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Autor: Ford, Mary

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MARY FORD

Key words: Basement-involved folds, Pelvoux, early Alpine

ABSTRACT

The Pelvoux basement massif lies within the NW corner of the external arc of the western Alps. In the Late Cretaceous–Early Eocene, this basement block was uplifted 1–3 km while the basement-cover interface and overlying thin Mesozoic cover were folded (on the south side) by SSE-vergent and (on the west side) by WSW-vergent fold systems under anchizone metamorphic conditions with subordinate thrusts on overturned limbs. These recumbent to semi-recumbent basement-involved folds face outward around the SW corner of the massif and die out rapidly away from the massif. At the SW corner of the massif, fold interference in Mesozoic strata shows that SSE-vergent folding commenced before WSW-vergent folding. A single cleavage is present in the Mesozoic carbonates, which transects most folds and is most intense at the SW corner. No equivalent cleavage has been detected in underlying basement lithologies. It is proposed that uplift and associated folding of basement and cover was achieved in broad, inward dipping shear zones. Similar structures on the N and NE sides of the Pelvoux massif suggest that the whole massif was uplifted as a basement block pop-up. Two possible origins for this three dimensional basement uplift are proposed. Either the regional contractional direction rotated from SSE-NNW to SW-NE, or the western and southern slopes of the Pelvoux paleogeographic high were obliquely folded in a N-S contractional regime. The latter history is favoured here. This N-S contraction could have been generated by a regional sinistral transpression along the pre-existing NE-SW fault system of the Tethyan passive margin which may, in turn, have been related to the sinistral migration of the Iberian plate south of the European plate. The uplifted Pelvoux massif then formed a positive feature that (a) formed a paleogeographic high in the Tertiary foreland basin and (b) may have acted as an obstruction in the path of the advancing late Alpine deformation front in late Oligocene times and hence influenced the evolution of the external Alpine arc.

RESUME

Le massif cristallin externe du Pelvoux affleure au NW de l'arc Alpin. Du Crétacé inférieur à l'Éocène inférieur, ce massif a été remonté de 1 à 3 km. L'interface soclecouverture et la fine couverture mésozoïque sont alors plissées dans les conditions métamorphiques de l'anchizone avec une vergence SSE, au sud, et une vergence WSW, a l'ouest. Des chevauchements mineurs affectent les flancs inverses de ce système de plis. Les plis couchés ou déversés, impliquant le socle avec une vergence centrifuge autour du coin SW du massif cristallin, s'amortissent rapidement et disparaissent en s'éloignant du massif. Au SW, l'interférence des plis affectant le Mésozoïque montre que la vergence SSE est antérieure à la vergence WSW. Une seule schistosité apparaît dans les carbonates mésozoïques. Elle transecte la plupart des plis et atteint son maximum d'intensité au coin SW. Aucune schistosité équivalente n'a été reconnue dans le socle sous-jacent. Nous proposons que l'exhumation et le plissement, tous deux impliquant le socle et sa couverture, soient dus au fonctionnement de

Geologisches Institut, ETH-Zentrum, CH–8092 Zürich

larges zones de cisaillement pentées vers l'intérieur de l'arc. Des structures similaires sur les flancs N et NE du massif du Pelvoux suggèrent que tout le massif fut exhumé comme un pop-up de socle cristallin. Nous proposons deux explications: soit la direction de compression régionale a tourné du SSE-NNW au SW-NE; ou bien les pentes ouest et sud du haut paléogéographique du Pelvoux ont été plissées par une compression oblique, N-S. Nous préférons la dernière hypothèse. La compression N-S peut être liée à une transpression régionale sénestre le long d'un système de failles préexistantes NE-SW de la marge passive Téthysienne. Cette dernière peut elle-même être reliée à la migration sénestre de l'Ibérie, au sud de la plaque européenne. Le massif du Pelvoux formait alors une structure positive responsable de (a) un haut paléogéographique dans les bassins d'avant-pays tertiaires et (b) une obstruction sur le trajet des déformations tardi-alpines à l'Oligocène supérieur, ce qui a influencé l'évolution de l'arc alpin externe.

Introduction

Across the Alpine foreland of SE France, there is abundant field evidence that significant deformation occurred locally before the Apulia-Europe plate convergence caused the onset of foreland basin subsidence and thin-skinned foreland thrusting in the Late Eocene. These early Alpine structures are traditionally divided into two phases based on stratigraphic relations, the Pyrenean-Provençal phase of Late Cretaceous to Late Eocene (Priabonian) age and the pre-Senonian phase (or Eoalpine phase) of Turonian age (Siddans 1979; Debrand-Passard et al. 1986). Large scale, pre-Priabonian basement-involved folds, which could be either Pyrenean-Provençal or pre-Senonian in age, occur around the Pelvoux Massif (Gidon 1979) one of the external basement massifs of the Western Alps. This rectangular basement block (approximately 40 km by 40 km) now lies in the immediate footwall of the Frontal Pennine Thrust – the boundary between internal and external Alpine units. The age of the various basement-involved structures of Pelvoux is equivocal due to lack of sufficient stratigraphical constraints. Some authors argue that they are all pre-Priabonian in age (also referred to as pre-Nummulitique, e.g. Gidon 1979; Brevard & Gidon 1979) while others argue that all are Oligocene or younger in age (e.g. Coward et al. 1991; Beach 1981). This paper describes the geometry and kinematics of unequivocal early Alpine (pre-Priabonian) structures unconformably overlain by Tertiary strata around the southern and western sides of the Pelvoux Massif. It is argued that, based on structural style alone, early and late Alpine structures can be distinguished around Pelvoux. Early structures comprise recumbent to semi-recumbent basement-involved folds that face outward and die out rapidly away from the massif, recording a major basement uplift. Thin-skinned imbrication of basement and its cover occurred along the massif's southern, eastern and northern borders during the later (Oligocene-Miocene) main stage of alpine deformation. Early Alpine Pelvoux folds are also geometrically distinct from, and interfere with, the early Alpine (Turonian) folds of the Devoluy area to the west (Fig. 1). Early external Alpine folds in SE France have been attributed to regional NE-SW sinistral strike slip (e.g. Vialon 1974; Debelmas 1975; Trümpy 1976; Laubscher & Bernoulli 1983; Ricou & Siddans 1986; Coward & Dietrich 1989). It is proposed here that Late Cretaceous–Early Tertiary deformation occurred within a regional sinistral transpressive system along the NE-SW passive margin fault system which cuts through SE France. This regional shear may have been generated by the sinistral migration of the Iberian plate south of Europe at this time (e.g. Stampfli & Marthaler 1990).

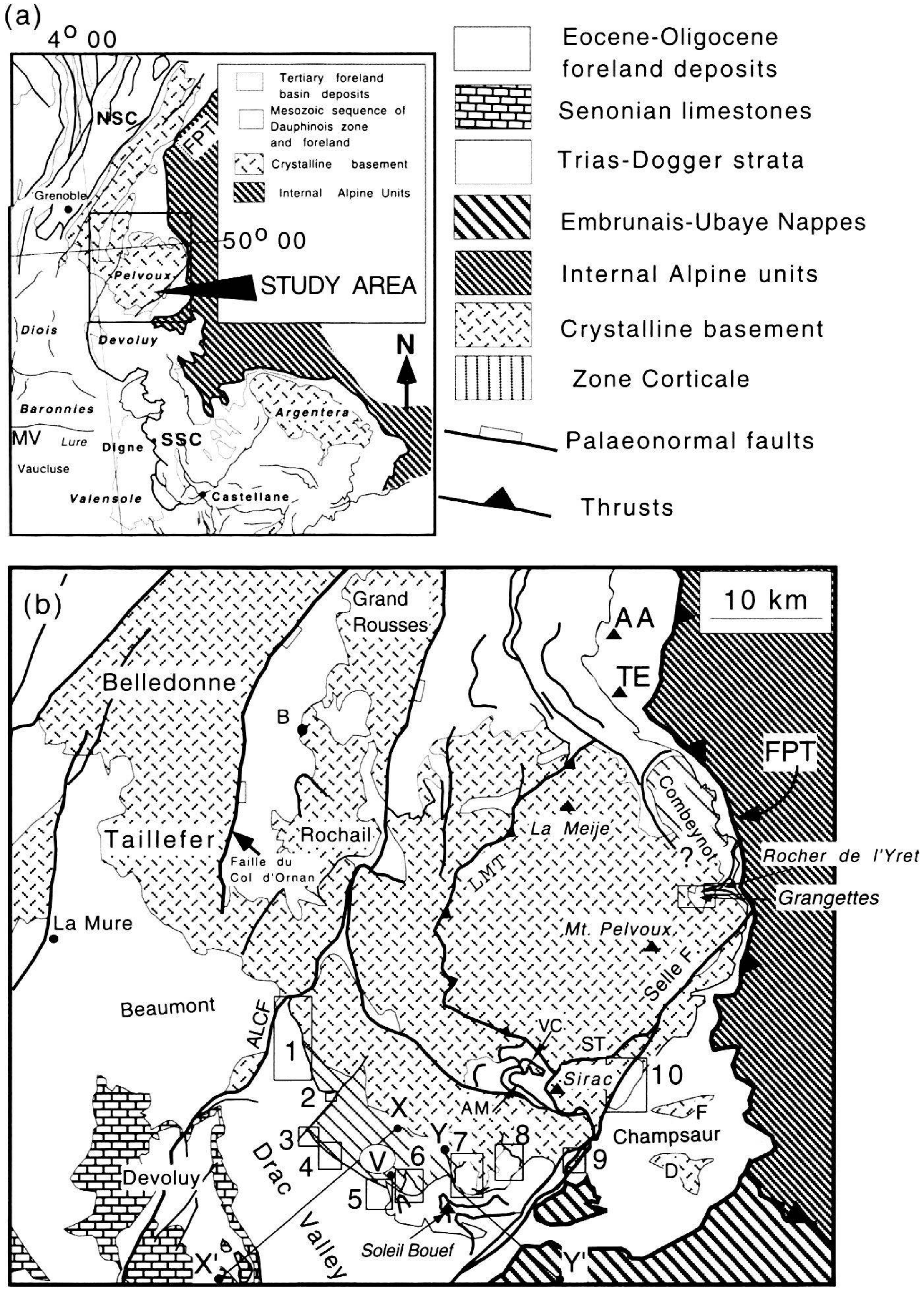


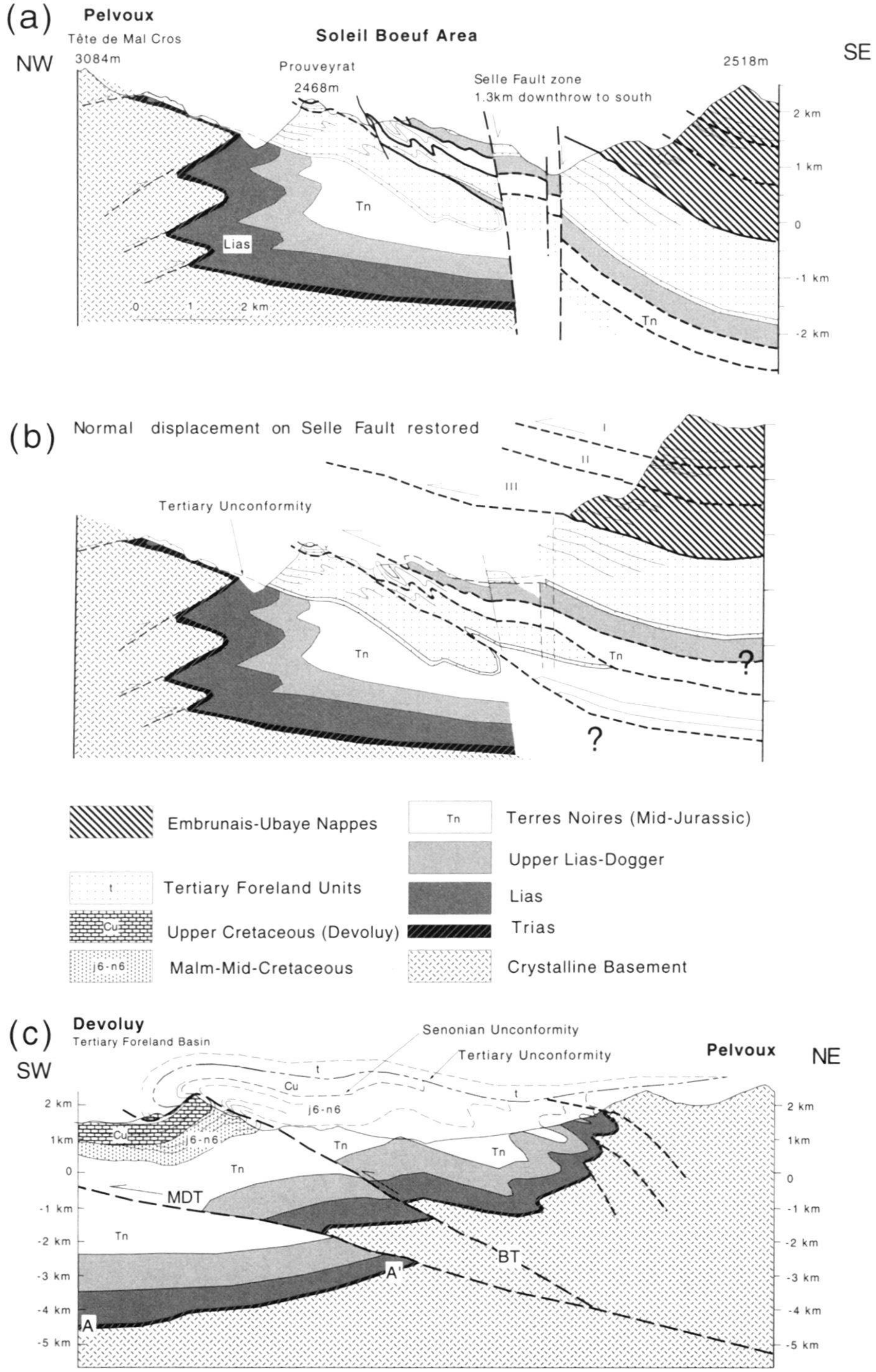
Fig. 1. (a) Map of the external Alpine arc in SE France showing the location of the Pelvoux Massif. MV, Mont Ventoux; SSC, Southern Subalpine chain; NSC, Northern Subalpine chain. (b) Simplified tectonic map of the Pelvoux Massif showing the location of subareas 1–10. AA, Aiguille d'Arves; ALCF, Aspres-les-Corps Fault: AM, Aiguille de Morges; B, Bourg d'Oisans; D, Dormillouse basement inlier; F, Fournel basement inlier; FPT, Frontal Pennine Thrust; LMT, La Meije Thrust; ST, Sirac Thrust; TE, Trois Eveches; VC, basement Klippe of Pic de Vallon Clos. South verging kink bands occur in basement at point V.

Geological setting

The Pelvoux massif is one of several basement massifs that lie in the Dauphinois zone at the NW corner of the external Alpine arc (Fig. 1; Ramsay 1963; Debelmas & Kerckhove 1980). The basement lithologies comprise granites, gneisses and migmatites, of Precambrian and Variscan age (Le Fort 1973), with pre-Carboniferous metasediments forming the Zone Corticale (Fig. 1) along the western and eastern sides of the massif (amphibolites, schists, metaconglomerates, some marbles). Some clastic Carboniferous sediments are preserved in places around the massif. The massif formed a palaeogeographic high during the Mesozoic, resulting in a highly condensed stratigraphy (Debrand-Passard et al. 1984; Lemoine et al. 1986). The thin (metres to tens of metres) basal Triassic succession (Rhetian) comprises non-evaporitic sequences of dolomites, collapse breccias, minor sandstones and spilitic lavas (Buffet-Croix-Blanche 1989). Although the Liassic half-graben of the Belledonne and Grand Rousses massifs further north are well documented (e.g. Gidon & Aprahamian 1980–81; Barféty et al. 1979; Barféty & Gidon 1980–81; Roux et al. 1988; Bas 1988; Coward et al. 1991; Lemoine et al. 1986; de Graciansky et al. 1989), there is little published data on the Jurassic stratigraphy around SW Pelvoux south of the Aspres-les-Corps Fault (Fig. 1) (Gidon et al. 1980; Debelmas et al. 1980). The marl-dominated Jurassic (Hettangian to Oxfordian) succession here varies in thickness between 900 and 1200 m. Thickening of Liassic strata in Area 1 (Fig. 1) of this study clearly indicates the presence of an inverted half-graben associated with the Aspres-les-Corps fault. This fault links into the palaeonormal fault system along the eastern border of the Grand Rousses massif (Fig. 1; the Deux Alpes half-graben; e.g. Barféty et al. 1979; Coward et al. 1991; Bas 1988). Cretaceous strata are absent across Pelvoux. South of the NE-SW-trending Selle Fault Tertiary strata lie directly on basement at Dormillouse and Fournel (Fig. 1).

Tertiary foreland sediments are found to the south of Pelvoux in the Champsaur region and to the west in Devoluy (Fig. 1). Late Alpine (post middle Oligocene) structures can be defined in these areas. The shallowly south dipping Tertiary succession that unconformably overlies the southern side of the Pelvoux Massif north of the Selle Fault (Soleil Boeuf area, Fig. 1) comprises local basal conglomerates and sandstones (> 5 m), Priabonian Nummulitic limestones (5–20 m), marls (> 5 m) and the Lower Oligocene Grès de Champsaur, a turbiditic succession up to 750 m thick (Waibel 1990). This autochthonous succession is overthrust by recumbent nappes of Jurassic and Tertiary strata, now preserved as a series of klippen in the Soleil Boeuf area (Fig. 1, 2). These nappes

Fig. 2. (a) A simplified regional NW-SE cross section (Y–Y' on Fig. 1) through the Soleil Boeuf area on the south side of Pelvoux showing the SE facing pre-Priabonian basement-involved folds unconformably overlain by Tertiary strata that are in turn tectonically overlain by late Alpine NW directed thrust sheets. Adapted from Debelmas et al. (1980). (b) The same cross section with the late displacement on the Selle Fault restored to show the late Alpine thrust stack more clearly. Deep structure is unconstrained. (c) A simplified regional NE-SW profile through the western side of Pelvoux and Devoluy (X–X' on Fig. 1) to show the SW facing pre-Priabonian basement-involved folds of Pelvoux and the later Alpine deformation of the Devoluy foreland basin remnant. Adapted from Gidon et al. (1980). Between A and A' depth to basement is constrained by the gravity data of Menard (1979). Abbreviations are MDT, Median Devoluy Thrust; BT, Banards Thrust.


(a)
Pelvoux
Tête de Mal Cros
3084m
NW
Soleil Boeuf Area
Prouveyrat
2468m
Selle Fault zone
1.3km downthrow to south
2518m
SE
2 km
1 km
0
-1 km
-2 km
Tn
Lias
0 1 2 km
(b)
Normal displacement on Selle Fault restored
I
II
III
Tertiary Unconformity
Tn
?
Embrunais-Ubaye Nappes
t
Tertiary Foreland Units
Cu
Upper Cretaceous (Devoluy)
j6-n6
Malm-Mid-Cretaceous
Terres Noires (Mid-Jurassic)
Upper Lias-Dogger
Lias
Trias
Crystalline Basement
(c)
Devoluy
Tertiary Foreland Basin
SW
Senonian Unconformity
Tertiary Unconformity
Pelvoux
NE
t
Cu
j6-n6
MDT
BT
A
A'
2 km
1km
0
-1 km
-2 km
-3 km
-4 km
-5 km

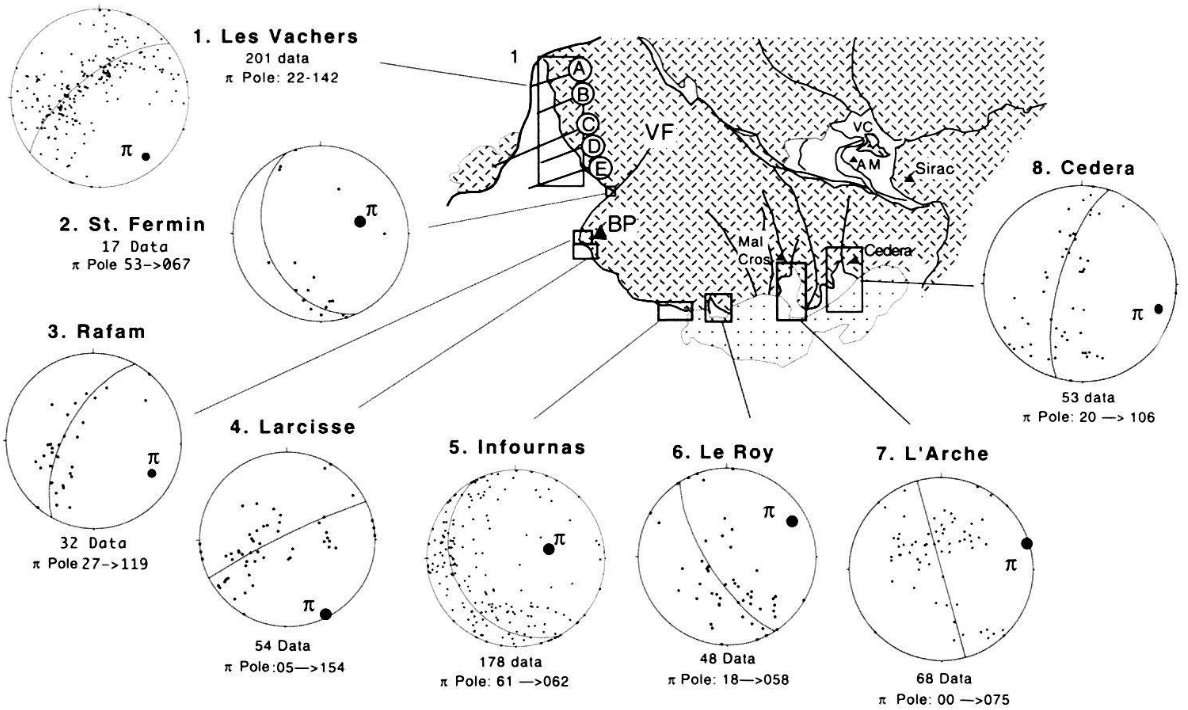


Fig. 3. Equal area lower hemisphere stereoplots of poles to bedding from Areas 1–8 around SW Pelvoux. Each plot shows the best fit great circle and the corresponding π pole representing the average fold axis. Abbreviations are VF, Valgaudemard Fault; BP, le Banc de Peyron.

were emplaced toward the NW and preliminary restoration indicates that they accommodated at least 35 km shortening. In places the thrusts appear to be refolded and there is some evidence of SW transport (Gidon & Pairis 1980–81; Debelmas et al. 1980). The underlying autochthonous Tertiary strata are also locally folded into NW-vergent, recumbent to semi-recumbent fold pairs, which are cut by shallow NW-directed thrusts. South of the Selle Fault, which records a late 1.3 km down-to-south displacement (Fig. 2) only SW vergent structures are found in the Tertiary foreland succession that lies directly below the Embrunais-Ubaye nappes.

In southern Devoluy to the west of Pelvoux the foreland basin sequence was overthrust toward the W-SW by the Banards Thrust sheet before both were folded above the Median Devoluy Thrust (Fig. 2). SW-W shortening is estimated to be 4–5 km. All structures in pre-Tertiary strata east of the Drac Valley are believed to be pre-Priabonian as argued in this paper.

The Soleil Boeuf Tertiary succession records prehnite-pumpellyite facies (Waibel 1990), implying that the area was buried in post-Middle Oligocene times to a depth of at least 6–8 km. Such as burial of foreland strata could only be achieved tectonically by the emplacement of the Soleil Boeuf nappes and overlying, more internal nappes including the Sub-Briançonnais Embrunais-Ubaye Nappes (Fig. 1b). Liassic and Dogger sediments, immediately underlying the Tertiary strata, record a higher anchizone metamorphism (Aprahamian 1974; 1988). Aprahamian (1988) proposes that there are two distinct metamorphic events, an older event in the Liassic strata related to the pre-Priabonian

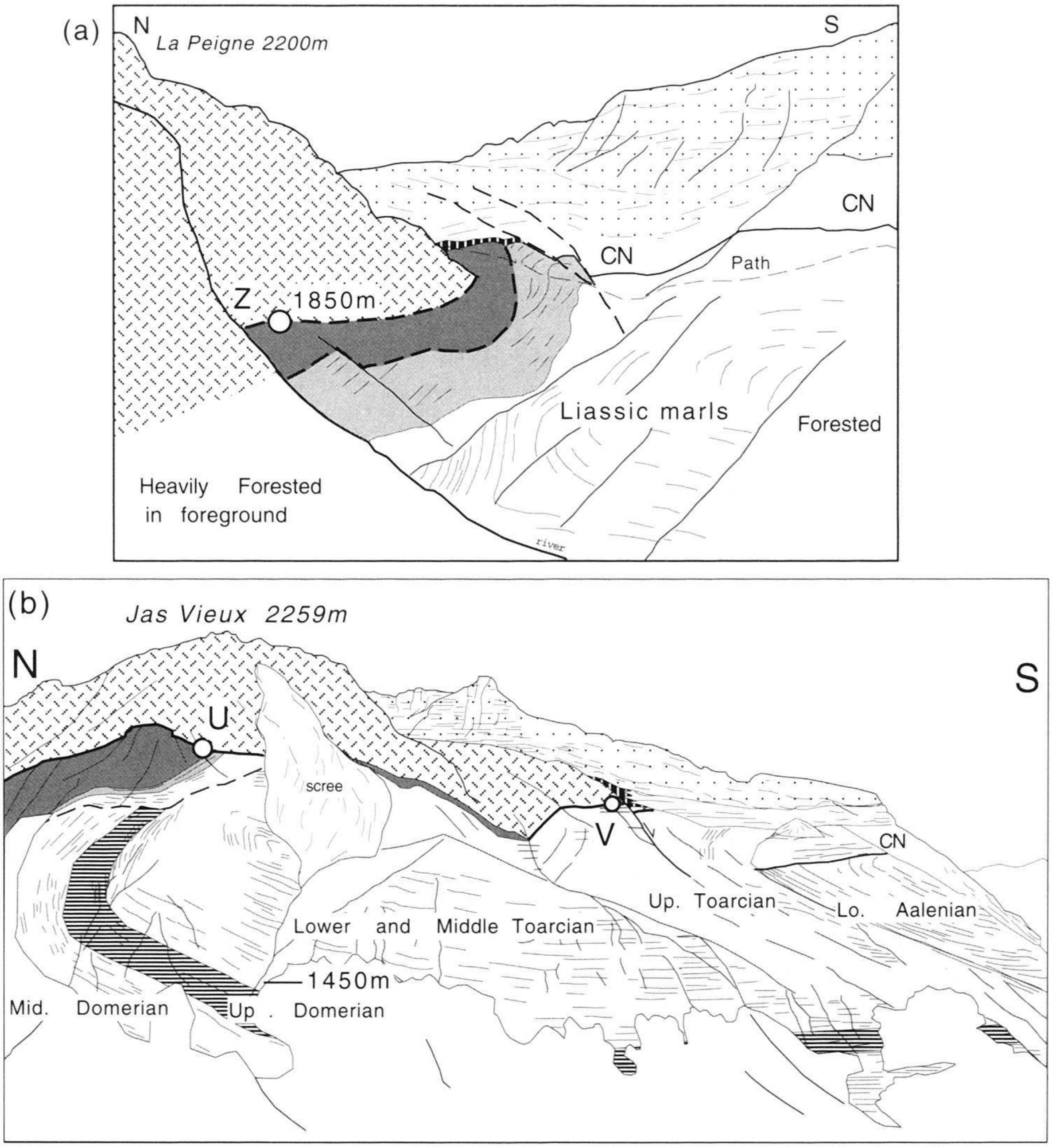


Fig. 4. Early Alpine folds on the south side of Pelvoux. (a) Field sketch of the SW corner of the Le Roy tectonic window looking east (Area 6). Liassic marls form a recumbent, south facing syncline. On the overturned limb the lowest Liassic limestones are overlain tectonically by Triassic spilites and basement. Fault kinematic data was collected from point Z (Fig. 11). The Tertiary sequence unconformably onlaps these structures. (b) Sketch of the western slopes of Cedera (Area 8) showing a south-facing syncline in Liassic strata overthrust by Triassic spilites and basement and unconformably overlain by Tertiary strata. Fault kinematic data was collected at localities U and V (Fig. 11). The Tertiary succession onlaps onto these structures. The stratigraphic key is given on figure 5.

folding discussed in this paper and a younger event related to nappe emplacement in the overlying Tertiary strata. In the Cedera area (Area 8, Fig. 1, 4b) he traces folded isograds in the Liassic strata of the Cedera Syncline (Fig. 4b), whereas the unconformably overlying Tertiary sediments record a weaker metamorphism. The geometry and kinematics of these late Alpine structures around SW Pelvoux have profound implications for the evolution of the late Alpine arc and are the subject of current research. The purpose of this paper is to first define and discuss the earlier Alpine tectonics which caused uplift of the Pelvoux massif.

Structural geometry and kinematics

The Pelvoux pre-Priabonian structures have been studied in a series of sub-areas numbered 1 to 10 around SW Pelvoux (Fig. 1). The structures encountered in Areas 1 to 4 and Areas 6 to 10 are similar in geometry and are described together. The structural features of Area 5 are more complex and are therefore described separately.

The western and southern sides of Pelvoux

Pre-Priabonian asymmetrical fold systems around the southern and western sides of the Pelvoux massif are tight and recumbent to semi-recumbent in proximity to the basement but abruptly become upright and more open away from the massif. Along the southern side of the massif Late Eocene–Middle Oligocene deposits lie unconformably upon south-facing folds involving basement and Mesozoic strata (Fs folds; Fig. 3). Major Fs folds have wavelengths of 2–3 km, amplitudes of up to 1.3 km and plunge shallowly towards the east (ENE-SE; Fig. 3). Minor folds are not common. Fs folds are observed in the Le Roy valley (SE of Molines-en-Champsaur), in the l'Arche area, on the western side of Cedera, Roches les Hommes and in the Selle Valley (Areas 6–10, respectively on Fig. 1; Fig. 3). At Le Roy (Area 4: Fig. 4a) a deep valley cuts down through Tertiary sediments and basement to reveal a tight to isoclinal syncline in Liassic sediments overthrust by overturned Triassic spilites and basement (mica schists). In the l'Arche area, the upper, south-dipping limb of the Tourond Anticline (cored by granite and some mica schist) forms a dip-slope north of the Tourond valley. The overlying Lacs de Salliers Syncline is preserved as a Liassic outlier exposed on both sides of the Crête de l'Arche (Fig. 5b; noted by Le Fort 1973: his figure 146). The higher Mal Cros Anticline (cored by mica schists) is defined here because of the previously undocumented presence of Triassic dolomites above basement on the Mal Cros Ridge (Point X, Fig. 5a). On the western slopes of Cedera (Area 8, Fig. 1), a recumbent isoclinal syncline of Liassic strata faces SSW (Fig. 4b) and is overthrust by basement (gneiss). On Roche les Hommes (Area 9, Fig. 1; Fig. 7d) a basement wedge (migmatites) is preserved between a right-way-up Liassic sequence and the Priabonian unconformity (Debelmas et al. 1980). In the Selle Valley (Area 10, Fig. 1) Liassic and basement rocks lie in recumbent south facing folds below the Priabonian unconformity (see figure 48 in Debelmas et al. 1989).

Although they are not overlain by any Tertiary deposits north of Area 5, pre-Priabonian W to SW facing folds (Fw), plunging shallowly towards the SE-SSE, can be followed northward along the western side of the Pelvoux massif (Areas 1–5, Fig. 1, 3). Area 2 is the exception. Here a mesoscopic fold pair (wavelength of 20 m), lying directly below the basement-cover contact plunges moderately towards the ENE and is strongly transected (axial and profile, *sensu* Johnson 1991) by an intense cleavage. The Fw folds have smaller amplitudes (maximum of 500–700 m) than Fs folds. Fold amplitudes decrease northward

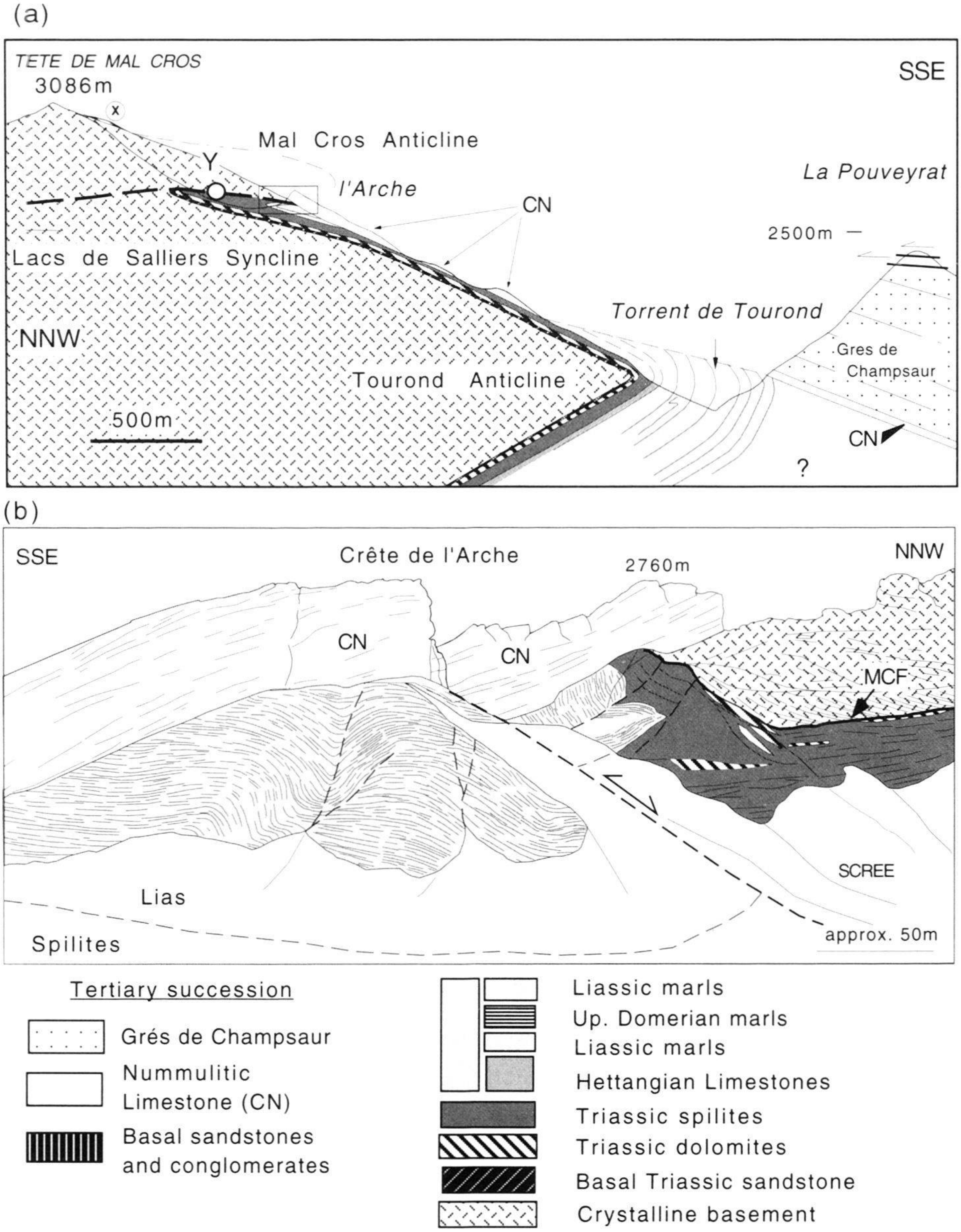


Fig. 5. (a) NNE-SSW profile through L'Arche (Area 7) showing recumbent folds unconformably overlain by outliers of Priabonian Nummulitic limestone. Dolomites are exposed on the upper limb of the Mal Cros Anticline at locality X. Fault kinematic data was collected at locality Y. Post-mid Oligocene klippen of NW-directed nappes are preserved on the peak of Le Pouveyret. (b) Detailed field sketch of Crete de l'Arche (boxed area in (a)) showing faulted closure of the Lacs de Salliers Syncline overthrust by basement (note strong shear fabric in basement above the Mal Cros Thrust (MCF)) and unconformably overlain by Calcaire Nummulitique.

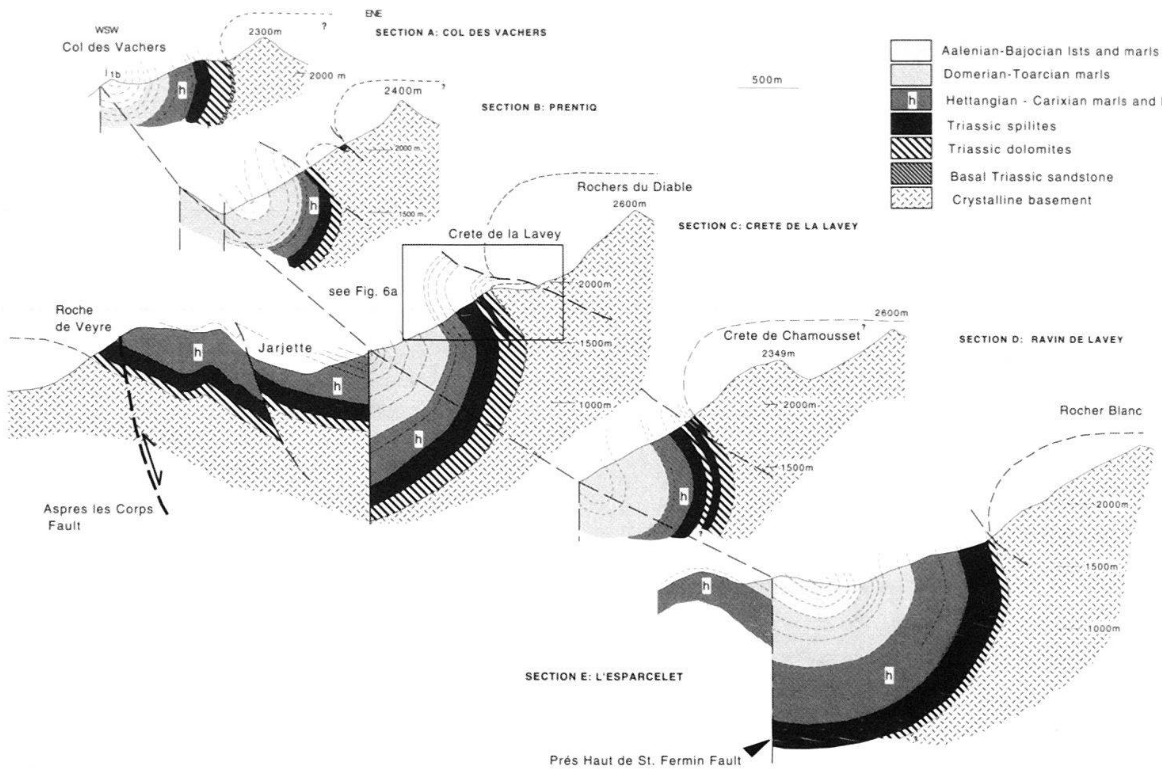


Fig. 6. Five WSW-ENE cross sections through Les Vachers (Area 1) on the western side of Pelvoux (Sections located on Fig. 3). The Prés Haut de St. Fermin Fault occurs in all the sections and provides a common reference. The Jurassic palaeonormal Aspres-les-Corps Fault is shown on Section C. Boxed area depicted in Figure 7a.

along the western side of the massif. Although not covered by this study, the Fw fold system continues north of the Aspres-les-Corps Fault (Aprahamian 1968) to La Mure (Fig. 1). Five serial profiles through Area 1 (Fig. 6; located on Fig. 3) show the geometry of the regional basement uplift as a large monoclinal fold affecting the basement-cover interface. Granitic basement forms the core of a mesoscopic anticline on Crete de la Lavey (projected onto Section C, Fig. 6) and Triassic rocks are preserved in a synclinal core on Section B, reminiscent of the pinched-in synclines of the Aar Massif (Pfiffner et al. 1990). The basement-cover contact on overturned fold limbs can be either sedimentary or tectonic. These profiles also show (1) the rapid facies and thickness changes in the Triassic strata and, (2) that the Liassic units thicken from N to S and westward towards the Aspres-les-Corps Fault (Section C, Fig. 6). Major N-S strike-slip faults cutting through the area and linking into the Aspres-les-Corps Fault, also show significant dip displacement (e.g. Faille de Prés Hauts de St. Fermin, Gidon et al. 1980).

A single cleavage of variable intensity occurs throughout Areas 1–8 with a consistent orientation, striking NW-SE to NNW-SSE and dipping around 45–60° NE (Fig. 8a). Cleavage is rare to absent in Areas 1, 7 and 8, weak in Areas 2, 3, 4 and 6, and most strongly developed in Area 5. The average cleavage is approximately parallel to both Fs and Fw axial planes although most folds are transected (Johnson 1991). Thus the bedding-cleavage intersection lineations plot along a great circle which represents the aver-

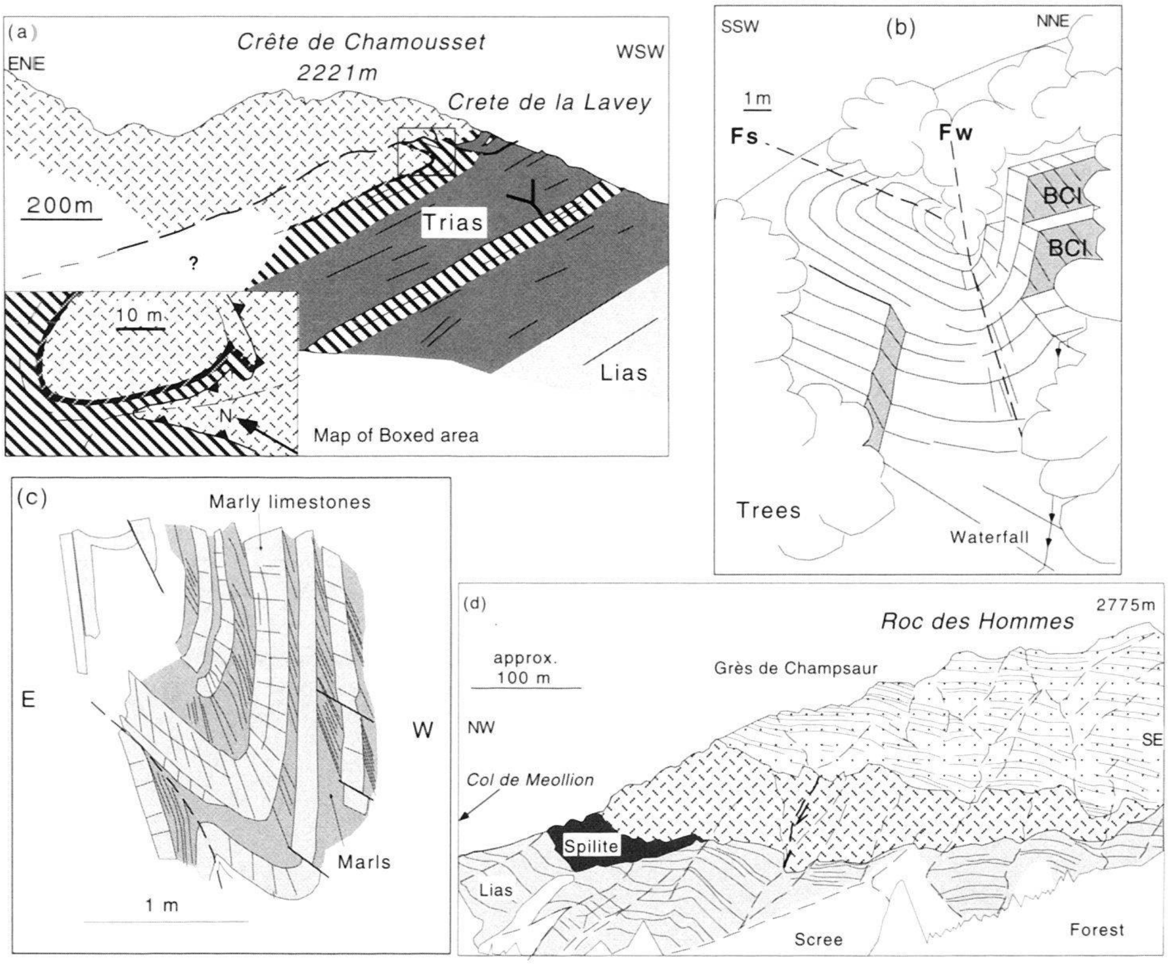


Fig. 7. (a) Field sketch of the northern face of Crete Lavey (Area 1, Located on Fig. 6c) where granitic basement occupies the core of a semirecumbent anticline that faces SW. Inset shows detailed map of the fold closure and overthrust basement. (b) Field sketch of outcrop at Infournas (see Fig. 9a) showing refolded folds. (c) Field sketch of Z-fold at Infournas (located on Fig. 9a) showing strong cleavage refraction. (d) Field sketch of Roc des Hommes (Area 9, Fig. 1).

age cleavage plane (Johnson & Woodcock 1991; Fig. 8b). The sense and degree of bulk axial transection (Δ) varies from area to area and from fold to fold (Fig. 8c) so that none of the current models to explain cleavage transection (e.g. transpression) may be applied. The cleavage is believed to be the same age as the folds because the average cleavage is approximately parallel to the axial planes of Fs and Fw folds. It is most intense where folding is most complex and intense and where thrusting of basement over Lias is best developed (Infournas Fault).

The south-western corner of Pelvoux: Area 5

In Area 5 (Fig. 1) Type 2 fold interference patterns (Ramsay 1967) are observed on both map scale and outcrop scale in the Bajocian and Aalenian limestones. Two map-scale anticlinal closures can be distinguished (Fig. 8), a south facing anticline that plunges mod-

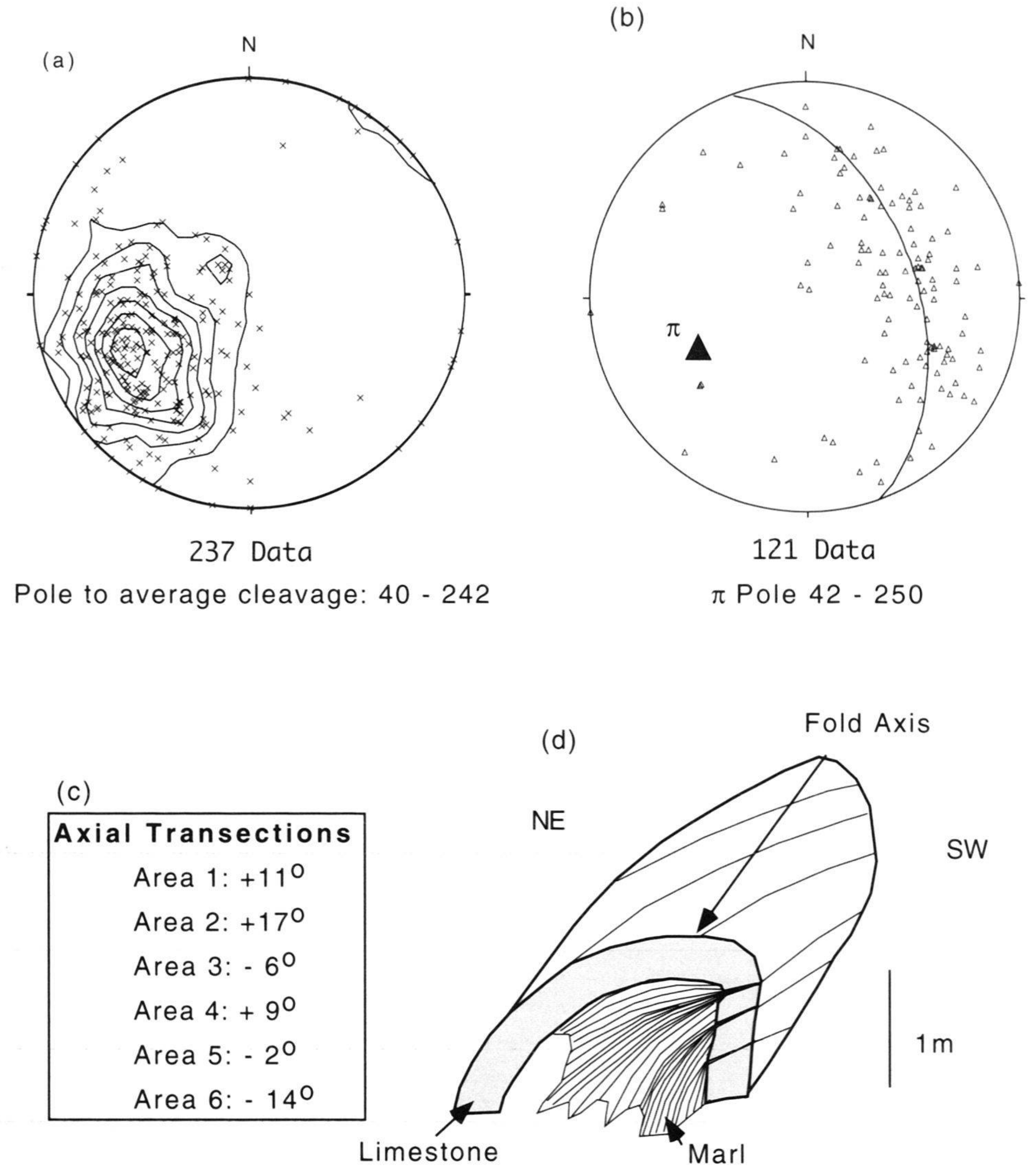


Fig. 8. Lower hemisphere, equal area stereonet plots of (a) all cleavage poles showing a strong cluster distribution and, (b) all bedding-cleavage intersection lineations and the best fit great circle which is the average cleavage plane. (c) List of bulk axial transections around Pelvoux (Δ, after Johnson 1991). (d) Field sketch of minor fold in Area 5 showing both axial and profile cleavage transection.

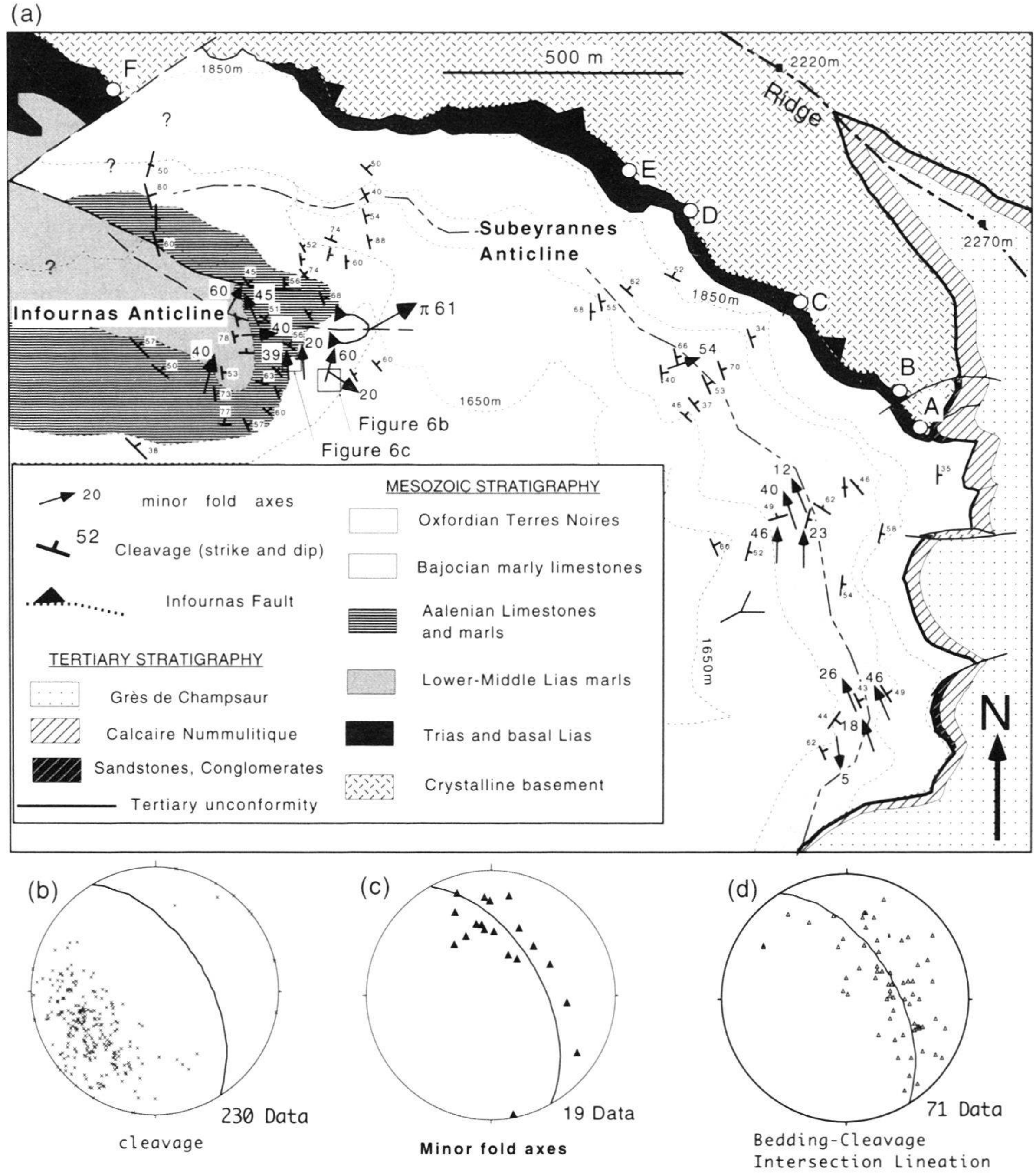


Fig. 9. (a) Detailed geological map of the Infournas area (Area 5) showing the half-mushroom outcrop pattern in Mesozoic strata produced by the interference between the Infournas (Fs) and Subeyrannes (Fw) Anticlines. These folds and the Infournas Fault are unconformably overlain by the Tertiary succession. The Tertiary unconformity is cut by small synsedimentary normal faults downthrowing to the south. Equal area lower hemisphere stereoplots show (b) poles to cleavage, (c) minor fold axes and (d) bedding-cleavage intersection lineations. All plots show the average cleavage plane (great circle). Fault kinematic data on the Infournas Fault (Fig. 10) were collected from localities A to F.

erately to steeply to the ENE (Infournas Anticline: 61-062), and a WSW-facing anticline (Subeyrannes Anticline) plunging shallowly towards the NNW. In the Subeyrannes Anticline mesoscopic M-folds plunge shallowly to moderately to the N-NNW and are therefore congruous. One minor antiformal closure plunges moderately to the ENE. In the Infournas Anticline however, mesoscopic folds are mainly incongruous Z-folds plunging to the N-NNW (e.g. Fig. 7c). These minor folds are however congruous with the overturned limb of the Subeyrannes Anticline. In one outcrop (Fig. 7b) a south facing minor fold is refolded by a west facing minor fold in a Type 2 interference pattern. The area is therefore interpreted as recording two phases of folding, where the Infournas Anticline has been refolded by the Subeyrannes Anticline and now lies on its overturned limb to give the half-mushroom interference pattern seen on the map (Fig. 9a). The Infournas Anticline is correlated with the recumbent south-facing folds (Fs) that can be traced eastward along the south side of the massif and the Subeyrannes Anticline is correlated with the west-facing fold systems (Fw) that can be traced northward along the western side of the massif (Fig. 3). Thus in this area, the Fs folds developed before the Fw folds. Fold interference in the Jurassic strata is only found in this area.

The single cleavage, most intensely developed in Area 5, shows a relatively consistent orientation dipping moderately NE (Fig. 8a, b), although refracting strongly in places through limestone-marl alternations (e.g. Fig. 7c). Both axial and profile transecting relationships are clearly observable across minor folds (e.g. Fig. 8d).

The Oxfordian Terres Noires in the upper limb of the Subeyrannes Anticline are overthrust by overturned lowest Liassic and Triassic strata (spilites and some dolomites), which form a disturbed imbricate zone below a major cataclastic fault zone (Fig. 8a). This fault zone, the Infournas Fault, is 5–20 m in width and carries basement (green chloritic schist) in its hangingwall. The basement was probably uplifted in the core of a major Fw anticline (similar to those seen to the north) whose overturned limb is cut by this thrust.

The Tertiary succession unconformably overlies basement, the Infournas Fault and the folded Jurassic strata (Figs. 9, 10). The Priabonian unconformity is cut only by small normal and dextral strike-slip faults. Thus *all* the structures described above are pre-Priabonian in age.

Pre-Priabonian basement-involved thrusts

The basement-cover contact on overturned fold limbs around SW Pelvoux is frequently cut by reverse faults (Gidon et al. 1980). These faults in Areas 5 to 8 are sealed by Tertiary strata which limits their age to pre-Priabonian. The largest single fault zone (the Infournas Fault) can be traced from St. Fermin to Infournas along the western side of Pelvoux (Fig. 1, 10). This fault zone is irregular and undulose but generally dips shallowly towards the NE to NNE. On the northern slopes of Le Banc de Peyron, (Area 3, Fig. 3; 2776 m) the basement overthrusts folded Liassic rocks by at least 2 km. Elsewhere it is difficult to estimate displacement, as comparative cutoffs are not exposed. North of St. Fermin the basement-cover contact on overturned fold limbs is not always tectonised indicating that the Infournas Fault terminates at the Valgodemard Fault (Fig. 3) and is replaced by smaller, locally developed faults. This transition corresponds to a change in basement lithology as the mica schists of the Zone Corticale are replaced to the north by granites and migmatites. The fault underlying basement in the Le Roy tectonic half-win-

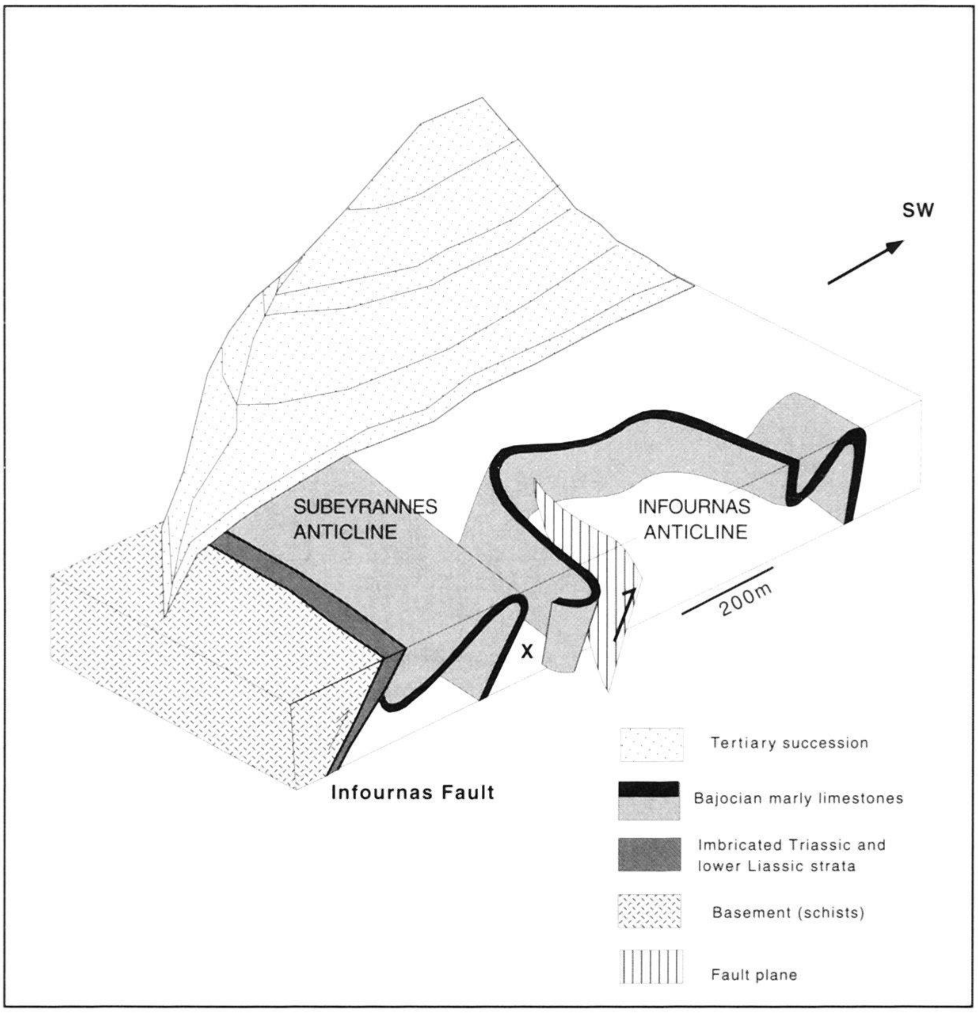


Fig. 10. Simplified block diagram of the Infournas area (Area 5) showing the Infournas and Subeyrannes Anticlines, the Infournas Fault carrying basement and the unconformably overlying Tertiary succession. Structural relationships are uncertain at point X.

dow (Area 6, Fig. 4a) which dips shallowly NNE, is here interpreted as the eastern continuation of the Infournas Fault. In Area 7 the Mal Cros Thrust (Fig. 5), dipping 30° SW has emplaced basement over Triassic and Liassic strata of the Lac de Sallier Syncline. Its trace is lost to the north in basement rocks and to the west below the Tertiary strata. In Area 8, the basement is thrust over a recumbent syncline in Liassic strata (Fig. 4b). This fault dips shallowly east and its trace is lost in basement rocks on the north. The basement wedge in Area 9 must also be overthrust onto the right-way-up Liassic succession, however this contact is inaccessible. Low temperature polysulphide mineralisation occurs locally in the breccias of these fault zones, for example at Le Roy (Area 6; Pierrot et al. 1972).

Faults can be sharp surfaces with no fault rock, or wide zones of cataclasite (up to 10 m), usually of basement lithologies. Cataclasites are best developed where the hangingwall is formed by schists (i.e. around the Zone Corticale). The cataclasite is usually

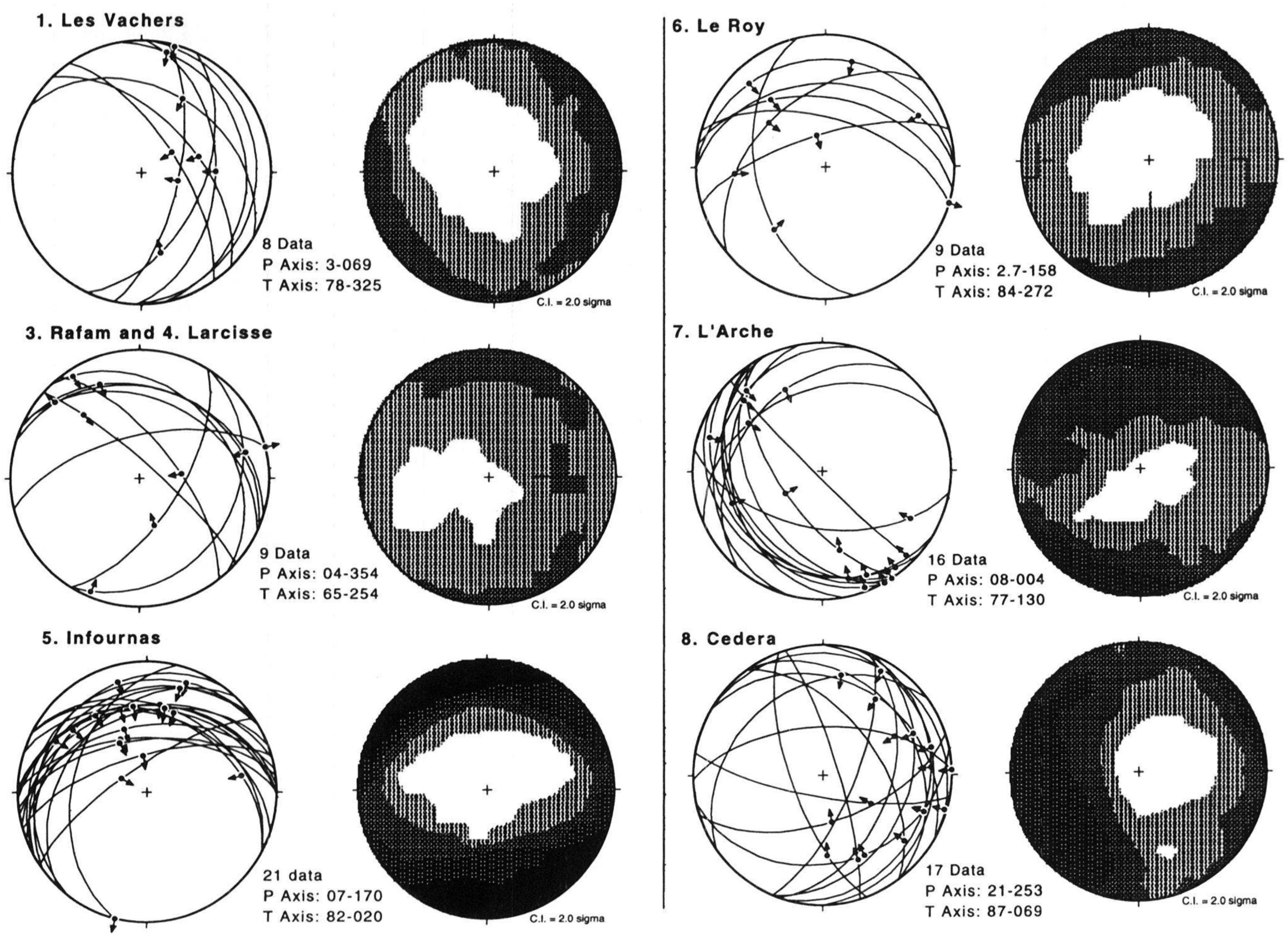


Fig. 11. Fault kinematic data from pre-Priabonian basement-involved faults around SW Pelvoux plotted on lower hemisphere equal area stereonets. For each area the raw data is shown and a contoured plot of compression (P) dihedra (average P and T given below plot).

foliated, showing a hierarchy of slip surfaces similar in form to S-C fabrics which give shear sense (S-C tectonites: Lister & Snoke 1984). The strong shear fabric above the Mal Cros Thrust is shown on the field sketch in Fig. 5b. Slip surfaces within cataclasites can show linear features such as grooves or very fine fibres. Where no cataclasites are present other features such as shear fractures can sometimes be used for displacement analysis (e.g. Petit 1987).

The directional data collected from these fault zones (Fig. 11) show a complex pattern of outward directed thrusting (i.e. thrusting away from the massif) that changes around the massif. These data have been analysed using the FAULT KINEMATICS program of Allmendinger et al. (FaultKin 3.8a, 1989–1994; Fig. 11). Where possible (Areas 5–8), the post-Oligocene tilting, as evidenced by the average sheet dips of the overlying Tertiary succession, was removed (Fig. 11b). The reoriented data varies only very slightly from the primary data and thus is not shown. On the contoured compressional dihedra diagrams the compressional field (dark areas) form girdles while the extensional fields (white areas) form point maxima indicating a constrictional paleostress regime with sub-vertical extensional (T) axes (Pfiffner & Burkhard 1987).

Area 1 shows thrusting towards the WSW. Areas 3 to 6 can be grouped together as they show a mixture of SW-WSW thrusting and SE-SSE thrusting indicating a polyphase movement history. In the Infournas area (Area 5) the foliated cataclasites are folded. The south facing folds have variable axial trends which lie within the main cataclastic fabric suggesting that they are curvilinear (Location C, Fig. 9).

The dip of faults is variable along the southern side of the massif. In Area 7, the Mal Cros Thrust dips towards the SW and shows NW-SE lineations (Fig. 11). The fault plane solution indicates a N-S contraction as do the stratigraphic relationships. The Cedera Fault data (Area 8) record mainly a WSW thrusting similar to Area 1, but some data indicate a NNW-SSE contraction, indicating a polyphase movement history. WSW-directed thrusting was probably later than formation of the SSW-facing Cedera Syncline that may have been contemporaneous with NNW-SSE thrusting.

In summary, most pre-Priabonian fault zones that emplaced basement over younger strata record polyphase contractional histories. All these thrusts occur on overturned fold limbs and thrusting appears to have been subordinate to folding except between Areas 3 and 6 (i.e. the Infournas Fault). The main contraction directions were WSW-SW and SE-SSE and the contoured compressional dihedra indicate that the paleostress was constrictional with sub-vertical extensional axes. Relationships, such as those on Cedera (Area 8) indicate that SSE to SE directed contraction may have pre-dated the SSW to SW-directed contraction. This sequence compliments the chronology of the two fold phases as seen in Area 5.

Discussion

Interpretation of Pre-Priabonian structures of SW Pelvoux

A simplified cut-away block diagram showing the principal features of pre-Priabonian deformation around SW Pelvoux is presented in Figure 12a. The basement-uplift folds developed on two sides of the massif roughly at right angles to one another and with overprinting relationships only preserved at the SW corner (cut-out corner of model).

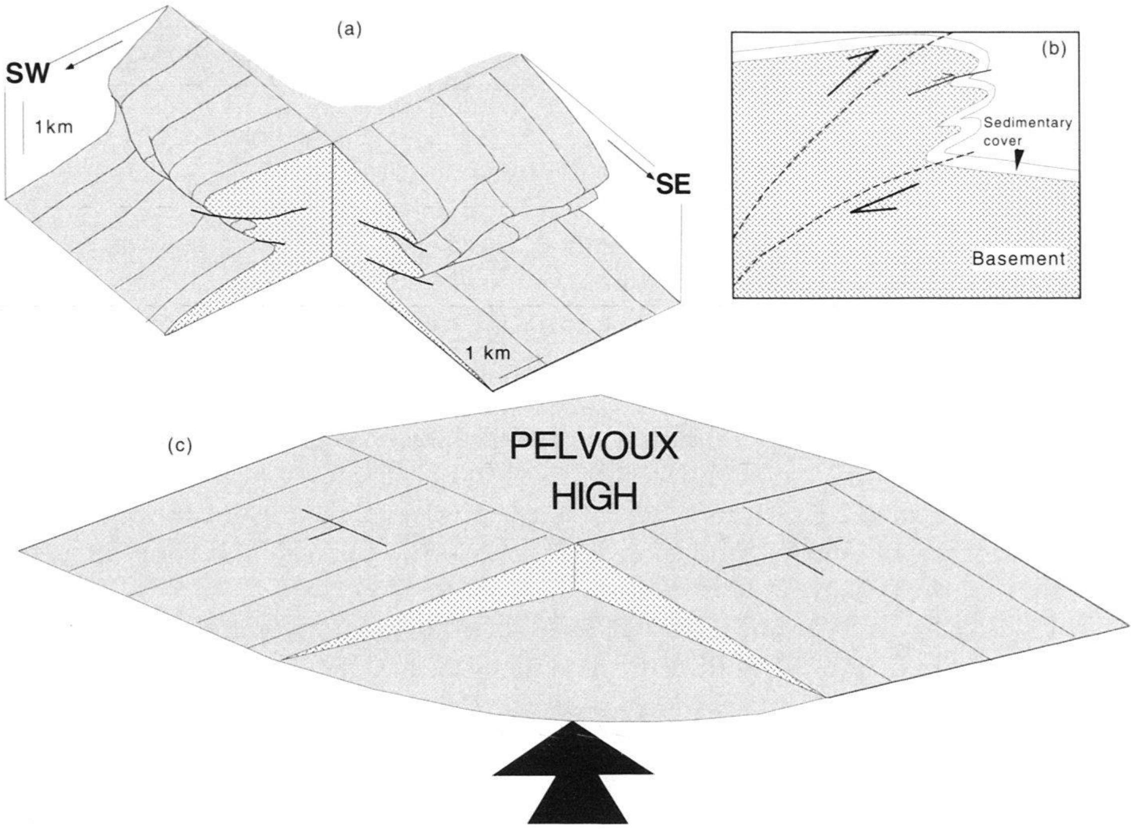


Fig. 12. (a) 3-D model of SW Pelvoux with the corner cut out showing the folded form of the basement-cover interface with outward facing folds. Thrusts cut overturned limbs. The two fold systems are superimposed in the SW corner which is cut out. (b) Schematic cross section through the southern and western boundary of SW Pelvoux showing how the uplift and folding of the basement-cover boundary could be achieved with a broad, inward dipping shear zone. (c) Conjectural pre-deformation form of the Pelvoux paleographic high showing WSW- and SSE-dipping slopes which become obliquely folded by a northward compression (large arrow) to form model shown in (a).

Fold superposition in Area 5 indicates that Fs folding at least *commenced* before the weaker Fw folding. The predominance of folding over thrusting suggests that the Pelvoux structures developed in a fashion similar to the fold-thrust model of Brown (1988) in which an initial stage of penetrative folding in both basement and cover is followed by thrust faulting breaking through over-steepened forelimbs of folds. It is proposed that the folding and thrusting of the basement and cover around Pelvoux occurred in broad, inward dipping shear zones that uplifted the massif (Fig. 12b). These shear zones were zones of asymmetrical folding at higher levels but became narrower zones of more homogenous deformation within basement at depth. Spang et al. (1985) suggest a similar 2-D model for the Laramide basement uplift structures in the foreland of the Rocky Mountains. Unlike the Laramide basement uplifts however, the Pelvoux structures record roughly simultaneous uplift and associated folding in two directions roughly at right angles to one another. Such three dimensional geometries could develop due to (1) a changing contractional direction or, (2) a single contractional direction affecting oblique surfaces.

Model 1

The deformational history can be interpreted as recording a clockwise rotation of the contractional direction with an initial SSE-NNW contraction being followed by a SW-NE contraction. This model is supported by the superposition of the two fold systems in Area 5 and by the fault kinematic data. However, the presence of a single cleavage, roughly axial planar to the two fold systems, is problematical.

Paleomagnetic data (e.g. Henry 1992) for the Pelvoux Massif have yielded unusual paleomagnetic directions compared to the rest of the external western Alps and have been interpreted as recording an early Alpine *anticlockwise* rotation of the massif in the order of 30°. However these data should perhaps be re-examined in the light of the findings of the present paper as, (a) the orientation of the early Alpine folds around Pelvoux were not previously well constrained and (b) most of the samples have been taken from Triassic strata which often lie on overturned limbs of Pre-Priabonian folds.

Model 2

Within a constant contractional system, folds of variable orientation can develop if, (a) original surfaces have different orientations with respect to the compressional direction (e.g. Hansen 1971; Hugon 1982) or (b) strong directional fabrics within metamorphic basement behave as a bending anisotropy and strongly influence the orientation of developing folds (Cobbold & Watkinson 1981). The importance of these parameters in the Pelvoux folds is currently under investigation. Assuming the former parameter was the predominant influence, figure 12c shows a conjectural pre-deformation configuration for the palaeotopographic Pelvoux basement high with the western side dipping shallowly to the WSW and the southern side dipping shallowly to the SE-SSE. If a N-S compressional stress were to fold these surfaces, two fold systems with quite different orientations could develop and would interfere at the corner. A regional N-S compression is favoured here because (1) it explains the presence of a single cleavage and (2) this seems to have been the dominant compressional direction recorded by pre-Eocene folds across SE France (e.g. Flandrin 1966; Ford 1995).

Folding of basement lithologies

The mechanical behavior of lithologies such as granite and migmatite, involved in large scale folding at anchizone metamorphic conditions as described above is not well understood. Evidence for cataclastic flow in basement lithologies within Laramide basement uplifts in the Rocky Mountain foreland suggests that some crystalline basement may accommodate folding by brittle deformation on a microscopic scale (Narr & Suppe 1994; Evans 1988; Mitra & Frost 1988). In contrast, the classic basement-cover folds of the Aar Massif are associated with intense foliation development in basement (Kammer 1985; Pfiffner et al. 1990). The deformation mechanisms involved in basement-cover folding of SW Pelvoux have not yet been investigated in detail. Nevertheless, some initial observations can be made. No Alpine fabric has been detected so far within the basement rocks but south-verging mesoscopic kink folds and associated thrusts occur in chlorite schists at location V (Fig. 1), which may be related to the Pre-Priabonian deformation. Two main basement lithology groups are involved in the pre-Priabonian structures, namely the well

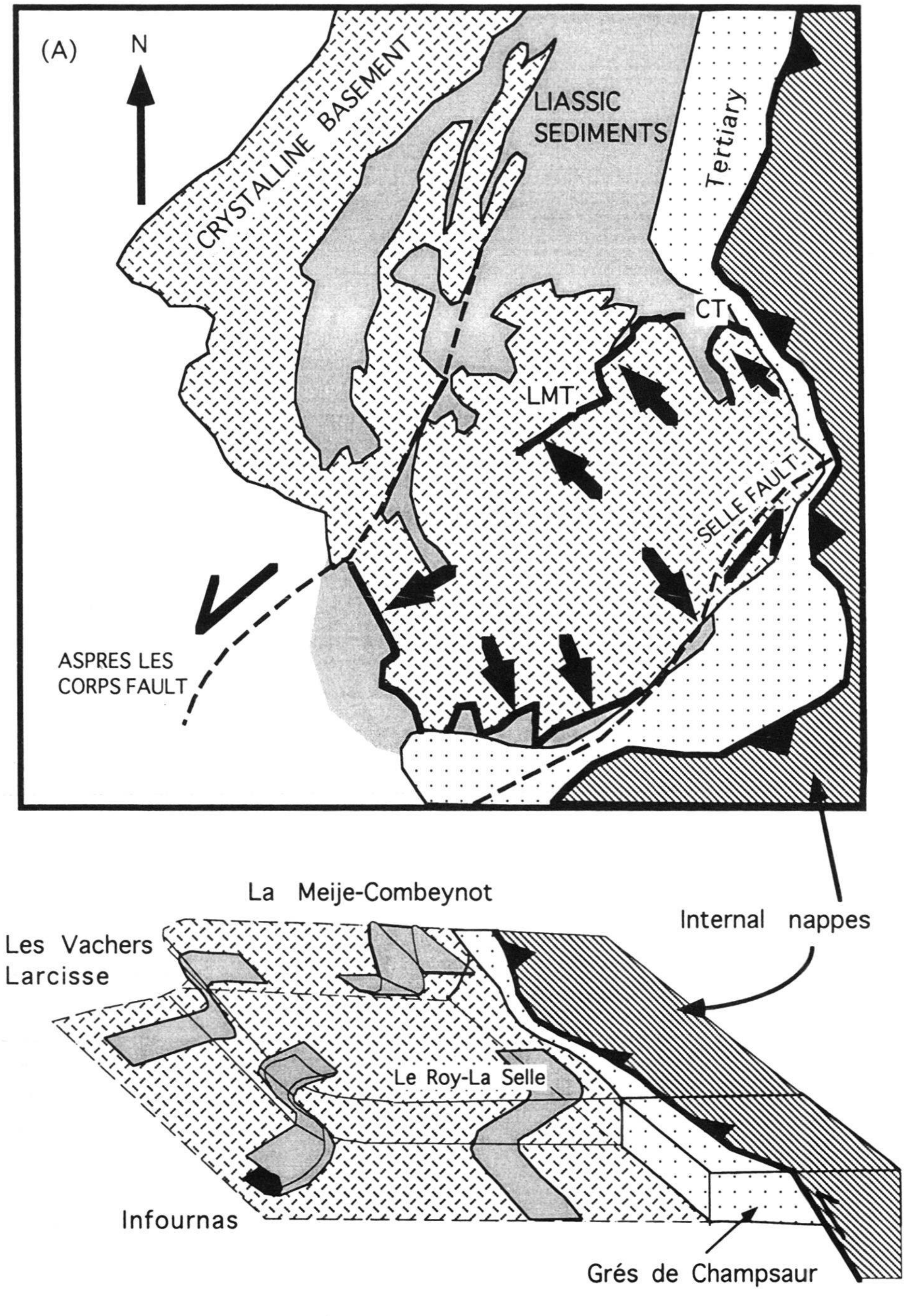


Fig. 13. (a) Simplified map of the Pelvoux massif showing all probable Pre-Priabonian transport directions and NE-SW faults. (b) Simplified block diagram of the main structures around Pelvoux today showing the pre-Priabonian outward facing structures related to major basement uplift around the Pelvoux massif, the erosionally overlying Tertiary succession and the overthrust internal nappes.

foliated schists and gneisses of the Zone Corticale and the more homogenous granites and migmatites. Fold closures whose forelimbs are not cut by thrusts are usually observed in the granites and migmatites (e.g. Areas 1 and 7) while the schists and gneisses are associated with the best developed thrust zones. For example, the Infournas Fault correlates in regional extent with the Zone Corticale.

Other Basement-involved Alpine Structures of the Pelvoux Massif

The presence of Pre-Priabonian structures around the northern and eastern margins of the Pelvoux Massif has been reported frequently in the literature (e.g. Gidon 1979; Barbier 1963; Brevard & Gidon 1979). Indeed these authors stated that all structures affecting the Pelvoux basement are pre-Priabonian and that the basement block behaved as a resistant block ("Môle resistant") that was not deformed during the later main Alpine events. Equally frequently but in more recent publications, the same structures have been interpreted as post-Eocene (e.g. Gillcrist et al. 1987; Beach 1981). The structures in question are the La Meije thrust, the Combeynot Thrust, the basement imbricates at Grangettes and Roche d'Yret, the Sirac Thrust and the imbricates of Aiguilles de Morges and Pic de Vallon Clos (Fig. 1).

Above the La Meije and Combeynot Thrusts the basement-cover contact is folded into a vertical to overturned orientation (Brevard & Gidon 1979, fig. 9). The Combeynot basement block (Fig. 1) has been deeply eroded and is unconformably overlain by Tertiary deposits, indicating a pre-Priabonian age. The La Meije Thrust is not overlain by any Tertiary deposits and thus its age is more problematical. The Tertiary unconformity north of Pelvoux (Fig. 1) may itself be tectonised in places leading Beach (1981) to propose that the La Meije and Combeynot Thrusts roofed into this unconformity and were thus post-Eocene in age. Gillcrist et al. (1987) show movement vectors along these thrusts as top to the W to WNW. Butler (1992) shows that the basement imbricates at Roche d'Yret, recording WNW displacements, are post-Eocene in age as they involve Tertiary sediments. The age of the underlying Grangettes imbricates (basement and Mesozoic) is still unclear. Within the massif itself, the ages of the Sirac Thrust and the imbricates of Aiguilles de Morges and Pic de Vallon Clos (Fig. 1) also need to be clarified. Coward et al. (1991) show kinematic data indicating a WSW to WNW transport direction for these imbricates.

The few kinematic data published (Gillcrist et al. 1987; Butler 1992) suggest that if two generations of structures do exist in northern Pelvoux, they would show the same tectonic transport direction (i.e. to the WNW). Where stratigraphic relationships (i.e. the Tertiary unconformity) are absent and transport directions are not distinguishable, structural style may be of use in distinguishing between two generations of structures. As shown in this paper, the pre-Priabonian structures are characterised by major basement uplift achieved by basement-involved folding while late Alpine structures are dominated by imbrication of basement and its cover as described by Butler (1992) at Roche d'Yret. Based on this hypothesis, one could provisionally suggest that the Combeynot and La Meije Thrusts are pre-Priabonian in age while the Grangettes thrusts, the Sirac Thrust and the imbricates of Aiguilles de Morges and Pic de Vallon Clos may be late Alpine.

A pre-Priabonian age for the Combeynot and La Meije structures indicates that the whole Pelvoux basement massif was uplifted and thrust outward, like a large-scale basement pop-up (Fig. 13). As proposed by Brevard & Gidon (1979) and Tricart (1986) this uplifted basement block may have later acted as a major obstruction to the advancing Oligocene Alpine deformation.

Early Alpine structures in adjacent foreland areas

Pre-Priabonian structures can be traced in a NE-SW swathe from Pelvoux to Mont Ventoux (Pelvoux-Devoluy-Diois-Baronnies-Ventoux; Fig. 1a). To the SW of Pelvoux, early Alpine structures have been recognised in the Devoluy area and in the Baronnies-Diois regions (Flandrin 1966; Fig. 1a). The age of the Devoluy folds is well constrained to Turonian by the overlying stratigraphic unconformity. Structural data published on these early folds mainly comprise isolated descriptions (Glangeaud & d'Albissin 1958; Debelmas et al. 1970; Gidon et al. 1970; Arnaud 1974; Odonne & Vialon 1987). On the eastern side of Devoluy, the Turonian fold train consists of NE-SW trending, recumbent, tight to isoclinal asymmetrical fold pairs facing NW, with long normal limbs and short overturned limbs that are often thrust out. These folds have been tilted to the west on the eastern limb of the post-Middle Oligocene Devoluy syncline and are locally overprinted by these late Alpine folds on a small scale (e.g. Odonne & Vialon 1987). This Devoluy fold system cannot be correlated with the Fw or Fs folds of SW Pelvoux (10 km to the east; Fig. 1; Gidon 1979). In fact, the Fw fold system interferes with the Devoluy system to give a dome and basin pattern in the Beaumont region (Fig. 1, Aprahamian 1968). Preliminary investigations suggest that the early Devoluy fold system is overprinted by the Fw Pelvoux folds, which implies that the latter are Pyrenean-Provençal or late Cretaceous–early Eocene in age.

The early Devoluy folds have themselves been correlated with the E-W folds of the Diois-Baronnies region to the SW (Fig. 1a; Flandrin 1966). E-W growth synclines in the Baronnies indicate that folding started here in mid-Cretaceous times within the marl-dominated infill of the Vocontian trough (Ford 1995) and continued to develop until Miocene times. Thus the two pre-Priabonian phases of deformation traditionally described in SE France may have been part of a more continuous regional deformation associated with a N-S contractional stress system that mainly affected a NE-SW area from Pelvoux to Mont Ventoux (Fig. 1a). Other more isolated early Alpine structures occur further south across the Alpine foreland (e.g. Ricou & Motte 1986; Hibsch et al. 1992).

Regional model

The Pelvoux-Ventoux zone of pre-Priabonian structures lies between the NE-SW-trending Nîmes and Durance Faults of the Tethyan passive margin fault system. Many paleonormal faults are known to have accommodated sinistral displacements during the mid-Cretaceous (e.g. Ricou & Motte 1986; Hibsch et al. 1992). A broad zone of NE-SW sinistral shear between the Durance and Nîmes fault zones would generate N-S contractional stresses. It is therefore proposed that the European passive margin was affected by a NE-SW sinistral transpressive system from the mid-Cretaceous onwards (Vialon 1979). This stress system may have been related to the sinistral movement of the Iberian plate to the south of the European plate from the Albian to the Santonian (Fig. 14; Stampfli 1993). The lateral continuation of such an early NE-SW sinistral system to the NE of Pelvoux is

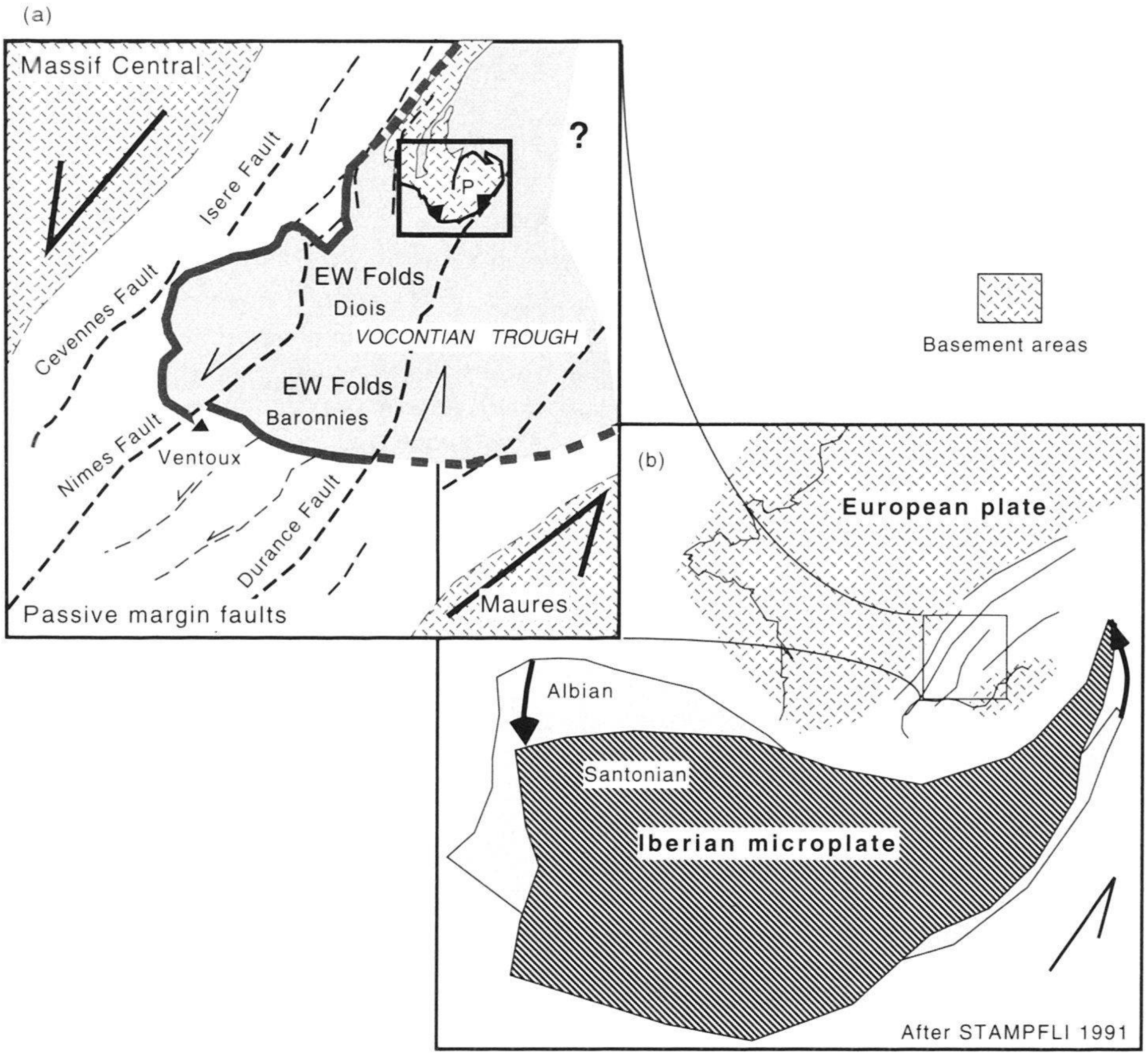


Fig. 14. (a) A regional model showing the development of pre-Priabonian structures within a NE-SW regional sinistral transpressive system which concentrated along a corridor from Pelvoux (P) to Mont Ventoux. E-W folds developed preferentially in the marl-dominated (i.e. incompetent) infill of the Vocontian trough (Diois and Baronnies areas). (b) shows a larger scale model where a sinistral couple is imposed on the weak European passive margin by the rotation and lateral migration of the Iberian plate further south (adapted from Stampfli 1991).

problematical as early events have been strongly overprinted by the later main Alpine structures. The relationships between this early foreland tectonic activity in the western Alps and the contemporaneous collisional orogenic processes in the eastern Alps is as yet poorly understood.

Conclusions

This work documents the uplift of a major basement block and its cover within the Alpine foreland in the Late Cretaceous–early Eocene. The structural style, which may be described as thick-skinned, is dramatically different from the thin-skinned main Alpine deformation that later affected the region. Similar basement uplifts have not been described elsewhere in the Alps although they are common in some other orogenic belts. Clearly, the field observations presented here raise many questions, for example, (1) the true origin of the transecting cleavage and its genetic relationship to the folds and thrusts and, (2) the deformation mechanisms within the various basement lithologies which accommodated folding of the basement-cover interface.

The Pelvoux massif lies in a critical position within the external Alpine arc and the structures described here represent only one phase in its long tectonic history which can be summarised as follows: (1) During Mesozoic passive margin development the Pelvoux formed a topographic high. Probable palaeonormal faults were the Aspres-les-Corps and the Selle Faults. (2) Uplift of the Pelvoux massif associated with basement-involved folding in the Late Cretaceous–early Eocene. (3) Considerable erosion of the uplifted block before (4) the onset of foreland basin subsidence and marine transgression which led to deposition along the eastern, southern and western borders of the Pelvoux block. (5) Late Oligocene NW emplacement of the Embrunais-Ubaye and more internal nappes over the Pelvoux massif and its Tertiary cover. (6) SW tectonic transport south of the Selle fault and west of Pelvoux in Devoluy (Fig. 1). (7) Major downthrow to the south on the NE-SW Selle Fault, related to late uplift of the Pelvoux massif. It can be no coincidence that the uplifted Pelvoux block is now found within the core of the later external Alpine arc. It has been previously suggested that the uplifted Pelvoux acted as a major obstruction in the path of the advancing late Alpine deformation front (Brevard & Gidon 1979; Tricart 1986). The role of the uplifted Pelvoux massif in the evolution of the late external Alpine arc is currently under investigation.

Acknowledgements

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