher de L'Yret region (Fig. 4). The geology was studied by ridge traverse from the Col des Grangettes to the Rocher de L'Yret, detailed mapping on the SE flank of L'Yret and excursions onto the southern side of the ridge. Additional information was gained from distant views from the Chambran valley (Fig. 3). Regrettably, the terrain prevented direct access to other outcrops. A sample of the small-scale structures used to deduce kinematics is illustrated in Fig. 5 while critical field relationships discussed later are shown in Fig. 6.

The section illustrates a series of basement thrust slices emplaced into the overlying cover sediments. However, the nature of these sediments changes. The oldest units are Triassic dolomites found on the Rocher de Montagnolle. These are classically considered to be 'pre-rift' and in basinal areas would be overlain by Jurassic units. To the west the Liassic basin sediments lie directly on basement, although thin remnants of the Triassic 'pre-rift' are preserved (Fig. 3). These relationships could be explained by minor amounts of uplift preceding local Jurassic sedimentation, either in the footwall to normal faults or by a regional doming. However, on the Rocher de L'Yret the basement units are stratigraphically overlain by a thin encrusting limestone of Eocene age, with a locally abundant nummulite fauna. The Mesozoic sediments must have been eroded by a period of early–pre Eocene uplift (Barfety & Gidon 1979). In summary, the sub-Nummulitic unconformity steps down from Liassic in the west, across Triassic, to basement in the east at L'Yret (Fig. 4).

Deformation of this sediment wedge and the underlying basement produced a range of structures which will be discussed after examining the kinematics. Suitable structures for the determination of shear sense are developed in the Nummulitic limestone which has been extensively mylonitized (Fig. 5a). The overlying sandstones and shales show more complex structures, particularly curvilinear folds, which have yet to be analysed. In addition to deformation in the sediment pile the underlying basement is also involved (Fig. 6a). Most common are discrete cataclastic faults of varying widths.

These faults, together with the mylonites, were used to determine kinematics directly in the field.

KINEMATICS

The kinematics of a shear zone may be determined by combining two structural observations; the orientation of the stretching lineation to define the movement axis and an asymmetric structure viewed on a face parallel to the lineation and perpendicular to the shear plane to determine the sense of shear. The first collection of linear data comes from the mylonitized Nummulitic limestone exposed on the SE flank of L'Yret. These lineations are contained on the mylonitic foliation plane (Fig. 5a) and are probably composite elongation lineations of more competent carbonate clots within the limestone together with an intersection of different generations of mylonitic foliation. Within measuring accuracy these could not be distinguished and the interfolial angle for recognizable intersections is generally less than a few degrees. Thus these lineations are assumed to have the same kinematic significance, lying parallel to the movement direction. The few intersection lineations resulting from higher interfolial angles were excluded from this study.

Lineation data from the calc-mylonites on the SE flank of L'Yret are displayed on an equal-angle lower-hemisphere stereoplot (Fig. 7a). The spherical mean azimuth of N099°E, plunging 18°, indicates the movement axis between W–E and WNW–ESE. The regional ESE plunge can be related to the later doming of the Pelvoux massif.

The range of movement axes was also measured from fault zones within basement on the summit block of L'Yret. These may be defined by fine striations with chlorite coatings (Fig. 5b) and larger corrugations of the fault planes (Fig. 5c). Here the spherical mean azimuth is N093°E with a plunge of 8.5° (Fig. 7b). So the two sets of data show essentially the same orientation for the movement axis: what of the sense of shear?

Shear bands are particularly abundant within the calc-mylonites. Consistently these imply a top-to-the-W–WNW shear sense (Fig. 5d). In the cataclastic fault zones developed in the basement there are apparent deflections of fabrics associated with sub-horizontal micro-faults (Fig. 5e). These imply a top-to-the-west slip sense on the fault zones. Although rather less common than the shear bands in the calc-mylonites these cataclastic structures confirm the overall kinematic picture.

A third collection of linear data was made along the Grangettes–L'Yret ridge (Fig. 4a) to characterize the kinematics of the major basement thrusts on this transect (e.g. Fig. 6a). Figure 7(c) is a stereoplot of these data, which have a greater spread than the detailed collections from L'Yret alone. These data do not discriminate between basement striations and stretching lineations. However, the three datapoints which plot with a SSE azimuth come from basement faults which have uncertain relationships to the major thrusts shown in Fig. 4. The spherical mean azimuth of all the data in Fig. 7(c) is N112°E but if we remove the three anomalous striations the mean azimuth is N105°E. These values are not significantly at variance from the mean azimuths for calc-mylonite and basement fault movement axes on L'Yret. The implications of this are discussed later.

BASEMENT–COVER RELATIONSHIPS

Critical geometries lie around the summit block of the Rocher de L'Yret, between about 2500 and 2800 m (Fig. 4). The structural geometry strongly suggests compressional deformation, dominantly by thrusting of basement on cover with movement towards about N275°E. Yet there are a series of structures which do not readily fit this model. In conventional thrust models (e.g. Boyer & Elliott 1982) we might expect the basement sheets on L'Yret to form continuous panels passing to depth (e.g. Fig. 1a). However, there are numerous isolated pods of crystalline basement lying within a 'matrix' of highly deformed limestones, presumably Eocene. These relationships led Bravard & Gidon (1979) to suggest that rather than being emplaced tectonically the blocks were olistoliths, eroded from a pre-existing basement high. The current studies refute this model because the Eocene-age sediments in which the large basement blocks are located is otherwise a clean carbonate, uncontaminated by significant fractions of smaller clasts. At L'Yret, siliciclastic material only becomes important in the younger, turbiditic parts of the Nummulitic succession but at these stratigraphic levels large basement blocks are absent.

Close examination reveals that the basement units have been emplaced downwards into the limestones along cataclastic faults which overprint the thrust contacts described earlier. These late faults are sub-horizontal and truncate E-dipping mylonitic foliation in their footwall (Fig. 6b). These faults are net extensional with respect to fabric within foliated cataclasites along the basement thrusts and in places extend the thrust planes themselves. Thus they must have developed after the emplacement of basement onto cover (Fig. 6c). The geometry of individual basement contacts resembles that of an array of shear bands (Fig. 8). All the late shears cut down towards the WNW, confirming the overall kinematic interpretation based on the smaller scale structures. In some situations these late faults and shears have isolated pods of mylonitized limestones, a geometry which could not be created by the Bravard & Gidon (1979) model.

Observations around the head-wall of the Chambran Valley (Fig. 3) suggest that the extensional shears are restricted to the highest levels of the basement thrust stack and do not penetrate to depth. There are indications that the shears become asymptotic to thrusts, perhaps branching onto the basement thrust exposed on the Col de la Montagnolle (Fig. 4a). Regrettably the terrain is not conducive to close examination of these levels of the thrust stack, away from the col.

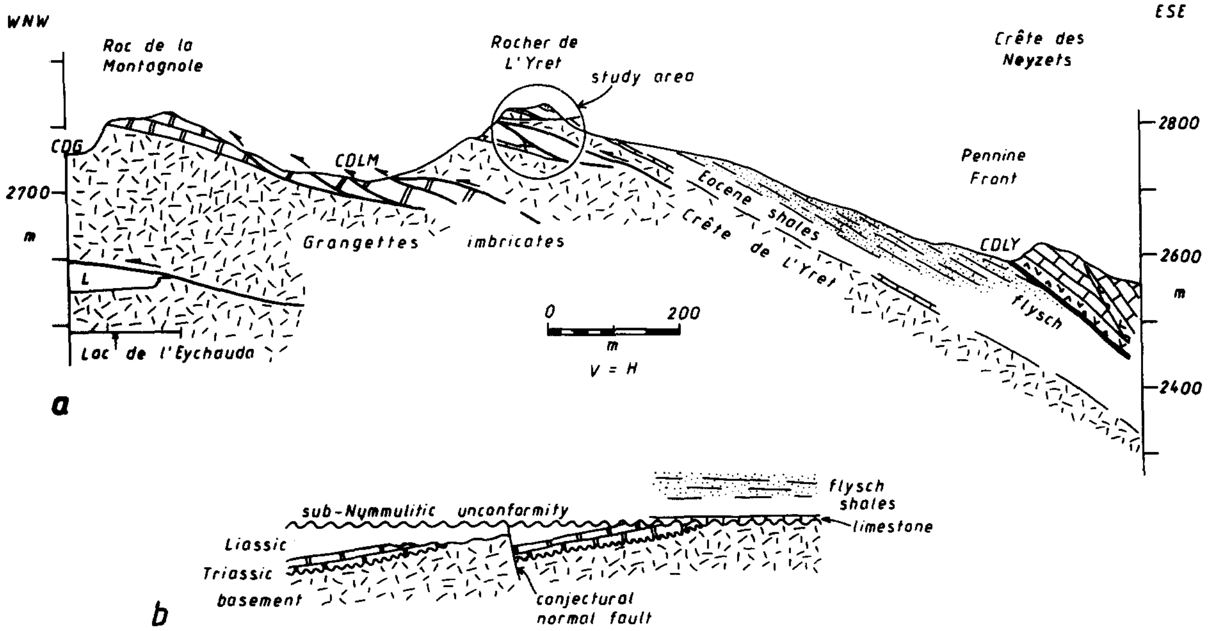


Fig. 4. (a) Simplified cross-section along the Rocher de L'Yret–Crête des Grangettes ridge on the eastern edge of the Pelvoux massif (see Fig. 3 for sketch map). The circled area is that covered by the detailed study described in this contribution. Access is achieved either from roadhead at Chambran (1719 m) above the village of Vallouise, or from a forestry track (1927 m) above Le Bez, Guisanne valley (Fig. 1). Allow *ca* 2 h for each approach to the critical summit area of L'Yret. Abbreviations as Fig. 3. (b) Idealized reconstruction of the stratigraphic relationships between Mesozoic, Eocene and basement rocks prior to Alpine deformation at L'Yret.

Late-stage disruption of imbricate geometry

We can compare the basement–cover relationships found on L'Yret (e.g. Fig. 8) with the hypothetical relationships illustrated in Fig. 1. The simple basement imbrication geometry (Fig. 1a) has already been eliminated as inappropriate. Likewise the breaching model involves only contractional fault relationships (Fig. 1b) because the tectonic pile is repeated. Here the problematic faults extend the tectonic pile. Since these faults develop after the stacking of the basement sheets they are not part of the old Mesozoic basin structure, as implied by Fig. 1(d).

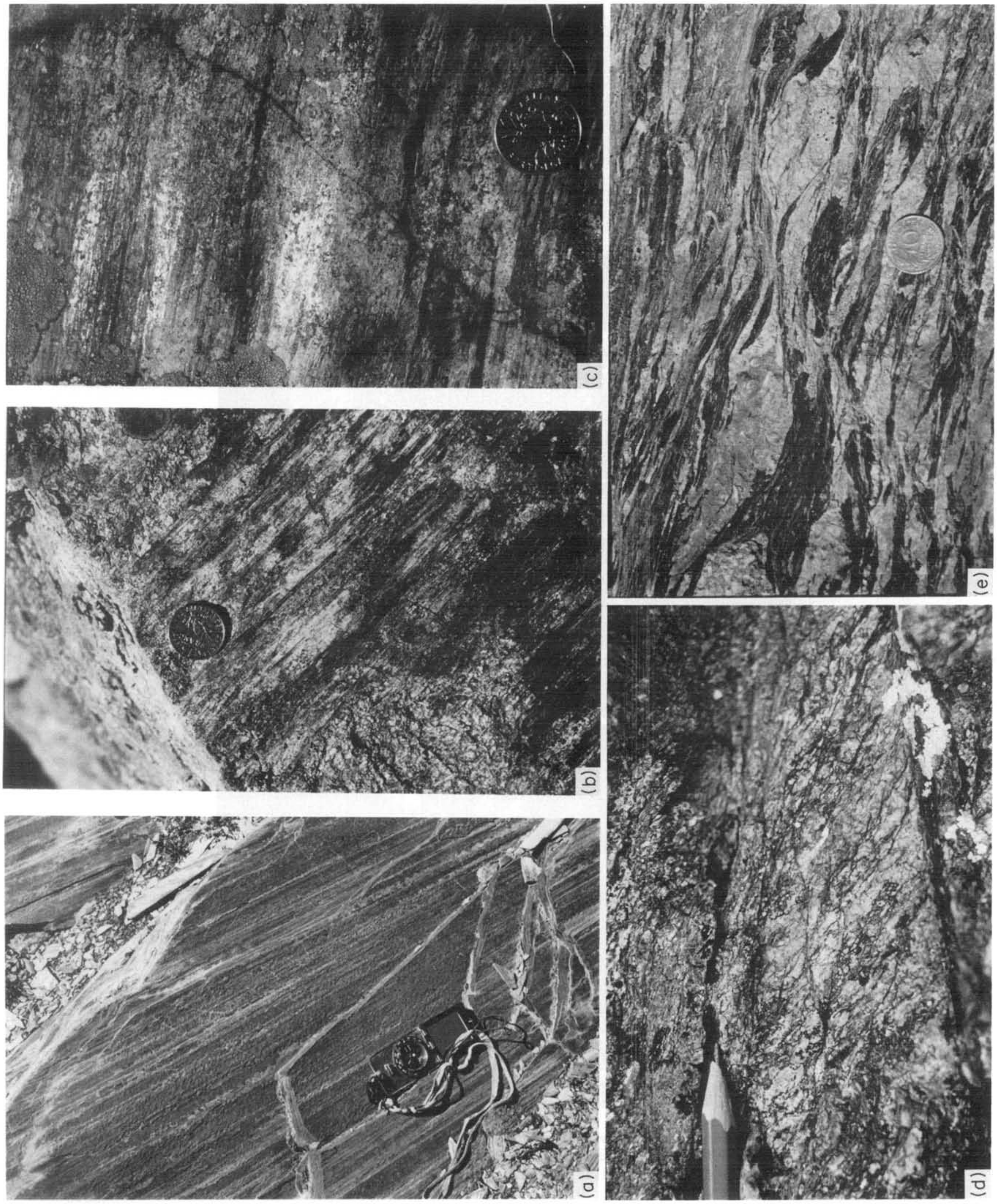
As indicated above, basement–cover relationships at L'Yret are best explained by the late-stage disruption of a suite of imbricate thrusts (Fig. 8). These thrusts emplaced basement into the cover units to produce a tectonic multilayer which then was modified by the late shears. In this way the trailing edges of cover slices can become isolated as pods, truncated upwards by the later shears which are extensional with respect to the tectonic layering. Clearly they represent a late-stage overprinting of the imbricate stack by some form of distributed shear. In this sense the geometry is similar to that proposed by Platt (1984) and illustrated in Fig. 1(c), although here the faults develop within an already tectonically thickened pile.

Distributed vs localized deformation

Grant (1990) describes alternations in the behaviour of a basement–cover thrust zone in the Pyrenees, from discrete slip on a fault surface to distributed, dominantly pure shear associated with transient tips. The conflict between distributed and localized deformation at thrust ramps has been discussed by Welbon & Butler (in press) for structures developed in cover sediments further north in the NW Alpine thrust belt. The structures at L'Yret can also be interpreted in these terms.

The earliest deformations recognized at L'Yret are recorded by the Nummulitic limestone which experienced layer-parallel shearing to develop an intense mylonitic foliation. The deformation was distributed above the rigid basement. However, the incorporation of basement occurred by displacement on discrete faults, imbricating it with the previously deformed Nummulitic limestones. Foliation within the limestones is folded around thrust-related fold culminations. The final major deformation event at L'Yret involved the extensional disruption of the imbricate stack along the

Fig. 5. Small-scale structures at L'Yret. The first photographs depict movement axis indicators. (a) The lineation developed in mylonitized Nummulitic limestone. The foliation planes are also visible. (b) Chlorite-coated striations on a basement fault. The coin is 1 cm in diameter. (c) Corrugations on a basement fault, highlighted by oblique natural illumination. Note also the finer chlorite-coated striations running parallel to the corrugations. The next photographs (d & e) show indicators of shear sense. Both photographs are viewed to the north (in landscape) and imply a top-to-the-west (i.e. to the left) sense of movement. (d) Shear band with asymmetric boudinage of calc-mylonite. Local foliation 041°/20° with local lineation 118°/20°. (e) Minor shears developed in foliated cataclasites derived from crystalline basement.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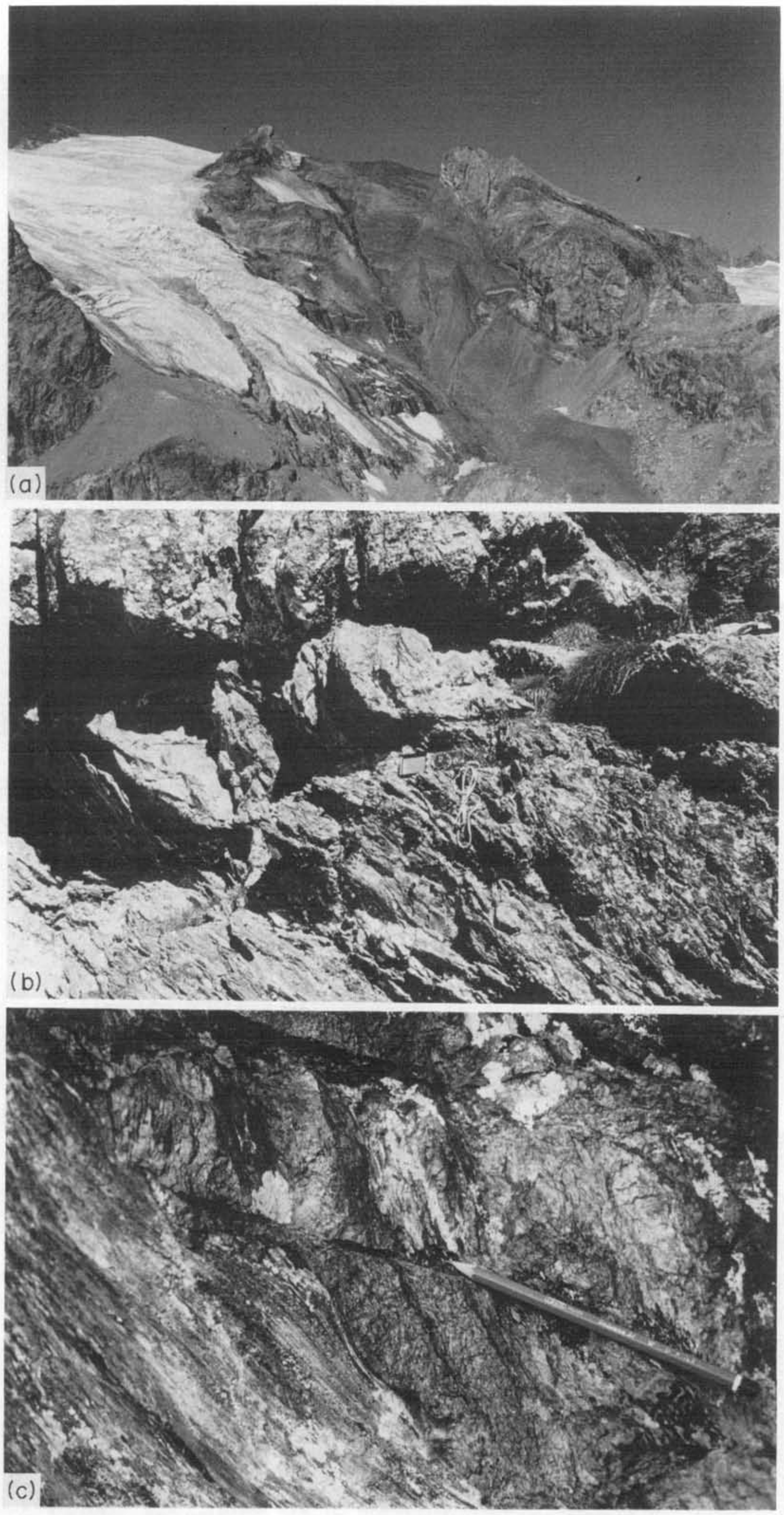

Fig. 6. Basement–cover relationships. (a) View of basement thrust sheet on the Crête des Grangettes, seen from the Rocher de L'Yret. The ice is the glacier du Seguret Foran. Looking WNW, with about 800 m of visible topography. Basement forms the cliff line to the right, with Liassic cover rocks in the more hospitable lower slopes. The other two photographs (b & c) are from the south face of the Rocher de L'Yret, *ca* 50 m below summit, both viewed to the north. (b) A basement fault cutting gently down to the west across foliated carbonates. The fault lies just above the compass and clearly truncates the foliation in its footwall. (c) Detail of a smaller example of a basement fault (at pencil point) cutting from basement into the underlying foliated carbonates. Foliations in the carbonates (mylonitic) and the overlying basement (cataclastic) are parallel to the early thrust contact but are truncated by the later small fault.

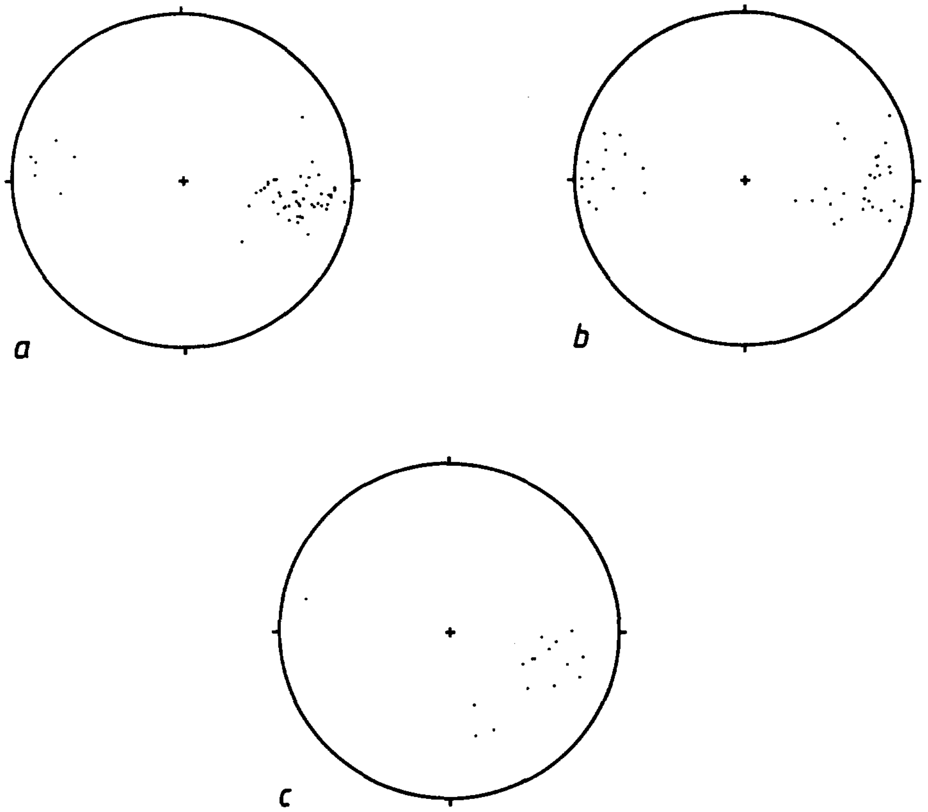

Fig. 7. Orientations of movement axes displayed on equal-angle lower-hemisphere stereoplots. (a) Lineations on mylonitic foliation planes (see Fig. 5a; 53 data points). (b) Striations and corrugations on basement fault planes (see Figs. 5b & c; 42 data points). (c) Combined stretching lineation and striation data from thrust zones between the Col des Grangettes and the Rocher de L'Yret (16 data points).

array of minor faults, as shown in Fig. 9. These structures may represent a return to distributed deformation, representing arrays of Riedel-type shears which link displacements down across the thrust stack. In this sense they are analogous to Platt's (1984) plucking faults. But need they imply regional extensional shear?

Extension of the tectonic pile

Intraorogenic extension can develop by many different mechanisms. Extensional faults may represent collapse of the entire orogenic edifice either by tectonic divergence or by gravitational processes (e.g. Dewey 1990). In this case they should post-date the regional compression. This model is unlikely for L'Yret since the extensional shears are restricted to a zone a few hundred metres wide, affecting only the highest basement sheets. Thus they do not appear to penetrate to depth, a basic requirement of the orogenic collapse model. An alternative to lithospheric extension may lie in the dynamics of the Alpine thrust belt. Platt (1986), following the ideas of Davis *et al.* (1983), suggested that the interiors of mountain belts may collapse on extensional structures if an active thrust ran into a particularly weak layer or the thrust belt was 'underplated' by particularly buoyant material. The dynamic orogenic wedge would then adjust to a finer taper. Clearly the Nummulitic limestones may represent a suitably weak layer but they had been disrupted by basement–cover imbrication prior to the extension. On geometric grounds it is difficult to trace a

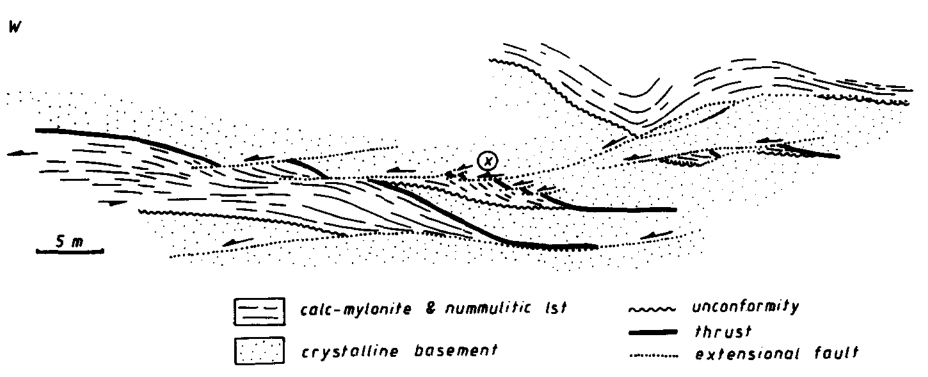

Fig. 8. Sketch section of basement–cover relationships along a fault zone exposed on the south face of Rocher de L'Yret, approximately 50 m below the summit. The photographs for Figs. 6(b) & (c) come from locality X on the sketch.

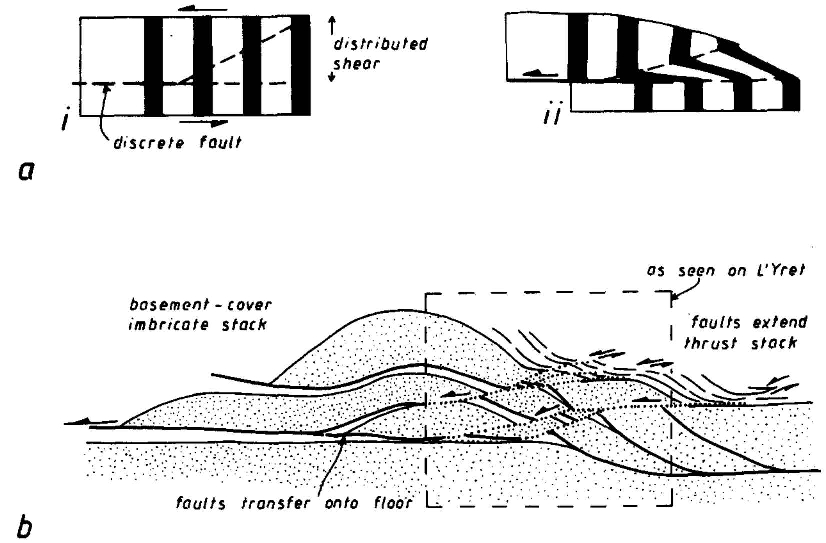

Fig. 9. (a) Schematic representation (i–ii in time) of a shear zone cutting down section and merging into a discrete fault zone. The extensional nature of the deformation stems from the shear zone merging downwards onto the fault, although the base of the shear zone remains at the same level. The vertical bars illustrate offset and do not represent tectonic layering. (b) Disruption of a basement thrust stack (three sheets) by extensional shears (dotted) which collectively cut down and merge onto a lower thrust. The various structural relationships between basement and cover found at the Rocher de L'Yret can be explained by this deformation model.

significant episode of extension into the overlying Pennine zones suggesting that the structures on L'Yret relate to local processes in the thrust zone. These can now be explored.

Distributed break-back thrusting

Break-back thrusting (Butler 1987) involves the development of new thrusts in the hanging-wall to the previously active thrust. Boyer & Elliott (1982) show that such thrusts could decapitate earlier imbricate structures and would thus have locally extensional geometries, with respect to bedding. However, it should be possible to find compressional as well as extensional bedding offsets at different structural levels if such a model is valid. At L'Yret a variety of erosion levels are exposed and the late faults cut various parts of the old compressional geometry (Fig. 9). Yet the extensional faults cannot be traced onto anything other than thrust flats.

A modification to this break-back model involves distributed deformation: simple shear distributed into the thrust sheet above the active floor. The principal Riedel shears developed within this zone would have extensional geometries with respect to the tectonic pile, linking higher levels in the hinterland with lower towards the foreland. Platt (1984) illustrates the consequences of this style of deformation, 'plucking' basement slices (Fig. 1c). Despite the geometric attractions of this model, the Riedel shear disruption of an imbricate stack undergoing distributed simple-shear deformation, the rheological controls on this change of behaviour remain obscure.

Throughout the above discussion the geometric evolution of the structure at L'Yret has been described as a series of tectonic events. However, it is not possible to distinguish these events kinematically. The kinematics recorded by the Nummulitic limestones (WNW-directed overthrust shear) are presumed to have developed largely during the early stages of structural development. They are inseparable from the kinematics of basement faults associated with the late-stage extensional disruption of the thrust stack. This implies a continuous episode of structural development. The L'Yret structures are back-stepped around the dorsal margin of the Pelvoux massif, as are the overlying thrust structures associated with the Pennine front (Matthews 1984). Thus they developed in a structural sequence, between the emplacement of the Pennine zones along the Pennine Front and the thrust stacking of basement and cover to develop the large-scale Pelvoux culmination.

CONCLUSIONS

Several conclusions can be made from this study. First, deformation at L'Yret itself clearly post-dates Nummulitic deposition, although there must have been some uplift and exhumation of the future Pelvoux massif so that Nummulitic rocks could be deposited directly on basement. The age of the thrusts exposed along the Grangettes ridge is less easy to establish. Bravard & Gidon (1979) assumed that these structures pre-dated Nummulitic deposition so that basement sheets provided a sedimentary source for blocks on L'Yret. The sedimentological origin of these blocks has been refuted in this paper, so the requirement for a pre-Nummulitic basement sediment source is redundant. The only indication offered in this study comes from the kinematics: the Grangettes thrusts have the same kinematics as the structures on L'Yret and thus are plausibly part of the same thrusting episode. Regrettably stratigraphic units younger than Liassic are no longer preserved in this area. Rather more safely we can conclude that demonstrably post-Nummulitic deformation involved dominantly an overthrust component directed towards the WNW. On L'Yret this developed in three phases: layer-parallel shear to develop mylonites within the Nummulitic limestones; imbrication of these limestones and higher units with their underlying basement; and extensional disruption of the imbricate stack. Deformation was initially distributed in the cover, later became localized onto discrete thrust faults during the phase of basement imbrication and finally the entire shear zone became wider with the extensional disruption of the thrust stack. The reasons for these changes in behaviour are obscure and require more study, particularly of a microstructural nature, in order to characterize deformation mechanisms.

The structural evolution established at the Rocher de L'Yret has some wider implications for Western Alpine tectonics. L'Yret lies in a pivotal position in the kinematic structure of the Western Alps, yet its kinematic history is very simple: WNW-directed overthrust shear. There is no indication of an additional SE-directed transport, as documented by Merle & Brun (1984), Gillcrist *et al.* (1987) and Fry (1989) for adjacent areas. The late-stage distributed shearing at L'Yret may represent break-back movements on the Pennine Front. It is likely that the thrust displacements represented by the L'Yret structures branch onto the Pennine Front along strike, both north and southwest (Butler *et al.* 1986, cf. Fry 1989). This supports the interpretation of the Pennine Front as a major zone of thrusting, the clearest imaged on deep seismic reflection profiles (Bayer *et al.* 1987) across the Western Alps. Regrettably we can be less certain of the crustal significance of the zone around the Alpine arc to the SSE, where the more complex kinematics have been documented, since deep seismic reflection profiles have yet to be acquired.

The importance of low-angle extensional disruption of thrust stacks remains to be seen, not only with the Western Alpine orogen but in other thrust systems. The preferred explanation here is that the extensional faults represent an episode of dominantly simple shear distributed through a basement–cover imbricate stack developed marginally earlier in the thrusting history. This distributed deformation on a bulk scale has been localized onto an array of net-extensional faults dipping in the direction of shearing. In this sense the faults are analogous to principal Riedel shears in fault zones. There are similarities with Platt's (1984) model of down-cutting fault segments 'plucking' isolated basement slices from beneath basement–cover unconformities. The main difference here is that the extensional faults develop through a pre-existing thrust stack.

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REFERENCES

Argand, E. 1911. Les nappes de recouvrement des Alpes pennines et leurs prolongements structuraux. *Mat. Carte Géol. Suisse.*

Bayer, R., Cazes, M., Dal Piaz, G. V., Damotte, B., Elter, G., Gosso, G., Hirn, A., Lanza, R., Lombardo, B., Mugnier, J. L., Nicolas, A., Nicolich, R., Polino, R., Roure, F., Sacchi, R., Scarascia, S., Tabacco, I., Tapponnier, P., Tardy, M., Taylor, M., Thouvenot, F., Torreilles, G. & Villien, A. 1987. Premiers resultats de la traversée des Alpes occidentales par sismique reflexion verticale (programme ECORS-CROP). *C. r. Acad. Sci., Paris* **305**, 1461–1470.

Beach, A. 1981. Thrust tectonics in the eastern Dauphinois Zone (French Alps), north of the Pelvoux massif. *J. Struct. Geol.* **3**, 299–308.

Boyer, S. J. & Elliott, D. 1982. Thrust systems. *Bull. Am. Ass. Petrol. Geol.* **66**, 1196–1230.

Bravard, C. & Gidon, M. 1979. La structure du refers oriental du Massif du Pelvoux: observations et interprétations nouvelles. *Géol. Alpine* **55**, 23–33.

Butler, R. W. H. 1983. Balanced cross-sections and their implications for the deep structures of the northwest Alps. *J. Struct. Geol.* **5**, 125–137.

Butler, R. W. H. 1987. Thrust sequences. *J. geol. Soc. Lond.* **144**, 619–634.

Butler, R. W. H., Matthews, S. J. & Parish, M. 1986. The NW external Alpine thrust belt and its implications for the geometry of the western Alpine orogen. In: *Collision Tectonics* (edited by Coward, M. P. & Ries, A. C.). *Spec. Publs geol. Soc. Lond.* **19**, 245–260.

Collet, L. W. 1923. *The Structure of the Alps.* Arnold, London.

Davis, D. M., Dahlen, F. A. & Suppe, J. 1983. Mechanics of fold and thrust belts and accretionary wedges. *J. geophys. Res.* **88**, 1153–1172.

Debelmas, J. 1955. Les zones subbrianconnaise et Brianconnaise occidentales entre Vallouise et Guillestre (Hautes Alpes). *Mem. Expl. Carte géol. Fr.*

Debelmas, J. & Kerckhove, C. 1980. Les Alpes Franco-Italiennes. *Géol. Alpine* **56**, 21–58.

Dewey, J. F. 1990. Extensional collapse of orogens. *Tectonics* **7**, 1123–1139.

Fry, N. 1989. Southwestward thrusting and tectonics of the western Alps. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Publs geol. Soc. Lond.* **45**, 83–109.

Gidon, M. & Pairis, J. L. 1981. Nouvelles données sur la structure des écailles de Soleil Boeuf (bordure sud du massif du Pelvoux). *Bull. Bur. Rech. géol. & Minières* **1**, 35–41.

Gillcrist, R., Coward, M. P. & Mugnier, J. L. 1987. Structural inversion and its controls: examples from the Alpine foreland and the French Alps. *Geodin. Acta* **1**, 5–34.

Goguel, J. 1948. *Introduction à l'Étude Mécanique des Déformations de l'Écore Terrestre. Mem. Carte géol. Fr.*

Grand, T. 1988. Mesozoic extensional inherited structures on the European margin of Ligurian Tethys. The example of the Bourg d'Oisans half-graben, western Alps. *Bull. Soc. géol. Fr.* **8**, 631–621.

Grant, N. 1990. Episodic discrete and distributed deformation: consequences and controls in a thrust culmination from the central Pyrenees. *J. Struct. Geol.* **12**, 835–850.

Gratier, J. P. & Vialon, P. 1980. Deformation pattern in a heterogeneous material: folded and cleaved sedimentary cover immediately overlying a crystalline basement (Oisans, French Alps). *Tectonophysics* **65**, 151–180.

Lemoine, M., Bas, T., Arnaud-Vannaeu, A., Arnaud, H., Dumont, T., Gidon, M., Bourbon, M., de Graciansky, P. C., Rudkiewicz, J. L. & Tricart, P. 1986. The continental margin of the Mesozoic Tethys in the Western Alps. *Mar. Petrol. Geol.* **3**, 178–199.

Matthews, S. J. 1984. Thrust sheet evolution in the Kinlochewe region of the Moine thrust zone, N.W. Scotland, and the Pelvoux-Briançonnais, French Alps. Unpublished Ph.D. thesis, University of Leeds.

Merle, O. & Brun, J. P. 1984. The curved translation path of the Parpaillon Nappe (French Alps). *J. Struct. Geol.* **6**, 711–719.

Pfiffner, O. A. 1985. Displacements along thrust faults. *Eclog. geol. Helv.* **78**, 313–330.

Platt, J. P. 1984. Balanced cross-sections and their implications for the deep structure of the northwest Alps: Discussion. *J. Struct. Geol.* **6**, 603–606.

Platt, J. P. 1986. Dynamics of orogenic wedges and the uplift of high pressure metamorphic rocks. *Bull. geol. Soc. Am.* **97**, 1037–1053.

Platt, J. P., Behrmann, J. H., Cunningham, P. C., Dewey, J. F., Helman, M., Parish, M., Shepley, M. G., Wallis, S. & Weston, P. J. 1989. Kinematics of the Alpine arc and the motion history of Adria. *Nature* **337**, 158–161.

Ramsay, J. G. 1963. Stratigraphy, structure and metamorphism of the western Alps. *Proc. Geol. Ass.* **74**, 357–391.

Ricou, L. & Siddans, A. W. B. 1986. Collision tectonics in the western Alps. In: *Collision Tectonics* (edited by Coward, M. P. & Ries, A. C.). *Spec. Publs geol. Soc. Lond.* **19**, 229–244.

Siddans, A. W. B. 1979. Arcuate fold and thrust patterns in the sub-Alpine chains of SE France. *J. Struct. Geol.* **1**, 117–126.

Welbon, A. & Butler, R. W. H. In press. Structural styles in thrust belts developed through rift basins: a view from the western Alps. In: *Tectonic Modelling and Petroleum Geology. Proc. Int. Conf.*, Stavanger.