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The structure of the Gran Paradiso basement massif and its envelope, Western Alps

By JULIAN R. VEARNCOMBE[1])

ABSTRACT

Lithologies and structures in the Gran Paradiso region of the Western Alps are discussed. Alpine deformation events are divided into five phases, the nature and interrelationships of which are described. The Schistes lustrés nappe, allochthonous cover to the basement, includes within it dismembered ophiolites. Lithological contacts are mostly tectonic and the ophiolitic slices are probably part of a tectonic mélange. Flat-lying LS tectonites, tectonic pods and possible sheath folds were formed during an early Alpine (D2) event of mélange development, ductile translation and nappe emplacement. Late tectonic (D3 and D4) events involved folding of earlier fabrics and thrusting (including rétrocharriage). These structures are usually asymmetric or have moved towards the Gran Paradiso basement, which is now an antiform. The nappe geometry is discussed in thrust tectonic terms, the rules of which are thought not applicable to the Schistes lustrés tectonic mélange but are more or less compatible with the larger scale geometry which is interpreted as an imbricate stack.

RIASSUNTO

Nel presente articolo vengono discusse la litologia e le strutture nella zona del Gran Paradiso (Alpi occidentali). Si riconoscono cinque fasi di deformazioni di età alpina, la cui natura e correlazione vengono qui descritte. La falda di Schistes lustrés (una copertura alloctona che copre lo zoccolo) contiene ofioliti smembrate. La maggior parte dei contatti litologici è tettonica e le scaglie ofiolitiche fanno probabilmente parte di un melange tettonico. Tettoniti LS orizzontali, lenti tettoniche e possibili «sheath folds» si formarono durante un primo evento alpino (D2) in cui vi verificarono lo sviluppo del melange, una traslazione duttile e la messa in posto della falda. Tardi eventi tettonici (D3 e D4) coinvolsero un piegamento di strutture precedenti ed uno scorrimento (incluso il «retrocharriage»). Queste strutture sono generalmente asimmetriche o hanno subito un movimento verso lo zoccolo del Gran Paradiso, che costituisce ora una antiforma. La geometria della falda viene discussa in termini di tettonica di scorrimento le cui regole si pensa non siano applicabili al melange tettonico degli Schistes lustrés, ma sono più o meno compatibili con la geometria a larga scala che viene interpretata come una pila imbricata.

Introduction

The Gran Paradiso region (Fig. 1, 2 and 3) comprises part of the Graien Alps which span the Italian–French frontier in the Western Alps.

Much of the work described here forms part of a Ph. D. thesis (VEARNCOMBE 1980). Geological maps of regions for which cross sections are presented here, without accompanying maps, are included in that thesis. The sections AA', BB' and CC' (Fig. 4) for the Valnontey–Valeille region are based, mostly, on vertical cliff sections. Sections for

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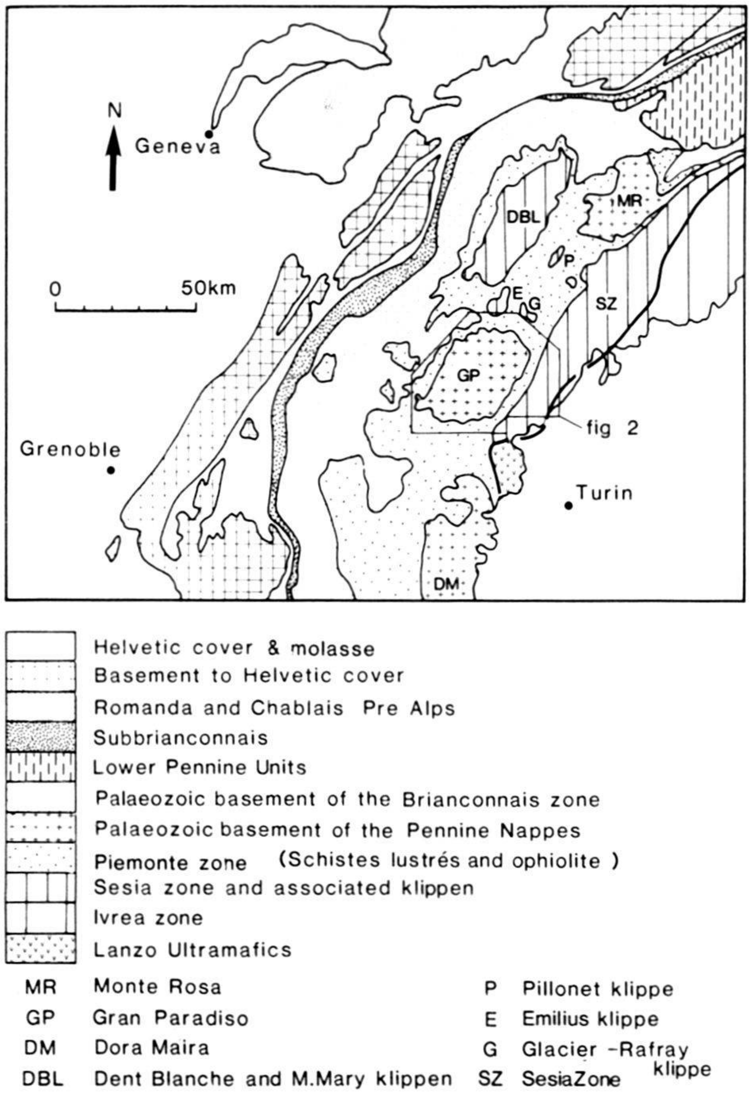

Fig. 1. Simplified geological map of the Western Alps, showing the principal tectonic units referred to in the text.

the Campiglia–Piamprato region (DD′D″ and FF′) are based on regional mapping with some along-strike extrapolation, hence the map (Fig. 5) is also presented. The Punta Vallone–L'Uja region sections are based on mapping in poorly exposed terrain and are of road-cut and valley section (GG′ and JJ′) and a mountain ridge (HH′). Sections in the Bonneval-sur-Arc region (KK′ and LL′) are based on regional mapping. The map presented by Vearncombe (1980) does not differ significantly from the published map of Bertrand (1968).

The Gran Paradiso basement

The basement complex comprises Hercynian fine grained metasedimentary gneisses (the gneiss minuti) with minor granitic and basic bands (Compagnoni et al. 1974, Compagnoni & Lombardo 1974) and an intrusive porphyritic granite. The gneiss minuti locally preserves high temperature Hercynian metamorphic minerals, as well as a strong Alpine overprint (Compagnoni & Prato 1969, Vearncombe 1983). As a result

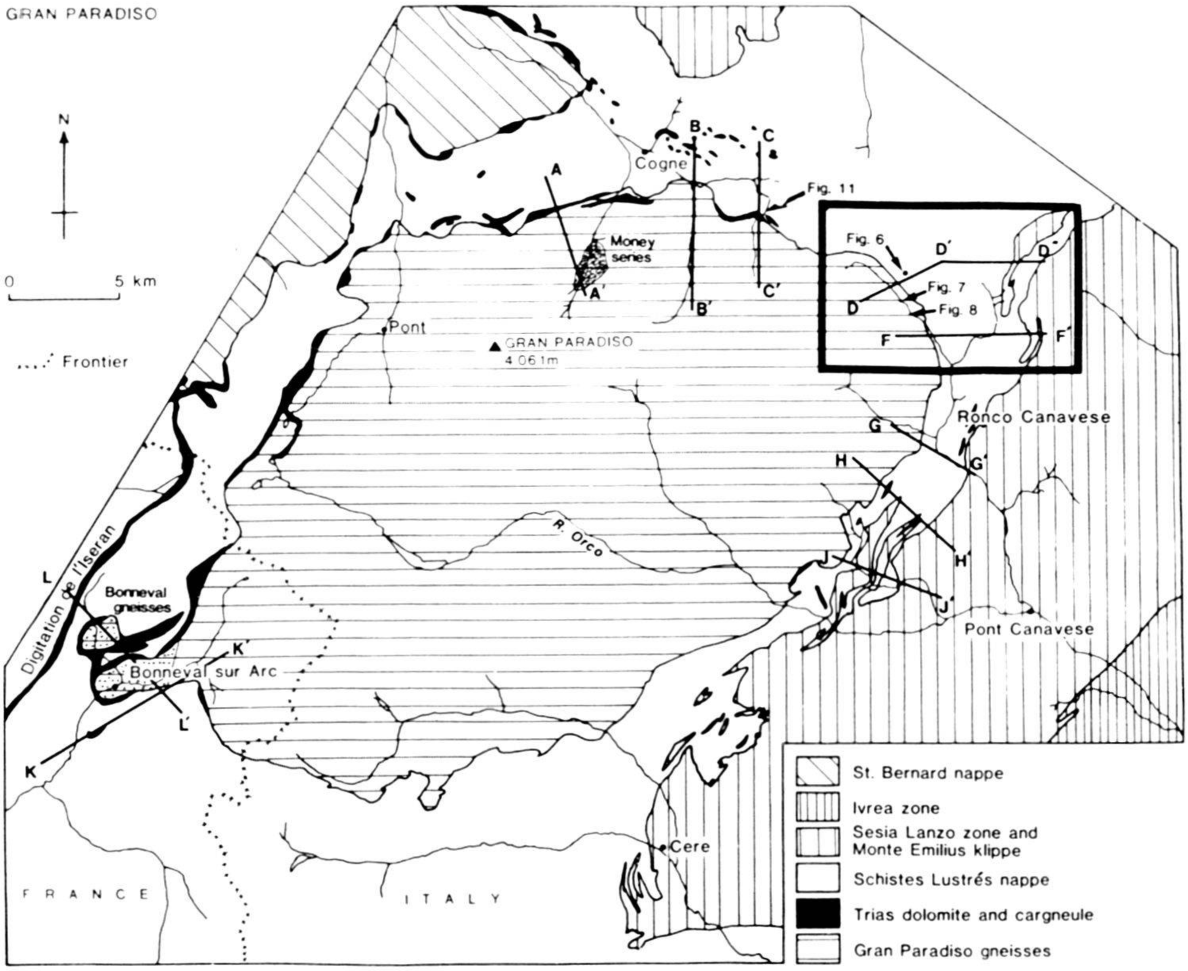

Fig. 2. Simplified geological map of the Gran Paradiso region. Section lines refer to Figure 4 and the location of other figures are given.

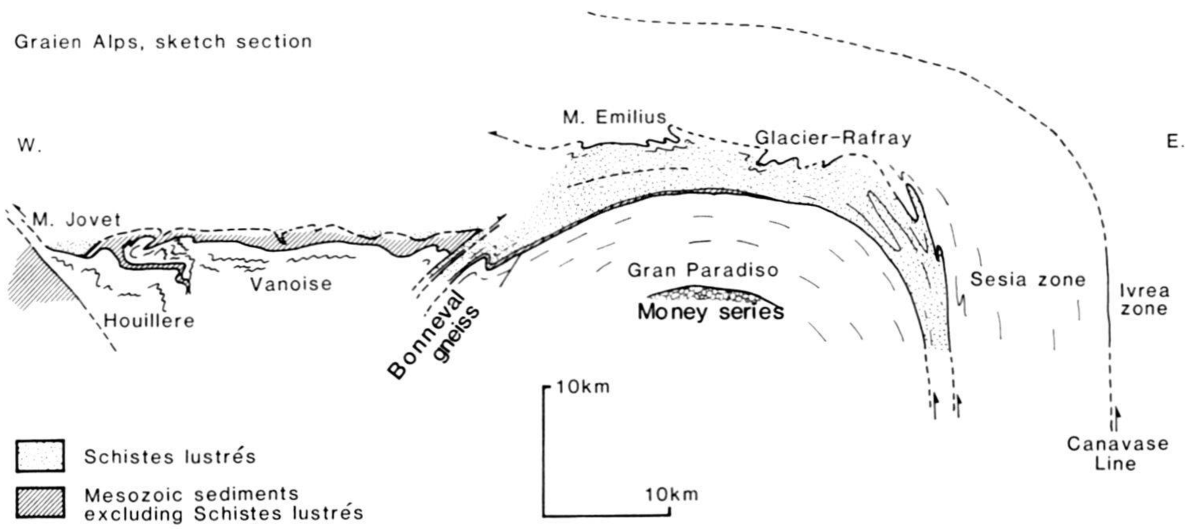

Fig. 3. An E–W geological cross section (scale approximate) through part of the Western Alps with some extrapolation along strike. Drawn after the authors own observations, ELLENBERGER (1958) for the Vanoise, and NERVO & POLINO (1976) for the Monte Emilius and Glacier-Rafray klippen.

of alpine tectonism the porphyritic granite is usually an augen gneiss. Pb dates on zircons obtained from the porphyritic granite range from 301 Ma to 350 Ma (BUCHS et al. 1962, CHESSEX et al. 1964, PANGAUD et al. 1957). These ages probably relate to the age of intrusion of the granite. The gneiss minuti, some of its deformation and Hercynian metamorphism are considered to be older than Upper Carboniferous (COMPAGNONI et al. 1974).

At the structurally lowest position in the Valnontey valley (north-central Gran Paradiso) a quartzite conglomerate (the Money series) crops out beneath the gneiss minuti. The conglomerate is without the high temperature metamorphic minerals and complex fold structures which pre-date the porphyritic granite. COMPAGNONI et al. (1974) regarded the Money conglomerates as younger than the gneiss minuti and probably Upper Carboniferous or Permian in age.

In the western (French) Bonneval-sur-Arc region, outcrop the Bonneval gneisses. These are frequently mylonitic fine-grained banded gneisses derived from Permian volcanics and sediments (BERTRAND 1968). The Bonneval gneisses are separated from the porphyritic granite of the main massif by a fault along which dolomite, cargneule, Schistes lustrés and anhydrite, all in fault gauge, have been reported (BOIS & FABRE 1956).

Triassic rocks

Overlying the basement and particularly well developed in the west are Trias dolomites and local gypsum (POLINO & DAL PIAZ 1978). These are usually allochthonous, above pinched-in synclines of Trias quartzite which are still attached by a highly tectonised unconformity, to the basement. The gypsum and dolomite are frequently altered to the undeformed cargneule, a yellow-brown dedolomite product of recent weathering (WARRAK 1974, VEARNCOMBE 1982).

The Schistes lustrés

The Schistes lustrés are highly deformed calcareous metasedimentary schists with local limestones, sandstones and basic lava horizons (AMSTUTZ 1962, ELTER 1971, DAL PIAZ 1974, CARON 1977). The Schistes lustrés in the region studied are highly deformed, bedding can rarely be detected and although planar and linear fabrics are well developed their interrelationships are often difficult to interpret. It is not possible to construct a stratigraphy for this region. Elsewhere in the Alps stratigraphic and paleontological evidence suggests Jurassic and Cretaceous ages for the Schistes lustrés (RAMSAY 1963, DEBELMAS & LEMOINE 1970, PANTIĆ & GANSSER 1977, PANTIĆ & ISLER 1978). The Schistes lustrés are a thick sequence of sediments deposited on the thinned crust of a passive continental margin (DAL PIAZ 1974, DAL PIAZ et al. 1975).

The basic, ultrabasic and associated rocks of the Schistes lustrés nappe

Included within the Schistes lustrés as sheets and pods are a series of basic and ultrabasic rocks (NICOLAS 1966 and 1967, ELTER 1971, DAL PIAZ 1974). These are highly deformed and have been successively metamorphosed in the eclogite, glaucophane-eclogite and upper greenschist facies. Descriptions of these rocks often emphasise their metamorphic state rather than their original nature. The high-pressure metamorphism is dated at about late Cretaceous and the greenschist metamorphism between 40 and 35 Ma (Bocquet et al. 1974; Hunziker 1974, Chopin & Maluski 1980).

Despite the complicated history and highly deformed state of the rocks it is possible to determine the original nature of at least some of the basic rocks. Pillow lavas are locally recognisable. Layered and homogenous unlayered gabbros with remnant igneous textures and discordant dykes are locally preserved. The serpentinite often contains pseudomorphs after clinopyroxene and some of the ultrabasic rock is thought to have originally been a lherzolite. Dunites, now talc schists and pyroxenites, now mostly actinolite are present. Other actinolite rich rocks appear to relate to rodingitic reaction zones between calcschists and serpentinite (Dal Piaz et al. 1980). A quartz-garnet rock from the col near Lago Tepon, Campiglia–Piamprato region, is interpreted, following Dal Piaz et al. (1979), as a metamorphosed chert. The association is typical of an ophiolite (Anonymous, 1972).

Well preserved ophiolites normally show a sequence of peridotite overlain by a layered series passing up into gabbro, intruded by dykes which fed pillow lavas, in turn overlain by oceanic sediments. Within this region and much of the Western Alps no simple ophiolite sequence is seen. In the Gran Paradiso region the various rocks occur as discrete sheets or pods within the Schistes lustrés and are not obviously genetically related. Nevertheless most of the rock units typical of an ophiolite are present. A sheeted dyke complex has not been recognised being either absent or sufficiently deformed to be unrecognisable. However representatives of all the other units are present.

The Gneiss du Charbonnel

Included within the Schistes lustrés of the western (French) region are the Gneiss du Charbonnel (Michel 1953). These are thin tectonic slices of metasedimentary and granitic gneiss. They are locally cut by quartz veins and intermediate dykes which do not occur in the Schistes lustrés. In the Gran Paradiso region they are restricted to areas of late Alpine (D4) backthrusts (rétrocharriage).

The Sesia Lanzo zone

The Sesia Lanzo zone (Compagnoni et al. 1977) within this region is mostly of fine-grained granitic gneisses with greenschist metamorphic assemblages. These assemblages are developed at the expense of earlier high pressure assemblages. The granites are probably Hercynian in origin and their metamorphic history is similar to that of the ophiolites.

Deformation events

Hercynian deformation

Two deformation events pre-dating the intrusion of the porphyritic granite are recognised in the gneiss minuti of the basement complex (Callegari et al. 1969,

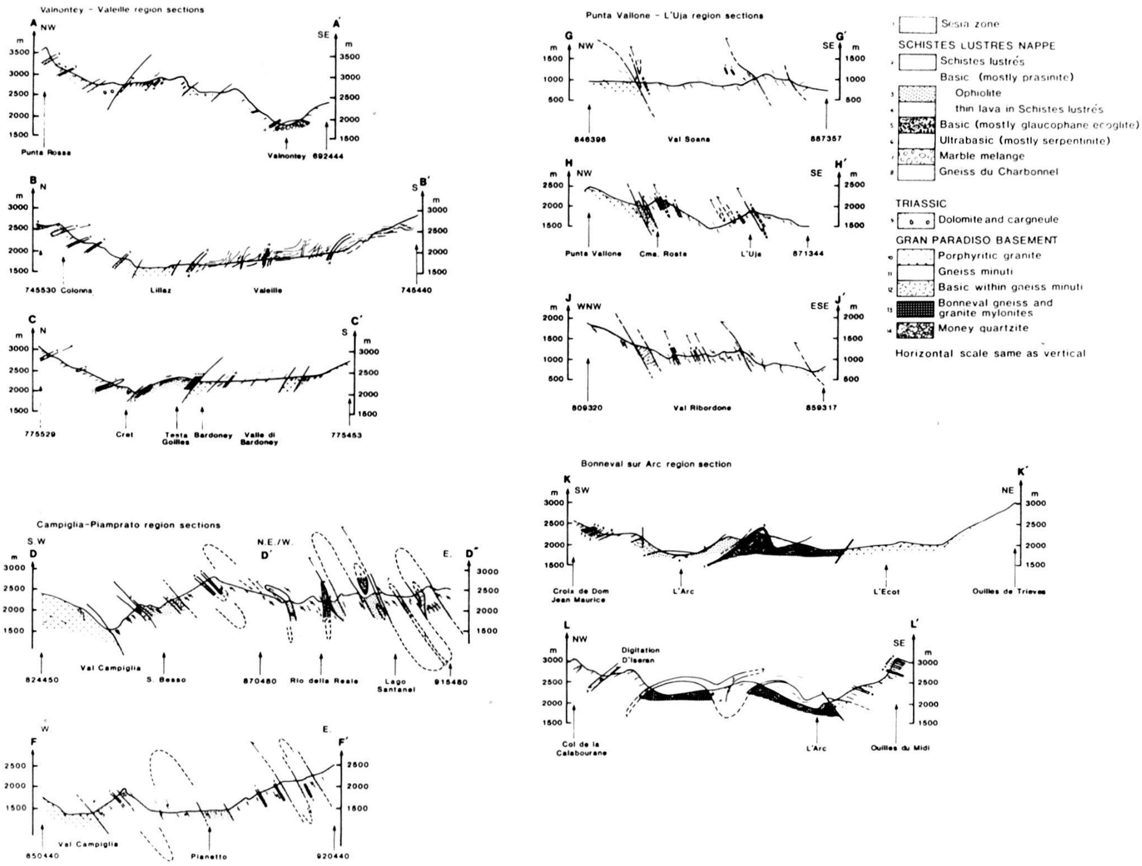

Fig. 4. Geological cross sections across the margin of the Gran Paradiso massif. The location of each section is given in Figure 2.

Campiglia–Piamprato Region

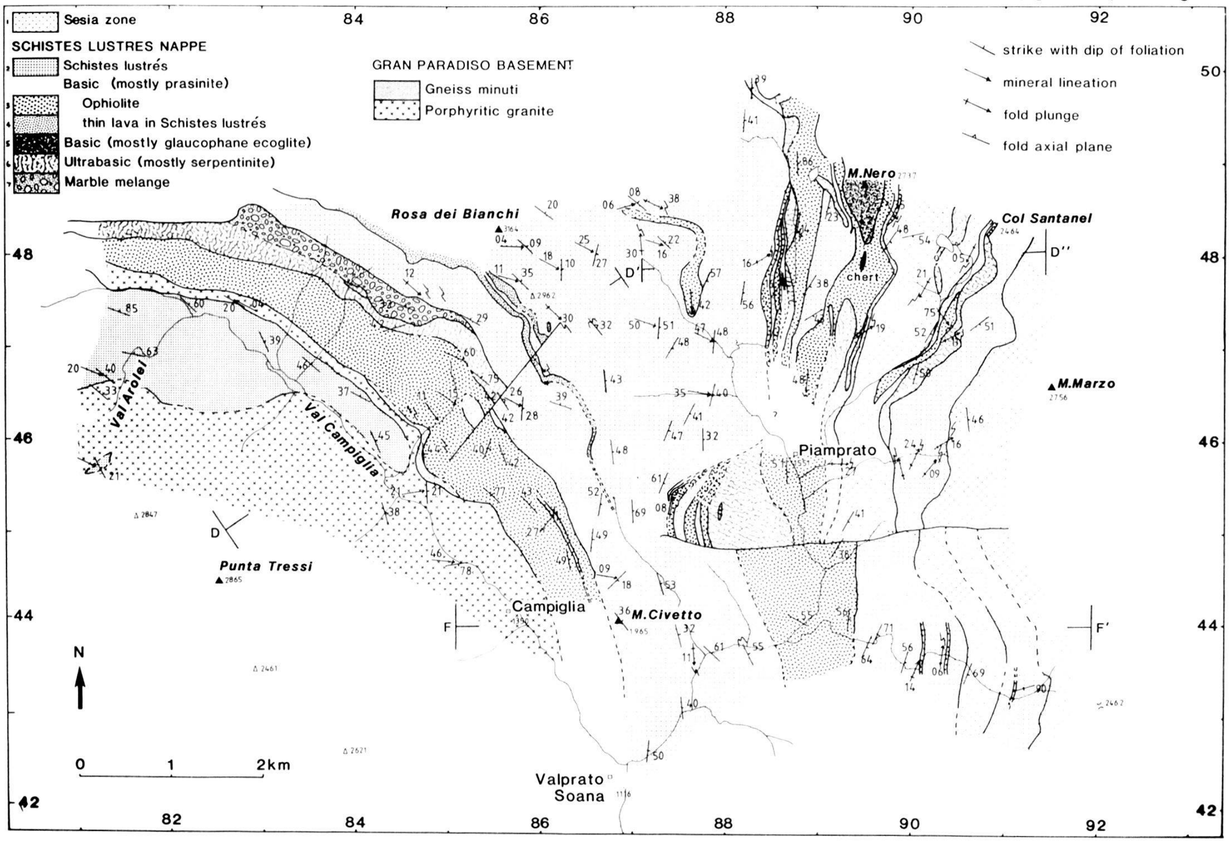

Fig. 5. Geological map of the northeastern Gran Paradiso. Map based on mapping at 1:25,000 by the author. This map is complementary to the sections DD′D″ and FF′ in Figure 4. Grid references are taken from the Valprato Soana, Carta D'Italia, 1:25,000, sheet 42, IV, S.O.

COMPAGNONI & PRATO 1969). The first is the development of a planar fabric and the second folding of this fabric. Superimposed Alpine folds and fabrics are frequently developed and it is not possible to deduce any major Hercynian structure.

The first Alpine deformation (D1)

Within the metagabbros and metalavas in the Schistes lustrés nappe, a series of less deformed pods unaffected by the extensive D2 deformation are recognised. Within these pods, rare eclogites, omphacite-bearing rocks and glaucophane eclogites are preserved in contrast to the prasinite preserved outside the pods (Fig. 6). The contact between the high and low pressure metamorphic assemblages is slightly discordant to the fabric and gradational with the later greenschist metamorphic overprint in more highly deformed gabbro. The glaucophane needles within the pod are usually aligned and constitute a foliation. This foliation is here described as D1. This fabric, like the first fabric described by GOSSO et al. (1979) from the Monta Rosa, pre-dates the nappe pile. No folds, shear zones or other similar structures of D1 age are known, nor has it been possible to determine any major structure. A D1 event has not been recognised in the Schistes lustrés.

Within the basement complex the dominant foliation is D2 in origin, but in less deformed zones, such as those illustrated in Figure 7, occasional weak fabrics with an orientation discordant to that of D2 may be either late Hercynian (after intrusion of the porphyritic granite) or early Alpine. Any correlation of D1 in the basement with D1 in the ophiolites is uncertain.

The second Alpine deformation (D2) in the ophiolites

The D2 event is responsible for the principle fabric seen in most rocks in the region. The D2 fabric is dominantly LS although locally L or S types are developed. In the metalavas and metagabbros it is defined by an alignment of amphibole and chlorite. The fabric is subparallel to the lithological boundaries (local discordances are usually small) and the mineral elongation lineation is E–W or ENE–WSW (Fig. 9).

Figure 6 shows a pod, or tectonic pip, of omphacitic gabbro with an internal D1 fabric, surrounded by prasinite. Similar gabbro pods are well developed through much of the region. The omphacitic rock and prasinite are both metamorphosed gabbro, the former a relic of the earlier metamorphism. The prasinite contains a well developed D2 fabric. The contact of this fabric with the pod is usually a zone of increasing strain, with an acute angle between the pod margins and the fabric.

Assuming that the large scale structure is related to the small scale features then the tectonic pods of omphacitic gabbro in prasinite may be comparable to the pods of ophiolite in Schistes lustrés. Tectonic pods, similar to those described above, with early metamorphic and structural features surrounded by intensely deformed rock with discordant fabrics to the pod margins, have been described from South Harris, Scotland (GRAHAM 1980). Graham interprets these pod structures as less deformed remnants between shear zones which locally coincide with belts of metasediment, and it is reasonable to make the same assumption here. Simple shear was probably an important component of the deformation although in detail was almost certainly more complex.

Gabbro at 851468 nr. S. Besso

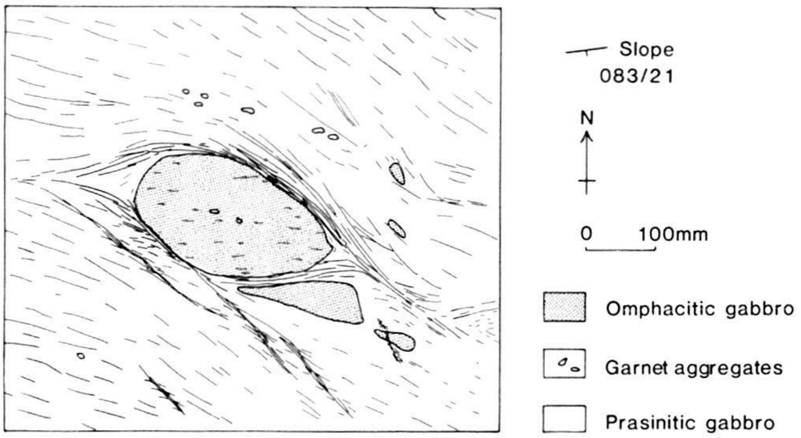

Fig. 6. A pod of omphacitic gabbro surrounded by prasinitic gabbro. Grid reference figures refer to those on Figure 5. The pods margins are gradational and the fabrics discordant suggesting that the prasinitic gabbro is derived by deformation from the omphacitic gabbro.

As these pods are interpreted as relics between shear zones it is in theory possible to use the sense of fabric discordance to the pod to determine the movement direction of the shear zones (RAMSAY & GRAHAM 1970, GRAHAM 1980). In fact the pods usually occur in clusters separated by mutually interfering shear zones. Here the sense of asymmetry is often ambiguous but individual isolated pods in metagabbro in the stream section above Alpetta (near Ronco Canavese) show that the sense of shear is that of the east overriding the west. This fits with the common assumption (e.g. DAL PIAZ et al. 1975) that the ophiolites were emplaced from the east.

Also occurring within the metalavas and metagabbros are folds of igneous layering and earlier fabrics. The folds usually have a strong D2 fabric, are frequently rootless, usually highly non-cylindrical and plunge subparallel to the mineral elongation lineation. Their wavelength has not been seen to exceed 10 m. These are similar to sheath folds described by QUINQUIS et al. (1977) and COBBOLD & QUINQUIS (1980) which develop in zones of very high strain in which simple shear may be a major component.

Correlation of the D2 event is possible by way of its persistent LS fabric which is subparallel to the lithological boundaries and has an elongation lineation trending E–W or ENE–WSW (Fig. 9). This fabric usually post-dates the high pressure metamorphism, is of similar style throughout the region and pre-dates the D3 folding event. Correlation of D2 events laterally and vertically is tentative. Over such a wide area it is unlikely that all the D2 structures are exactly synchronous, nevertheless all numbered structural events described here occurred in a consistent time sequence throughout the region. Any one event may be regarded as a family of similar events. Reconnaissance between the detailed study areas has enabled the D2 foliation to be traced laterally in both the basement and the Schistes lustrés throughout the region.

The second Alpine deformation (D2) in the Schistes lustrés and Trias dolomite

The Schistes lustrés often possess an LS fabric with the elongation lineation running approximatly E–W. Despite difficulties in deducing the age of particular fabrics in the Schistes lustrés, it is suggested that much of this fabric is D2 in origin. Rootless,

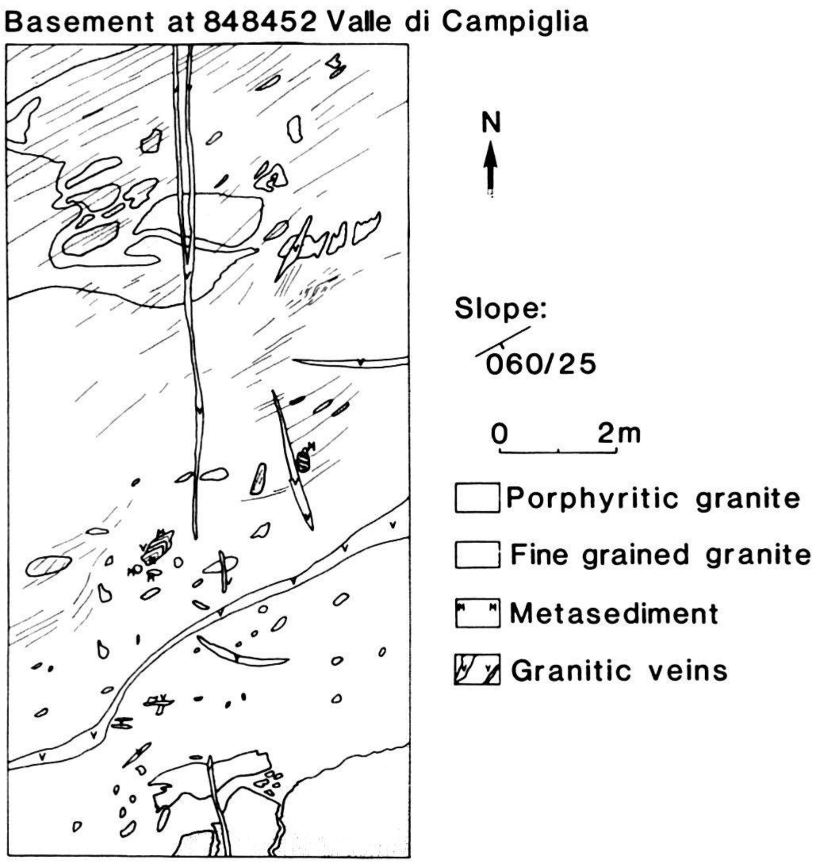

Fig. 7. Detailed geological map of mildly deformed basement from the Campiglia Valley. Grid reference refers to grid of Figure 5. The outcrop shows an intrusive porphyritic granite with xenoliths of fine-grained granite and metasediment, some of which preserve Hercynian fold structures.

non-cylindrical, sheath type folds which deform lithological banding and early calcite veins, are associated with a fabric of probable D2 age. These folds, like the possible sheath type folds in the meta-ophiolites plunge approximately parallel to the elongation lineation. The Triassic dolomites also possess a prominent LS fabric which parallels that in the basement and Schistes lustrés.

The second Alpine deformation (D2) in the Sesia zone

The Sesia zone, especially that region adjacent to the Schistes lustrés, has a weak, usually planar fabric. The fabric is defined by the orientation of greenschist minerals and is folded by D3 structures. The fabric post-dates a high pressure metamorphism. It is probably D2 in origin although it lacks the intense linear component characteristic of this deformation at lower structural levels. D3 folds of the contact of the Sesia zone with Schistes lustrés indicate that the Sesia zone was emplaced prior to D3, contrary to models, such as Caby et al. (1977), which suggest late Alpine emplacement of the Sesia zone.

The second Alpine deformation (D2) in the basement

Locally the basement granite is without a prominent fabric allowing intrusive contacts as well as earlier structural features to be preserved (CALLEGARI et al. 1969 and Fig. 7) but for the most part the granite is a tectonic gneiss. Xenoliths of metasediment are flattened, discordant angles reduced and shear zones developed (Fig. 8). In the gneiss minuti Hercynian folds are refolded and a new fabric developed. Locally in both the gneiss minuti and the porphyritic granite the D2 fabric is an S or L tectonite but is usually LS.

Despite the lack of physically continuous structures the consistency of orientation of both L and S components implies a correlation with D2 in the other units. The Bonneval gneiss has a similar LS fabric.

In the Valeille (section BB', Fig. 4) the D2 foliation is alternately steep and flat, with the downside to the north. The style and southward dipping axial surface of the structures differ from the D3 folds whose axial surfaces dip away from Gran Paradiso. Throughout the structure the mineral elongation lineation remains subhorizontal and E–W trending. Strain although heterogenous does not regularly vary between steep and flat zones. Similar structures occur in Valnontey, although their recognition in

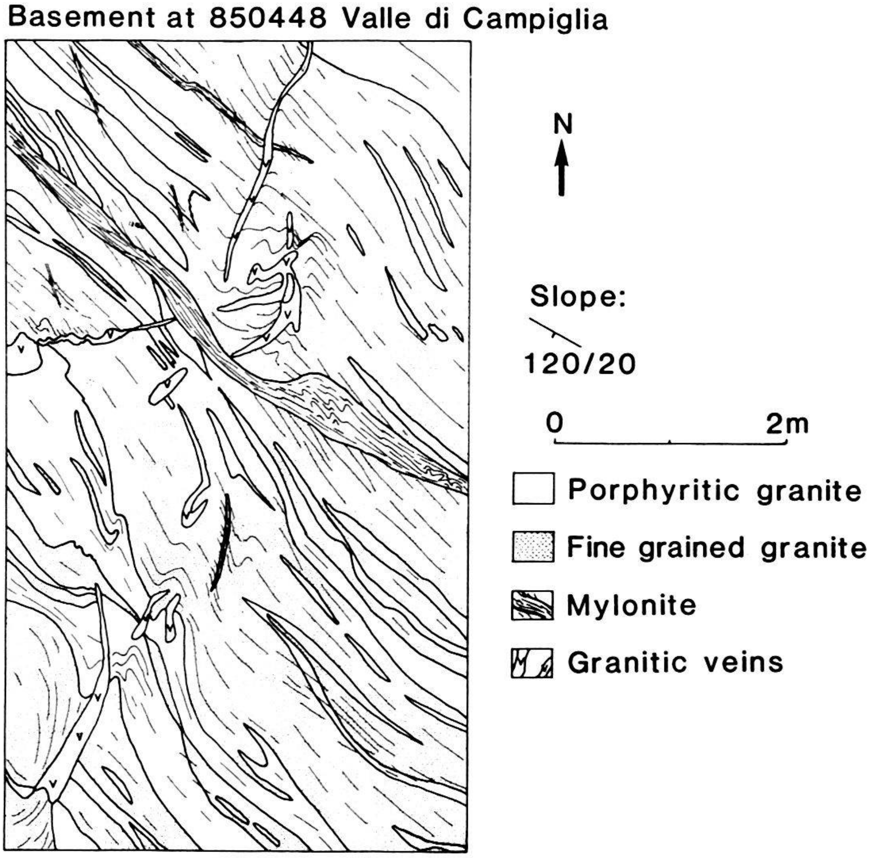

Fig. 8. Detailed geological map of highly deformed basement, including shear zone, in the Campiglia Valley. Grid reference refers to grid of Figure 5. The features shown in this figure represent highly deformed versions of the lithologies illustrated in Figure 7. The xenoliths are flattened subparallel to the main (D2) fabric and the outcrop cut by a shear zone within which are developed mylonites and non-cylindrical folds of the mylonitic fabric.

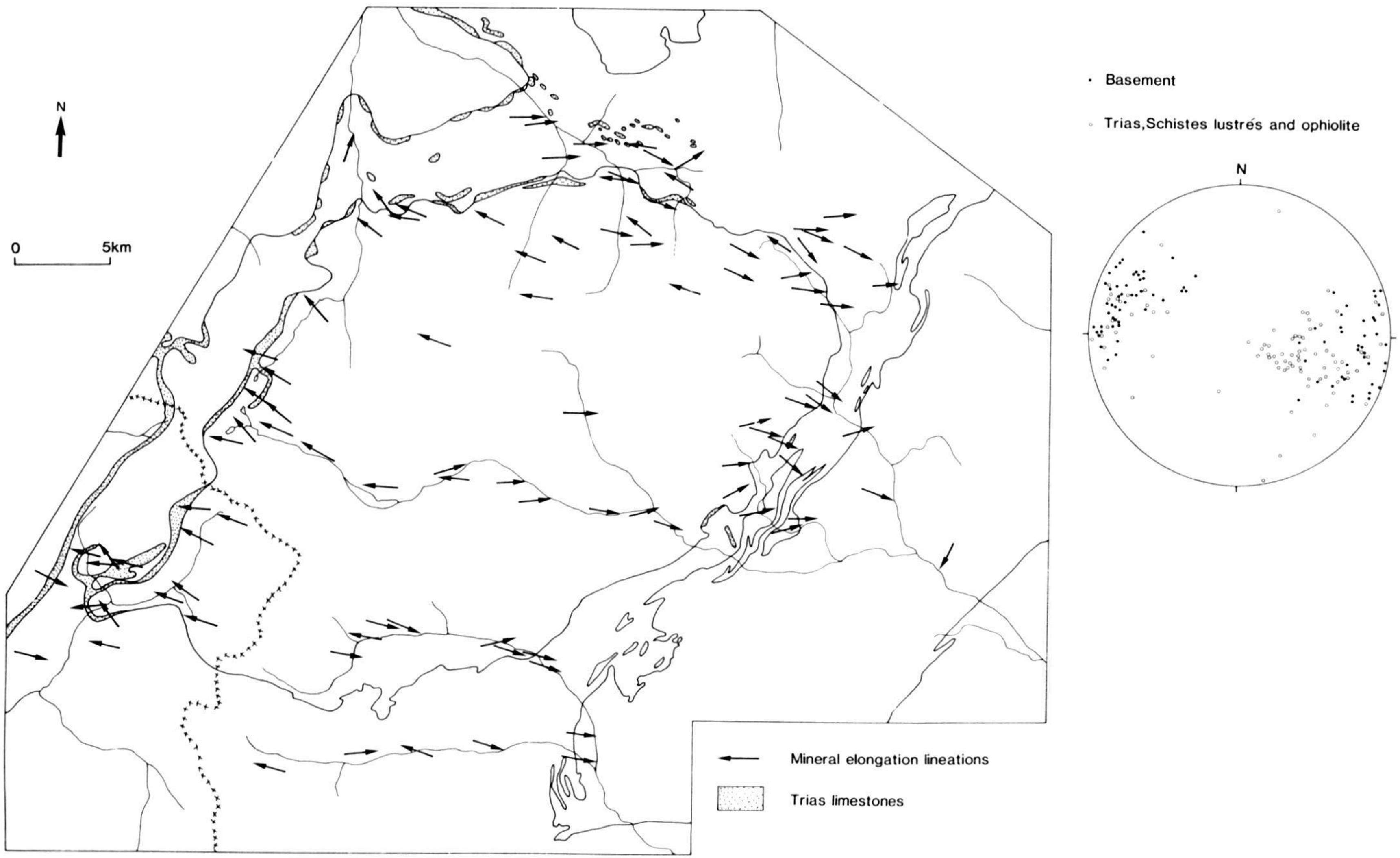

Fig. 9. Map of orientations of D2 mineral elongation lineations and a lower hemisphere, equal angle plot of plunges of D2 mineral elongation lineation for the Gran Paradiso region.

Valle di Bardoney is uncertain. The orientation of the mineral elongation lineation suggests they are probably D2. If so they may represent a corrugated or irregular ductile lateral ramp.

The third Alpine deformation (D3)

The third Alpine deformation is a major phase of folding. The D2 fabric is folded, D2 folds are locally refolded and a new axial planar D3 fabric developed. This fabric is usually defined by greenschist facies minerals. The folds occur on a variety of scales, the small scale folds being parasitic on the larger structures which are open to tight antiforms and synforms with wavelengths between 1 and 5 km and amplitudes up to 10 km.

The major fold structures are asymmetric in the direction of Gran Paradiso independant of locality. Mutual interference structures of D3 folds of different orientations are not seen. D3 fold axial planes can be traced around the dome from Cogne in the north where they are open to the Orco valley in the southeast where they are usually tight or isoclinal.

The fourth Alpine deformation event (D4)

The fourth Alpine event in the region is thrusting, usually associated with and probably synchronous or immediately after D3. These thrusts are relatively minor compared with those developed during D2. In the Campiglia–Piamprato region (Fig. 4) at least two thrusts associated with D3 folds are seen. These are developed on the short limbs of asymmetric D3 folds. The Rio della Reale thrust, along which pods of serpentinite occur, cuts both limbs of an isoclinal synform in its footwall and carries both limbs of an antiform in its hanging wall. Whether they were originally complementary folds is uncertain.

In the Punta Vallone–L'Uja region where Gran Paradiso basement and Sesia zone are spatially closest a succession of repeated slices of Sesia zone occur. These slices have the following properties:

1. Folds in both the Sesia rocks and Schistes lustrés have a consistent asymmetry toward Gran Paradiso (west).
2. The Sesia slices are laterally discontinuous.
3. The Sesia slices are often very thin.
4. The foliation in the Schistes lustrés and Sesia zone is usually concordant, although local discordances occur at some contacts.

Assuming that prior to D3 the Sesia zone overlay the Schistes lustrés these structures can be reasonably interpreted as D3 folds, the short limbs of which became thrust planes during the D4 deformation.

On the eastern side of Gran Paradiso identification of some of the D4 thrust planes is facilitated by the presence of Trias dolomite along them. These thrusts have associated D3 folds asymmetric to the SE or ESE. The thrusts occur in a zone characterised by thrusting towards the hinterland (rétrocharriage or backthrusting). The Digitation de l'Iseran (Ellenberger 1958, Polino & Dal Piaz 1978) is a major D4 thrust marked

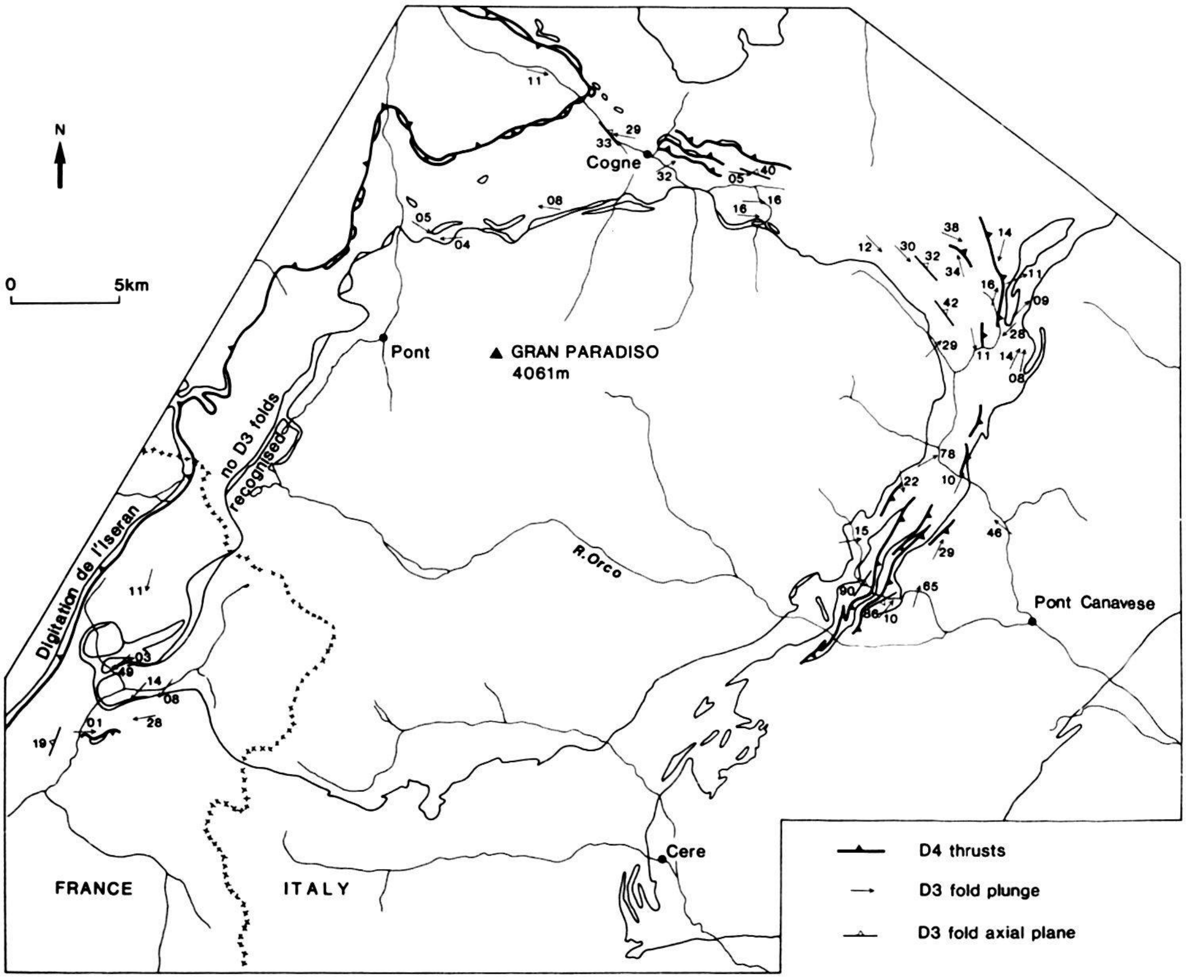

Fig. 10. Map of D3 and D4 structures in the Gran Paradiso region. For details of lithologies see Figure 2. The map shows a parallelism of D3 and D4 structures which, where examined, wrap around the Gran Paradiso dome.

by a belt of Trias dolomite and cargneule carrying Schistes lustrés over Schistes lustrés in an ESE direction. Other D4 thrusts may occur at the base of each slice of Gneiss du Charbonnel which is restricted to this western region.

Rétrocharriage in the Graien Alps affects:

1. Some of the Sesia klippen, especially those which are furthest travelled (see section in Nervo & Polino 1976).
2. The Schistes lustrés and basement of western Gran Paradiso, where D3 folds including folds of Bonneval gneiss are asymmetric towards the east.
3. The Briançonnais zone (Caby 1963, Ellenberger 1958).

Rétrocharriage is not recognised in the Sub-Briançonnais (see geological cross section in Ellenberger 1958), the Alpine external zones or the region to the east of Gran Paradiso.

From the structural section in the otherwise petrological paper of Nervo & Polino (1976) folds with an easterly or southeasterly asymmetry (towards the hinterland) are related to folds of similar style and relationship but with the opposite asymmetry between the Monte Glacier klippe and the Santanel klippe. These folds are shown on the regional section (Fig. 3) and are probably parasitic structures on the limbs of a large scale antiform, the Gran Paradiso dome. The rétrocharriage structures are developed in a deformation zone with the opposite sense of movement to that of both early Alpine structures (D2) and Alpine structures of similar age (D3 and D4) to the west (foreland) and east (hinterland).

The fifth Alpine deformation (D5)

This event is restricted to the local development of crenulation cleavage. Extensional shear bands in Schistes lustrés of the type decribed by PLATT & VISSERS (1980) are also grouped in this event. No correlation has been made between these various features, nor have any major structures been deduced.

The Schistes lustrés nappe

The Schistes lustrés nappe is the structurally highest unit in the Vanoise (west of the Gran Paradiso region), where outliers (see Fig. 3) sit with structural discordance on Briançonnais zone rocks (ELLENBERGER 1958). Although the present form of their tectonic contact may have been affected by late Alpine movement the original emplacement of the Schistes lustrés is thought to be approximately Eocene (DEBELMAS 1976, SALIOT 1978).

In the Gran Paradiso region it is possible to demonstrate that the Schistes lustrés has a tectonic contact at its base. At Bardonney (Fig. 11) small outcrops of Schistes lustrés occur between the Trias dolomite and the basement granite, suggesting a thin slice of Schistes lustrés along a tectonic contact. The local evidence of thrust contacts and the evidence from the Vanoise (ELLENBERGER 1958, DEBELMAS 1976, SALIOT 1978)

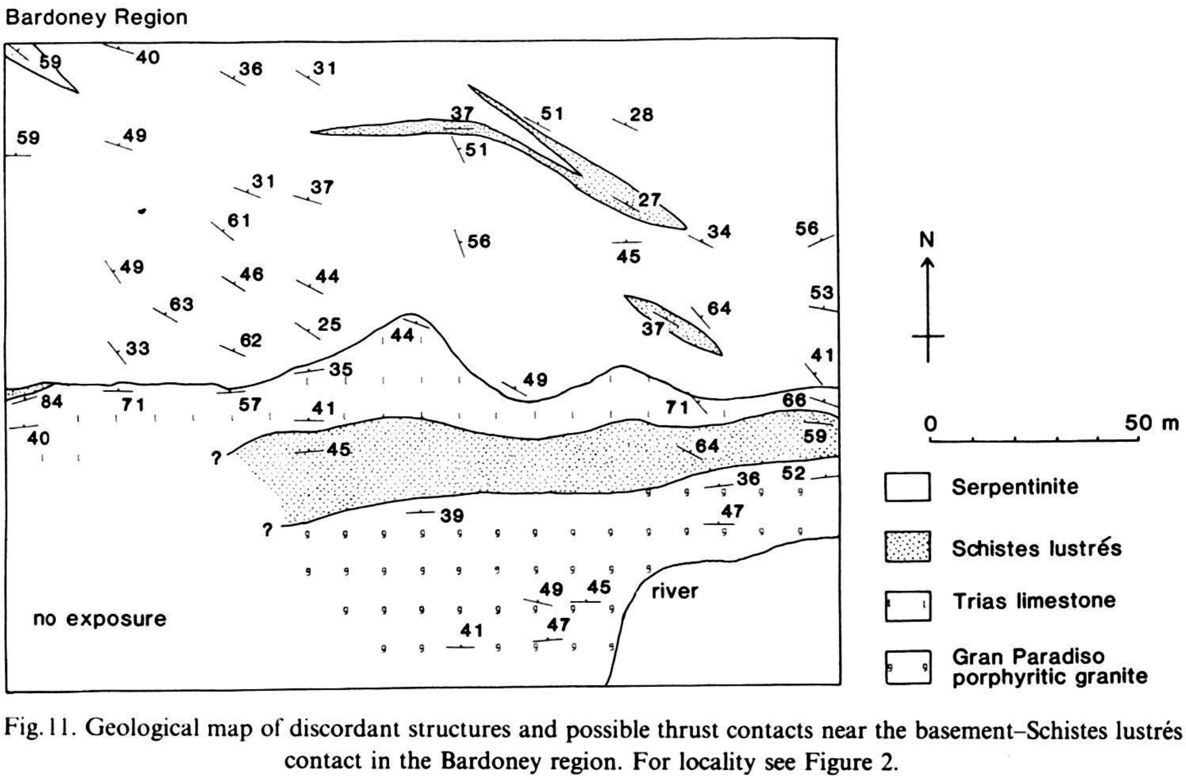

Fig. 11. Geological map of discordant structures and possible thrust contacts near the basement–Schistes lustrés contact in the Bardoney region. For locality see Figure 2.

confirms that the base of the Schistes lustrés nappe is a major tectonic movement plane (DAL PIAZ et al. 1972). The movement plane is a thrust or slide active during D2 and folded by D3 structures (Fig. 3 and 4).

The Schistes lustrés mélange

The Schistes lustrés nappe, in the area discussed in this paper, is thought to compose a mélange (in the sense of HSÜ 1968) because:

1. It contains included discrete pods of (exotic) Gneiss du Charbonnel and ophiolitic material.
2. Pods occur at most structural levels within the nappe.
3. The pods are of variable size and no consistent variation is recognised.
4. It is not possible to predict the rock type of any pod.

The mélange has the following features:

1. No sedimentary features such as injection dykes are seen.
2. All rock types are intensely deformed; suggesting mélange formation either during or before deformation.
3. Contacts are sometimes marked by a structural discordance in deformation structures (Fig. 11), e.g. the final emplacement of some pods post-dated a significant deformation.
4. Mylonites and slivers of Schistes lustrés occur at some (tectonic) contacts.
5. The pods do not have angular contact and are subparallel to the deformation fabric.

The contacts within the mélange are all tectonic suggesting that the mélange is tectonic in origin, but this does not exclude the possibility of some of the original mixing process being of syn-sedimentary origin with subsequent intense deformation modifying the mélange to its present form.

To deduce the nature of the mixing process and determine when the mélange was formed the techniques of transition analysis are used, as were applied to disturbed sequences by NAYLOR & WOODCOCK (1977). Transition analysis allows the quantification of successive rock types in a geological sequence.

The Schistes lustrés mélange is divided into the following rock types between their upper (E) and lower (B) bounding units:

E Sesia Lanzo zone
C Gneiss du Charbonnel
L Prasinitic lava horizons
S Schistes lustrés
P Prasinites: metalavas, dykes and gabbros of the ophiolitic suite
U Ultrabasic and serpentine rocks
T Triassic rocks (including cargneule)
B Gran Paradiso basement

The transition frequency matrix and the succeeding matrices have all been derived and then tested at the 1% significance level as described by NAYLOR & WOODCOCK (1977).

The first matrix (Fig. 12a) has been derived from counting all the transitions in a structurally upwards direction as drawn in the sections (Fig. 4). Fold axial planes (in-

(a) Transition frequency matrix.

	B	T	U	P	S	L	C	E	
B	0	4	2	3	2	0	0	0	11
T	0	0	2	0	8	0	0	0	10
U	0	1	0	3	8	0	2	1	15
P	0	0	5	0	17	0	1	0	23
S	0	6	6	14	0	7	5	14	52
L	0	0	0	0	7	0	0	0	7
C	0	0	2	1	4	0	0	0	7
E	0	0	0	0	10	0	0	0	10
	0	11	17	21	56	7	8	15	135

(b) Transition probability matrix.

	B	T	U	P	S	L	C	E
B	0	0.36	0.18	0.27	0.18	0	0	0
T	0	0	0.2	0	0.8	0	0	0
U	0	0.07	0	0.2	0.53	0	0.13	0.07
P	0	0	0.22	0	0.74	0	0.04	0
S	0	0.12	0.12	0.27	0	0.13	0.1	0.27
L	0	0	0	0	1	0	0	0
C	0	0	0.29	0.14	0.57	0	0	0
E	0	0	0	0	1	0	0	0

x^2 0.01; 42 = 66.21 x^2_0 = 124.95

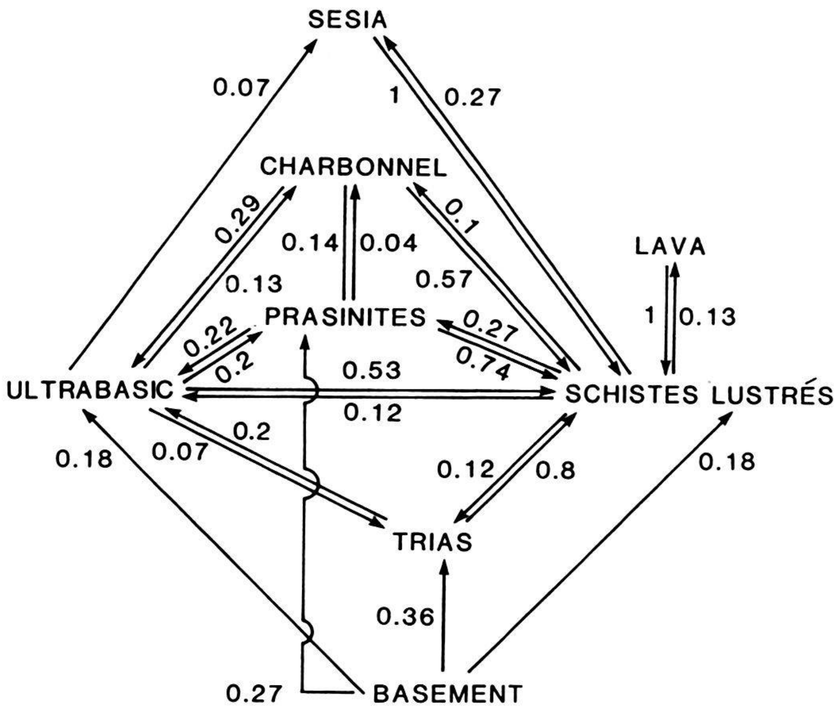

Fig. 12. Transition frequency matrix, transition probability matrix and transition probability diagram for all transitions, the Gran Paradiso region. For discussion see text.

(a) Transition frequency matrix.

	B	T	U	P	S	L	C	E	
B	0	4	2	3	2	0	0	0	11
T	0	0	2	0	8	0	0	0	10
U	0	1	0	2	5	0	2	1	11
P	0	0	3	0	11	0	1	0	15
S	0	5	3	9	0	1	5	5	28
L	0	0	0	0	1	0	0	0	1
C	0	0	2	1	4	0	0	0	7
E	0	0	0	0	0	0	0	0	0
	0	10	12	15	31	1	8	6	83

(b) Transition probability matrix.

	B	T	U	P	S	L	C	E
B	0	0.36	0.18	0.27	0.18	0	0	0
T	0	0	0.2	0	0.8	0	0	0
U	0	0.09	0	0.18	0.45	0	0.18	0.19
P	0	0	0.2	0	0.73	0	0.07	0
S	0	0.17	0.11	0.32	0	0.04	0.18	0.18
L	0	0	0	0	1	0	0	0
C	0	0	0.28	0.14	0.57	0	0	0
E	0	0	0	0	0	0	0	0

X^2 0.01;42 = 66.21 X^2_0 = 61.22

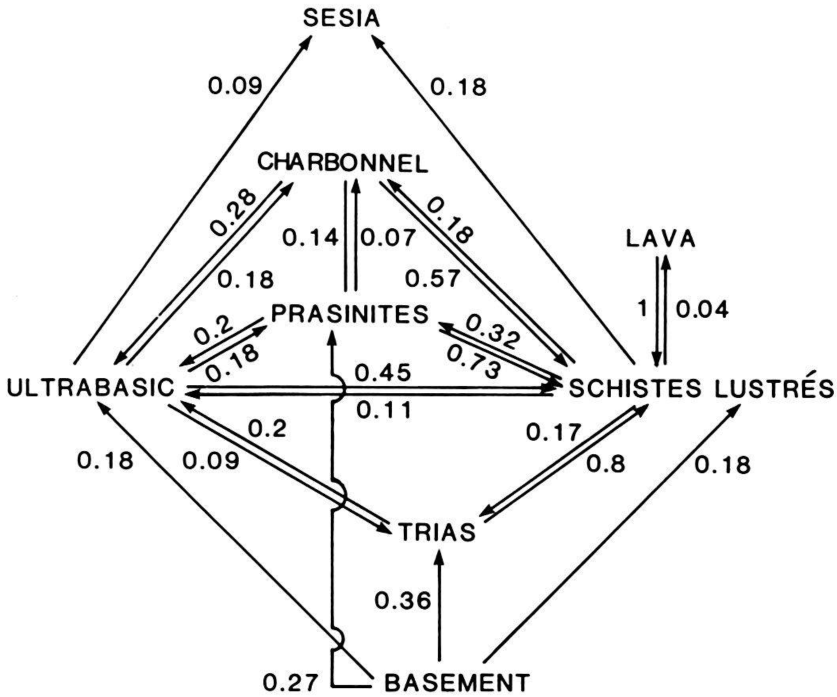

Fig. 13. Transition frequency matrix, transition probability matrix and transition probability diagram for pre-D3 transitions, the Gran Paradiso region. For discussion see text.

cluding D3 planes have been crossed, hence some transitions may have been counted twice. This matrix is referred to as the "all transitions frequency matrix". Its transition probability diagram (Fig. 12c) shows the likelihood of any transition occurring.

In order to compare the effects of pre-D3 and syn- or post-D3 deformation a "pre-D3 transitions frequency matrix" (Fig. 13a), a derived transition probability matrix (Fig. 13b) and a probability diagram (Fig. 13c) have been constructed by measuring only those transitions on the section thought to pre-date D3. No known D3 fold axial planes have been crossed and transitions resulting from known D4 thrusts have not been counted. A number of transitions caused by D3 or D4 structures may have escaped this net, for instance, the Gneiss du Charbonnel transitions which may be D4 thrusts have been counted.

One of the most interesting results from this study is in the comparison of the statistical validity of the transition matrices. The "all transitions probability matrix" has an X_0^2 value well above the tabulated $X_{42}^2;0.01$ value and it is therefore possible to reject the null hypothesis that the transitions from one rock type to another are independant of rock type. In other words there is a non-random pattern in the transitions. The "pre-D3 transitions probability matrix" has a X_0^2 value very similar to that of the tabulated $X_{42}^2;0.01$ value. This implies that the null hypothesis is not rejected and that the transitions may be independant of rock type and approaching random. In other words, the "pre-D3 mélange" is thoroughly mixed yet the "post all deformations mélange" has some order within it. Examination of the probability diagrams (Fig. 12c and 13c) shows only one significant difference, that of the Sesia to Schistes lustrés transition. The Sesia zone is the upper bounding unit and the transition Sesia to Schistes lustrés only occurs as a result of interleaving by D3 folds and D4 thrusts. The mélange forming event is therefore regarded as complex, if not chaotic and pre-dating D3, probably D2. The D3 and D4 events were ordered.

If the mélange is of tectonic origin it may have formed in either the Dl or D2 events. Alternatively the chaotic nature may suggest a syn-sedimentary component to the origin of the mélange which was subsequently intensely deformed by the D2 event. Figure 12c shows that the transitions are most frequently to Schistes lustrés. This is because the Schistes lustrés forms the matrix of the mélange.

The deformation and emplacement of the Schistes lustrés

The deformation necessary to emplace the ophiolites into the Schistes lustrés, the Schistes lustrés over the basement and the Sesia zone over the Schistes lustrés all involved major horizontal translation. These translations were not restricted to unique discrete movement planes but were ductile, involving vast volumes of rock. Assuming that the large scale structures relate to the small scale it is suggested that the pods of ophiolite, now in Schistes lustrés are structurally similar to the pods of omphacitic gabbro in prasinite and originated from an ophiolite sequence interrupted by extensive shear zones. For the most part the shear zones travelled parallel to the lithological features but also cut up section, emplacing ophiolite blocks into Schistes lustrés. The ophiolite pods now appear randomly distributed in a highly deformed mélange of probable tectonic origin. Although at any one time displacement may have occurred on a single surface, displacement was frequently transferred to other surfaces and extensive ductile deformation occurred in both the footwalls and hangingwalls, when the flat-lying LS tectonites were developed. The Schistes lustrés probably acted as a ductile horizon in the emplacement of the Sesia nappe. The Schistes lustrés, with their more competent ophiolitic rocks, formed a large scale movement zone in which shear zones anastomose, cutting up and down section within the zone. I suggest that this deformation, where sufficiently intense, resulted in the formation of tectonic mélange.

SHACKLETON et al. (1982) suggested that the recumbent cleavage in the Variscan of southwestern England implies a major recumbent shear zone (RAMSAY & GRAHAM 1970). A similar interpretation is suggested here for the flat-lying D2 fabric which formed in a vast shear or movement zone during major ductile translation. Alternatively gravity spreading phenomena associated with nappe emplacement may be invoked, but the extensional structures seen in the region are shear bands similar to those described by PLATT & VISSERS (1980) which are late (D5) and deform the already existent foliation.

The large scale geometry

In this section the overall geometry of the region will be analysed and discussed in terms of the thrust geometry based on studies from the Canadian Rockies (BALLY et al. 1966, DAHLSTROM 1970) and successfully applied elsewhere by JACOBEEN & KANES (1974) and HARRIS & MILICI (1977) for the southern Appalachians, ELLIOT & JOHNSON (1980) for the Moine Thrust, northwestern Scotland and BEACH (1981) for part of the external French Alps. The "rules" of thrust faulting (DAHLSTROM 1970, ELLIOT & JOHNSON 1980) state that thrusts do not cut down section but emplace older over younger rocks. Exceptions to these rules are made for previously deformed sequences and sequences with marked lateral variations including unconformities. Their applicability to the ductilely deformed internal zones of orogenic belts is speculative.

The absence of order in the ophiolitic rocks of the Schistes lustrés nappe, suggesting a probable tectonic mélange, is not compatible with the geometrical requirements of thrust emplacing older over younger in an ordered sequence. But in the following discussion the Schistes lustrés nappe (prior to D3) is regarded as a single unit where the applicability of the thrust rules to even larger scale structure is examined.

The Money complex, in the lowest structural position in Valnontey, is not part of the Hercynian gneiss minuti but a younger conglomerate of Upper Carboniferous of Permian age (COMPAGNONI et al. 1974). There is no evidence for a large scale fold closure in the basement which is not thought to be a fold nappe. The basement is probably a thrust sheet of older rock overlying younger, obeying the thrust rules.

The Bonneval gneisses are probably derived from Permian volcanics and sediments (BERTRAND 1968). They are now separated from the porphyritic granite gneiss of the Gran Paradiso massif by a fault along which occurs a fault mélange of dolomite, Schistes lustrés, anhydrite and cargneule (BOIS & FABRE 1956). If the effects of the Gran Paradiso doming are removed then the tectonic contact of the Bonneval gneiss with basement is subhorizontal, subparallel to the D2 fabric and does not pass upwards into the main Schistes lustrés body (Fig. 4, section KK'). In the Alpine external zones Carboniferous and Permian sequences including volcanics are unconformable on the crystalline basement and a similar relationship probably existed on the internal zone massifs. The Bonneval gneisses are now allochthonous, a thrust sheet which apparently cut upsection, into the Triassic limestones and evaporites which acted as a thin décollement horizon.

The Triassic dolomite is for the most part in its original stratigraphic position (excluding the Digitation de l'Iseran and other backthrust Trias dolomite) although it has a tectonic contact with underlying basement. This tectonic movement was along flats ("substitution de couverture").

The Schistes lustrés with ophiolites although younger than the basement was not necessarily topographically higher than the basement when deposited. The Schistes lustrés by virtue of lateral variation may have been at a lower topographic level and is now above the basement. The Sesia zone is likewise another lateral variation, but also of older rocks, now thrust over the younger Schistes lustrés. The Schistes lustrés nappe as a whole therefore obeys the spirit if not the letter of thrust tectonic rules.

Ductile deformation as well as brittle movement on discrete surfaces has played a major role in the geological evolution of this region. Problems exist in applying the thrust model to such terrains but tectonic movement along flats (substitution de couverture) does not as such break the rules of thrusting. Although deformation within each of the units (such as the Schistes lustrés nappe) is ductile and not necessarily conforming with thrust rules the large scale Alpine geometry may be regarded as that of an imbricate stack; the Money complex, Gran Paradiso basement, Bonneval gneiss, the Schistes lustrés with ophiolites and the Sesia zone each an imbricate or horse. The alternate steep and flat belts of Valeille (Fig. 4, section BB′) probably represent ductile corrugations during D2 deformation and may represent a northern lateral ramp.

The D3 and D4 rétrocharriage structures are geometrically similar to backward directed thrusts described by JACOBEEN & KANES (1974) from thrust sheets in the Appalachians. Jacobeen and Kanes suggested that these faults form by underthrusting and proposed the name "chisel faults". SHACKLETON et al. (1982) on southwestern England described large scale shear zone structures with opposed movement sense to that on the main décollement and suggested a similar underthrusting, with analogous backward directed, structures, formed synchronously with progressive forward movement on the main décollement when shortening cannot be accommodated by either movement on the thrusts leading edge of footwall collapse. This mechanism of under- or chisel-thrusting may have been responsible for the rétrocharriage zone and explains its location between foreland directed structures of similar age.

Conclusions

1. Ductile translation in which simple shear was probably a major component, characterised the major D2 deformation in which flat-lying LS tectonites, possible sheath folds and tectonic pods in the Schistes lustrés nappe were developed.
2. The ophiolitic rocks in the Schistes lustrés nappe are probably part of a tectonic mélange to which the "rules" of thrusting are inapplicable.
3. The Sesia zone was emplaced prior to D3, probably during D2 with the other principle nappe units. Tectonic models for the Alps involving late Alpine emplacement of the Sesia zone are thought incorrect.

4. With allowance for some primary lateral variations the large scale geometry is compatible with the "rules of thrusting".
5. The late Alpine (D3 and D4) eastward directed rétrocharriage is probable coeval with other westward directed structures and may represent under- or chisel-thrusting above the principle westward directed décollement.

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