Pergamon

Journal of Structural Geology, Vol. 18, No. 7, pp. 909 to 923, 1996

0191–8141/96 $15.00 + 0.00

PII: S0191–8141(96)00005–3

Can crustal extension be distinguished from thrusting in the internal parts of mountain belts? A case history of the Entrelor shear zone, Western Alps

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(*Received* 27 *March* 1995; *accepted in revised form* 15 *January* 1996)

Abstract—Criteria for the distinguishing between structures that accommodate crustal-scale extension or crustal-scale shortening may be applied to late orogenic shear zones developed in the internal parts of mountain belts. This is done for a large shear zone that has been mapped in the NW Italian Alps, around the internal basement massif of Gran Paradiso. The structure involved is termed the Entrelor shear zone. It carries greenschist facies European continental rocks (the Briançonnais–Grand St. Bernard unit) onto an old subduction complex of oceanic (Piemonte) and continental (Gran Paradiso) material that preserve eclogitic assemblages. Evidence for the map-scale continuity of the Entrelor shear zone is presented together with kinematic data to show how folds, stretching lineations and shear criteria relate to a regional episode of ESE-directed shearing. However, folds initiated systematically oblique to the shear direction, on a NE–SW axis. With continued shearing, the fold population remains skewed E–W of the population of stretching lineations. The shear zone may be traced for 70 km around the dome of the Gran Paradiso massif and displays a minimum displacement of 20 km. This Entrelor structure shows variable offset of metamorphic grade. However, for much of its length, greenschist facies rocks are carried in its hanging-wall onto eclogites in the footwall. Tracing these units regionally shows that this apparent extensional offset of metamorphic facies is the result of restacking of an originally 'inverted' metamorphic sequence (i.e. HP Piemonte on LP Briançonnais). This contractional behavior is consistent with the profile of the shear zone relative to the modern surface. The Entrelor shear climbs up from generally buried in the west to generally eroded in the east. The conclusion that the Entrelor shear zone is probably a thrust rather than an extensional structure relies on linking outcrop data into a semi-regional context. False interpretations may result from examining only small parts of the structure. However, although these map and structural criteria are consistent with contractional kinematics associated with crustal shortening, confirmation is required through linked petrological and isotopic studies. The Entrelor shear zone is thus a good illustration of the need for caution in inferring the contractional or extensional nature of structures developed late in the history of the internal parts of mountain belts. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The kinematics of shear zones within the internal parts of mountain belts must be understood if dynamic models of orogenic wedges are to be tested against field data. These models have been used to make various predictions as to the nature of shear zones on a crustal scale — particularly the importance of structures that extend the crust (e.g. Platt 1986). Although the proposal of extensional structures may be appealing, particularly as an explanation for exhumation of ultra-high-pressure metamorphic rocks (Wheeler 1991), their identification may not be simple (Wheeler & Butler 1994). The problem is essentially one of establishing a syn-kinematic reference datum (Fig. 1). In regions of geology less complex than the internal parts of mountain ranges, strata may have been near horizontal at the time of faulting. Thus faults that extend the lithosphere also extend strata (e.g. Wernicke & Burchfiel 1982). In the outer part of mountain belts, where thrust sheets may form simple stacks, faults that extend the tectonic pile may be inferred to also extend the lithosphere (e.g. Bertini *et al.* 1991). These criteria are ambiguous once applied to areas where the initial structure was complex (Fig. 1) and consequently, alternative markers for datum surfaces have been used. Of these it is the concept of metamorphic separation that has been applied most widely. The presence of high grade rocks immediately beneath much lower grade, with the omission of a palaeobarometric section, is widely used as an indicator of extensional tectonics (e.g. Dewey 1988, Selverstone 1988). But in polyphase parts of orogens even this criteria is ambiguous unless the orientation of metamorphic facies terrains can be demonstrated for the period immediately preceding the inferred extensional episode (Wheeler & Butler 1994).

While the theoretical models which predict extensional tectonics within orogenic interiors have been developed, there have been few field studies to test these predictions that go beyond using a single criterion. In this contribution we examine a single, continuous shear zone, initially through its kinematics and map-scale continuity and then in its behaviour with respect to tectonic and metamorphic 'layering'. The purpose is to show that invoking some geometric criteria may lead to erroneous interpretations of intra-orogenic extension. Then we outline some tests of the kinematics inferred for the shear zone through thermo–chronometric methods. Our chosen example comes from the Western Alps.

Intraorgenic extension has been described from many mountain ranges. However, in recent years much attention has focussed on the Alpine chain of Europe,

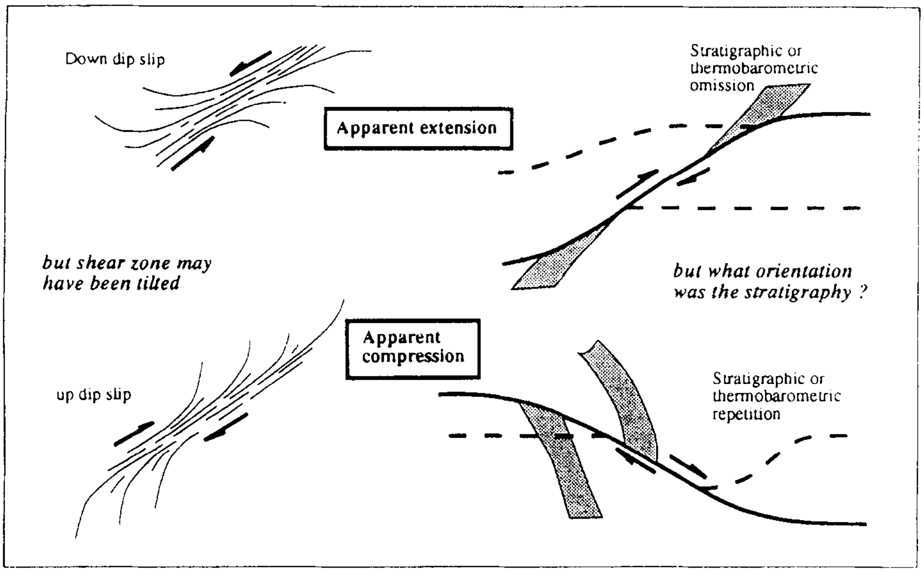

Fig. 1. Problems of relating outcrop-scale structures to regional tectonics. The present orientation of faults and shear zones may not correspond to that at the time of displacement. Pre-offset markers (either physical features or inferred surfaces) need not have been parallel to datum. The recognition of the original orientation of shear zones and the markers that they offset is fundamental to evaluating the roles of horizontal shortening and horizontal extension in orogenic belts.

at least in part because of the discovery of ultra-high-pressure metamorphic assemblages (e.g. Chopin 1987, Reinecke 1991) and the inference that the exhumation of coherent high pressure terrains could only have been accomplished by extensional tectonics (e.g. Platt 1993). Field evidence for extensional tectonics is, however, rather limited. In the Central Alps, Mancktelow (1990) inferred that the Simplon fault was an extensional structure on the basis of its kinematics in its modern orientation: the hanging-wall has moved down with respect to the footwall. Additionally, fault rocks are cooler in the hanging-wall than the footwall, suggesting omission of thermal structure during displacement. The Brenner Line in the Eastern Alps shows similar relationships (Selverstone 1988). This shear zone omits structural section and cuts out thermal structure, as indicated by old ^{40}Ar–^{39}Ar cooling ages from biotites in the hanging-wall juxtaposed against young ones in the footwall.

Both of these examples are 'post nappe' — that is they disrupt the previous tectonic statigraphy of thrust sheets. They are distinct from structures that extend the primary stratigraphy which can date from Mesozoic times and are related to the formation of sedimentary basins adjacent to the evolving Tethys ocean (e.g. Lemoine *et al.* 1986). In this contribution, the nature of a post-nappe shear zone in the Western Alps is discussed.

TECTONIC SETTING

Western Alps

The large-scale structure of the Western Alps has been established for almost a century. Argand (1916) outlined the overall framework with further details and terminology developed later (reviewed and modified by Debelmas & Kerckhove 1980, Trumpy 1980, Escher *et al.* 1993 and many others). The modern form of the Western Alps largely developed in Oligo–Miocene times, although the orogen includes rocks that experienced earlier deformation and metamorphism related to the subduction that preceeded the collision between Europe and Adria (Italy). The orogen has a bulk westward vergence so that the Franco–Swiss side is referred to as the foreland and the Italian side the hinterland (Fig. 2). The external zones of the foreland contain a major thrust belt with material exclusively derived from foreland-type successions. The internal zones contain metamorphosed material derived from varied palaeogeographic settings. In essence, the orogen represents a sandwich with the upper plate material (termed the Austroalpine complex) consisting, in the Western Alps, largely of polymetamorphic basement. These units include high pressure rocks of the Sesia zone (Fig. 2) and some outlying klippen. Structurally underlying the Austroalpine complex is the Piemonte zone — a collection of oceanic metasediments, metabasic lavas and gabbros together with serpentinites. These ophiolitic units can also contain relics of HP metamorphic mineral assemblages which, rarely, imply peak pressures in excess of 30 kbar (e.g. Reinecke 1991). It is the presence of HP rocks in the western Alps that has led to a widespread search for extensional structures, some of which may relate to their exhumation. In general, however, much of this terrain has experienced an extensive greenschist facies overprint.

The Piemonte units are generally interpreted as representing the exhumed samples of subducted oceanic lithosphere that originally formed the floor of the Ligurian Tethys (e.g. Lemoine *et al.* 1987). Mesozoic

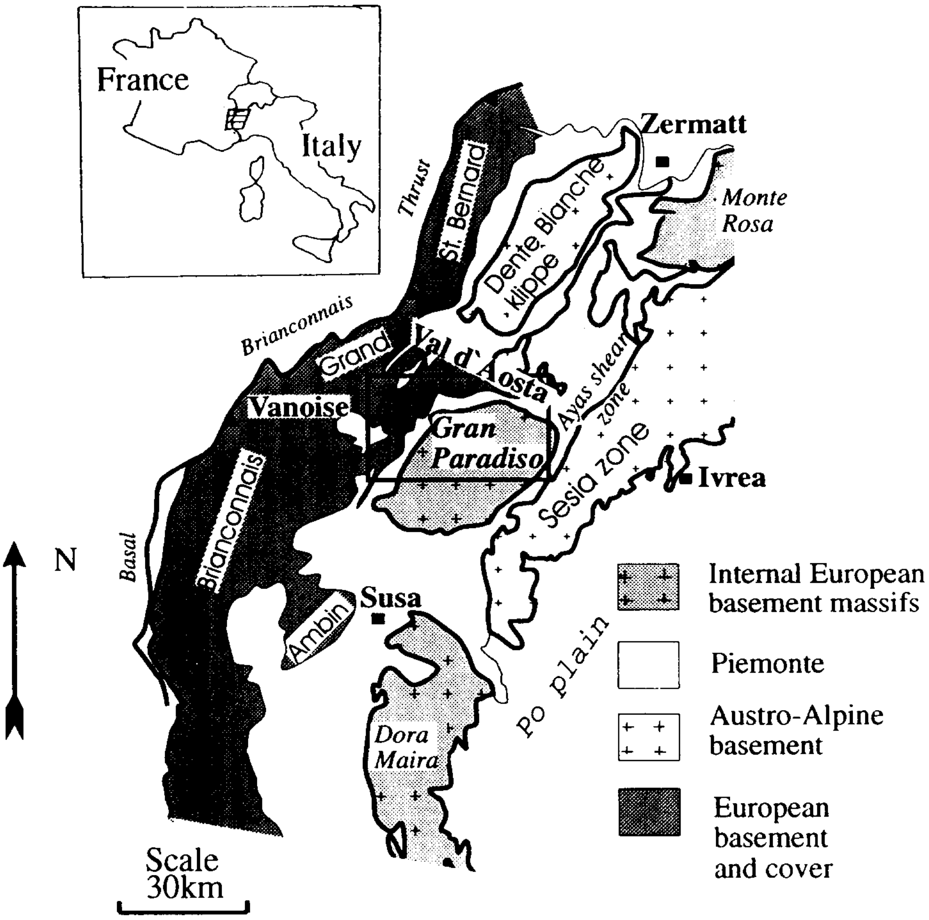

Fig. 2. Simplified tectonic sketch map for the western Alps, illustrating the distribution of major tectonic 'zones'.

sedimentary basins were developed on the western and northern flank of this ocean upon the palaeo-European continental margin. These sediments and their basement underpinnings now occupy structural positions beneath the Piemonte material in two broad sites. The most internal (eastern) of these are the internal basement massifs (Monte Rosa, Gran Paradiso and Dora Maira, Fig. 2). These massifs all show evidence for HP metamorphism, with the Dora Maira massif having experienced peak pressures up to ca 35 kbar (Chopin 1987). Collectively, they represent the cores to composite antiforms, rimmed by Piemonte material.

Structurally underlying the Piemonte zone and forming the western flank to its outcrop is the Briançonnais zone and its northern continuation, Grand-Saint-Bernard nappe (Fig. 2). The subsurface continuity of this zone beneath the Piemonte with the internal basement massifs is unknown. The Briançonnais zone represents the restacked continental margin on the west of Tethys (Lemoine *et al.* 1986). In general it experienced a metamorphic episode that peaked at greenschist facies although, in the basement, rare and weakly developed blueschist-facies assemblages with peak pressures of ca 12 kbar (e.g. Bocquet *et al.* 1974, Platt & Lister 1985, Hunziker *et al.* 1989) have been reported. Thus, in general, rocks with relict HP assemblages (i.e. Piemonte) structurally overlie those without any trace of HP metamorphism (i.e. much of the Briançonnais). Locally, however, this apparent metamorphic separation may be only due to the Briançonnais units having inappropriate compositions to record diagnostic HP metamorphic mineral assemblages.

Late, hinterland-directed structures

In addition to the major nappes of the Piemonte and Austroalpine complexes, the Briançonnais–Grand-Saint-Bernard units show evidence for early, westward-directed thrusts and shears (e.g. Platt *et al.* 1989, Escher *et al.* 1993). However, these nappes are redeformed by important hinterland-directed structures (e.g. Caby 1964, Debelmas 1986, Caby *et al.* 1978). In places these structures juxtapose European passive margin sediments of the Briançonnais zone above oceanic material of the Piemonte 'nappe'. Along the eastern (internal) margin of the Briançonnais, these shear zones dip west and associated folds face east (Caby 1964, Caby 1968, Elter 1972). Consequently these structures are traditionally inferred to have been associated with back thrusting (rètrocharriage, e.g. Caby *et al.* 1978). They form a long belt through the Franco–Italian Alps. Platt *et al.* (1989), following Caby (1964, 1968), reported the regional continuity of eastward facing structures around the eastern margin and within the

Briançonnais zone of the French Alps. These structures are particularly well-developed in the Vanoise (Fig. 2) from where Platt *et al.* (1989) report top-to-the-east shear criteria. Again they interpret these structures as being backthrusts and further show them to restack earlier, westward-directed thrust sheets.

Hinterland-directed thrusting has been inferred for the internal Alps in the Monte Rosa area (Fig. 2, Ellis *et al.* 1989, Ring & Merle 1992). However, there are other structures present that show evidence for extensional displacements. North of the Aosta valley (Fig. 2), a major belt of E–SE directed shearing is extensional with respect to tectonic layering, drawing down the high-level Sesia zone units into the underlying Piemonte 'nappe' (Wheeler & Butler 1993). Additionally, a major metamorphic and structure break has been identified within the Piemonte units that places the greenschist facies metasediments, with peak pressures of ca 10 kbar (Ernst & Dal Piaz 1978) of the Combin zone onto Zermatt Saas zone eclogites with local peak pressures of 30 kbar (Reinecke 1991). On the basis of these results Merle & Ballèvre (1992) inferred that the basal Combin contact was once an extensional fault that moved top-to-ESE (cf. Wheeler & Butler 1994). Thus the ground south of the Aosta valley and north of the Vanoise (Fig. 2) is critical in that it separates hinterland-directed structures that have been interpreted as net extensional (in the north) from structures that have been interpreted as net contractional (in the south).

Around the Gran Paradiso massif

The critical ground to examine the continuity of hinterland-directed structures lies around the western and northern flanks of the Gran Paradiso massif (Fig. 3). The massif is one of three so-called 'internal basement massifs' (Fig. 2) generally regarded as being of European origin and having experienced HP metamorphism (Hunziker *et al.* 1989). Peak metamorphic conditions for the massif are estimated at 8–15 kbar, 400–500°C (Dal Piaz & Lombardo 1986) with $^{40}Ar–^{39}Ar$ cooling ages on phengites at about 80–110 Ma (Chopin & Maluski 1980). The basement, with a local rim of apparently autochthonous metasedimentary cover of presumed Triassic age (e.g. Bertrand 1968), is mantled by Piemonte material. Both the deepest and highest structural levels in the study area contain HP rocks. The highest levels are represented by klippen of the Austroalpine sheet. The largest of these, at Mt Emelius (Fig. 2), contains eclogite-facies asssemblages that imply peak

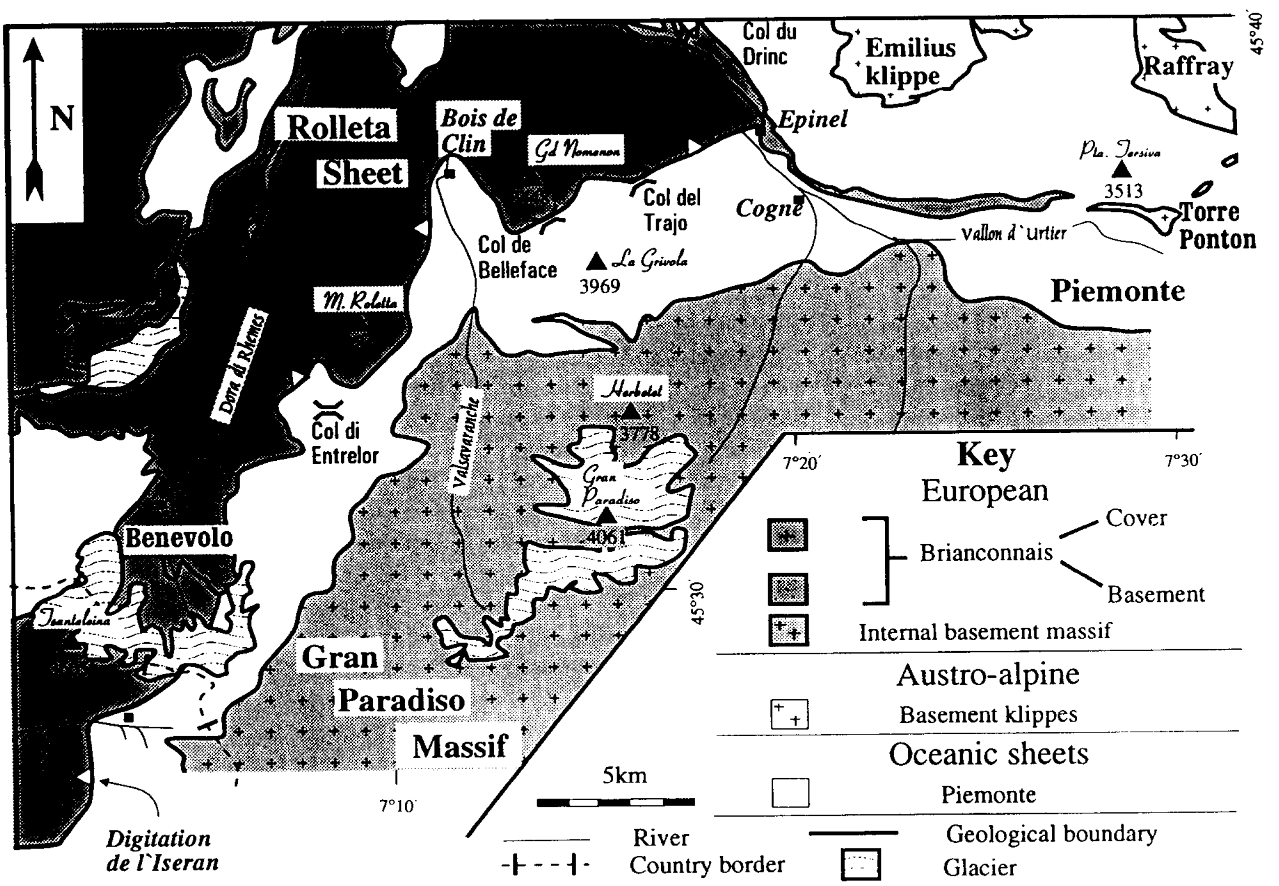

Fig. 3. Simplified tectonic sketch map of the internal western Alps showing the location of the NW margin of the Gran Paradiso massif (boxed area in Fig. 2). The elevations of the mountain peaks are in metres. The Entrelor shear zone forms the contact on the SE flank of the Rolleta sheet and is marked with open triangles along its hanging-wall.

conditions of 440–480°C and pressures in excess of 10 kbar (Dal Piaz *et al.* 1983). Similar conditions are recorded in the immediately adjacent and underlying ophiolite of the Piemonte sheet, leading Dal Piaz *et al.* (1983) to infer that both the ophiolite and klippe shared the same tectonometamorphic history during the Alpine orogeny. A similar conclusion was reached for the smaller Torre Ponton klippe (Ballèvre *et al.* 1986) where eclogitic continental basement overlies eclogitic ophiolite (Fig. 3).

The simple, three-piece sandwich (Austroalpine–Piemonte–Gran Paradiso) structure that pertains to the NE of the Gran Paradiso massif is more complicated on the NW and W flanks. Structurally overlying the Piemonte material, along the NW quadrant of the Gran Paradiso massif lies Briançonnais basement (Elter 1972). The tectonic contact between Piemonte and Briançonnais units has been inferred to be hinterland-directed (Caby 1968) although no kinematic data have been published to substantiate this interpretation. Our petrological work has found that the shear zone contains a penetrative, syn-kinematic greenschist-facies mineral assemblage (albite, chlorite, actinolite, epidote, white mica, ± quartz) indicative of syn-kinematic conditions of ca 300°–350°C at pressures of less than 6 kbar.

The thermochronology of the Gran Paradiso massif and its surroundings has been studied by Hurford *et al.* (1989). Fission track data from zircon and apatite indicate that the massif cooled through 225 ± 25°C by about 30 Ma and through about 100–120°C by 24–19 Ma. However, the fission track lengths from apatite, relating to the lower temperature dates, indicate rapid cooling to well below the annealing temperature. These data suggest that the massif was exhumed rapidly to within a few km of the surface by about 20 Ma. There are no published fission track data from the areas immediately to the west of the Gran Paradiso massif.

Regional maps for the Gran Paradiso area have been produced by Bertrand (1968), Amstutz (1962) and Elter (1987), although there is little structural data provided by these authors. The basic lithological distributions are followed here (Fig. 3). The importance of major tectonic breaks around the Gran Paradiso massif was emphasised by Vearncombe (1985) who interpreted these structures purely in terms of ductile thrusting. However, he did not present any shear criteria to support the claims for backthrusting. Ballèvre *et al.* (1986) suggest major top-to-ESE shearing structurally above the NE quadrant of the Gran Paradiso massif which juxtaposed Piemonte and Austroalpine material, at the Torre Ponton klippe (Fig. 3). The ground west of the Gran Paradiso massif includes a major E–SE closing antiform (Caby 1968, Elter 1972) that folds Briançonnais basement and cover into the structurally overlying Piemonte units. The fold is carried on a major tectonic break termed here the Entrelor shear zone. The immediate aim of this contribution is to discuss the continuity of this structure and to trace its relationships to other tectonic levels. This work is aided by the presence of the Gran Paradiso massif. The massif is generally inferred to be a late domal structure (e.g. Bertrand 1968, Vearncombe 1985) that consequently provides a profile across regional strike along its northern margin as a result of the dome's plunge.

STRUCTURE OF THE ENTRELOR SHEAR ZONE

Map-scale continuity

The type area for the Entrelor shear zone lies ca 150m north of the Colle di Entrelor (Fig. 3). It carries chlorite–albite–epidote–actinolite schists, inferred to be a metavolcanic sequence of Permo–Carboniferous age (Caby 1968), onto calcschists of the Piemonte 'nappe'. This relationship is inferred to represent a tectonic contact that places European basement onto oceanic material. The contact is decorated by discontinuous lenses of cargneule and marbles — locally the products of precipitation from fluids that migrated along the shear zone. Such features are very common along tectonic contacts in the western Alps (Warrak 1974).

The relationship of Briançonnais basement overlying Piemonte metasediments has been mapped north and east across Valsavaranche as far as the Colle di Trajo (Fig. 3). In these more eastern localities, the hanging-wall to the shear zone consists of barely metamorphosed hornblende granodiorite which contain undeformed autoliths of more basic igneous composition. The granodiorite becomes intensely deformed within a few metres of the tectonic contact with the Piemonte material in the footwall. These basement units are continuous and are referred to here as the Roletta sheet.

There are indications that the basement of the Roletta sheet represents the core of a SSE-facing anticline. On the western side of Valsavaranche (Bois de Clin area, Fig. 3) the basement is structurally underlain by a well-developed metasedimentary sequence of dolomites, marbles and calcareous pelites that appear to represent a cover succession. These units are infolded with the basement. At the Col de Belleface (Fig. 3) there are similar relationships. Minor folds here and at the Col de Trajo verge to the NNW, consistent with an antiformal closure within the basement. The hinge line for the basement-cover contact is inferred to occur at Epinel (Fig. 3). Further east the shear zone carries a carbonate-rich metasedimentary sequence that is interpreted as the partially detached cover to the Roletta basement sheet. On the northern flank of the Vallon di Cogne-Vallon d'Urtier (Fig. 2), the calcareous metasediments are infolded with calcschists, serpentinites and metabasic material of the Piemonte nappe. The calcareous metasediments appear to lie in the cores of S-closing, gently inclined antiforms. These folds can be mapped eastward to the Torre Ponton district (Fig. 3). Here a major synform, opening towards the SSE, is cored by continental basement of the Austroalpine nappe, termed the Torre Ponton klippe (Ballèvre *et al.* 1986, Fig. 4). The klippe contains relics of eclogite facies metamorphism

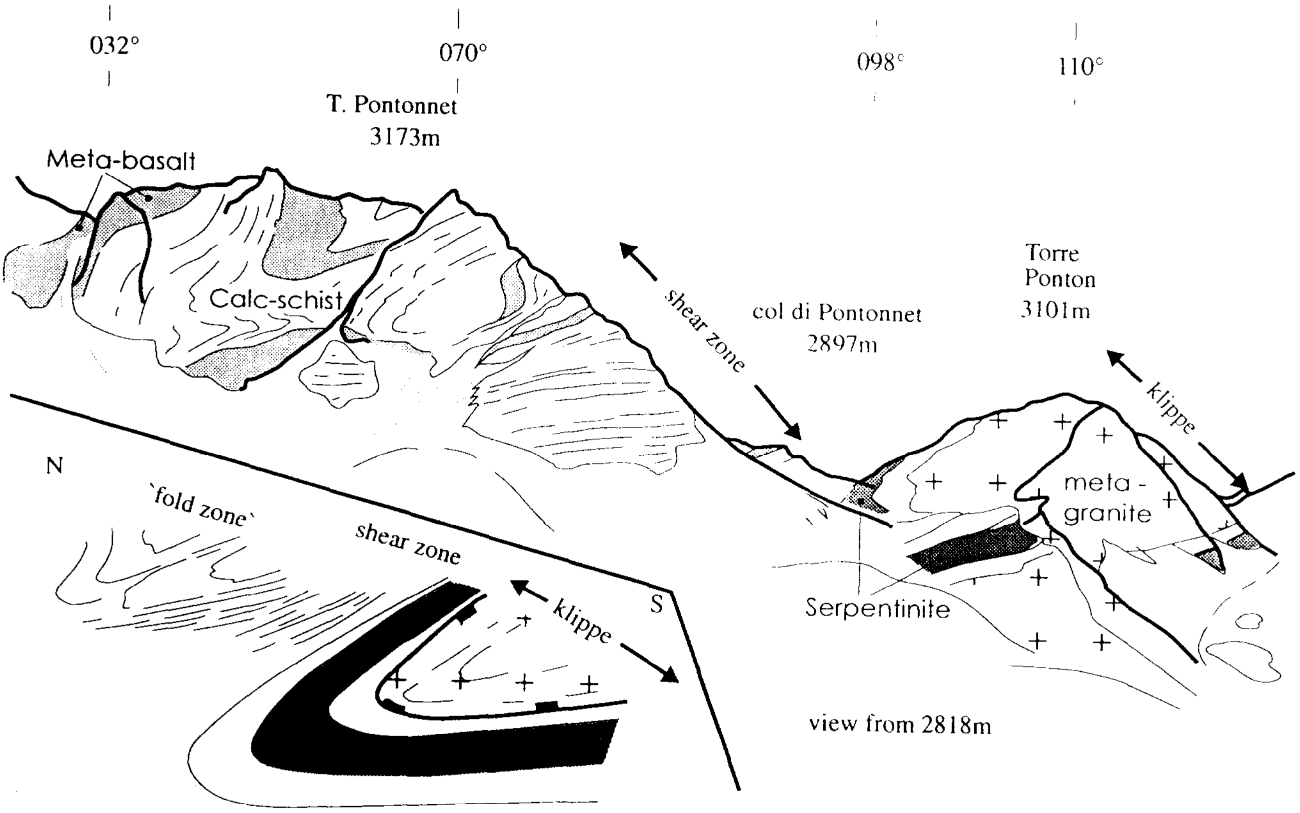

Fig. 4. Field sketch and interpretation (inset) of structural relationships of Piemonte serpentinites (dark stipple), metabasites (light stipple) and calcschists (unornamented) with Austroalpine units (crosses) at the Torre Ponton klippe (Fig. 3).

and it is thought to have represented part of a once continuous thrust sheet with the nearby Emelius klippe (Fig. 3, Ballèvre *et al.* 1986).

The basal contact of the Torre Ponton klippe appears to have operated at HP metamorphic conditions (Ballèvre *et al.* 1986). The underlying calcschists contain syn-kinematic garnets and top-to-W shear bands. The calcschists are interleaved with omphacitic metagabbros and serpentinites. Consequently, the tectonic contact between Austroalpine and Piemont material at Torre Ponton is not associated with a significant metamorphic break. The klippe is infolded with the eclogitic Piemonte material (Fig. 4) although there is a substantial greenschist facies (albite, actinolite in metabasites) overprint that is particularly strong in the upper limb of the synform. Figure 4 shows a package of folds of Piemonte calcschists and metabasites that separates the Torre Ponton from the Emelius klippe. Thus we conclude that the lower contact of the klippe is an early, relatively HP structure that predates the folds at greenschist facies that overlie the klippe. These folds are interpreted to represent the continuation of the Entrelor shear zone.

South of the Colle di Entrelor, basement of the Roletta sheet can be mapped as far as the Dora di Rhemes to the south of the Benevelo hut (Fig. 3). In the southern area the cover metasediments of the Roletta sheet crop out as a succession of quartzites and dolomites of inferred Triassic age. The well-differentiated cover succession permits the structure of the Roletta sheet to be mapped. A stack of curvilinear folds which deform early nappe contacts can be distinguished. However, the facing and kinematics of these structures is unclear. They are considered to be carried by the Entrelor shear zone since lithologies typical of the footwall Piemonte nappe are not incorporated in the fold stack.

Further south again, across the glaciated French–Italian border (Fig. 3), the Entrelor shear zone may be correlated with the so-called 'Digitation de l'Isèran' (Ellenberger 1958). This tectonic contact places carbonates of the Briançonnais zone onto Piemonte material. The Digitation is one of a number of west-dipping shears within the eastern Briançonnais of the Vanoise (e.g. Platt *et al.* 1989) but further discussion of these structures lies outside the scope of this paper.

The structure of the Entrelor shear zone can be summarised as follows. The shear zone has been traced for a map length of 70 km from the northern Vanoise to the Torre Ponton klippe (Figs. 2 and 3). It rims the Gran Paradiso massif and its allochthonous cover of Piemonte 'nappe' on the west and north. At its most eastern outcrop, at Torre Ponton, the shear zone cuts to high structural levels, carrying Piemonte units into the Austroalpine basement. Along the western part of its trace the shear zone dips beneath ground and, in this section, carries European basement and cover rocks onto the Piemonte 'nappe'. Although the shear zone appears to be folded around the Gran Paradiso massif it has a regional westward dip both with respect to the modern orogenic surface and tectonic layering.

Kinematics

Knowing the orientation of the major structure, the kinematics as defined by small-scale structures can be discussed. Throughout the shear zone there are abundant mineral lineations, defined by actinolite needles, mica aggregrates, calcite fibres and, rarely, quartzitic pressure shadows around albite porphyroblasts. The mineralogy is consistent with the lineations forming during the greenschist facies shearing episode. The consistency of their orientation within outcrops supports the inference that these mineral lineations represent the axis of tectonic transport for the shear zone. The lineation data are presented grouped into subareas around the map trace of the shear zone in Fig. 5. The subarea approach permits recognition of any systematic variation in the tectonic transport axis along the length of the shear zone. However, no such variation exists and consequently it is concluded that the shear zone operated consistently on a WNW–ESE axis.

Shear sense has been determined using shear bands, deformed veins, asymmetric boudinage and S–C fabrics from numerous sites around the map trace of the Entrelor shear zone. The best data come from calcschists and other Piemonte lithologies in the footwall. One example is presented from Valsavaranche (Fig. 6) where a band of eclogitic metagabbro has experienced asymmetric boudinage with an inferred top-to-ESE shear sense. The S–C fabrics associated with the boudinage give the same shear sense. The shear criteria operated at the same metamorphic grade as the mineral lineations so they are probably linked by the same kinematics. As such, they can be readily distinguished from the HP deformation fabrics.

Although the minor structures along much of the trace of the Entrelor shear zone imply a simple kinematic history, in the eastern part of its outcrop the shear criteria are not consistent (cf. Ballèvre *et al.* 1986). Individual shear bands occur with geometries that imply top-to-W while others show top-to-E shear senses. However, the calcschists and carbonates within which they occur have no diagnostic mineral assemblages (phengite, carbonate) which might allow some shear bands to be related to, say, the HP deformation episode. The area of 'anomalous' shear criteria coincides with that part of the Entrelor structure that is dominated by folds. The folds have hinge line orientations subparallel to the mineral lineation. One explanation for the two sets of shear senses is that these structures initially

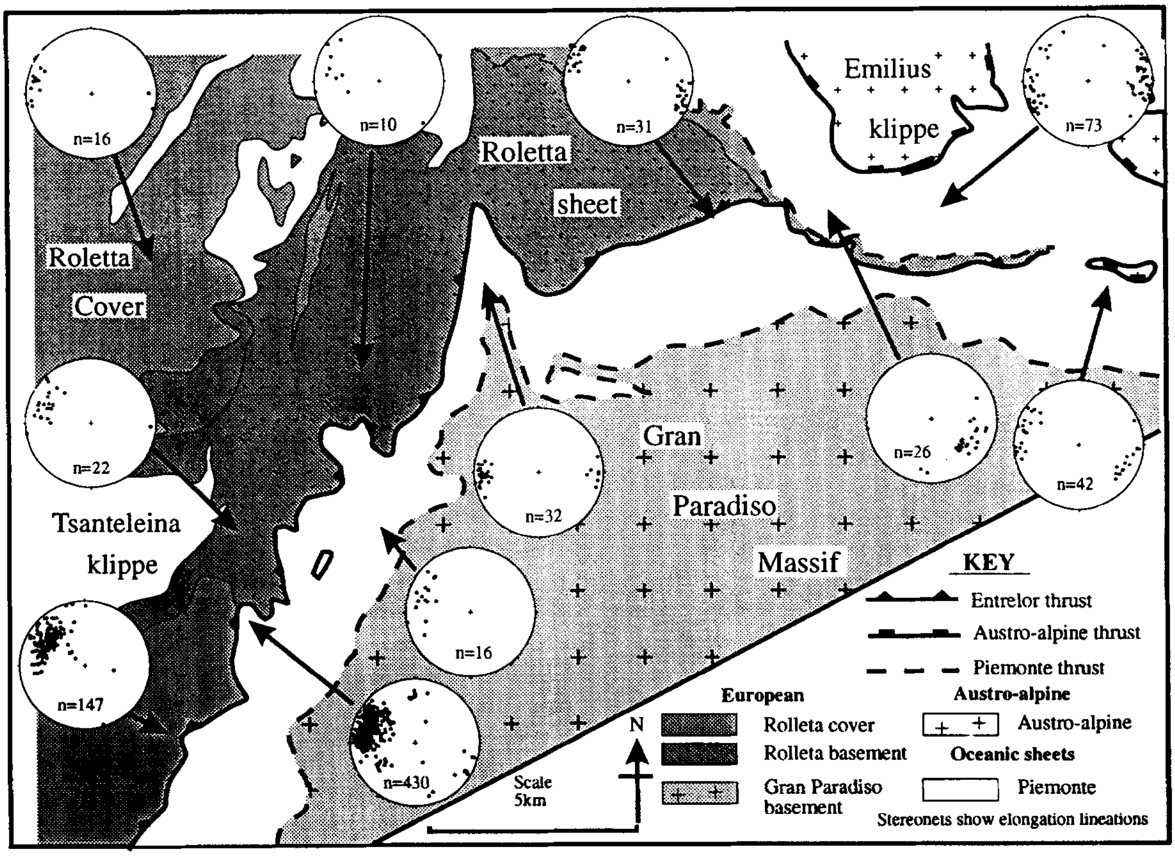

Fig. 5. Sketch map of the NW flank of the Gran Paradiso massif, showing grouped stretching lineation data (on lower hemisphere stereographic projections) for subareas along the Entrelor shear zone and environs. All these lineations are defined by greenschist facies minerals.

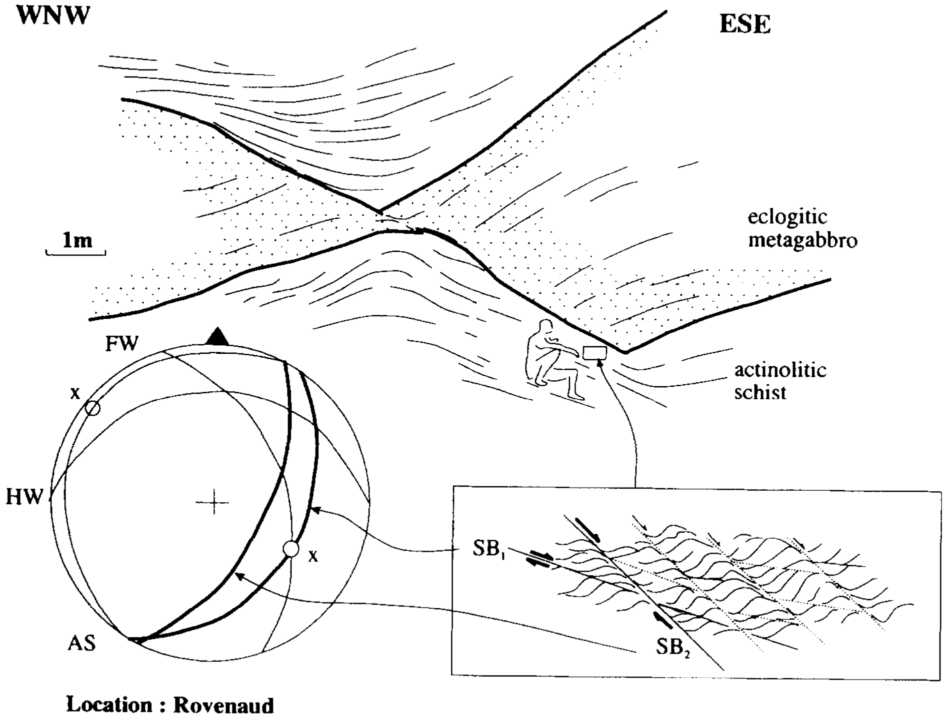

Fig. 6. Shear criteria from the close footwall to the Entrelor shear zone. These field sketches show asymmetric boudinage of an eclogitic metagabbro sheet and the associated fabrics, defined by greenschist facies mineral assemblages. The stereonet (lower hemisphere) shows measured linear and planar fabrics linked to the detailed sketch, together with bounding fabric orientations from the hanging-wall (HW) and footwall (FW) of the shear zone that crosses the eclogite. From a stream section above Rovenaud hamlet in the Valsavarenche valley.

had a single sense and that refolding has caused apparent reversals. Note that this explanation relies on passive folding of an early shear sense population about structures with hinges near parallel to the early stretching lineation. A test of this hypothesis would be to log shear criteria relative to positions on large folds but regretably the terrain is not conducive to such a study. The fold population however will be discussed shortly.

Displacement magnitude

Displacements on faults and shear zones may be established by measuring the offset of pre-existing markers. Knowing the transport direction and shear sense on the Entrelor structure, it is possible to establish a minimum offset on it by referring to the hanging-wall and footwall geology and assuming aspects of its 3D structure. The Entrelor shear appears to be folded by the Gran Paradiso massif and, with its present outcrop trace, appears to have largely enveloped the massif prior to regional exhumation. Assuming that the hanging-wall structure, in particular that the terminations of Briançonnais basement and Briançonnais cover, project perpendicular to the transport direction, we may use the minimum offset of these features to determine minimum displacement values (Fig. 3). These terminations are the equivalent of cut-off lines (i.e. hanging-wall ramps) in thrust belts. The shear zone carries Briançonnais basement for approximately 10 km over a footwall of Piemonte zone ophiolites. The Briançonnais cover has been carried a total of at least 20 km, over the Piemonte.

The map pattern, however, suggests a different assumption for the trend of the basement termination. This is, in essence a fold hinge-line, which is oblique to the transport direction on the Entrelor shear zone (Fig. 7). Assuming passive translation of this orientation, so that the fold hinge-line represents the position of an oblique hanging-wall ramp, the minimum offset is just 8 km. By performing a similar construction for the Briançonnais cover, linking folds in Val d'Urtier with the southern limit of cover along the Digitation de l'Iseran (Fig. 7), derives a minimum offset of about 12 km on the shear zone. These values could, of course, be much more because the matching footwall cut-offs remain buried to the west.

Folds

The displacement analysis above draws on the inferred orientation of major fold hinge-lines for the Briançonnais basement and cover. These hinge-lines trend NE–SW, highly oblique to the inferred transport direction on the Entrelor shear zone. A similar pattern may be established using minor folds (Fig. 8).

Information on the orientation of hinge lines of minor folds was collected during the study of minor structures around the Entrelor shear zone. The regional dataset of fold hinges lie on a girdle with a mean hinge line orientation plunging 24° towards N259E. This contrasts with the mean orientation of the stretching lineations (24/285). These data have been grouped into sub-areas for comparison between the local populations of mineral

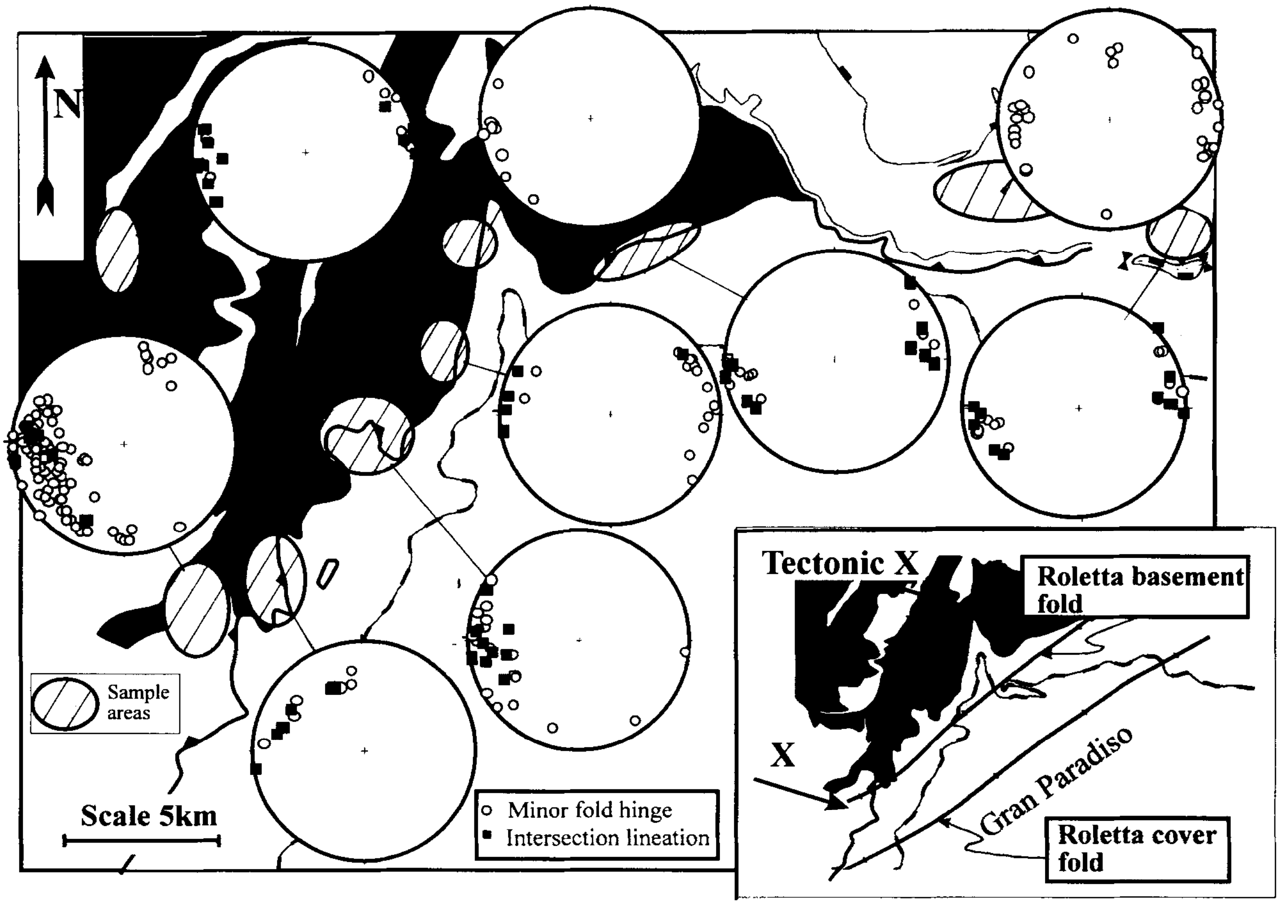

Fig. 7. Fold hinge and intersection lineation orientations (lower hemisphere stereographic projections) for subareas along the Entrelor shear zone. The map is simplified from Figs. 3 and 5, and shares a common key. Inset: orientation of the principal hinge lines.

lineations and fold hinges (Fig. 9). Although the hinge data are few relative to the lineations they consistently define a population asymmetrically dispersed around the mean mineral lineations. At all sites, with the exception of the 'Balettaz' sub area, the hinge populations lie counter-clockwise from the mineral lineations. This is most clearly seen on the frequency plot of fold axis azimuth which charts the dispersal of axes away from the modal lineation direction (Fig. 7). The modal direction of fold axes is shifted by about 5° anticlockwise with respect to the lineations.

Collectively, the data confirm the general observation that the region is characterised by broadly E–W trending fold hinges. Traditionally these observations have been used to infer a N–S orientation for maximum orogenic compression (e.g. Ricou & Siddans 1986). However, the mineral lineation and shear criteria data clearly point to a different explanation. Note that the minor folds trend ENE–WSW while the major fold hinge-lines appear to trend NE–SW. Thus the minor folds are closer to the regional transport direction than the major folds. One explanation is that all of these structures have experienced moderate amounts of top-to-ESE simple shear and that the fold hinge population has been reoriented towards parallelism with this direction. If so, the minor folds have experienced a greater value of shear strain than the major structures.

Fold populations and simple shear

Classical models for the development of sheath folds (e.g. Cobbold & Quinquis 1980) require that fold hinges initiate near perpendicular to the tectonic transport direction (X) and, with progressive simple shear, are reoriented towards X. Lacassin and Mattauer (1985) point out that for passive rotation of fold hinges during ideal simple shear, the angle between the fold hinge and X is dependent on the amount of simple shear and the shape of the original fold. In their analysis, fold shape (in the XZ section) is defined by the ratio between fold amplitude and wavelength for the degree of along-hinge plunge variation. The along-hinge continuity for the regional backfold in the hanging-wall of the Entrelor shear zone is tens of km with an amplitude of < 1 km. Using these values, the fold hinge and stretching lineation populations would be dispersed by less than 20° only after a bulk shear strain in excess of 15. Although this result is attractive given the apparent offset in excess of 8 km across a plausible shear zone width of 500 m, there are problems with this analysis.

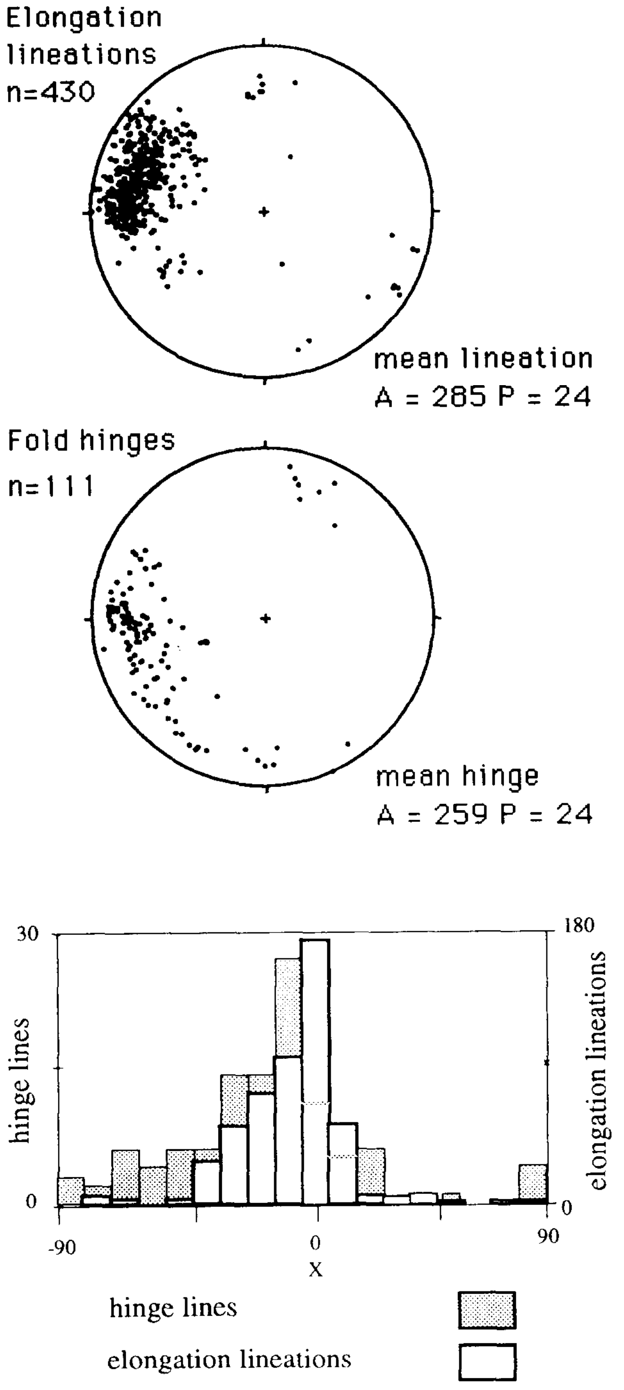

Fig. 8. Linear structural data from the Entrelor shear zone. The upper stereonet shows the amalgamated stretching lineation dataset while the lower shows amalgamated fold hinges. Both are lower hemisphere projections. These data are also displayed on a frequency plot, normalised to the mean stretching lineation azimuth (285) with the azimuths for the linear data grouped into 10° intervals.

At very high simple shear strains, the stretching lineation and fold hinge populations should be co-linear, but at intermediate strain values the fold hinge population will be bimodal and symmetrically dispersed around X (e.g. Ramsay 1980). This prediction is not supported by the data presented here: the folds are asymmetrically dispersed about X. Clearly the analytical approach of Lacassin & Mattauer (1985) is not applicable to this setting. Asymmetric populations may imply a component of wrench shear together with overshear (Coward & Potts 1983). In wrench shear zones the fold hinges may initiate with a mean plunge azimuth at 45° to X, in contrast to 90° for ideal overshear. Using the statistical method of Lloyd (1983; Fig. 9), the passive reorientation of such a fold population by overshear alone generates near parallelism (dispersion of $< 2°$) with an overshear strain of 5. The observed dispersal of 10–20° is achieved with a shear strain of less than 2. If the overshear and wrench shear were to operate in tandem, a shear strain of 1 on each generates a dispersal of 14° for the mean fold hinge from X.

The above calculations are not meant to reflect any particular precision because they make assumptions of the initial fold population that are difficult to verify. Nevertheless, wrench shear acting with overshear explains the asymmetric dispersal of fold hinges about X and implies much lower values of penetrative overshear compared with the ideal simple shear model (Lacassin & Mattauer 1985). The inferred wrench shear component is required to have had a right-lateral sense, in part reflected by the orientation of the major fold hinge-lines. This raises some interesting regional questions that are discussed later.

Summary

The Entrelor shear zone moved on a WNW–ESE axis with a top-to-ESE shear sense. This direction is updip with respect to the modern orogenic surface and is contractional with respect to both tectonic layering and modern orogenic structure. The orientation of hinges to minor folds are asymmetrically dispersed around X. These imply a right-lateral wrench shear component to have operated with the ESE-directed overshear along the western and northern flanks of the Gran Paradiso massif.

EXTENSION VERSUS COMPRESSION

There are several published criteria that purport to indicate structures that extend the crust within orogenic belts. These give mixed results when applied to the Entrelor shear zone. The shear zone repeats tectonic stratigraphy and cuts up through the modern orogenic structure in its transport direction. These two attributes are consistent with the shear zone having operated as a thrust, albeit directed towards the orogenic hinterland. In contrast, the shear zone omits metamorphic stratigraphy along much of its outcrop trace, placing LP onto HP rocks, and has rapidly-cooled rocks in its footwall. Ostensibly these criteria indicate extension. What is the solution?

The two results that appear to support an extensional origin for the Entrelor shear zone are ambiguous. The metamorphic layering pre-dates the shear zone and involves HP rocks emplaced regionally onto LP. This geometry is preserved in structural continuity near the Col du Drinc (Fig. 3). A transect through the pre-shear

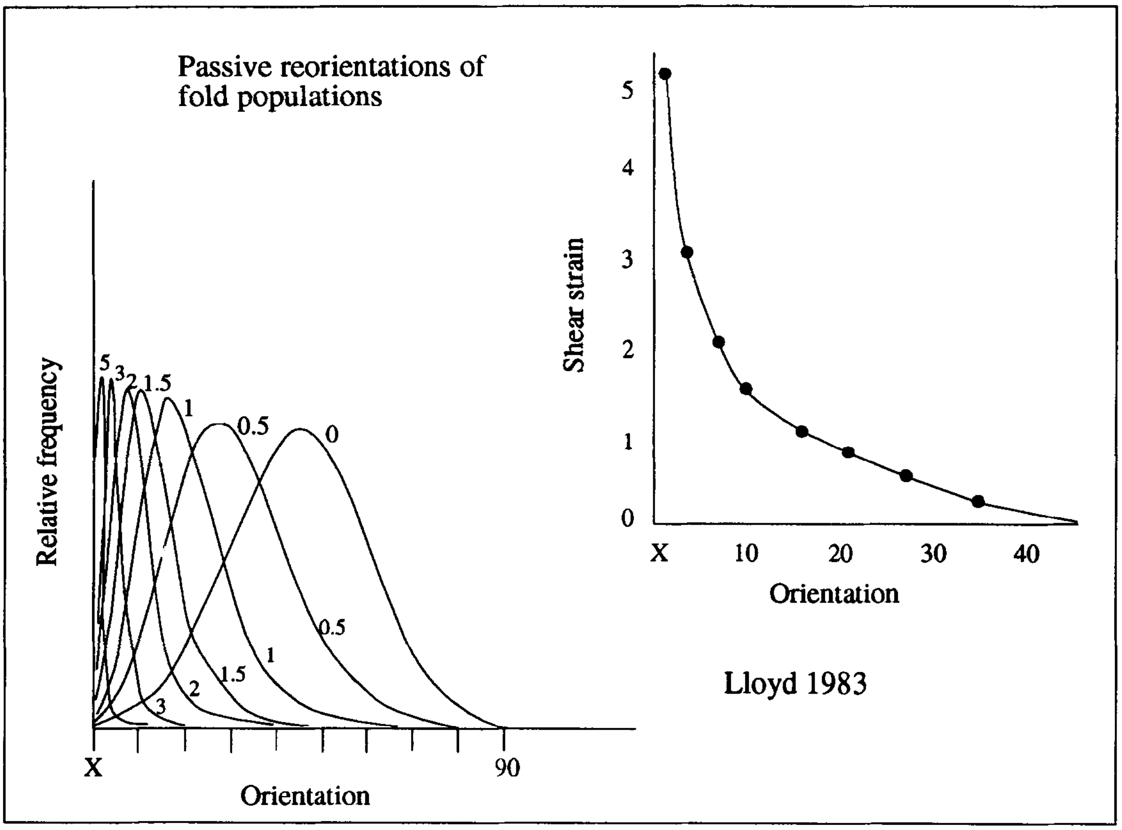

Fig. 9. The passive reorientation of fold hinge azimuth populations that originate oblique to regional overshear (X) but with increasing strain are modified towards parallelism with X, after Lloyd (1983). The frequency plot shows an initial ($\gamma = 0$) normal distribution of fold hinges symmetrically distributed about a mean 45° from X. Progressive modification of this population with increasing simple shear is indicated by the other distributions (labelled in γ). The other graph shows the modification of a single hinge (initially at 45° to X, i.e. $\gamma = 0$) with increasing shear strain.

zone pile has the Mt Emelius klippe of the (eclogitic) Austroalpine nappe together with its eclogitic footwall, collectively emplaced onto Briançonnais LP rocks (Fig. 3). Such a situation is to be expected in contractional orogens — it is a thrust relationship with originally deeper rocks emplaced onto originally shallower rocks. Hence the metamorphic 'layering' was imbricated prior to the Entrelor shear zone (Fig. 10). The action of this shear zone was to reimbricate margins of the Austroalpine thrust, placing the LP footwall onto the HP hanging-wall. This reimbrication geometry is commonplace in thrust belts where it is termed 'breaching' (Butler 1987).

The rapid cooling for the footwall to the Entrelor shear zone is determined from fission track data, largely for apatite (Hurford *et al.* 1989). However, these data relate to cooling through 150 to 100°C, some 200°C cooler than the synkinematic temperature for the Entrelor shear zone. Hurford *et al.* (1989, 1991) recognise that their data do not reflect tectonics operating at greenschist facies and consequently they have no relevence to the Entrelor shear zone. However, they put a minimum age on the deformation structures discussed here. The Entrelor shear zone is older than 20 Ma. We are currently embarking upon a programme of absolute dating of deformation fabrics along the shear zone.

LARGE-SCALE STRUCTURAL EVOLUTION

The previous discussions lead to the conclusion that the Entrelor shear zone operated as a hinterland-directed structure that shortened the crust — a backthrust. As such it restacked the orogenic complex and thickened the tectonic pile. The kinematic evolution of backthrusts is discussed elsewhere (Butler 1987). They may link at depth onto forethrusts to form a linked fault system. Thus, as displacement is accumulated, the hanging-wall to the forethrust drives wedge-like, in the footwall to the backthrust (Fig. 10). This geometry has the potential to deform the backthrust as it develops. Over time this may mechanically harden this portion of the thrust belt leading to a migration in the locus of deformation.

Although lacking verification, hinterland-directed, E-facing structures like the Entrelor shear zone have been interpreted from elsewhere in the Western Alps (e.g. Caby *et al.* 1978, Platt *et al.* 1989). These structures were inferred to detach from foreland-directed thrusts at depth, structures that may emerge on the western

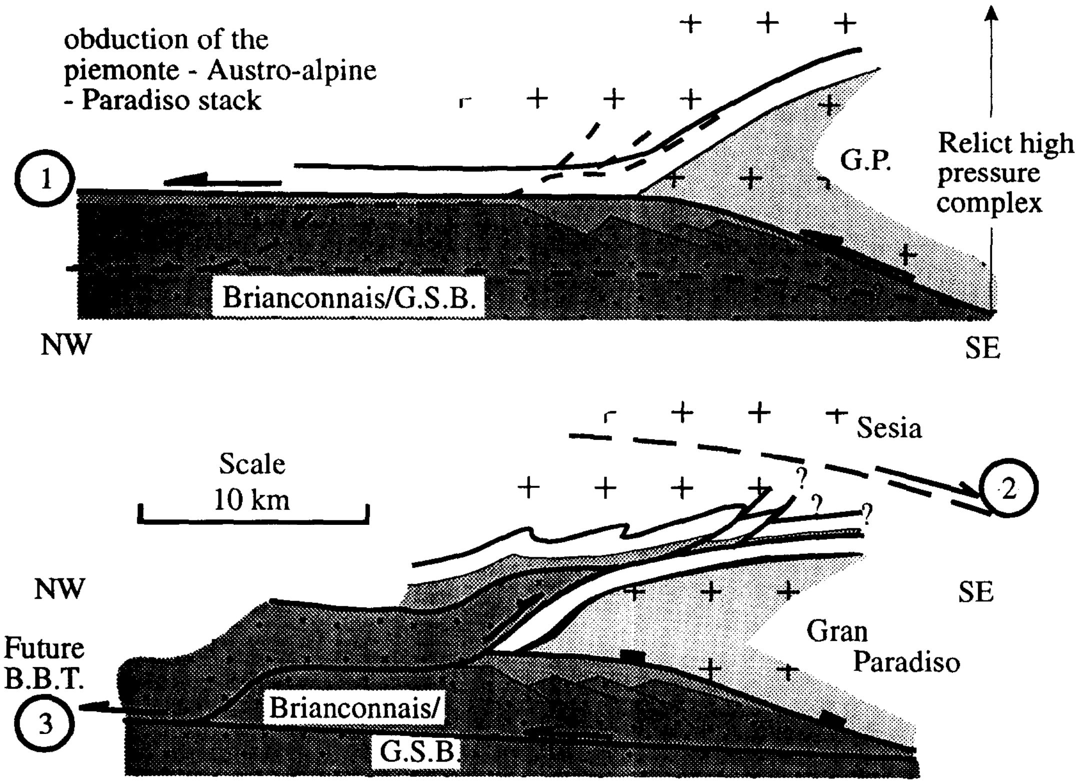

Fig. 10. Proposed evolution of the Entrelor shear zone in a semi-regional context (evolves top to bottom). The earliest deformation (1) is the obduction of the HP oceanic and continental (Austroalpine and Gran Paradiso massif) onto the Briançonnais–Grand St. Bernard unit. Deformation then migrates into the footwall as a WNW-directed thrust above which is spawned an ESE-directed backthrust. This emplaces relatively LP rocks from the footwall of thrust (1) into its hanging-wall (breaching) thereby restacking the tectonic and metamorphic stratigraphies. The timing of this structure relative to apparently extensional (2) structures that outcrop to the north and east (e.g. the Ayas shear zone of Wheeler & Butler 1993) is unclear. However, we propose that the backthrust system eventually breaks through to the west as the Basal Briançonnais thrust (3).

margin of the internal zones (e.g. Butler 1986). The most likely candidate is the so-called Basal Briançonnais thrust (Fig. 2). Deep seismic reflection data (ECORS-CROP, Nicolas *et al.* 1990) are consistent with this picture; specifically that foreland-directed thrusts are likely to pass at depth beneath the Gran Paradiso massif. Consequently the massif, lying in the hanging-wall to the forethrust, is likely to have amplified as the backthrusts developed at its western margin. This large-scale evolution provides an explanation for the development of minor structures within the Entrelor shear zone.

As noted above, the asymmetric distribution of the hinges to minor folds around the transport axis of the Entrelor shear zone is consistent with a right lateral wrench shear component having operated along the northern flank of the Gran Paradiso massif. Such a shear component is indicative of the differential movement that occurs across oblique ramps (e.g. Coward & Potts 1983). Uplift of the massif in the footwall to the Entrelor shear zone would create an effective oblique ramp during shearing.

Relationship with extensional structures

The large-scale bipolar thrusting model for the internal Western Alps, within which resides the Entrelor shear zone, requires further testing. Specifically, the kinematics of the Basal Briançonnais thrust and its hanging-wall structures have yet to be established forelandward of the area studied here. The thrusting model predicts contractional structures with top-to-WNW kinematics. If it showed top-to-ESE extension, the regional conclusions outlined here would require modification. One option would be that the entire internal Western Alps, structurally overlying the Gran Paradiso massif, is an ESE-directed allochthon, in the hanging-wall of a major backthrust system. Alternatively the allochthon could be extensional, because the criteria used earlier — that the Entrelor shear zone cuts up-section regionally through the orogen — would be invalid.

As noted earlier, the application of the same criteria as used here to areas further north in the Western Alps implied that some structures accommodated orogenic extension (e.g. the Ayas shear zone of Wheeler & Butler 1993). Although both structures are directed top-to-ESE they differ in that the Entrelor shear zone cuts up into the Austroalpine units while the Ayas shear cuts beneath (Fig. 10). Both operated at the same broad metamorphic grade so, in broad terms, they occurred during the same period of exhumation in the Western Alps. They need not have been active simulataneously. For models of

Alpine orogenesis it is clearly important to establish the relative age of and kinematic links between these two structures.

CONCLUSION AND DISCUSSION

The Entrelor shear zone is a major structure in the Western Alps that emplaced the European basement and cover rocks of the Briançonnais zone onto ophiolitic material of the Piemonte nappe. This shear can be traced up-section in the orogenic pile where it carries Piemonte material into the high-level Austroalpine nappe. Kinematic data consistently show a top-to-ESE transport direction, except in regions where fold-hinges are near parallel to the regional transport axis. The shear zone cuts up-section in its transport direction with respect not only to tectonic layering but also the modern orogenic surface. These observations strongly suggest that the shear zone accommodates net orogenic contraction and that it operated as a backthrust. Nevertheless, it locally omits metamorphic stratigraphy, emplacing LP onto HP rocks. However, this observation is still consistent with contractional behaviour because the HP rocks were emplaced onto LP prior to movement on the Entrelor shear zone. This behaviour is to be expected in contractional orogens where reimbrication is a common occurrence. There are direct similarities with thrust belts where breaching of structurally lower thrusts into earlier-emplaced thrust sheets generally places younger rocks back on top of older (Butler 1987). Thus the recognition of offsets of metamorphic stratigraphy alone is insufficient to determine if a shear zone is contractional or extensional on a crustal scale or indeed if any structures in the orogen were extensional (cf. Merle & Ballèvre 1992).

The orientation of hinge-lines to minor and major folds associated with the Entrelor shear zone are oblique to the tectonic transport direction but are asymmetrically dispersed around it. The counter-clockwise deflection of minor fold hinges with respect to the transport direction suggests a component of right lateral wrench shear associated with ESE-directed overshear. This conclusion is consistent with the inferred orientation of major fold hinges and suggests that the studied segment of the Entrelor shear zone formed from an oblique ramp cutting from the Briançonnais into the tectonically overlying Piemonte nappes. Modification of the hanging-wall ramp may have occurred because of continued right-lateral wrench shear along the northern margin of the Gran Paradiso massif. If so, the domal shape of the Gran Paradiso massif was at least partially developed during displacement on the Entrelor shear zone. This inference is consistent with the Entrelor shear zone forming part of a regional array of backthrusts that detached from a forethrust that in turn carries the massif. This interpretation is consistent with crustal models of thrust geometry developed from surface geology (Butler 1986) and the ECORS-CROP deep seismic reflection profile (e.g. Nicolas *et al.* 1990).

Future tests

Futher testing of the conclusion that the Entrelor shear zone is a contractional structure on a crustal scale that accommodated orogenic shortening requires non-geometric data. One approach is to determine offsets of palaeo-thermal structure of the hanging-wall and footwall (e.g. Selverstone 1988). However, as Wheeler & Butler (1994) point out, the thermal structure being used must be that at the time of shearing, rather than merely inherited from an earlier part of the orogenic history. Additionally, the isotherms should have been horizontal at the onset of deformation. In practice this requires dating the crystallisation age of shear zone rocks, to establish the timing of displacement, and matching this to appropriate thermochronological data. A thrust is expected to repeat syn-kinematic thermal structure, placing hotter rocks on top of cooler ones. Consequently a palaeo-geothermal gradient across the thrust immediately after displacement should be relatively low, compared with the opposite situation of extensional shearing.

The Entrelor shear zone offers an opportunity to apply thermo-chronometry to test regional kinematics. Metamorphic data indicate that the Entrelor shear operated at temperatures of 300 to 350°C. Consequently the Rb–Sr isotopic system for white mica, with a closure temperature of ca 500°C, may provide dates on deformation within the shear zone, provided that the white mica crystallised syn-kinematically and is in equilibrium with an additional (Ca/Sr-rich) phase. Thus, absolute ages on the deformation may be obtained. The deformation temperature is also particularly suited to investigation by ^{40}Ar–^{39}Ar studies on mica. Consequently, profiles of these ages from hanging-walls and footwalls may provide insights into the palaeothermal structure associated with the deformation. Regrettably however, the Western Alps is characterised by extensive argon flux from basement, leading to a widespread excess of the radiogenic isotope and apparently old ages. Careful microstructural and microchemical studies may help to eliminate this problem (e.g. Dempster 1992). Work is underway to provide these data and thereby test the kinematic models developed here.

Finally, it is worth emphasising invalid tests of the hypothesis. Using any features, including mineral cooling ages, that are not synchronous with deformation, may be highly ambiguous. The offset of earlier metamorphic facies (e.g. LP on HP rocks) is insufficient without establishing a larger structural framework. As Hurford *et al.* (1991) point out, cooler parts of the thermal history, as provided by fission track data on apatite and zircon, are meaningless with respect to structures that operated exclusively above these minerals' annealing temperatures. These data reflect displacements on shallow faults or, in areas of high relief, merely differential erosion. Rather than cast doubt on these studies, these comments emphasise the importance of taking a regional view in analysing the kinematics of a small part of an orogen. Studies of ancient orogens may yield ambiguous results. Uncertainties in cooling ages may be too great to distinguish between different tectono-thermal models, the exposure and tectonic relief may be insufficient, the structure discontinuous and masked by younger deposits. Future work may bear fruit if it concentrates on young orogens such as the Western Alps where these limitations are not great.

Acknowledgements—This work was supported by a grant GR9/497 (RWHB) and a research studentship (SF), both funded by the Natural Environment Research Council. We thank J. Wheeler, R.A. Cliff, A.C. Barnicoat, and S. Inger for discussions, together with the authorities of the Gran Paradiso National Park for permission to collect rock specimens. Neil Mancktelow and Reinoud Vissers provided useful and stimulating reviews for which we are grateful.

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