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Autor: Platt, John P. / Compagnoni, Roberto

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Alpine ductile deformation and metamorphism in a Calabrian basement nappe (Aspromonte, south Italy)

By John P. Platt[1]) and Roberto Compagnoni[2])

ABSTRACT

The Aspromonte Unit in southernmost Calabria and NE Sicily is a thrust sheet of Variscan amphibolite-facies gneiss, forming part of the Calabrian nappe complex. This assemblage of crystalline nappes, metamorphosed ophiolites, and flysch was emplaced onto the margins of Adria and North Africa probably in early Miocene time, prior to the formation of the Apennine and Maghrebide thrust belts and the southeastward migration of the Calabrian arc in front of the opening Tyrrhenian Sea.

Parts of the Aspromonte Unit were affected by greenschist-facies metamorphism and related ductile deformation of Alpine (i.e., post-Variscan) age. Two stages in the metamorphic evolution can be distinguished. The earlier stage is undated, but may have immediately predated the second. It is characterized by moderately high-pressure assemblages including kyanite, garnet, chloritoid, blue-green amphibole, albite, and zoisite/clinozoisite: peak conditions reached 500±30 °C and 5±1 kbar. Crystallization was mainly static: moderate ductile deformation preceded and locally accompanied metamorphism. This stage may have been associated with crustal thickening. The second stage is characterized by biotite and/or chlorite, white mica, and albite/oligoclase, and occurred under lower pressure conditions than the first. It is dated at 25-30 Ma. It was accompanied by intense ductile deformation that produced a flat-lying mylonitic foliation, a strong N-S stretching lineation, and several sets of folds and shear-bands. The sense of shear was consistently towards the north. This deformation appears to have been related to uplift and exhumation of the Aspromonte Unit, which reached the surface by late Oligocene or early Miocene time.

RÉSUMÉ

L'Unité de l'Aspromonte, située à l'extrême sud de la Calabre et au nord-est de la Sicile, est une nappe de gneiss de faciès amphibolite, d'âge varisque, constituant une partie de l'ensemble de nappes calabraises. Cet ensemble de nappes cristallines, ophiolites métamorphisées et flysch, a été mis en place sur les marges des plaques Adria et Nord-Africaine, probablement au début du Miocène, avant la formation des chaînes à nappes de l'Apennin et du Maghreb, et la migration vers le sud-est de l'arc calabrais, face à l'ouverture de la mer tyrrhénienne.

Des parties de l'unité de l'Aspromonte ont été affectées par un métamorphisme de faciès schistes verts et soumises à une déformation ductile d'âge alpin (postvarisque). On peut distinguer deux phases dans l'évolution métamorphique. La première n'est pas datée mais elle s'est probablement produite à la fin du Crétacé ou au Paléogène. Elle est caractérisée par des paragenèses de pression moyennement élevée comprenant le disthène, le grenat, le chloritoïde, l'amphibole bleu-vert, l'albite et la zoïsite/clinozoïsite; les conditions maximales atteintes ont été de 500±30 °C et 5±1 kbar. La cristallisation a été essentiellement statique: une déformation ductile modérée a précédé et localement accompagné le métamorphisme. Cette phase a dû être associée à un épaississement de la croûte. La seconde phase est caractérisée par la biotite et/ou la chlorite, le mica blanc, et l'albite/oligoclase, et s'est produite dans des conditions de pression inférieures à celles de la première phase. Elle est datée de 25-30 Ma. Elle s'est accompagnée d'une intense déformation ductile qui a produit une foliation mylonitique sub-horizontale, une forte linéation d'étirement N-S et plusieurs séries de plis et de bandes de cisaillement. Le sens de cisaillement est uniformement au nord. Cette déformation semble avoir été en relation avec le soulèvement et l'exhumation de l'unité de l'Aspromonte, qui a atteint la surface à la fin de l'Oligocène ou au début du Miocène.

[1]) Department of Earth Sciences, Oxford University, Oxford OX1 3PR, England.

[2]) Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 37, 10125 Torino, Italy.

Introduction

The Calabrian arc (Fig. 1) extends from the toe of Italy (Calabria) into Sicily, thereby linking the Neogene thrust belt of the Apennines (thrust NE) with that of the Maghrebides in Sicily and North Africa (thrust S or SE). Geologically and tectonically, however, it is quite distinct from these two chains. The Mesozoic carbonate rocks of the southern Apennines disappear southwards in Calabria under a series of thrust sheets composed (from top to bottom) of continental crystalline rocks, ophiolites, and Cretaceous to Miocene flysch (Amodio-Morelli et al. 1976). The ophiolitic and flysch units have locally been affected by high P/T ratio metamorphism (Beccaluva et al. 1982). In the Peloritani Mountains of Sicily the Calabrian crystalline nappes are juxtaposed against Maghrebide flysch along the transpressive Longi-Taormina Line. These relationships seem to have resulted from the emplacement in early Miocene time of the Calabrian nappe complex onto the continental margins of North Africa and of Adria (the continental lithosphere underlying the Adriatic Sea and the east and north of Italy). Thrusting continued through the Neogene in both the Apennines and Maghrebides, as well as in the external Calabrian arc, which lies offshore in the Ionian Sea (Fig. 1). This was accompanied by southeastwards migration of the Calabrian arc

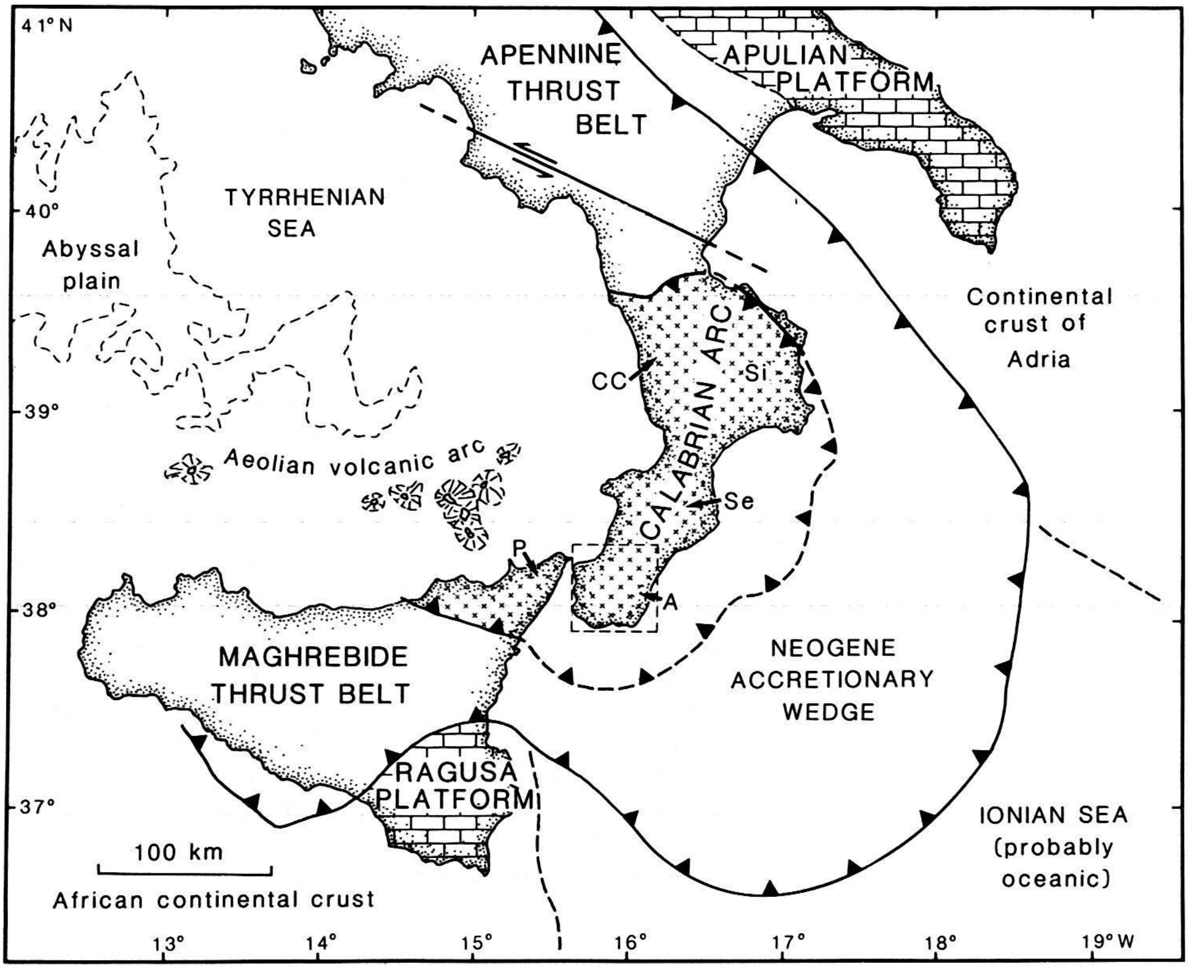


Fig. 1. Sketch map showing the main tectonic elements around the Calabrian arc. A, Aspromonte massif; CC, Catena Costiera; P, Peloritani mountains; Se, Serre massif; Si, Sila massif.

as a whole, a process accommodated by the opening of the Tyrrhenian Sea behind it, and subduction of Ionian Sea crust in front of it (SCANDONE 1982; MALINVERNO & RYAN 1986; DEWEY et al. 1989). During this process, the Calabrian arc was significantly modified by both extensional and strike-slip tectonics (BOCCALETTI et al. 1984).

The provenance and tectonic history of the Calabrian nappes have long been subject to debate. AMODIO-MORELLI et al. (1976) proposed that the crystalline thrust sheets originally formed the basement of the leading western margin of Adria. Convergence along this margin in late Cretaceous or Palaeogene time caused them to be emplaced northwestwards onto Tethyan ophiolites, forming what they considered to be a southern extension of the Alpine chain. During subsequent collision with the European continental margin (represented by Corsica/Sardinia), the whole complex of basement sheets and ophiolites was thrust in the opposite direction (east and south) onto the African and Adrian margins. The collisional chain was then disrupted by the opening of the Tyrrhenian Sea. This concept of an early "Europe-vergent" phase of thrusting in the Calabrian nappes, which has been generally accepted for the last decade, was based on the overall geometry of the thrust-sheets, which become thinner to the north and west, and on limited structural evidence (ALVAREZ 1976, FAURE 1980). There is, however, an alternative simpler scenario (OGNIBEN 1973, BOUILLIN 1984, BOUILLIN et al. 1987, KNOTT 1987, DIETRICH 1988, DEWEY et al. 1989), in which the Calabrian basement nappes represent the leading edge of Europe, and were emplaced progressively eastwards onto ophiolitic crust and flysch, and then onto the Adrian and African margins in early Miocene time.

Very little systematic structural information has been published from the Calabrian arc. CARRARA & ZUFFA (1976) documented E-W-trending stretching lineations from deformed crystalline rocks of the Bagni and Castagna Units in the Catena Costiera. FAURE (1980) studied similar rocks in the Sila massif, and reported that mylonites there indicated an early W-directed and late E-directed shear sense, supporting the ideas of AMODIO-MORELLI et al. (1976) on a change in polarity of the thrusting. DIETRICH (1988) showed evidence for an E-directed shear sense in the Catena Costiera, and KNOTT (1987) for NE-directed thrusting of probable Oligocene age in the underlying flysch nappes. No kinematic data are available from further south.

The research reported on here was aimed at obtaining information on the deformational history of the Aspromonte Unit (Fig. 2), which is one of the crystalline thrust sheets in the Calabrian arc. Our work arose out of the discovery in this unit of Alpine (i.e., post-Variscan) metamorphic events (BONARDI et al. 1984b). We have been able to relate ductile deformation fabrics to the metamorphic history, and hence to radiometric dates (BONARDI et al. 1987). A structural map of part of the Aspromonte Unit (Fig. 3), a cross-section (Fig. 4) and structural data (Fig. 5) illustrate some aspects of the internal structure of this unit. Our results were unexpected, in that the dominant structures in the unit were caused by N-directed shear, and are probably related to exhumation rather than to nappe emplacement.

Geological setting of the Aspromonte Unit

The Aspromonte Unit occupies much of the Aspromonte massif in southernmost Calabria (Fig. 2) and extends across the Strait of Messina into the Peloritani Mountains

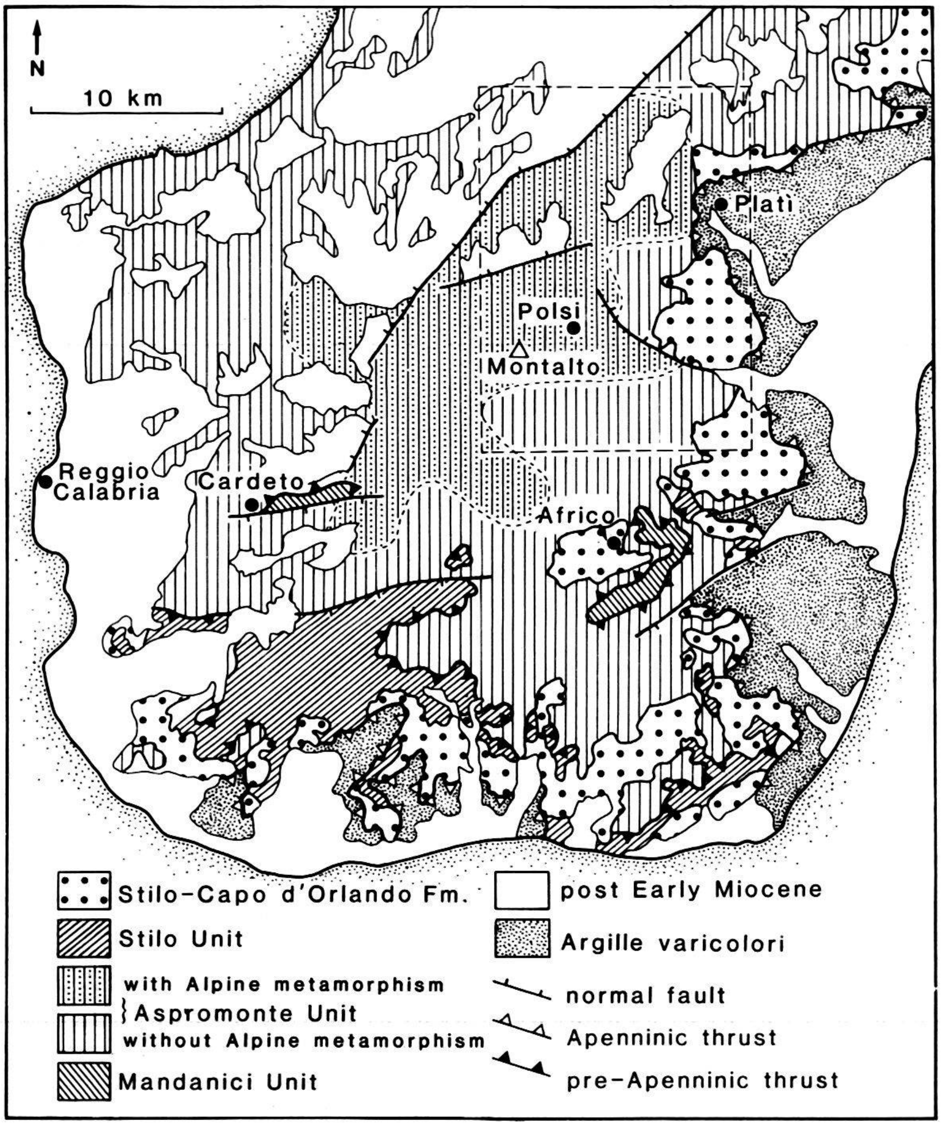


Fig. 2. Geological sketch map of the Aspromonte massif (for location see Fig. 1) showing the areas in the Aspromonte Unit known to contain the Alpine index minerals garnet, kyanite, chloritoid and biotite (after Bonardi et al. 1984). Mandanici Unit refers to Palaeozoic phyllites exposed in the Africo and Cardeto windows.

of Sicily. It comprises a distinctive lithological assemblage of upper amphibolite-facies paragneiss, biotitic orthogneiss, augengneiss, minor amphibolite and marble, abundant pegmatite and aplite dykes, and larger intrusive bodies of granite. Structural relationships with surrounding rocks suggest that it is a thrust sheet with tectonic contacts above and below. In the Peloritani Mountains it forms the highest of several thrust sheets (Bonardi et al. 1976). The lower units (Mandanici and Fondachelli) include low to medium grade Palaeozoic phyllite, and remnants of Mesozoic-Palaeogene cover sequences. The relations among these units may partly reflect Variscan events (Chabrier & Mascle 1979), but the presence of intercalated Mesozoic cover sequences indicates significant post-Palaeozoic thrusting (Bonardi et al. 1976). In the Aspromonte massif, phyllites similar to the Mandanici unit occur locally in tectonic

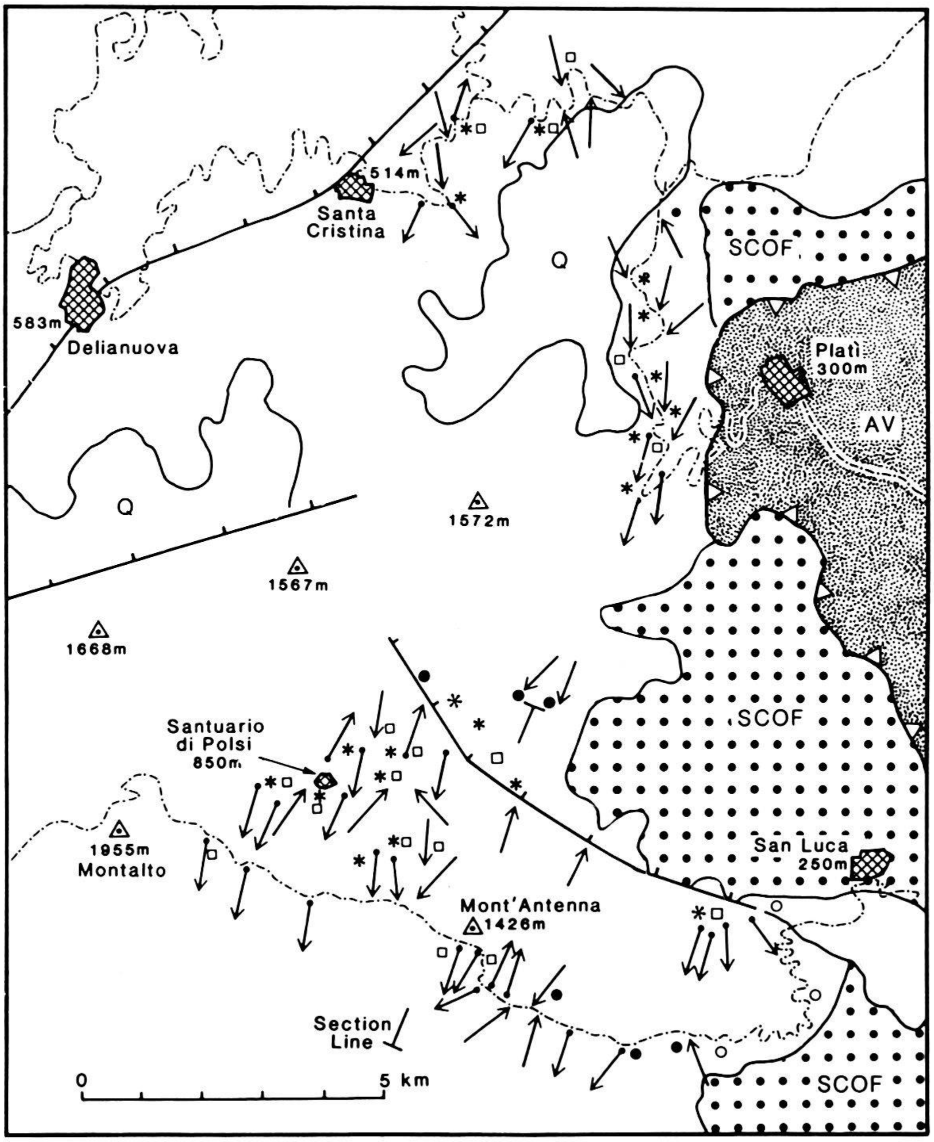


Fig. 3. Structural map of part of the Aspromonte Unit (for location see Fig. 2), showing the trend of mylonitic stretching lineations, and the nature of the Alpine metamorphism. Fault symbols as on Fig. 2. Open circles: no detectable Alpine metamorphism, cataclastic deformation only. Filled circles: chlorite zone. Stars: early Alpine assemblages including garnet, kyanite, or chloritoid. Squares: late Alpine assemblages including biotite. AV: Argille varicolori thrust sheet. Q: Quaternary terrace deposits. SCOF: Stilo-Capo d'Orlando Formation.

windows near Africo and Cardeto (Fig. 2, after Bonardi et al. 1980b). On the north and southwest margins of the massif a higher thrust sheet, the Stilo Unit, composed of low-medium grade phyllites with granite intrusives, lies above the Aspromonte Unit (Bonardi et al. 1984a).

The Calabrian nappes in the Aspromonte massif and Peloritani mountains are overlain unconformably by the late Oligocene(?) to early Miocene Stilo-Capo d'Orlando formation (Bonardi et al. 1980a). This is overlain in turn by the Argille Varicolori Unit, a thrust sheet of mainly Cretaceous pelagic argillite and Tertiary clastics, that must have been emplaced in Middle Miocene time (Fig. 2). No structural

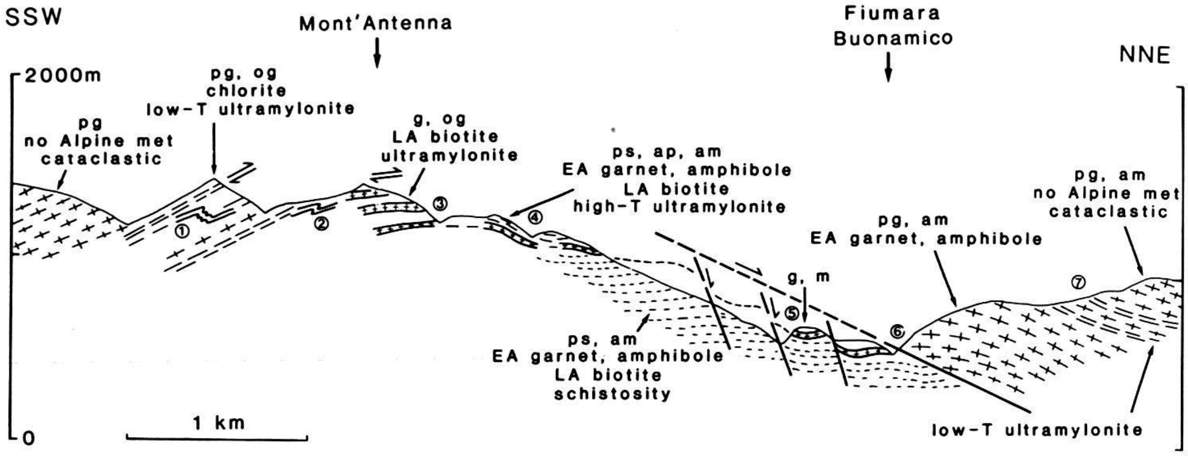


Fig. 4. Sketch section across the Fiumara Buonamico between Santuario di Polsi and San Luca (see Fig. 3 for location). *Lithological abbreviations:* am, amphibolite; ap, aplite; g, granite; m, marble; og, orthogneiss; pg, paragneiss; ps, paraschist. *Notes.* (1) Low-temperature ultramylonite with 10 m scale syn- and post-mylonitic folds associated with an intense crenulation fabric. Alpine chlorite only. (2) Ultramylonite with fine-grained biotite. Intense small-scale syn-mylonite folds. Stretching lineations very variable: refolded in the plane of the mylonitic foliation. (3) Granite sheets interlayered with ultramylonitic orthogneiss. Late Alpine biotite, dynamic recrystallization of plagioclase. (4) Finely laminated bands of mylonitic aplite, paraschist, and amphibolite. Early Alpine garnet and green amphibole; coarse late Alpine biotite. Dynamic recrystallization of plagioclase. Late N-vergent folds. (5) Sheets of granite and marble overlie grey paraschist with layers and boudins of amphibolite. Regional Alpine schistosity with garnet, amphibole, biotite and plagioclase. Series of steep normal faults drops sequence down to N. (6) Major low-angle normal fault (dip 20–30° N) brings down massive amphibolite and paragneiss with early Alpine blue-green amphibole and garnet, rare late Alpine biotite. (7) Very low-temperature ultramylonite, cataclasite and fault gouge in paragneiss and amphibolite; Alpine chlorite only.

information on its sense of emplacement is available, but its position suggests that it was emplaced by W-directed backthrusting onto the Calabrian Units as they moved E or SE relative to Adria and Africa.

Metamorphism

The metamorphic history of the Aspromonte Unit reported by Bonardi et al. (1984b) provides essential constraints on our interpretation of the structure, and will be summarized here, together with our most recent findings.

Variscan metamorphism

The Aspromonte Unit was metamorphosed during the Variscan orogeny under amphibolite-facies conditions, and a common relict assemblage in paragneiss is quartz + plagioclase + biotite + garnet + K-feldspar + sillimanite. Coarse white mica occurs everywhere in such rocks as a result of late-stage rehydration of the K-feldspar + sillimanite assemblage, and in some areas there are abundant late porphyroblasts of andalusite up to 5 cm long. Amphibolites locally have layers with cummingtonite, clinopyroxene, or garnet, and diopside occurs in some calc-silicate layers. Preliminary Rb/Sr dates on mica separates (Bonardi et al. 1987) suggest that this metamorphism peaked at or before 330 Ma.

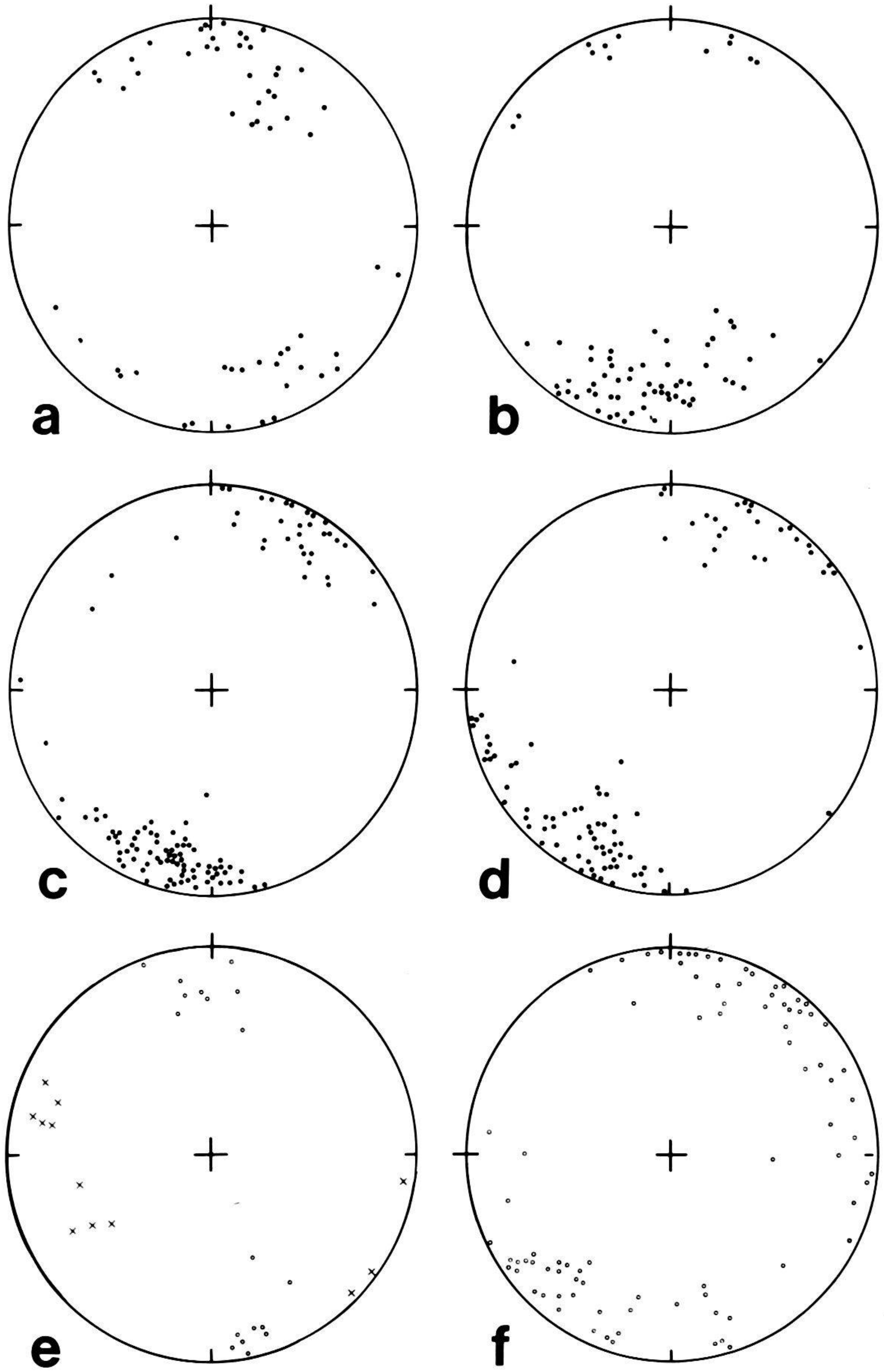


Fig. 5. Structural data from the part of the Aspromonte Unit shown in Figure 3. (a–d) Late Alpine mylonitic stretching lineations from around (a) Santa Cristina, (b) Platì, (c) Polsi, and (d) Mont'Antenna to San Luca. (e) Variscan fold axes (crosses) and early Alpine mineral and stretching lineations (filled circles). (f) Late Alpine fold axes (mainly syn-mylonite folds).

Alpine metamorphism

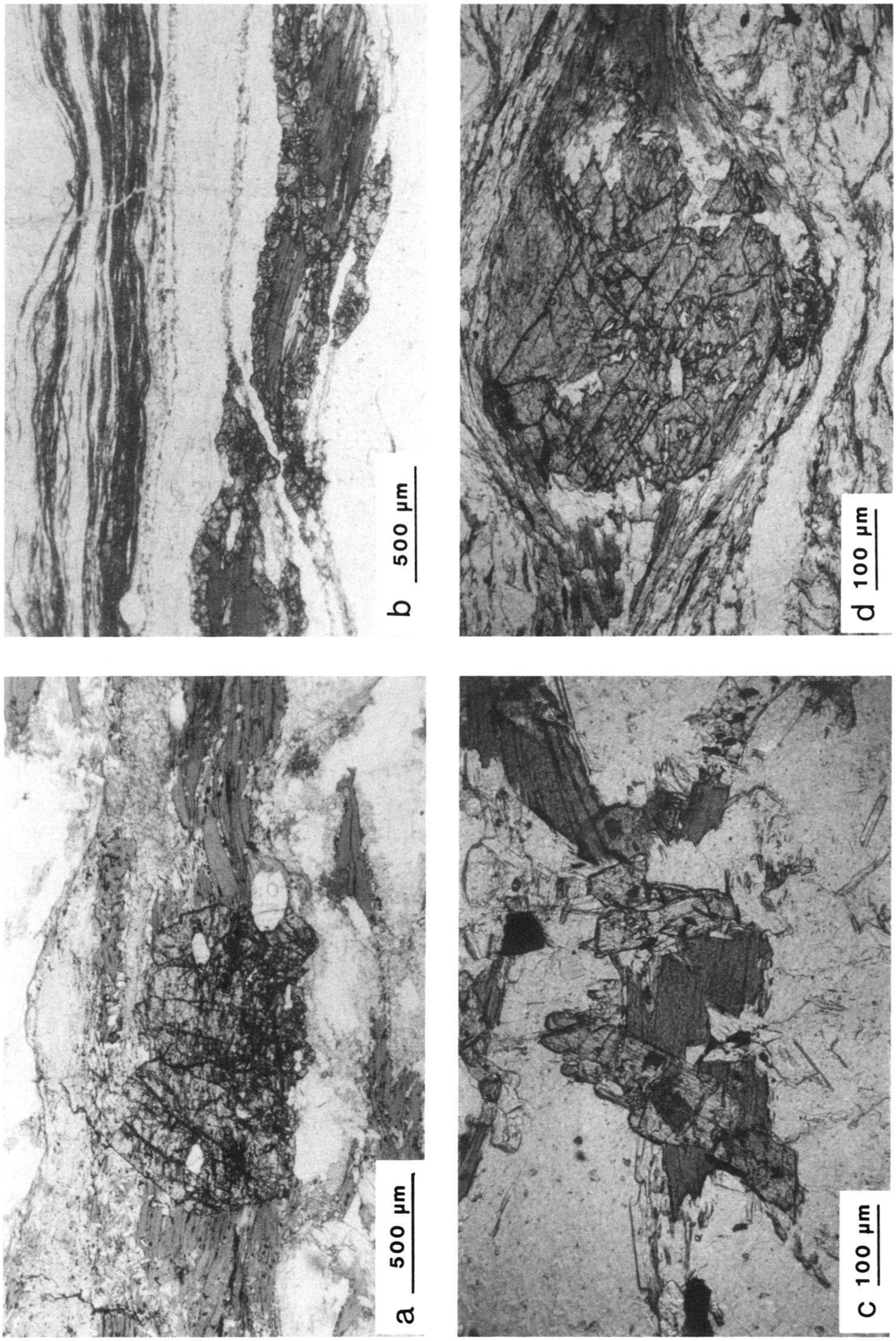
In the central part of the unit, the Variscan assemblages were variably retrogressed under greenschist facies conditions during tectonic events that we infer to be of Alpine age (Figs. 2 and 3). The Alpine metamorphic evolution was probably continuous, but we recognize two stages for convenience, partly on the basis of differing mineral assemblages, and partly by their different microstructural characteristics. The first stage apparently occurred under somewhat higher pressure than the second, and in many areas was apparently static in character. The second stage, by contrast, was commonly associated with strong ductile deformation, which produced mylonitic or ultramylonitic microstructures in some areas. Both sets of assemblages tend to be localized in anastomosing zones that surround islands of largely unaltered Variscan gneiss, and first stage assemblages are commonly overprinted by the second. Reactions rarely proceeded to completion during either stage, so that in many cases we are dealing with disequilibrium assemblages, involving armoured and pseudomorphous relationships. Only in the east-central part of the Aspromonte Unit, around Madonna di Polsi (Fig. 2) were the rocks completely re-equilibrated during the Alpine events.

We refer to these stages here as early and late Alpine, but we do not intend to imply any correlation with metamorphic events in the Alps themselves. The timing of the first stage is unknown, but it must postdate the Variscan metamorphism, from which it differs markedly in character. It could be related to the high-P low-T metamorphism in the ophiolitic units of Calabria, of probable late Cretaceous-Palaeogene age (Amodio-Morelli et al. 1976), and it may well have immediately preceded the second stage. Rb/Sr dates on mica separates from rocks thoroughly recrystallized during the second stage cluster around 25–30 Ma (late Oligocene) (Bonardi et al. 1987). A rough younger age limit is also provided by the unconformity with the late Oligocene(?) to early Miocene Capo d'Orlando formation.

The first Alpine stage produced the following transformations in paragneiss and pelitic schist.

a) Sillimanite may be altered to fine-grained kyanite or chloritoid, commonly along kink-bands and shear zones. Alternatively, it may be pseudomorphed by masses of decussate sericitic white mica, containing large randomly oriented crystals of chloritoid, white mica, garnet, or chlorite.
b) Biotite is commonly partly replaced by almandine garnet, which can be distinguished from Variscan garnet by fine plates of ilmenite exsolved parallel to the basal plane of the original biotite (Fig. 6a and b). In some rocks, however, it is partly replaced by blue-green amphibole (Fig. 6c).

Fig. 6. (a) Early Alpine garnet formed at the expense of Variscan biotite in paragneiss. Ilmenite exsolved parallel to cleavage in the biotite forms distinctive inclusion trails in the garnet. The biotite shows signs of extension along the foliation before growth of the garnet. Lenticular aggregates of sericitic white mica above the central biotite band have replaced Variscan sillimanite. (b) Quartz-rich paragneiss with early Alpine mylonitic lamination. Dark laminae (above) consist of very fine-grained kyanite formed at the expense of Variscan sillimanite. Variscan biotite (below) is partly replaced by early Alpine garnet along shear bands and grain-boundaries. (c) Paragneiss with Variscan biotite partly overgrown by early Alpine blue-green amphibole. Note the lack of Alpine deformation. (d) Early Alpine blue-green amphibole as augen in late Alpine mylonitic schist. Late Alpine biotite has formed in the pressure shadows. Sense of shear is top to the right (N).


a 500 µm
b 500 µm
c 100 µm
d 100 µm

c) In amphibolite and metagranitoid rocks, plagioclase is altered to albite + zoisite/clinozoisite ± sericitic white mica.
d) In metabasic and ultrabasic rocks, green to blue-green amphibole has formed at the expense of hornblende and clinopyroxene.

These assemblages suggest a relatively high-pressure greenschist-facies metamorphism, reaching 500 ± 30 °C and 5 ± 1 kbar (Bonardi et al. 1984b).

The second Alpine stage is characterised in particular by a new generation of fine-grained biotite that has developed in pressure-shadows and pullaparts around blue-green amphibole and garnet of stage 1 (Fig. 6d and e), in shear-bands (Fig. 6f), and distributed together with fine-grained white mica and chlorite throughout the matrix of more strongly deformed rocks. The relative proportions of chlorite and biotite that formed in this stage vary, and reflect temperature differences during this event. Fracture (of feldspar, garnet, amphibole and mica), and dynamic recrystallization (of quartz, Fig. 6g, and of plagioclase in the highest temperature areas, Fig. 6h) contributed to the overall reduction in grain-size. As a result, rocks that have been strongly affected by this event have the field appearance of fine-grained mica-schist, phyllonite, or mylonite. In metabasic rocks, there was some recrystallization of actinolitic amphibole during this event, plus growth of chlorite, biotite, and sodic plagioclase.

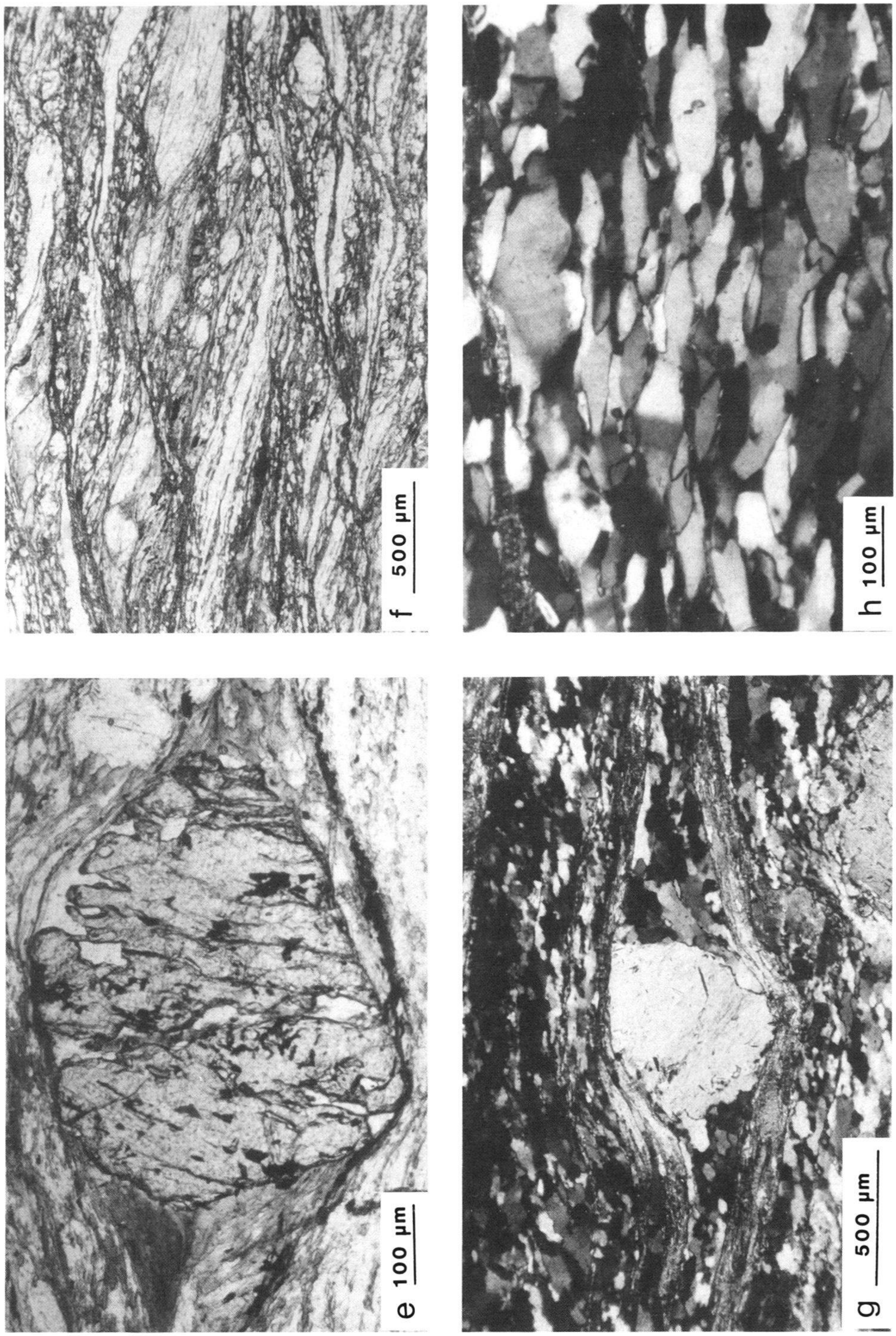
We cannot yet determine precisely the physical conditions during the second stage, but the appearance of biotite at the expense of garnet and amphibole suggests a decrease in pressure relative to the first stage.

Structure

The Aspromonte Unit is bounded above and below by major tectonic contacts of Alpine age. The nappe itself, which is probably several km thick, has a complex internal structure produced by the superposition of Alpine deformation on several sets of Variscan structures. The most prominent marker units are sheets and pods of granite gneiss, augengneiss, pegmatite, aplite, and amphibolite that are discontinuous and probably had irregular original geometries. Large-scale structures are therefore difficult to identify. The main emphasis of our research has been to establish zones of high Alpine strain, and to determine the kinematics of the Alpine deformation.

On a small scale, the structure is locally quite complicated, involving several sets of superposed structures. In zones of high strain several sets of structures may be produced in a single progressive tectonic event (e.g. Cobbold & Quinquis 1980), so we have not attempted to identify or correlate deformation "phases" based on single sets of associated structures. We have instead related the observed structures and microstructures to the three sets of metamorphic assemblages, which represent significantly different P-T conditions and which developed at different times.

Fig. 6. (e) Early Alpine garnet with ilmenite inclusion trails as rotated augen in late Alpine mylonitic schist. Late Alpine biotite has formed in the pressure shadows. (f) Shear bands in micaceous phyllonite derived from Variscan paragneiss by late Alpine mylonitization. The bands are occupied by fine-grained late Alpine biotite. Sense of shear is top to the left (N). (g) Asymmetric quartz-filled pressure shadows around feldspar augen in late Alpine mylonitic orthogneiss. Note oblique new grain-shape fabric in dynamically recrystallized quartz (top). Sense of shear is top to the right (N). (h) Dynamically recrystallized plagioclase in late Alpine high-temperature mylonite.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g 500 µm

Variscan structures

The Variscan gneisses are characterised by regionally sub-horizontal layering and a foliation defined by lenticles of quartz, feldspar, and oriented micas, amphibole, and sillimanite. The gross parallelism of augengneiss sheets and related granitoid dykes to this foliation, and the presence of tight to isoclinal folds, particularly visible in amphibolites, suggest that it was caused by substantial distributed ductile strain. Related linear structures, including fold axes, are very poorly developed, and have been largely overprinted by Alpine deformation in the areas we have studied. Those structures we were able to measure are plotted in Fig. 5e, but their orientations are unlikely to be significant.

Some pegmatite and aplite dykes cut the gneissic foliation, and appear to lack Variscan deformation fabrics. Undeformed granitoid bodies from the western side of the massif have yielded Rb/Sr whole rock ages ranging from 280–300 Ma (Del Moro et al. 1982, Paglionico 1985). This age may therefore provide a younger limit to the age of foliation.

Some small-scale close to tight folds that deform the gneissic foliation are also of Variscan age. In paragneisses Variscan biotite has been kinked and crenulated, and a new generation of coarse biotite has developed roughly parallel to the axial-plane of the folds. In some examples both generations of biotite are overgrown by early Alpine blue-green amphibole.

Early Alpine structures

Early Alpine minerals commonly overgrow the Variscan fabric helicitically, and replacement minerals in pseudomorphs are randomly oriented, suggesting that there was little ductile deformation at this time. There is some evidence, however, for deformation before, and locally during, mineral growth. Paragneisses with early Alpine assemblages are consistently finer-grained and better foliated than pristine Variscan gneiss. This appears to have been mainly a result of stretching in the plane of the foliation, causing microboudinage and pinch-and-swell structures in Variscan platy and tabular minerals such as biotite and sillimanite (Fig. 6a). The minerals were mechanically pulled apart and the degree of their preferred orientation increased. In most areas this stretching predated the growth of the early Alpine minerals, which lack preferred orientation.

Some samples also show evidence for synkinematic transformations. Figure 6b shows an apparently mylonitic banding in a quartz-biotite-kyanite-garnet schist. One band consists of fine-grained well orientated kyanite needles, suggesting that kyanite grew or was stable during the deformation. In the same sample, early Alpine garnet has started to replace Variscan biotite along a shear-band. Shear-bands of this sort are typical of the effects of the early Alpine stretching described above: in this case it presumably predated growth of the garnet, which was able to grow more rapidly where diffusion paths were available to allow the reaction to proceed.

Some amphibolite layers have a strong lineation that is refolded by late Alpine folds; and mylonitic rocks containing synkinematic kyanite, as described above, also show a stretching lineation. These early Alpine lineations trend N-S (Fig. 5e). Their orientation is close to that of the late Alpine stretching lineation, and they may well have been rotated into this orientation by late Alpine strain. Early Alpine folds appear to be very rare, and we have no orientation data.

Late Alpine structures

Late Alpine metamorphism was accompanied by ductile deformation that was intense over much of the area that we have studied. The effects of this event tend to be dominant in many outcrops, and to obscure earlier structures. We distinguish four different classes of late Alpine deformational phenomena.

1. In paragneiss and mica schist, the commonest late Alpine effect is the modification and intensification of the earlier foliation (Variscan or early Alpine), accompanied by a stretching lineation, discontinuous shear-bands (extensional crenulation cleavage of Platt & Vissers 1980), and a considerable reduction of grain-size. The stretching lineation is only poorly visible in the micaceous rocks, but shows up well on interlayered quartzite bands or deformed quartz veins. It trends around N-S (Fig. 5a–d). The shear-bands form a very crude irregular set of cleavage surfaces, spaced 2–20 mm apart, at an angle of 20–30° to the foliation (Fig. 6f). The sense of shear on these bands is almost invariably top to north. The cleavage surfaces are so irregular that they rarely make a measurable intersection lineation with the foliation: where it is measurable it trends roughly E-W. Rocks strongly affected in this way have a phyllonitic appearance in the field. In thin-section, such rocks show marked grain-size reduction as a result of fracture of rigid minerals, pinching and pulling-apart of mica, dynamic recrystallization of quartz, and the growth of fine-grained biotite, white mica, and chlorite in shear-bands, pull-aparts, and in the matrix.

2. Late Alpine folds of the Variscan and early Alpine foliations occur locally, particularly in amphibolite and marble layers. Like the syn-mylonite folds discussed below, they have very variable orientations, ranging between E and N (Fig. 5f). Most are N or NW vergent. The orientation pattern suggests variable amounts of rotation of the hinge-lines towards the late Alpine stretching direction. Platy and tabular minerals are crenulated in the hinges of these folds, but a new preferred orientation or crenulation cleavage is in general not developed. The shape-fabric of dynamically recrystallized quartz is roughly axial-planar to the folds, however. In amphibole-rich rocks, early Alpine lineated amphibole is folded around late Alpine fold hinges, producing rapid and abrupt changes in orientation. Dilation voids in some crenulation hinges have been filled with chlorite, biotite, or sodic plagioclase.

3. In metagranitoids, aplite, and pegmatite, Variscan and early Alpine foliations are weakly developed or absent. Late Alpine deformation in these rocks produced a distinctive new foliation of mylonitic character, commonly characterised by composite *C-S* fabrics (Berthé et al. 1979) and a strong stretching lineation. Feldspar form augen, commonly with asymmetric tails (Passchier & Simpson 1986), and together with mica "fish" (Lister & Snoke 1984), and dynamically crystallized lenticular quartz aggregates, define a coarse grain-shape fabric *(S)*. This fabric is traversed by narrow through-going zones of high shear strain *(C)*, in many cases defined by the streaked-out recrystallized tails of feldspar and mica porphyroclasts. The *C* bands are spaced at 1–5 mm intervals, and tend to anastomose.

The "tails" on the feldspar porphyroclasts vary in character, and this primarily reflects differences in the temperature during late Alpine deformation. Where low temperature conditions are indicated by the presence of chlorite and the absence of late Alpine biotite, the feldspars contain fractures filled with quartz, they are strongly altered to albite, white mica, and clinozoisite, and the pressure shadows consist largely of quartz and white mica. These minerals were probably produced in part by the metamorphic breakdown of the feldspar, and were transported by diffusion and precipitated in the pressure shadows. Where late Alpine biotite is present, on the other hand, the feldspar porphyroclasts show marginal dynamic recrystallization as well as fracture, and the tails consist of dynamically recrystallized sodic plagioclase with a significant admixture of quartz. A combination of fracture, solution-reprecipitation, and plastic deformation leading to dynamic recrystallization seems to have been involved.

4. In zones several tens of metres thick, rocks of various compositions have been converted by high strain to ultramylonites. These are uniformly fine-grained (10–50 μm), with an intense platy foliation and strong stretching lineation, and earlier fabrics and microstructures have been largely obliterated. In thin section they show well-oriented newly crystallized white mica, chlorite, or biotite, and fine-grained dynamically recrystallized quartz (Fig. 6) and in the higher temperature areas dynamically recrystallized sodic plagioclase (Fig. 6h).

A characteristic feature of these mylonites are "syn-mylonite folds" that range from 1 cm to more than 10 m wavelength. These fold a foliation and stretching lineation that were already mylonitic, yet the following features suggest that they formed during the same progressive deformational event. a) The folds are largely restricted to the mylonite zones. b) They are asymmetric, with axial planes sub-parallel to the regional orientation of the mylonitic foliation. c) They vary in orientation from early tight folds subparallel to the regional stretching lineation, to late open folds at high angles to it (Fig. 5f). d) They have an axial-planar foliation that is microstructurally similar or identical to the main mylonitic foliation.

Syn-mylonite folds are characteristic of zones of high strain, and their origin has been discussed by, among others, Cobbold & Quinquis (1980), Hudleston (1977), and Platt (1983). We have emphasized them here because they are the most abundant and obvious small-scale structures in the Aspromonte Unit, but their geometry and orientation have little tectonic significance.

Kinematics of the late Alpine deformation

The marked variations in late Alpine strain, which occur on a scale of a few tens of metres in the Aspromonte Unit, require the deformation to have been non-coaxial; and this is borne out by the abundance of asymmetric features visible in the microstructure. On the other hand, the deformation is widespread, and we have not identified clearcut boundaries to it, so we have no grounds for assuming that the deformation was simple shear. Any non-coaxial deformation can be considered as containing a component of simple shear, and the sense of this shear can be determined from the microstructure.

Sense of shear indicators in these rocks include the following.

a) Shear-bands in phyllonitic paragneiss or mica-schist give a consistent N sense of shear (Fig. 6f).

b) *C-S* fabrics in metagranitoids and pegmatites are similarly quite consistent.
c) Asymmetric tails on porphyroclasts of feldspar, mica, garnet, and amphibole give a N sense of shear (Fig. 6d, e, and g).
d) New grains in dynamically recrystallized quartz aggregates are commonly oblique to the main foliation (Fig. 6g) and this can be used as a sense of shear indicator (Lister & Snoke 1984, Law et al. 1984).
e) The quartz *c*-axis preferred orientation pattern is a potential sense-of-shear indicator (Simpson & Schmid 1983). We have not yet measured the full preferred orientation pattern, but it is so strong in many quartzites and deformed quartz veins and lenses, that the obliquity of the preferred extinction direction is clear using a flat microscope stage.

All sense-of-shear criteria seen so far in the area of Fig. 3 indicate a northerly sense, with the exception of a few rocks with anomalously oriented E-W stretching lineations. These few examples give both E and W shear sense. These anomalous lineations mainly occur in ultramylonites affected by synmylonitic folding.

The most important zone of late Alpine mylonite that we have identified occurs along the Mont'Antenna ridge (Fig. 4). It appears to separate rocks showing little or no effects of Alpine metamorphism and ductile deformation above, from highly deformed and thoroughly re-equilibrated rocks below. There is also a marked temperature gradient within the mylonite itself, from low-temperature chloritic ultramylonites above to high-temperature mylonites with biotite and dynamic recrystallization of plagioclase below. These features suggest that the mylonite zone may have acted as a low-angle ductile normal fault, bringing rocks lower in the metamorphic pile into contact with rocks that had been less deeply buried.

Post-mylonite structures

A variety of structural phenomena postdate the late Alpine mylonitic deformation, and are therefore younger than 25–30 Ma.

1. Folds that post-date the late Alpine foliation are widespread. These are usually several metres in amplitude, with short steep limbs that correspond to semi-brittle shear zones, and moderately to steeply dipping axial planes. Some of these are associated with normal faults.

2. Brittle faults, marked by zones of cataclasite or clay gouge, are common, and have a wide range of orientations. Most appear to be normal faults. A large normal fault, dipping about 25° NE, with at least 1 km of vertical displacement, follows the Fiumara Buonamico (Figs. 3 and 4). This fault offsets the base of the Stilo-Capo d'Orlando Formation, and is therefore younger than early Miocene. The geometry and sense of shear of this fault suggest that it may represent a continuation of the extensional deformation that produced the Mont'Antenna mylonite zone (Fig. 4).

3. Eastward tilting of the eastern margin of the Aspromonte massif affects both the Capo d'Orlando Formation and the overlying Argille Varicolori thrust sheet, so this must be a Neogene effect.

Discussion

The two stages in the Alpine greenschist-facies metamorphism are spatially related; and on the scale of the unit as a whole, the greatest degree of early Alpine re-equilibration is associated with the highest temperature late Alpine effects. The P-T path suggested by these two stages is one characteristic of continental collision or crustal thickening processes (ENGLAND & THOMPSON 1984): an initial increase of pressure along a low P-T ratio geotherm as a consequence of crustal thickening, followed by a decrease in pressure at constant or increasing temperature as the rocks are exhumed and the thermal gradient returns to a "normal" value. The significance of the deformation can be very broadly interpreted in terms of this history. The early Alpine deformation, which largely predated the growth of the early Alpine assemblages, may have been related to the crustal thickening stage. This occurred at fairly low temperatures, and in view of its non-penetrative character, may have involved brittle thrusting. The late Alpine deformation would appear to be related to the uplift and exhumation of the rocks, and may have involved substantial vertical shortening and horizontal extension. This is supported by the extensional character of the Mont'Antenna mylonite zone (Fig. 4).

The northerly trend of the late Alpine stretching lineations in the Aspromonte massif, and the northerly sense of shear, are unexpected in the context of current ideas about the origin of the Calabrian arc. They differ markedly from the roughly E-W directed lineations recorded in Calabrian units further north (CARRARA & ZUFFA 1976, FAURE 1980, DIETRICH 1988), and they do not allow us to contribute with confidence to the debate about the provenance of the crystalline thrust sheets. It should be noted, however, that significant relative rotations of different parts of the Calabrian arc may have occurred during its Neogene history. If, for example, the Aspromonte Unit has been rotated clockwise during the Neogene, as suggested by AÏFA et al. (1988), the lineations and sense of shear may originally have been directed northwest. This might support an Adrian or African provenance for the crystalline nappes. The microstructural relationships, however, suggests that the mylonitic deformation is related to uplift and exhumation of the metamorphic rocks, rather than to the initial thrusting. The N-directed shear may therefore be related to a relatively late stage of extension, possibly associated with the initial stages of opening of the Tyrrhenian Sea. In this case, the significance of mylonitic deformation elsewhere in the Calabrian arc may need to be reassessed.

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