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Crustal stacking and extension recorded by tectonic fabrics of the SE margin of the Tauern Window, Austria

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Abstract—Structural and metamorphic analyses show that Alpine deformation in the Austroalpine–Pennine contact zone around the margin of the SE Tauern Window can be divided into two main stages: (i) early crustal thickening associated with prograde metamorphism; and (ii) a younger history of ductile flow that added to cumulative displacement of the upper units to the NW quadrant but was associated with substantial subvertical attenuation of the contact zone, and most probably of the overriding Austroalpine plate as well. During the history of this region strain localization progressively shifted down section. Radiometric ages constrain the early deformation to be older than 75 Ma. The onset of contact-zone attenuation and upper-plate extension was after this date but before 35 Ma (before major involvement of European basement in the collisional orogen), and associated with both retrograde metamorphism and a degree of non-coaxiality less than simple shear. Estimates of thinning in the contact zone and on a regional scale are in good agreement and indicate vertical attenuation of approximately 40%. These results suggest that pre-collisional tectonic thinning of the Austroalpine domain may be more widespread and significant than generally recognized. Copyright © 1996 Published by Elsevier Science Ltd

INTRODUCTION

Research over the last ten years has drastically changed the consensus of opinion about the tectonics of the eastern Alps. The uppermost tectonic unit in the eastern Alps is the Austroalpine domain (Fig. 1) and this has traditionally been treated as an essentially rigid sheet that was emplaced over the underlying Pennine domain in a N–S or NE–SW direction (e.g. Tollmann 1961, Clar 1965, Bickle & Hawkesworth 1978). However, more recent studies have recognized the widespread occurrence

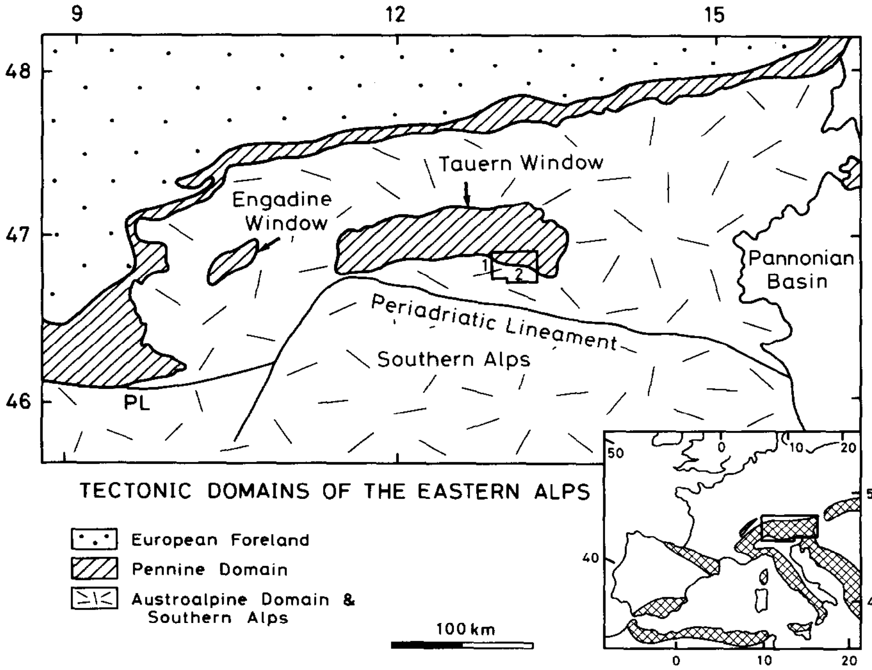

Fig. 1. Three principal tectonic domains of the Eastern Alps the Austroalpine Domain, the Pennine Domain and the European Foreland. The Pennine Domain is exposed in three main tectonic windows through the Austroalpine Domain. The area covered by Fig. 2 is shown by a box. 1, 2 give the general areas covered by the geological maps in Figs. 3 & 5.

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of W–E to NW–SE oriented stretching lineations in the eastern Alps and shown that the dominant associated sense of shear causes emplacement of higher units to the western quadrant (e.g. Ratschbacher 1986, Behrmann 1988, Selverstone 1988, Wallis 1988, Platt *et al.* 1989, Ratschbacher & Neugebauer 1989, Ratschbacher *et al.* 1989, Schmid & Haas 1989, Behrmann 1990, Wallis *et al.* 1993, Linzer *et al.* 1995) and not to the north.

A second major change in our understanding of the tectonics of the eastern Alps has come through the recognition that structures are not only related to thrusting and crustal thickening but that extensional deformation causing crustal thinning has also been an important process in producing the present distribution of tectonic units (Selverstone 1985, 1988, Platt 1986, Behrmann 1988, Wallis 1988, Genser & Neubauer 1989, Ratschbacher *et al.* 1989, 1991, Behrmann 1990, Wallis *et al.* 1993, Neubauer *et al.* 1995). An important corollary to this work is that large parts of the Austroalpine domain were strongly deformed during the Alpine orogeny and this cannot be treated as a rigid sheet with little or no internal deformation.

The present consensus of opinion is, then, that emplacement of the Austroalpine domain over the underlying Pennine Domain was polyphase with periods of deformation related to both crustal thickening and thinning and that the dominant movement direction was to the northwestern quadrant throughout orogenesis. Although the importance of extensional deformation during the eastern Alpine orogeny has generally been accepted, there is still dispute about its extent and tectonic setting. Most workers emphasize Oligocene to Miocene extension which took place after European continental basement became involved in orogenesis: during continental collision (e.g. Ratschbacher *et al.* 1991, Linzer *et al.* 1995). Important extensional features predating collision have also been recognized but most workers suggest this is localized to the east of the Tauern Window (Ratschbacher *et al.* 1989, Neubauer *et al.* 1995). In contrast, Wallis *et al.* (1993) suggest there may have been a more widespread precollisional phase of extension related to general dynamic processes acting in a convergent plate margin.

Down-dip displacements on shear zones in the present-day geographical reference frame have been used in several studies as an indication of extensional deformation (e.g. Ratschbacher *et al.* 1989, Linzer *et al.* 1995). This is, however, only valid if such zones have suffered no rotation with respect to the horizontal during and subsequent to their formation. In the present work we have selected a region to the SW of the Tauern where foliation that formed during continental convergence dips in general to the S and is associated with a predominant NW–SE oriented stretching lineation and a top-to-the NW sense of shear. These structures have also been recognized by other workers and interpreted as the result of early stacking of the tectonic units (Ratschbacher *et al.* 1989, Linzer *et al.* 1995). In this paper we present structural and metamorphic evidence for a polyphase evolution of the region including phases of both crustal stacking and extension. However, in contrast to other workers, we emphasize that although asssociated with oblique up-dip displacement, deformation of this region is dominantly related to extension and not crustal stacking. This implies that the precollisional extensional phase of deformation within the Austroalpine domain may be more widespread than generally recognized; a conclusion that has important consequences for understanding the driving forces behind it.

There are many problems in trying to relate a particular phase of deformation to orogenic thickening or thinning and before discussing this problem we first describe the geology and structural analysis of the region.

GEOLOGICAL SETTING

The Alpine orogeny represents the long processes of convergence and eventual collision between the European and Austroalpine continental domains from lower Cretaceaous to Tertiary times (Smith 1971, Dewey *et al.* 1973, Trümpy 1975, Biju-Duval *et al.* 1977, Frisch 1979, Laubscher & Bernoulli 1982). The intervening oceanic units were progressively deformed and accreted to the continental margins and are now represented by the Pennine domain, which is sandwiched between the overlying Austroalpine domain and the underlying European domain. The Austroalpine domain can be divided into a series of Mesozoic cover units (locally metamorphosed) and largely metamorphic basement commonly referred to as Altkristallin (e.g. reviews in Oxburgh 1968, Tollmann 1977). The Pennine domain typically consists of graphitic calcareous schist associated with greenschist and lesser amounts of dolomite and quartzite, collectively known as Bündnerschiefer (Frasl 1958). Significant bodies of continental crust are, however, also preserved within the Pennine domain (e.g. Sonnblick and Ankogel gneiss domes of Fig. 2).

In detail, the Austroalpine–Pennine boundary is a structurally complex zone with affinities to both the overlying and underlying domains. In the SE Tauern this transitional zone is known as the Matrei Zone (Bickle & Hawkesworth 1978, Frisch *et al.* 1987, Fig. 2). Our proposed division of the Matrei Zone into Pennine and Austroalpine units is shown in Fig. 3.

Metamorphic history

In the SE Tauern and adjacent regions two regionally developed phases of Alpine metamorphism can be recognized. The older phase, present only in the Austroalpine domain, is a mid-Cretaceous Barrovian facies metamorphism reaching a maximum of amphibolite grade. Radiometric dating gives a range of ages for this metamorphism in the SE Tauern of 90–75 Ma (biotite and white mica K–Ar ages Oxburgh *et al.* 1966, Brewer 1970, Waters 1976, Lambert 1970 and Rb–Sr biotite and white mica ages—Cliff pers. comm.) which is in good agreement with dating of this phase of metamorphism from other parts of the Austroalpine Domain (Thöni

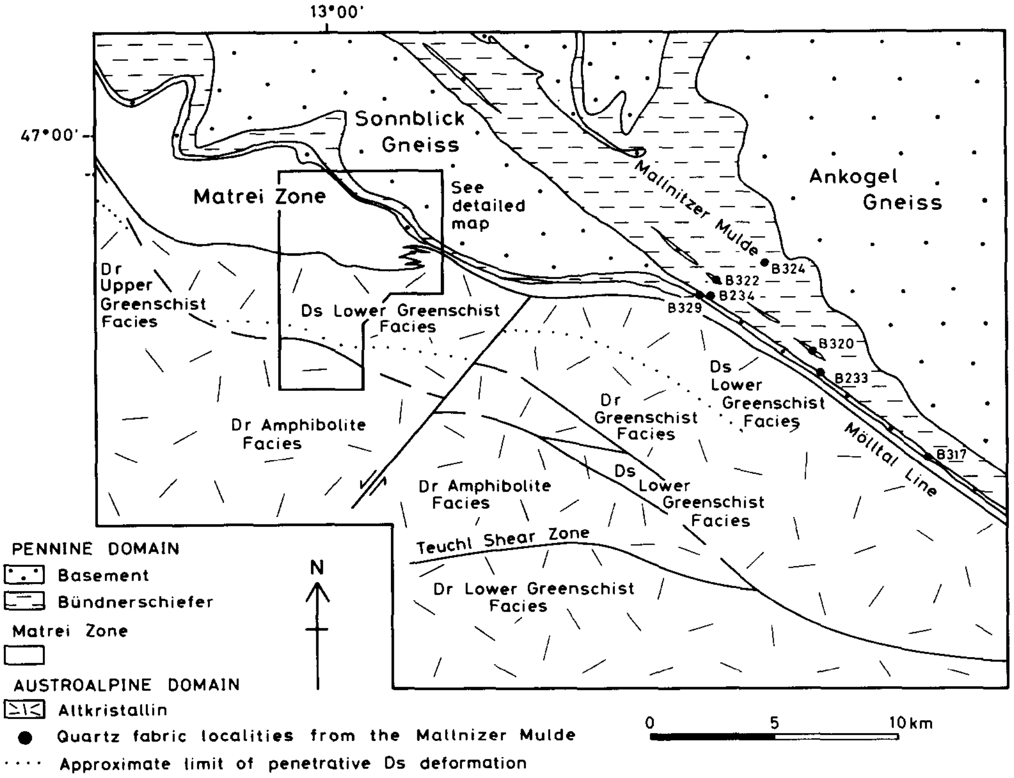

Fig. 2. Tectonic elements of the region around the SE of the Tauern Window. The boxed region is shown in more detail in Fig. 3. The Matrei Zone consists of a mixture of Austroalpine and Pennine units (see Figs. 3 & 4). The position of shear zones within the Austroalpine basement (Altkristallin) is after Waters (1976), Hoke (1987) and our own observations. The distribution of the Pennine basement units is after Cliff *et al.* (1971). Location of *Ds* quartz fabric localities shown by black dots (Fig. 10).

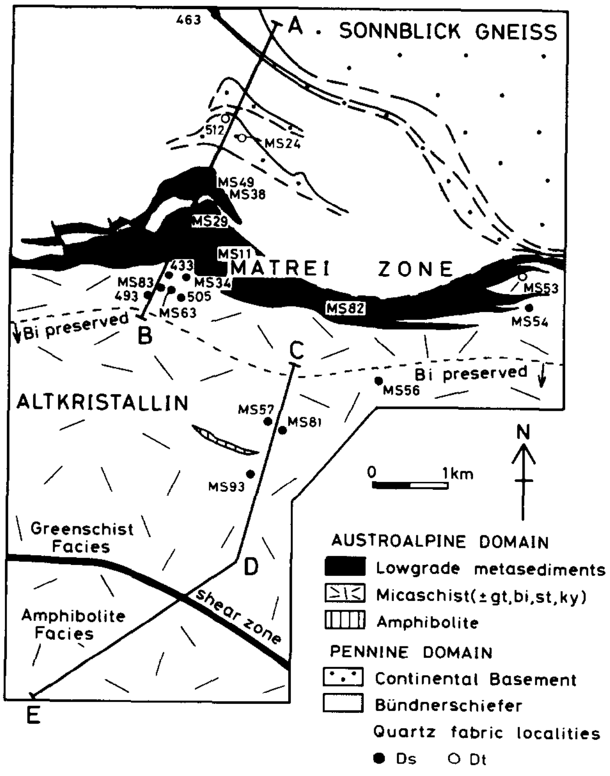

Fig. 3. Geological map of part of Fig. 2 incorporating data from Gommeringer (1985). Location of quartz fabric localities for Figs. 9 & 10 shown by open circles (*Dt*) and black dots (*Ds*) respectively. *Dr* biotite is preserved to the south of the dashed line.

1986, Frank *et al.* 1987, Neubauer *et al.* 1995). Barrovian-type metamorphism in the overriding plate of a convergent margin is unusual and its causes in the eastern Alps are not well understood. Reports of eclogite with ages as young as 100 Ma in the Austroalpine Domain (Miller *et al.* 1988, Thöni & Jagoutz 1992) further emphasizes that there are still many aspects of the Cretaceous tectonics of the Austroalpine domain that are not well-understood.

The second, younger, metamorphic event recognized in the SE Tauern region is the largely static Tauern metamorphism that mainly affects the Pennine domain and reaches amphibolite grade at deep structural levels (Droop 1981). Rb–Sr dating of phengite and amphibole (Cliff *et al.* 1985, Blanckenburg *et al.* 1989, Inger & Cliff 1994) as well as U–Pb dating of allanite and sphene (Inger & Cliff 1994) have been used to estimate a peak age of the Tauern Metamorphism from 30 Ma to 20 Ma. The younger ages are generally found at deeper structural levels and can be explained as the result of diachronous cooling in a progressively exhuming domain (Blanckenburg *et al.* 1989, Inger & Cliff 1994). These results are in good agreement with dating from higher structural levels in the SE Tauern (Lambert 1970, Hawkesworth 1976, Waters 1976) which suggest peak metamorphism was attained slightly earlier at around 35 Ma. The reliability of this estimate could, however, be questioned due to potential problems with inherited argon (Brewer 1969, Roddick *et al.* 1980).

In addition to the above two phases of metamorphism, there is also evidence for a distinct phase of regional high P/T metamorphism in the Pennine domain (Holland 1979, Franz & Spear 1983, Selverstone *et al.* 1984, Selverstone 1985). In the SE Tauern, however, the affects of this stage have been largely overprinted by the later Tauern metamorphism and were not recognized in the present study.

STRUCTURAL ANALYSIS

In the margin of the SE Tauern we recognize three distinct phases of penetrative ductile deformation. These phases are *Dr*, *Ds*, and *Dt* from oldest to youngest and form a sequence that decreases in age from south to north or from high structural levels to low (Figs. 4–6). Each of the phases can be characterized by its relationships to the metamorphic history and other phases of deformation. Lithological mapping also reveals a phase of imbrication which took place before *Ds*. The following section is mainly concerned with characterizing these four stages of deformation. There are, however, at least two geometrically distinct phases of folding that occur after *Dt*. Neither of these phases is associated with the development of a penetrative fabric on more than a local scale. *Ds* forms the dominant fabric of the region and the majority of the kinematic data are related to this phase. We will, however, describe the deformation phases in chronological order (Figs. 5 & 6).

Dr—*oldest alpine deformation in Altkristallin*

Dr is the oldest Alpine deformation in the region and is restricted to the Altkristallin units of the Austroalpine basement. *Dr* structures are closely associated with the mid Cretaceous Barrovian facies metamorphism, which is well-developed in this area (Figs. 2 & 7a). Minimum P–T conditions for this metamorhpism in the study area of around 7 kbar and 630 °C can be estimated from biotite–kyanite–staurolite–garnet assemblages (Spear & Cheney 1989) which are locally preserved (Fig. 7a). The presence of garnets with spiral-shaped inclusion trails suggests synmetamorphic deformation (Fig. 7b). In many cases, however, the deformational fabrics are overprinted to some extent by the growth of metamorphic minerals. Radiometric dating to the southeast of the Tauern area (see above) gives cooling ages for minerals formed during this phase of metamorphism as 90–75 Ma.

In general the Sr foliation strikes E–W with a steep dip and the stretching lineation is oriented E–W. Towards the base of the Altkristallin these structures are progressively overprinted by *Ds* deformation. There is, however, a general increase in the intensity of *Dr* features towards the Austroalpine Pennine boundary suggesting that this deformation is related to relative movements between the two domains. Indicators of the sense of shear associated with *Dr* are only rarely preserved. Quartz *c*-axis fabrics were measured in four samples. Three of these fabrics

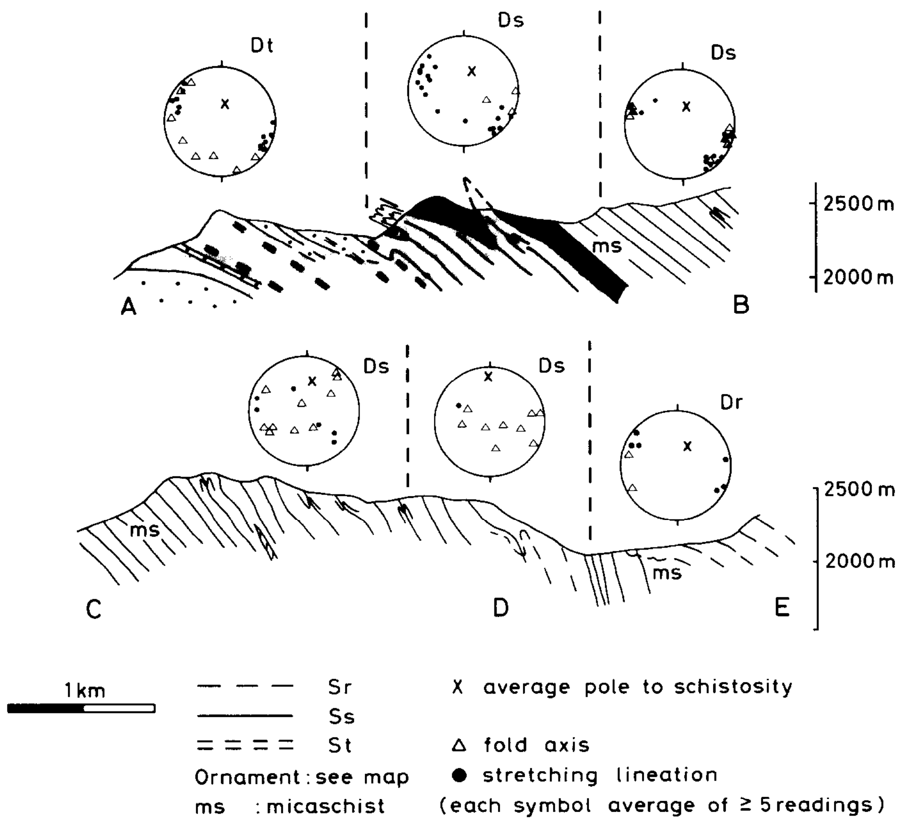

Fig. 4. Representative cross-sections through the area covered by Fig. 3 show structural relationships from the Sonnblick Gneiss at deep levels to higher levels within the Altkristallin. The ornament has been omitted from some of the Altkristallin units for clarity, ms = mica schist.

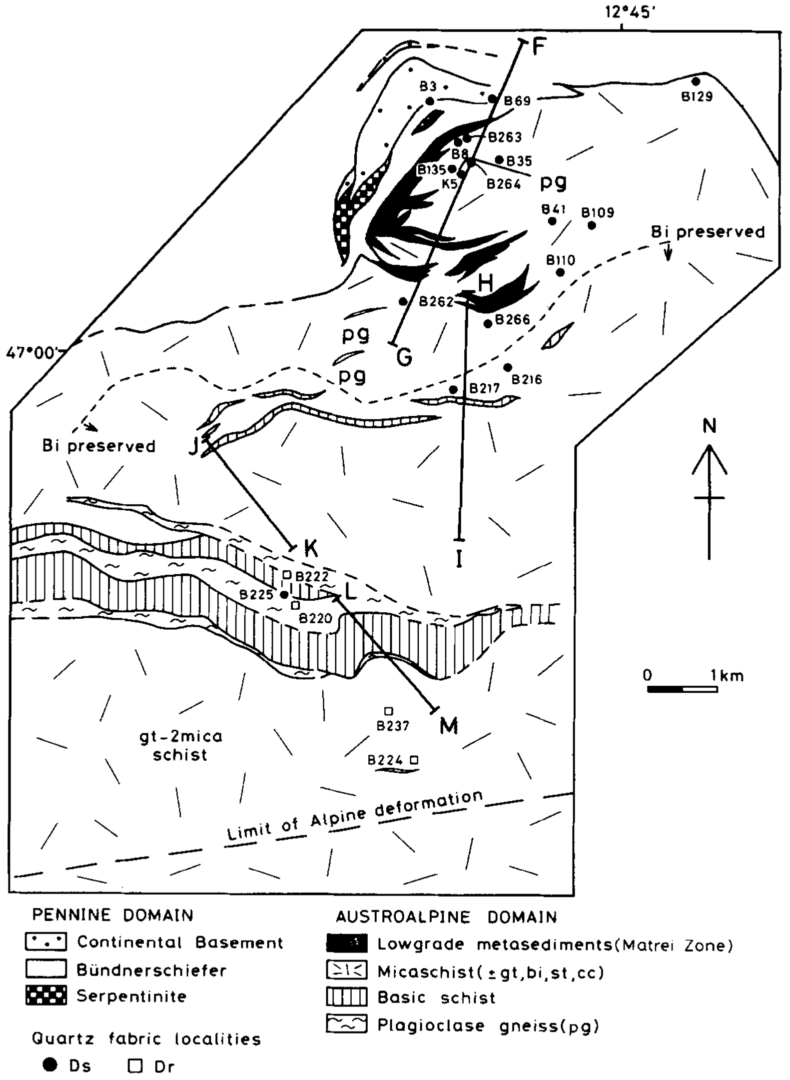

Fig. 5. Geological map of the Schober Group, SE Tauern. The locations of quartz fabrics shown in Figs. 8 and 11 are marked by black dots (*Ds*) and open squares (*Dr*), gt = garnet, bi = biotite, st = staurolite, cc = calcite. *Dr* biotite is preserved to the south of the fine dashed line.

have a general asymmetry suggesting a top to the W sense of shear (Fig. 8).

Imbrication of Austroalpine sheet

The base of the Altkristallin metamorphic basement is locally imbricated with the underlying metasedimentary units (Figs. 3–6). These imbricates are deformed by *Ds* folds and therefore predate *Ds*. The relationship to *Dr* is less clear. However, the imbricates occur close to but structurally lower than the region affected by *Dr* and yet preserve no evidence for metamorphism above low greenschist facies. These observations, therefore, suggest that the imbricates formed after *Dr* and before *Ds*.

Imbrication mainly affects a sheet of dominantly white quartz schist and the overlying Altkristallin. Locally, however, carbonate (mainly dolomite) is associated with the quartz schist. The units structurally underlying this quartz phyllite sheet are dominated by Bündnerschiefer characteristic of the Mesozoic sediments of the Pennine domain. The local presence of slivers of metamorphic basement and serpentinite along the base of the quartz phyllite sheet (Prey 1964, Frisch *et al.* 1987, Wallis 1988) and the contrasting lithologies either side suggest that the basal contact is a fault with a large displacement (Fig. 4). Repetitions of units within the Bündnerschiefer suggest that thrusting also affects this region. *Ds* deformation in the Pennine domain can locally be shown to deform a differentiated fabric (Fig. 7c & d) which may be related to early thrusting.

The thrusting along the base of the Altkristallin affects rock-types sufficiently distinct that the geometry of the imbricates can be mapped out (Figs. 3 & 5) and it can be shown that the cut-off lines of the imbricates plunge to the E (Behrmann & Wallis 1987). Subsequent *Ds* deformation will have modified the geometries of these imbricates. However the plunge of the cut-off lines is consistently greater than that of the later *Ds* stretching lineation suggesting an original eastward plunge. Thrust geometries do not closely constrain associated displacement directions. However, the eastward plunging cut-off lines suggest a sense of thrusting to the NE quadrant.

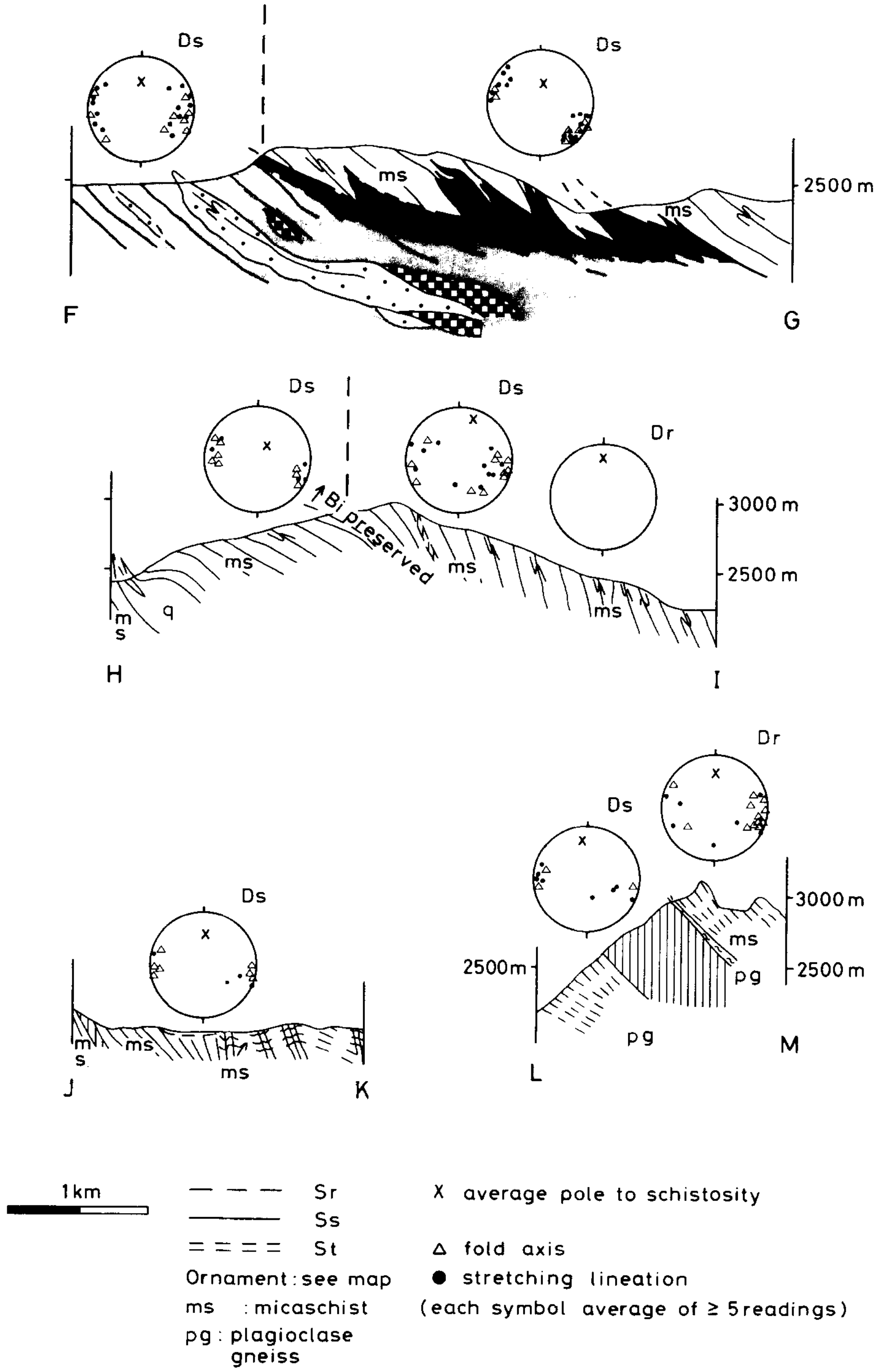

Fig. 6. Cross-sections of the area shown in Fig. 5. These sections show the whole thickness of the Altkristallin that has been affected by penetrative Alpine deformation. For the sake of clarity the ornament has been omitted from some units in the Altkristallin; ms = mica schist, pg = plagioclase gneiss. The tightly folded basement slice within the Pennine domain consists dominantly of dolomite lenses and quartz phyllite and has a complicated internal structure.

Ds—*dominant ductile deformation*

Ds deformation forms the dominant tectonic fabric throughout much of the study region including the basal few kilometers of the Altkristallin and the underlying metasediments. In general, *Ds* forms a pervasive platy or schistose foliation, Ss, associated with greenschist facies mineral assemblages. The variety of lithologies within the Matrei Zone, in particular the presence of large bodies of competent dolomite, leads to complex strain patterns and considerable local variation in the orientation of the mesoscopic structures (Figs. 4 & 6). However, the pattern of deformation is essentially the same as that within the Altkristallin: high-strain deformation under low-grade metamorphic conditions that is associated with a NW–SE oriented stretching lineation. In the Altkristallin the *Ds* stretching lineation, Ls, is most commonly defined by prominent ridges in deformed vein quartz but is also represented by pull-apart fracturing of various minerals (e.g tourmaline, amphibole, garnet) and strain shadows

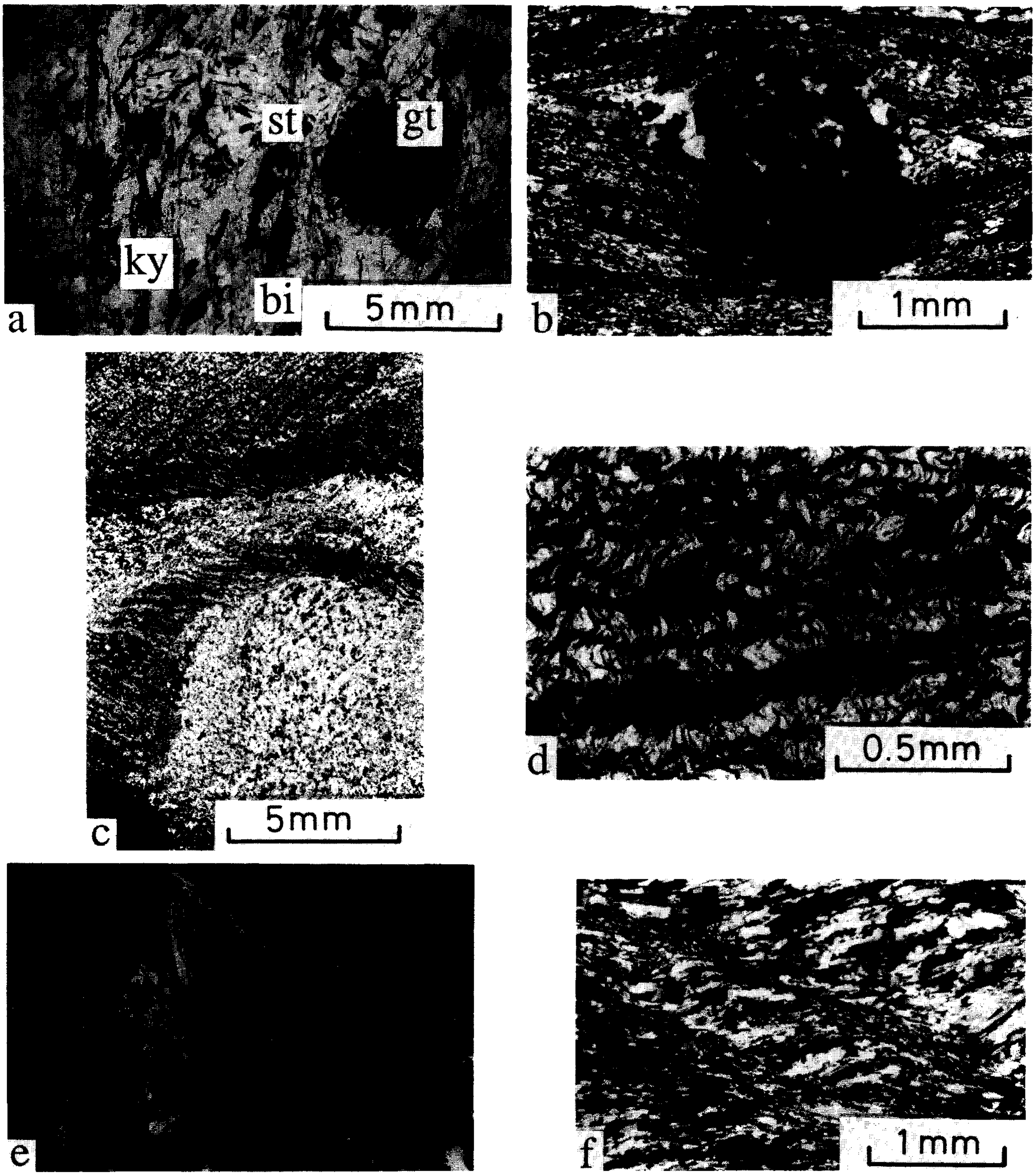

Fig. 7. ***Dr* microstructures**: (a) *Dr* amphibolite grade metamorphism in paragneiss (st = staurolite, ky = kyanite, gt = garnet, bi = biotite); (b) *Dr* synkinematic rotated garnets with spiral inclusion trails. **Folding and shear bands:** (c) *Ds* crenulations associated with a roughly horizontal foliation overprint an earlier differentiated fabric. The youngest crenulations with steep axial planes belong to the *Du* phase (graphitic calcschist of the Pennine domain in the Schober group); (d) detail of (c) showing *Ds* folds with roughly horizontal axial planes; (e) *Ds* folds of amphibolite and orthogneiss with *Dr* foliation in the Altkristallin of the Schober Group (hammer for scale); (f) *Dt* quartz–mica schist with shear bands indicating top to the NW sense of displacement and plastic deformation of quartz grains. ***Ds* kinematic indicators**: (g) shear bands in outcrop; (h) shear bands in thin section, the garnet grain in the centre of the picture is partially retrogressed to chlorite and forming a δ clast; (i) rotated albite porphyroblast from augen gneiss of the Altkristallin. (*Continued overleaf.*)

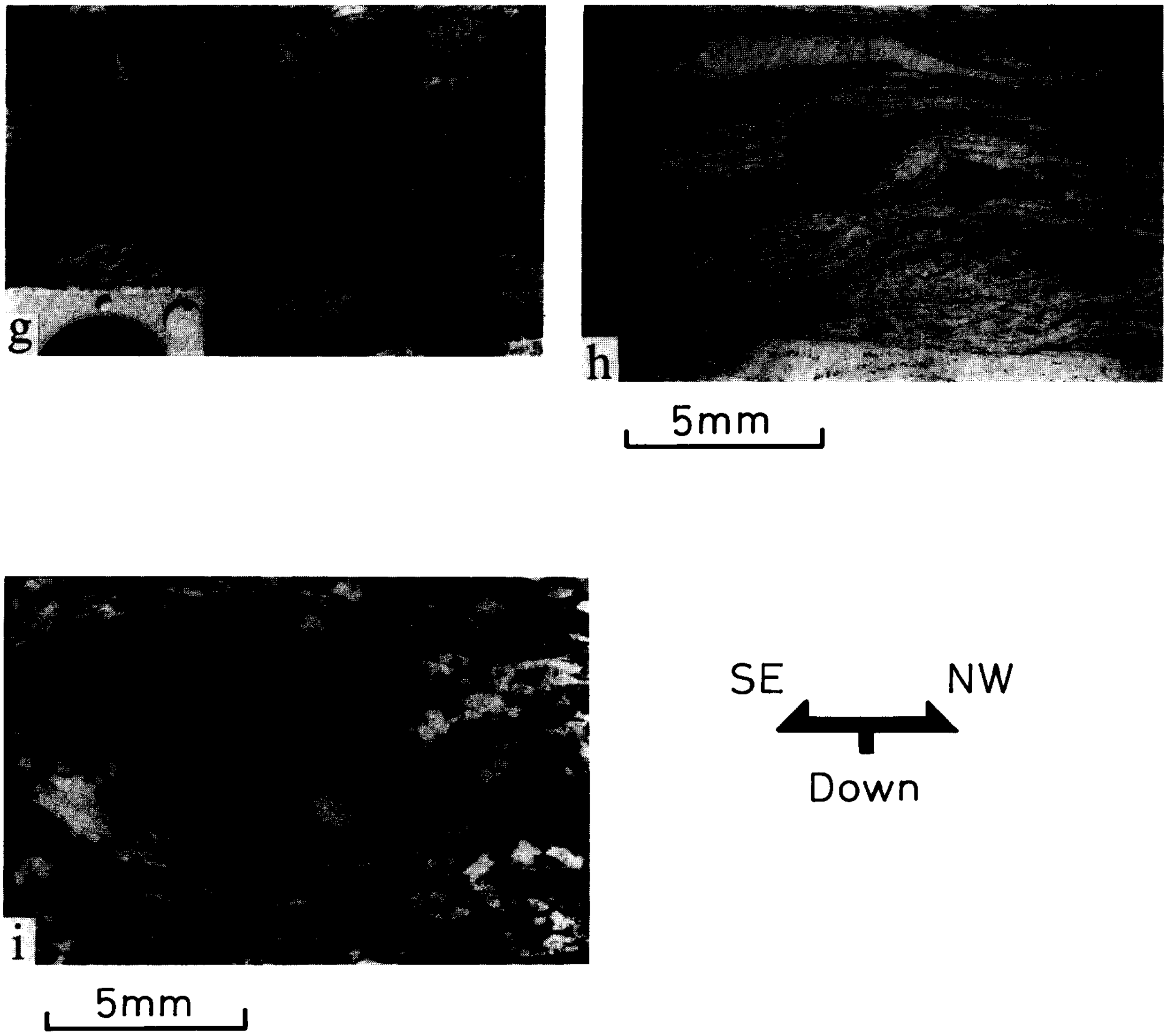

Fig. 7. (*Continued.*)

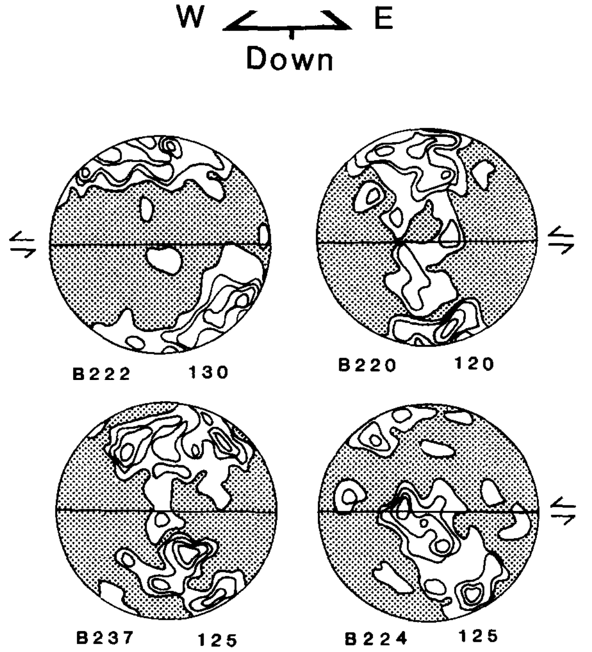

Fig. 8. Quartz *c*-axis fabrics for *Dr* deformation contours at intervals of 1% per 1% area. Beneath each fabric the sample number is given to the left and the number of measured points to the right. The general asymmetry indicates a top to the W sense of shear. See Fig. 5 for location of samples.

around porophyroclasts. A variety of indicators show that the sense of shear during *Ds* was at its top to the NW. These *Ds* kinematic data are discussed in more detail in a separate section below.

Ds strain increases towards the base of the Altkristallin. This strain gradient is marked by an increase in the intensity of the mesoscopic *Ds* fabric and a marked change in both orientation and style of *Ds* folds (Figs 4 & 6). Near the base of the Altkristallin, the folds are isoclinal with their axes sub-parallel to the stretching lineation. At progressively higher structural levels there is an increase in both the opening angle of the folds (Fig. 7e) and in the range of divergence between the fold axis orientation and the stretching direction. These observations can be readily interpreted as the result of fold axes progressively rotating into the stretching direction with increasing strain. Only one example of a highly curvilinear fold was observed suggesting the folds may in general have nucleated oblique to the stretching direction and rotated with the same sense. *Ds* folds in the Matrei Zone are tight to isoclinal and have their axes subparallel to the local stretching direction.

In the Altkristallin, *Ds* structures overprint the earlier *Dr* fabrics and associated metamorphic minerals. Within the zone of *Ds* deformation biotite is only locally preserved (Figs. 3 & 5) and *Dr* garnet is commonly fractured and strongly retrogressed to chlorite. This shows that *Ds* must be younger than *Dr* and the associated metamorphism, i.e. <75 Ma. The affects of the Tauern Metamorphism can also be recognized: at high structural levels the *Ds* microstructures are only partially annealed but this effect becomes more pronounced with increasing structural depth. Locally within the Matrei Zone new mineral growth can be recognized that cross-cuts *Ds* fabrics and is clearly related to the Tauern metamorphism. *Ds* in the study region is therefore constrained to be older than the Tauern metamorphism and younger than *Dr*, i.e 35 Ma < *Ds* < 75 Ma. To try to constrain this age more closely, Rb–Sr dating of white micas was carried out in two samples of white quartz schist with a strong *Ds* fabric from within the Austroalpine basement. The temperature of the Tauern metamorphism at these levels is too low to reset the Rb–Sr age and we therefore interpret the results as giving the age of dynamic recrystallization during *Ds*. The two ages are 50 ± 1 Ma and 40 ± 1 Ma (Wallis 1988).

Dt—*most recent penetrative deformation*

Dt deformation is less widely developed than *Ds* but locally produces a strong platy fabric with a clear stretching lineation. *Dt* folds defor‘m the *Ds* foliation and these folds progressively tighten and rotate towards the stretching direction with increasing finite strain (Fig. 4). The *Dt* quartz mylonites show good preferred crystallographic orientation of *c*-axes with a generally orthorhombic symmetry (Fig. 9). Quartz grains in *Dt* mylonites generally show strong undulose extinction and have sutured grain boundaries (Fig. 7f). Locally highly elongate ribbon grains are preserved. This contrasts with the largely annealed *Ds* microstructures at the same structural level. The orthorhombic *c*-axis fabrics suggest deformation with a low degree of non-coaxiality. This is supported by the presence of globular grains, i.e. relatively undeformed round grains with *c*-axes generally at a high angle to the foliation (Law *et al.* 1986). In more micaceous *Dt* tectonites, well-developed shear bands are common and indicate a consistent top to the WNW sense of shear (Fig. 7f).

Dt deforms not only annealed *Ds* microstructures but also prograde minerals developed during the Tauern metamorphism and, therefore, post date the Tauern metamorphism. Calcite–dolomite geothermometry suggests that the peak T of the Tauern metamorphism within the Matrei Zone was around 400 °C (Bickle & Powell 1977). Radiometric dating suggests that this temperature was attained <35 Ma (see above).

Youngest deformation

There are at least two geometrically distinct phases of folding, *Du* and *Dv*, that clearly deform the St foliation. Neither phase produces a penetrative fabric on more than a local scale in the present study region. Both phases are, however, widely developed and maintain consistent geometries. These phases are associated with the development of kinks and crenulations. Both *Du* and *Dv* folds have roughly WNW–ESE trending fold axes. Du folds, however, characteristically have steeply dipping axial planes in contrast to *Dv* folds that have gently dipping axial planes. Locally *Dv* folds are associated with a spaced cleavage (Figs. 7c & d).

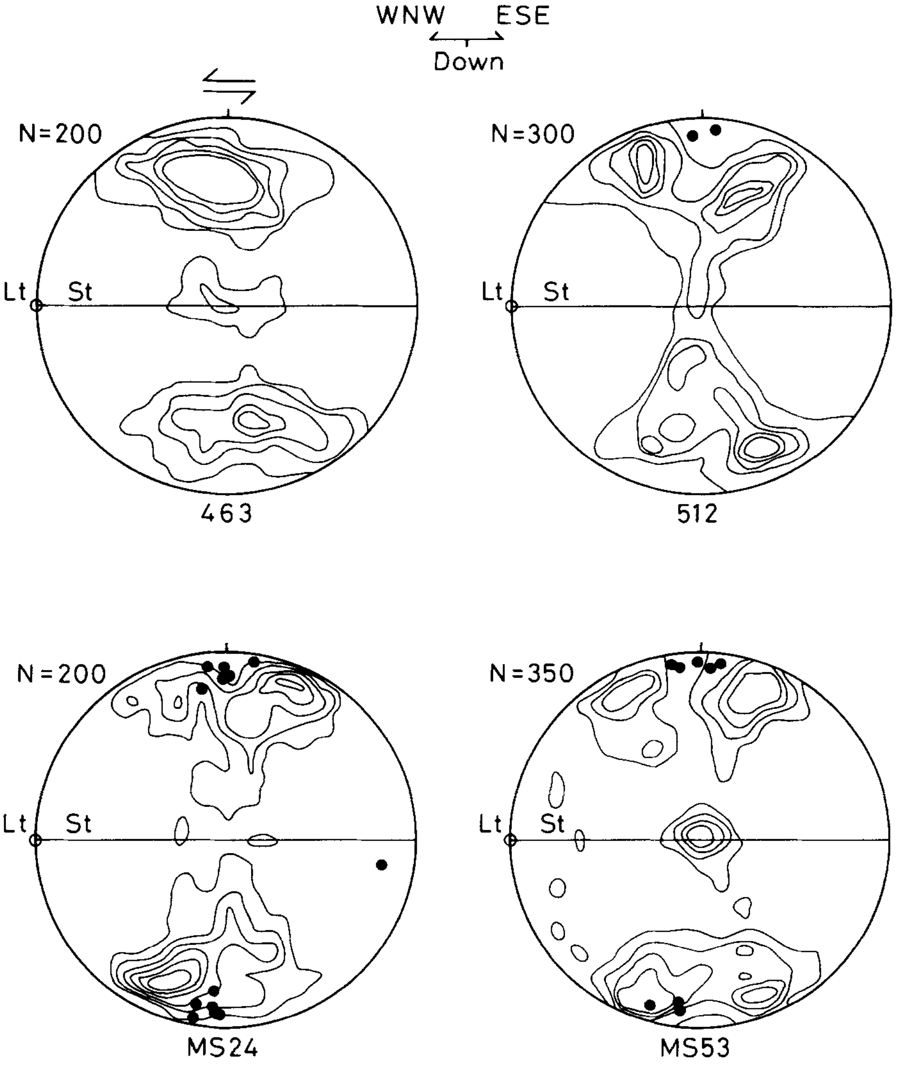

Fig. 9. *Dt* quartz *c*-axis fabrics. See Fig. 3 for location of samples. Contour intervals 1% per 1% area. Black dots give the *c*-axis orientation of globular grains. Sample number given below each diagram, the number of measured grains is given on the top left.

KINEMATICS OF *Ds* DEFORMATION

The kinematic data for most deformation phases is summarized above. For the *Ds* deformation, however, a much larger number of data could be collected and these are presented in the following section. The stretching lineation associated with *Ds* is consistently oriented NW–SE. Thin sections parallel to this lineation and perpendicular to the foliation commonly show asymmetric microstructures that can be used to determine the sense of shear. In micaceous *Ds* tectonites shear bands that intersect the main foliation roughly perpendicular to the stretching lineation are common. Two sets of shear bands with top to the NW and SE senses of displacement can be recognized, however the top to the NW set is dominant (Figs. 7g & h). Locally asymmetric strain shadows are also well-developed. These structures give a consistent top to the NW sense of shear.

In quartz-rich tectonites oblique grain-shape fabrics can locally be recognized and these fabrics give a top to the NW sense of shear consistent with the orientation of shear bands and asymmetric strain shadows. The most widely developed indicator of the *Ds* sense of shear is, however, the preferred orientation patterns of quartz *c*-axes (Figs. 10 & 11 and fig. 10 in Wallis *et al.* 1993) (Lister & Hobbs 1980, Schmid & Casey 1986). There is a trend for better developed fabrics to be found at low structural levels within the Altkristallin, reflecting the strain gradient within this unit. The *c*-axis fabrics are less-well developed in the Matrei Zone and Mallnitzer Mulde. This is probably related to the importance of solution transfer processes in the low-grade metasediment dominated units beneath the Altkristallin. When fabrics have a clear asymmetry (e.g. MS29, B69, B8, B35, K5 and others in Wallis *et al.* 1993) the inferred sense of shear is consistently top to the NW.

Albite porphyroclasts that are oriented at various angles with respect to the foliation can be observed in deformed gneiss samples (Fig. 7i). The orientation of long axes of albite porphyroclasts of different aspect

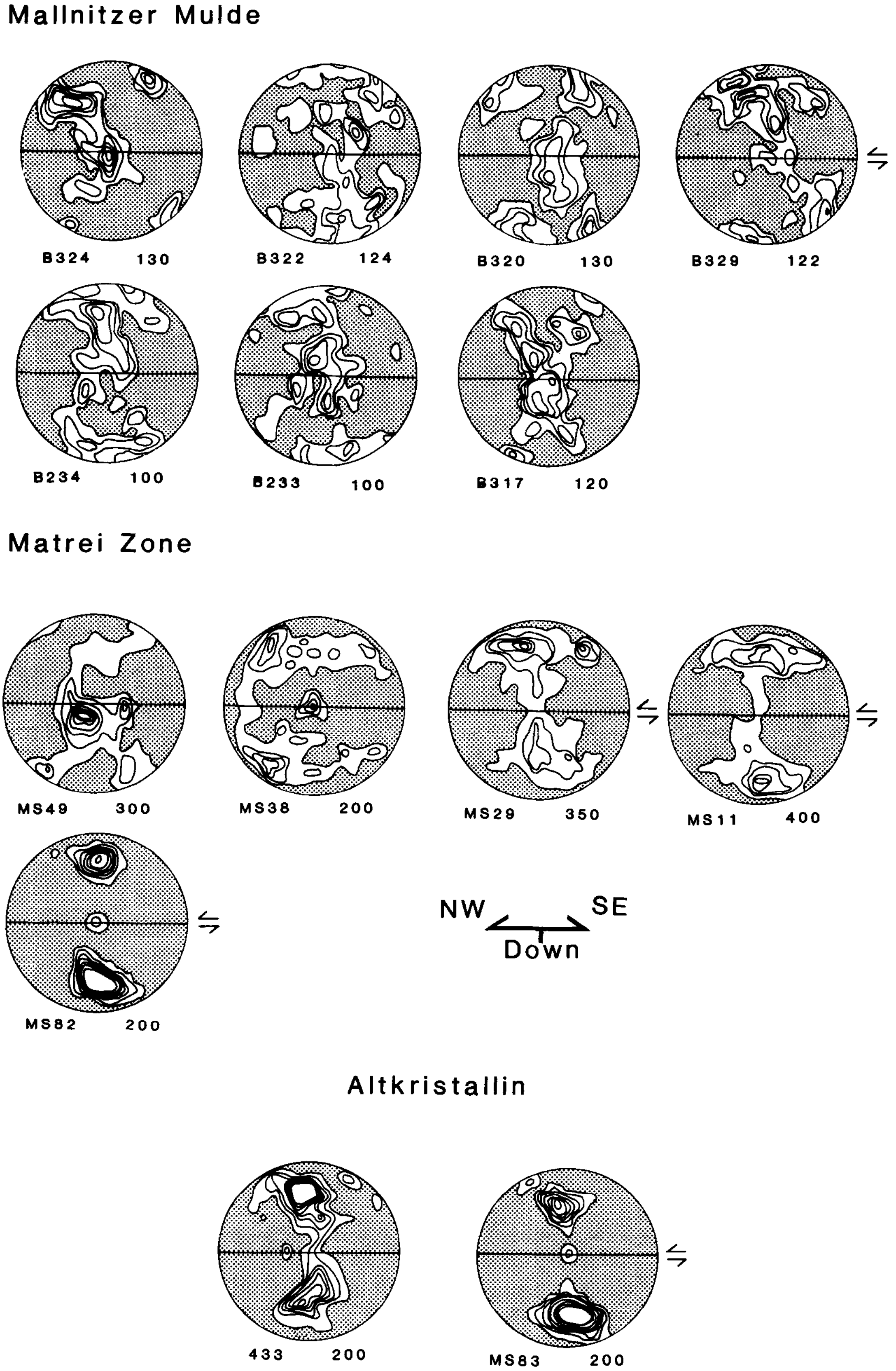

Fig. 10. *Ds* quartz *c*-axis fabrics from the Sadnig Group region including the Mallnitzer Mulde (Fig. 2) and the area covered by Fig. 3. Shaded region <1% per 1% area, contours at 1% intervals. Sample number and number of readings given at the bottom of each diagram. The fabrics are divided into three groups: (i) Mallnitzer Mulde, (ii) Matrei Zone, and (iii) Altkristallin. The data for another 10 samples from this area have already been published in Wallis *et al.* (1993) and are not repeated here. Fabric localities given in Figs. 2 and 3.

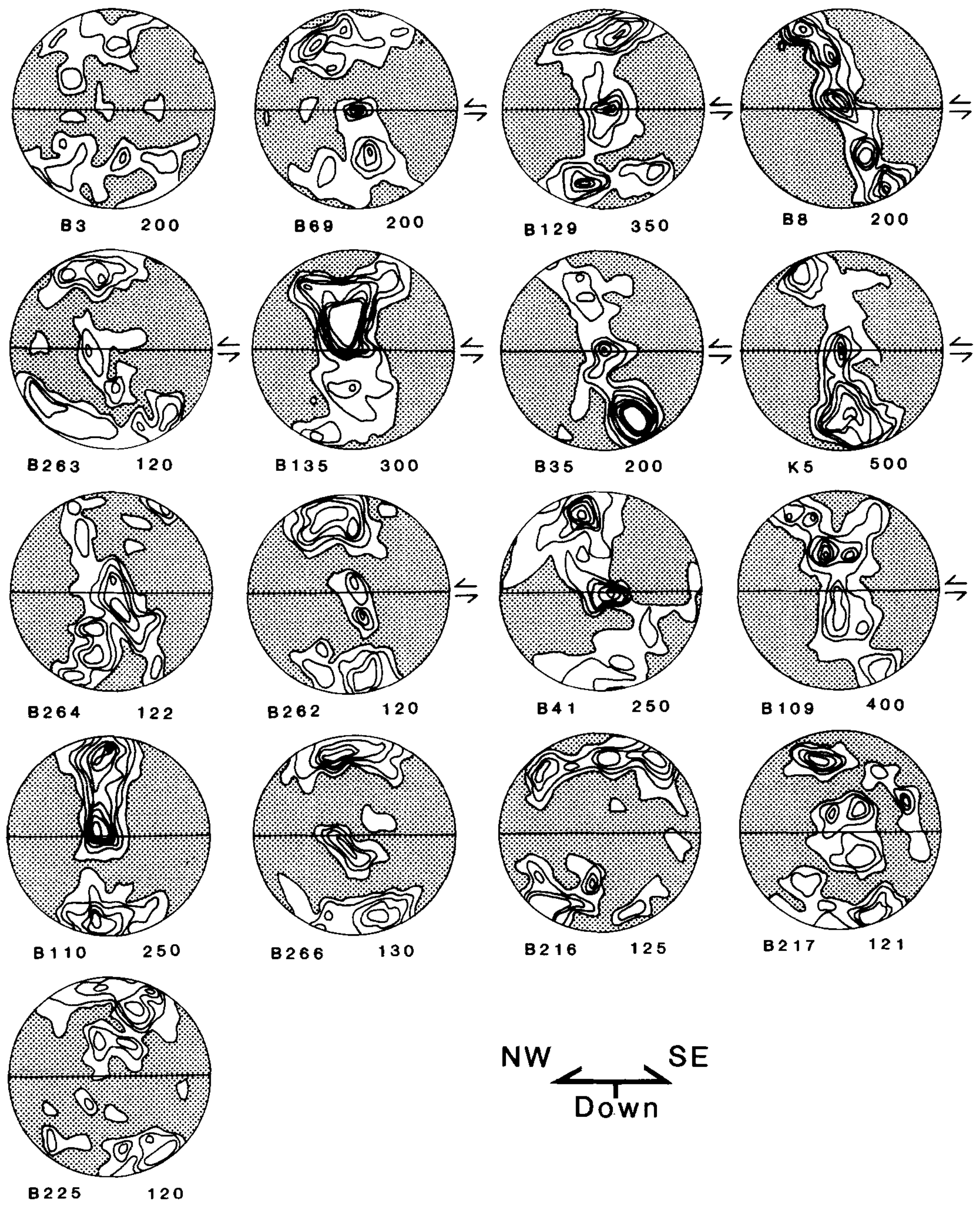

Fig. 11. *Ds* quartz *c*-axis fabrics from the Schober Group. The sample localities are given in Fig. 5. The samples are ordered from low to high structural levels. Other features are the same as Fig. 10.

ratios were measured in two samples (Fig. 12 and fig. 13b in Wallis *et al.* 1993). These data have two important features: (i) in nearly all cases the acute angle between the long axes of the clasts and the foliation has the same sense; and (ii) in general, the more equidimensional the cross section of the clast, the higher the angle that the long axis makes with the foliation. This pattern is most easily explained as the result of dextral rigid-body rotation of the albite porphyroclasts during bulk non-coaxial deformation with a dextral, i.e. top to the NW sense of shear.

Plots such as those given in Fig. 12 can also be used to estimate the degree of non-coaxiality of flow (Passchier 1987, Vissers 1989, Wallis *et al.* 1993, Wallis 1995). This analysis is based on the fact that after high strain flow with a degree of non-coaxiality less than simple shearing, rigid objects with an aspect ratio above a critical value will not continue to rotate but come to rest in some stable orientation (Ghosh & Ramberg 1976, Passchier 1987). For both samples in this study there is a distinction between grains with a relatively high aspect ratio that lie close to the foliation and those with a low aspect ratio that show less clear preferred orientation. The aspect ratio at which this change in behaviour takes place is related to the degree of non-coaxiality of the flow. In both samples this suggests a degree of non-coaxiality less than simple shear. Such a departure from simple shear can also account for the development of kinked quartz *c*-axis

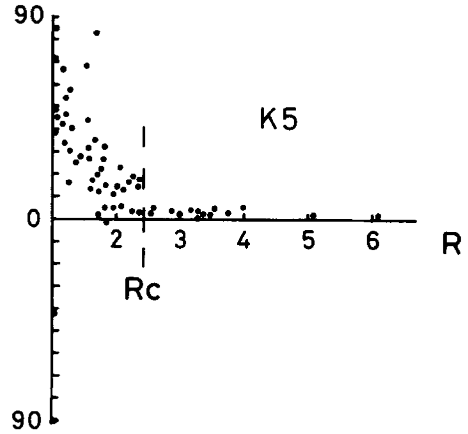

Fig. 12. Diagram showing aspect ratio (*R*) plotted against angle between long axis of albite porphyroclasts and the Ss schistosity. The dashed line is drawn for a value of $R = 2.4$ which divides clasts whose long axes lie close to the foliation and those with lower values of *R* showing a significantly larger scatter in readings. This change suggests deformation deviated significantly from simple shear. Location of sample K5 given in Fig. 5.

fabrics and conjugate sets of shear bands that are seen in the region (see Wallis *et al.* 1993 for more discussion of this point).

RELATIONSHIPS TO CRUSTAL STACKING AND EXTENSION

Crustal stacking

Prograde syntectonic Barrovian metamorphism which took place at crustal depths of at least 25 km (assuming average density of 2.75 g cm^{-3}) is widespread in the Austroalpine domain (see above). Some estimate of the amount of the associated crustal thickening can be obtained from considering the Austroalpine crust prior to metamorphism in the mid Cretaceous as follows: Late Jurassic pelagic sediments deposited in water depths of 2–3 km are widespread throughout the Austroalpine realm (Bernoulli & Jenkyns 1974), which by comparison with present-day submerged continental margins (Boillot 1981) implies a crustal thickness of 10–15 km. This in turn implies that a thickening of at least 10 km is necessary to cause metamorphism. Behrmann (1990) documents an increase in overburden thickness of about 7 km during this period using geobarometers based on the Si content of phengite (Massonne & Schreyer 1987) and the compositions of minerals in the biotite–chlorite–muscovite–quartz assemblage (Powell & Evans 1983). The timing and top to NW quadrant sense of shear of the *Dr* deformation to the south east of the Tauern area is matched by evidence for crustal thickening from other parts of the Austroalpine domain (Ratschbacher 1986, Ratschbacher *et al.* 1989, Schmid & Haas 1989, Linzer *et al.* 1995).

Following the Barrovian facies metamorphism the next phase of deformation we distinguish is imbrication at the base of the Austroalpine nappes (see above). This imbrication represents at least local shortening but it occurred after the peak of Cretaceous metamorphism suggesting it may not be related to continued burial. The duplications of sequence in the Pennine domain represent a complex sequence of events which, at least in part, are probably related to early crustal stacking.

Crustal extension

The mid Cretaceous metamorphic rocks and imbrication discussed above are overprinted by a penetrative deformation *Ds*, which affects both Pennine units and the base of the overlying Austroalpine units. The associated metamorphic ferro–magnesian minerals are dominantly chlorite and actinolitic amphibole (although locally biotite is also stable) indicating a drop in both temperature and pressure compared to *Dr* assemblages. Radiometric dating suggests that *Ds* took place from latest Cretaceous to Eocene, before major involvement of the European continental crust in the collision belt and therefore before major surface uplift and erosion. Active erosion of the Austroalpine domain is necessary to supply the detritus deposited as flysch throughout the Cretaceous (Frisch 1984). However, the widespread development of marine facies until the Tertiary shows that any associated relief was relatively minor (Trümpy 1960).

If, as argued above, thinning of the Austroalpine domain by erosion was relatively minor prior to the Eocene, decompression (or exhumation) of metamorphic rocks during this period must be related to tectonic events, or more specifically, extension. Our analysis of the tectonic fabrics related to *Ds* show that deformation is concentrated in a zone subparallel to the base of the Austroalpine domain and was associated with a degree of non-coaxiality less than simple shear. A persistent flow of this type will cause thinning perpendicular to the walls of a shear zone (see Wallis *et al.* 1993 for more details). Assuming steady flow, estimates of strain and the degree of non-coaxiality can be combined to calculate a value for thinning, in this case giving a thinning of around 40% (Wallis *et al.* 1993). An alternative approach to estimating the amount of tectonic thinning is to compare the thickness of the overburden in the eastern Alps to the depth implied by metamorphic pressures. The Austroalpine units have been been deeply incised by erosion in the Tauern region, however, projection from other areas suggests a total thickness of less than 15 km (Clar 1965, Oxburgh 1968). In contrast, pressure estimates for *Dr* mineral assemblages imply a depth of formation of 25 km. The missing 10 km gives an estimate of the amount of thinning of the Austroalpine units and the amount implied closely matches the 40% calculated from our fabric studies. We suggest, therefore, that the evidence is strongly in favour of *Ds* representing a major phase of extension and tectonic thinning in the Austroalpine domain.

Dt overprints *Ds* structures and is younger than the Tauern metamorphism. Similar to *Ds*, this deformation is associated with a low degree of non-coaxiality and a top to the WNW sense of shear which may indicate a relationship with late Tertiary extension. However, such relationships could not be established in the present study.

DISCUSSION

A note on 'transpression' versus oblique convergence

Tectonic studies in the eastern Alps, including our own, show that deformation is polyphase and consistently oblique to the documented general E–W trend of facies boundaries and former continental margins. In the literature on the tectonics of this region the term 'transpression' has commonly been used to emphasize this obliquity of tectonic transport during convergence between the European and Austroalpine continental domains. Transpression is a term originally coined by Harland (1971) as a synonym for oblique plate convergence. The term subsequently fell into disuse until resurrected by Sanderson & Marchini (1984), who use the term in a rather different way: to express a particular kinematic picture resulting from a combination of horizontal shortening and strike-slip tectonics. In this second case, transpression can be thought of as shorthand for a tectonic regime of non-coaxial non-plane strain flow where a vertically oriented vorticity vector is stretching along its length. The associated planer tectonic fabric should be subvertical, although it may be related to low-angle thrusts through the development of flower structures. In the eastern Alps, however, tectonic fabrics that formed during convergence between the Austroalpine and European domains are not generally subvertical and most workers assume deformation is broadly plane-strain (Ratschbacher & Oertel 1987, Ratschbacher *et al.* 1989, Wallis *et al.* 1993), with negligible stretching along the vorticity vector. In such cases it seems otiose to apply the term 'transpression' to tectonic movements which are quite adequately described by the unambiguous term 'oblique convergence'. 'Transpression' does, however, seem to be a useful term for describing a complex type of non-coaxial deformation in the narrower sense of Sanderson & Marchini (1984).

Emplacement of the Austroalpine domain

The tectonic fabrics of the southeast Tauern and adjacent regions provide evidence for a poly phase emplacement history of the Austroalpine domain. There are two main ductile deformation events: (i) a mid Cretaceous phase (*Dr*) related to prograde metamorphism and crustal thickening of the order of 10 km; and (ii) a second late Cretaceous to early Tertiary phase (*Ds*) which is associated with decompression and thinning of a similar order to the thickening. Although representing distinct periods of crustal stacking followed by crustal extension, both phases contributed to the cumulative displacement of the Austroalpine domain to the NW quadrant. An important conclusion of this and other recent tectonic studies (Wallis 1988, Ratschbacher & Neugebauer 1989, Ratschbacher *et al.* 1989, Behrmann 1990, Wallis *et al.* 1993, Linzer *et al.* 1995) is that throughout Alpine times the Austroalpine domain has undergone regional penetrative deformation. The widespread polyphase deformation implies that the Austroalpine domain cannot be treated as a rigid sheet emplaced rapidly during a single event, as assumed in several attempts to relate tectonics to the post-collisional metamorphic history of the eastern Alps (Oxburgh & Turcotte 1974, Bickle *et al.* 1975, Oxburgh & England 1980).

Despite the strong internal deformation of the Austroalpine domain the kinematic indicators are strikingly consistent. During phases related to both thickening and thinning the dominant sense of shear is top to the W quadrant. This may help to constrain large-scale plate movements (Platt *et al.* 1989). There is, however, local evidence suggesting that there may also have been some early movements to the NE quadrant (Sonnblick gneiss region—Exner 1964, Behrmann & Wallis 1987, Krohe 1987, Wallis 1988, Behrmann & Ratschbacher 1989). These phases of deformation took place under contrasting metamorphic conditions and it is unlikely that they can be simply correlated. It may, however, be premature to exclude the possibility of significant movements to the NE quadrant during the early stages of convergence. Such a motion would be compatible with the Africa–Europe plate motion between 118 and 65 Ma (Dewey *et al.* 1989).

CONCLUSIONS

Structural analyses of tectonic fabrics in the southeast Tauern region reveal a polyphase history with a dominant displacement of the structurally higher tectonic units to the NW quadrant. Two main phases of ductile deformation can be identified which can be related to an initial phase of crustal stacking followed by a phase of thinning. Microstructural observations and radiometric dating show that the earlier phase took place synchronously with a mid Cretaceous Barrovian metamorphism, which in the study area occurred at depths of around 25 km. Comparison with estimates of pre-convergnence thickness of the Austroalpine domain implies that crustal thickening of around 10 km is required to explain the metamorphism. Ductile extension affects the base of the Austroalpine domain and parts of the underlying Pennine domain. Quantitative analysis of the rotational and stretch components of deformation suggests an associated thinning of around 40%. A similar value of thinning on a larger scale is suggested by comparing the potential overburden in the eastern Alps to the depth of burial implied by the earlier metamorphism. Radiometric dating shows that this phase of ductile extension took place between latest Cretaceous and early Tertiary and before the involvement of stable European basement in the collision zone. This suggests that pre-collisional extensional tectonics in the eastern Alps may be more important than generally recognized.

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